CHAPTER-7

7. Interdependence and Mutual Impact of the Physico-chemical Properties of the Soils and the Badland Processes

7.1 Introduction

There have been detailed researches on the initial factors and conditions responsible for theon-setting of erosive networks on soil systems, but these initial conditions are not enough to describe the self-enhancing nature of the erosive processes. There is a lack of such studies which deal with the changes in soil properties with the erosive processes which make the gully- channel network ever spreading. Obviously, the properties of soil systems, such as moisture-based limiting properties, grain size analysis, chemical properties, mineralogical characteristics etc. should provide insight into conditions that keep on accelerating badlands formation. Therefore, the main objective of this chapter is (i) to study the dispersive nature of soil by grain size analysis (ii) to determine the shift in physico-chemical properties of the soils characterising land degradation in the areas of an active network of rill-gully-ravine (iii) to categorise the zones of theseverity of land degradation which may be helpful in prioritisation and planning.

7.2 Methodology

The detail methodology adopted for this study is as follows:

7.2.1 Sampling

Soil samples were collected in the dry season (February) from each pedo-lithological unit in the study area (90.51 Km^2). The sampling locations include gully slopes (top slope, mid-slope and basal slope), agricultural fields, river flood plain, reclaimed land, barren land, shrub land and forested lands. Total 42 samples were collected from 32 different locations. To ascertain better representation, samples of soils were taken from different localities covering all types of land useland cover classes. The extension of badlands takes place through mega-rills and gullies initiallyshallow in nature. Three to four kilograms of soil samples from each sampling point were collectedusing an auger of 9 cm diameter from the depth of about 30 cm. The top litter layer was removedbefore the use of the auger. The samples were carried in air-tight poly bags to the laboratory andwere analysed. Nine calcrete samples were collected from different gullied sites in the study area,to analysis the long term climatic influence over the region.

7.2.2 Description of the Methods

The analytical data determined in the study includes grain size distribution, clay mineralogical study, the physical, index and chemical properties of soil, such as bulk density, total porosity of the soil, Atterberg limits, available nutrients in the soil, exchangeable cations in the soil, pH, EC,sodium absorption ratio (SAR) and soil organic matter (SOM).

Indian Standard Codes (for civil engineering purposes) were used to derive most of the parameters. *IS (Indian Standard) code 2720 (Part 4) 1985* was adopted for the grain size analysis.Grain size analysis gives the percentage of each constituent fraction (i.e**.** sand, silt and clay) presentin the soil. For better accuracy, analysis of each sample was carried out twice and there was a minor difference in the values, so the average value was taken into consideration. For the determination of bulk density of the collected soil samples, *IS code 2720 (Part 8) 1983* was followed. The pH, EC and SOM were obtained by the *IS code 2720(Part 26) 1987, IS code 14767:2000* and (*Part 22) 1972*, respectively. The reader should keep in mind that sampling and investigation were carried out as per *the Indian Standard Code.* The international readers should be careful during the utilization of the results because there are minor variations in the specification, sample size, units etc. amongst different accepted standards.

The concentrations of available sodium and potassium were analysed by ‘Flame photometer’. The alicod of sodium was prepared by the ammonium acetate method (Hanway and Heidel, 1952) whereas the alicod of available phosphorus was extracted with the help ascorbic acid method (Watanabe and Olsen, 1965) and analysed using spectrophotometer. The available concentration of N, Ca and Mg were analysed by titration method and their alicods were extracted;Subbiah and Asija method (1956) was adopted for available nitrogen whereas Schoonover method(1952) was followed for available calcium and magnesium. The methodology adopted for the isotopic study of the calcretes is listed in the Appendix-A.

Clay mineralogy was analysed with the help of X-ray diffraction (XRD) using a Rigaku Miniflex X-ray diffractometer with a Cu Kα radiation source and Fourier transform infrared (FTIR) spectra using Nicolet iS5 spectrometer using sample / KBr pallets. Imageries have been achieved by High-Resolution Scanning Electron Microscopy (HRSEM).

The spatial maps of various parameters of soil properties were prepared from point data inthe GIS environment using Arc GIS software (10.6.1) (Figure 7.1).

7.2.3 Statistical Methods

For estimating the spatial distribution of various parameters of soils, inverse distance weighting (IDW) interpolation technique was used in ArcGIS (10.6.1) and cross-validation was applied to evaluate the accuracy of the interpolation method using root mean square error measurement (RMSE) (Figure 7.1). Inverse distance weighted (IDW) interpolation explicitly assumes that thingsthat are close to one another are more alike than those that are farther apart (Tomislav, 2009). To predict a value for any unmeasured location, IDW uses the measured values surrounding the prediction location. The measured values closest to the prediction location have more influence on the predicted value than those farther away. Thus, it gives greater weights to points closest to the prediction location and the weights diminish as a function of distance. The interpolation value wascalculated by the following formula:

$$Z(x_0) = \frac{\sum_{i=1}^{n} \frac{x^i}{h_{ij}^{\beta}}}{\sum_{i=1}^{n} \frac{1}{h_{ij}^{\beta}}} \quad (7.1)$$

where $Z(x_0)$ is the interpolation value, n represents the total number of sample data values, x_i is the i^{th} sample in prediction, h_{ij} is the separation distance between interpolated value and the sampledata value and β denotes the weighting power (Robinson and Metternicht, 2006). The root mean square error (RMSE) was calculated as:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Oi - Si)^2} \quad (7.2)$$

where Si is the predicted value, O_i is the observed (known) value; *N* is the number of values. To have an appropriate estimation, RMSE should be as small as possible (Johnston et al., 2001; Mishra et al., 2018).

The methodological flowchart for the preparation of spatial maps is shown in Figure 7.1. The metadata of soil property having geo-tagged location points was imported into the GIS environment, followed by the exploration of the data location point. Then, the data set was cross-validated by two interpolation techniques, IDW and normal kriging. In this process, IDW performed better and has a lower RMSE value than the normal kriging method; hence IDW methodhas been selected for the interpolation and final spatial maps were prepared using this technique. The measured points (soil data) were used in the calculation of each interpolated cell (soil data grid), these raster results were further extrapolated beyond the point data up to the feature point, i.e. the bound map (vector data) of the study area, so as to mask the raster in the shape of the featurepoint.

The kind of huge data may cause confusion in conclusion. So to avoid information overlapping from high dimensional data sets, statistical analysis, such as Pearson Correlation Coefficient (PCA) (Sedgwick, 2012) was carried out to reduce the data. The detailed study is carried out with eighteen physico-chemical parameters.

The distribution of pH, electrical conductivity, soil organic matter and nutrient contents inthe soils are plotted in the form of box plots (Tukey, 1977). These plots represent the maximum, minimum and mean values of the dataset whereas the outliers are seen outside the range of the characteristic dataset of the soils.

