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RESEARCH ARTICLE

Digital soil fertility mapping of a Pashupathihal-2 micro-watershed in Kundgol taluk, Karnataka state through GIS

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Abstract

The study evaluates the spatial variability of soil fertility in the Pashupathihal-2 micro-watershed (428.8 ha) using remote sensing-assisted digital soil mapping and GIS-based geostatistical techniques to support precision nutrient management. The study revealed considerable spatial variability in soil physicochemical and nutrient characteristics, indicating heterogeneous soil health and fertility status. The soils were primarily slightly to strongly alkaline, with pH values ranging from 8 to 9.16 (mean 8.66). They exhibited non-saline electrical conductivity levels (mean 0.57 dS/m), typical of the black clay *vertisols* found in the region. Organic carbon levels varied from 0.15 to 0.87 %, with 79.61 % of the area falling into the medium organic carbon category, reflecting moderate organic matter content. Nitrogen levels were predominantly low (mean 140.83 kg/ha), with nearly 30 % of the area classified as very low, suggesting potential nutrient depletion possibly linked to reduced organic matter. Phosphorus availability (mean 27.92 kg/ha) remained within a moderate range, although its uneven distribution suggests the need for site-specific fertilization. Potassium content was generally sufficient (mean 475.32 kg/ha) due to inherent soil properties but showed spatial discrepancies that may affect nutrient balance. Micronutrient assessment revealed a critical deficiency in iron, with 80.56 % of the area below the sufficiency threshold (<4.5 ppm), while manganese, copper and zinc were reported in adequate quantities throughout the watershed. These findings highlight the contribution of geospatial tools in identifying soil constraints, facilitating precision nutrient management and supporting sustainable agricultural practices through informed land-use planning.

Keywords: digital soil mapping; GIS; soil fertility; watershed

Introduction

The fertility of soil is fundamental to global food security, environmental sustainability and the economic well-being of farming communities. It determines the soil's capacity to supply essential nutrients to crops and is impacted by factors such as the amount of organic matter and soil texture, pH, erosion and land management practices. Globally, about 33 % of soils are moderate to highly degraded due to erosion, nutrient depletion and improper agricultural practices (1). In India, approximately 52 % of agricultural soils lack enough available nitrogen, 40 % are low to medium in phosphorus and around 20 % are deficient in potassium, according to the Soil Health Card Scheme data (2023-24). Indian cropping systems, with nutrient deficiencies directly impacting the productivity of key crops such as maize, jowar, pulses, groundnut and cotton, which are integral to food and livelihood security in semi-arid regions during the 2023-24 cultivation cycle. As agriculture intensifies and land resources come under pressure, understanding the spatial variability of soil fertility has become essential for precision agriculture. Conventional methods of assessing soil fertility are limited in coverage and resolution. Digital Soil Fertility Mapping (DSFM) integrates geospatial tools like GPS and GIS with spatial interpolation techniques such as Kriging and Inverse Distance Weighting (IDW), along with soil data, to generate high-resolution nutrient distribution maps (2). These maps enable targeted interventions, improved nutrient use efficiency and cost-effective management of soil resources (3). This approach supports the objectives of climate-smart and sustainable agriculture by optimizing fertilizer inputs, reducing greenhouse gas emissions and minimizing environmental degradation (4, 5).

Recent national and regional statistics reveal notable variability in soil fertility across India, particularly in rainfed and semi-arid zones. As per the Soil Health Card Scheme (2023-24), about 52 % of cultivated soils across India are often poor in available macronutrients is generally sufficient but declining in intensively farmed regions. Micronutrient deficiencies, especially of zinc (Zn) and boron (B), are emerging as critical concerns. Zinc deficiency affects roughly 36 % of soils nationally, while boron deficiency affects around 20 %. These imbalances hinder crop productivity, soil resilience and the long-term viability of agricultural systems (6).

Materials and Methods

The Pashupathihal-2 micro-watershed is situated in the northern region of Karnataka, within Kundgol taluk of Dharwad district. It spans an area of approximately 428.8 hectares and is geographically positioned between 15°10'30" to 15°12'00" N latitude and 75°21'30" to 75°24'00" E longitude (Fig. 1). The watershed is bordered by the villages of Yare Bhudhihala, Sulthanapura, Pashupathihala and Samsi. The Pashupathihal-2 micro-watershed is situated in Agro-Ecological Sub Region (AESR 6.4), part of the North Sahyadris and Western Karnataka Plateau and falls within the semi-arid zone with an average annual precipitation is nearly 669 mm. The pedological properties of this area were mainly medium to deep black clays, well-suited for rainfed cropping. The primary cropping season is *kharif*, during which crops such as maize, jowar, pulses, groundnut and cotton are cultivated. Vegetables like chilli, peas and onion are also grown, supporting a mixed cropping system adapted to variable rainfall conditions.

Soil sampling and analysis

Soil sample collection was carried out from the Pashupathihal-2 micro-watershed using a stratified random sampling technique. A grid of sampling points was established at 320 x 320 m, covering the entire micro-watershed. Soil samples were acquired at a depth of 30 cm from each sampling point. Soil was carefully collected and mixed to create a composite sample in each grid (a total of 42 samples). After air drying and grinding, the samples were passed through a 2 mm sieve before laboratory analysis.

Soil pH and Electrical Conductivity (EC) were assessed following the standard procedure. pH was determined using a 1:1 soil to water ratio, while EC was measured in a 1:1 soil to water extract using a conductivity sensor. Nitrogen (N) was determined using the Kjeldahl method, phosphorus (P) by the Olsen method and potassium (K) was quantified using a flame photometer. Organic Carbon (OC) was estimated using the Walkley-Black method, which involves the oxidation of OC with potassium dichromate in the presence of sulfuric acid and quantification by titration (7- 10). Micronutrients, including zinc (Zn), iron (Fe), copper (Cu) and manganese (Mn), were extracted using DTPA and assessed using AAS. Boron (B) was determined using a spectrophotometric method.

Remote Sensing (RS) and GIS methodology

RS data and Geographic Information System (GIS) tools were employed to create digital soil fertility maps. High-resolution satellite imagery from WorldView-2, with a 0.5 m spatial resolution, was utilized in the analysis. This satellite imagery was obtained from the Karnataka State Remote Sensing Application Centre (KSRSAC). This high-resolution imagery was incorporated to enhance the precision of localized soil fertility assessments (11).

