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Land Resource Inventory for 14 Selected Watersheds of Maharashtra for Land Use Planning Using Geo-spatial Techniques (PMKSY 2.0)

(WDC-2.0)3/2021-22: Gangakhed, Dist - Parbhani

ICAR-National Bureau of Soil Survey and Land Use Planning
Nagpur, Maharashtra

Vasundhara Watershed Development Agency
Pune, Maharashtra

About the ICAR-NBSS&LUP

The ICAR-National Bureau of Soil Survey and Land Use Planning (ICAR-NBSS&LUP), Nagpur was set up in the year 1976 with the objective to prepare soil resource maps at the national, regional, state and district levels, to provide research inputs for land evaluation, land use planning, land resource management and database management using GIS, and to impart training on soil survey and land use planning. The Bureau has the mandate to correlate and classify soils of the country and maintain a National Register of all the established soil series.

During the past decades, ICAR-NBSS&LUP provided the country with the first comprehensive soil resource maps of India and her states on 1:1 million and 1:250000 scales, respectively. The Bureau generated land resource inventories (LRIs) on different scales (1: 50,000 or larger) at watershed, block and district levels to aid planning agencies in the formulation and implementation of agricultural land use plans. Other landmark data products generated by the Bureau include the land degradation map of India, potential soil loss maps of different states, and agro-ecological region and sub-region maps of the country. The Institute has received commendable mention by the NITI Aayog for providing land use plans in respect of 27 Aspirational districts of India. Taking cognizance of the demands of various agencies to develop regional land use plans in the shortest possible time, the Bureau has recently developed a revised standard operating protocol (SOP) by combining traditional knowledge with GIS and machine learning tools. The revamped SOP was successfully adopted for bringing out the Land Resource Inventory of Bundelkhand, Vidarbha, Bikaner, Kachchh and South Gujarat regions of India. The Bureau has also released the first soil depth map and the National Soil Spectral Library of the country and is in the process of bringing out the digital soil map of Maharashtra state. ICAR-NBSS&LUP has also assisted several state governments in watershed planning through LRI under the PMKSY 2.0.

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PREFACE

Watershed development requires the systematic and integrated planning of social and technological interventions based on its socio-economic and bio-physical characteristics. Activities related to conservation/management of natural resources, enhancement of systems' productivity, livelihood support through micro-enterprises and businesses, are all planned in a holistic manner for ensuring sustainable gains from the watershed programme. Implementation of watershed plans follows the preparation of detailed project report (DPR), which in turn is based on comprehensive information obtained through on- and off-field surveys. While the data requirement for DPR preparation is substantial, adoption of a minimum data set covering major aspects of the watershed through use of advanced RS, GIS and machine learning tools could significantly reduce time taken for the same, while making it more pragmatic and user-friendly.

Comprehensive land use planning of any area begins with large-scale land resource inventory, which provides valuable data for crop and nutrient management planning, and supports scientific decision-making. Generation of Land Resource Inventory (LRI) by the ICAR-NBSS&LUP during the last two decades has been a proven critical input for planned agricultural development. Encouraged by the success of LRI based watershed programmes in Karnataka, many states have started using soil/land data for rural development. It is essential that LRI based development is extended to other parts of India through spreading awareness of its benefits. Administrators at national and state level(s) have recognized it and instructed that at least 10% area of the watersheds be covered under LRI in the plateau and upland region under the section 19.1.2 (b) of WDC-PMKSY 2.0 guidelines**.**

Being a frontrunner on several aspects of agricultural development, the Government of Maharashtra, through the Vasundhara Watershed Development Agency (VWDA), proactively entrusted the Bureau with the generation ofLRI for 14 selected watersheds across different agro-ecological sub regions of Maharashtra for formulation of scientific land use plans using geo-spatial techniques. This report presents a comprehensive understanding of soils of the watershed in terms of their physical and chemical characteristics, nutrient status, crop suitability and soil and water conservation requirements. It is expected that this report will serve as a valuable resource for land users, watershed planners, researchers and policy developers in rationalizing land use and for implementing ongoing agricultural development schemes.

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The publication titled "Land resource inventory for 14 selected watersheds of Maharashtra for land use planning using geo-spatial techniques (PMKSY 2.0). (WDC-2.0)3/2021-22: Gangakhed, Dist – Parbhani" is the result of the collaborative efforts of the officials from the ICAR-National Bureau of Soil Survey and Land Use Planning (ICAR-NBSS&LUP), Nagpur and the Vasundhara Watershed Development Agency (VWDA), Government of Maharashtra.

We are grateful to the Deputy Director General (NRM), Indian Council of Agricultural Research for his continuous support and guidance in successful completion of this project. We also sincerely thank the Assistant Director General (S&WM), NRM Division for his timely efforts and encouragement while implementing the project.

We place on record our deep sense of gratitude to the Chief Executive Officer(s), Deputy Chief Executive Officer(s), technical and administrative staff of the VWDA for entrusting us with this important project and for their financial and logistic support from the beginning to the completion of the project.

The authors express their sincere gratitude to all the scientists and technical staff, the I/c PME Cell, I/c Library, Chief Administrative Officer, Chief Finance and Accounts Officer, Administrative Officer, Assistant Administrative Officers and all other administration, accounts and audit sections of ICAR-NBSS&LUP, Nagpur, who ensured that the project continued smoothly. Their valuable help and cooperation in all respects are gratefully acknowledged.

Finally, we heartfully thank to all the project staff involved in the PMKSY 2.0-Maharashtra project for their untiring and steadfast efforts in the successful implementation of the project through data collection, analysis and documentation of the report.

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EXECUTIVE SUMMARY

The Pradhan Mantri Krishi Sinchayee Yojana - Watershed Development Component (PMKSY-WDC 2.0) emphasizes a scientific and participatory approach to watershed development through systematic assessment and management of land and water resources. In this context, Land Resource Inventory (LRI) provides a critical technical input for informed planning, prioritization of interventions, and sustainable management of natural resources. The ICAR-National Bureau of Soil Survey and Land Use Planning (ICAR-NBSS&LUP) was entrusted with the responsibility of conducting the LRI and offering technical assistance in the formulation of a holistic watershed development plan in accordance with the PMKSY-WDC 2.0 guidelines. ICAR-NBSS&LUP conducted the assessment for the Parbhani (WDC-2.0)/3/2021-22 watershed located within the Gangakhed Taluka of Parbhani District, Maharashtra, underlain with the characteristic basaltic terrain of the Deccan Plateau, with the Galaati river traversing the area. Agriculture constitutes the dominant land use within this watershed, primarily dependent upon monsoon precipitation, augmented by groundwater resources.

The primary objectives of the study were to systematically characterize soil and land resources at watershed level, assess land capability and crop-site suitability, support watershed-based land use planning, and evaluate groundwater potential to aid sustainable watershed development under PMKSY-WDC 2.0.The assessment was conducted using the standard methodologies prescribed by ICAR-NBSS&LUP, involving pre-field analysis, detailed soil survey, laboratory characterization of soil samples, and GIS-based spatial analysis. Base maps were prepared using authenticated datasets, and Terrain Mapping Units (TMUs) were delineated through integration of landform, slope, and land use information. Soil characteristics were recorded through field observations and laboratory analysis and subsequently classified following established soil classification systems. The watershed exhibits variability in landforms, slope, soils, and land use, which governs runoff generation, soil erosion, moisture availability, and groundwater occurrence. Soils show variations in depth, texture, drainage, and fertility status, reflecting differences in terrain position and land management practices. Hydrological assessment and groundwater potential evaluation were carried out using integrated thematic analysis to support identification of suitable areas for soil and water conservation and groundwater recharge interventions. The outcomes of the Land Resource Inventory provide a scientific basis for watershed-level land use planning, identification of resource constraints, and prioritization of soil and water conservation measures. The technical inputs generated by ICAR-NBSS&LUP are intended to support implementing agencies in designing location-specific interventions and promoting sustainable management of land and water resources under PMKSY-WDC 2.0. In conclusion, the Land Resource Inventory and watershed assessment carried out by ICAR-NBSS&LUP for the Gangakhed sub-watershed constitutes an provide a comprehensive technical framework for scientific watershed planning and sustainable resource management, in accordance with the objectives and guidelines of PMKSY-WDC 2.0.

CHAPTER 1

INTRODUCTION

A region, block, district, or village's Land Resource Inventory (LRI) has proven to be an essential component of planned agricultural development. This inventory provides critical baseline data for effective watershed management and sustainable land use planning, particularly through the application of advanced geospatial technologies. Encouraged by the success of LRI-based watershed programs in Karnataka, many states have started using soil/land data for rural development.

Administrators at the national and state level(s) have recognized the significance of LRI and documented in the PMKSY 2.0 document that at least 10% area of the watersheds be covered under LRI in the plateau and upland region of the country. In addition to LRI, the agro-ecological zone approach is deemed to be most effective for regeneration of *in-situ* resources for sustaining the biological growth and, in turn, soil health. Agro-ecological regions and subregions delineated by the ICAR-National Bureau of Soil Survey and Land Use Planning (ICAR-NBSS&LUP) therefore form the ideal base for selection and planning of watershed development, as our understanding of soil-crop and weather interactions is greatly enhanced under this approach.

The Government of Maharashtra directed the Bureau to conduct a Land Resource Inventory (LRI) in 14 watersheds located in different agro-ecological zones of the state. The objective is to measure improvements and ensure the long-term health of farming and related activities in rainfed areas, which will benefit the local farmers.

The process for selecting these watersheds was designed to fairly represent where existing projects were located across Maharashtra's distinct regions. As a result, four watersheds were selected for both the Vidarbha and Konkan regions, as they had a high number of ongoing projects. Western Maharashtra, Marathwada, and Northern Maharashtra were each assigned two watersheds, reflecting a lower concentration of implemented projects.

The project, planned for 48626 ha was implemented with the following objectives:

1. To characterize and map the soil and water resources of the watersheds.
2. To assess the soil-site suitability of the crops based on land evaluation at the watershed level.
3. To develop watershed-based alternate land use options and soil and water conservation plans.
4. To assess and characterize the groundwater potential of the watersheds.

This report presents the Land Resource Inventory (LRI) conducted in the Parbhani (WDC-2.0)/3/2021-22 sub-watershed of Gangakhed taluka under the Pradhan Mantri Krishi Sinchayee Yojana - Watershed Development Component (PMKSY-WDC 2.0). The study involved detailed field visits, soil observations, mapping, and assessment of local hydrological conditions. The information collected was carefully analyzed to understand land capability, soil suitability, drainage patterns and groundwater potential. These findings provide a practical foundation for planning watershed development and soil and water conservation measures suited to local conditions.

List of micro watersheds (MWS) earmarked for LRI studies by the ICAR-NBSS&LUP

District	**Project name**	**Block**	**No. of MWS**	**No. of villages**	**Area (ha)**
Akola	Akola (WDC-2.0)1/2021-22	Barshitakli	11	8	4898.0
Buldhana	Buldhana (WDC-2.0)3/2021-22	Lonar	21	4	2498.5
Nandurbar	Nandurbar (WDC-2.0/4/2021-22	Nandurbar	5	14	3533.2
Nashik	Nashik (WDC-2.0)3/2021-22	Malegaon	7	7	2760.4
Osmanabad	Osmanabad (WDC-2.0)3/202 1-22	Tuljapur	25	10	3380.0
Palghar	Palghar (WDC-2.0) 6/2021-22	Dahanu	7	23	3926.2
Parbhani	Parbhani (WDC-2.0)/3/2021-22	Gangakhed	8	9	3791.0
Raigad	Raigad (WDC-2.0)/2/2021-22	Roha	3	11	3825.0
Ratnagiri	Ratnagiri (WDC-2.0)/3/2021-22	Chiplun	13	9	2548.0
Sangli	Sangli (WDC-2.0)3/2021-22	Jath	23	5	3200.0
Sindhudurg	Sindhudurg (WDC-2.0)/3/2021-22	Dodamarga	5	5	3604.4
Solapur	Solapur (WDC-2.0)2/2021-22	Mangalwedha	31	7	4198.1
Wardha	Wardha (WDC-2.0)/3/202 1-22	Seloo	12	7	2657.5
Washim	Washim (WDC-2.0)/5/202 1 -22	Malegaon	21	8	3806.1
Total			**192**		**48626.9**

CHAPTER 2

GANGAKHED WATERSHED AT A GLANCE

2.1 Location and Extent

The watershed (Fig. 2.1) is situated in Gangakhed Taluka which is one of the administrative subdivisions of Parbhani district, located in the southern part of Parbhani District within the Marathwada region of Maharashtra. The cluster area lies between 18.79° to 18.90° N latitude and 76.785° to 76.88° E longitude, based on geographical extent. The region is characterized by undulating to moderately hilly terrain, moderate to high surface runoff occurrence, and agrarian rural settlements surrounded by cultivated lands and fallow areas. Gangakhed Taluka falls under the Aurangabad Revenue Division and is predominantly rural in nature. The Galaati River is the major river flowing through the study area and serves as an important source of water for agriculture and domestic use. Several seasonal streams contribute to the drainage system and play a significant role in surface runoff and groundwater recharge processes.

