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Assessing the Spatial Variability of Soil Quality Index of Ganjigatti Sub-Watershed Using GIS-Based Geostatistical Modeling

M. Bhargava Narasimha Yadav, P.L. Patil[1], V. Rundan[2], R. Veda Vyas and Knight Nthebere[3]

Department of Soil Science and Agricultural Chemistry, UAS, Dharwad-580 005, India
[1]Vice-Chancellor, UAS, Dharwad-580 005, India
[2]Department of Agronomy, UAS, Dharwad-580 005, India
[3]Department of Soil Science and Agricultural Chemistry, PJTSAU, Hyderabad-500 030, India
E-mail: bhargavnarasimha444@gmail.com

Abstract: The present study was conducted to appraise the soil quality and its spatial variability from 393 surface soil samples of the Ganjigatti sub-watershed of Karnataka by using geospatial techniques. Principal component analysis was applied to identify the MDS from a set of fourteen soil quality indicators. The major factors that influence soil quality include pH, OC, available N, Zn, B, P and Mn. Six leading PCs were significant based on an eigenvalue of '>1' and explained 74.71% of the variance in soil parameters. SQI (Soil Quality Index) and RSQI (Relative Soil Quality Index) values ranged from 0.41 to 0.81 and 0.51 to 1.00 respectively. The geo-database was subjected to ordinary kriging through the best-fit experimental semivariogram based on the lowest root mean square error. The study concluded that the measured SQI (range 720.82 m) in regular gird sampling at a given scale was enough to capture spatial dependence using the ordinary kriging technique and to derive thematic maps for efficient soil management strategies at the sub-watershed level. The higher nugget: sill ratio (0.81) indicates that the spatial variability or dependency is primarily caused by stochastic factors. The SQI map of the Ganjigatti sub-watershed showed that about 9.69% of the sub-watershed had medium SQI (0.35-0.55), whereas 80.87% of the area had higher SQI (0.55-0.75).

Keywords: Soil quality index, Principal component analysis, Spatial variability, Ordinary kriging

Assessment of soil quality is a sensitive and dynamic method for documenting the status of the soil, as well as the soil's response to management and its resilience to stress, whether that stress is imposed by natural forces or by human interventions. Karlen et al (1997) defined soil quality as the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation. In agricultural research, soil productivity is analogous to soil quality. Soil quality is an important aspect that is closely related to soil degradation and defined as the change in soil quality over time. Soil suffers from a mix of physical degradation by puddling or excessive cultivation, chemical degradation by nutrient depletion, pollution from industrial wastes and excessive use of pesticides and fertilizers and biological degradation by organic matter depletion and losses of soil flora and fauna. In order to evaluate the status of soil degradation and the shifting patterns that have resulted from various land uses and smallholder management interventions and required to conduct a fundamental assessment of soil quality.

Maintaining or enhancing soil quality is a key to sustaining soil resources of the world and there is a need for better understanding of the relationship between soil quality and agricultural productivity. In order to estimate soil quality, a variety of soil parameters or indicators have been identified. Yin et al (2021) assert that soil nutrients and other physicochemical properties are useful indicators for determining the overall soil quality. Harsha et al (2021) evaluated the soil quality index of the Channegowdarapalya micro-watershed (Karnataka) using 16 soil physical, chemical and biological characteristics. The most crucial critical indicator of soil quality was soil pH, which was followed by exchangeable Ca, DTPA extractable Zn, OC and available N. Yadav et al (2022) assessed the soil quality of the sub-humid southern plains of Rajasthan by using fertility characters. Geospatial modelling advances, such as geographical information system (GIS) and geostatistical tools, can be used effectively to assess the spatial variability of SQI. Geostatistical analyses, including fitting semi-variogram model and ordinary kriging procedure was carried out using *Arc*GIS to assess the degree of spatial variability of SQI. Kriging is an interpolation technique used in geostatistics using known values and a semivariogram to determine unknown values (Marques et al. 2015). Thus, keeping in view the importance of soil quality in land use planning and management, the present study was carried out with the specific objectives of determining the soil quality index and mapping the spatial variability of the soil quality index using remote sensing techniques in the Ganjigatti sub-watershed of the Hilly zone of Karnataka.