For data integration and analysis, ArcGIS 10.8.1 software was used to combine various spatial datasets, including soil fertility parameters (such as pH, EC, NPK and micronutrients), along with topographical factors like slope, elevation, land use and drainage patterns. To generate continuous soil fertility maps from discrete point data, spatial

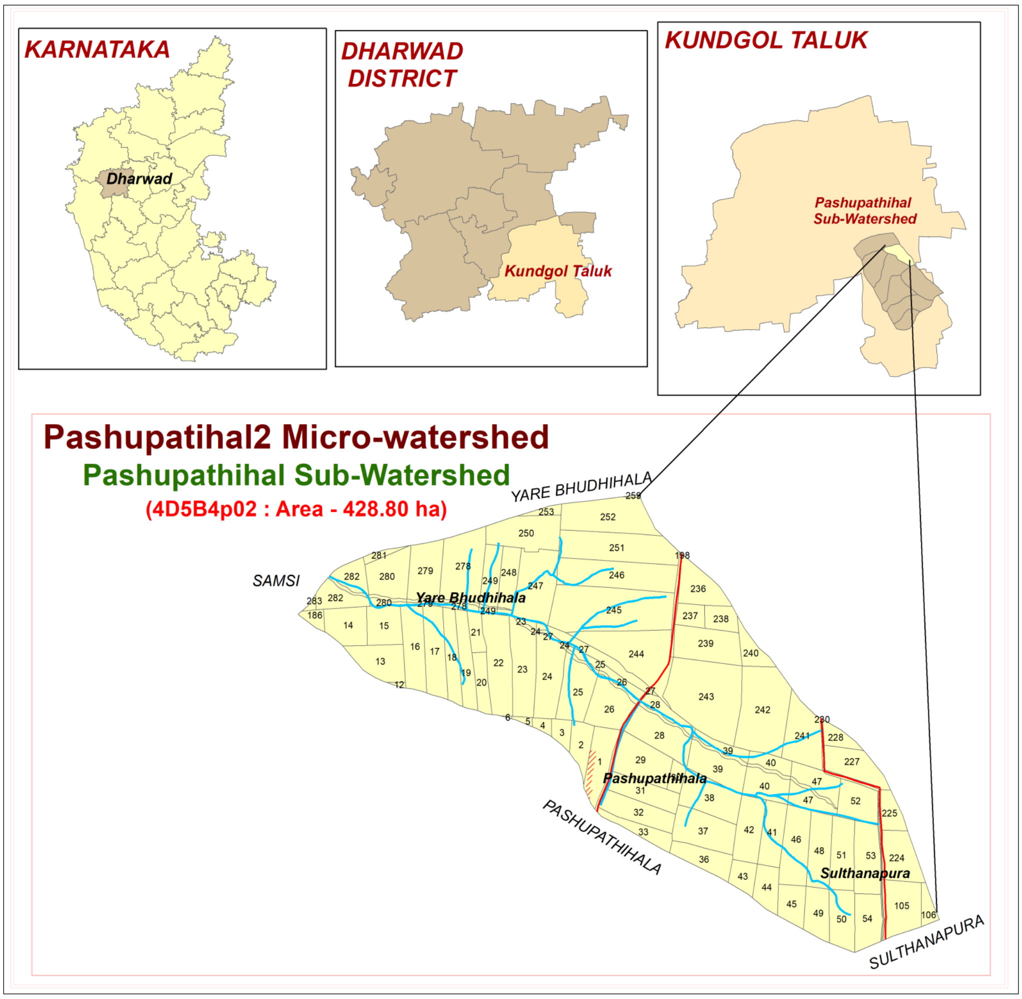

Fig. 1. Spatial map of the study area.

interpolation approaches, including IDW and Kriging, were applied (12). Both IDW and Kriging interpolation methods were employed to enhance the spatial prediction accuracy of soil fertility parameters. IDW is a deterministic technique that assigns greater weight to nearer observations, relying on the assumption that spatially closer samples exhibit more similarity. It is computationally efficient and suitable for areas with dense sampling. Kriging, on the other hand, is a stochastic geostatistical method that utilizes the spatial structure of the data through variogram modeling to account for spatial autocorrelation. It not only provides interpolated values but also quantifies prediction uncertainty, making it more robust for heterogeneous and sparsely sampled environments. These methods allowed for estimating nutrient levels at unmeasured locations, resulting in high-resolution predictions of soil fertility variability across the watershed. The geo-referenced soil samples, collected at 320 x 320 m intervals, were crucial for the accurate integration of soil data with RS and GIS layers, ensuring the reliability and precision of the final maps.

Results and Discussion

The soil analysis results for the Pashupathihal-2 micro-watershed show notable variations in nutrient and soil properties, reflecting the region's diverse fertility status (Table 1). The pH values ranged from 8 to 9.16, with an average of 8.66, indicating slightly alkaline soil, that are characteristic of the region's black clay soils. EC values varied between 0.36 and 0.93 dS/m, with a mean of 0.57, suggesting moderate saline conditions, which may be a concern for crops sensitive to salinity (13). OC content ranged from 0.15 % to 0.87 %, with a mean of 0.57 %, suggesting moderate soil organic matter levels; however, low OC could affect soil fertility and microbial activity (14). Nitrogen (N) values ranged from 84 to 203 kg/ha, with a mean of 140.83 kg/ha, indicating that while the average falls within an adequate range for crop growth, areas with values below 140 kg/ha as per ICAR guidelines are considered very low in fertility and thus require appropriate nutrient management (15). Phosphorus (P_2O_5) exhibited considerable variations, ranging from 6.87 to 65.84 kg/ha, with a mean of 27.92 kg/ha, highlighting the need for targeted fertilization practices to address phosphorus deficiencies in certain areas (16). Potassium (K_2O) content, ranging from 196.6 to 625.8 kg/ha, with a mean of 475.32 kg/ha was adequate, but variations across the watershed suggest localized imbalances. The micronutrient levels of iron (Fe), manganese (Mn), copper (Cu) and zinc (Zn) showed marginal to low sufficiency, particularly zinc, which ranged from 0.09 to 0.86 ppm, with a mean of 0.48 ppm, indicating a need for micronutrient supplementation (17).

The soil reaction (pH) and EC maps (Fig. 2 and 3) of the Pashupathihal-2 micro-watershed (428.80 ha) reveal that 86.58 % of the area was strongly alkaline (pH 8.4-9), while 12.62 % was moderately alkaline (pH 7.8- 8.4) and the entire area falls within the non-saline range (EC < 2 dS m^{-1}). While moderate alkaline soils generally support a wide variety of crops due to favorable microbial activity and nutrient availability, strongly alkaline soils have the potential to inhibit plant growth through nutrient imbalances, particularly Fe and Zn deficiencies and structural degradation from sodicity (18, 19). These alkaline conditions were often the result of calcareous parent materials, poor internal drainage and suboptimal water management. However, the non-saline nature of the soil indicates a low risk of osmotic stress and supports healthy root development and nutrient uptake. This favorable EC status may be attributed to natural drainage, limited salt accumulation and the use of good -quality irrigation water, with *vertisols* moderate permeability further preventing salt buildup (20). However, regular monitoring is necessary to prevent secondary salinization, especially under high alkalinity and potential groundwater misuse (21). Ameliorative practices such as gypsum application, organic matter addition and salt-tolerant crop cultivation are recommended to manage soil alkalinity and ensure sustained productivity (22).

The OC spatial map indicated that 79.61 % of the watershed had medium OC levels (0.5-0.75 %), while 2.85 % exhibited low OC (<0.5 %) (Fig. 4). Medium OC levels in semi-arid regions are often due to intensive cultivation, minimal biomass return and sparse vegetative cover (23). OC was essential for enhancing soil structure, moisture retention, microbial dynamics and as well as nutrient cycling, which plays a key role in sustainable crop productivity (24). Areas with low organic matter were more susceptible to drought, erosion and nutrient depletion, highlighting the need for targeted soil fertility management. Site-specific interventions, such as applying organic matter sources including farmyard manure, compost, green manure and adopting conservation agriculture, can significantly improve OC levels and long-term soil health (25). These strategies significantly enhance carbon sequestration but also increase soil resilience and productivity. The OC spatial map indicated that 79.61 % of the watershed had medium OC levels (0.5-0.75 %), while 2.85 % exhibited low OC (<0.5 %). Medium OC levels in semi-arid regions are often due to intensive cultivation, minimal biomass return and sparse vegetative cover (26).

