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# Characterization and classification of soils in the Bettadapura micro-watershed of lower Tungabhadra catchment using a geospatial approach

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**Abstract**
Detailed soil resource information is crucial for effective land use planning, especially at the micro-watershed level. This study aimed to characterize and classify the soils of the Bettadapura micro-watershed (690.69 ha), part of the Harisamudra sub-watershed in Kadur taluk, Chikkamagaluru district, Karnataka, India, using field studies and geospatial techniques. Soil profiles were examined along transects, and seven representative master pedons were selected from detailed morphological, physico-chemical analysis. Soils were classified according to USDA Soil Taxonomy. Geospatial tools (Remote Sensing and GIS) were employed using high-resolution QuickBird satellite imagery and cadastral maps (1:7920 scale) as a base for mapping soil variations. Morphological studies revealed soil depths ranging from moderately shallow (50-75 cm) to very deep (>150 cm). Soil colours varied from dark red (2.5YR 3/4) to reddish yellow (10YR 6/6). Soil texture varied from sandy loam in surface horizons to sandy clay or clay in subsurface horizons, exhibiting subangular blocky structure. Physico-chemical analysis indicated slightly acidic to moderately alkaline reaction (pH 6.17-8.51), non-saline nature (EC 0.05-0.44 dS $m^{-1}$), low to high soil organic carbon (3.6-9.6 g $kg^{-1}$), and variable calcium carbonate content (4.00-12.50%). Cation exchange capacity ranged from 8.40 to 30.85 cmol ($p^+$) $kg^{-1}$, generally increasing with clay content and depth. The soils were classified under two orders: *Inceptisols* (*Typic Haplustepts* - Loamy, isohyperthermic; Chikkathur series) and *Alfisols* (*Typic Haplustalfs* - Fine, isohyperthermic or Clayey-skeletal, isohyperthermic; Vittalapura, Duglapura, Gijikatte, Sappinahalli, Madhugundi, and Giriyapura series). A total of 33 soil phases were delineated and mapped, providing a detailed soil resource inventory crucial for site-specific management and sustainable land use planning in the watershed.

**Keywords:** Soil characterization, soil classification, soil taxonomy, geospatial approach, GIS, remote sensing, bettadapura watershed, *Alfisols, inceptisols*, Karnataka

## Introduction
Soil and water stand as one of the most critical and indispensable natural resources, forming the very foundation for terrestrial life. It serves as the primary reservoir of nutrients supporting diverse flora and fauna, and directly underpins human survival through agriculture (Vikas, 2016) [29]. This vital resource, however, is formed over geological timescales through complex weathering processes, making it essentially non-renewable within human timeframes. Despite its importance, escalating human pressures, coupled with unsustainable and often indiscriminate land-use practices, are leading to significant degradation of soil resources globally. This degradation manifests as reduced soil quality, loss of productive topsoil, and diminished capacity to support ecosystems and agricultural production, posing a serious threat to food security and environmental stability (Ravikumar, 2020; FAO, 2015) [6, 18, ].
Effective land use planning is crucial to mitigate degradation and ensure the long-term productivity and sustainability of land resources. Such planning requires a thorough understanding of the inherent properties, potential, and limitations of the soils within a given area. Soil surveys provide this essential baseline information, documenting the types of soils present, their physical, chemical, and morphological characteristics, their spatial distribution, and their suitability for various uses (Sehgal *et al*., 1989) [22].

While traditional soil surveys are fundamental, their integration with modern geospatial technologies, including Remote Sensing (RS) and Geographic Information Systems (GIS), offers powerful tools for enhancing the accuracy, efficiency, and applicability of soil resource inventories (Mendas and Delali, 2012) [11]. These technologies facilitate the analysis and visualization of complex spatial data, enabling the generation of detailed thematic maps crucial for site-specific management interventions.

Watersheds, particularly micro-watersheds, are recognized as logical and functional units for natural resource management and planning (Zhang *et al*., 2009) [32]. Effective planning at this scale necessitates detailed soil information that captures local variability often missed in smaller-scale, generalized maps. The Bettadapura micro-watershed, situated within the Lower Tungabhadra catchment in Karnataka, India, is an area reliant on agriculture, primarily rainfed, making it vulnerable to land degradation and climatic variability. Understanding the specific soil resources within this micro-watershed is therefore paramount for developing targeted strategies for soil conservation, optimizing crop production, and promoting sustainable agricultural practices.

The Bettadapura micro-watershed, located in the Lower Tungabhadra catchment, requires detailed soil resource information for implementing site-specific land management practices. While broader soil maps may exist, micro-watershed level planning necessitates detailed characterization and mapping at a larger scale (e.g., cadastral level) to capture local variability. Understanding the inherent properties and spatial distribution of different soil types is the first step towards optimizing land use and ensuring agricultural sustainability.

## 2. Materials and Methods

### 2.1. Description of Study Area

The Bettadapura micro-watershed (690.69 ha) is part of the Harisamudra sub-watershed, located in Kadur taluk, Chikkamagaluru district, Karnataka, India. It lies between 13°34'17.832" to 13°36'3.816" N latitude and 76°11'28.824" to 76°13'30" E longitude (Fig. 1). Geologically, the area predominantly consists of granite gneiss, including migmatites and granodiorite/tonalitic gneiss variants. The climate is warm, with an average annual rainfall of 787.65 mm (based on 2013-2022 data, Fig. 2), received mainly during the southwest monsoon (June-September). Elevation ranges from 613 to 708 m above mean sea level (Fig. 3), with relief characterized by gently sloping uplands, mounds, ridges, and nearly level valleys. Drainage is from east to west via intermittent streams active during the rainy season Natural vegetation includes trees like Neem, Tamarind, Mango, Pongamia, and Eucalyptus, alongside shrubs like Lantana. Rainfed agriculture is common, with finger millet, jowar, and maize being major crops; coconut and vegetables are grown under limited irrigation.