MATERIAL AND METHODS

Field description of the study area: Ganjigatti sub-watershed belongs to Kalghatgi *taluk* of Dharwad district. It is located between 15° 10' 10.114″ to 15° 17' 1.147″ N latitude and 75° 0' 57.672″ to 75° 4' 50.525″ E longitude in the Hilly zone of Karnataka, India. The area covers 4323.84 ha and receives an annual average rainfall of 917.00 mm (average annual rainfall of the zone ranges from 539 to 1256 mm). Annual average *kharif* (June to September), *rabi* (October to January) and *summer* (February to May) rain fall 616.00 mm, 139 mm and 162 mm, respectively. The annual temperature ranges from 24.68 to 26.67°C, with an average maximum temperature of 40.72°C during April and an average minimum temperature of 12.33°C in December. Soils of the study area were derived from schist parent material.

Soil sampling and laboratory analysis: The topographic map of the study area in a scale of 1:7,920 was digitized and geo-referenced to a map coordinate system so as to generate spatial information and subsequent use in a GIS environment. Soil samples (0-30 cm) were collected in summer by grid method. The grid interval was fixed 320 × 320 m^2 and 393 composite soil samples were collected from the field covering whole area of Ganjigatti sub-watershed. The samples were labelled, air-dried and sieved through a 2-mm sieve for analysis of soil fertility parameters. The pH and EC were analyzed using soil-water suspension in 1:2.5 ratio (Richards 1954). Soil organic carbon was determined using Walkley and Black (1934) method. Available N ($KMnO_4$-N) was estimated through alkaline permanganate method given by Subbiah and Asija (1956). Olsen et al (1954) method was used for available P estimation in which 0.5 M $NaHCO_3$ (Olsen's reagent) is used as an extractant. The available K (NH_4OAc-K) was determined by flame photometry method (Jackson 1973). Exchangeable calcium and magnesium were determined in neutral normal ammonium acetate extract by Versanate Titration (Thomas 1982). Available sulphur was extracted from the soil using 0.15 per cent calcium chloride solution and sulphur in solution was determined by turbidometry (Black 1965) using Spectrophotometer (Spectronic 20-D) at 420 nm. Micronutrients (Zn, Cu, Fe and Mn) were analyzed in atomic absorption spectrophotometer (AAS) using DTPA extractant (Lindsay and Norvell 1978). Available Boron were extracted by using hot water method (Berger and Truog 1939).

Statistical analysis: Descriptive statistics of measured soil properties including minimum, maximum, mean, standard deviation, coefficient of variation, skewness and kurtosis were calculated by using Statistical Package for Social Sciences (SPSS) ver.26.0. Correlation and regression analysis of soil properties were carried out by using SPSS ver.26.0.

Soil quality assessment: The SQI was calculated on the basis of minimum data set (MDS) framework. To identify the MDS, various successive steps of data analysis were followed, primarily employing the PCA technique (Andrew et al 2002a) using SPSS (version 26.0). The principal components (PCs), which received eigen values ≥1 and variables which had high factor loading were considered to the best representative of the system attributes. Within each PC, only highly weighted factors were considered for the MDS. The 'highly weighted' variables were defined as the highest weighted variable under a certain PC and absolute factor loading value within 10% of the highest values under the same PC (Wander and Bollero 1999). The values of each indicator were transformed using linear scoring technique (Andrew et al 2002b). To assign the scores, indicators were arranged in an order depending on whether a higher value was considered 'good' or 'bad' in terms of influencing the soil function. For the 'more is better' category of indicators, each observation was divided by the highest observed value such that the highest observed value received a score of one. For the 'less is better' indicators, the lowest observed value (in the numerator) was divided by each observation (in the denominator) such that the lowest observed value received a score of one. After transformation using linear scoring procedure, the MDS indicators for each observation was weighted using the PCA results. Each PC explained a certain amount (%) of the variation in the total data set. This percentage when divided by the total percentage of variation explained by all PCs with eigen vectors >1 gave the weighted factors for indicators chosen under a given PC. After performing these steps to obtain SQI, the weighted MDS indicator scores for 'n' observations (no. of indicators qualified from PCA) were summed up according to following equation:

SQI = Σ Principal component weight × Individual soil parameter score

For better understanding and relative comparison, the SQI values were reduced to a scale of 0-1 by dividing all the SQI values with the highest SQI value (relative SQI).