The nutrient status assessment of the Pashupathihal-2 micro-watershed reveals that nitrogen availability was remarkably low, with 29.65 % of the study area categorized as

Table 1. Descriptive statistics of soil properties in Pashupathihal-2 micro-watershed

Soil properties	N	Minimum	Maximum	Mean	Std. Deviation	Variance	Skewness	Kurtosis
pH	42	8.00	9.16	8.66	0.27	0.07	-0.56	-0.07
EC	42	0.36	0.93	0.57	0.12	0.02	0.85	1.02
OC (%)	42	0.15	0.87	0.57	0.15	0.02	-0.51	0.79
N (kg/ha)	42	84.00	203.00	140.83	26.20	686.48	0.23	0.09
P_2O_5 (kg/ha)	42	6.87	65.84	27.92	14.65	214.72	0.73	0.18
K2O (kg/ha)	42	196.60	625.80	475.32	91.89	8443.67	-1.16	1.70
Fe (ppm)	42	5.06	25.24	16.17	5.23	27.31	-0.13	-0.69
Mn (ppm)	42	6.36	29.98	17.26	5.48	29.99	0.20	0.04
Cu (ppm)	42	0.30	2.90	1.44	0.76	0.57	0.35	-0.74
Zn (ppm)	42	0.09	0.86	0.58	0.20	0.04	0.40	-0.89

(N- Total number of samples collected for analysis)

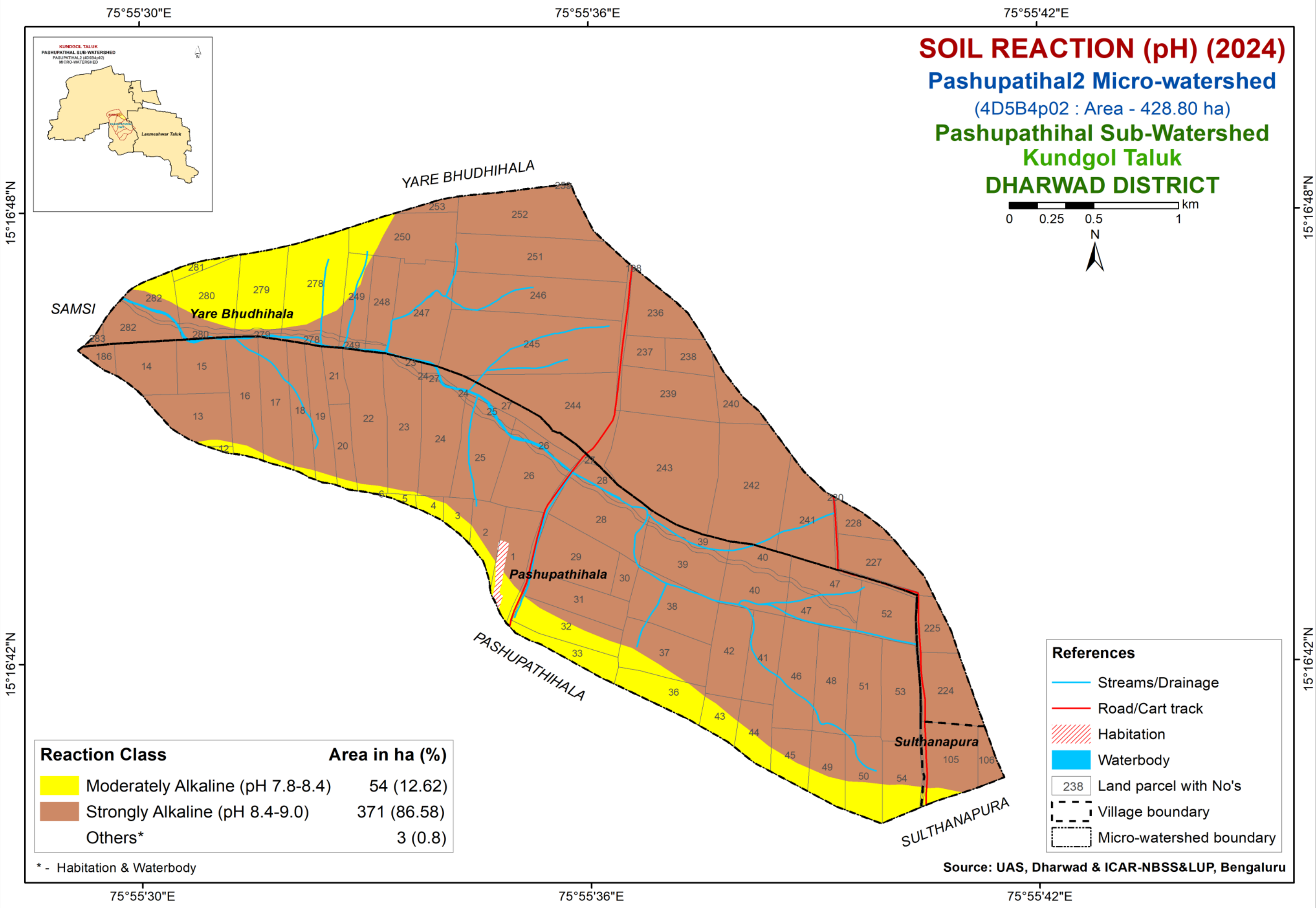

Fig. 2. Map of soil reaction.