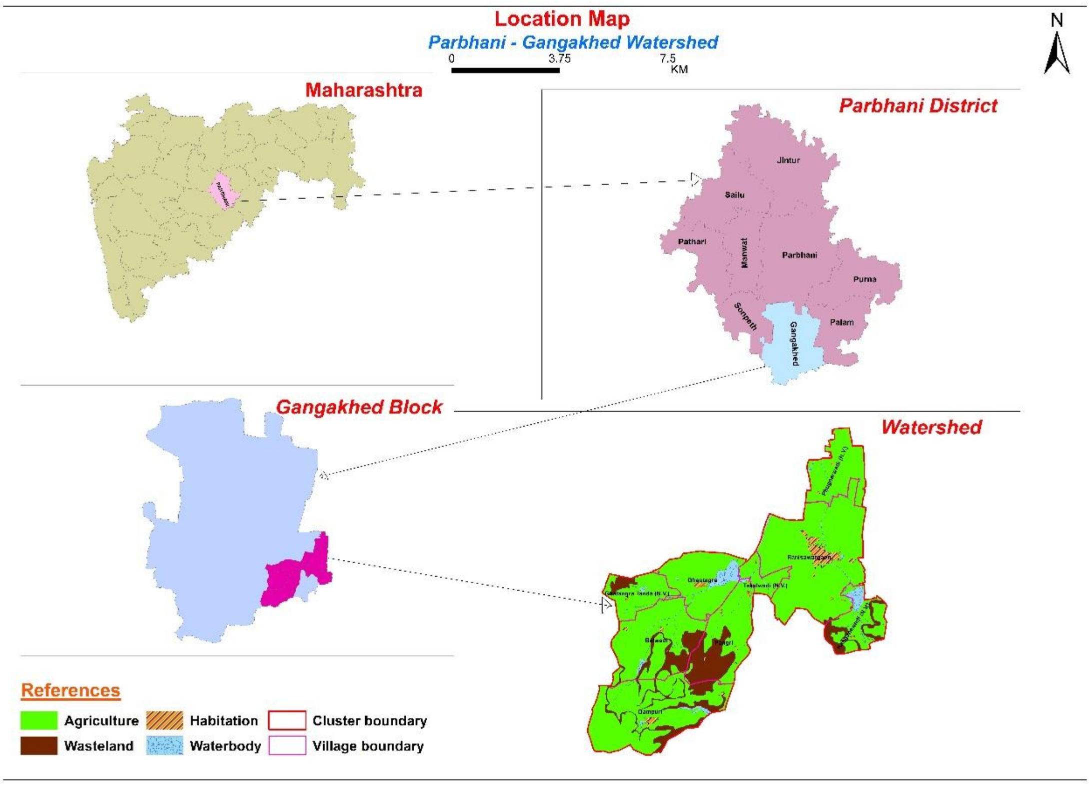


Fig. 2.1: Location map of the Gangakhed watershed

These villages of the watershed are largely rural and predominantly rainfed, with agriculture being the main livelihood activity. The region experiences substantial surface runoff during monsoons, which results in soil erosion, reduced infiltration, and declining groundwater levels, leading to water scarcity during post-monsoon months. This recurring condition formed the basis for selecting the cluster for watershed-based natural resource management interventions.

Table 2.1: Geographical and administrative profile

S. No.	Particulars	Details
1	District	Parbhani
2	Taluka	Gangakhed
3	Revenue Division	Aurangabad
4	Total sub-watershed Area	4848 ha (Approx)
5	Villages	09 (Belwadi, Dampuri, Ghantagra, Ghatangra Tanda, Kanganewadi, Pangri, Phugnarwadi, Ranisawargaon, Takalwadi)
6	Major River	Galaati River
7	Drainage Pattern	Seasonal dendritic drainage network
8	Climate	Semi-arid
9	Average annual Rainfall	842 mm

2.2 Geology

The geology of the Gangakhed cluster is fundamentally rooted in the expansive Deccan Volcanic Province, a massive formation from the late Cretaceous and early Eocene epochs. The primary lithology is characterized by the Deccan Traps, a thick, horizontal succession of basaltic lava flows that erupted from ancient fissures. These hard, dense basalt layers are often separated by intertrappean beds and layers of reddish clay known as red bole. The basaltic bedrock dominates the landscape and is primarily useful only for building stone. However, the older basement is locally covered by a younger veneer of Quaternary alluvial sediments. These valuable sediments are typically found near major river valleys, specifically along the Godavari River, which flows directly through the Gangakhed region, adding a critical layer of fertile soil over the volcanic rock.

2.3 Geomorphology

The geomorphology of the Gangakhed region is the result of millions of years of subaerial denudation acting upon a volcanic basaltic plateau, punctuated by recent neotectonic activity. The landscape presents two contrasting features: expansive, undulating agricultural plains formed by the Godavari River basin and residual plateau forms, including flat-topped hills and deeply eroded scarp faces. Topographically, the district generally slopes from a maximum elevation of approximately 580 meters in the northern Jintur hills down to about 366 meters along the southeastern Godavari river plains. Gangakhed taluka is situated in the southern part of the district, positioned near the transverse Balaghat hill ranges. Here, the rugged, residual hills transition into broad, deeply entrenched alluvial valleys, which are a product of the region’s intense and sustained stream erosion.

2.4 Physiography and Soil

The terrain is undulating to moderately hilly, with slope variation ranging from 0% to 56%. Higher slope zones show visible erosion due to rapid surface runoff and reduced vegetation cover.

Basalt forms the dominant lithology of the area, reflecting its geological setting within the Deccan Traps. The soils in the study area are predominantly clay, with patches of clay-loam and silt-loam. These soils possess good moisture retention capability but are susceptible to erosion on slope-dominant surfaces.

2.5 Climate

The Parbhani-Gangakhed region is defined by a semi-arid, dry tropical climate, characterized by intense summer heat and general dryness throughout the year, with the exception of the vital southwest monsoon season. The annual climatic cycle is divided into four distinct seasons. The year begins with a mild winter from December to February, followed by a scorching summer lasting from March to May. The essential southwest monsoon arrives between June and September, and a brief post-monsoon transition period occurs in October and November. During the peak summer month of May, maximum daytime temperatures consistently exceed 40°C, with historical extremes reaching 46.6°C. In contrast, the winters are generally pleasant, featuring mean minimum temperatures that typically drop to between 10°C and 12.6°C. However, the region occasionally experiences cold waves originating from northern India, which can push minimum temperatures down to as low as 5°C.

2.6 Drainage

The drainage within the Gangakhed cluster, a key part of the larger Godavari Peninsular basin, is fundamentally shaped by the Godavari River, known locally as "Dakshinganga." While the Godavari traverses the region, the Galaati River, a tributary of the Godavari, is a vital water source for the cluster itself. The Galaati River's flow is essential water for both agricultural irrigation and domestic use throughout the cluster area.

2.7 Cropping Patterns, and Demography and Socioeconomics

2.7.1 Cropping Pattern

Agriculture pattern is primarily rainfed and follows a seasonal cropping cycle, with different crops grown in the Kharif and Rabi seasons. During the Kharif season, Jowar, Soybean, Tur, Urad, and Cotton are widely cultivated, making optimal use of the monsoon rainfall and the clay to clay-loam soils of the watershed. In the Rabi season, Wheat and Rabi Jowar are grown in areas with residual soil moisture or access to supplementary irrigation.

2.7.2 Demographic and Socioeconomic Status

Gangakhed taluka has a total population of 202,867, with its urban center holding 49,891 residents (Census, 2011). The city demonstrates a strong female sex ratio of 952 females per 1,000 males, surpassing the state average, and an overall literacy rate of 76.46%. The socioeconomic status is deeply rooted in agriculture, with a substantial portion of the taluka workforce comprising 36,227 cultivators and 39,169 agricultural laborers.

2.8 Water Resources

2.8.1 Surface Water

The study area lacks perennial rivers and does not fall under any major canal network. Drainage is primarily through seasonal streams and nalas that carry monsoon runoff for a short duration before flowing rapidly downstream. Due to the limited number of functional water-harvesting structures such as check dams, farm ponds, and percolation tanks, only a small portion of this runoff is retained, resulting in restricted surface water availability for agriculture and domestic use. The Galaati River, the main watercourse in the area, receives considerable monsoon flow; however, inadequate storage capacity leads to the loss of most of this water. Similarly, smaller nalas and micro-channels discharge quickly into the river without adequate measures for flow regulation or storage

2.8.2 Groundwater

Groundwater occurs mostly in weathered and fractured zones of basalt rock. According to the Dynamic Ground Water Resources of Parbhani District (CGWB), 2024, annual extractable ground water resources place the region under the “safe” category, with the groundwater extraction level are 41.1%

2.8.3 Irrigation and Water Management

Agriculture in the Gangakhed cluster is predominantly rainfed, making irrigation vital for crop survival. Many farmers rely heavily on groundwater extracted via borewells and open dug wells. This over-extraction, coupled with traditional flood irrigation practices, has led to severe water wastage, declining water tables, and increased soil salinity

2.9 Constraints

The following key issues were observed in the cluster villages, both through field surveys (2024-2025) and community consultations:

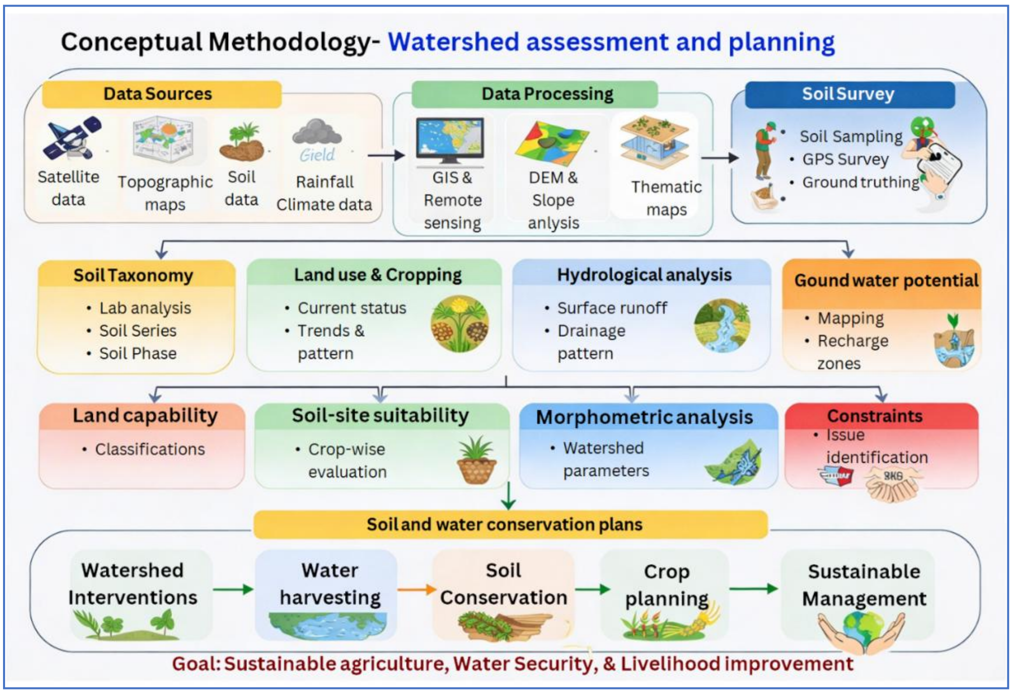
1. Declining Groundwater Levels: Monitoring of shallow aquifers indicates a downward trend in pre-monsoon water levels, highlighting stress on groundwater resources.
2. Limited Irrigation Coverage: A significant portion of the cultivated area remains rainfed due to lack of developed irrigation infrastructure, resulting in dependence on monsoon rainfall for agriculture.
3. Partial Utilization of Water Conservation Programs: Water availability is still insufficient in some areas, indicating that existing structures and programs need continued support and maintenance to fully meet local water demand.
4. Weak Asset Maintenance: Existing check dams, and old bunds built under earlier schemes (like Jalyukt Shivar) are in poor repair, lacking community ownership or technical upkeep.

