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RESEARCH ARTICLE

Soil fertility status and assessment of nutrient soil quality index of Ganasandra micro-watershed using GIS-based geo-spatial tool

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Abstract

Despite growing concerns about sustainable land management, limited studies have comprehensively evaluated soil fertility and spatial variability of nutrient soil quality at the micro-watershed level using geospatial techniques. The current research (2023-24) aimed to assess nutrient levels, soil health and the spatial variability of soil fertility within the Ganasandra micro-watershed, a component of the Naganahalli sub-watershed in Nagamangala taluk, Mandya district, Karnataka, using geospatial methods. Statistical evaluation of analytical data was performed using parameters such as range, mean and standard deviation. The soil was found to be slightly to strongly alkaline and non-saline. Organic carbon levels ranged from low to medium; nitrogen and phosphorus availability were moderate; potassium was high and sulfur levels ranged from low to moderate. Diethylene triamine pentaacetic acid (DTPA) extractable micronutrients analysis indicated that half of the samples lacked sufficient zinc and iron, whereas copper and manganese concentrations were adequate. Shortages of N (nitrogen), P (phosphorus), S (sulphur), Zn (zinc) and Fe (iron) were identified as significant limitations to soil fertility. Principal component analysis (PCA) was employed to obtain the minimum data set (MDS) from the assessed soil parameters. Essential factors affecting soil quality include pH, organic carbon content and the availability of nitrogen and zinc. Three principal components with eigenvalues exceeding 1 accounted for 73.00 % of the overall variance. The soil quality index (SQI) ranged from 0.10 to 0.62. The study established that SQI, derived through grid sampling at a 320 m scale, successfully reflected spatial dependence through ordinary kriging and enabled the creation of thematic maps for soil management at the micro-watershed level. The SQI map showed that 46.63 % of the region was classified as low to very low soil quality, 22.79 % as medium and 31.32 % as high-quality categories.

Keywords: ordinary kriging; principal component analysis; soil quality index; spatial variability

Introduction

Soil quality evaluation serves as a responsive and adaptable method for assessing soil health, its reaction to diverse management techniques and its resilience to both human-induced and natural pressures. Soil quality refers to the capacity of a specific soil type to function effectively within natural or managed ecosystems, sustaining plant and animal productivity, improving or preserving air and water quality and supporting human health and habitation (1). In agricultural contexts, soil quality is often associated with soil productivity, as it is essential for evaluating long-term soil health and is directly linked to soil degradation and changes in soil function over time.

Soil degradation is driven by multiple factors including physical degradation due to intensive farming, chemical degradation from nutrient depletion, pollution from industrial waste and excessive agrochemical use and biological degradation caused by a decline in organic matter and microbial populations. To fully understand the extent and dynamics of soil degradation, particularly in relation to different land use patterns and smallholder farming systems, fundamental soil assessment is essential.

Preserving global soil resources relies heavily on maintaining or improving soil quality and a deeper understanding of its relationship to agricultural productivity is vital. A variety of soil parameters or indicators have been identified for effectively evaluating soil quality. Studies indicate that soil nutrients, together with other physical and chemical properties, serve as dependable indicators for assessing overall soil quality (2). In the Channegowdarapalya micro-watershed of Karnataka, a soil quality index was created based on 16 different physical, chemical and biological attributes. Among these, pH emerged as the most influential indicator, followed by exchangeable calcium, DTPA-extractable zinc, organic carbon and available nitrogen (3). Similarly, research in the sub -humid southern plains of Rajasthan assessed soil quality based on fertility-related attributes (3, 4).

Advancements in geospatial modeling, particularly geographic information systems (GIS) and geo-statistical tools provide powerful methods for evaluating the spatial variability of the soil quality index (SQI). Geo-statistical methods, including semivariogram modeling and the ordinary kriging technique, were utilized with ArcGIS software to analyze the spatial distribution of SQI. Kriging, a widely used interpolation technique in geostatistics, employs known data points and semivariograms to predict unknown values across a study area (5). Recognizing the importance of soil quality in guiding land use planning and sustainable agricultural practices, this research was undertaken with the specific objectives of evaluating the SQI and mapping its spatial variability through remote sensing and geospatial methods in the Ganasandra micro-watershed situated in the southern dry zone of Karnataka.

Materials and Methods

Field description

The study was conducted in the Ganasandra micro-watershed, part of the Naganahalli sub-watershed in Nagamangala taluk, Mandya district, Karnataka. Geographically, it lies between 13° 0′56.212″-12°59′31.647″ N latitude and 76°45′13.293″+76°46′ 56.438″ E longitude, within the southern dry zone of Karnataka (Fig. 1). The total area spans 585 ha, with an average annual rainfall of 946 mm. Soils in the region range from shallow (25-50 cm) to moderately shallow (50-75 cm), covering 96.3 ha (16.4 %). Gently sloping lands (3-5 %) occupy 169 ha (28.9 %), while moderately eroded areas account for 22.2 ha (2.8 %).