Spatial variability mapping: Spatial variability of soil quality index was mapped by ordinary kriging interpolation method. For mapping the soil quality index, all the analyzed data from sample sites were first fed into GIS as point-based, geo-coded data through table management. The data on SQI processed and classified into homogenous groups of SQI, as per the classification of low category of SQI (<0.35), medium category of SQI (0.35-0.55) and high category of SQI (>0.55).

RESULTS AND DISCUSSION

Apart from maintaining soil physical conditions to optimise yield, one of the major components of soil fertility that would impact the productivity of agricultural system is the efficiency of soils to supply nutrients for crop growth. The results of soil fertility parameters based on 393 surface samples taken from grids are described and SQI is calculated. Out of total geographic area of sub-watershed of 4323.84 ha, 343 ha (7.93%) was covered by gullied area, waterbody and settlements, while 13 ha area (0.29%) was under mining. About 3969 ha (91.77%) area was observed as cultivable land.

Assessment of soil quality index: The soils of total cultivable areas of Ganjigatti sub-watershed were assessed for soil quality in which PC analysis was performed for 14 variables (Table 1). The surface soil properties of 393 samples were subjected to PCA to reduce the data dimension. The PCA data for the sub-watershed showed that six PCs have an eigenvalues >1, which explained 74.71% of the cumulative variance in the data (Table 2). The MDS were chosen based on the highly weighted factor loading of variables. The representative screen plot showing the variation of eigenvalues with soil components is shown in Figure 1 and 2.

The parameters in each PC were considered based on higher values of the factor loading. The soil parameters obtained from PCA under PC1 were exchangeable Ca, exchangeable Mg and pH. However, multivariate correlation matrix was utilised to calculate the correlation coefficients between the parameters when more than one variable was retained under a given PC (Andrews et al 2002 a, b). To avoid redundancy, only the parameter with the highest loading factor was kept in the MDS if there was a significant correlation between them (r >0.60, p 0.05). The non-correlated parameters under a particular PC were considered important and retained in the MDS (Andrews and Carroll 2001, Andrews et al 2002a). Among these highly weighted variables of PC1, pH is a parameter that governs nutrients availability and is an indicator of soil fertility. It is a very significant soil parameters that affects the stability of the soil's structure, the availability of nutrients and soil microbial activity. Other parameters are highly correlated to each other, so pH was retained for MDS in PC1 (Table 3). Available Zn, available B, available P_2O_5 and available Mn were selected as indicators from PC2, PC4, PC5 and PC6, respectively. From PC2 both OC% and available N were considered for MDS due to wide variability of OC and complete low levels of available N in soils of the Ganjigatti sub-watershed. Among the variables included in the MDS, pH has most significant weight and contribution in the SQI determined by MDS, followed by OC, available N, Zn, B, P and available Mn, which have been widely reported as effective and sensitive factors

Table 1. Descriptive statistics of measured surface soil properties

Parameter	Maximum	Minimum	Mean	SD	CV (%)	Kurtosis	Skewness
pH (1:2.5)	8.65	5.02	7.07	0.78	11.03	-0.668	-0.157
EC (dS m^{-1})	1.00	0.03	0.21	0.16	76.19	4.335	1.803
OC (%)	1.22	0.11	0.68	0.21	30.88	-0.358	-0.091
Available N (kg/ha)	245.50	18.50	158.60	32.65	20.59	0.632	-0.213
Available P (kg/ha)	120.23	7.35	46.24	23.15	50.06	-0.206	0.463
Available K (kg/ha)	948.00	72.00	369.24	178.65	48.38	-0.539	0.482
Ex. Ca [cmol (p^+) kg^{-1}]	24.72	3.13	15.01	4.01	26.72	-0.180	-0.167
Ex. Mg [cmol (p^+) kg^{-1}]	16.87	2.04	8.45	2.70	31.95	0.800	0.499
Available S (kg/ha)	89.38	1.25	27.55	16.02	58.15	0.764	0.995
Available Fe (ppm)	69.40	2.37	27.32	11.82	43.27	1.018	0.892
Available Mn (ppm)	30.42	1.17	14.70	5.91	40.20	0.382	0.090
Available Cu (ppm)	8.42	0.96	3.20	1.18	36.87	0.737	0.638
Available Zn (ppm)	4.26	0.18	1.11	0.67	60.36	5.918	2.251
Available B (ppm)	0.90	0.10	0.35	0.14	40.00	0.572	0.542

for the development of SQI (Harsha et al 2021, Sathish and Madhu 2021, Yadav et al 2022).