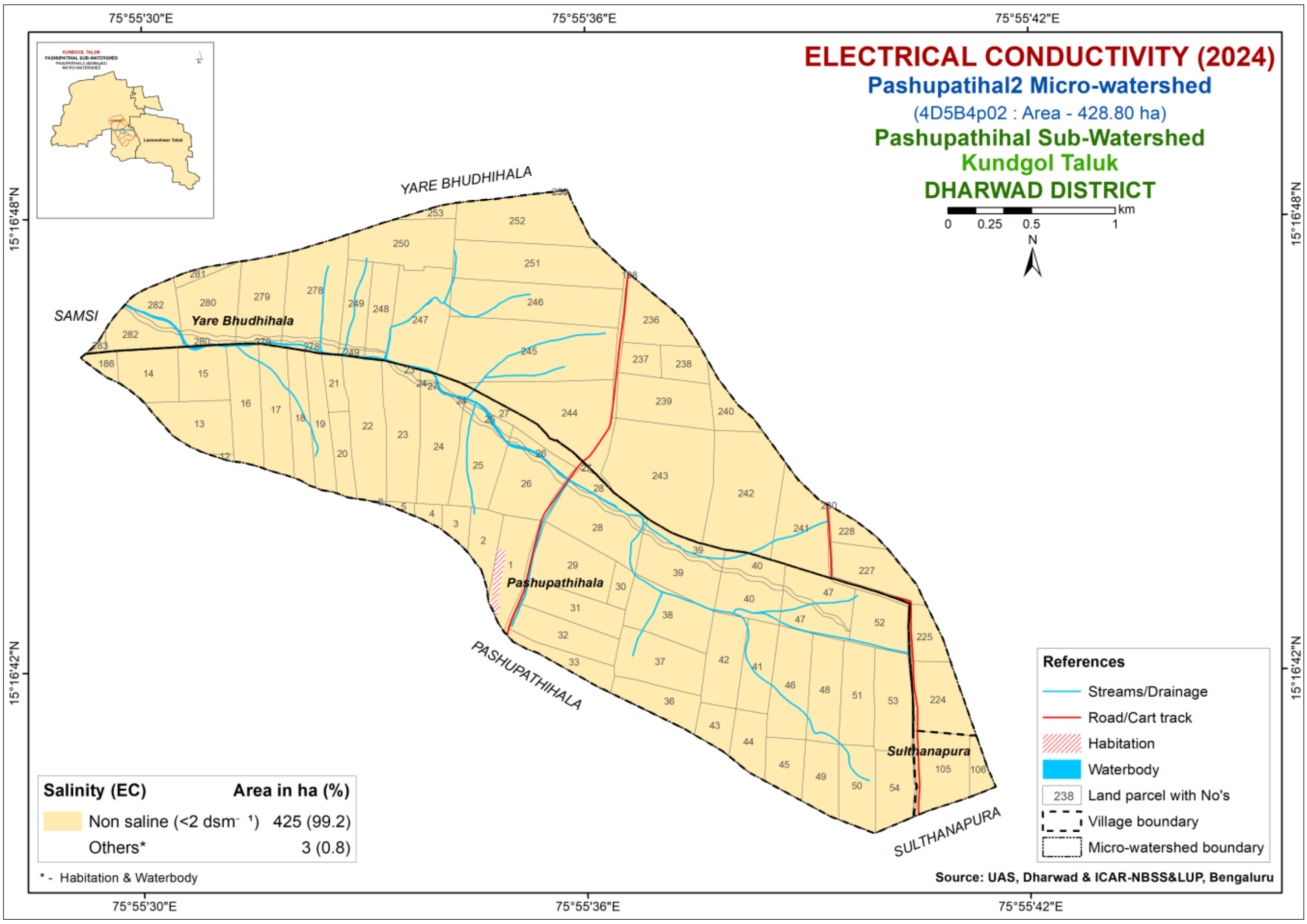

Fig. 3. Map of EC.

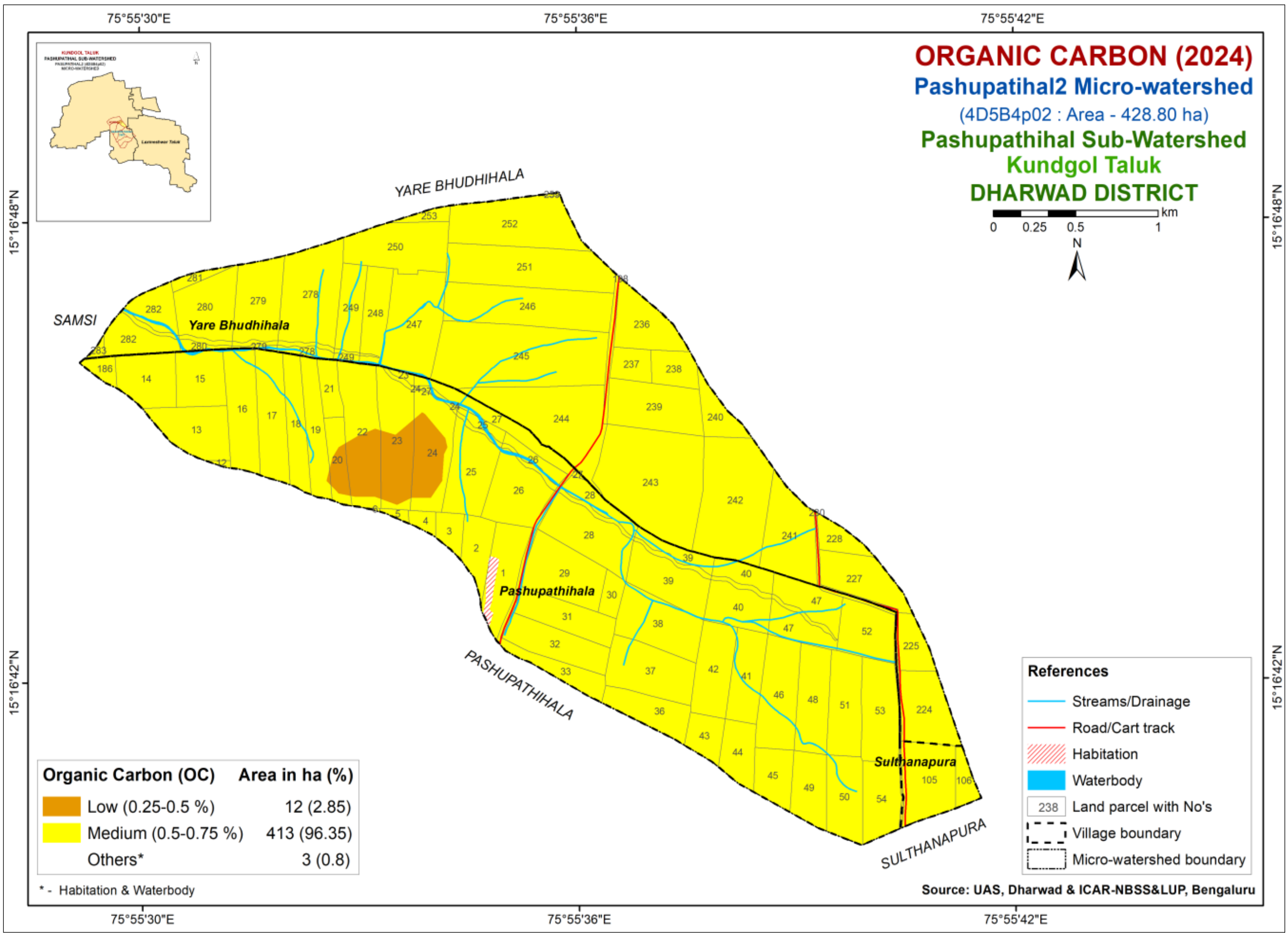

Fig. 4. Map of OC.

very low (<140 kg/ha) and 69.55 % as low (<280 kg/ha), a condition typical of dryland *vertisols* had low OC matter, continuous agricultural activity without nutrient replenishment and nitrogen losses through leaching and volatilization (27) (Fig. 5). Since nitrogen is critical for chlorophyll synthesis, protein formation and vigorous vegetative growth, its deficiency severely constrains crop productivity and soil microbial activity. Overcoming these issues involves the use of integrated nutrient management strategies such as organic manure application, legume incorporation, crop residue recycling and site-specific nitrogen fertilizer use based on soil test data (28).

Phosphorus levels across the watershed fall entirely within the medium range (23-57 kg/ha), reflecting moderate availability but also highlighting inherent limitations of *vertisols* under rainfed, alkaline conditions where phosphorus gets fixed by calcium or iron and aluminum compounds (Fig. 6). As phosphorus is essential for early root establishment, its moderate levels may still limit crop performance unless managed properly using practices like rock phosphate application with Phosphate-Solubilizing Bacteria (PSB), phosphorus-enriched compost and water-soluble fertilizers (29).

Potassium status was generally high (337- 675 kg/ha), with 5.12 % of the area in the very high category. This is beneficial due to potassium's roles in stress resistance, enzyme activation and photosynthesis (30) (Fig. 7). Such high values may be caused by potassium-rich parent material, high cation exchange capacity in clay-dominated *vertisols* and residual potassium from past fertilization practices. However, very high potassium may disrupt nutrient balance, particularly antagonizing calcium and magnesium uptake, necessitating balanced nutrient management to maintain the health of soil and crop productivity (31).