Soil sampling, processing and laboratory analysis

A topographic map of the study region at a 1:7920 scale was digitized and geo-referenced to a coordinate system for the creation of spatial data in a GIS context. In the summer season, geo-referenced soil samples (0-30 cm depth) were gathered through a grid sampling approach with a constant interval of 320 × 320 m, yielding 46 composite samples that span the entire Ganasandra micro-watershed. Samples were tagged, air-dried, processed and sieved through a 2.00 mm mesh for laboratory analysis. The examined chemical properties comprised soil pH, electrical conductivity (EC), soil organic carbon (SOC), available N, P, S, exchangeable potassium (K), DTPA-extractable micronutrients (Zn, Mn, Cu, Fe) and available boron (B). Information regarding the parameters and analytical techniques is presented in Table 1.

Statistical analysis

Descriptive statistics of measured soil properties including maximum, minimum, mean, standard deviation, coefficient of variation, skewness and kurtosis were calculated using Microsoft Excel (Table 2). Correlation and regression analysis of soil properties were also performed.

Nutrient index values (NIV) and nutrient rating

The nutrient index values (NIV) of Ganasandra micro-watershed were calculated for organic carbon, available N, P, K and S (14). The significance of the nutrient index approach in cultivation areas lies in its ability to provide a structured, data-driven assessment of soil fertility. In regions like the dry zone (arid conditions), where rainfall is erratic and resource use must be optimized, the NI approach helps in planning to precise nutrient management strategies. By identifying which nutrients are deficient or sufficient, farmers can tailor fertilizer applications, improve input efficiency and crop productivity, while avoiding overuse of fertilizers that can degrade soil health. Moreover, the nutrient index serves as a useful tool for establishing baseline soil fertility conditions, enabling long-term monitoring of soil health changes under different farming practices such as conventional, organic or natural farming. It also supports government initiatives and extension services in targeting soil health programs and subsidies more effectively. Overall, the nutrient index approach is a practical, cost-effective framework for

Table 1. Methods used to measure soil fertility attributes for soil quality

Soil attribute	Abbreviation	Unit	Method	References
Soil reaction	pH		1:2.5 soil/water	(6)
Electrical conductivity	EC	dS m^{-1}	1:2.5 soil/water	(6)
Soil organic carbon	SOC	g kg^{-1}	Wet digestion method	(7)
Available nitrogen	N	kg ha^{-1}	Alkaline $KMnO_4$ method	(8)
Available phosphorous	P	kg ha^{-1}	Olsen's method	(9)
Available potassium	K	kg ha^{-1}	Flame photometer	(10)
Available sulfur	S	ppm	Extraction with 0.15 % $CaCl_2$	(11)
Available boron	B	mg kg^{-1}	Hot water-soluble method	(12)
DTPA extractable zinc, copper, manganese and iron	Zn, Cu, Mn, Fe	mg kg^{-1}	Atomic absorption spectroscopy	(13)

Table 2. Descriptive statistics of soil properties used for soil quality assessment

Particulars	pH	EC	OC	N	P_2O_5	K_2O	S	Fe	Mn	Cu	Zn	B
Maximum	8.86	0.98	1.17	388.86	114.39	381.56	20.28	17.96	14.84	3.61	1.93	1.32
Minimum	4.14	0.03	0.18	175.62	34.37	74.46	3.68	0.66	0.39	0.14	0.09	0.11
Mean	7.09	0.38	0.53	292.33	79.00	198.33	10.29	6.12	4.14	1.38	0.36	0.61
Median	7.27	0.31	0.47	301.06	85.92	202.88	10.60	3.91	2.35	1.02	0.22	0.64
Standard deviation	1.18	0.27	0.22	51.75	26.25	78.61	3.90	5.38	4.26	1.15	0.46	0.38
Skewness	-0.66	0.83	0.73	-0.48	-0.31	0.33	0.08	1.00	1.47	0.41	2.76	0.07
Kurtosis	-0.38	-0.40	0.24	-0.08	-1.50	-0.33	-0.47	-0.28	0.86	-1.36	6.50	-1.42