After the selection of parameters for the MDS, all selected observations were transformed using linear scoring functions (less is better, more is better and optimum). The organic carbon, available nitrogen, phosphorous, Mn, Zn and B were considered as more is good from the soil quality point of view when they are in increasing order, hence the 'more is better' approach was followed. In pH, the 'optimum is better' approach was followed. Once the selected observations were transformed into numerical scores (ranged 0-1), a weighted additive approach was used to integrate them into indices for each soil sample (Andrews et al 2002b; Mukherjee and Lal, 2014). Thereafter, to obtain the weighted additive SQI, the weighted MDS indicator scores for each observation were summed up. The mean contribution of soil parameters to SQI ranged from 0.0421 (Zn) to 0.30 (pH) (Table 4). The pH had minimum CV, while available Zn had maximum CV in the contribution to SQI. The SQI values ranged from 0.41 to 0.81 with mean of 0.69. Using SQI values, RSQI was derived for

Table 2. Principal components of soil quality parameters, eigenvalues and component matrix variables

	PC1	PC2	PC3	PC4	PC5	PC6
Eigen values	3.255	1.683	1.655	1.319	1.291	1.256
% of Variance	23.247	12.023	11.824	9.425	9.218	8.974
Cumulative %	23.247	35.269	47.093	56.518	65.736	74.710
Weightage factor	0.3112	0.1609	0.1583	0.1262	0.1234	0.1201
Factor loadings (Rotated component matrix)						
pH	0.871	-0.204	0.079	0.210	-0.113	-0.228
EC	0.310	-0.084	-0.021	0.638	0.152	0.250
OC	0.032	0.123	0.882	0.008	0.110	-0.042
Available N	0.023	-0.007	0.890	0.060	-0.018	0.158
Available P_2O_5	0.063	0.049	0.126	0.096	0.843	0.105
Available K_2O	0.276	0.633	-0.114	0.294	0.323	0.130
Exchangeable Mg	0.921	0.045	0.039	-0.083	0.062	-0.201
Exchangeable Ca	0.909	0.063	0.044	0.04	-0.005	-0.021
Available S	0.087	-0.144	0.048	0.057	-0.635	0.459
Available Fe	-0.751	0.198	0.089	-0.045	-0.111	-0.295
Available Mn	-0.161	0.011	0.102	0.002	-0.024	0.846
Available Cu	-0.367	0.704	0.052	-0.061	0.073	-0.115
Available Zn	-0.033	0.800	0.123	-0.005	-0.019	-0.010
Available B	0.107	-0.119	-0.089	-0.867	0.034	0.144

Table 3. Correlation between the highly weighted variables of PC at 0-30 cm depth of soil

	pH	OC	N	P	Mg	Ca	Fe	Mn	Zn	B
pH	1									
OC	0.025	1								
N	0.070	0.520**	1							
P	-0.014	0.183**	0.065	1						
Mg	0.755**	0.076	0.002	0.104*	1					
Ca	0.697**	0.039	0.056	0.095	0.660**	1				
Fe	-0.499**	0.036	0.000	-0.090	-0.549**	-0.572**	1			
Mn	-0.222**	0.015	0.197**	0.014	-0.248**	-0.078	-0.015	1		
Zn	-0.166**	0.159**	0.094	0.091	-0.044	0.000	0.162**	-0.006	1	
B	-0.099*	-0.074	-0.048	-0.099*	0.096	-0.043	-0.078	-0.020	-0.097	1

**. Correlation is significant at the 0.01 level (2-tailed)

*. Correlation is significant at the 0.05 level (2-tailed)

393 grids, which ranged from 0.51 to 1.00 with mean of 0.78. SQI was highest in parts of lowlands and midlands where soil has neutral to slightly alkaline pH and more OC due to good cultivation practices. It was lowest in upland, where soil has acidic pH and low OC indicating less soil productivity (Mandal et al 2011; Harsha et al 2021).