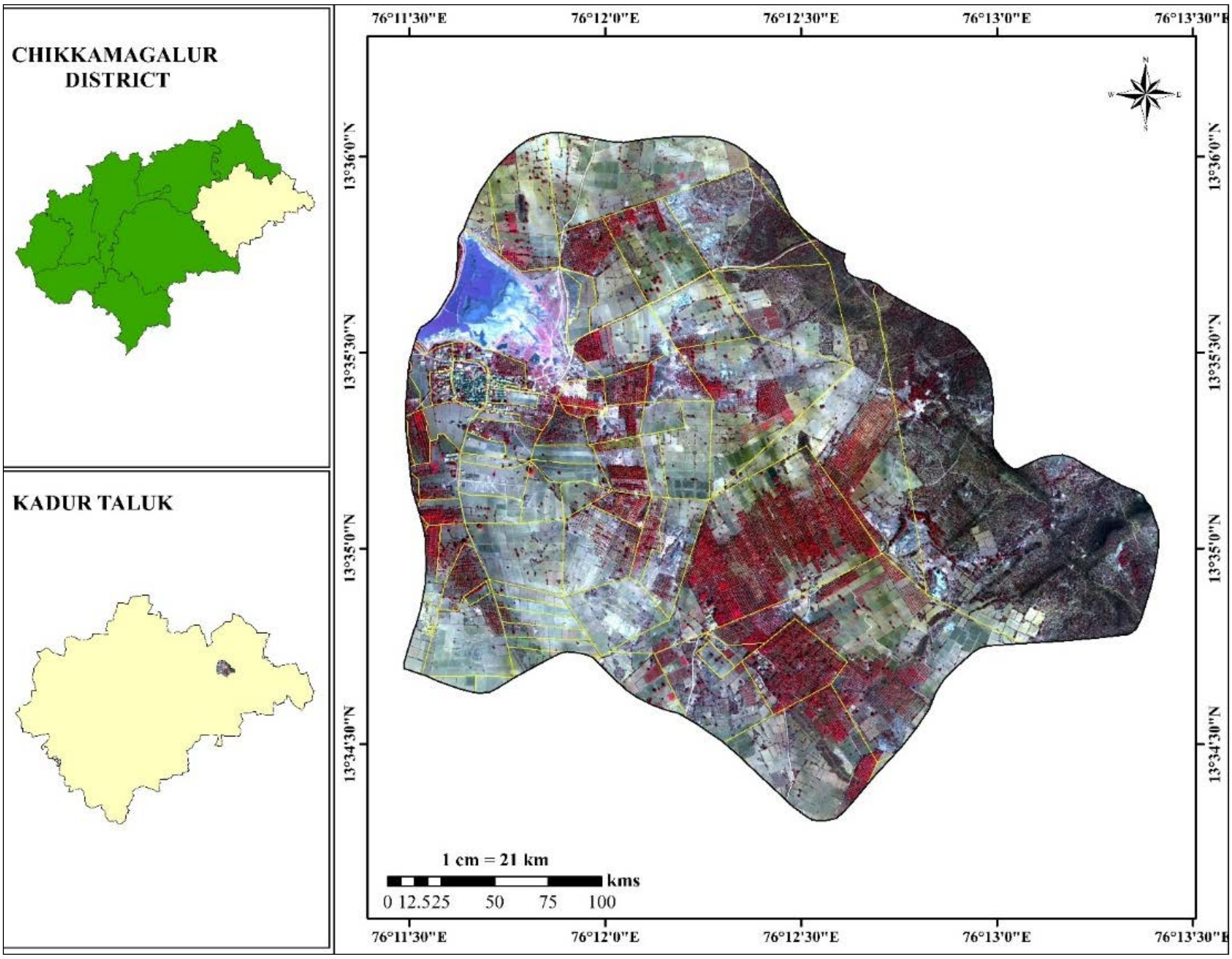


**Fig 1:** Location of the study area

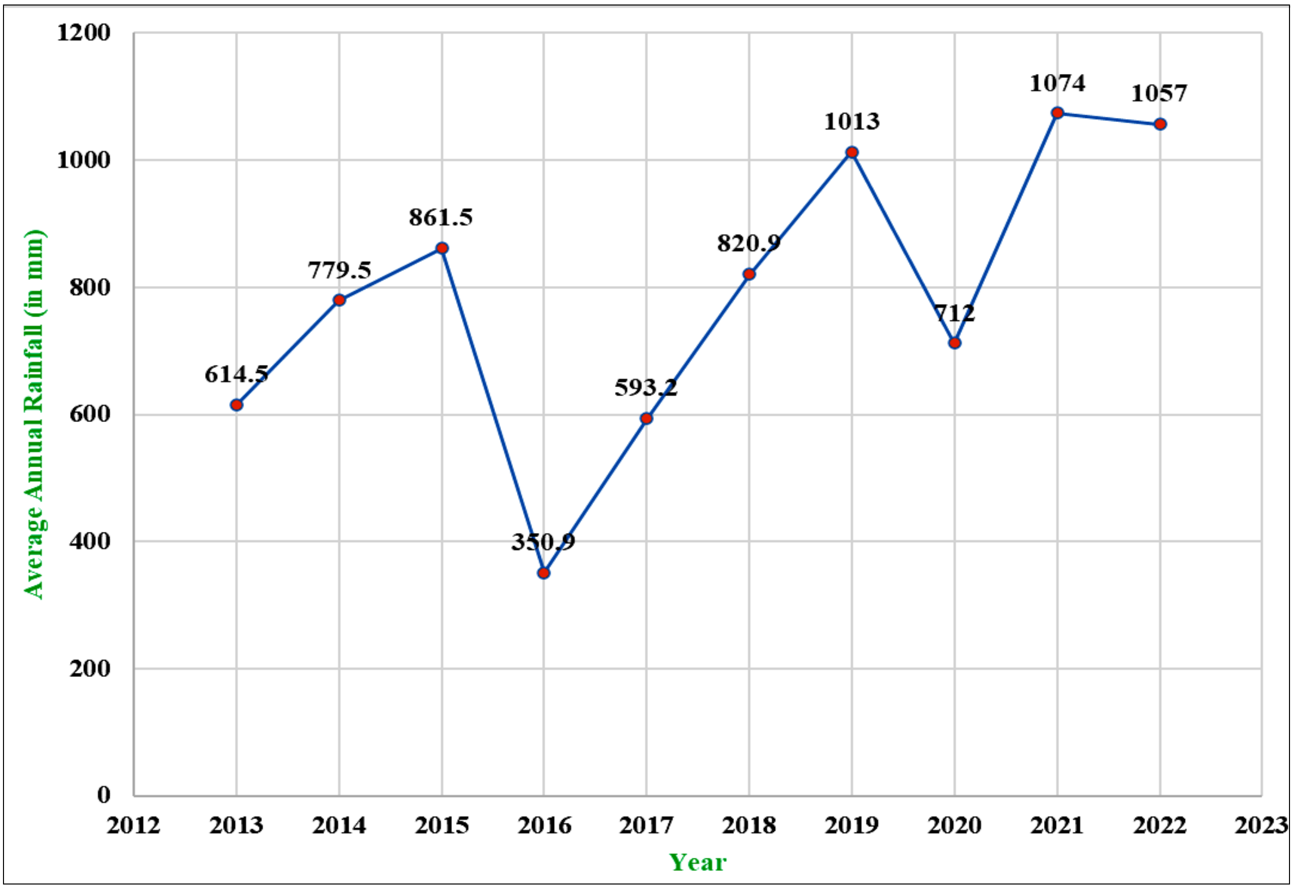


**Fig 2:** Graph representing the distribution of rainfall during 2013-2022 period

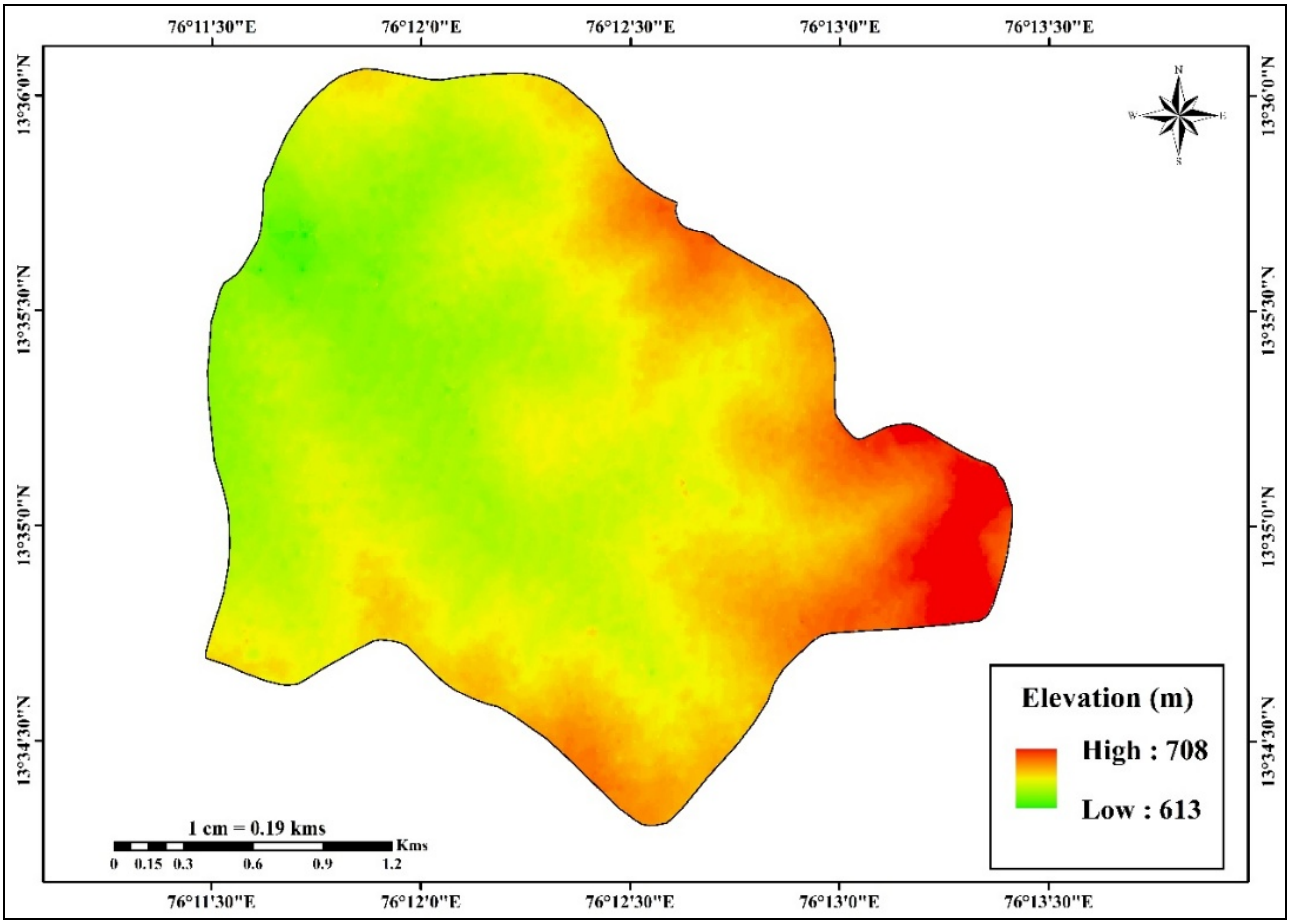


**Fig 3:** Digital elevation model (DEM) of Bettadapura micro-watershed

## 2.2. Soil Survey and Mapping

A detailed soil survey was conducted at 1:7920 scale using cadastral maps (Survey of India Toposheet No. 57 C/2) overlaid with high-resolution QuickBird satellite imagery (Fig. 4) as a base. Field traverses were carried out following standard procedures (Anon., 2017) [1-2] to identify landforms, physiographic units, and variations in soil properties. Transects were selected across varying slopes, and soil profiles were examined at regular intervals (Fig. 5). A total of 22 profiles were studied, out of which seven master pedons representing distinct soil variations were selected for detailed investigation (Fig. 6).