CHAPTER 3

METHODOLOGY

3.1 Overview of Activities

The following figure depicts the overall flow of activities adopted for the project:



The various activities involved in the generation of land resource data and maps can be broadly grouped under pre-field, soil survey, post-field and post-LRI activities, as listed below:

A. Pre-field

- Procurement of high-resolution satellite imageries, cadastral maps, geology/physical maps
- Image interpretation for physiography/landforms/land use
- Finalization of physiography/landform map with legend as base maps.

B. Soil Survey

- Selection of transects (cutting across as many physiographic units as possible)
- Digging of soil profile pits up to 1.5 m depth or hard rock, whichever is earlier
- Examination and description of soil profiles in transects
- Study and record of soil-site characteristics
- Collection of soil samples from the pedons of each soil series
- Field review (preliminary, progressive and final) for soil correlation
- Grouping of soil profiles studied at each transect into soil series
- Development of progressive soil legend
- Mapping of soil phases (management units)

- Mapping of current land use/land cover, existing soil and water conservation structures etc.

C. Post-field phase

- Processing of soil samples, and laboratory analysis for physical, physico-chemical properties
- Compilation and interpretation of data
- Generation of thematic maps (slope, erosion, soil depth, drainage, pH, SOC, N, P, K and micronutrients, etc.)
- Land evaluation for various suitability classes for different crops and irrigation
- Preparation of soil and water conservation maps
- Developing soil mapping unit wise alternate land use options
- LRI Report write-up

3.2 Preparation of Base Maps

Spatial data preparation began by georeferencing Survey of India (SOI) toposheets at a 1:50,000 scale, utilizing the WGS 84 datum and UTM projection supported by field - verified Ground Control Points (GCPs). Landform delineation was executed within a GIS environment, integrating 30 m resolution SRTM Digital Elevation Models (DEM) with systematic on-screen visual interpretation. This geomorphic analysis relied on fundamental image elements - including shape, tone, colour, pattern, shadow and texture - to identify land features. To enhance interpretation, False Colour Composites (FCC) were generated through various satellite band combinations. Final mapping of land use/land cover (LULC) and landform units was conducted using ArcGIS software.

3.3 Ground-truth Verification

The area was traversed to identify different landform units, slope and present land use/land-cover (LULC) classes, and correlated with image interpretation units. The boundaries that were originally derived during the base map preparation were verified and corrected wherever necessary. To understand the soil variability in the study area, representative sites on each landform unit were selected, located using handheld Global Positioning System (GPS) and 30 profiles observations were taken and studied for morphological properties in the field following the guidelines for field soil descriptions (Soil Survey Division Staff 2000) and were recorded in the standard format.

3.4 Soil Sampling and Analysis

Soil samples from each horizon of all of the representative soil series were collected for laboratory studies. The soil samples collected during the fieldwork were initially air dried in the laboratory at room temperature, ground using a wooden pestle and mortar, screened through a 2 mm sieve, properly labelled, and stored in polythene bags for laboratory analysis. The soil samples were analysed in the laboratory for physical and chemical parameters using standard procedures. The particle size analysis was done by international pipette method. A combined glass-calomel electrode was used to determine the pH measured (1:2.5 soil/solution ratio). Soil organic carbon (SOC) was determined using the wet digestion method of Walkley and Black (1934). Available nitrogen (N) was measured by the alkaline permanganate method as described by Subbiah and Asija (1956). Available phosphorus (P) was determined by the Bray II method (Bray and Kurtz 1945). Cation exchange capacity (CEC) of soil was measured as per the procedure outlined by Jackson (1976). Exchangeable cations [calcium (Ca), potassium (K), and magnesium (Mg)] were extracted with 1 M ammonium acetate (NH4Oac) (pH 7.0). Potassium content was determined by flame photometry (Rich 1965), while Ca and Mg were determined in ethylene diamine tetra acetic acid (EDTA) titration. Exchangeable Al was extracted with 1 N potassium chloride (KCl) solution and titrated with 0.1 N sodium hydroxide (NaOH) solution. Available micronutrient content [copper (Cu), manganese (Mn), iron (Fe), and zinc (Zn)] was determined by diethylene triamine penta-acetic acid (DTPA) extraction (Lindsay and Norvell 1978), followed by atomic absorption spectrophotometry. Soils were classified according to Keys to Soil Taxonomy (Soil Survey Staff 2010).

3.5 Development of Soil Mapping Legend

In the present study, soil series phases were used as the basic mapping units. A soil series refers to a group of soils or polypedons that exhibit similar horizon sequences and share closely related properties within a narrow range of variation (Soil Survey Division Staff, 2000). The phases considered in this study included soil depth, surface texture, slope, erosion status and flooding conditions.

Soil profiles were examined and correlated within each major landform and soil series were identified accordingly. The identified soil series information was then extended to the sub-units of major landforms based on diagnostic soil characteristics observed from soil profile descriptions and auger observations.

A detailed soil map depicting soil series and their respective phases was prepared at a scale of 1:10,000. The soil legend code developed for the map represents the soil series name followed by surface texture, slope class, erosion status and soil depth, as described by Singh et al. (2016).

3.6 Surface Runoff Estimation

Surface runoff is a key factor influencing water availability and watershed functioning in Gangakhed Taluka. The region receives an average annual rainfall of about 842 mm (2014-2024), yet the hydrological response across the landscape varies significantly due to differences in slope, land use and soil conditions. The nine study villages fall within mixed terrain-from river-adjacent low-lying plains to upper upland zones which results in varying runoff behaviour and water retention characteristics.

Field assessments indicate that water availability near valley regions and river-side settlements is comparatively better, owing to improved recharge and access to surface water. However, upland areas and hilly locations face persistent challenges such as limited infiltration, seasonal drying of water sources, loss of fertile topsoil, and rapid movement of rainwater due to insufficient bunding and slope control. These site-specific constraints highlighted the need for systematic runoff estimation to understand the scale of water lost as direct surface flow and to identify areas requiring priority intervention.

The runoff estimation study was carried out using the SCS-Curve Number (CN) method, utilizing actual rainfall records from 2014-2024 along with verified land use and soil characteristics. Rainfall data was compiled daily and analysed seasonally, and CN values were assigned after considering ground conditions informed by satellite interpretation and field verification. Based on these inputs, annual and seasonal runoff was computed for each monsoon period.

Surface runoff in the watershed exhibits clear seasonality and is closely linked to the timing and intensity of monsoon rainfall. Analysis of the monthly data for the period 2014-022024 (Table 1) indicates that July and September consistently generate the highest runoff, reflecting periods of concentrated rainfall and saturated soil conditions. Runoff during June is generally low, as early monsoon rains are absorbed by dry soils, while October runoff is minimal due to reduced rainfall and declining soil saturation. August runoff remains moderate across most years.

3.7 Groundwater Potential Zone Mapping

Groundwater is a crucial source of water supply in Gangakhed Taluka, sustaining domestic needs, drinking water requirements, and agricultural irrigation. In upland and non-command areas, where surface water is either scarce or unreliable, dependence on groundwater is particularly high. The region receiving an average annual rainfall of 842.3 mm, which is relatively low, the recharge of groundwater remains insufficient to meet the overall demand. The limited rainfall, coupled with variations in soil types, landforms, and the complex hydrogeological framework, results in uneven distribution of groundwater across the study area. Certain areas, particularly those with steep slopes, rocky outcrops, and shallow soils, experience minimal recharge, while other low-lying and gently undulating terrains have moderate potential for water storage. This uneven availability presents significant challenges for sustainable water management and highlights the need for a detailed spatial understanding of groundwater potential.

In response to these challenges, a comprehensive assessment was undertaken to delineate groundwater potential zones for the nine-village cluster watershed of Gangakhed Taluka. The study adopted a multi-criteria spatial analysis approach, integrating eight key thematic layers that influence groundwater occurrence and movement: lithology, land use and land cover (LULC), drainage density, soil type, slope, elevation, landform, and rainfall distribution. Each of these parameters plays a significant role in determining the capacity of the terrain to store and transmit groundwater. Lithology controls the subsurface porosity and permeability, while soil type influences infiltration and runoff characteristics. Similarly, slope and drainage patterns dictate the flow of surface water, impacting the areas that are more favorable for recharge. Landforms and elevation contribute to natural water retention zones, and rainfall, although low, is a critical factor in replenishing shallow aquifers. Integrating all these factors provides a robust framework for assessing groundwater potential in a systematic and scientific manner.

The analysis was carried out using a weighted overlay technique within a Geographic Information System (GIS) environment. Each thematic layer was assigned a weight according to its relative influence on groundwater potential, determined through the Analytical Hierarchy Process (AHP). This method was supported by expert consultation and a review of relevant scientific literature to ensure that the assigned weights realistically reflected local hydrogeological conditions. Data for the layers were sourced from remote sensing imagery, field surveys, and secondary datasets from government and research publications. Each layer was standardized and classified into sub-categories, which allowed the study to capture subtle variations in recharge potential across the watershed. By combining these weighted layers, a detailed Groundwater Potential Zonation (GWPZ) map was developed, categorizing the landscape into five classes: Very Good, Good, Moderate, Poor, and Very Poor.

The final map provides clear spatial insights into groundwater distribution. Approximately 19.3% of the watershed is classified as "Very Poor," representing areas with steep terrain, and shallow soil cover, where natural recharge is highly limited. Around 24.7% of the area falls under the "Poor" category, typically characterized by high runoff and low infiltration. An additional 23%, is identified as "Moderate" potential, reflecting gently undulating terrains that allow moderate recharge of shallow aquifers. Areas with "Good" and "Very Good" potential together cover approx. 33% of the watershed, indicating that high-yield groundwater zones are limited. These findings highlight that the majority of the taluka, approximately 67%, requires careful management interventions to sustain groundwater resources and meet future water demands.

The delineation of groundwater potential zones has significant implications for planning and implementing water resource management strategies in Gangakhed Taluka village cluster watershed. The map serves as a scientific basis for designing groundwater recharge structures, promoting soil and moisture conservation, and implementing land treatment measures, especially under programs like the Pradhan Mantri Krishi Sinchayee Yojana - Watershed Development Component 2.0 (PMKSY-WDC 2.0). By identifying priority micro-watersheds with poor groundwater potential, interventions can be focused where they are most needed, ensuring optimal utilization of resources. Conversely, areas identified with good to very good potential can be prioritized for sustainable groundwater extraction and irrigation planning. The integration of these spatial insights into watershed management ensures that both surface and groundwater resources are effectively harnessed, minimizing water scarcity risks for domestic, agricultural, and ecological needs.

The low rainfall of the region, combined with its varied terrain and complex hydrogeology, makes sustainable groundwater management particularly challenging. Therefore, an integrated approach, combining scientific mapping, field validation, and strategic interventions, is essential. Enhancing recharge in moderate and poor potential zones through, percolation tanks, farm ponds, and contour bunding can improve groundwater availability and help stabilize water supply in critical areas. Furthermore, protection of recharge zones from encroachment and over-extraction, along with careful monitoring of groundwater levels, can ensure the long-term sustainability of aquifers. The insights derived from the GWPZ mapping not only guide immediate water management decisions but also contribute to long-term planning for climate resilience and food security in Gangakhed Taluka village cluster watershed.

In conclusion, the Groundwater Potential Zonation provides a detailed understanding of the spatial distribution of groundwater resources, emphasizing areas of scarcity and zones suitable for sustainable exploitation. While high-yield groundwater areas are limited, strategic management and targeted interventions can improve recharge, optimize groundwater utilization, and enhance water security across the area. This comprehensive assessment forms the foundation for evidence-based decision-making, ensuring that groundwater resources continue to support domestic, agricultural, and ecological needs in Gangakhed Taluka for years to come.

3.8 Land Evaluation

The evaluation of soil-site suitability was carried out to understand how well the land resources of the watershed can support sustainable crop production under existing environmental conditions. The approach combines information on soil properties, terrain features, and climate to assess the capability of different land units to meet the growth requirements of various crops, thereby supporting scientific land-use planning.

The assessment was conducted using the maximum likelihood method based on the guidelines proposed by Sys et al. (1993) and Naidu et al. (2006). Detailed field surveys, laboratory analysis of soil samples, and interpretation of spatial datasets were used to generate a comprehensive soil and site database. Since the watershed area is relatively small, temperature and rainfall were considered uniform across the entire area and treated as constant climatic inputs for the suitability evaluation.