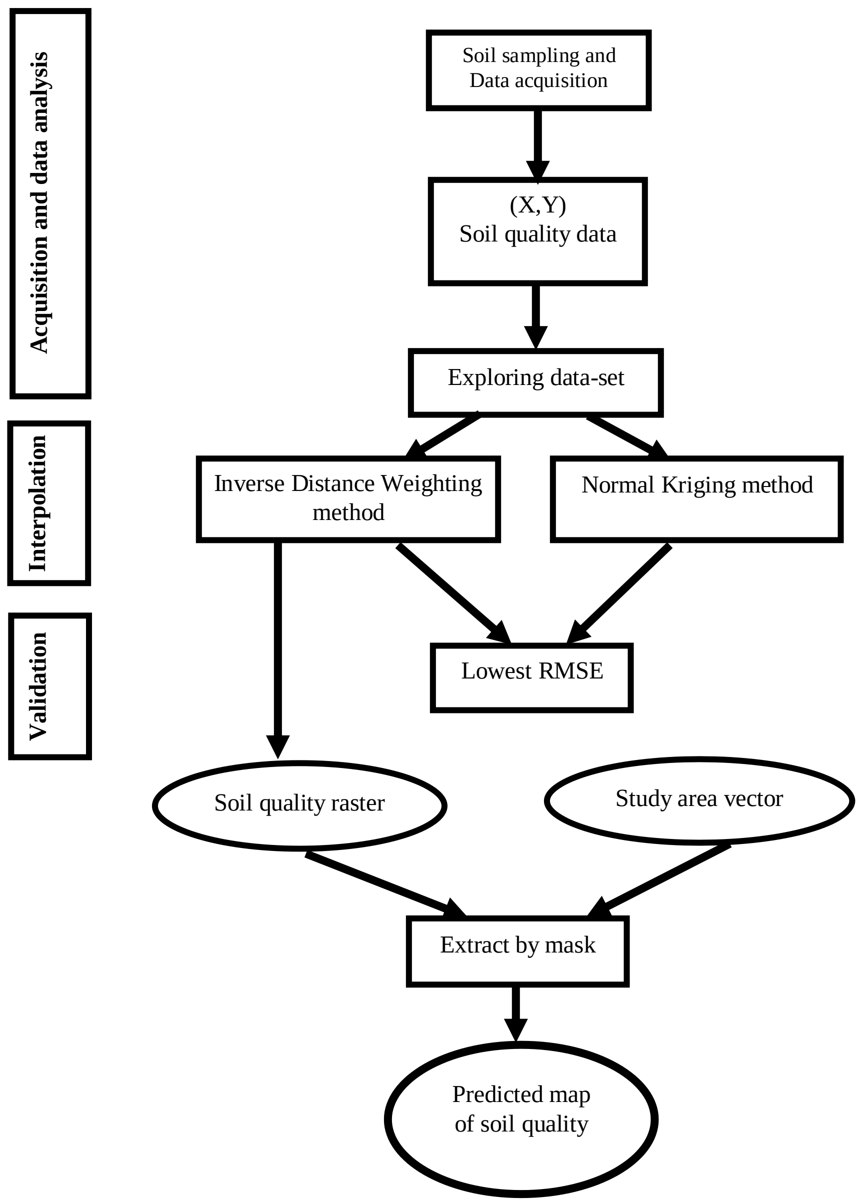

Figure 7. 1 Methodological flow chart of spatial mapping

7.3 Results

7.3.1 Grain Size Analysis

Badlands may form in a variety of soil systems. They may develop on soft sedimentary terrain (Gallart et al., 2002), where soil textures are silty or clayey (Howard, 2009). On the other hand, the silty and fine sandy textured soil is reported to be prone to erosion compared to clayey (containing less activated clay minerals) and coarse-grained sandy soil (Moreno-de-las-Heras et al., 2019). Badlands can also develop in terrain with high clay content with a considerable amountof swelling clay minerals such as smectite (Gallart et al., 2002). Owing to the shrinkage and swelling capacity of smectite, the internal weathering process dominates and influences the formation of badlands.

The present study brings forth such facts of soil characteristics that can be held responsiblefor the process of soil erosion and badlands formation. Based on the soil texture triangular plot (Figure 7.2), the majorities of soil particles in the samples are silt and have a uniform soil texture, i.e. silt loam (as per triangular textural classification by USDA). Sand, silt and clay particles werefound to vary in the range of 21-39%, 49 - 67% and 7-16%, respectively (Table 7.2). In the UnifiedSoil Classification System (USCS), these soils are grouped under ML class having inorganic silt,very fine sand, liquid limit < 50%, with low plasticity.

Table 7. 1 Grain size distribution and physico-chemical property of the studied soil samples

Sample No.	Location	Clay %	Silt %	Sand %	Bd (gm/cm^3)	TP %	LL %	PL %	Ip %	USCS	EC (ds/m)	SAR	SOM %	pH	Ca^{+} (ppm)	Mg^{+} (ppm)	Na^{+} (ppm)	N^{+} (ppm)	P^{+} (ppm)	K^{+} (ppm)
L-1	Gully slope	11	63	26	1.90	32.99	17.53	13.91	3.62	ML	0.342	0.55	0.243	7.89	3200	547	129	54.21	66.84	84.5
L-2	Gully slope	15	64	21	1.97	30.77	18.69	15.57	3.12	ML	0.48	0.66	0.27	7.58	2950	678	154	56.65	54.68	74.5
L-3	Gully slope	14	59	27	1.89	35.57	18.57	16.00	2.56	ML	0.29	0.59	0.39	7.82	1800	560	112	78.35	45.24	165.5
L-4	Gully slope	7	55	38	1.94	32.57	14.65	11.44	3.21	ML	0.233	0.42	0.31	7.86	2400	468	86	65.74	79.34	169.5
L-4.1	Gully slope	16	56	28	1.93	31.91	18.94	15.52	3.42	ML	0.621	0.43	0.24	7.24	2160	1308	102	50.89	35.96	173.5
L-5	Gully slope	14	61	25	1.93	32.40	17.54	14.73	2.81	ML	0.654	0.73	0.27	7.65	1765	846	149	57.25	75.48	101.5
L-6	River flood plain	10	56	34	-	-	-	-	-		1.329	0.72	0.26	7.36	1900	60	116.5	56.41	35.72	112
L-6.1	River flood plain	13	50	37	-	-	-	-	-		0.526	0.60	0.1	7.21	1720	1248	133.5	22.54	44.59	104
L-7	Reclaimed land	10	64	26	1.90	32.06	17.54	14.73	2.81	ML	0.396	0.53	0.2	8.63	1300	1020	106	42.41	40.15	175
L-7.1	Gully slope	11	66	23	1.94	30.73	15.49	13.95	1.54	ML	0.184	0.68	0.2	7.88	1800	792	138	46.88	55.93	121.5
L-8	Gully slope	14	60	26	1.96	33.02	16.57	14.53	2.04	ML	0.971	0.65	0.37	7.65	1890	1254	149	75.98	61.54	105.5
L-8.1	Gully slope	11	61	28	1.92	32.51	16.38	14.49	1.89	ML	0.24	0.46	0.27	7.57	2460	1150	110	57.25	68.94	164
L-9	Gully slope	15	59	26	1.90	35.01	17.97	14.49	3.48	ML	0.416	0.53	0.37	7.76	2960	36	106	76.19	65.54	161.5
L-9.1	Gully slope	14	54	32	1.97	31.41	15.98	13.31	2.67	ML	0.28	0.74	0.29	7.51	1860	924	156	62.98	58.39	99.5
L-9.2	Gully slope	13	59	28	1.92	31.98	17.94	15.6	2.34	ML	0.228	0.75	0.23	7.49	2380	816	166	48.98	64.06	189.5
L-10	Gully slope	15	54	31	1.90	37.21	18.02	15.14	2.88	ML	0.218	0.71	0.49	7.37	3060	588	163	88.93	69.24	86
L-10.1	Gully slope	13	57	30	1.94	34.29	16.98	15.27	1.71	ML	0.208	0.38	0.40	7.62	3380	276	86	80.56	21.42	57
L-10.2	Gully slope	13	63	24	1.90	33.75	15.48	13.46	2.02	ML	0.198	0.81	0.29	7.54	2300	924	182.5	61.50	41.39	187
L-10.3	Gully slope	14	60	26	1.90	35.10	17.21	15.5	1.71	ML	0.238	0.45	0.38	6.81	1300	480	74.5	78.04	39.91	183.5
L-11	Gully slope	12	64	24	1.98	29.89	15.57	13.77	1.8	ML	0.198	0.47	0.24	7.42	2100	984	105	50.89	46.32	146.5
L-11.1	Gully slope	13	59	28	1.92	30.89	16.58	14.08	2.5	ML	0.429	0.61	0.18	7.56	2260	372	118.5	38.17	63.08	80.5
L-12	Gully slope	14	57	29	1.89	33.80	18.59	16.74	1.85	ML	0.37	0.67	0.28	7.87	3100	545	155	59.38	64.78	94.5
L-13	Barren Land	7	54	39	2.09	27.02	15.35	13.04	2.31	ML	0.215	0.70	0.28	5.86	420	396	83.5	59.38	25.54	110.5