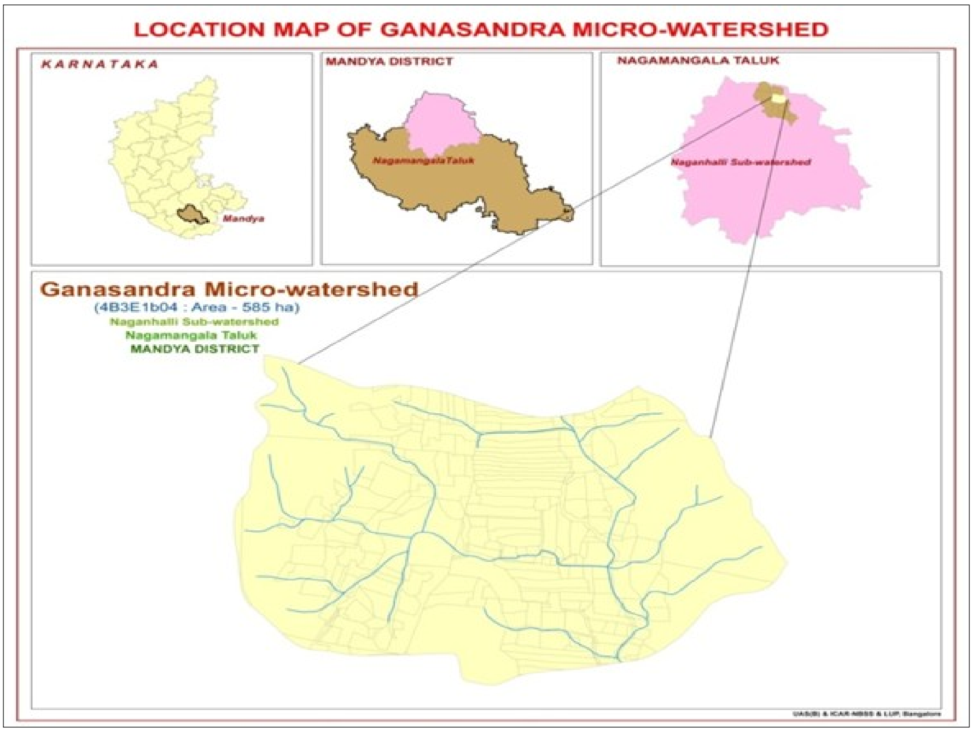

Fig. 1. Location of the study area (Source: REWARD phase-II atlas).

improving agricultural sustainability and productivity in semi-arid regions.

NIV = (NL + 2NM + 3NH)/ (NT) or NIV = (% NH*3 + % NM*2 + % NL*1)/100…… (Eqn. 1)

Where, NL: number of samples under low, NM: number of samples under medium, NH: number of samples under high, NT: total number of samples.

Soil quality assessment

The soil quality index (SQI) was assessed utilizing a minimum data set framework through sequential data evaluation, mainly using principal component analysis (PCA) (14). Principal components (PCs) with eigenvalues ≥ 1 and variables with significant factor loadings were considered the most indicative. Only the most significant variables were chosen from each PC for the MDS. A linear scoring approach was applied to normalize these indicators (15). For indicators where more is better, values were divided by the highest observed value (max = score 1), while for less is better, values were divided by the lowest (min = score 1). These standardized scores were subsequently multiplied according to each PC's impact on overall variance. The weight was obtained by dividing the variance accounted for by a PC by the overall variance from all PCs with eigenvalues greater than 1. The final SQI was derived by adding the weighted scores of all chosen MDS indicators for each observation (Eqn. 2).

SQI = Σ principal component weight × individual soil parameter score….. (Eqn. 2)

Spatial variability mapping: Spatial variability of soil quality index was mapped using the ordinary kriging interpolation method ArcGIS software version 10.5. To map the soil quality index, all analyzed data from sample locations were initially input into GIS as point-based, geo-coded information through attribute tables. The SQI data has been processed and categorized into uniform groups of SQI, according to the classification ranging from very low to very high.

Results

Beyond optimizing physical conditions, soil fertility especially nutrient availability is a key factor influencing agricultural productivity. The results of soil fertility parameters based on surface samples at 0-30 cm depth taken from grids were analyzed and SQI was calculated.

Soil Properties: A total of 12 soil fertility properties were analyzed for each soil sample. The maximum, minimum, mean, median, standard deviation, skewness and kurtosis values for each parameter are presented in Table 2.

The examined data indicated that soil pH varied between 4.14 and 8.86, with an average of 7.09, reflecting differences from acidic to alkaline conditions affected by topography and parent material. This wide pH range implies varying soil fertility conditions across the area, strongly acidic soils (below pH 5.5) can lead to aluminum and manganese toxicity and reduced nutrient availability, while alkaline soils (above pH 8.0) may hinder the uptake of micronutrients like iron, zinc and phosphorus, potentially affecting crop productivity and soil microbial activity. Out of the 46 soil samples, 32.61 % were acidic, 26.10 % exhibited neutrality and 41.30 % were slightly alkaline to alkaline (Table 3 and Fig. 2). Electrical conductivity (EC) measurements varied between 0.03 and 0.98 dS/m, yielding an average of 0.38 dS/m throughout the study area values below the sensitivity limits.

Soil samples from the micro-watershed area show the OC in the range of 0.18 to 1.17, with the average value of 0.53 indicate low in quantity. From the collected samples, 52.17 % samples fall under low, 28.26 % medium and remaining 19.57 % under high range of OC in study area.