The micronutrient status of the Pashupathihal-2 micro-watershed reveals a prominent deficiency in iron, with 80.56 % of the area falling below the critical threshold (<4.5 ppm), while only 18.73 % shows adequate levels (>4.5 ppm). This widespread iron deficiency is primarily attributed to the alkaline soil conditions prevalent in the region, which lead to the precipitation of iron into insoluble forms, rendering it unavailable to plants (32) (Fig. 8). Effective management strategies such as foliar application of iron chelates, use of acidifying amendments, or cultivation of iron-efficient diverse crop varieties may help counteract the deficiency (33). The status of manganese, copper and zinc across the watershed was uniformly sufficient, indicating favorable conditions for micronutrient availability (Fig. 9 and 10). Manganese, essential for photosynthesis and nitrogen metabolism, is adequately available in all areas (>1 ppm), likely due to suitable soil pH and mineralogy (34, 35). Similarly, zinc availability is sufficient in all sampled areas (>0.6 ppm) (Fig. 11), supporting its vital role in enzymatic activities, hormone regulation and photosynthesis, with adequate levels maintained by favorable pH, organic matter content and possibly previous fertilization practices.

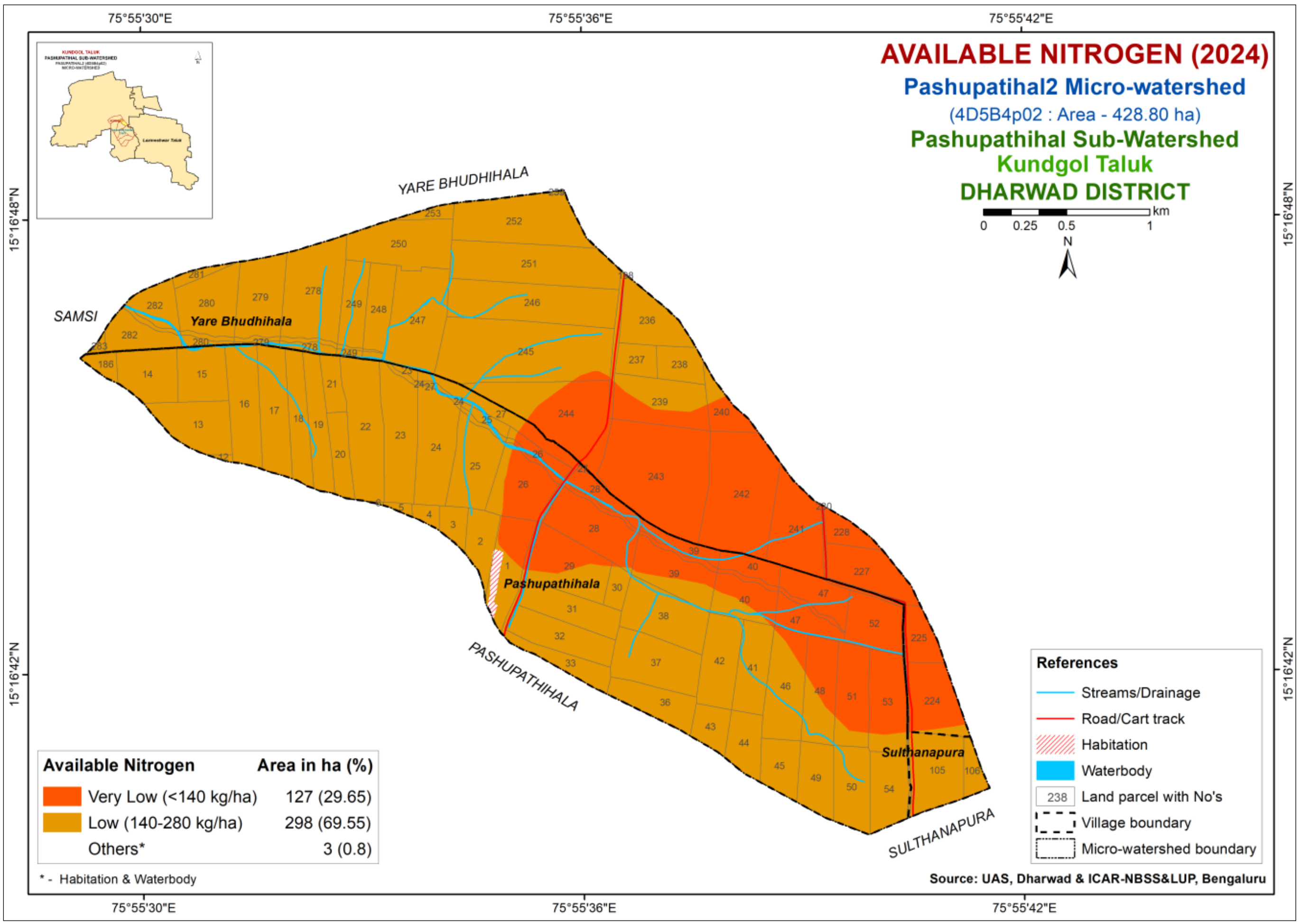

Fig. 5. Map of available nitrogen.