Soil wetness conditions, including drainage status and the possibility of flooding, were examined to understand soil aeration and moisture availability. Physical soil characteristics such as surface texture and effective soil depth were assessed to evaluate their influence on root growth, water retention, and nutrient uptake. Soil fertility indicators, including pH, soil organic carbon, apparent cation exchange capacity, base saturation, and exchangeable cations, were analyzed to determine the nutrient-supplying capacity of soils. In addition, terrain features such as slope and erosion risk were considered to understand their impact on runoff, soil loss, and field operations.

Each soil and site factor was rated according to its degree of limitation to crop growth, and the combined effect of these limitations was used to determine overall land suitability. Based on this integrated analysis, soils were grouped into five suitability classes: highly suitable (S1), moderately suitable (S2), marginally suitable (S3) and not suitable (N). This classification helps in identifying suitable crops, planning appropriate management practices, and promoting sustainable agricultural development within the watershed.

3.9 Identification of Soil and Water Conservation Measures

The identification and spatial allocation of soil and water conservation (SWC) measures within the village cluster watershed of Gangakhed Taluka were carried out through an integrated geospatial and land resource assessment approach. A comprehensive spatial database was prepared using high-resolution satellite imagery, digital elevation models (DEM), soil resource maps, land use/land cover data, and drainage network information. From the DEM, slope classes, flow accumulation, and drainage patterns were derived to understand runoff movement and erosion-prone areas within the watershed. Soil resource information, including soil depth, texture, and drainage characteristics, was integrated with land use data to assess land capability and constraints affecting agricultural productivity.

Based on these datasets, land capability assessment and terrain analysis were performed to delineate management units within the watershed. Each unit was evaluated for its suitability for specific conservation interventions by considering parameters such as soil depth, slope gradient, existing land use, runoff potential, and proximity to drainage lines. Decision rules commonly used in watershed planning were applied to assign appropriate measures. For example, field bunding and strengthening of existing bunds were recommended in cultivated lands with gentle slopes to reduce runoff and enhance in situ moisture conservation, while conservation bench terraces were proposed in unbunded agricultural areas with moderate slopes where soil depth permitted terracing. The Broad Bed and Furrow (BBF) system was identified for agricultural fields, particularly in medium to deep soils, to improve surface drainage and soil moisture distribution under rainfed conditions.

Water harvesting interventions were identified based on runoff contributing areas, drainage density, and storage potential. Farm ponds were proposed in agricultural fields with suitable catchment areas, while lined farm ponds were recommended in locations with higher seepage potential. Structural measures such as cement nala bunds (CNB) and earthen nala bunds (ENB) were proposed along drainage lines after evaluating channel characteristics, contributing catchment area, and groundwater recharge potential. Renovation and desilting of existing water bodies and farm ponds were suggested based on field observations and spatial identification of existing structures.

Vegetative interventions were planned in areas characterized by scrubland, degraded lands, or drainage margins, where afforestation and stream bank plantations could help stabilize soil and reduce erosion. Horticultural plantations supported with in situ moisture conservation practices were proposed in suitable land parcels to enhance land productivity. Additional measures such as rooftop rainwater harvesting in built-up areas and road-side drainage protection works were identified to capture and safely manage runoff from non-agricultural surfaces. Through the integration of terrain analysis, soil resource information, land use assessment, and hydrological considerations, site-specific conservation measures were systematically identified and spatially allocated within the watershed. This approach ensured that the proposed interventions are technically suitable, hydrologically effective, and aligned with the existing land resource conditions of the watershed.

CHAPTER 4

RESULTS AND INTERPRETATIONS

4.1 Irrigation, Cropping Patterns, and Demography and Socioeconomics

A field survey was conducted to document the availability of water resources, cropping patterns, and the demographic and socio-economic characteristics of farmers in the watershed. The results obtained from this survey are presented in the following sub-sections.

4.1.1 Irrigation and water management

The irrigation pattern of the Gangakhed watershed is presented in Table 4.1. Well irrigation contributed 42.2% to the total irrigation. Borewells contribute 42.0% of the total irrigation. Borewells support irrigation during Kharif, Rabi and Summer seasons. Ponds contribute 12.9% to the irrigation.

The irrigation system of the watershed is primarily dependent on groundwater sources such as wells and borewells, while ponds and river water provide support during critical stages.

Table 4.1 Seasonal Distribution of Irrigation Sources in the Parbhani watershed

Sr. No.	Number of Farmers Interviewed (n)	Irrigation Source	Seasonal Water Availability	Contribution to Season's Total Irrigation (%)
1	Kharif, Rabi & Summer	Borewell	35	42.0
2	Kharif & Rabi	Pond	12	12.9
3	Rabi & Kharif	Rainfed	120	0.0
4	Kharif & Rabi	River	4	3.0
5	Kharif & Rabi	Well	43	42.2

4.1.2 Cropping Pattern

The cropping pattern of the Gangakhed watershed is presented in Table 4.2. The gross cropped area of the cluster is 296.80 ha, while the net sown area is 185.33 ha.

$$Cropping\ intensity(\%) = \frac{Gross\ cropped\ area}{Net\ sown\ area} \times 100$$

$$Cropping\ intensity(\%) = \frac{296.80}{185.33} \times 100 = 160.1\%$$

The cropping intensity of the area is calculated as 160.1%, indicating that a significant area of agricultural land is cultivated more than once during the year.

In the Kharif season, cotton occupies 52.4% of the total cropped area with a productivity of 1135.0 kg/ha, making it the most important crop in the region. Soybean is the second major Kharif crop, covering 26.6% of the cropped area with a productivity of 1141.7 kg/ha.

In the Rabi season, sorghum occupies 7.0% of the total cropped area with a productivity of 367.5 kg/ha, making it the major crop of the season. Gram covers 3.1% of the cropped area with a productivity of 557.3 kg/ha, while wheat occupies 2.7% of the cropped area producing 369.1 kg/ha. Groundnut is cultivated on 1.6% of the cropped area, recording a productivity of 213.9 kg/ha.

The cropping pattern of the cluster shows a dominance of cotton and soybean during the Kharif season, while sorghum, gram, wheat, and groundnut are cultivated during the Rabi season.

Table 4.2 Crop-wise distribution in the Parbhani watershed

Sr. No.	Season	Crop	No. of Farmers Interviewed (n)	Irrigation Type	Total Cropped Area (%)	Productivity (kg/ha)
1	Kharif	Cotton	111	Irrigated	52.4	1135.0
2	Kharif	Soyabean	91	Irrigated	26.6	1141.7
3	Rabi	Sorghum	36	Irrigated	7.0	367.5
4	Rabi	Gram	17	Irrigated	3.1	557.3
5	Rabi	Wheat	17	Irrigated	2.7	369.1
6	Rabi	Groundnut	5	Irrigated	1.6	213.9
7	Kharif	Tur	8	Irrigated	0.8	150.2

4.1.3 Socioeconomic Status

4.1.3.1 Land holding pattern

The landholding pattern of farmers in the Gangakhed watershed is presented in Table 4.3, From the table, it was observed that small farmers (1-2 ha) constitute the highest population with 44.4% of the total farmers, having an average landholding of 1.4 ha followed by semi-medium farmers (2-4 ha) constitute 25.9% with an average landholding of 2.5 ha.

Marginal farmers (<1 ha) constitute 22.2% of the farmers with an average landholding of 0.6 ha, while medium farmers (4-10 ha) account for 7.4% with an average landholding of 4.1 ha. No farmers were recorded under the large farmer category (>10 ha).

Average landholding size in the Gangakhed watershed was found to be 1.7 ha, indicating that agriculture in the region is characterized by small landholdings.

Table 4.3 Land holding pattern in Parbhani watershed

Category	Criteria Land (ha)	No. of Farmers Interviewed (n)	Farmers (%)	Average Land Holding (ha)
Marginal Farmers	<1	24	22.2	0.6
Small Farmers	1-2	48	44.4	1.4
Semi-Medium Farmers	2-4	28	25.9	2.5
Medium Farmers	4-10	8	7.4	4.1
Large Farmers	>10	0	0.0	0.0
Average land holding				1.7

4.1.3.2 Income distribution

The income pattern from different crops in the watershed is presented in Table 4.4. Cotton occupies the largest cropped area (52.4%) with an average income of 1,51,305 Rs, indicating that it is the major income-generating crop, followed by soyabean, which covers 26.6% of the cropped area with an average income of 41,582 Rs.

Sorghum occupies 9.1% of the cropped area with an average income of 3,500 Rs, indicating comparatively lower income returns. Gram (3.4%), wheat (2.8%), groundnut (2.9%), and Tur (0.9%) occupy relatively smaller cropped areas. However, the average income for these crops was not recorded because they are mainly cultivated for household consumption.

The results indicate that cotton and soybean dominate the income structure of the watershed, while other crops are grown on smaller areas.

Table 4.4 Average annual income of farmers in Parbhani watershed

Name of Crops	No. of Farmers Interviewed (n)	Crop Area (%)	Average Income (Rs.)
Cotton	111	52.4	151305
Soyabean	91	26.6	41582
Sorghum	43	9.1	3500
Gram	19	3.4	-
Wheat	19	2.8	-
Tur	9	0.9	-
Groundnut	7	2.9	-

4.1.3.3 Education

The educational profile of the population in the villages of the watershed is presented in the Table 4.5. Kanganewadi recorded the highest illiteracy rate (82%), indicating very poor educational status in the village, followed by Dampuri (44%) and Ghatangra (36%), where a considerable population is illiterate. Comparatively lower illiteracy was observed in Ranisawargaon (19%) and Phugnarwadi (9%), indicating relatively better literacy levels in these villages. With respect to primary education, Phugnarwadi recorded the highest population (52%), followed by Ghatangra (41%), Dampuri (32%), and Ranisawargaon (30%), while Kanganewadi recorded only 5% of the population with primary education.

With respect to the secondary education level, Phugnarwadi recorded the highest population (22%), followed by Ranisawargaon (15%) and Ghatangra (14%), while Dampuri and Kanganewadi recorded 8% each. With respect to higher secondary education, Dampuri recorded the highest (12%), while Phugnarwadi and Ranisawargaon recorded 4% each. Regarding higher studies, Ranisawargaon recorded the highest (33%), followed by Phugnarwadi (13%), Ghatangra (9%), Dampuri (4%), and Kanganewadi (2%).

The results indicate significant variation in educational attainment in the villages, with some villages having higher levels of primary and secondary education, while others still show high levels of illiteracy.

Table 4.5 Education profile of villages in Parbhani-Gangakhed watershed by population

Village	No Education (%)	Primary (%)	Secondary (%)	Higher Secondary (%)	Higher Studies (%)
Dampuri	44	32	8	12	4
Ghatangra	36	41	14	0	9
Kanganewadi	82	5	8	3	2
Phugnarwadi	9	52	22	4	13
Ranisawargaon	19	30	15	4	33

4.2 Land-use/Land-cover

The classification of the area reveals that agriculture is the primarily land use type, occupying 3991.9 ha, and constitutes 82.4% of the total area (Table 4.6 and Fig. 4.1). Wasteland covering 589.7 ha (12.2%) of the area, which may indicate areas unsuitable for cultivation. Waterbodies are limited to 170.8 ha, making up 3.5% of the total area, reflecting the presence of limited surface water resources in the region. This LULC distribution highlights the primarily of agricultural activities in the area with secondary coverage by Habitation and Waterbody categories.