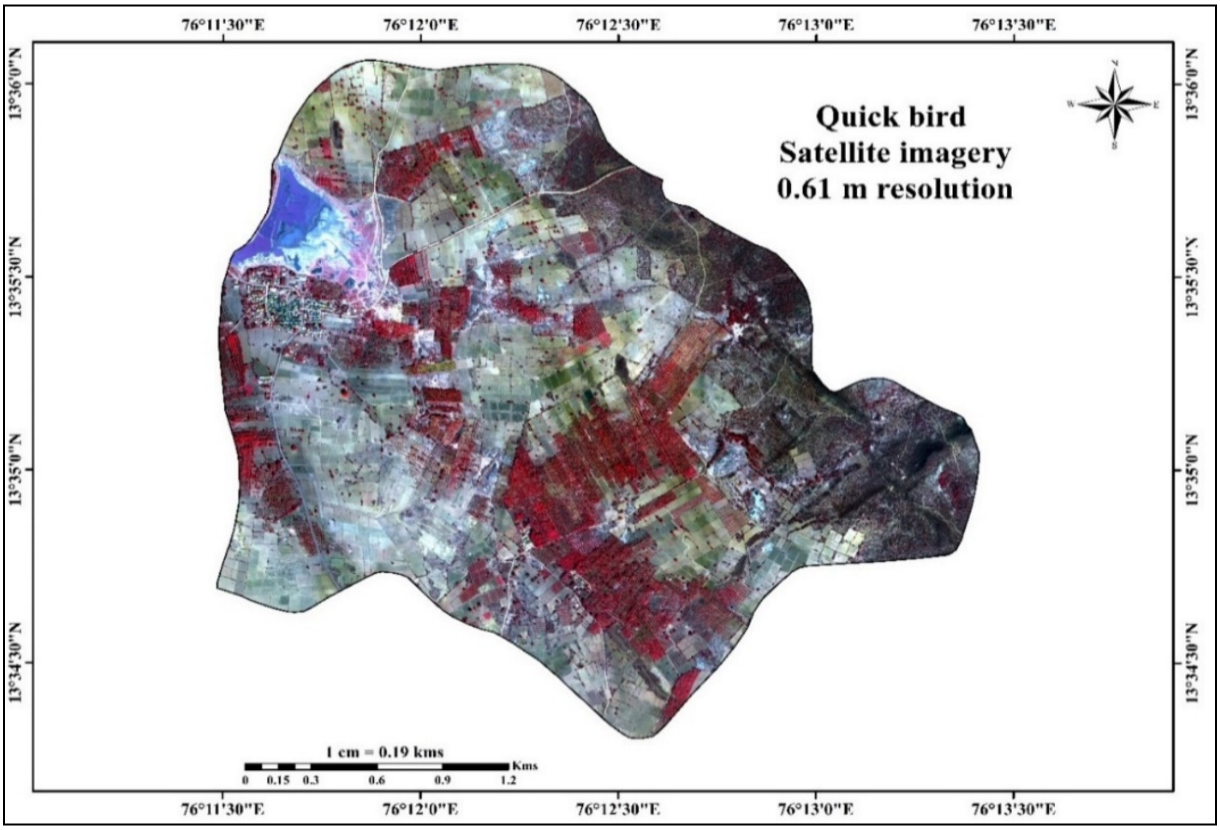


**Fig 4:** Satellite imagery of Bettadapura micro-watershed

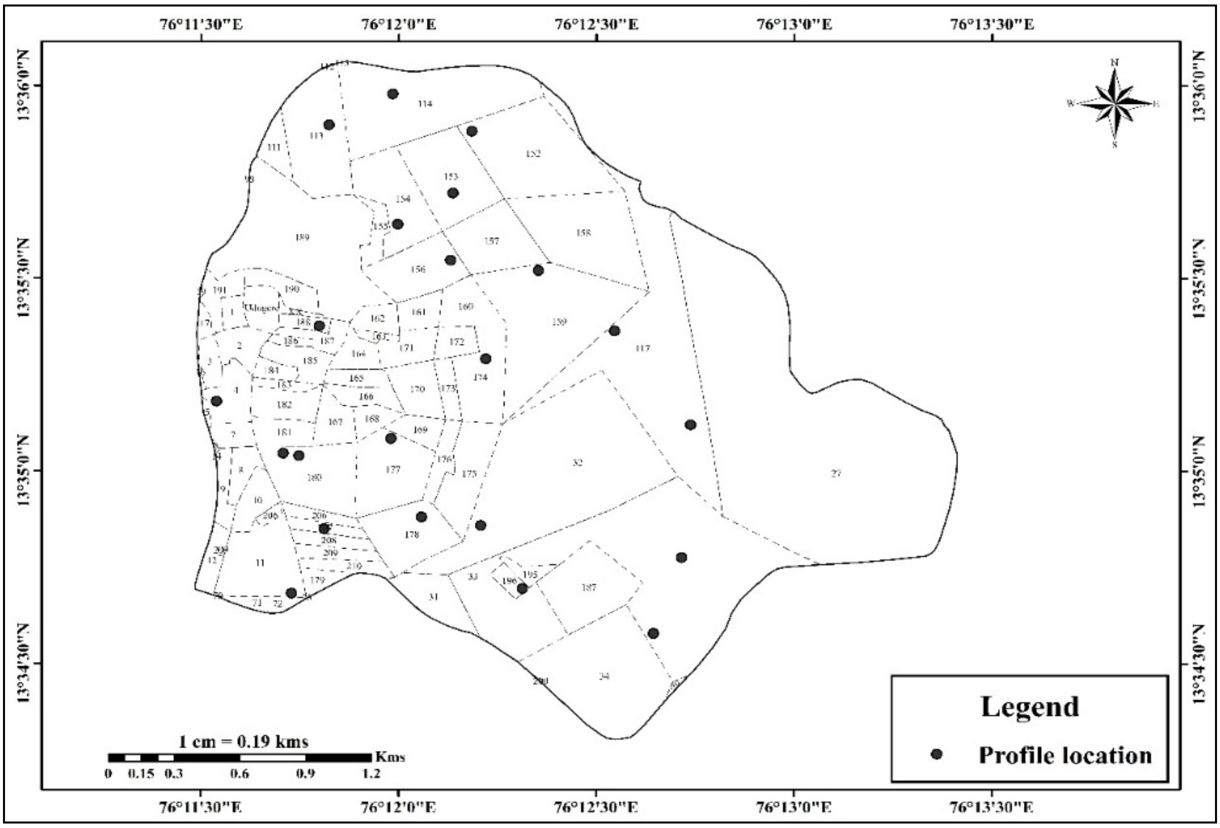


**Fig 5:** Profile locations in the study area

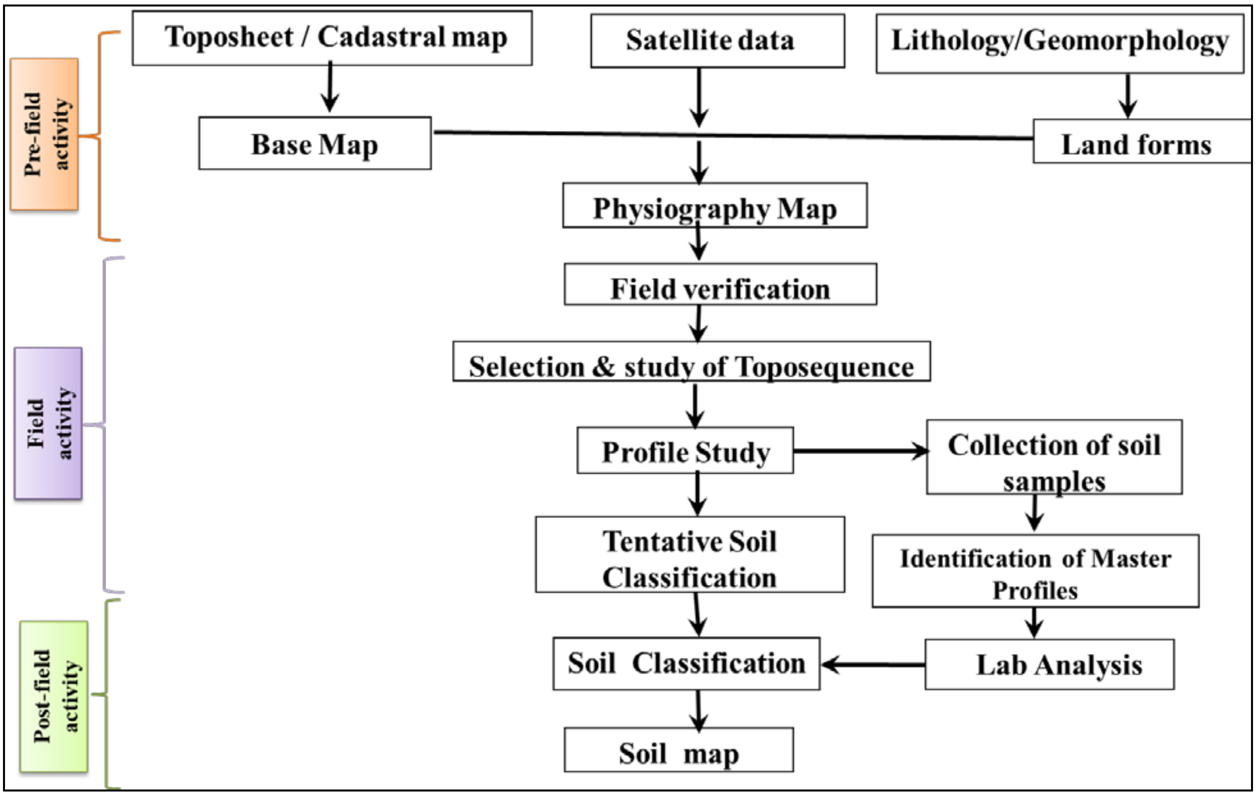


**Fig 6:** Flowchart showing methodology adopted for soil survey

### 2.3. Morphological Description

The seven master pedons were described in situ for their morphological characteristics, including site features and horizon properties (depth, colour, texture, structure, consistency, roots, coarse fragments, boundary characteristics), following the guidelines provided in the Soil Survey Manual and Keys to Soil Taxonomy (Anon., 2017; Soil Survey Staff, 2017) [1-2]. Munsell soil colour charts were used for colour determination under moist and dry conditions. Representative field photographs of the pedons were taken (Plates 1-7).

### 2.4. Laboratory Analysis

Horizon-wise soil samples collected from the master pedons were air-dried, processed
(<2 mm), and analysed for various physio-chemical properties relevant to characterization and classification.

- **Physical Properties:** Particle size distribution (sand, silt, clay) was determined by the International Pipette method using sodium hydroxide as the dispersant (Black, 1965) [4]. Bulk density was measured using the Keen's box method (Black, 1965) [4]. Water retention characteristics, including Field Capacity (FC) at -0.33 bars (300 kPa) and Permanent Wilting Point (PWP) at -15 bars (1500 kPa), were determined using pressure plate apparatus (Page *et al.*, 1982) [14]. Available Water Content (AWC) was calculated as the difference between FC and PWP. Maximum water holding capacity (MWHC) was determined using Keen-Raczkowski boxes (Sankaram, 1960) [20].
- **Chemical Properties:** Soil pH and Electrical Conductivity (EC) were measured in a 1:2.5 soil-water suspension using a pH meter and conductivity bridge, respectively (Jackson, 1973) [8]. Soil Organic Carbon (SOC) was determined by the wet oxidation method of Walkley and Black (1934) [30]. Free calcium carbonate ($CaCO_3$) was estimated using a rapid titration method. Cation Exchange Capacity (CEC) was determined using the neutral normal ammonium acetate method. Exchangeable cations ($Ca^{2+}$, $Mg^{2+}$, $Na^+$, $K^+$) were extracted with ammonium acetate, and $Ca^{2+}$ and $Mg^{2+}$ were determined by EDTA titration, while $Na^+$ and $K^+$ were estimated using a flame photometer. Base Saturation (BS) and Exchangeable Sodium Percentage (ESP) were calculated from the cation data obtained from analysis.

### 2.5. Soil Classification

The soils were classified according to the USDA system of Soil Taxonomy up to the family level based on diagnostic horizons, soil properties, and soil moisture/temperature regimes (Keys to Soil Taxonomy, Soil Survey Staff, 2017). The identified soil series were named after local villages.

### 2.6. Geospatial Analysis and Mapping

Geospatial analysis was performed using GIS software (ArcGIS). Base layers including cadastral maps, drainage network (Fig. 7), DEM (Fig. 3), and satellite imagery (Fig. 4) were prepared. Soil boundaries identified during the field survey were digitized and linked to the attribute data (morphological, physical, chemical properties, classification). Thematic maps showing the spatial distribution of soil texture (Fig. 8), soil depth (Fig. 9), soil series (Fig. 10), and soil phases (Fig. 11) were generated. Soil phases were delineated based on variations in surface texture, slope, erosion status, gravelliness, and stoniness associated with each soil series.