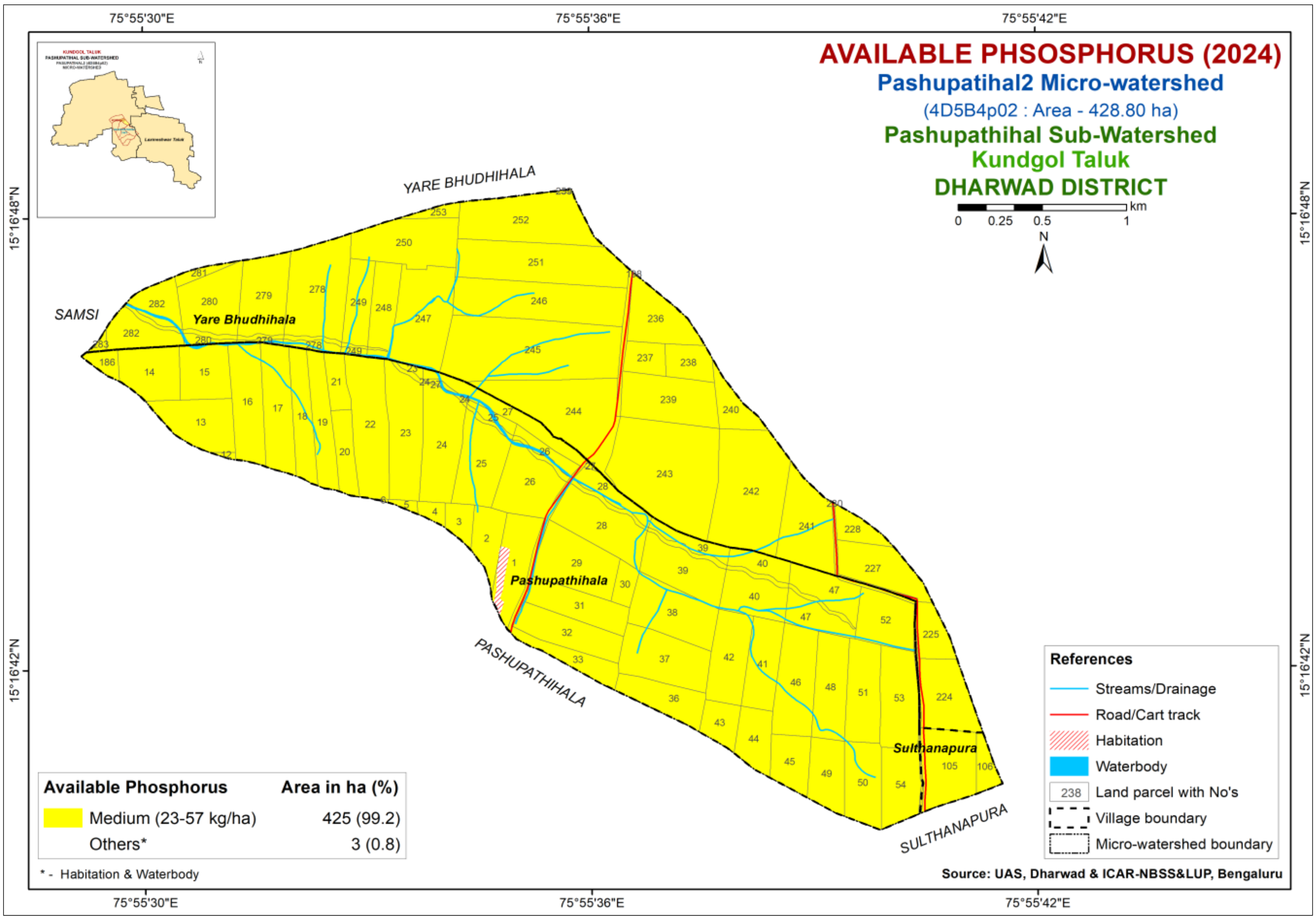

Fig. 6. Map of available phosphorus.

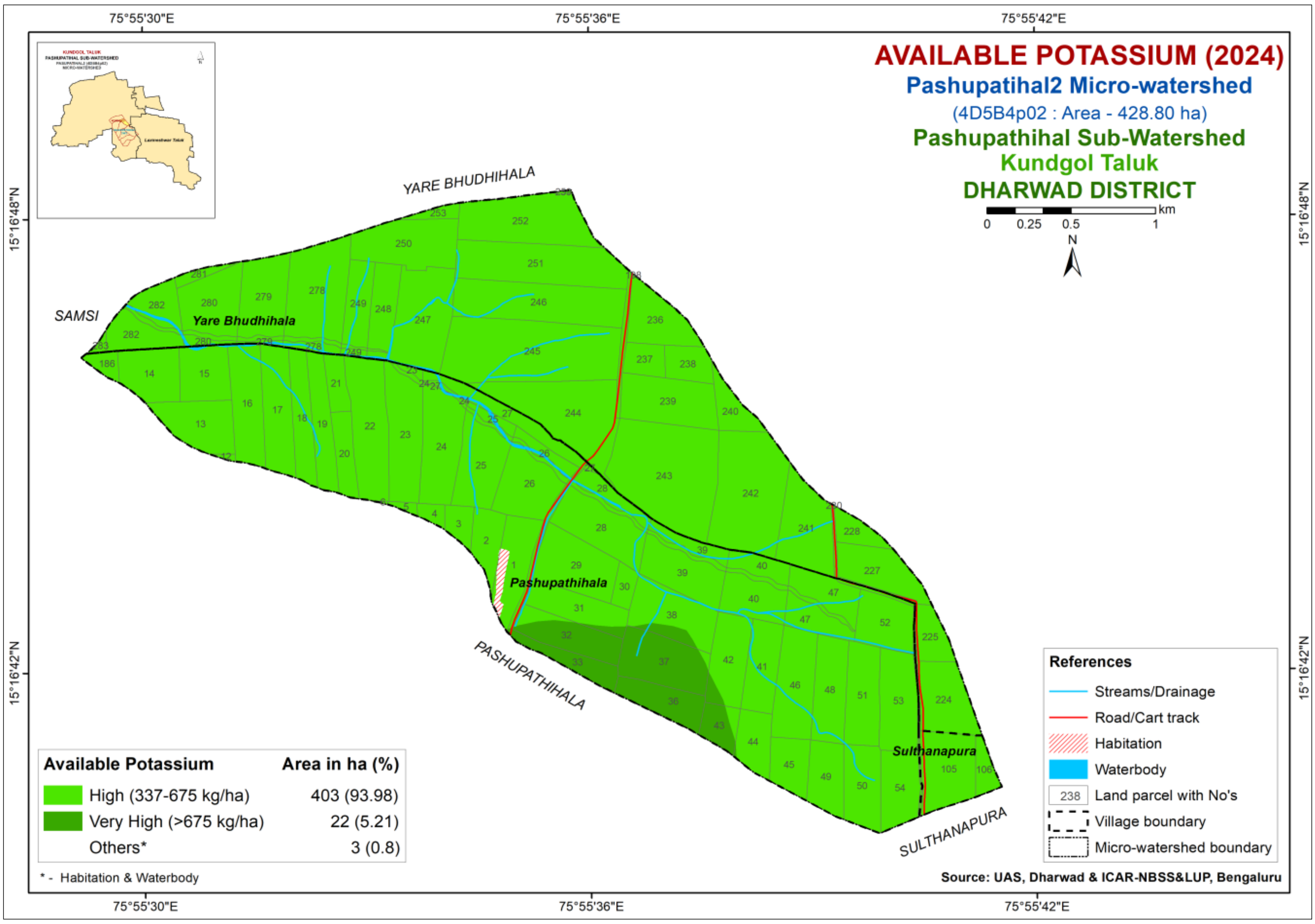

Fig. 7. Map of available potassium.