Table 4.6 Land-use/land-cover statistics of Parbhani-Gangakhed watershed

Sr. No.	LULC Class	Area (ha)	Percent (%)
1	Agriculture	3991.9	82.4
2	Wasteland	589.7	12.2
4	Waterbody	170.8	3.5
3	Habitation	94.5	1.9
	Total	**4846.9**	**100.0**

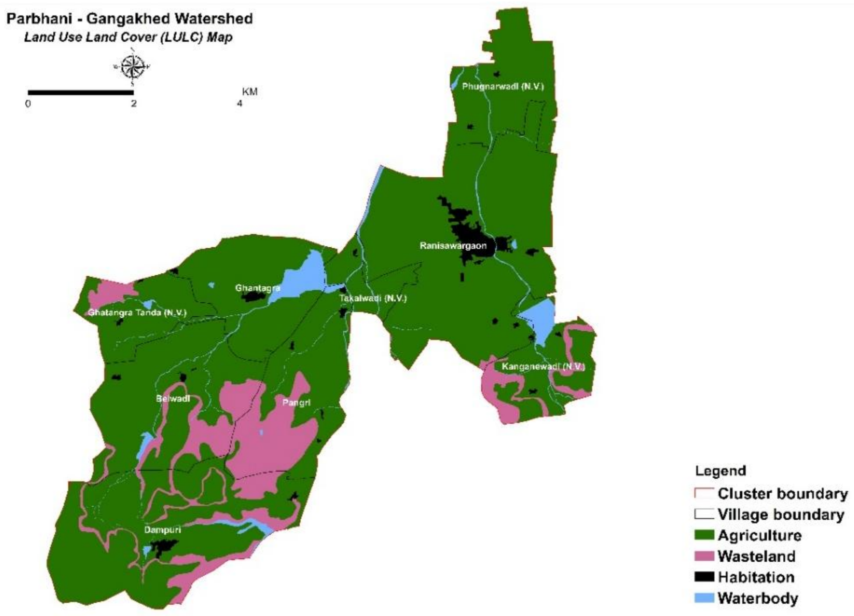


Fig. 4.1: Land-Use/Land-Cover Map

4.3 Landform Delineation

The landform distribution of the Parbhani-Gangakhed watershed indicates the presence of varied geomorphological units (Table 4.7 and Fig. 4.2). Plateau is the most dominant landform in the watershed, covering about 1460.5 ha which constitutes 30.1 per cent of the total area. Valley landforms occupy 1111.8 ha (22.9%), reflecting the influence of drainage and erosional processes in shaping the terrain. Lower pediments cover 962.6 ha, accounting for 19.9 per cent of the watershed area and generally occur as gently sloping surfaces along the foothills. Escarpments extend over 492.2 ha (10.2%), indicating areas of steep slopes and abrupt changes in elevation. Upper pediments occupy 444.9 ha (9.2%), while pediplains cover only 109.6 ha (2.3%). Habitation areas account for 94.5 ha (1.9%), and water bodies cover 170.8 ha (3.5%). Overall, the watershed landscape is mainly dominated by plateau, valley, and pediment features.

Table 4.7: Landform features existing in Parbhani -Gangakhed watershed

Landform	Area(ha)	Percent (%)
Plateau	1460.5	30.1
Escarpment	492.2	10.2
Valley	1111.8	22.9
Upper Pediments	444.9	9.2
Lower Pediments	962.6	19.9
Pediplains	109.6	2.3
Habitation	94.5	1.9
Waterbody	170.8	3.5
Total	**4846.9**	**100.0**

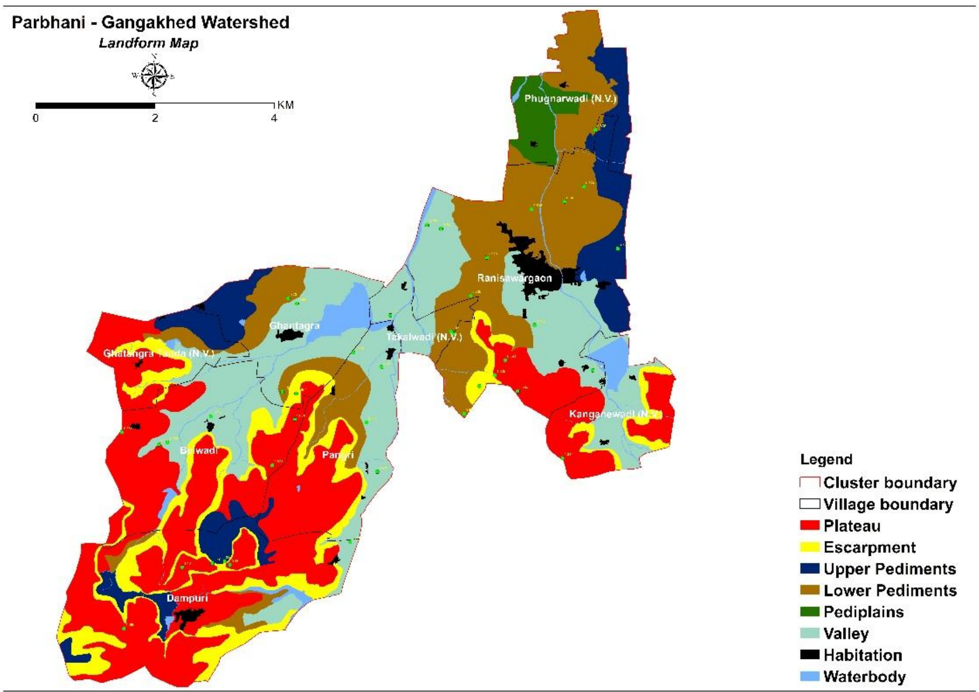


Fig. 4.2: Landform map of Gangakhed watershed

4.4 Soil Series and Phases

Eight soil series have been identified and mapped with 21 soil mapping units (phases of series) (Fig 4.4). The taxonomic classification and mapping legend of the soil series along with its landform and polygon were shown in Table 4.8. The detailed descriptions of each series are given in Table 4.9.

Table 4.8. Dominant soil series identified in the watershed.

Sr. No.	Series	Area (ha)	Percent (%)
1	Belwadi	580.7	12.0
2	Dampuri	951.1	19.6
3	Ghatangra	375.8	7.8
4	Ghatangra Tanda	492.2	10.2
5	Pangri	110.6	2.3
6	Phugnarwadi	444.9	9.2
7	Ranisawargaon	22.9	0.5
8	Takalwadi	1603.3	33.1
9	Habitation	94.5	1.9
10	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

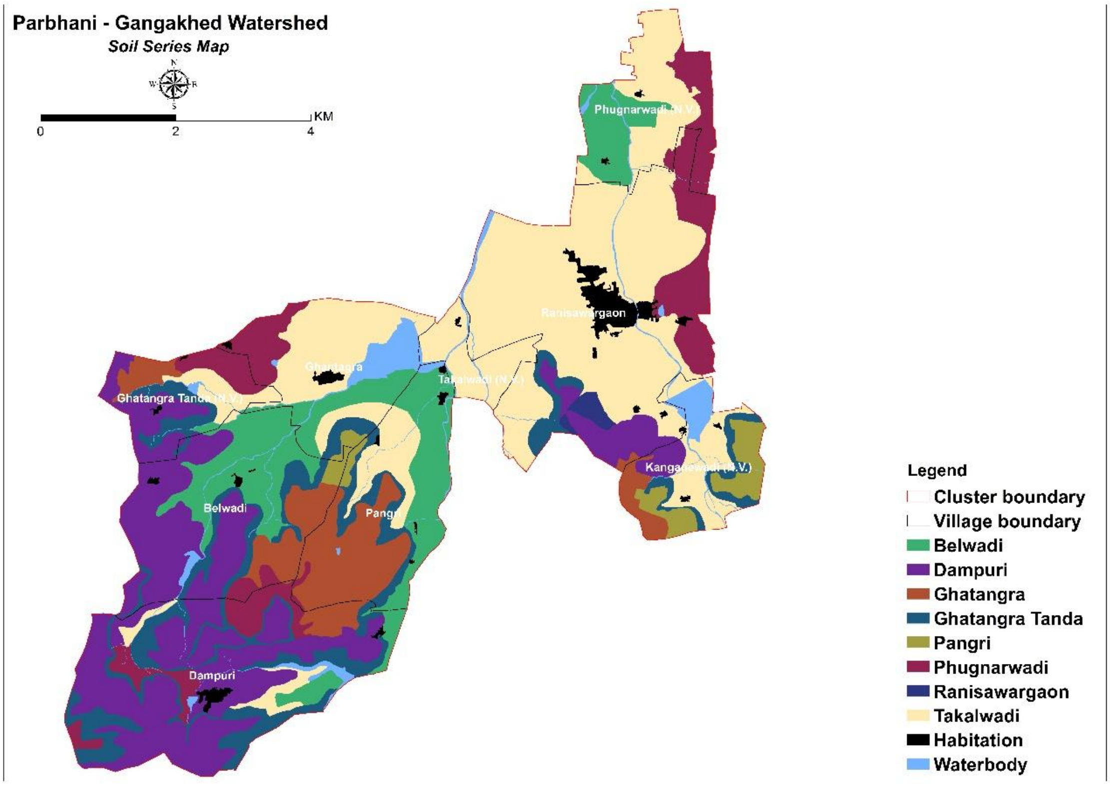


Fig. 4.3: Soil series map of Gangakhed watershed

Table 4.9. Soil phases existing in Gangakhed watershed

Sr. No.	Phase	Area(ha)	Percent (%)
1	Bel4mB1	128.9	2.7
2	Bel5mB1	451.9	9.3
3	Dam2eE2	22.8	0.5
4	Dam2mB1	135.3	2.8
5	Dam2mC1	21.8	0.4
6	Dam2mD2	354.9	7.3
7	Dam2mE2	263.6	5.4
8	Dam2mF3g1	152.7	3.2
9	Gha1fE4g2	375.8	7.8
10	Ght1mG3g2	213.9	4.4
11	Ght1mG4g2	220.5	4.5
12	Ght2mG4g2	57.8	1.2
13	Pan2mB1	29.0	0.6
14	Pan2mC2	27.9	0.6
15	Pan2mD2	53.8	1.1
16	Phu2mB1	256.1	5.3
17	Phu2mC2	106.6	2.2
18	Phu2mD2	82.3	1.7
19	Ran5mB1	22.9	0.5
20	Tak2mB1	640.7	13.2
21	Tak3mB1	962.6	19.9
22	Habitation	94.5	1.9
23	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

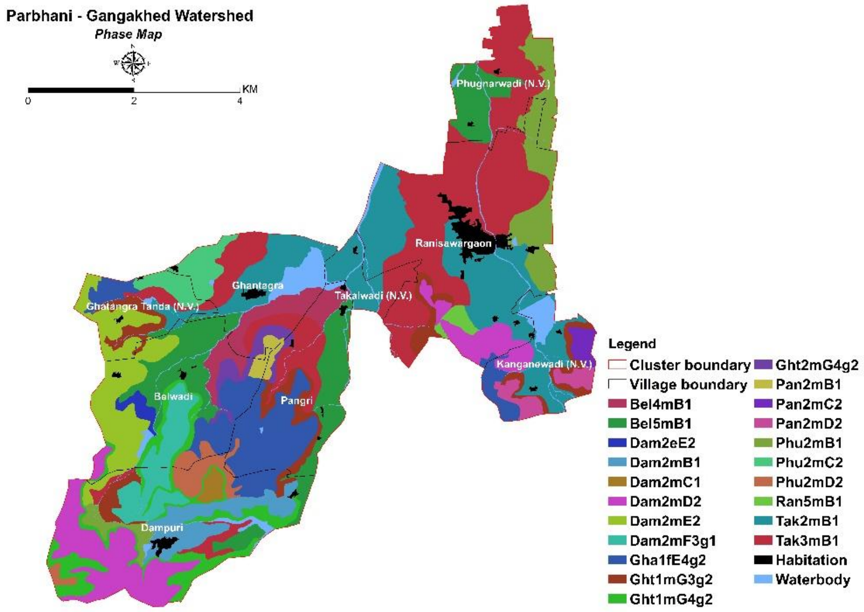


Fig. 4.4: Soil Phase map of Gangakhed watershed

4.5 Soil Survey Interpretation

4.5.1 Slope

Land slope plays a crucial role in agriculture, as it affects water drainage, soil erosion, and the ease with which crops can be cultivated. Gentle slope tends to have higher rates of surface runoff, which can lead to soil erosion and loss of valuable topsoil, reduce soil fertility and compromise crop yields. On the other hand, very gently sloping lands allow for better water retention, easier mechanization, and more efficient irrigation practices, leading to higher productivity. The slope also influences the microclimate of the area, with sloped terrains potentially being more prone to temperature extremes or frost in certain regions. By considering the slope of land, farmers can implement soil conservation techniques, such as terracing, bunding or contour farming, to reduce erosion and optimize land use. Among the different slope classes (Table 4.10, Fig. 4.5) the maximum area of watershed is under very gently sloping (1 - 3%) covering 54.2% followed by moderately sloping (8 - 15%) covering 13.7%, gently sloping (3 - 8%), covering 13.4%, Steep sloping (30 - 50) covering 10.2% moderately steep sloping (15 - 30%) covering 3.2%.