Soil pH, which influences soil physical, chemical, and biological properties and processes, has emerged as a key indicator for the soils of Ganjigatti sub-watershed. It is a crucial factor that significantly influences the health and productivity of the soil, as well as the plants that grow in the sub-watershed. pH is a measure of the acidity or alkalinity of a substance, and in the context of soil, it refers to the concentration of hydrogen ions (H^+) in the soil solution. The result suggests that pH increases as the slope of the landscape decreases. The soil at higher elevations on the landscape displays the lowest pH, likely due to the leaching away of exchangeable bases through runoff and erosion, which then accumulate on the lower slopes. This circumstance leads to an escalation in the presence of hydrogen ions within the soil, consequently causing a reduction in pH. Comparable research, including Dessalegn

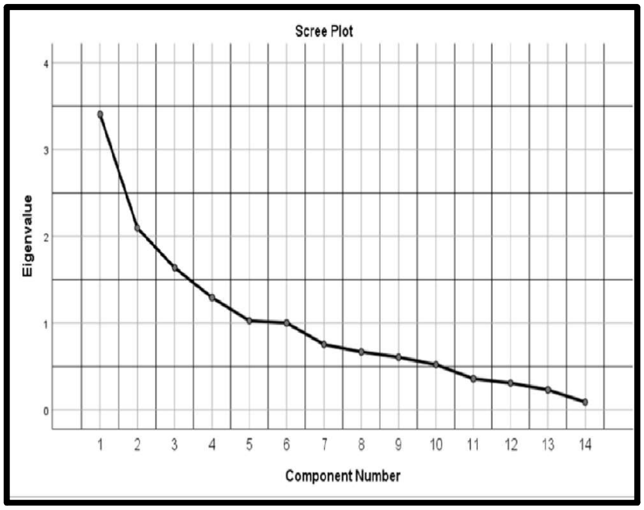

Fig. 1. Screen plot explaining the relationship of eigenvalue and principle component for 0-30 cm depth of soil

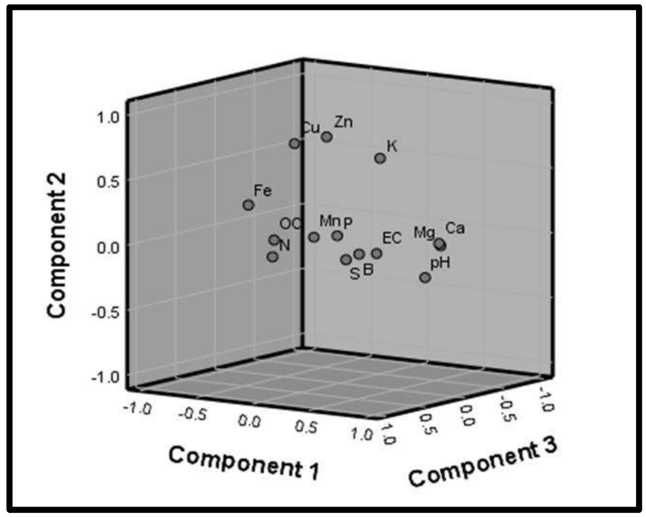

Fig. 2. Rotation of components (PCs)

Table 4. Contributions of significant soil parameters to soil quality index

Parameters	Contribution to SQI	Minimum	Maximum	Mean	SD	CV (%)
pH	W × Optimum is good	0.240	0.311	0.300	0.0140	4.67
Available Zn	W × More is good	0.0068	0.1608	0.0421	0.0253	60.09
Organic carbon	W × More is good	0.0149	0.1586	0.0879	0.0272	30.94
Available N	W × More is good	0.0120	0.1583	0.1023	0.0211	20.63
Available B	W × More is good	0.0141	0.1262	0.0492	0.0191	38.82
Available P	W × More is good	0.0076	0.1234	0.0475	0.0238	50.11
Available Mn	W × More is good	0.0047	0.1202	0.0581	0.0234	40.28
SQI		0.41	0.81	0.69	0.0699	10.18
RSQI		0.51	1.00	0.78	0.0789	10.17

Table 5. Parameters for different theoretical semivariogram models used to fit the experimental semivariogram of soil quality index (SQI)

Semi variogram model	ME	RMSE	MSPE	RMSP	Average standard error
Circular	-0.0007	0.1897	-0.0036	1.0100	0.1876
Spherical	0.0003	0.1906	0.0015	1.0123	0.1878
Exponential	0.0006	0.1934	0.0029	1.0134	0.1903
Gaussian	0.0004	0.1917	0.0024	1.0121	0.1889

et al (2014), Miheretu and Yimer (2018) and Bufebo et al (2021), echoes the current study's observations, indicating that the average soil pH is higher in the lower slope position compared to the higher areas of the landscape. Maintaining the appropriate soil pH is crucial for maximizing nutrient availability, supporting beneficial microbial communities, promoting plant growth, preserving soil structure and making informed decisions about crop selection and soil management practices.