L-14	Barren Land	8	55	37	2.02	30.91	15.25	12.8	2.45	ML	0.138	0.91	0.36	4.96	700	60	93.5	76.34	27.69	84
L-15	Agricultural Field	15	56	29	1.96	31.41	18.88	16.93	1.95	ML	0.186	0.35	0.28	8.24	2820	48	69.5	59.38	41.63	188.5
L-16	Reclaimed land	13	60	27	1.95	31.22	18.5	16.3	2.2	ML	0.21	0.33	0.24	7.68	3580	950	85.5	50.89	61.57	140
L-17	Reclaimed land	16	56	28	1.98	33.15	18.5	13.31	5.19	CL+ ML	0.175	0.31	0.41	7.89	3250	650	75.4	82.77	57.94	135
L-18	Agricultural Field	10	52	38	1.97	30.35	13.6	10.55	3.05	ML	0.144	0.39	0.24	8.07	1700	684	76	51.10	45.33	79
L-19	Gully slope	16	63	21	1.89	34.32	20	17.28	2.72	ML	0.38	0.57	0.31	7.07	2350	450	115.7	65.74	47.97	95.5
L-20	Reclaimed land	14	64	22	1.92	31.74	19.34	16.89	2.45	ML	0.246	0.29	0.22	7.7	3300	96	62.5	46.65	50.75	149.5
L-21	Agricultural Field	15	61	24	1.94	33.05	18.75	16.6	2.15	ML	0.238	0.85	0.34	7.23	940	120	104	72.10	57.16	96.25
L-22	Barren Land	12	67	21	1.96	33.14	16.5	13.87	2.63	ML	0.198	0.37	0.38	7.78	1920	696	75.5	80.58	52.72	112
L-23	Forested Land	16	55	29	1.93	35.85	23.1	17.95	5.15	CL+ ML	0.984	1.32	0.48	6.67	920	144	164	96.43	63.57	180
L-24	Forested Land	15	58	27	1.90	37.55	19.2	16.75	2.45	ML	2.012	2.32	0.54	6.77	860	144	280	93.54	36.70	127
L-25	Shrub Land	15	60	25	1.98	33.27	19	17.04	1.96	ML	0.956	0.81	0.42	7.32	1260	816	150	84.38	58.15	149
L-26	Forested Land	14	59	27	1.91	37.25	21.75	18.43	3.32	ML	2.103	2.08	0.52	7.38	960	276	285	94.29	45.33	388
L-27	Barren Land	11	53	36	2.02	29.69	15.48	13.11	2.37	ML	0.248	0.64	0.31	5.14	540	280	73.5	65.74	26.57	94.5
L-28	Barren Land	13	49	38	2.04	28.92	15.27	13.27	2	ML	0.214	0.67	0.29	4.91	630	345	85	61.50	28.64	85
L-29	Barren Land	12	51	37	2.00	31.41	15.67	12.84	2.83	ML	0.154	0.77	0.35	5.08	460	364	91.5	74.22	24.87	89
L-30	Barren land	11	51	38	2.10	25.06	14.94	12.55	2.39	ML	0.247	0.61	0.21	4.96	680	515	86.5	44.53	29.54	97.5
L-31	Agricultural field	15	57	28	1.95	31.60	18.94	15.52	3.42	ML	0.289	0.78	0.28	7.87	1040	320	112	59.38	54.62	86.5
L-32	Reclaimed land	13	62	25	1.96	32.04	17.54	14.77	2.77	ML	0.24	0.38	0.32	7.84	2540	755	84.7	67.86	56.72	138
Mean		12.93	58.19	28.88	1.95	32.42	17.44	14.80	2.64		0.44	0.68	0.31	7.23	1926.55	571.07	120.26	64.21	49.80	130.03
Max.		16	67	39	2.10	37.55	23.1	18.43	5.19		2.103	2.32	0.54	8.63	3580	1308	285	96.43	79.34	388
Min.		7	49	21	1.89	25.06	13.6	10.55	1.54		0.138	0.29	0.1	4.91	420	36	62.5	22.54	21.42	57

Abbreviation: Bd- Bulk density, TP- Total porosity, PL- Plastic limit, LL- Liquid limit, Ip- Plasticity index, SOM- Soil organic matter, pH- Potential of Hydrogen, EC- Electrical conductivity of soil, SAR- Sodium absorption ratio, Ca^+- Calcium, Mg^+- Magnesium, Na^+- Sodium, N^+- Nitrogen, P^+- Phosphorous, K^+- Potassium

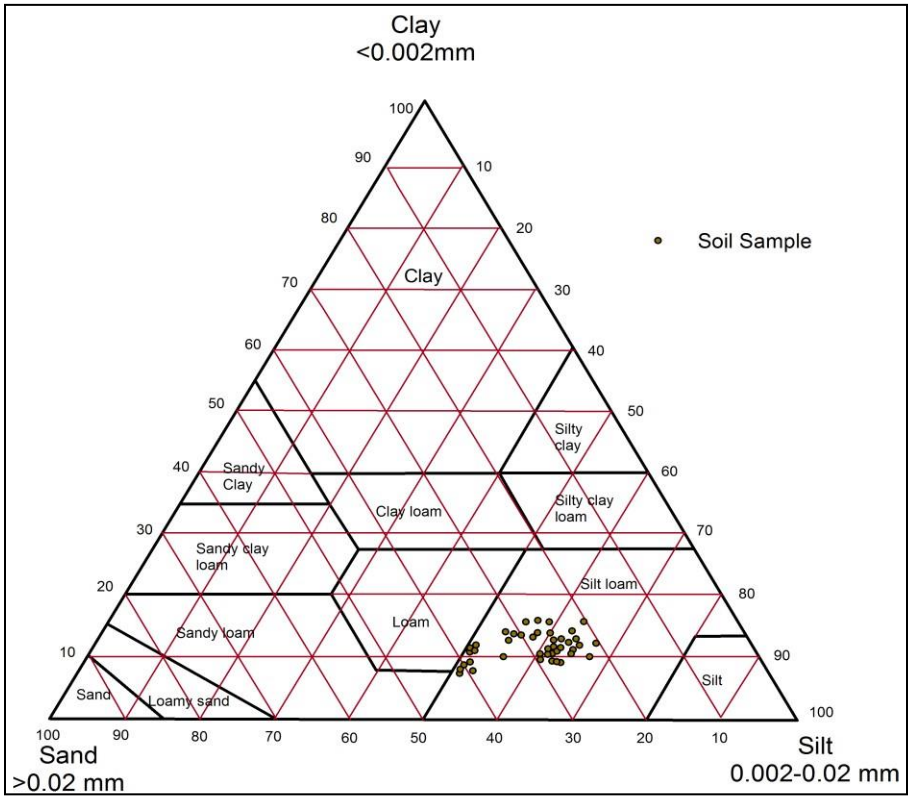

Figure 7. 2 Soil textural classifications (Soil Survey Staff, 1951, USDA) of the soils of the studyarea

7.3.2 Clay Mineralogy

Clay minerals may be physico-chemically active and dispersive in the presence of saturating levelsof monovalent cations (Levy et al., 1993) and large sodium ions weaken the bonds in the clay particles resulting in expansion, swelling and soil dispersion. The dispersive soils are structurally unstable on wetting because the individual clay particles disperse into solution (Quirk and Schofield, 1955; Appelo and Postma, 1993; Maheshwari and Jayawardane, 1992).

Based on XRD and FTIR analysis, most samples have illite (2Ɵ value of 8.9, 19.8, 36.6, 55.6 and wavenumber of 1640, 1431, 1635, 1639 and 1420) as the dominant clay mineral with thesecondary amount of montmorillonite (2Ɵ value of 5.8 and 35.3) (Figure 7.3). Illite is moderately prone to erosion during weathering and runoff and it has the ability to clog pore spaces and reduce permeability considerably (Stern et al., 1991; Appelo and Postma, 1993).