Table: 4.10. Land slope classes in Gangakhed watershed

Sr. No.	Slope Class (%)	Area (ha)	TGA (%)
1	Very gently sloping (1 - 3)	2627.2	54.2
2	Gently sloping (3 - 8)	647.2	13.4
3	Moderately sloping (8 - 15)	662.3	13.7
4	Moderately steep sloping (15 - 30)	152.7	3.2
5	Steeply sloping (30 - 50)	492.2	10.2
6	Habitation	94.5	1.9
7	Waterbody	170.8	3.5
		Total	**4846.9**

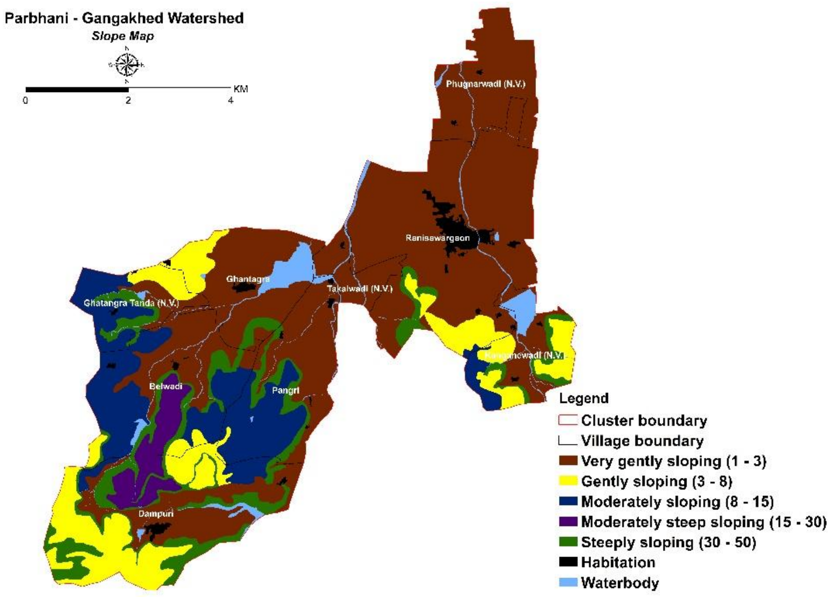


Fig. 4.5: Slope map of Gangakhed watershed

4.5.2 Soil Erosion

Soil erosion in the Parbhani-Gangakhed watershed varies from none to severe depending on local terrain and land conditions (Table 4.11). The analysis indicates that the majority of the watershed area, about 54.7%, falls under the very slight erosion category, suggesting that soil loss is present but generally easy to manageable. A small portion of the area, 7.6%, experiences severe erosion, indicating relatively constraints to manage soil conditions with conservation agriculture practices and 18.8% of the watershed is affected by moderate erosion. However, about 13.5% of the watershed is affected by very severe erosion, representing zones were soil relatively stable soil conditions with maximum loss.

Table 4.11: Soil erosion status in Gangakhed watershed

Sr. No.	Erosion class	Area (ha)	Percent (%)
1	Very Slight	2649.0	54.7
2	Moderate	912.0	18.8
3	Severe	366.6	7.6
4	Very Severe	654.1	13.5
5	Habitation	94.5	1.9
6	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

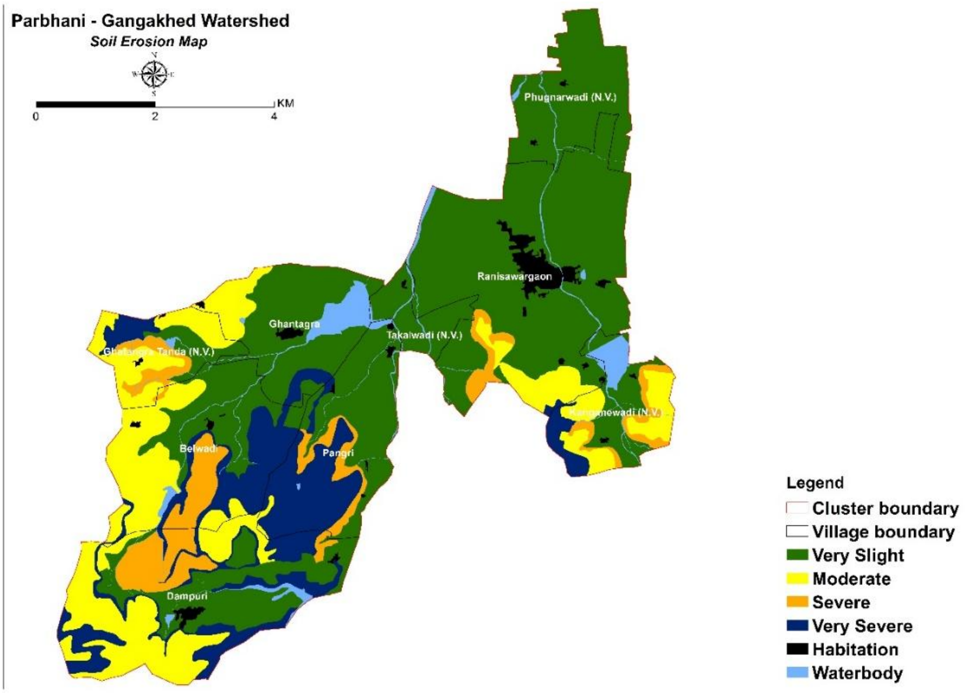


Fig. 4.6: Erosion map of Gangakhed watershed

4.5.3 Soil Depth

Soil depth is an important soil property that greatly influences crop growth and agricultural productivity. It determines the extent of root penetration, moisture storage, nutrient availability, and the overall development of the soil profile. Soil depth is also affected by soil forming processes such as weathering, erosion, deposition, and biological activity. Variations in soil depth across a watershed are often related to topography, slope, drainage conditions, and landscape position. Generally, deeper soils provide more favorable conditions for plant growth because they allow better root expansion and improve the storage of water and nutrients. In contrast, shallow soils restrict root growth and limit the availability of moisture and nutrients, particularly during dry periods, which may reduce crop productivity.

The distribution of soil depth classes in the Parbhani-Gangakhed watershed is shown in Fig. 4.7 and summarized in Table 4.12. The soils of the watershed vary from shallow (<25 cm) to very deep (>100 cm), indicating considerable spatial variability in soil development. Moderate soils (25-50 cm) occupy the largest area of the watershed, covering 2026.8 ha which accounts for 41.8 per cent of the total area. Moderately deep soils (50-75 cm) extend over 1141.1 ha (23.5%). Shallow soils (<25 cm) cover 810.2 ha, representing 16.7 per cent of the watershed area. Very deep soils (>100 cm) occupy 474.7 ha (9.8%), while deep soils (75-100 cm) cover only 128.9 ha (2.7%). Overall, moderate and moderately deep soils dominate the watershed.

Table 4.12. Soil depth classes in Gangakhed watershed

Sr. No.	Depth Class (cm)	Area (ha)	TGA (%)
1	Shallow (< 25)	810.2	16.7
2	Moderate (25 - 50)	2026.8	41.8
3	Moderately Deep (50 - 75)	1141.1	23.5
4	Deep (75 - 100)	128.9	2.7
5	Very Deep (> 100)	474.7	9.8
6	Habitation	94.5	1.9
7	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

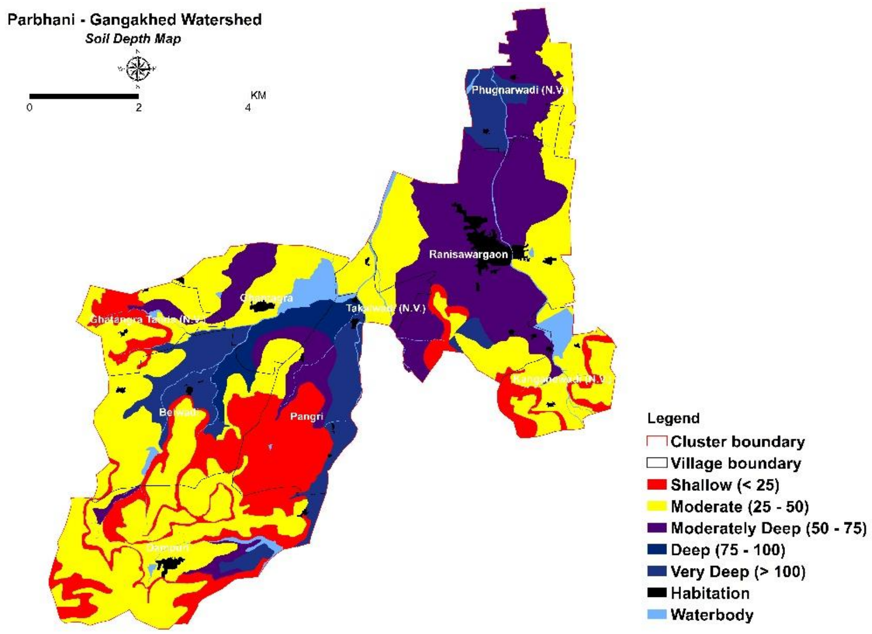


Fig. 4.7: Depth map of Gangakhed watershed

4.5.4 Surface texture

Soil texture is an important physical characteristic of soil that affects water retention, aeration, drainage, and nutrient availability. It also influences root development, crop suitability, and soil management practices. Fine-textured soils such as clay generally have higher water holding capacity but may show poor drainage and limited aeration. In contrast, medium-textured soils provide a better balance between moisture retention and air movement, which supports plant growth. Therefore, studying the distribution of soil texture within a watershed is essential for proper land use planning and sustainable agricultural management.

The soil texture distribution of the Parbhani-Gangakhed watershed is presented in Fig. 4.8 and summarized in Table 4.13. The soils in the area are mainly classified into clay, clay loam, and silty loam. Among these, clay is the most dominant texture, covering 4183.0 ha and accounting for 86.3 per cent of the total geographical area. Clay loam occupies about 375.8 ha, representing 7.8 per cent of the watershed. Silty loam occurs in a very small area of about 22.8 ha, which is 0.5 per cent of the total area. The dominance of clay soils suggests that the watershed generally has good moisture retention capacity, which is beneficial for agricultural activities when managed properly.

Table 4.13. Soil texture distribution in Gangakhed watershed

Sr. No.	Texture	Area (ha)	TGA (%)
1	Clay	4183.0	86.3
2	Clay loam	375.8	7.8
3	Silty loam	22.8	0.5
4	Habitation	94.5	1.9
5	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

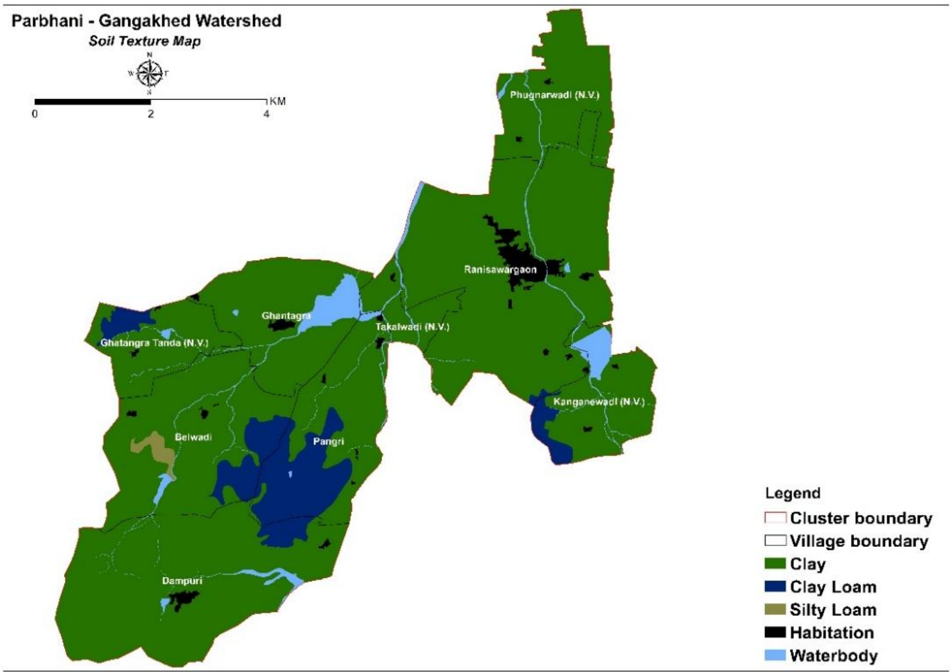


Fig. 4.8: Soil texture map of Gangakhed watershed

4.5.5 Soil reaction

Soil reaction or pH is an important soil chemical property that indicates whether the soil is acidic or alkaline. It plays a vital role in regulating nutrient availability, microbial activity, and overall soil fertility, thereby affecting crop growth and productivity.