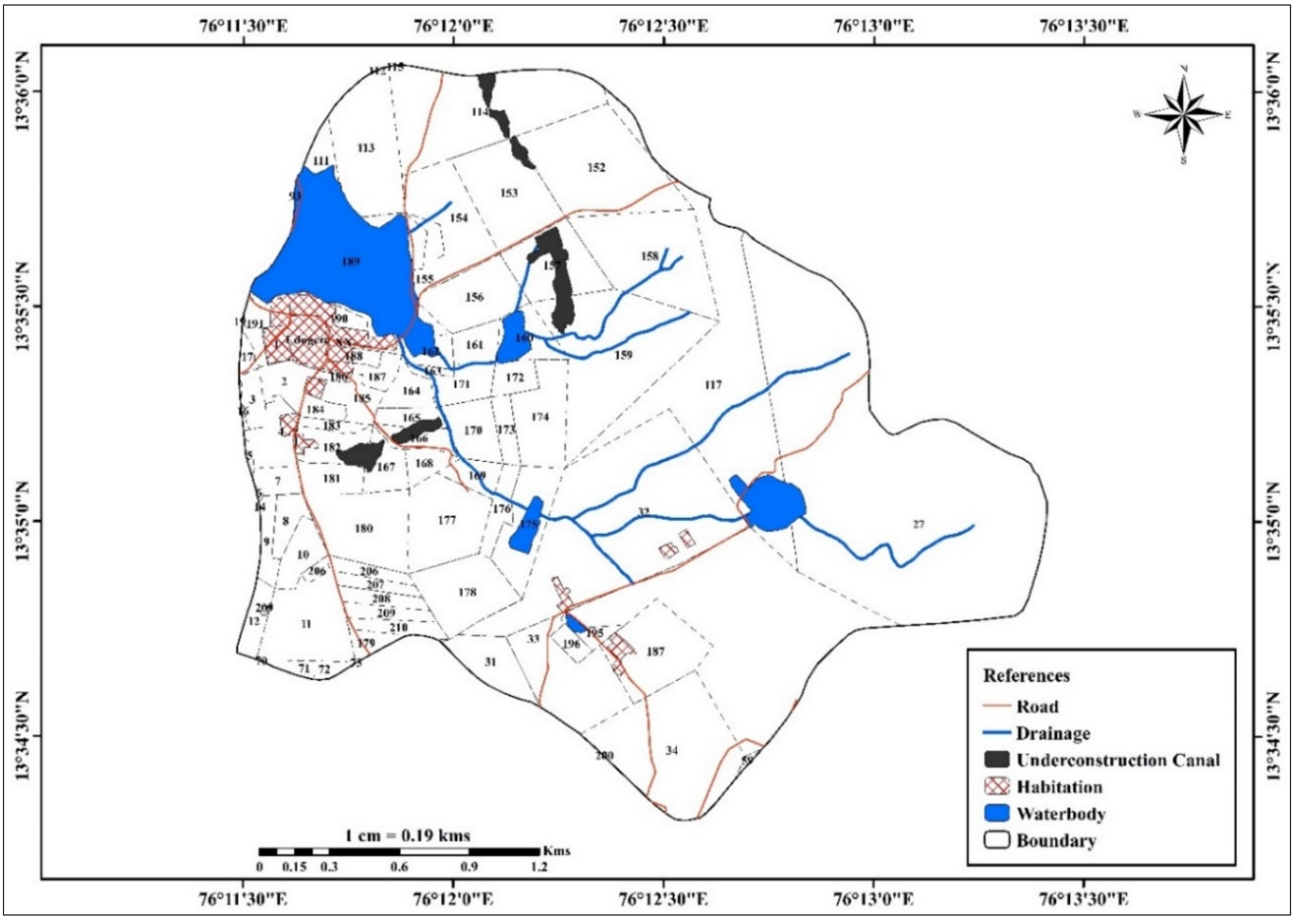


**Fig 7:** Cadastral map of Bettadapura micro-watershed

## 3. Results

### 3.1. Morphological Characteristics

Detailed morphological characteristics of the seven master pedons are presented in Table 1. Key observations include:

- **Soil Depth:** Varied significantly across the watershed. Pedon 1 (Vittalapura) was very deep (>150 cm); Pedons 5 (Sappinahalli) and 7 (Giriyapura) were deep (100-150 cm); Pedons 3 (Chikkathur) and 6 (Madhugundi) were moderately deep (75-100 cm); and Pedons 2 (Duglapura) and 4 (Gijikatte) were moderately shallow (50-75 cm).
- **Soil Colour:** Soil colour ranged widely, from dark red (2.5YR 3/4) and dark reddish brown (5YR 2.5/2, 5YR 3/2) in Bt horizons of *Alfisols* (Pedons 1, 4, 5) to yellowish brown (10YR 5/4, 10YR 6/6) and pale brown (10YR 6/3) in surface (Ap) and some subsurface horizons (Bw, BC) of both *Alfisols* and *Inceptisols* (Pedons 2, 3, 6, 7). Colour generally became redder or darker with depth in well-developed profiles, indicating iron oxide accumulation and illuviation.
- **Soil Texture:** Surface horizons (Ap) were predominantly sandy loam. Subsurface horizons showed textural differentiation, particularly in *Alfisols*, with textures ranging from sandy clay loam to sandy clay or clay in the Bt horizons (e.g., Pedons 1, 4, 5, 6, 7). Pedon 3 (Inceptisol) showed less pronounced textural change, with sandy clay loam in Bw horizons.
- **Soil Structure:** Weak to moderate, medium, subangular blocky structure was dominant in most subsurface horizons. Surface horizons often had weaker structure due to cultivation.
- **Consistency:** Soils were generally slightly hard to hard when dry, friable to firm when moist, and slightly sticky/plastic to very sticky/very plastic when wet, reflecting variations in clay content and type.
- **Horizons:** *Alfisols* typically exhibited Ap-Bt-BC/C sequences, characterized by an argillic (Bt) horizon showing clay accumulation. The Inceptisol (Pedon 3) showed an Ap-Bw-C sequence, indicating a cambic (Bw) horizon with structure and/or colour development but without significant clay illuviation.

**Table 1:** Morphological characteristics of soil pedons of Bettadapura micro-watershed

| Horizon | Depth (cm) | Colour | | Texture | Structure | Consistency | | | Roots |
|---|---|---|---|---|---|---|---|---|---|
| | | Dry | Moist | | G S T | Dry | Moist | Wet | |
| **Pedon 1 (Vittalapura)** | | | | | | | | | |
| Ap | 0-10 | 7.5YR 6/4 | 7.5YR 4/4 | sl | 2 m sbk | sh | fr | ss sp | f vf |
| Bt$_1$ | 10-31 | | 5YR 2.5/2 | scl | 1 m sbk | sh | fr | ms mp | f f |
| Bt$_2$ | 31-59 | | 5YR 3/2 | sc | 1 m sbk | sh | fr | ms mp | |
| Bt$_3$ | 59-119 | | 5YR 2.5/3 | sc | 1 m sbk | sh | fr | ms mp | |
| Bt$_4$ | 119-152 | | 7.5YR 2.5/3 | sc | 1 m sbk | sh | fr | ms mp | - |
| BC | 152-187 | | 7.5YR 3/3 | scl | | sh | fr | ms mp | - |
| Weathered Parent Material | | | | | | | | | |
| **Pedon 2 (Duglapura)** | | | | | | | | | |
| Ap | 0-14 | 10YR 6/4 | 10YR 5/4 | sl | 1 m sbk | sh | fr | ss sp | f f |
| Bt | 14-42 | | 10YR 5/2 | sc | 1 m sbk | sh | fr | ms mp | - |
| BC | 42-75 | | 10YR 6/6 | sc | 1 m sbk | sh | fr | ms mp | - |
| Weathered Parent Material | | | | | | | | | |
| **Pedon 3 (Chikkathur)** | | | | | | | | | |
| Ap | 0-16 | 10YR 6/3 | 10YR 5/4 | sl | 1 m sbk | sh | fr | ss sp | f m |
| Bw1 | 16-45 | | 10YR 4/4 | scl | 1 m sbk | sh | fr | ms mp | f f |
| Bw2 | 45-100 | | 10YR 5/4 | scl | 1 m sbk | sh | fr | ms mp | - |
| Weathered Parent Material | | | | | | | | | |
| **Pedon 4 (Gijikatte)** | | | | | | | | | |
| Ap | 0-18 | 7.5YR 4/6 | 7.5YR ¾ | sl | 2 m sbk | Sh | fr | ss sp | m vf |
| Bt$_1$ | 18-47 | | 2.5YR ¾ | sc | 1 m sbk | sh | fr | ms mp | c vf |
| Bt$_2$ | 47-74 | | 5YR 3/4 | sc | 1 m sbk | sh | fr | ms mp | - |
| Weathered Parent Material | | | | | | | | | |

**Note-** G= grade, S= size, T= type, Structure: 1- Weak, 2- moderate, f- fine, m- medium, sbk- subangular blocky, abk- angular blocky, Consistency: sh- slightly hard, h- hard, fr- friable, fi- firm, vh- very hard, Stickyness and Plasticity: ss- slightly sticky, sp- slightly plastic, ms- moderately sticky, mp- moderately plastic, vs- very sticky, vp- very plastic, Roots: vf- very fine, f- fine, c- coarse, m- medium, ff-few fine, mf- many fine, vff- very few fine, fc- few coarse, fm- few medium

**Table 1:** (continued)

| Horizon | Depth (in cm) | Colour | | Texture | Structure | Consistency | | | Roots |
|---|---|---|---|---|---|---|---|---|---|
| | | Dry | Moist | | G S T | Dry | Moist | Wet | |
| **Pedon 5** (Sappinahalli) | | | | | | | | | |
| Ap | 0-19 | 7.5YR 5/4 | 7.5YR ¾ | sl | 1 m sbk | sh | fr | ss sp | m vf |
| Bt$_1$ | 19-67 | | 5YR ¾ | sc | 1 m sbk | sh | sh | ms mp | m vf |
| Bt$_2$ | 67-110 | | 5YR 3/4 | sc | 1 m sbk | sh | sh | ms mp | - |
| Weathered Parent Material | | | | | | | | | |
| **Pedon 6** (Madhugundi) | | | | | | | | | |
| Ap | 0-15 | 10YR 7/3 | 10YR 4/3 | sl | 1 m sbk | sh | fr | ss sp | m vf |
| Bt$_1$ | 15-40 | | 7.5 YR 3/4 | sc | 1 m sbk | sh | fr | ms mp | c vf |
| Bt$_2$ | 40-62 | | 7.5YR 3/4 | sc | 1 m sbk | sh | fr | ms mp | - |
| Bt$_3$ | 62-81 | | 10YR 6/6 | sc | 1 m sbk | sh | fr | ms mp | - |
| Weathered Parent Material | | | | | | | | | |
| **Pedon 7** (Giriyapura) | | | | | | | | | |
| Ap | 0-10 | 10YR 6/3 | 10YR 4/3 | sl | 1 m sbk | sh | fr | ss sp | f vf |
| Bt$_1$ | 10-26 | | 10YR 4/4 | sc | 2 m sbk | sh | fr | ms mp | f vf |
| Bt$_2$ | 26-55 | | 10YR 4/1 | c | 2 m abk | sh | fr | vs vp | f vf |
| Bt$_3$ | 55-88 | | 7.5YR 4/2 | c | 1 m sbk | sh | fr | vs vp | - |
| Bt$_4$ | 88-109 | | 5YR 4/4 | sc | 1 m sbk | sh | fr | ms mp | - |
| BC | 109-148 | | 5YR 4/4 | sc | 1 m sbk | sh | fr | ms mp | - |
| Weathered Parent Material | | | | | | | | | |

Note- G= grade, S= size, T= type, Structure: 1- Weak, 2- moderate, f- fine, m- medium, sbk- subangular blocky, abk- angular blocky, Consistency: sh- slightly hard, h- hard, fr- friable, fi- firm, vh- very hard, Stickyness and Plasticity: ss- slightly sticky, sp- slightly plastic, ms- moderately sticky, mp- moderately plastic, vs- very sticky, vp- very plastic, Roots: vf- very fine, f- fine, c- coarse, m- medium, ff-few fine, mf- many fine, vff- very few fine, fc- few coarse, fm- few medium