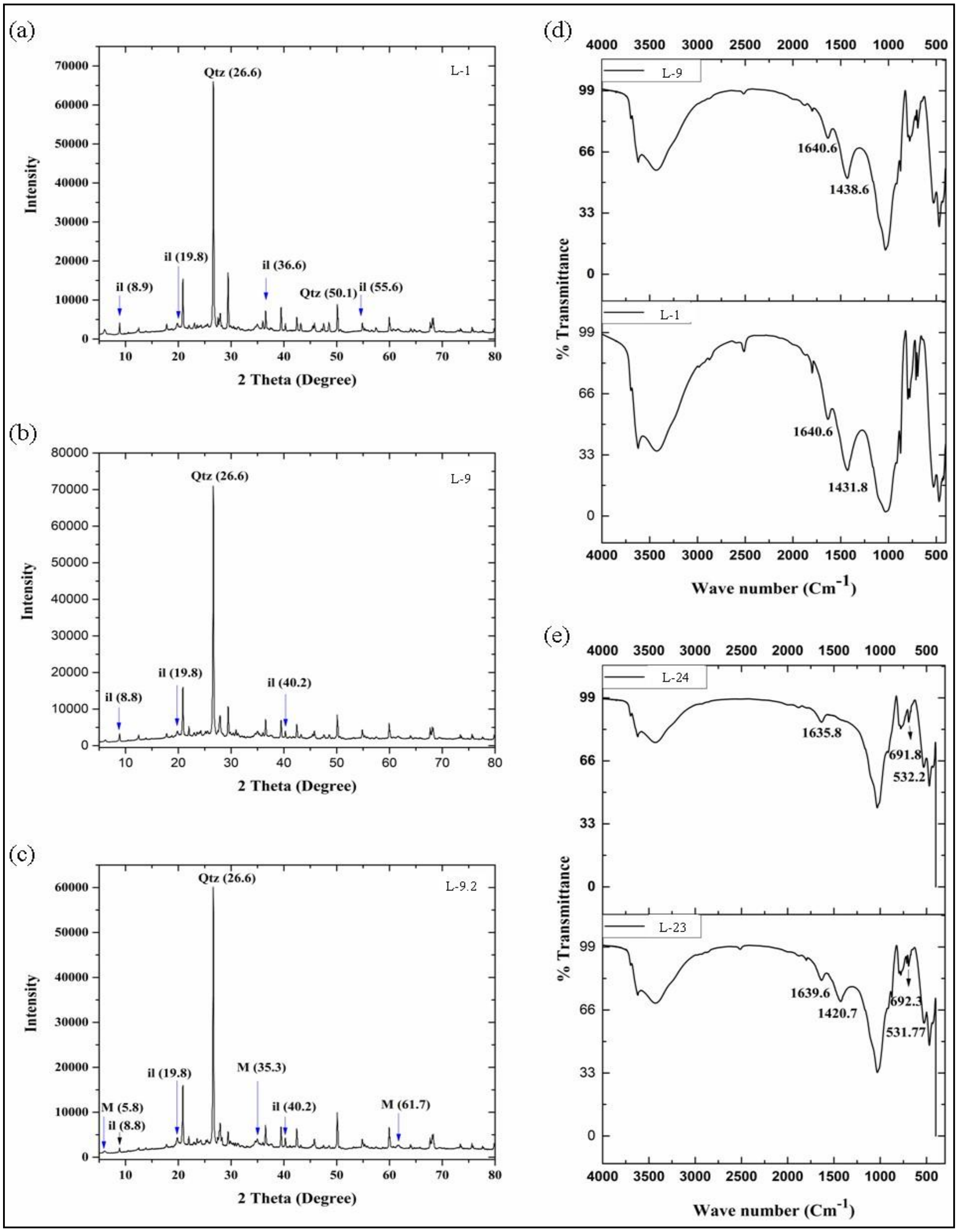

Figure 7. 3 XRD data of (a) soil sample L-1; (b) L-9; (c) L-9.1;FTIR data of (d) L-1 and L-9; (e)L-23 and L-24

Abbreviation: il- Illite, Qtz- Quartz, M- montmorillonite

In addition to illite, soils have calcrete grains and hardpan layers having a microscopic overgrowth of fibre calcite crystals (Figure 7.4) that possibly restrict the hydraulic movement. The clogging behaviour of clay minerals and the presence of calcrete hardpan enhance the runoff on the ground,accelerating erosion resulting in a rugged topography.

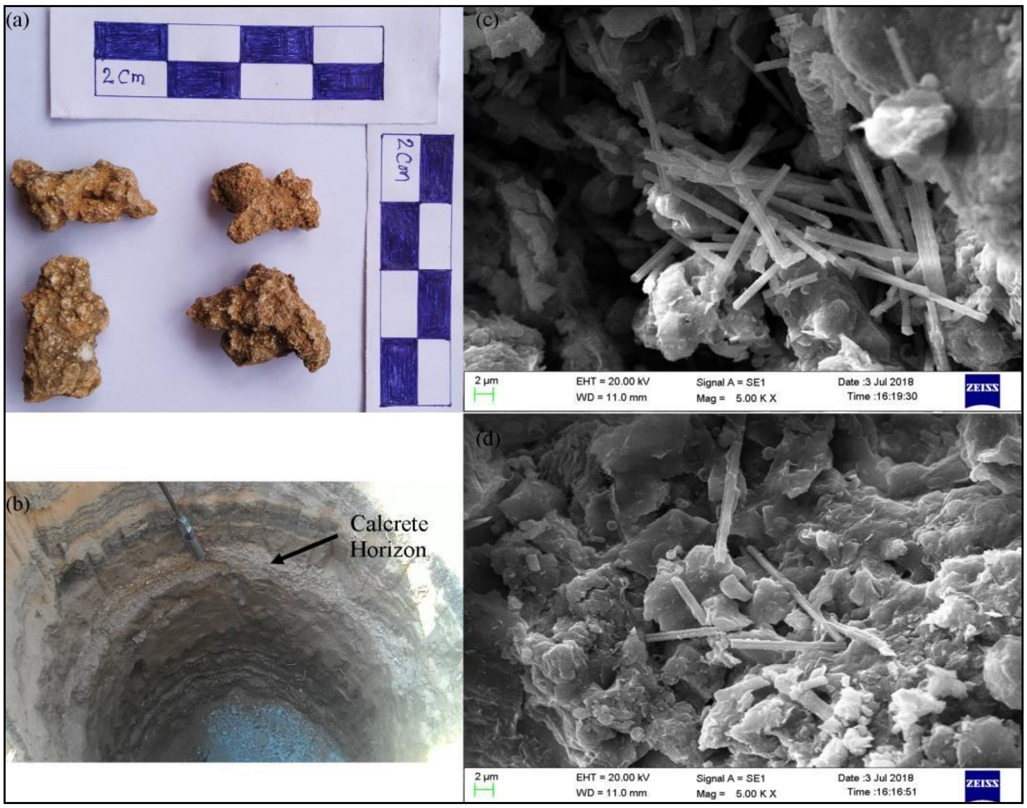

Figure 7. 4 (a) Calcrete nodules; (b) Calcrete horizon; (c) and (d) Microscopic fibre of calcite

7.3.3 Bulk Density and Total Porosity

Parameters like bulk density, total porosity of the soil may be used in defining soil behavior responsible for the badlands formation. Soil bulk density is an indicator of soil compaction. Compacted material reduces infiltration and total soil porosity while increases the runoff and promotes sheet and rill erosion (Parker et al., 1995; Bennett et al., 2000). According to USDA – NRCS (Technical Bulletin No.1355), soil bulk density >1.75 (gm/cm^3) restricts plant root growthin silts and silt loam textured soil. The results show that bulk density in the study area varies within the range of 1.89 - 2.1gm/cm^3. Consequently, the soils here have only limited total porosity owingto higher bulk density (Table 7.1 and Figure 7.5a and 7.5b). The total porosity of the soil in the study area ranges from 25.06 to 37.55 %. This eventually enhances runoff and causes soil erosion.

7.3.4 Atterberg Limits

The Atterberg limits seem to have played a central role in the formation of badlands in the study area. These limits decipher soil behaviour in different water saturation conditions. Plastic and liquid limits of soil manifest soil vulnerability to degradation or erosion (Sharmeen and Willgoose,2006) and both are directly proportional to the clay content of soil (Wagner, 2013). Dahms and Fritz (1998) restricted the *lower limit* of plastic limit in the range of 20 - 28% and that of the liquidlimit between 25 - 23% in silty soil. Plasticity index is the difference of liquid and plastic limits and its smaller values are correlated with tunnelling activity in the soil horizons. The low value ofthe plasticity index (< 5.0) explains pipe erosion of the ground (Perry, 1975).

The values of the plastic and liquid limits in this study are of the magnitude of 10.55 - 18.43% and 13.6 - 23.1%, respectively (Figure 7.5c and 7.5d). The soils of the area are silty in composition with a low liquid limit (less than 50%) and low plasticity index (1.54 - 5.19%), whichis classified as ML (silt with low liquid limit) in the Unified Soil Classification System (USCS) (Figure 7.6). The less compressive and plastic property of the soil makes it erodible and prone tothe piping process.

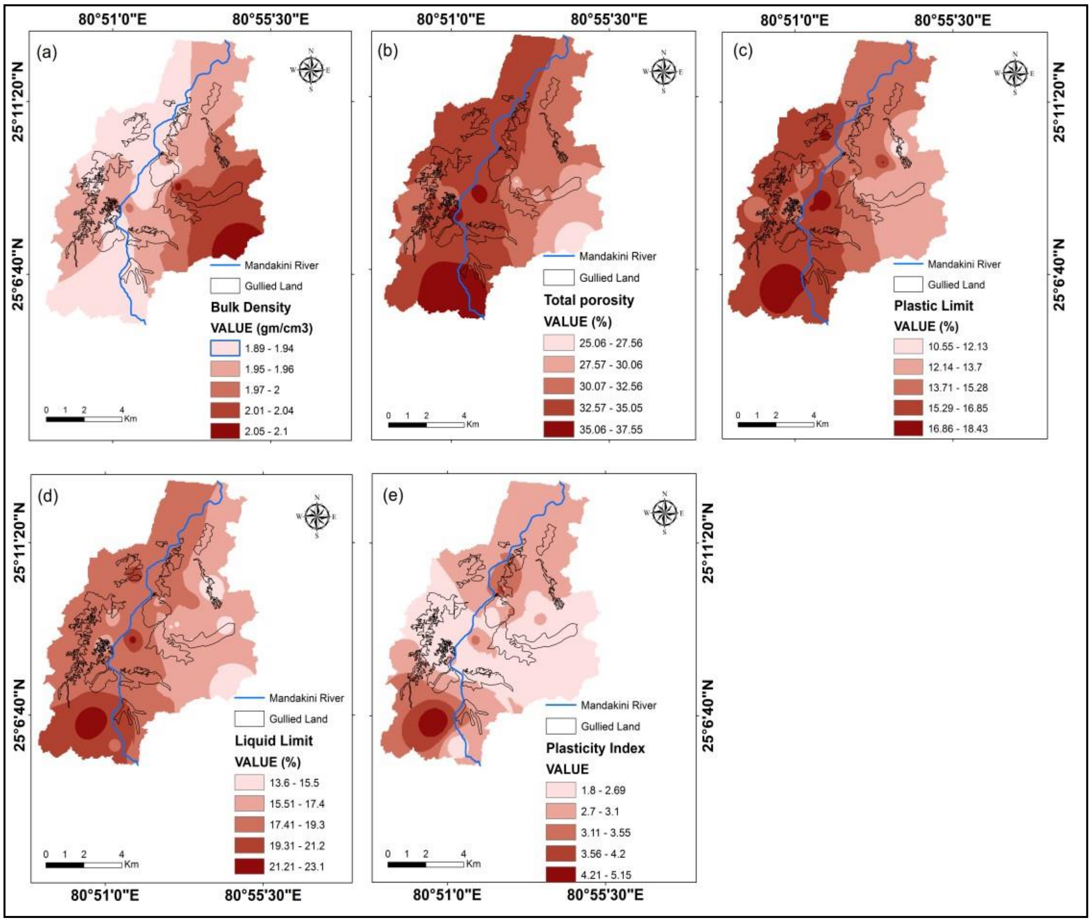

Figure 7. 5 Spatial distribution map of (a) Bulk density (b) Total porosity (c) Plastic limit (d) Liquid limit and (e) Plasticity index