The distribution of soil pH classes in the Parbhani Gangakhed watershed is illustrated in Fig. 4.9 and presented in Table 4.14. Neutral soils (pH 6.5-7.5) are the most widespread, covering 2106.7 ha and accounting for 43.5 per cent of the total watershed area. Moderately alkaline soils (pH 8.0-9.0) occupy 1421.7 ha (29.3%), while slightly alkaline soils (pH 7.5-8.0) extend over 981.6 ha (20.3%). Slightly acidic soils (pH 6.0-6.5) are found in a very small portion of the watershed, covering 71.7 ha (1.5%). Overall, the watershed is mainly characterized by neutral to moderately alkaline soils.

Table 4.14. Soil pH distribution in Gangakhed watershed

Sr. No.	Soil pH	Area (ha)	TGA (%)
1	Slightly Acidic (6.0 - 6.5)	71.7	1.5
2	Neutral (6.5 - 7.5)	2106.7	43.5
3	Slightly Alkaline (7.5 - 8.0)	981.6	20.3
4	Moderately Alkaline (8.0 - 9.0)	1421.7	29.3
5	Habitation	94.5	1.9
6	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

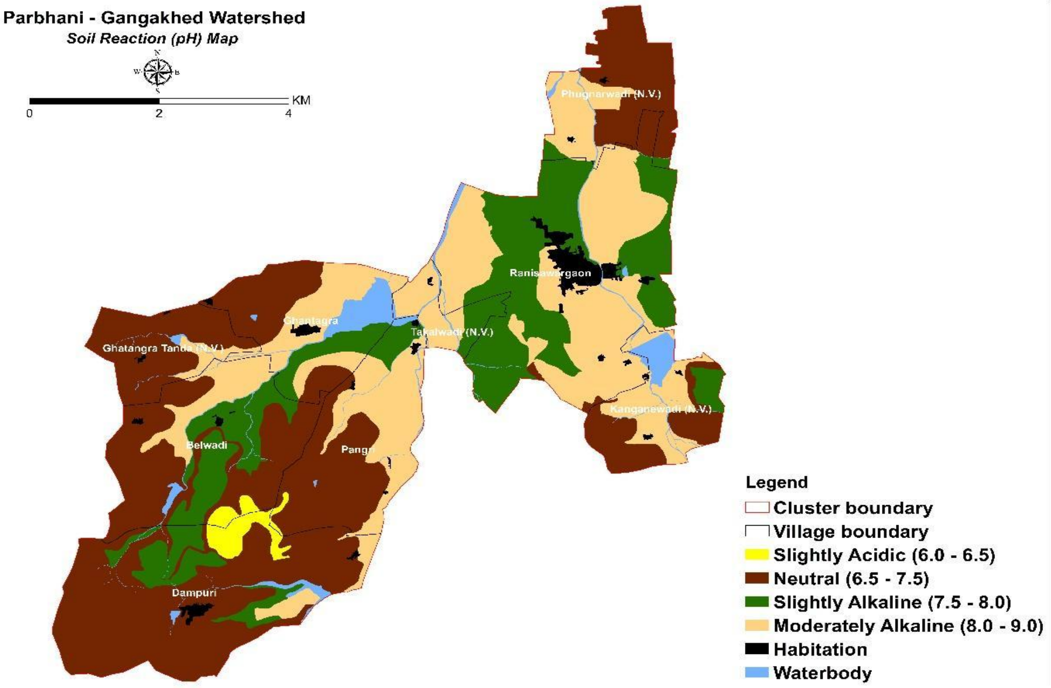


Fig. 4.9: Soil pH map of Gangakhed watershed

4.5.6 Soil salinity

Soil salinity, represented by electrical conductivity (EC), reflects the concentration of soluble salts present in the soil solution and is commonly used to assess the salinity condition of soils. It also provides an indication of whether the accumulation of salt ions may influence plant growth and crop productivity. The spatial distribution of EC in the watershed is illustrated in Fig. 4.10, while the extent of different salinity classes is presented in Table 4.15.

The results show that a major portion of the watershed is categorized under the normal salinity class (EC < 1 dS m^{-1}), covering 4581.7 ha, which constitutes 94.5% of the total geographical area. This suggests that the soils of the watershed are generally non-saline and suitable for agricultural activities. Overall, the EC status indicates favorable soil conditions for sustainable crop cultivation in the watershed.

Table 4.15. Soil salinity classes in Gangakhed watershed

Sr. No.	Electrical conductivity (dSm^{-1})	Area (ha)	TGA (%)
1	Normal (< 1)	4581.7	94.5
2	Habitation	94.5	1.9
3	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

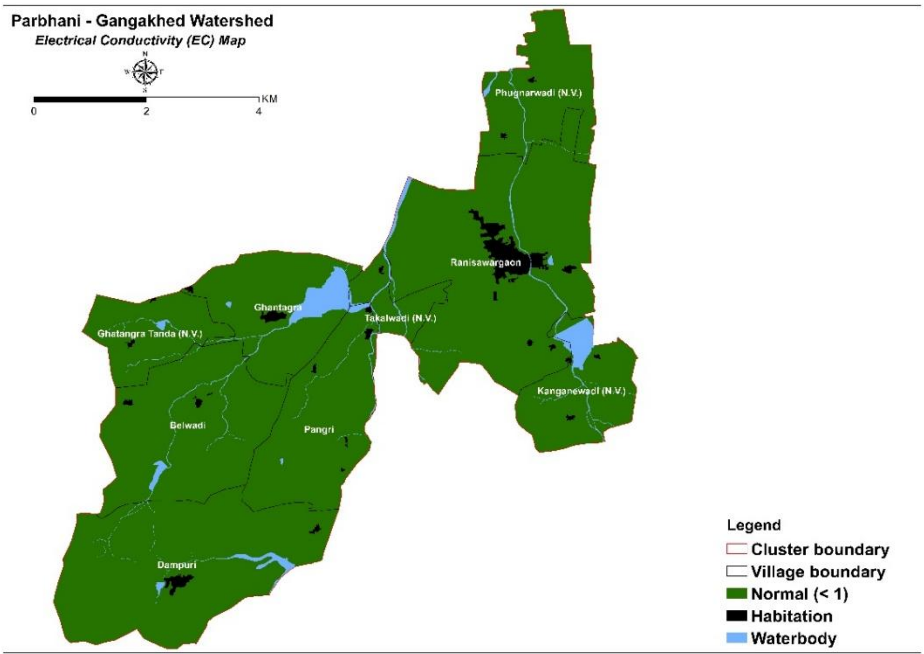


Fig. 4.10: Soil EC map of Gangakhed watershed

4.5.7 Calcium carbonate ($CaCO_3$) content

The distribution of calcium carbonate ($CaCO_3$) in the soils of the Parbhani-Gangakhed watershed is illustrated in Fig. 4.11 and detailed in Table 4.16. Calcium carbonate content plays a significant role in influencing soil reaction, nutrient dynamics, and overall soil productivity. The results reveal that soils with very high $CaCO_3$ content (>10%) dominate the watershed, covering 3598.2 ha, which accounts for 74.2% of the total geographical area. Areas with high $CaCO_3$ levels (5.0-10.0%) extend over 983.4 ha (20.3%). Overall, the findings indicate that a major portion of the watershed soils are strongly calcareous in nature.

Table 4.16 Status of soil calcareousness in Gangakhed watershed

Sr. No.	$CaCO_3$ content (%)	Area (ha)	TGA (%)
1	High (5.0 - 10.0)	983.4	20.3
2	Very High (> 10.0)	3598.2	74.2
3	Habitation	94.5	1.9
4	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

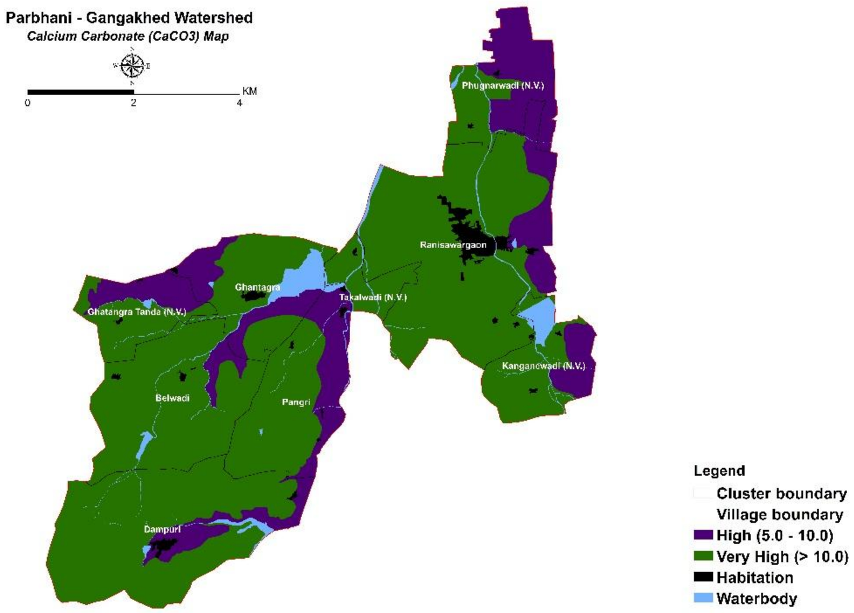


Fig. 4.11: Calcium Carbonate ($CaCO_3$) map of Gangakhed watershed

4.5.8 Soil organic carbon

Soil organic carbon (SOC) is an important indicator of soil quality and plays a key role in maintaining soil productivity and ecological balance. It originates mainly from the decomposition of plant residues, roots, and animal remains. SOC improves soil structure, enhances nutrient availability, increases water-holding capacity, and stimulates microbial activity. In addition, soils rich in organic carbon act as a storage pool for carbon, thereby helping to reduce atmospheric carbon dioxide and contributing to climate change mitigation. Hence, evaluating SOC levels is essential for sustainable soil and land management.

The distribution of SOC in the Parbhani-Gangakhed watershed is illustrated in Fig. 4.12 and summarized in Table 4.17. The analysis indicates that high SOC content (0.80-1.00%) covers the largest area of the watershed, extending over 2015.6 ha, which represents 41.6% of the total geographical area. This is followed by medium SOC (0.41-0.60%), occupying 1329.3 ha (27.4%). Soils with moderately high SOC (0.61-0.80%) account for 784.3 ha (16.2%), whereas very high SOC (>1.00%) occurs in 452.4 ha (9.3%) of the area. Overall, the watershed exhibits moderate to high organic carbon levels, indicating relatively favorable soil fertility conditions.

Table 4.17 Soil organic carbon status of Gangakhed watershed

Sr. No.	Organic carbon (%)	Area (ha)	TGA (%)
1	Medium (0.41 - 0.60)	1329.3	27.4
2	Moderately High (0.61 - 0.80)	784.3	16.2
3	High (0.80 - 1.00)	2015.6	41.6
4	Very High (> 1.00)	452.4	9.3
5	Habitation	94.5	1.9
6	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