**Plate 1:** Profile view of Pedon 1

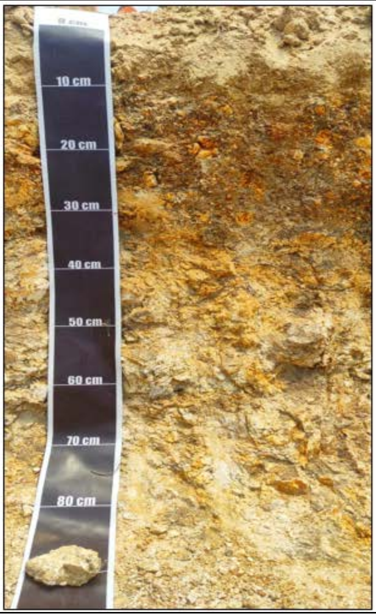


**Plate 2:** Profile view of Pedon 2

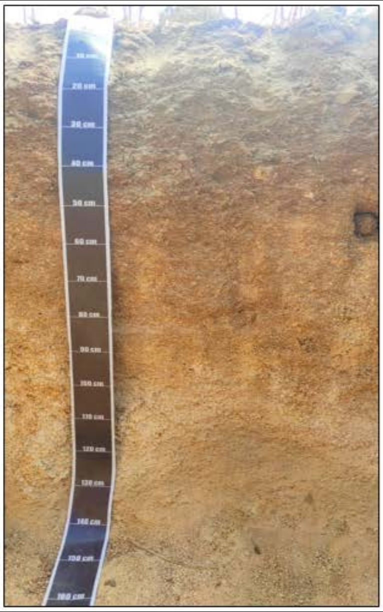

**Plate 3:** Profile view of Pedon 3

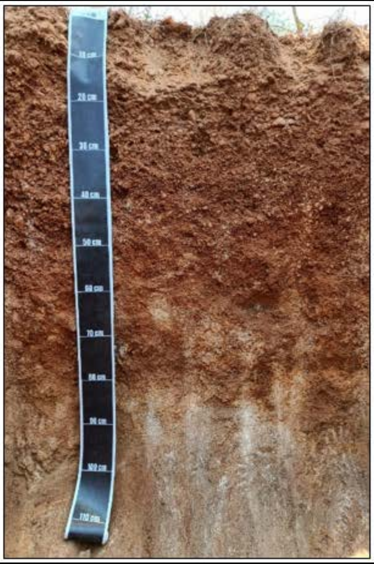

**Plate 4:** Profile view of Pedon 4

**Plate 5:** Profile view of Pedon 5

**Plate 6:** Profile view of Pedon 6

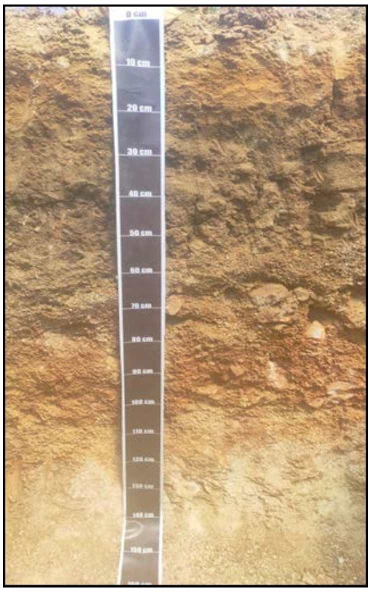

**Plate 7:** Profile view of Pedon 7

(Plates 1-7 show visual representations of the profile morphology for each series)

### 3.2. Physical Properties

The physical properties of the master pedons are summarized in Table 2.

- **Particle Size Distribution:** Sand content generally decreased with depth in most profiles, ranging from 43.40% to 64.90%. Silt content was relatively low, varying from 4.00% to 26.00%, without a consistent depth trend. Clay content varied significantly (13.00% to 47.50%), generally increasing from the surface to the subsurface (Bt or Bw horizons), confirming textural differentiation and illuviation processes, particularly in *Alfisols*.
- **Bulk Density (BD):** Ranged from 1.08 to 1.48 Mg m$^{-3}$. BD generally increased with depth, likely due to lower organic matter content and higher compaction in subsurface layers.
- **Water Retention:** MWHC ranged from 25.92% to 66.68%, FC from 16.02% to 36.74%, and PWP from 5.07% to 24.43%. AWC varied from 8.65% to 20.64%. These parameters generally increased with increasing clay and organic matter content.
- **Gravel Content:** Coarse fragment content varied, with significant gravelliness (>35%) noted in some pedons (e.g., Pedons 1, 4, 5).
- **Spatial Distribution:** The soil texture map (Fig. 8) shows the dominance of sandy loam (56.89%) and sandy clay loam (30.62%) textures in the surface layer across the watershed. The soil depth map (Fig. 9) highlights the prevalence of moderately deep (29.55%) and moderately shallow (27.65%) soils, with deep and very deep soils covering smaller areas (21.28% and 12.50%, respectively).

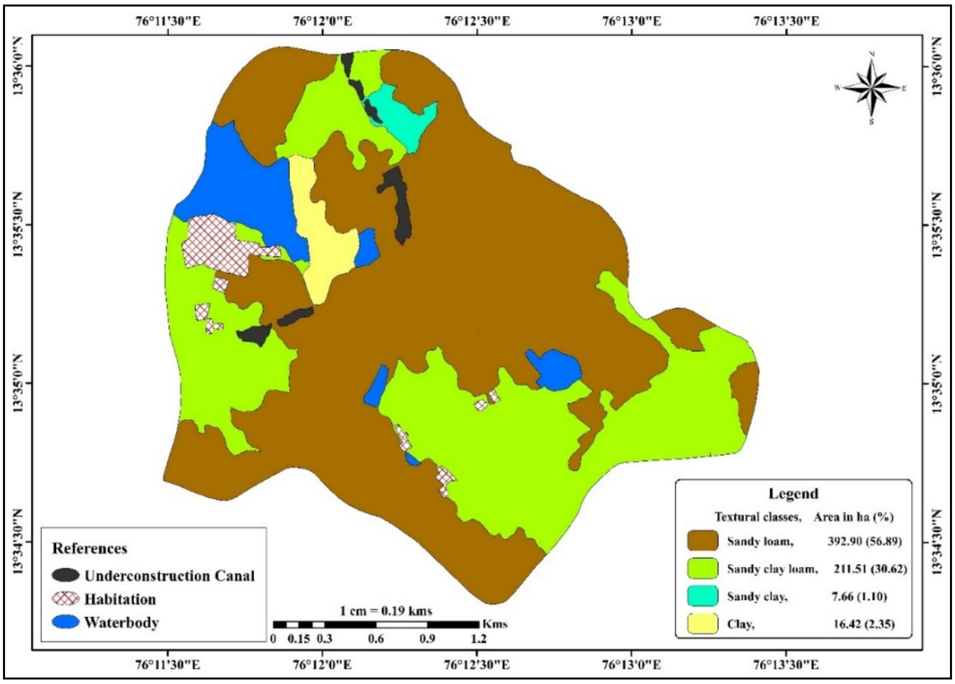


**Fig 8:** Soil texture map of Bettadapura micro-watershed

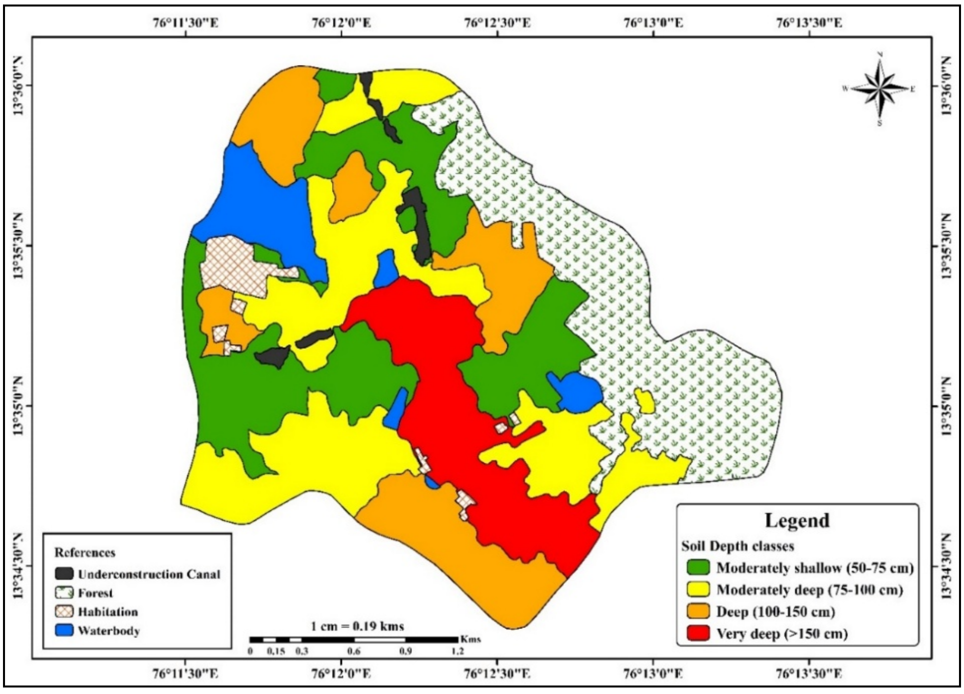


**Fig 9:** Soil depth map of Bettadapura micro-watershed

### 3.3. Chemical Properties

Key chemical properties are presented in Table 3.

- **Soil Reaction (pH):** Ranged from slightly acidic (6.17) to moderately alkaline (8.51). pH generally showed an increasing trend with depth in most pedons.
- **Electrical Conductivity (EC):** Values were low, ranging from 0.05 to 0.44 dS $m^{-1}$, indicating non-saline conditions throughout the watershed.
- **Organic Carbon (OC):** Ranged from 3.6 to 9.6 g $kg^{-1}$. OC content was generally higher in the surface horizons and decreased with depth.
- **Calcium Carbonate ($CaCO_3$):** Content varied from 4.00 per cent to 12.50 per cent, generally increasing with depth, particularly in pedons with higher pH.
- **Cation Exchange Capacity (CEC) & Exchangeable Cations:** CEC ranged from 8.40 to 30.85 cmol ($p^+$) $kg^{-1}$, generally correlating positively with clay content and increasing with depth in horizons with clay accumulation. Exchangeable $Ca^{2+}$ was the dominant cation, followed by $Mg^{2+}$, $K^+$, and $Na^+$ ($Ca^{2+} > Mg^{2+} > K^+ > Na^+$) in most horizons.
- **Base Saturation (BS):** Soils were highly base saturated, ranging from 77.86% to 97.16%, typical for soils developed under the prevailing semi-arid climate with ustic moisture regimes.