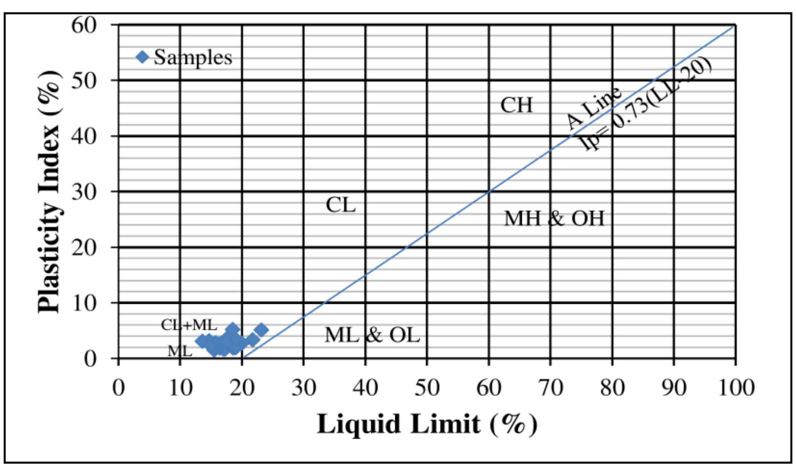

Figure 7. 6 Plasticity chart of the soil samples of the study area (after Casagrande, 1948)

Abbreviation: Ip- Plasticity Index; LL- Liquid Limit; ML- Low Plastic Silt; CL- Low Plastic Clay; MH- HighPlastic Silt ; CH- High Plastic Clay; OL- Low Organic Soil; OH- High Organic Soil

7.3.5 Chemical Properties

Chemical properties like electric conductivity (EC), sodium absorption ratio (SAR), pH and soil organic matter (SOM) play an important role in deciding badlands morphology (Waskom et al., 2003).

The study area has low sodium (Na) value that influences EC as well as SAR values. EC value ranges from 0.13 to 2.10 ds /m and SAR varies from 0.29 to 2.23 (Table 7.1) (Figure 7.7a and 7.7d). The EC, Sodium and SAR parameters have low values in the studied badlands.

The pH of the soil and SOM largely influence the mobility of trace elements (iron, manganese, zinc, copper and cobalt), biological as well as enzyme activities, conditions of mineralization, nitrification/denitrification and biodegradation (Chaney and Swift, 1984; Neina, 2019; Ostovari et al., 2020; Ullah et al., 2020; Yang et al., 2020). Less than 2% SOM indicates erodible soil and erodibility decreases with an increase in SOM content (Brady and Weil, 2008).

The alluvial soils of the area are of denudation origin and come from the Vindhyan sandstones. The cement of the sandstone is non-calcareous in the study area (Gupta et al., 2003), leading to acidic pH 4.96 - 5.86 of the soil on the sandstone (Figure 7.7c). On the contrary, in thealluvial part, the pH of soils is high (alkaline) and the maximum value goes up to 8.63 (Table 7.1).Solubility of SOM increases with the increase of pH in the soil (Curtin, 1998; Andersson et al., 2000). The adsorption of the trace element is maximum in intermediate pH conditions but in narrow ranges (Carrillo-González et al., 2006). This fact of the increase in pH in badlands has reduced SOM in the soils. However, part of badlands that has low pH also contains low SOM, where the low value of the latter may be due to higher bulk density. Hence, the distribution of SOM in the study area is very less and ranges from 0.1to 0.54% (mean 0.31%) (Table 7.1 and Figure 7.7b).

The results of the Carbon-Oxygen isotopic analysis of several calcrete samples from the study area, shows a range of -1 to -8.28 ‰ of $\delta^{13}C$ ‰ value (Table 7.2). The range indicates an abundance of C4 plants at the time of calcrete secretion (Lerman, 1972). Furthermore, $\delta 18O$ ‰ values vary from -4.59‰ to -6.48 ‰ with a standard deviation of 0.56. The values of $\delta 18O$ ‰ depict that the evaporation rate in the study area was relatively high at the time of formation of the calcrete (Salomons et al., 1978). The low standard deviation indicates that the climate remained unchanged over a longer period of time. A dry, arid, semi-arid, or alternate dry and wet conditionreduces the moisture content of the soil, plants availability and consequently decreases the organic matter availability of the soil (Jenny 1941; Selhorst and Lal, 2012). In the study area, calcretes arefrequent in multiple soil horizons and crest of the mound. The abundance of calcrete in the soil depicts that the study area has a history of the multiple dry or alternating wet and dry periods in the past. This may affect the decomposition rate of the organic matter and result in a low (averageSOM= 0.31%) occurrence of the soil organic matter (Table 7.1).

Table 7. 2 Carbon-Oxygen isotopic distribution in the calcrete samples of the study area

Sample No.	ʓ18O ‰	ʓ13C ‰
C1	-6.05	-7.41
C2	-6.48	-8.28
C3	-6.04	-4.94
C4	-6.18	-5.37
C5	-5.76	-2.14
C6	-6.36	-6.53
C7	-5.64	-1.01
C8	-5.64	-5.22
C9	-4.59	-6.41

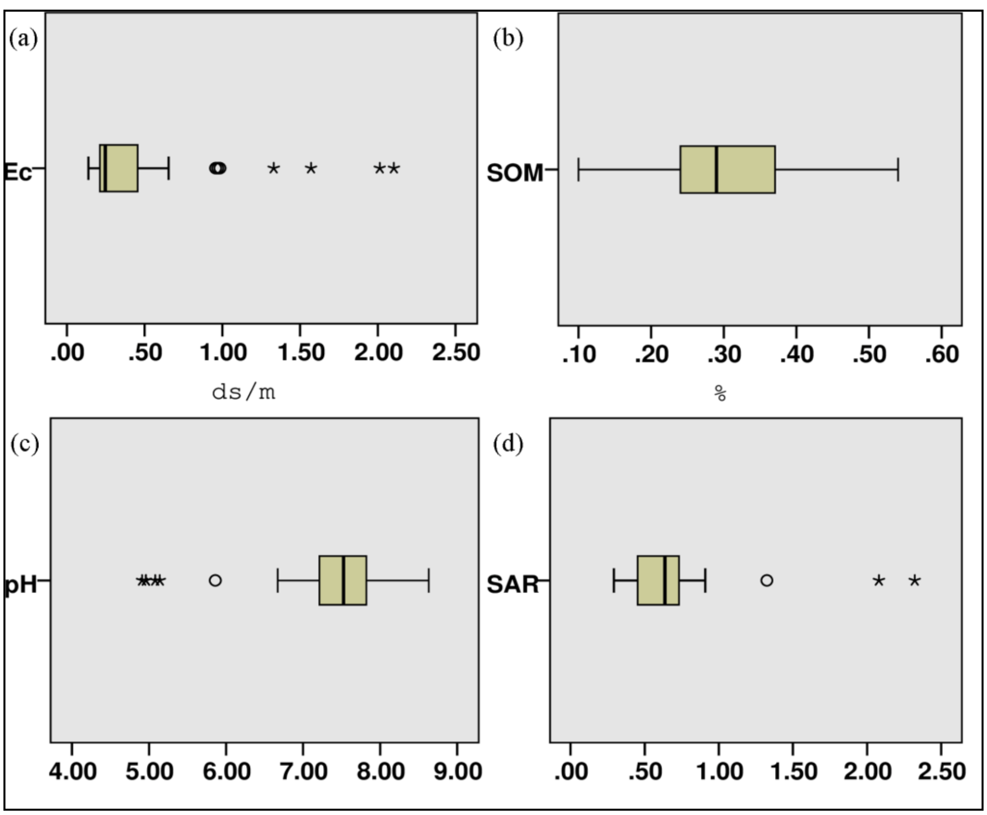

Figure 7. 7 Box plot of (a) Electric conductivity (b) Soil organic matter (SOM) (c) pH (d) SAR

7.3.5a Nutrients

Plants and vegetation cover act as a natural barrier against erosion (Hao et al., 2020; Kumar et al.,2021). There are three kinds of nutrients present in the soil, namely macronutrients (nitrogen, phosphorous and potassium), secondary nutrients (calcium, magnesium) and micronutrients (iron,manganese, zinc, etc,). The optimal concentration of macronutrients for plant health should be 140-350 ppm nitrogen, 30 - 60 ppm phosphorous and 110 - 200 ppm potassium (Espinoza et al., 2012). A higher concentration of calcium should be up to 5% of available calcium in the soil; thelower limit of available calcium for optimal plant growth is 400 ppm (Espinoza et al., 2012).