Available N varied from 175.62-338.86 kg/ha with a mean value of 292.33. Most of the land was medium, while the area growing slowly under low category of N. Overall, from collected samples the 41.30 % samples under low and 58.70 % fallen under medium range, this indicates the

Table 3. Distribution of soil samples under varied soil reaction

Acidic condition		Neutral condition		Alkaline condition	
Grid no.	**pH level**	**Grid no.**	**pH level**	**Grid no.**	**pH level**
7	6.0	5	7.2	1	7.8
10	5.3	6	7.4	2	8.3
11	5.7	14	7.2	4	8.6
15	4.8	16	7.1	8	7.7
19	6.3	20	7.4	9	8.2
37	6.4	22	7.0	12	7.9
41	5.3	29	7.2	13	8.4
44	4.7	30	7.0	17	7.8
45	6.1	48	7.5	21	8.3
46	6.4	49	7.0	25	8.1
50	6.2	51	7.3	26	8.0
52	5.3	54	6.9	31	8.4
53	4.1			32	8.3
55	6.0			35	8.3
56	6.0			36	7.8
				38	7.7
				39	8.9
				40	8.1
				47	8.7

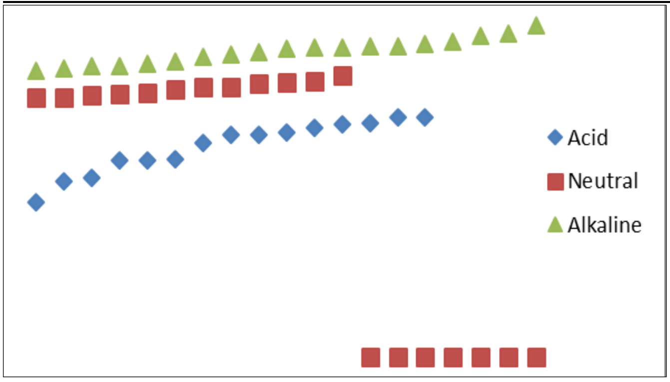

Fig. 2. The distribution of soil samples under different soil reaction.

different management practice were impacted on soil nitrogen content in the micro-watershed area (Fig. 3).

Available phosphorus (P) ranged from 34.37 to 114.39 P_2O_5 kg/ha with mean of 79.00. P_2O_5 (Table 1). The results showed that, the phosphorus content in micro-watershed is medium (22.9 to 56.33 kg/ha) to high (> 56.33 kg/ha) in range and from the collected samples 34.78 % was falls under the medium range and the remaining 65.22 % under high phosphorus content distribution in study area (Fig. 4).

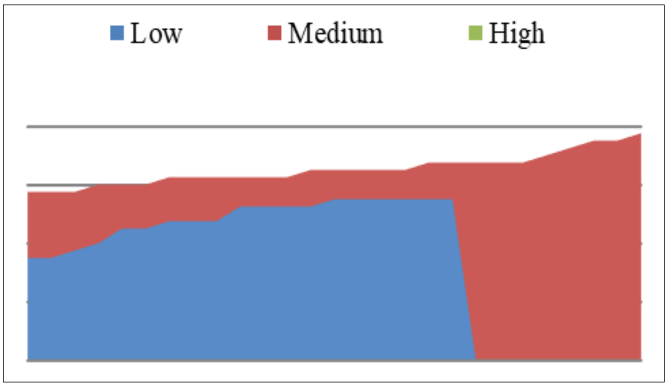

Fig. 3. Number of samples fallen under different range of nitrogen.

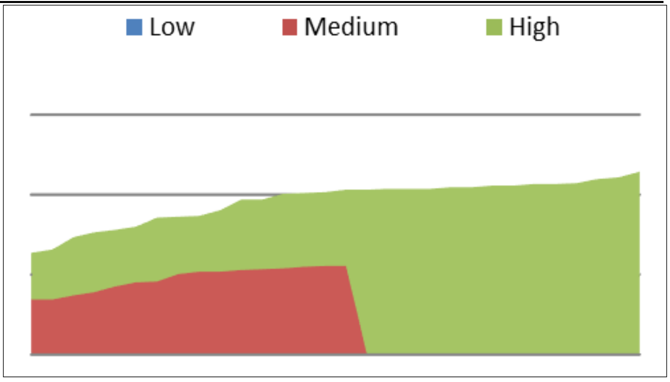

Fig. 4. Number of samples fallen under different range of phosphorus.

Potassium (K) availability varied from 74.46 to 381.56 kg/ha, with a mean of 198.33 kg/ha. The majority of the micro-watershed region was categorized within the medium potassium range (Table 1). Of the samples, 26.10 % were low, 67.39 % medium and 6.52 % high in potassium levels (Fig. 5).

The available sulphur (S) ranged from low to medium (3.68-20.28 mg/kg) with mean of 10.29 mg/kg (Table 1). Overall, from collected samples, 41.30 % comes under low and remaining samples fallen under medium range of sulphur in study area (Fig. 6).