**Exchangeable Sodium Percentage (ESP):** Values were low (< 4.15%), indicating no sodicity hazard.

**Table 2:** Physical properties of the soil pedons of Bettadapura micro-watershed

| Horizon | Depth (cm) | Texture | Particle size distribution (%) | | | Water retention capacity (%) | | | AWC mm $m^{-1}$ | Bulk density (Mg $m^{-3}$) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Sand | Silt | Clay | MHWC | FC | PWP | | |
| **Pedon 1** | | | | | | | | | | |
| Ap | 0-10 | sl | 63.65 | 12.85 | 21.52 | 36.95 | 21.65 | 12.52 | 142.25 | 1.25 |
| $Bt_1$ | 10-31 | scl | 45.74 | 10.50 | 43.50 | 36.69 | 26.79 | 16.02 | 144.09 | 1.29 |
| $Bt_2$ | 31-59 | sc | 59.36 | 5.00 | 35.50 | 41.56 | 33.37 | 20.75 | 173.41 | 1.34 |
| $Bt_3$ | 59-119 | sc | 54.25 | 9.50 | 36.00 | 32.31 | 20.44 | 9.33 | 138.86 | 1.37 |
| $Bt_4$ | 119-152 | sc | 58.73 | 4.00 | 37.00 | 45.19 | 36.74 | 24.43 | 172.48 | 1.39 |
| BC | 152-187 | scl | 59.87 | 6.50 | 33.50 | 39.77 | 19.18 | 9.74 | 121.51 | 1.40 |
| Weathered Parent Material | | | | | | | | | | |
| **Pedon 2** | | | | | | | | | | |
| Ap | 0-14 | sl | 64.90 | 22.00 | 13.00 | 66.68 | 36.16 | 19.74 | 164.69 | 1.08 |
| Bt | 14-42 | sc | 53.45 | 8.95 | 35.85 | 64.11 | 35.17 | 16.42 | 243.47 | 1.12 |
| BC | 42-75 | sc | 51.25 | 9.86 | 35.62 | 63.15 | 33.14 | 15.32 | 253.32 | 1.25 |
| Weathered Parent Material | | | | | | | | | | |
| **Pedon 3** | | | | | | | | | | |
| Ap | 0-16 | sl | 62.10 | 20.50 | 17.00 | 25.92 | 16.02 | 5.07 | 157.70 | 1.44 |
| Bw1 | 16-45 | scl | 47.58 | 11.50 | 40.50 | 52.25 | 29.91 | 18.93 | 150.50 | 1.37 |
| Bw2 | 45-100 | scl | 52.80 | 10.50 | 35.50 | 50.57 | 19.28 | 9.42 | 144.40 | 1.46 |
| Weathered Parent Material | | | | | | | | | | |
| **Pedon 4** | | | | | | | | | | |
| Ap | 0-18 | sl | 52.88 | 6.50 | 40.50 | 54.87 | 24.64 | 15.20 | 129.39 | 1.37 |
| $Bt_1$ | 18-47 | sc | 49.88 | 4.00 | 46.00 | 61.05 | 26.67 | 17.88 | 123.04 | 1.40 |
| $Bt_2$ | 47-74 | sc | 49.50 | 12.50 | 37.50 | 49.02 | 23.89 | 11.98 | 176.37 | 1.48 |
| Weathered Parent Material | | | | | | | | | | |

(Note- MHWC= Maximum water holding capacity, FC= Field capacity, PWP= Permanent wilting point, AWC= Available water content, scl= sandy clay loam, sc= sandy clay, c= clay, sl= sandy loam)

**Table 2:** (continued)

| Horizon | Depth (cm) | Texture | Particle size distribution (%) | | | Water retention capacity (%) | | | AWC mm $m^{-1}$ | Bulk density (Mg $m^{-3}$) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Sand | Silt | Clay | MHWC | FC | PWP | | |
| **Pedon 5** | | | | | | | | | | |
| Ap | 0-19 | sl | 64.90 | 22.00 | 13.00 | 37.19 | 25.43 | 16.47 | 114.23 | 1.28 |
| $Bt_1$ | 19-67 | sc | 50.50 | 5.00 | 44.00 | 61.03 | 27.09 | 15.51 | 163.99 | 1.42 |
| $Bt_2$ | 67-110 | sc | 47.78 | 7.00 | 45.00 | 31.82 | 25.54 | 14.88 | 153.57 | 1.44 |
| Weathered Parent Material | | | | | | | | | | |
| **Pedon 6** | | | | | | | | | | |
| Ap | 0-15 | sl | 54.65 | 26.00 | 19.00 | 48.32 | 32.30 | 17.44 | 164.10 | 1.25 |
| $Bt_1$ | 15-40 | sc | 53.50 | 8.50 | 37.50 | 56.84 | 34.44 | 16.15 | 144.35 | 1.36 |
| $Bt_2$ | 40-62 | sc | 51.00 | 10.00 | 38.50 | 42.05 | 35.06 | 14.42 | 122.15 | 1.41 |
| $Bt_3$ | 62-81 | sc | 46.80 | 10.50 | 42.50 | 43.22 | 29.93 | 16.71 | 135.66 | 1.42 |
| Weathered Parent Material | | | | | | | | | | |
| **Pedon 7** | | | | | | | | | | |
| Ap | 0-10 | sl | 64.90 | 22.00 | 13.00 | 44.54 | 20.78 | 12.13 | 141.17 | 1.24 |
| $Bt_1$ | 10-26 | sc | 51.00 | 10.00 | 38.50 | 47.00 | 23.45 | 13.14 | 169.24 | 1.25 |
| $Bt_2$ | 26-55 | c | 44.76 | 12.50 | 42.50 | 46.12 | 24.58 | 12.22 | 140.55 | 1.32 |
| $Bt_3$ | 55-88 | c | 43.40 | 9.00 | 47.00 | 48.33 | 25.92 | 16.81 | 160.73 | 1.36 |
| $Bt_4$ | 88-109 | sc | 50.12 | 7.00 | 42.50 | 42.97 | 23.97 | 14.32 | 171.13 | 1.42 |
| BC | 109-148 | sc | 45.31 | 7.00 | 47.50 | 43.00 | 24.95 | 12.03 | 168.32 | 1.45 |
| Weathered Parent Material | | | | | | | | | | |

Note- MHWC= Maximum water holding capacity, FC= Field capacity, PWP= Permanent wilting point, AWC= Available water content, scl= sandy clay loam, sc= sandy clay, c= clay, sl= sandy loam

**Table 3:** Chemical properties of the soil pedons of Bettadapura micro-watershed

| Horizon | Depth (in cm) | pH | EC | OC | CEC | Exch. Ca | Exch. Mg | Exch. $K_2O$ | Exch. Na | Free $CaCO_3$ | BS | ESP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | dS $m^{-1}$ | (g $kg^{-1}$) | [cmol (p+) $kg^{-1}$] | | | | | % | % | |
| **Pedon 1** | | | | | | | | | | | | |
| Ap | 0-10 | 8.20 | 0.260 | 7.6 | 25.85 | 14.50 | 9.25 | 0.88 | 0.40 | 12.50 | 96.83 | 1.55 |
| $Bt_1$ | 10-31 | 8.20 | 0.348 | 7.4 | 29.95 | 15.75 | 10.50 | 0.97 | 0.44 | 12.00 | 92.35 | 1.47 |
| $Bt_2$ | 31-59 | 8.15 | 0.312 | 6.9 | 30.85 | 16.75 | 10.00 | 1.03 | 0.53 | 10.75 | 91.77 | 1.72 |
| $Bt_3$ | 59-119 | 8.48 | 0.253 | 6.6 | 32.60 | 19.50 | 9.25 | 1.10 | 0.72 | 8.00 | 93.77 | 2.21 |
| $Bt_4$ | 119-152 | 8.40 | 0.354 | 5.4 | 28.85 | 14.00 | 11.00 | 1.17 | 0.84 | 12.00 | 93.62 | 2.91 |
| BC | 152-187 | 8.45 | 0.275 | 4.2 | 27.50 | 13.00 | 11.50 | 1.22 | 1.00 | 11.25 | 97.16 | 3.64 |
| Weathered Parent Material | | | | | | | | | | | | |
| **Pedon 2** | | | | | | | | | | | | |
| Ap | 0-14 | 8.15 | 0.178 | 7.8 | 20.80 | 9.25 | 9.75 | 0.70 | 0.49 | 7.50 | 97.07 | 2.36 |
| Bt | 14-42 | 8.26 | 0.233 | 7.1 | 23.00 | 12.00 | 8.00 | 0.80 | 0.71 | 8.75 | 93.52 | 3.09 |
| BC | 42-75 | 8.51 | 0.255 | 6.8 | 18.08 | 10.25 | 5.25 | 0.66 | 0.75 | 9.50 | 93.53 | 4.15 |
| Weathered Parent Material | | | | | | | | | | | | |
| **Pedon 3** | | | | | | | | | | | | |
| Ap | 0-16 | 6.18 | 0.051 | 7.8 | 8.80 | 4.50 | 2.00 | 0.42 | 0.23 | 6.25 | 81.25 | 2.61 |
| $Bw_1$ | 16-45 | 6.50 | 0.086 | 6.6 | 10.96 | 5.75 | 2.75 | 0.48 | 0.34 | 8.50 | 85.04 | 3.10 |
| $Bw_2$ | 45-100 | 7.33 | 0.157 | 6.0 | 12.96 | 7.50 | 3.00 | 0.60 | 0.29 | 8.00 | 87.89 | 2.24 |
| Weathered Parent Material | | | | | | | | | | | | |
| **Pedon 4** | | | | | | | | | | | | |
| Ap | 0-18 | 6.31 | 0.083 | 6.6 | 13.65 | 6.25 | 3.75 | 0.37 | 0.45 | 4.00 | 79.27 | 3.30 |
| $Bt_1$ | 18-47 | 6.42 | 0.105 | 6.0 | 14.85 | 7.00 | 4.25 | 0.43 | 0.46 | 4.75 | 81.75 | 3.10 |
| $Bt_2$ | 47-74 | 6.77 | 0.146 | 3.6 | 18.15 | 9.00 | 5.00 | 0.44 | 0.53 | 5.50 | 82.48 | 2.92 |
| Weathered Parent Material | | | | | | | | | | | | |

**Table 3:** (continued)

| Horizon | Depth (in cm) | pH | EC | OC | CEC | Exch. Ca | Exch. Mg | Exch. $K_2O$ | Exch. Na | Free $CaCO_3$ | BS | ESP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | dS $m^{-1}$ | (g $kg^{-1}$) | [cmol (p+) $kg^{-1}$] | | | | | % | % | |
| **Pedon 5** | | | | | | | | | | | | |
| Ap | 0-19 | 6.17 | 0.058 | 7.8 | 8.40 | 4.00 | 1.75 | 0.51 | 0.28 | 8.00 | 77.86 | 3.33 |
| $Bt_1$ | 19-67 | 6.29 | 0.129 | 7.2 | 10.20 | 5.25 | 2.00 | 0.59 | 0.36 | 9.00 | 80.39 | 3.53 |
| $Bt_2$ | 67-110 | 7.33 | 0.128 | 6.0 | 11.20 | 5.75 | 2.25 | 0.59 | 0.41 | 9.25 | 80.36 | 3.66 |
| Weathered Parent Material | | | | | | | | | | | | |
| **Pedon 6** | | | | | | | | | | | | |
| Ap | 0-15 | 7.91 | 0.151 | 9.6 | 13.28 | 11.25 | 6.50 | 0.82 | 0.51 | 11.25 | 91.55 | 2.45 |
| $Bt_1$ | 15-40 | 8.08 | 0.266 | 8.4 | 15.28 | 8.75 | 4.50 | 0.69 | 0.37 | 7.50 | 93.65 | 2.42 |
| $Bt_2$ | 40-62 | 8.03 | 0.269 | 8.4 | 18.84 | 10.00 | 6.50 | 0.80 | 0.45 | 9.75 | 94.21 | 2.39 |
| $Bt_3$ | 62-81 | 8.02 | 0.267 | 7.8 | 20.84 | 7.75 | 3.75 | 0.77 | 0.43 | 9.00 | 95.63 | 3.24 |
| Weathered Parent Material | | | | | | | | | | | | |
| **Pedon 7** | | | | | | | | | | | | |
| Ap | 0-10 | 6.74 | 0.153 | 8.6 | 17.65 | 7.75 | 5.25 | 0.48 | 0.57 | 9.25 | 79.60 | 3.23 |
| $Bt_1$ | 10-26 | 6.24 | 0.107 | 7.2 | 17.60 | 8.50 | 4.50 | 0.35 | 0.42 | 4.00 | 78.24 | 2.39 |
| $Bt_2$ | 26-55 | 6.47 | 0.120 | 6.8 | 19.00 | 9.50 | 4.75 | 0.42 | 0.45 | 4.25 | 79.58 | 2.37 |
| $Bt_3$ | 55-88 | 6.71 | 0.184 | 6.4 | 20.40 | 10.25 | 5.50 | 0.44 | 0.43 | 5.00 | 81.47 | 2.11 |
| $Bt_4$ | 88-109 | 6.85 | 0.159 | 5.9 | 18.83 | 8.50 | 6.25 | 0.47 | 0.48 | 5.50 | 83.38 | 2.55 |
| BC | 109-148 | 7.20 | 0.211 | 5.4 | 22.55 | 11.50 | 6.50 | 0.63 | 0.52 | 6.75 | 84.92 | 2.31 |
| Weathered Parent Material | | | | | | | | | | | | |