The available nitrogen, phosphorous and potassium concentration in the study area are 21.65 - 96.42 ppm, 21.41 - 79.34 ppm and 57 - 388 ppm, respectively, whereas available calciumand magnesium range from 420 - 3580 ppm and 36 - 1308 ppm, respectively (Table 7.1). Nitrogen concentration in the study area is very low; potassium concentration is moderate, whereas phosphorous concentration is optimum (Figure 7.8b). Calcium and magnesium concentrations arehigher in the alluvial part of the basin and considerably lower in the sandstone dominating the southern and eastern parts of the study area (Figure 7.8a). The concentration of available sodium ranges between 62.5 – 285ppm (Figure 7.8b). The distribution of sodium is low in most of the areas (62.5 – 151.53) except the central and southern shrubby and forested parts (151.54 – 284.91ppm). A relatively higher value of sodium in the shrubby and forested area may be due to the rootaction of plants (Maas and Ogata, 1972).

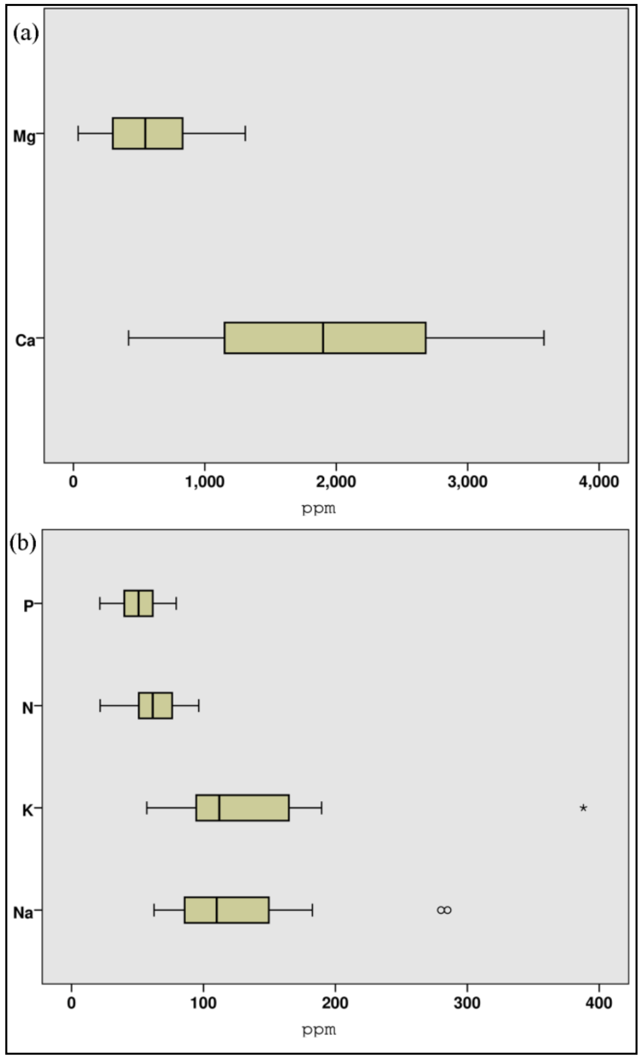

Figure 7. 8 Box plot of nutrient value of soil (a) Ca, Mg; (b) Na, K, N, P

7.3.6 Overlay Analysis

The liquid limit, plasticity index, bulk density and drainage frequency are the most important factors characterizing badlands in the study area. An overlay analysis has therefore been made todelineate zones of the severity of the land degradation. The four factors taken in the overlay analyses are intrinsically related to badlands conditions and processes. The liquid limit, plasticityindex and bulk density indicate the conditions favorable for rill - gully - channel development. The fourth-factor drainage frequency (Figure 5.6) shows the current status of channel formation or the intensity of the operative processes. Spatial maps of all the four factors were prepared in GIS using inverse distance weighting (IDW) interpolation technique and weights were assigned tothe different classes of these layers depending upon their vulnerability to erosion on the scale of 1-10. (Figure 7.9); the value closer to one is safe and the severity increases towards greater values.In overlay analysis, each factor is assigned 25% weight. Thus, the overlay analysis brings out three categories, namely severe, very severe and extremely severe zones of land degradation in the study area (Figure 7.10).

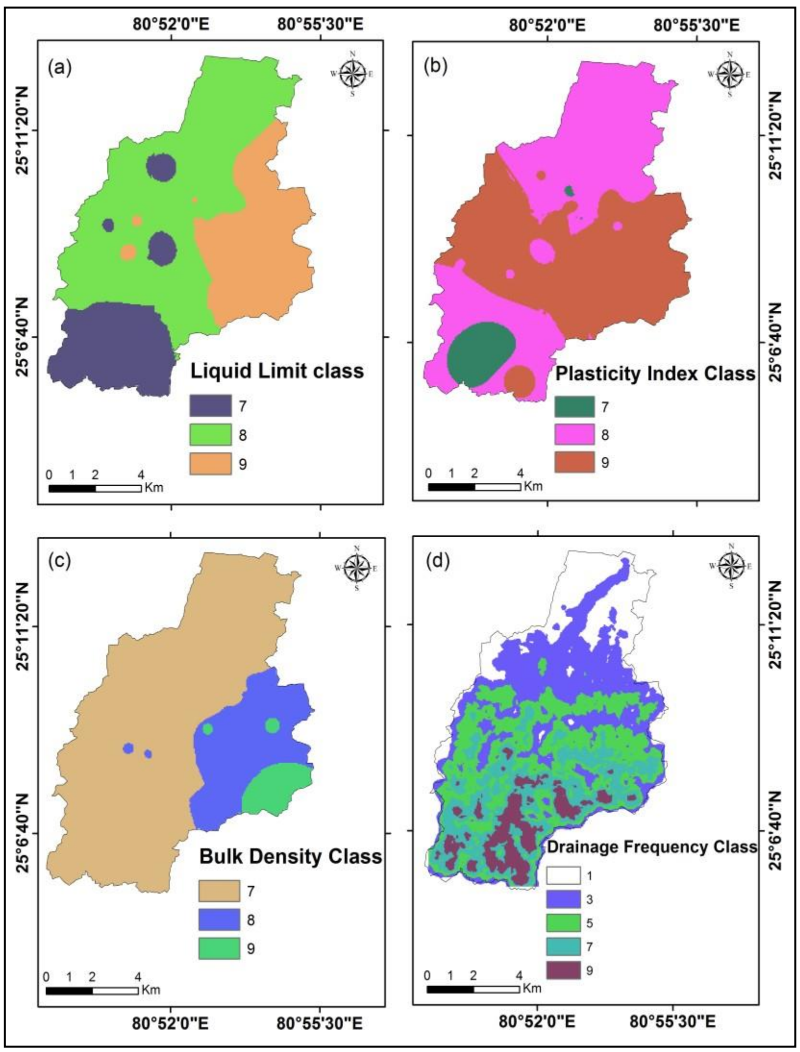

Figure 7. 9 Spatial map showing assigned classes for overlay analysis of (a) Liquid limit (b) Plasticity index (c) Bulk density (d) Drainage frequency