Nutrient index values (NIV)

The values and ratings of the nutrient index are shown in Table 4. The NIV measurements indicated that soils largely had a medium level of available nitrogen (1.587), a high level of available phosphorous (4.043) and available sulphur (1.587), while also being high in available potassium (1.998). Calcium, magnesium, manganese and copper levels were adequate, while in certain soils, zinc and iron were lacking, although sufficient overall in the study location

Table 4. Nutrient index value (NIV) for organic carbon, N, P_2O_5, K_2O and S in surface soils of Ganasandra micro-watershed

Parameters	NL	NM	NH	NVI	Nutrient Index Rating
Organic carbon	52.18 %	28.26 %	19.57 %	2.261	Medium (1.5 to 2.5)
Nitrogen	41.30 %	58.70 %	0	1.587	Medium (> 1.5)
Phosphorus	0	34.78 %	65.22 %	4.043	High (> 2.5)
Potassium	26.10 %	67.39 %	6.52 %	1.998	Medium (1.5 to 2.5)
Sulphur	41.30 %	58.70 %	0	1.587	Medium (1.5 to 2.5)

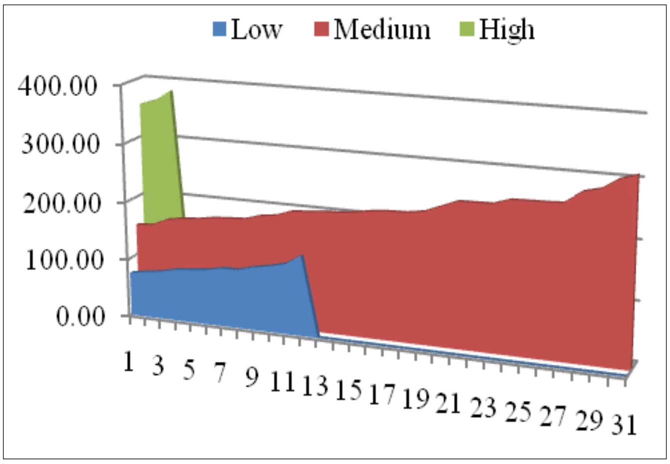

Fig. 5. Number of samples fallen under different range of potassium.

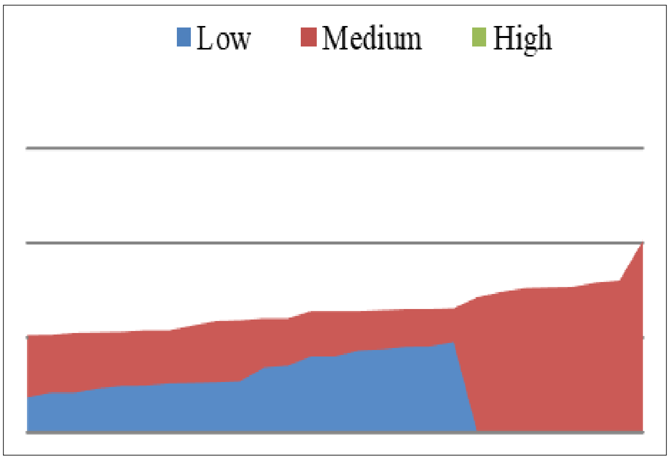

Fig. 6. Number of samples fallen under different range of sulphur.

Distribution of DTPA extractable micronutrients in surface soils of Ganasandra micro-watershed

DTPA extractable Fe in collected soil samples ranged from 0.66 to 17.96 mg/kg with an average value of 6.12 mg/kg (Table 1). In collected samples, 39.13 % of samples fallen under low category (< 2.5 ppm) and remaining 60.87 % of soil samples comes under sufficient (> 2.5 ppm), higher Fe content found in entire area.

DTPA-extractable Mn varied between 0.39 and 14.84 mg/kg, averaging 4.14 mg/kg (Table 1). Approximately 17.40 % of samples fell below the critical limit (< 2.0 ppm), whereas 82.60 % exceeded it, demonstrating adequate Mn across a majority of the region. Cu varied between 0.14 and 3.61 mg/kg, with an average of 1.38 mg/kg. Among the samples, 63.04 % fell below the critical level (< 2.0 ppm), while 36.96 % surpassed it, indicating generally sufficient levels attributed to the parent material. Zn ranged from 0.09 to 1.93 mg/kg, averaging 0.36 mg/kg; 91.30 % of samples fell below the critical threshold (< 0.6 ppm), suggesting a common Zn deficiency. The available B varied between 0.11 and 1.32 mg/kg (average: 0.61 mg/kg), with all samples classified in the low category.

Assessment of soil quality index

The soils of total cultivable areas of Ganasandra micro-watershed were assessed for soil quality in which PC analysis was performed for variables of soil fertility (Table 4). The soil properties of surface samples were subjected to PCA to reduce the data dimension. The PCA data for the micro-watershed showed that three PCs have an eigenvalues > 1, which explained 73 % of the cumulative variance (Table 4). The MDS were chosen based on the highly weighted loading factor of variables.