### 3.4. Soil Classification

Based on the diagnostic horizons and soil properties, the soils of Bettadapura micro-watershed were classified into two soil orders: *Inceptisols* and *Alfisols* (Table 4, Table 5).

- ***Inceptisols*:** Represented by the Chikkathur series (Pedon 3). These soils lack significant clay accumulation (argillic horizon) but exhibit a cambic (Bw) horizon. Classified as:
    - **Order:** *Inceptisols*
    - **Suborder:** Ustepts (indicating an ustic soil moisture regime)
    - **Great Group:** Haplustepts (simple horizonation)
    - **Subgroup:** Typic Haplustepts
    - **Family:** Loamy, mixed, isohyperthermic
- **Alfisols:** Represented by Vittalapura (Pedon 1), Duglapura (Pedon 2), Gijikatte (Pedon 4), Sappinahalli (Pedon 5), Madhugundi (Pedon 6), and Giriyapura (Pedon 7) series. These soils are characterized by an argillic (Bt) horizon showing illuvial clay accumulation and high base saturation (>35%). Classified as:

- **Order:** *Alfisols*
- **Suborder:** Ustalfs (ustic soil moisture regime)
- **Great Group:** Haplustalfs (simple horizonation)
- **Subgroup:** Typic Haplustalfs
- **Family:** Fine, mixed, isohyperthermic (Vittalapura, Duglapura, Giriyapura); Clayey-skeletal, mixed, isohyperthermic (Gijikatte, Sappinahalli, Madhugundi) - differing mainly in particle size class (texture and coarse fragments).

**Table 4:** Classification of soil pedons of Bettadapura micro-watershed

| Pedon | Classification |
|---|---|
| Pedon 1 | Fine, Isohyperthermic, Typic Haplustalfs |
| Pedon 2 | Fine, Isohyperthermic, Typic Haplustalfs |
| Pedon 3 | Loamy, Isohyperthermic, Typic Haplustepts |
| Pedon 4 | Clayey skeletal, Isohyperthermic, Typic Haplustalfs |
| Pedon 5 | Clayey skeletal, Isohyperthermic, Typic Haplustalfs |
| Pedon 6 | Clayey skeletal, Isohyperthermic, Typic Haplustalfs |
| Pedon 7 | Fine, Isohyperthermic, Typic Haplustalfs |

**Table 5:** Individual Classification of soil pedons of Bettadapura micro-watershed (up to family level)

| Pedon | Order | Suborder | Great group | Sub group | Family | Soil series |
|---|---|---|---|---|---|---|
| 1 | Alfisol | Ustalfs | Haplustalfs | Typic Haplustalfs | Fine, Isohyperthermic | Vittalapura |
| 2 | Alfisols | Ustalf | Haplustalf | Typic Haplustalf | Fine, Isohyperthermic | Duglapura |
| 3 | Inceptisol | Ustepts | Haplustepts | Typic Haplustepts | Loamy, Isohyperthermic | Chikkathur |
| 4 | Alfisol | Ustalfs | Haplustalfs | Typic Haplustalfs | Clayey skeletal, Isohyperthermic | Gijikatte |
| 5 | Alfisol | Ustalfs | Haplustalfs | Typic Haplustalfs | Clayey skeletal, Isohyperthermic | Sappinahalli |
| 6 | Alfisol | Ustalfs | Haplustalfs | Typic Haplustalfs | Clayey skeletal, Isohyperthermic | Madhugundi |
| 7 | Alfisol | Ustalfs | Haplustalfs | Typic Haplustalfs | Fine, Isohyperthermic | Giriyapura |

A total of 7 soil series were identified. These were further subdivided into 33 soil mapping units (soil phases) based on variations in surface texture, slope class (A: 0-3%, B: 3-5%, C: 5-10%, D: >10%), erosion severity, gravelliness, and stoniness (Table 6). The spatial distribution of the identified soil series and phases are depicted in Fig. 10 and Fig. 11, respectively.

**Table 6:** Various soil phases identified in Bettadapura micro-watershed

| Sl. No. | Soil Series | Soil Phase | Area (ha) | Area (% of TGA) |
|---|---|---|---|---|
| 1 | CKT | CKTcC2g2St2 | 39.73 | 5.75 |
| 2 | | CKTcC3g2St2 | 10.00 | 1.45 |
| 3 | | CKTcD3g2St2 | 5.69 | 0.82 |
| 4 | DGP | DGPcC2g1St1 | 52.34 | 7.58 |
| 5 | | DGPhA2g1 | 2.54 | 0.37 |
| 6 | | DGPhA2g1St1 | 10.43 | 1.51 |
| 7 | | DGPhC2g1St1 | 9.38 | 1.36 |
| 8 | | DGPhC2g1St2 | 20.83 | 3.02 |
| 9 | GIJ | GIJcC2g1st3 | 10.52 | 1.52 |
| 10 | | GIJcC3g1St1 | 3.25 | 0.47 |
| 11 | | GIJhA2g1St2 | 7.25 | 1.05 |
| 12 | | GIJhC2g1St2 | 7.45 | 1.08 |
| 13 | | GIJiC3g2St2 | 7.66 | 1.11 |
| 14 | GIR | GIRcA2 | 1.53 | 0.22 |
| 15 | | GIRcA2g2St2 | 3.35 | 0.48 |
| 16 | | GIRcA3g3St3 | 7.50 | 1.09 |
| 17 | | GIRcC2 | 42.13 | 6.10 |
| 18 | | GIRcC2g2St2 | 3.89 | 0.56 |
| 19 | | GIRcC3g1St1 | 2.29 | 0.33 |
| 20 | | GIRcC3g3St3 | 12.48 | 1.81 |
| 21 | | GIRhC2 | 8.00 | 1.16 |
| 22 | MDG | MDGcC2g1St2 | 20.49 | 2.97 |
| 23 | | MDGcC3g3St3 | 5.33 | 0.77 |
| 24 | | MDGhC2g1 | 17.29 | 2.50 |
| 25 | | MDGhC2g1St2 | 12.55 | 1.82 |
| 26 | | MDGhC3g3St3 | 34.79 | 5.04 |
| 27 | | MDGmA2g1 | 14.65 | 2.12 |
| 28 | | MDGmC2g1 | 1.78 | 0.26 |
| 29 | SPN | SPNcC2g1St2 | 21.98 | 3.18 |
| 30 | | SPNcC3g1St2 | 3.98 | 0.58 |
| 31 | VIT | VITcC3g3St4 | 29.90 | 4.33 |
| 32 | | VIThA2g3St4 | 1.32 | 0.19 |
| 33 | | VIThC3g3St4 | 55.12 | 7.98 |
| % of TGA= percentage of total micro-watershed area | | | | |

## 4. Discussion
### 4.1. Soil Morphology and Genesis
The morphological characteristics observed in the Bettadapura micro-watershed reflect the influence of parent material, topography, climate, and time on soil development. The predominant granite gneiss parent material contributed to the sandy nature of the soils, particularly in the initial stages of weathering. The variation in soil depth, from moderately

shallow on upper slopes and ridges to very deep in lower landscape positions, is consistent with topographic influence on erosion and deposition processes (Sawhney, 2000; Jhanavi, 2020) [21, 9]. The range of soil colours, from yellowish browns to reddish browns and dark reds, is indicative of the weathering intensity and drainage conditions. Redder hues (lower YR values, higher chroma) in subsurface horizons, particularly Bt horizons of *Alfisols*, suggest the accumulation of oxidized iron compounds (hematite) under well-drained conditions over time (Thangasamy *et al*., 2005) [25]. Lighter colours in some subsurface horizons might relate to lower organic matter or specific mineralogy (Tripathi *et al*., 2006) [26].

The development of subangular blocky structure in subsurface horizons is typical for soils with moderate to high clay content experiencing cycles of wetting and drying (Rajashekar, 2018) [17]. The textural differentiation, with sandy loam surfaces overlying finer textured (sandy clay loam, sandy clay, clay) subsurface horizons, clearly indicates clay illuviation, a key process in the formation of the argillic (Bt) horizons diagnostic for *Alfisols* (Khan and Kamalakar, 2012; Vasundhara *et al*., 2020) [10, 28]. The presence of a cambic (Bw) horizon in the Inceptisol (Chikkathur series) suggests less advanced pedogenesis compared to the *Alfisols*, characterized by alteration (structure/colour development) without significant clay translocation (Sanjeev *et al*., 2005) [19, ].

## 4.2. Physico-Chemical Properties

The observed increase in clay content with depth in most profiles supports the morphological evidence of illuviation. The relatively low silt content across profiles might reflect the nature of the granitic parent material weathering. The general increase in bulk density with depth is attributable to reduced organic matter, less aggregation, and overburden pressure from overlying horizons (Nagendra and Patil, 2015; Vikas, 2016) [13, 29]. Water retention properties (MWHC, FC, PWP, AWC) are strongly linked to texture and organic matter; the higher clay content in subsurface horizons generally contributes to higher water holding capacity, although high gravel content in some skeletal families can reduce effective water storage (Yitbarek *et al*., 2016; Harshitha, 2018) [31, 7].

The slightly acidic to moderately alkaline pH range (6.17-8.51) and the increasing pH trend with depth are common in soils of semi-arid regions underlain by base-rich parent materials. Leaching of bases from the surface and their accumulation (sometimes as $CaCO_3$) in lower horizons contribute to this trend (Dasog and Patil, 2011; Jhanavi, 2020) [5, 9]. The presence of $CaCO_3$, particularly in deeper horizons of higher pH profiles, confirms this accumulation. The consistently low EC values (<0.44 dS $m^{-1}$) classify these soils as non-saline, indicating sufficient leaching of soluble salts due to seasonal rainfall and good internal drainage in most profiles (Sireesha and Naidu, 2013; Pramod and Patil, 2015) [24, 16].