Organic carbon (OC) is a fundamental component of soil health and plays a vital role in maintaining soil fertility, productivity and overall ecosystem functioning (Abebe et al 2020, Ebabu et al 2020). Zhang et al (2002) suggested that organic carbon (OC) constitutes a crucial element influencing soil quality and long-term sustainability. The reduction in carbon content results in a decrease in the cation exchange capacity (CEC) of soils, the stability of soil aggregates and crop yield. Organic carbon serves as a primary nutrient source and the depletion of organic matter corresponds to a decline in soil productivity. The presence of organic matter significantly impacts both the growth and yield of crops, either by directly supplying nutrients or by indirectly altering soil physical characteristics, which enhance root conditions and foster plant growth (Hati et al 2007). In addition to its role as a supplier and reservoir of nutrients for plants, organic carbon also plays a vital role in the carbon cycle. The reduction in organic matter content would lead to the physical deterioration of soils and properties reliant on organic matter become valuable indicators for evaluating soil quality.

Available nitrogen (N) is a critical component of soil quality and plays a central role in supporting plant growth, crop productivity and overall ecosystem functioning. Nitrogen is an essential nutrient required by plants in relatively large quantities and availability in the soil significantly influences various aspects of soil quality and health (Sathish and Madhu 2021, Prasad et al 2023). When assessing SQI, available phosphorus is typically considered within the context of other soil properties and factors. The phosphorus is essential for soil fertility and plant growth, but availability should be balanced to avoid over-application, which can lead to environmental issues. Sustainable soil management practices, such as precision nutrient application, cover cropping and soil erosion control, can help maintain optimal available phosphorus levels while promoting overall soil quality and minimizing negative environmental impacts (Mesfin et al 2022). Available zinc (Zn), manganese (Mn) and boron (B) are essential micronutrients that play critical roles in soil quality and plant health, which are crucial for promoting healthy plant growth, preventing nutrient deficiencies and maximizing crop yields (Harsha et al 2021).

Digital mapping of SQI by using kriging: Ordinary kriging was used to assess the spatial variability of SQI. Based on the lowest root mean square error (RMSE), circular semivariogram model was selected for the significant fit for SQI (Table 5). The geostatistical approach begins by identifying the spatial variation parameters (nugget, sill and range) from a spatial soil database using a semivariogram and uses kriging to estimate the unbiased soil characteristics at an unsampled location. The best-fit semivariogram model (Fig. 3) and model parameters (range, nugget and partial sill) of SQI are presented in Table 6. The range was higher for SQI (720.82 m) than distance of grid interval indicated that the rational sampling distance for the Ganjigatti sub-watershed was within their spatial correlation range. The C_0 values show a positive nugget effect, which may be explained by the sampling error, short-range variability, randomness and inherent variability (Liu et al 2006). The, nugget value for SQI is 0.0282 and is small and close to zero indicate a spatial continuity between the neighboring points. The finding is similar to the result of Jafarian and Kavian (2013) and Khan et al (2021). C_0/ C_0 + C (N:S ratio) represents the degree of spatial variability, which is affected by both structural and stochastic factors. The higher ratio (0.81) indicates that the spatial variability/ dependency is primarily caused by stochastic factors such as fertilisation, farming measures, cropping systems and other human activities.

In present study, geostatistical tools along with GIS used to map the spatial variability of SQI. They were grouped into various classes based on range which, represent their magnitude in soil and the area of each class were estimated. The cadastral integrated spatial variability maps indicate survey number wise spatial distribution of SQI (Fig. 4). SQI map of Ganjigatti sub-watershed showed that about 9.69% of