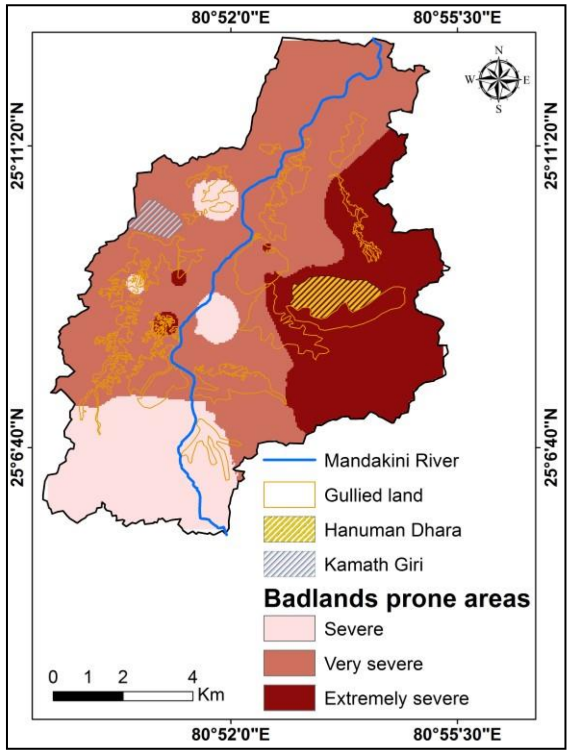

Figure 7. 10 Spatial map of the badlands prone areas

7.3.7 Statistical Analysis

7.3.7 a Principal Component Analysis

Principal component analysis (PCA) of eighteen physico-chemical parameters was carried out in SPSS software (version 16.1). Out of eighteen parameters, two principal components (PC1 and PC2) were detected with eigenvalues greater than two (Table 7.3); these components account for more than 58% of the total variance, reflecting the mutual relationship and impacts of parameters. PC1, with more than 35% variance, has five parameters with a loading value of more than 0.7 (Table 7.3). Parameters like liquid limit, plastic limit, total porosity, electrical conductivity have positive loading values, whereas bulk density has negative loading values. This indicates thatthese four parameters are varied together. The result shows that soil health increases with an increase in total porosity, liquid limit, plastic limit, electric conductivity, whereas PC1 decreases with a rise in soil bulk density.

PC1 is strongly correlated with soil's total porosity (87%) and this becomes the most vitalcomponent regarding soil health. Genetically total porosity is governed by grain size distribution;further, if the porosity of the soil is good, then it opens up the scope to thrive microorganisms in the soil, which helps to build the soil structure and enhances the soil organic matter; that also increases soil nutrients. However, the liquid and plastic limits are governed by grain size distribution and influenced by SOM. On the other hand, bulk density has a negative impact on soilhealth. So we can say that total bulk density, porosity, plastic and liquid limit are the primary factors in this system, influenced by grain size distribution, SOM and pH.

PC2, with a variance of more than 22%, has two significant parameters with a loading value greater than 0.7. The result shows that PC2 decreases with increasing available calcium, pH.This indicates a negative impact of increased calcium and pH concentration on soil health.

Thus we can say the clusters of negative value in the bivariate plot (Figure 7.11) have a negative influence on soil health and causes erosion and badlands formation.

Table 7. 3 Principal component analysis (PCA) of the physico-chemical parameters of soil

Parameter	***PC1***	***PC2***	***PC3***
CLAY	**0.67**	-0.1	0.29
SILT	0.39	**-0.66**	-0.34
SAND	**-0.62**	**0.6**	0.15
Bd	**-0.72**	0.45	-0.023
TP	**0.87**	0.02	0.18
LL	**0.84**	0.01	0.19
PL	**0.8**	0.04	-0.02
Ip	0.29	0.13	**0.53**
Ec	**0.71**	0.44	-0.36
SAR	**0.57**	**0.66**	-0.37
SOM	**0.63**	**0.57**	0.26
pH	0.43	**-0.75**	0
Ca	0.2	**-0.75**	0.33
Mg	-0.09	**-0.5**	-0.4
Na	**0.7**	0.28	-0.45
N	**0.58**	**0.55**	0.33
P	0.37	**-0.54**	0.13
K	**0.53**	0.09	-0.32
Eigenvalue	6.47	4.11	1.64
Variance%	35.95	22.83	9.15
Cumulative %	35.95	58.78	67.94

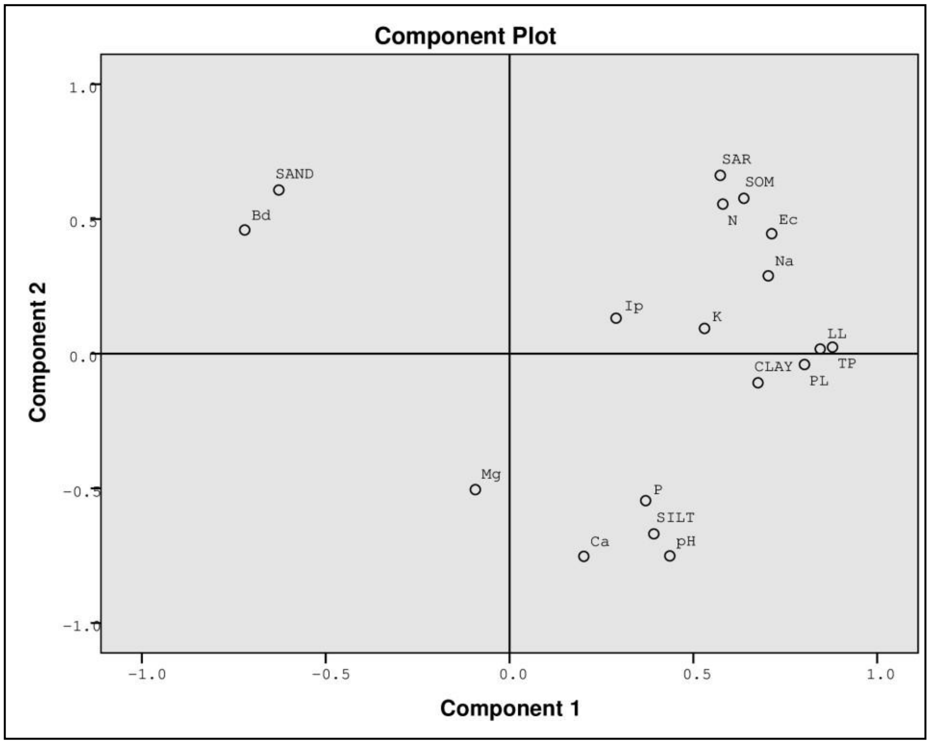

Figure 7. 11 Component plots of PC1 and PC2

7.3.8 Comparison of Key Parameters of Soils of Different LULC Sites

Levelling of gullied land by heavy machinery for agriculture and housing purposes has become common practice in recent times in the study area because it is an easy, quick and cost-effective technique. But the sustainability of levelled land by the cut and fill method is still debatable (Figure7.12). In India, levelling of badlands is new; it probably started in the first or second decades of the 21st Century (Ranga et al., 2016), but in western countries, these techniques are 3-4 decades older because of technological advancements (Poesen and Hooke, 1997).

After some local dialect with natives, we came to know that a much greater region in the study area was affected by gully or rill erosion. Later, some of those land was reclaimed by locals and used for agricultural purposes, where they used to cultivate Mustard (brassica rapa) and pigeon pea (cajanus cajan), but crop yield from these land is low. Therefore, the physico-chemical study of soil plays an important role in achieving land degradation neutrality.

To better understand local reclamation work, some important soil physico- chemical properties from different land-use classes (cropland, fallow land, forest, gully and reclaimed land) will correlated. The correlation shows that fallow land has the highest (1.96- 2.10 gm/cm^3) soil bulk density and the lowest (25.1- 33.1%) total porosity value among all major five classes. The soil bulk density value in gullied land, crop land and reclaimed land ranges between 1.89-1.98 gm/cm3, 1.94-1.97 gm/cm^3 and 1.92-1.97 gm/cm^3, respectively (Figure 7.13a), whereas total porosity in gullied land, crop land and reclaimed land vary between 29.9- 37.2%, 30.4-31.4%and 31.2- 33.2%, respectively (Figure 7.13b). In comparison with the other four classes, forested land has a moderate soil bulk density value (1.90- 1.97 gm/cm^3) but achieves the highest amount of soil porosity (33.3-37.6%).

The available calcium and pH distribution in fallow land is minimal among the other classes (420-1920 ppm and 4.91-7.78) (Figure 7.13c and 7.13d). These two parameters have moderate concentrations (860-1260 ppm and 6.67-7.38). In contrast, reclaimed land has the highest(2540-3580ppm) calcium concentration, followed by gullied land (1300-3380 ppm) crop land (940-2820 ppm). However, crop land has the highest (7.23-8.24) value of pH, followed by reclaimed (7.68-7.89) and gullied land (6.81-8.63).

Since present agricultural land and reclaimed land have been derived by levelling of pre- existing gullies and in this process, compact anoxic soil comes up to the surface, which certainly contains a greater bulk density and lower soil porosity. These soils also have a high calcium concentration and pH value. On the other side, fallow land is developed on a sandstone dominatingterrain, where soil thickness is less, pH and calcium concentration is low.