The parameters in each PC were assessed based on the greater values of the factor loading. The soil parameters derived from PCA for PC1 included exchangeable Ca, exchangeable Mg and pH. Nevertheless, a multivariate correlation matrix was employed to determine the correlation coefficients among the parameters when multiple variables were selected under a specific PC (14, 15). To prevent redundancy, only the parameters with the greatest loading factors were retained in the MDS when a significant correlation existed between them ($r > 0.60$). The parameters that do not correlate under a specific PC were deemed significant and kept in the MDS (16).

Among the key variables of PC1, pH is a factor that regulates nutrient availability and serves as a measure of soil fertility. It is a crucial soil factor that influences the stability of the soil framework, the accessibility of nutrients and microbial processes. Other parameters show a strong correlation with one another; thus pH was kept for MDS in PC1 (Table 4). Organic carbon (OC), available nitrogen and Zn were chosen as indicators from PC2 and PC3, respectively (Fig. 7). Among the variables present in the MDS from PC1, pH carries the greatest significance and influence on the SQI established by MDS, which has been extensively documented as an effective and sensitive factor for SQI development (17).

Following the parameter selection for the MDS, all chosen observations underwent transformation through linear scoring functions (where less is better, more is better and optimum is better). The organic carbon, accessible nitrogen and Zn were regarded as more favorable for soil quality when arranged in ascending order, thus adopting the more is better method. In pH, the approach of better is optimal was adopted. After the chosen observations' correlation between the highly weighted PC variables was converted into numerical scores (0-1), a weighted additive method was employed to combine them into indices for every soil sample (18). Subsequently, the weighted MDS indicator scores for every observation were aggregated to derive the weighted additive SQI (Table 5). SQI peaked in areas of lowlands and midlands where the soil exhibits neutral to slightly alkaline pH and higher OC because of effective agricultural methods. It was at its minimum in upland areas, characterized by acidic pH and low organic carbon, pointing to reduced soil productivity (19).

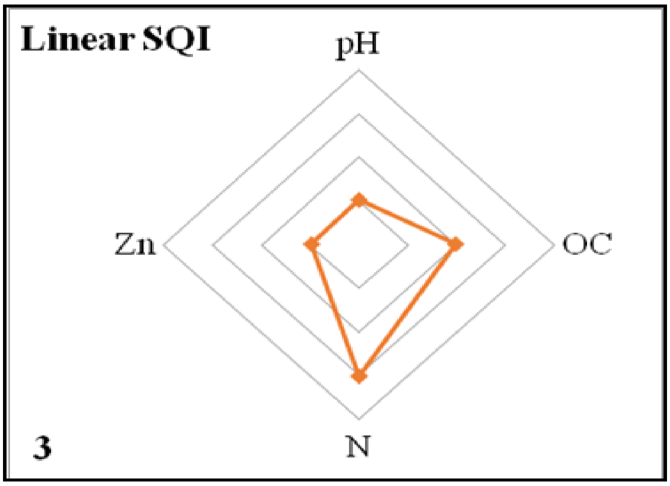

Fig. 7. Selected MDS for SQI under Ganasandra micro-watershed.

Discussion

Soil fertility parameters (macro- and micro-nutrients)

An alkaline soil reaction was discovered in the lower midland when the sub watershed areas, lower portions accrued lost bases due to runoff and percolation (19). The acidic soil reaction was found in summit area of topography/upland due to intensive leaching of cations and associated with nutrient deficiencies of basic cations. The alkaline soil pH was noticed in lowlands of tank bunds where mono-cropping systems fallows and these soils are prone to phosphorus, iron and zinc deficiency. An EC value that is below the sensitivity limits of FAO classification to being toxic for most of the crops and it is normal in entire sub-watershed due to well drainage conditions which removed released cations by percolation or through runoff and the results are in line with other study (19).

The organic carbon was quite low, possibly due to reduced farmyard manure application and the elimination of crop residues, along with a rapid decomposition rate caused by elevated temperatures. The removal and degradation of organic matter have occurred more quickly with reduced vegetation cover, resulting in fewer opportunities for organic matter accumulation in the soil alongside the transformation of plantation areas into crop fields. Comparable findings were noted in the soils of Bhubaneswar and Andhra Pradesh (19, 20).

The reduced nitrogen observed in the study region may be attributed to inorganic nitrogen being closely associated with the mineralization process, which is affected by various factors, including organic matter levels, pH and specific tropical conditions that result in quicker degradation (21). Nitrogen is among the most restrictive elements affecting plant growth. Organic nitrogen forms originate from the breakdown of organic material and represent the main types found in the soil. During mineralization, organic nitrogen slowly becomes accessible to plants, primarily in the forms of nitrate (NO^-_3) and ammonium (NH_4^+), while medium and high levels of P are largely influenced by frequent fertilizer application, pH, OC, soil texture and diverse agronomic practices (22, 23).