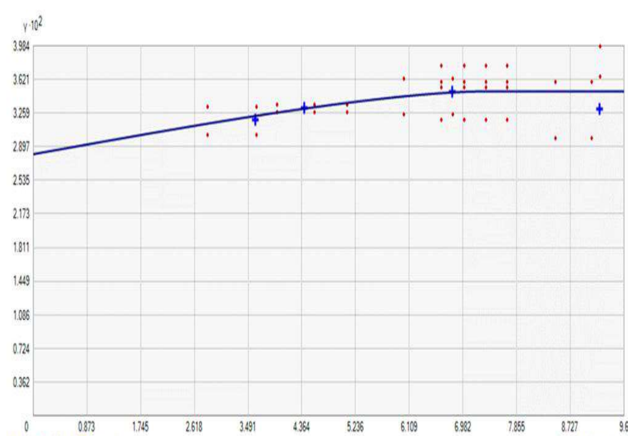

Fig. 3. Experimental semivariogram of soil quality index with fitted model

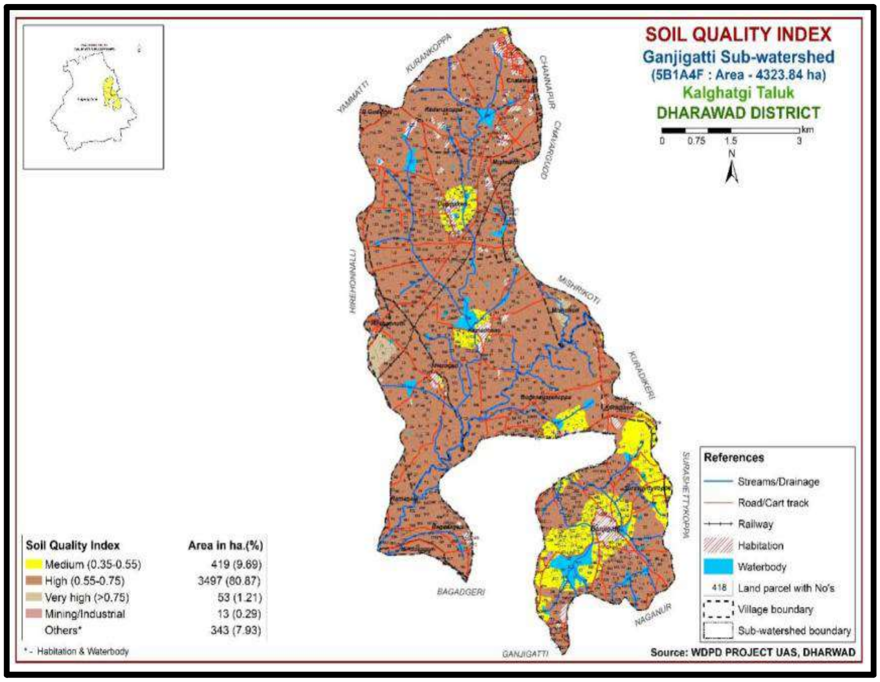

Fig. 4. Spatial distribution of soil quality index of Ganjigatti sub-watershed

Table 6. Semivariogram model parameters for soil quality index (SQI)

Model	Lag distance (m)	Range (m)	Nugget (Co)	Partial Sill (C)	Sill (Co+C)	N:S ratio	Spatial dependence
Circular	80	720.82	0.0282	0.0067	0.0349	0.81	Weak

the sub-watershed has a medium category of SQI (0.35-0.55). The high category of SQI (0.55-0.75), which is the bulk of the area covered in the sub-watershed, comprises about 80.87%.

CONCLUSION

Examining the variability present in soil parameters to assess soil quality clearly reveals that the SQI within the sub-watershed ranges from medium to very high. Investigating parameter relationships and conducting a principal component analysis highlighted the substantial contribution of seven parameters to the SQI. Foremost among these indicators is soil pH, serving as a pivotal factor for gauging soil quality. Following closely are organic carbon, available nitrogen, manganese, boron, phosphorus, and zinc. For areas with a medium SQI, farmers can enhance soil quality by regulating soil pH and enhancing soil aggregation using amendments and fertilizers rich in calcium. To ensure the sustainability of agricultural systems and uphold soil quality, the preservation and augmentation of organic matter are imperative. The augmentation of organic matter exerts a noteworthy influence on the mineralization and recycling of carbon and nitrogen. Addressing deficiencies in available zinc (Zn) and boron (B), which are of paramount importance for crop growth and consequently higher yields, holds significance. The higher N:S ratio (0.81) points towards spatial variability and dependency predominantly stemming from land management practices implemented in the sub-watershed. Further in-depth investigations in this realm will be instrumental in generating crucial insights required for sustainable land use planning. These studies will also aid in comprehending soil quality under diverse management practices and appropriate nutrient management within the sub-watershed.

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