Soil organic carbon levels (3.6-9.6 g $kg^{-1}$), falling mostly in the low to medium range typical for semi-arid tropical regions, decreased with depth. This pattern reflects the concentration of biomass input at the surface and progressively lower incorporation and higher decomposition rates with depth (Singh and Mishra, 2012; Vikas, 2016) [23, 29]. The CEC values (8.40-30.85 cmol ($p^+$) $kg^{-1}$) showed a positive relationship with clay content, increasing in the Bt horizons where clay accumulation occurred (Pillai and Natarajan, 2004; Vasundhara *et al*., 2020) [15, 28]. The high base saturation (>77%) across all profiles is characteristic of *Alfisols* and *Inceptisols* (Ustalfs/Ustepts) in regions where leaching is not intense enough to remove the majority of base cations (Balpande *et al*., 2007; Tumbal and Patil, 2015) [3, 27].

## 4.3. Soil Classification and Distribution

The classification confirmed the presence of two major soil orders: *Inceptisols* and *Alfisols*. The Chikkathur series (*Typic Haplustepts*) represents soils at an earlier stage of development, likely on more stable landscape positions but without sufficient time or conditions for significant clay illuviation. The remaining six series, classified as *Typic Haplustalfs*, represent more developed soils with distinct argillic horizons, indicating significant pedogenesis involving clay translocation. This differentiation aligns with findings in similar agro-ecological settings (Mini *et al*., 2007; Vikas *et al*., 2018; Ravikumar, 2020) [12, 29, 17]. The differentiation at the family level based on particle size class (fine vs. clayey-skeletal) and the consistent isohyperthermic temperature regime further refines the classification, providing crucial information for management interpretations related to water holding capacity, workability, and root restriction (Soil Survey Staff, 2017). The geospatial approach was instrumental in mapping the spatial extent of these 7 series and their 33 phases (Fig 10, Fig 11), clearly visualizing the soil variability within the micro-watershed at a detailed cadastral scale, which is essential for precision agriculture and site-specific resource management.

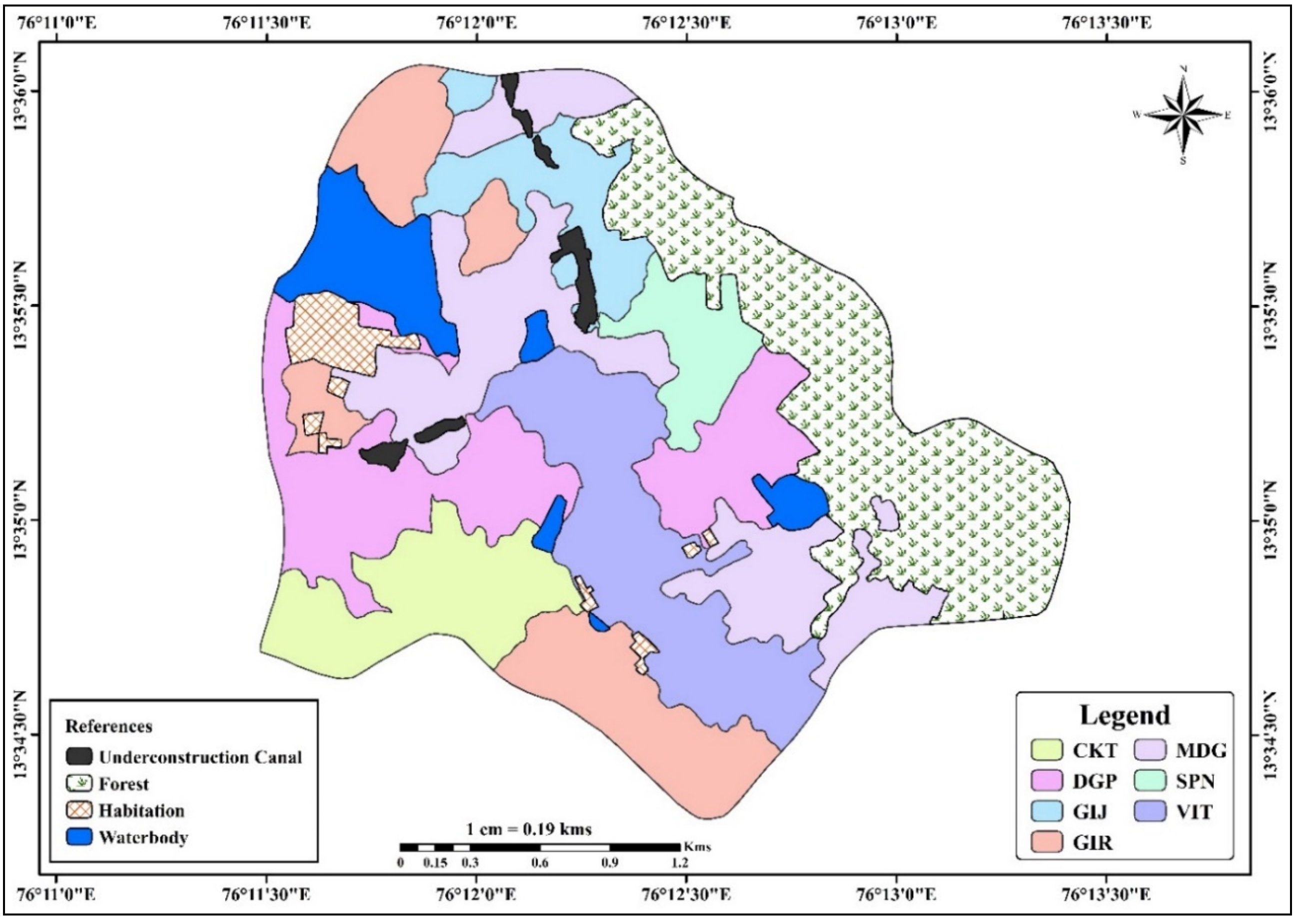


**Fig 10:** Soil series map of Bettadapura micro-watershed

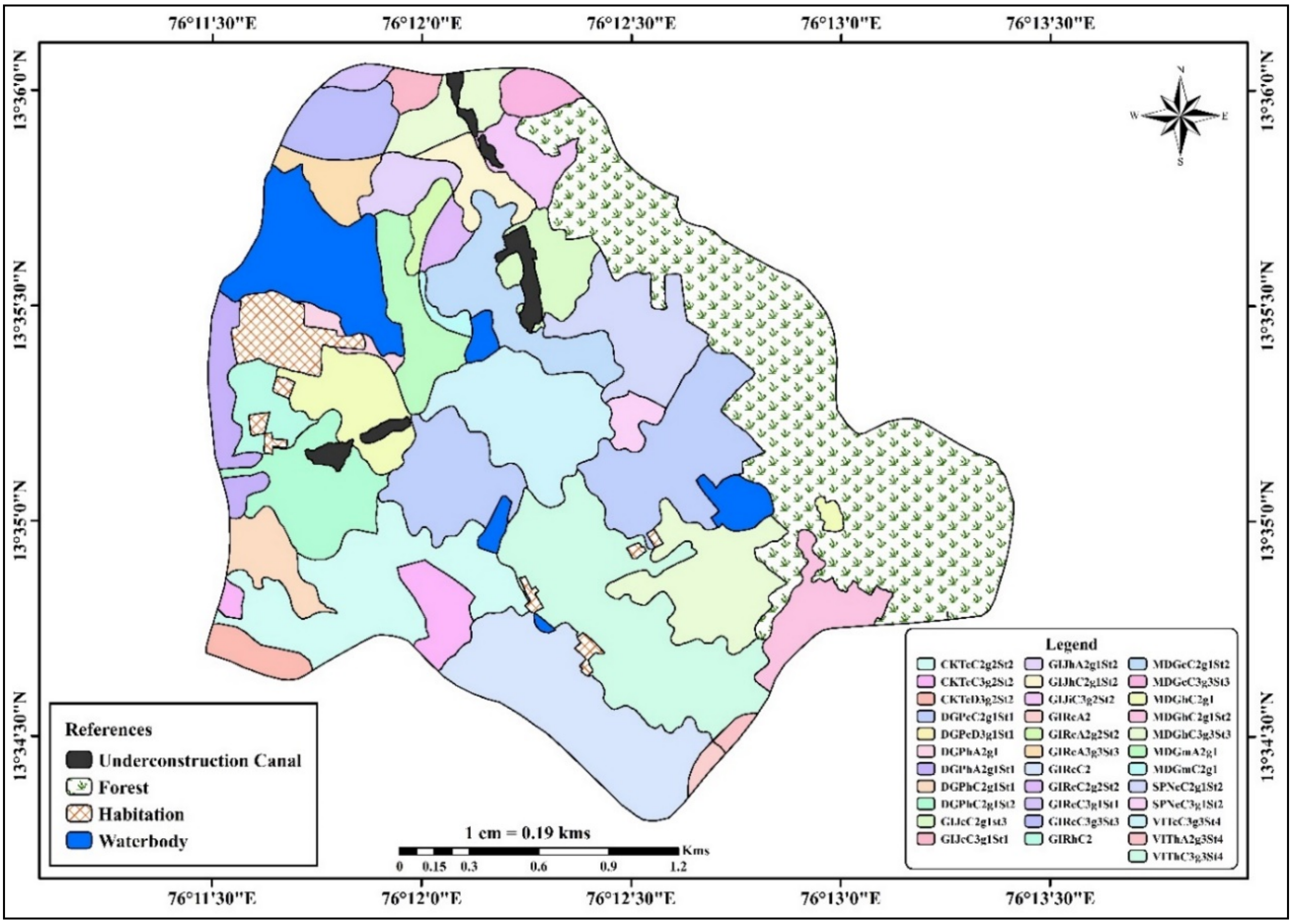


**Fig 11:** Soil phase map of Bettadapura micro-watershed

## 5. Conclusion
This study successfully characterized and classified the soils of the Bettadapura micro-watershed using a combination of detailed field studies and geospatial techniques. The soils are primarily derived from granite gneiss and exhibit variations related to topography and pedogenesis. Morphological, physical, and chemical analyses revealed depths ranging from moderately shallow to very deep, textures from sandy loam to clay, slightly acidic to moderately alkaline pH, and non-saline conditions. Two soil orders were identified *i.e.*, *Inceptisols* (*Typic Haplustepts*; Chikkathur series) and *Alfisols* (*Typic Haplustalfs*; Vittalapura, Duglapura, Gijikatte, Sappinahalli, Madhugundi, Giriyapura series). Seven distinct soil series and 33 soil phases were mapped at a 1:7920 cadastral scale. The generated detailed soil resource inventory, including thematic maps of soil properties and classification units, provides a vital baseline for developing sustainable land use plans, implementing appropriate soil and water conservation measures, and guiding site-specific agricultural management practices within the Bettadapura micro-watershed.

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