Adequate S levels across most of the area may be due to application of S containing fertilizers and higher Mn in soils originated from granite gneiss and schist parent material with semiarid and tropical climate, apart from neutral to low pH in majority of areas. Highly porous nature of tropical soils, originated from granite gneiss parent material, which assists fast removal of B from soil (24, 25).

Selected MDS

Soil pH significantly affects the physical, chemical and biological characteristics of soil within the Ganasandra micro-watershed. It serves as an essential measure of soil vitality, output and plant efficiency. Observations indicated that pH raises down slope and falls at higher elevations, probably due to the leaching of exchangeable bases from runoff and erosion, which gather in lower regions, elevating hydrogen ion concentration upslope and reducing pH. Comparable patterns have been observed in additional research (26–28). Keeping the ideal pH is vital for nutrient accessibility, microbial function, plant development, soil composition and efficient soil and crop management.

Organic carbon (OC) plays a crucial role in soil health, directly affecting fertility, productivity and the sustainability of ecosystems (29, 30). A decrease in OC diminishes cation exchange capacity (CEC), compromises soil aggregate stability and decreases crop yields. The depletion of organic matter, being key nutrient source, results in reduced soil productivity (31). OC aids plant growth by providing nutrients and improving soil physical characteristics, which boosts root development and overall plant vitality (32). Furthermore, OC is instrumental in the carbon cycle. Its decrease leads to physical soil deterioration, making OC-dependent characteristics vital indicators for assessing soil quality.

Nitrogen (N) is an essential nutrient crucial for soil health, plant development and ecosystem performance. Its presence greatly affects soil quality and crop yield (33). Sustainable soil management techniques like precision nutrient application, cover crop utilization and erosion management support ideal nitrogen levels while enhancing soil health and reducing environmental effects. Zinc (Zn), although needed in lesser amounts, is a vital micronutrient important for plant growth, avoiding nutrient shortages and improving crop production, hence significantly contributing to the health of soil and plants (34).

Digital mapping of SQI

The spatial variability of the soil quality index was assessed using geo-statistical interpolation through ordinary kriging, which is well-suited for continuous spatial variables. The soil quality data derived from the minimum data set were first analyzed for spatial dependence using semivariogram modeling. Among several tested models (spherical, exponential, Gaussian, etc.), the circular semivariogram model provided the best fit based on the lowest root mean square error (RMSE) and was therefore selected for interpolation.

Table 5. Principal components of soil quality parameters, eigenvalues and component matrix variables

	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12	C	WF
pH	0.391	0.101	0.083	0.091	0.108	0.061	0.011	0.314	0.206	0.360	0.727	0.090	0.170	0.118
EC	0.343	0.177	0.072	0.200	0.243	0.217	0.554	0.017	0.547	0.226	0.189	0.074	-	-
OC	0.140	0.304	0.539	0.086	0.287	0.673	0.083	0.174	0.046	0.118	0.006	0.025	0.403	0.281
N	0.138	0.516	0.328	0.025	0.002	0.616	0.226	0.275	0.001	0.251	0.063	0.185	0.393	0.274
P_2O_5	0.265	0.256	0.343	0.061	0.659	0.283	0.108	0.065	0.038	0.438	0.088	0.109	-	-
K_2O	0.300	0.193	0.273	0.389	0.272	0.146	0.341	0.427	0.318	0.327	0.059	0.205	-	-
S	0.279	0.336	0.283	0.174	0.149	0.107	0.535	0.385	0.396	0.219	0.163	0.006	-	-
Fe	0.363	0.118	0.042	0.430	0.135	0.008	0.057	0.162	0.306	0.211	0.267	0.641	-	-
Mn	0.320	0.082	0.151	0.610	0.084	0.052	0.060	0.295	0.027	0.266	0.094	0.561	-	-
Cu	0.375	0.082	0.163	0.103	0.086	0.026	0.119	0.574	0.275	0.215	0.434	0.392	-	-
Zn	0.057	0.448	0.515	0.057	0.496	0.001	0.311	0.028	0.333	0.070	0.254	0.060	0.470	0.327
B	0.273	0.395	0.027	0.434	0.196	0.014	0.322	0.131	0.341	0.479	0.248	0.118	-	-
EV	5.411	1.856	1.496	0.863	0.551	0.485	0.381	0.311	0.253	0.172	0.122	0.099		
Var.	45.1	15.5	12.5	7.2	4.6	4.0	3.2	2.6	2.1	1.4	1.0	0.8		
CV	45.1	60.6	73.0	80.2	84.8	88.9	92.0	94.6	96.7	98.2	99.2	100.0		

The results of semivariogram revealed that the spatial dependence of SQI extended within the grid interval (320 m), indicating that the chosen sampling interval was appropriate for capturing spatial variability within the micro-watershed. Using the interpolated surface, the SQI values were classified into five categories: very low, low, medium, high and very high. The spatial output was integrated with cadastral maps in a GIS environment to generate final thematic maps showing the spatial distribution of SQI. These maps were further used to calculate the area under each class and interpret land suitability for cultivation.