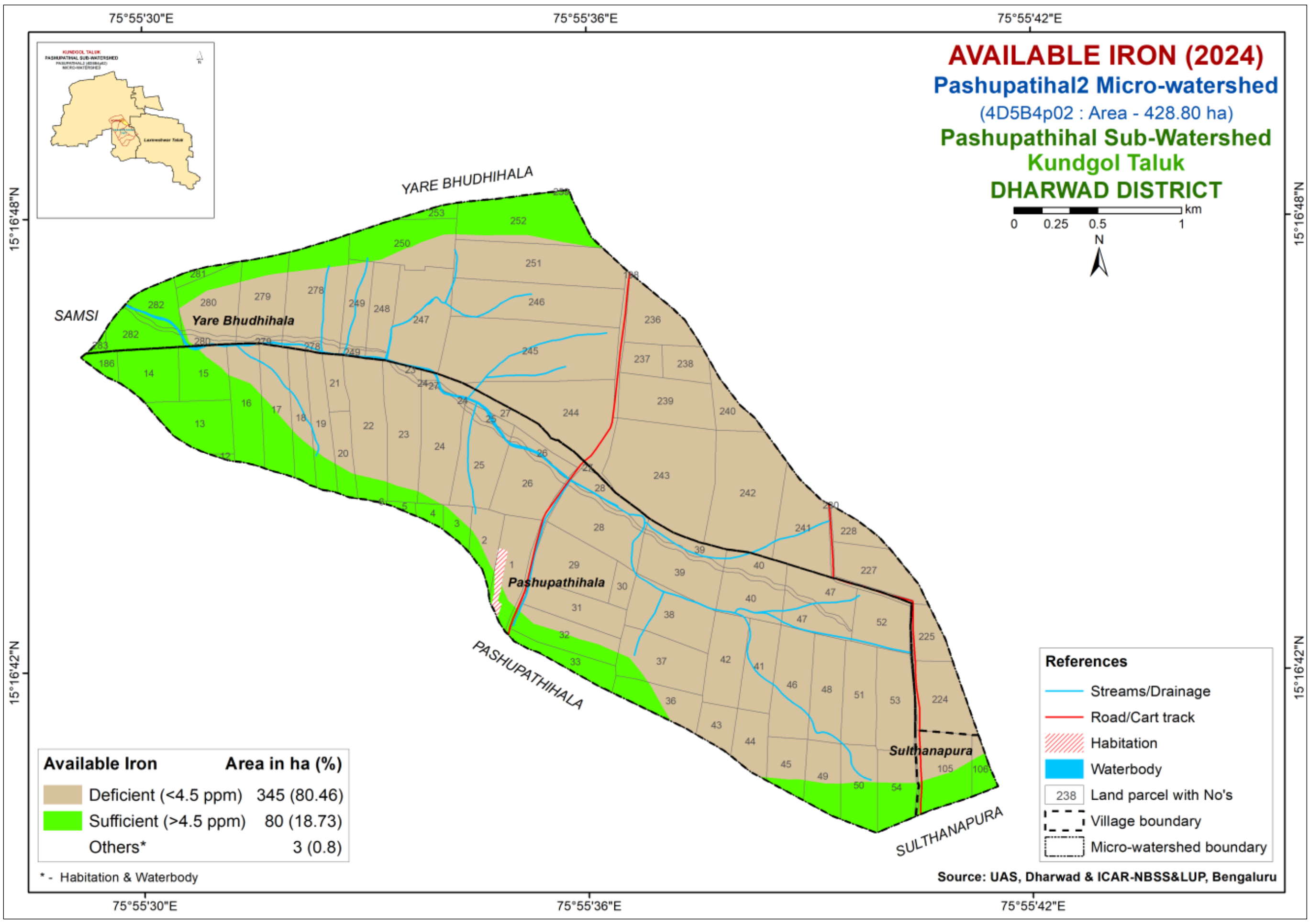

Fig. 8. Map of available iron.

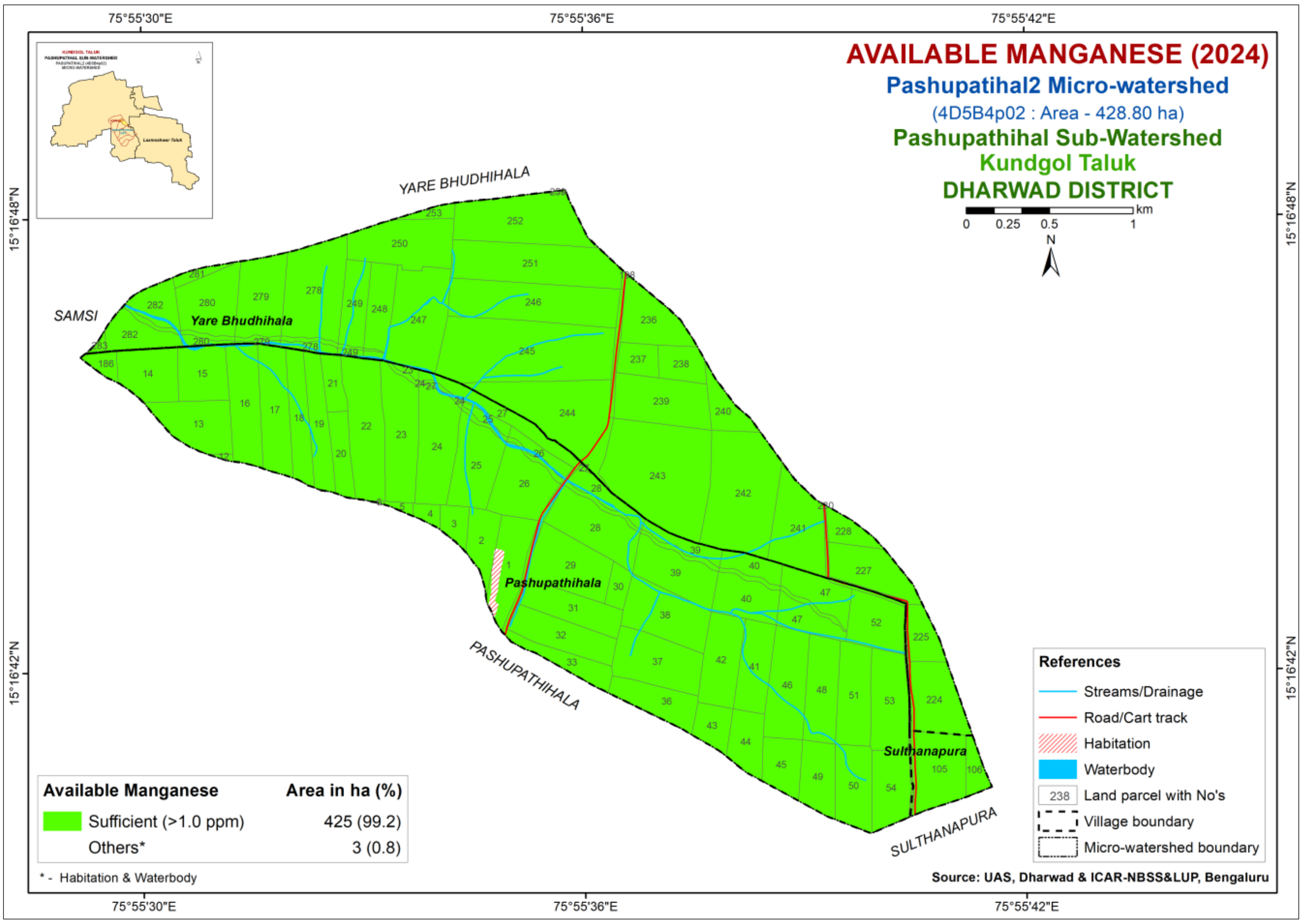

Fig. 9. Map of available manganese.