Figure 7. 12 Field photographs showing (a) and (b) Levelling of land by cut and fill method; (c)and (d) Rejuvenation of rills and gully in freshly reclaimed land by cut and fill method

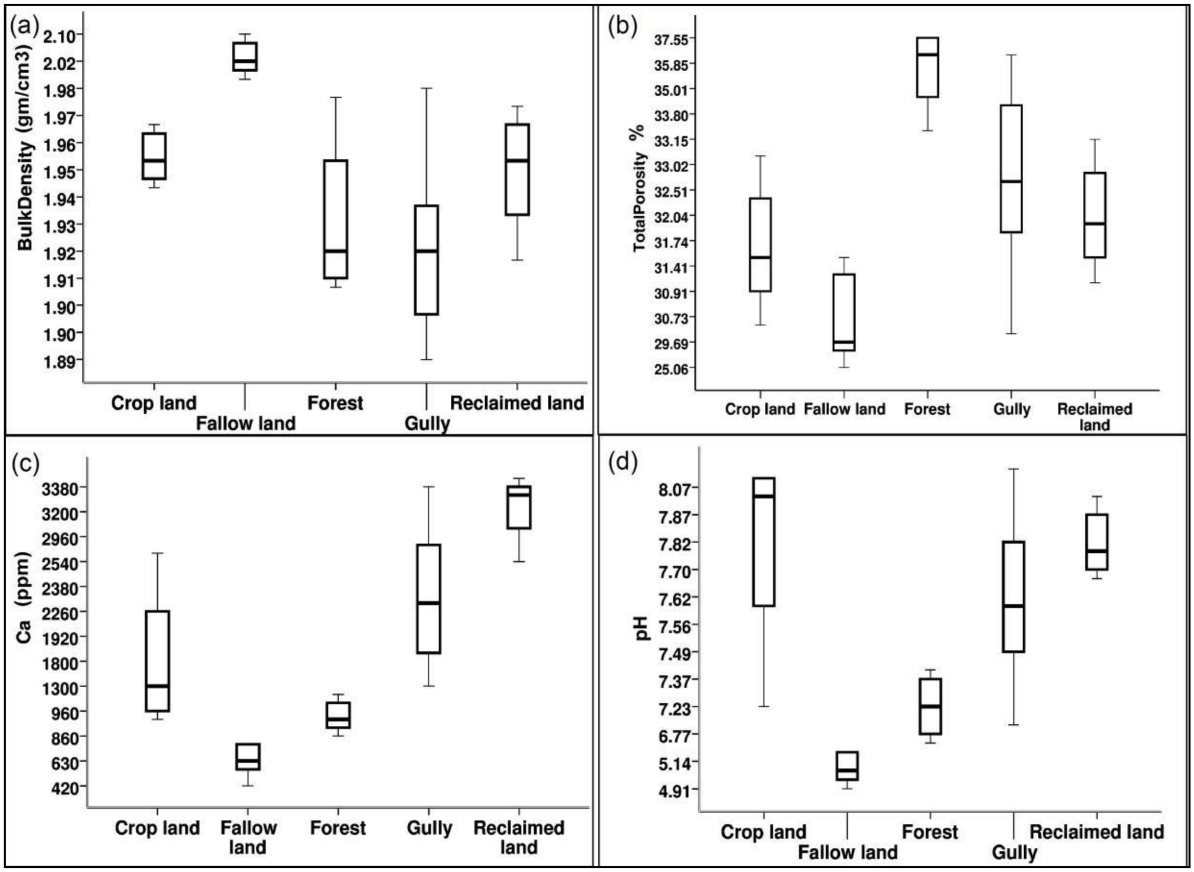

Figure 7. 13 Comparison of (a) Bulk Density; (b) Total Porosity; (c) Available Calcium; (d) pH ofsoil at various land use classes

7.4 Discussion

The present study reveals significant information and understanding of the badlands forming processes in the area. All the characterizing parameters of the soils determined in this study are presented in the Table 7.1 and their significance has been interpreted in the following discussion.The fraction of fines (clay) being most susceptible to transportation got depleted under greater runoff conditions from the area and plasticity consequently reduced (Figure 7.6c and Figure 7.7).These conditions made the area prone to be set upon by erosive processes, which furtheraugmented in time with more and more loss of fines from the system. The clay minerals decayed and occupied pore spaces decreasing porosity as well as permeability (Figure 7.3 and 7.4). With the loss of fines, organic matter was also washed away, leading to an increase in the bulk density (Figure 7.5a). An increase in bulk density further diminished the chances of vegetation growth.

The area has high pH soils with the presence of calcretes (Figure 7.7c). Both these factorsshould also have contributed to the processes eroding soils at higher rates. The presence of high calcium (Figure 7.8a) shows that it has not followed the sodic chain of events of flocculation anddispersion; rather calcium chain is more important here. The area shows calcrete layer formation at shallow depths (Figure 7.4b). Calcretes are known to form hardpan which hinders infiltration insuch cases, runoff increases in the soil zone above the calcrete horizon. Calcareous material is soluble in water and renders the material loose, free to be eroded away. All these interdependent chains of processes led to conditions that were favorable for continued erosion and unsuitable forplant growth. These conditions were detrimental to soils as the soil profile and the systems behavior of soils cannot sustain under higher rates of erosion and in the scarcity of organic matter.Hence, a self-enhancing positive feedback loop formed, which led to the formation of badlands. Another significant aspect of the impact of the feedback loop is confirmed by the lower values of Atterberg limits. Soil with such low values of liquid limit (Figure 7.5d) is highly unstable and flows away under moderate moisture conditions. It signifies that under a small pore water pressure,the soil disperses away. Thus, the badlands of the area typically represent the case of highly unstable soils easily erodible from their places. These soils have plasticity in a very small range of moisture content (Figure 7.5e). Low plastic index (Figure 7.5c) lends support to the statement thatthe soils of the area are unstable and erodible at quite low moisture content. The low plastic indexshows that piping and collapsing also enhanced gully formation (Figure 4.3 c, d and e). It is also a matter of discussion whether the soils were originally depleted in fines and organic matter with high bulk density and calcium content or they show a shift of properties withtime owing to the processes as discussed above. The study suggests that the system of soils has certainly undergone changes and was originally a different system. The parts of the study area which are still in original conditions with old and natural forest cover show different values and there is a gradual deterioration of the soils towards erosion-prone areas of the badlands. It is important to note in this regard that the plastic and liquid limits and also the clay fraction are relatively higher in the southern shrub and forested region (Figure 7.5c and 7.5d). A relatively higher value of SOM is also observed in this part of the study area. The value of SOM is well correlated with soil bulk density, as higher bulk density was found to be associated with low SOMas observed away from the shrub and forests.

Overlay analysis effectively showed variation in the degree of severity of land degradation(Figure 7.10). This is helpful in delineating the areas accordingly. The lowest in severity is a partof the land in the south in the upper reaches of the study area. The remaining area from south to north is a very severe zone. Overlay analysis map can prove to be helpful in the planning of land development and restoration of a stable ecosystem in the badlands. Land development planning must start from the extremely severe zone; otherwise, the planning would not be successful. The use of indigenous soils for restoration work and conventional reclamation methods like levelling/terracing is not suitable or successful in this terrain, as the lands reclaimed by refilling local material have again degraded with the regeneration of gullies (Figure 7.12 and 7.13).

7.5 Conclusions

I. The study concludes that the area underwent such changes which rendered the soils unstable. Soil texture, Atterberg limits, bulk density and soil pH, have a central role in soildegradation and badlands formation. The presence of calcrete in soil horizons and illite asa clay mineral seems to have choked the pore spaces, reduced permeability and enhanced runoff over the area. An increase in runoff led to the loss of fine particles and organic matter from the soils. This loss resulted in the destruction of the soil profile and soil texturewhich limited the vegetation growth and increased the bulk density. Higher bulk density, in turn, restricted microbial activity and hampered the replenishment of organic matter in the soils. In such unstable, deteriorated ground, the higher pH and moderate to low nutrient conditions limited vegetation growth and further accelerated erosion. This series of interactions changed the plastic and liquid limits of the soils. Lowered plasticity index promoted cavity and piping in the ground, which led to sub-surface erosion also. Hence thesoil system turned into the site of surface erosion through rills and gullying, making headward growth supported by subsurface piping and collapsing of grounds.

II. Overlay analysis based on the liquid limit, plasticity index, bulk density and drainage frequency shows the area is thoroughly affected by badlands processes. Three zones were categorized as severe, very severe and extremely severe depending upon their conditions and rill - gully - channel processes.

III. Land degradation through the badlands forming processes involves a series of interconnected changes through a complicated chain of interdependent influences of the various components of soils, hydrology, geomorphology, vegetation, climate, humaninterference and changes in land use and land cover of the area. The system turns into a self-enhancing deteriorating system which poses extreme difficulty in the way ofrestoration of ecosystem and turning the system back to a self-sustainable state.