Standard kriging was employed to evaluate the spatial variation of the SQI using soil fertility factors. The circular semivariogram model (0.125) demonstrated the best fit, shown by the lowest RMSE. The 320 m grid spacing was within the spatial correlation range for the Ganasandra micro-watershed, confirming the sampling distance (35). Spatial variability originated mainly from random factors such as fertilization, farming practices and human actions. GIS combined with geostatistics was utilized to illustrate and categorize SQI variability. The SQI map based on cadastral data revealed that 43.03 % of the area was classified as low to very low SQI, 20.01 % as medium and 31.02 % as high to very high-collectively encompassing 94.06 % of the watershed (Fig. 8). The SQI distribution directly influenced crop yield, pinpointing areas of high or low soil quality. Areas with higher SQI demonstrated enhanced productivity and input efficiency, while those with lower SQI highlighted a necessity for soil enhancement. This spatial understanding facilitates focused soil management and land use strategies, enhancing sustainable farming.

Conclusion

Examination of soil fertility metrics indicated that the SQI within the micro-watershed varied from moderate to very high. PCA revealed four crucial factors viz., soil pH, organic carbon, available nitrogen and zinc as significant elements influencing SQI. In regions with moderate SQI, enhancing soil quality by improving pH and structure through calcium-rich amendments can be beneficial. Preserving soil health and ensuring agricultural sustainability necessitates the conservation and enhancement of organic matter, essential for carbon and nitrogen cycling. Tackling zinc deficiencies is essential for crop yield. More comprehensive studies like precision nutrient assessment and application, soil quality assessment with mapping and nutrient dynamic studies are crucial for guiding sustainable land use planning and improving nutrient with soil quality management across different soil management practices within the micro-watershed.

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Authors' contributions

HM carried out the studies, participated in the manuscript draft . AMA and SR planned and prepared the draft for research. YSB participated in the design of the study and DCA performed the statistical analysis. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

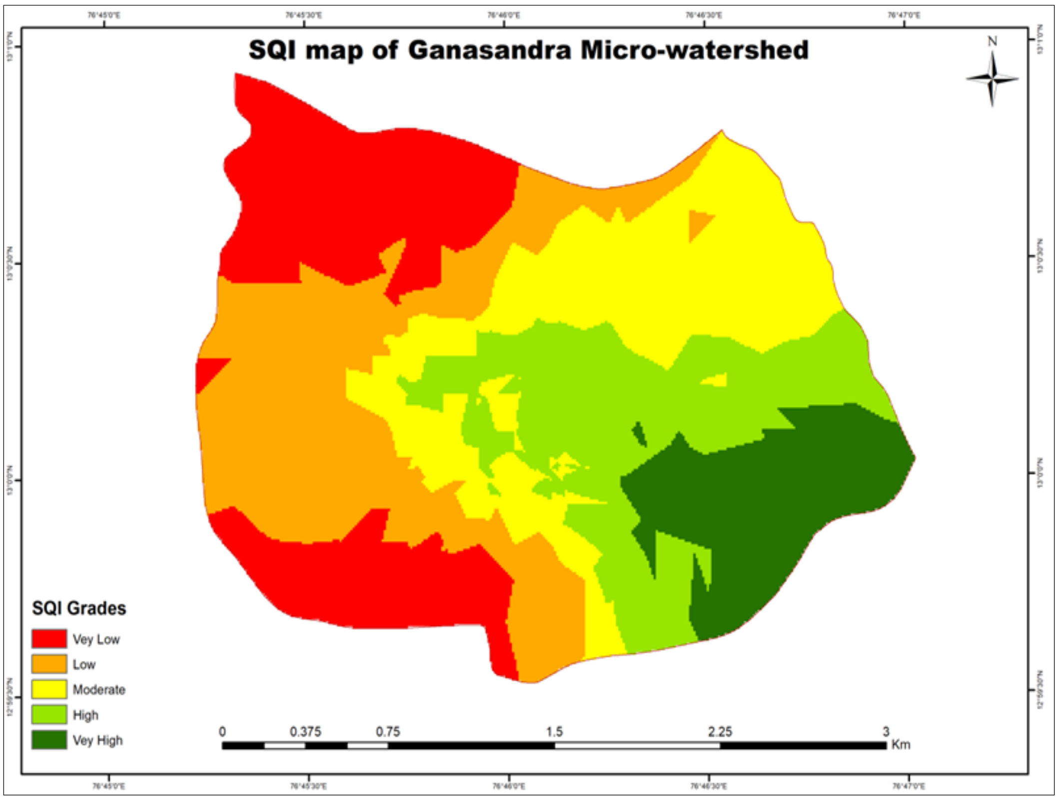

Fig. 8. SQI map of the Ganasandra micro-watershed.

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