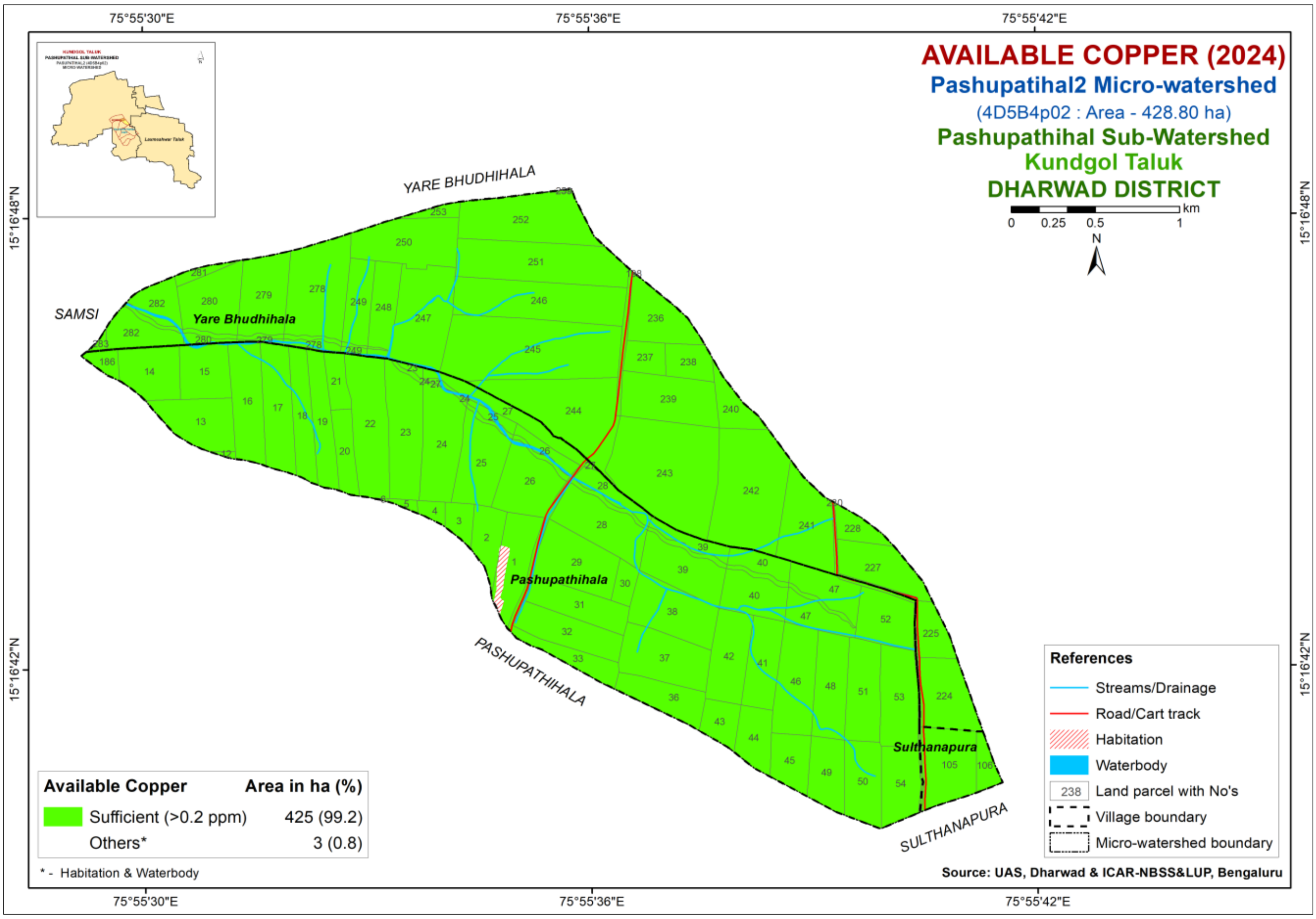

Fig. 10. Map of copper.

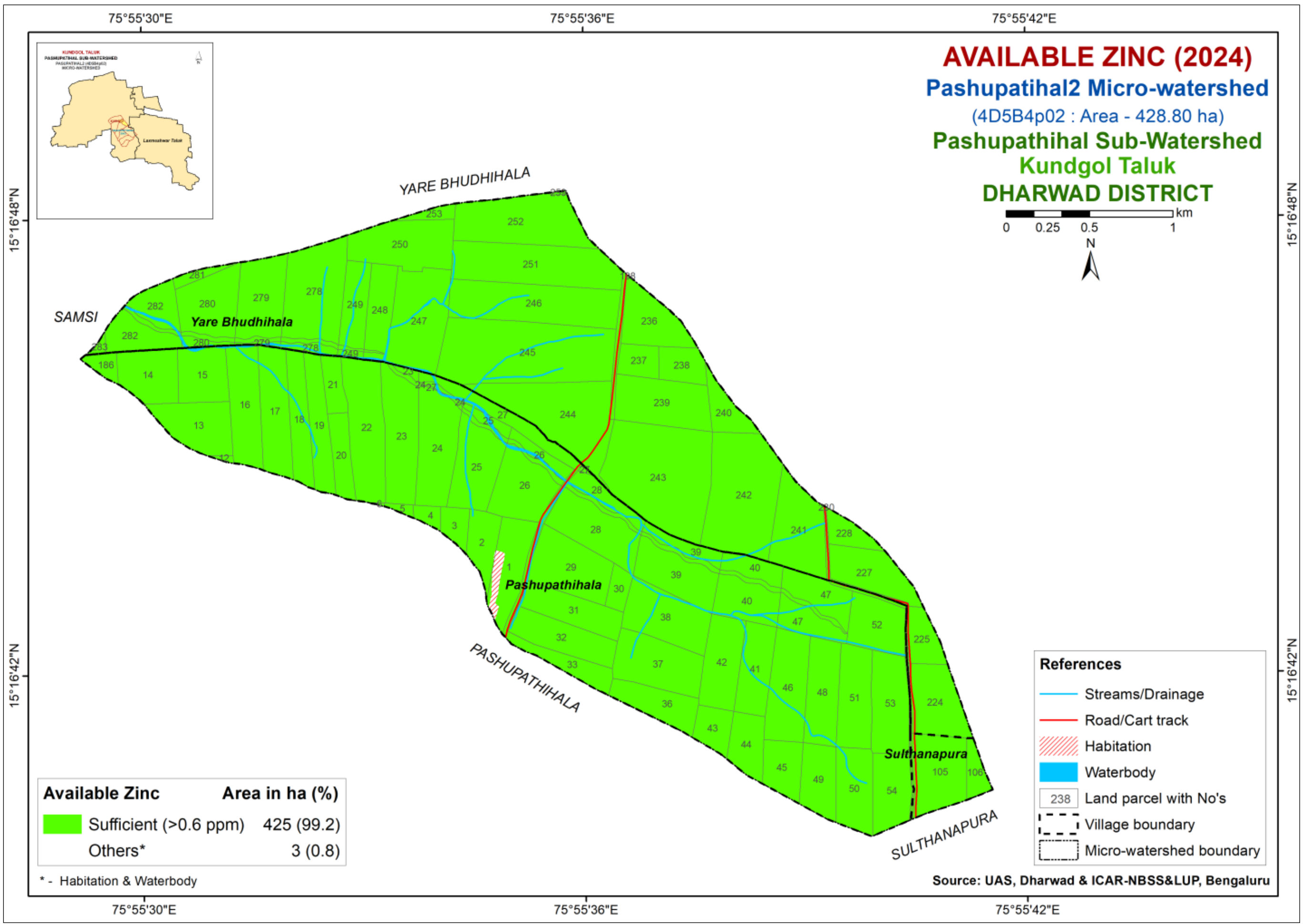

Fig. 11. Map of zinc.

Conclusion

The fertility assessment of the Pashupathihal-2 micro-watershed, conducted through digital soil mapping integrated with RS and GIS technologies, revealed pronounced spatial heterogeneity in soil physico-chemical properties. The soils were predominantly alkaline in reaction, moderately sufficient in OC and exhibited a widespread deficiency in available nitrogen. Available phosphorus showed moderate variability across the landscape, while available potassium and micronutrients such as manganese, zinc and copper were generally adequate. However, available iron (Fe) levels were deficient in several locations. The application of geostatistical interpolation techniques (IDW and Kriging) coupled with high-resolution spatial data effectively delineated fertility constraints and nutrient distribution patterns.

These findings highlight the need for precision nutrient management and site-specific soil fertility interventions to enhance nutrient use efficiency. The integration of soil, topographic, climatic and land use data enables spatially explicit recommendations, facilitating sustainable intensification in semi-arid *vertisols* regions. Implementing Integrated Nutrient Management (INM) strategies, supported by geospatial decision tools, can substantially improve soil health and ensure long-term agricultural productivity and resource conservation in semi-arid regions.

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Authors' contributions

JHKN contributed to conceptualization, remote sensing and GIS analysis, data processing and manuscript drafting. JBR was responsible for methodology, supervision and validation. MMV, GSS, RGR and PP contributed to the methodology.

Compliance with ethical standards

Conflict of interest: The authors declare that they have no conflict of interest.

Ethical issues: None

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