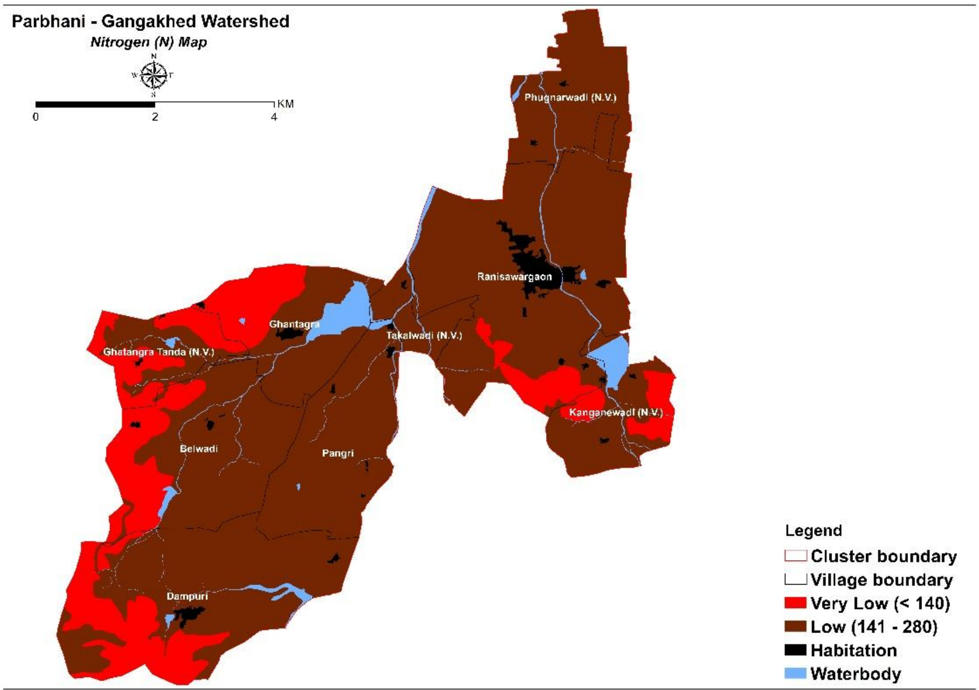


Fig. 4.12: Soil organic carbon map of Gangakhed watershed

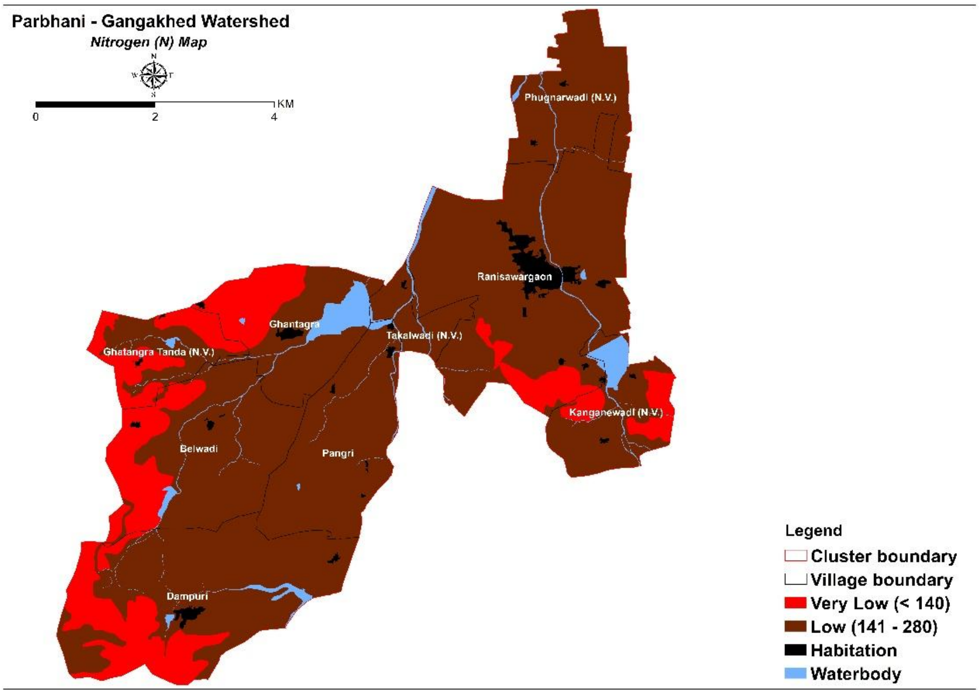
4.5.9 Available nitrogen (N)

Available nitrogen (N) is an essential nutrient required for proper plant growth and crop development. It plays a key role in the formation of proteins, amino acids, and chlorophyll, which are necessary for photosynthesis and plant metabolism. Therefore, evaluating the distribution of available nitrogen in soils helps in understanding soil fertility and planning suitable nutrient management strategies.

The spatial pattern of available nitrogen in the soils of the Parbhani-Gangakhed watershed is illustrated in Fig. 4.13 and summarized in Table 4.18. The findings indicate that very low nitrogen content (<140 kg ha^{-1}) is the dominant category in the watershed, covering 3725.2 ha, which represents 76.9% of the total geographical area. Areas with low nitrogen levels (141-280 kg ha^{-1}) extend over 856.5 ha (17.7%). Overall, the results suggest that a large portion of the watershed soils have inadequate nitrogen levels, highlighting the need for appropriate nutrient management to improve soil fertility and crop productivity.

Table 4.18: Available N content in soils of Gangakhed watershed

Sr. No.	Available N (kg ha^{-1})	Area (ha)	TGA (%)
1	Very Low (< 140)	3725.2	76.9
2	Low (141 - 280)	856.5	17.7
3	Habitation	94.5	1.9
4	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**



`Fig. 4.13: Available soil nitrogen map of Gangakhed watershed

4.5.10 Available Phosphorous (P)

Phosphorus (P) is an essential plant nutrient that plays a major role in root development, flowering, seed formation, and energy transfer within plants. It is involved in several biochemical processes, including photosynthesis and the transformation of energy through compounds such as ATP and ADP. Therefore, the availability of phosphorus in soil is an important factor influencing crop growth and soil fertility.

The spatial distribution of available phosphorus in the soils of the Parbhani-Gangakhed watershed is illustrated in Fig. 4.14 and summarized in Table 4.19. The results show that the low phosphorus category (16-30 kg ha^{-1}) covers the largest area, extending over 1398.9 ha (28.9%) of the watershed. This is followed by medium phosphorus levels (31-50 kg ha^{-1}) occupying 1001.0 ha (20.7%), and very low phosphorus (<15 kg ha^{-1}) covering 873.2 ha (18.0%). Areas with moderately high (12.0%), very high (11.7%), and high (3.3%) phosphorus levels are comparatively smaller. Overall, the distribution indicates considerable variation in phosphorus availability across the region.

Table 4.19: Available P content in soils of Gangakhed watershed

Sr. No.	Available P (kg ha^{-1})	Area (ha)	TGA (%)
1	Very Low (< 15)	873.2	18.0
2	Low (16 - 30)	1398.9	28.9
3	Medium (31 - 50)	1001.0	20.7
4	Moderately High (51 - 65)	579.9	12.0
5	High (66 - 80)	160.5	3.3
6	Very High (> 80)	568.1	11.7
7	Habitation	94.5	1.9
Total		**4846.9**	**100.0**

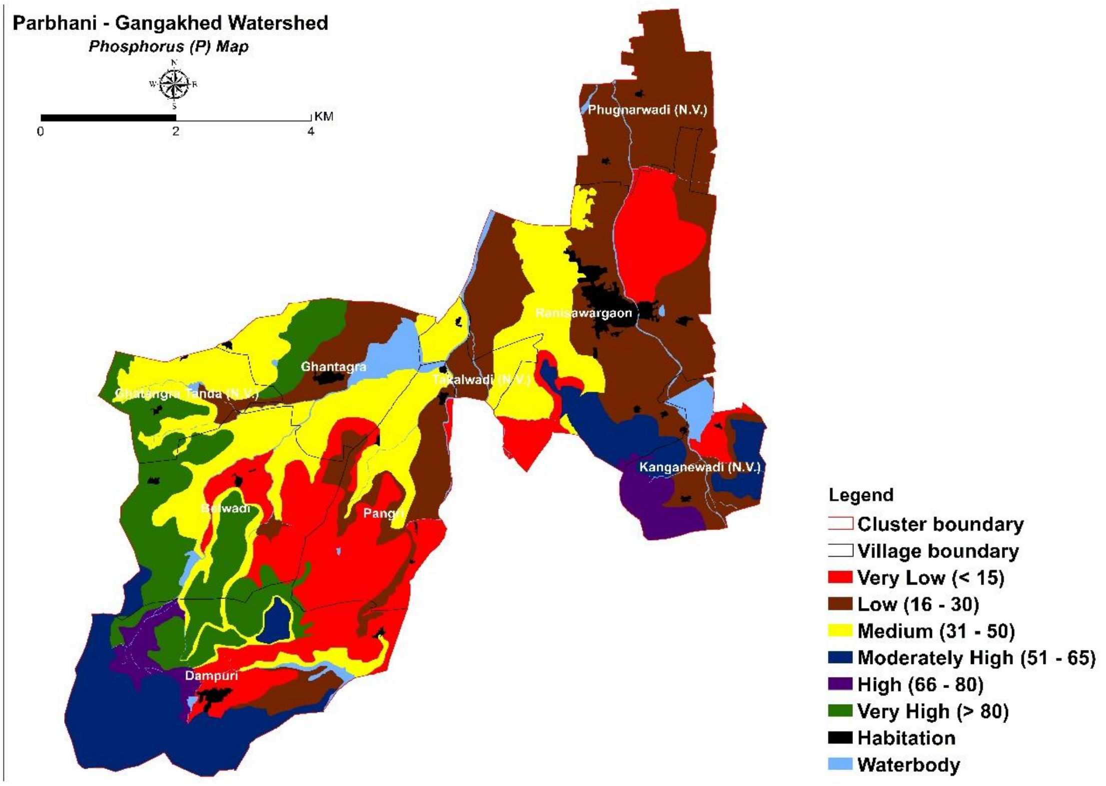


Fig.4.14: Available soil Phosphorus map of Gangakhed watershed

4.5.11 Available Potassium (K)

Potassium (K) is one of the essential nutrients required for proper plant growth and development. It plays an important role in regulating enzyme activity, improving water use efficiency, enhancing photosynthesis, and increasing plant tolerance to environmental stress. Hence, the level of available potassium in soil is widely used to assess soil fertility and crop nutrient requirements.

The spatial distribution of available potassium in the soils of the Parbhani-Gangakhed watershed is shown in Fig. 4.15 and summarized in Table 4.20. The results indicate that medium potassium content (181-240 kg ha^{-1}) occupies the largest area, covering 1870.4 ha, which accounts for 38.6% of the total geographical area. This is followed by low potassium levels (121-180 kg ha^{-1}) occupying 1142.1 ha (23.6%). Soils with very high potassium (>360 kg ha^{-1}) cover 695.1 ha (14.3%), while high (301-360 kg ha^{-1}) and moderately high (241–300 kg ha^{-1}) potassium classes account for 8.9% and 6.2%, respectively. Areas with very low potassium (<120 kg ha^{-1}) occupy 3.0%. Overall, potassium levels show considerable spatial variation across the region.

Table 4.20: Available K content of soils of Gangakhed watershed

Sr. No.	Available K (kg ha^{-1})	Area (ha)	TGA (%)
1	Very Low (< 120)	144.8	3.0
2	Low (121 - 180)	1142.1	23.6
3	Medium (181 - 240)	1870.4	38.6
4	Moderately High (241 - 300)	300.0	6.2
5	High (301 - 360)	429.4	8.9
6	Very High (> 360)	695.1	14.3
7	Habitation	94.5	1.9
8	Waterbody	170.8	3.5
	Total	4846.9	100.0

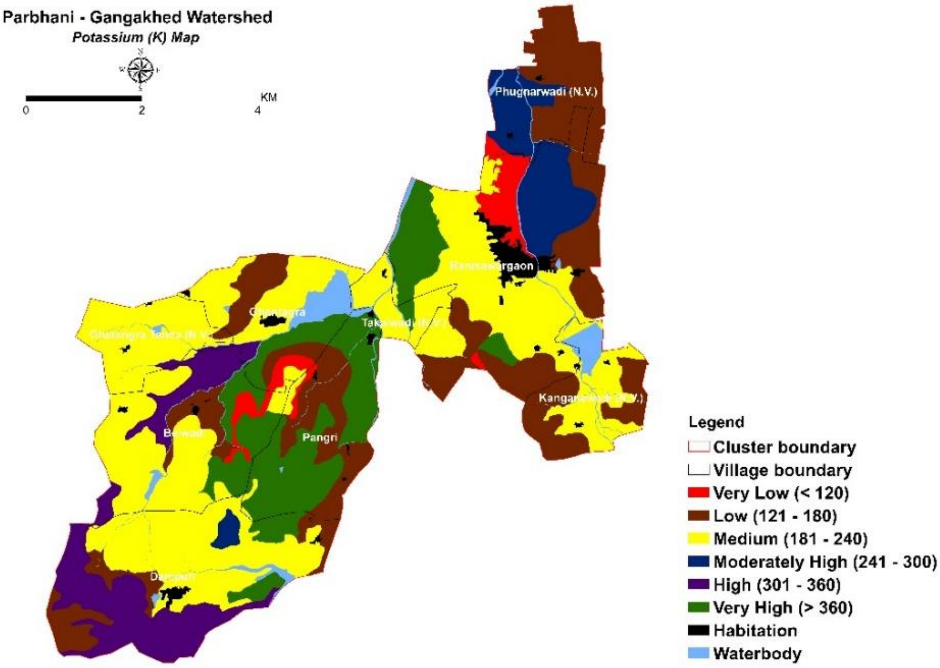


Fig. 4.15: Available soil Potassium map of Gangakhed watershed

4.5.12 Micronutrient status of soils

Micronutrients are required in small quantities but are essential for maintaining soil productivity and supporting plant growth. Elements such as iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn) play important roles in various physiological and biochemical processes including enzyme activity, photosynthesis, respiration, and nutrient metabolism. Therefore, evaluating their spatial distribution is necessary for effective nutrient management and balanced fertilization.

The distribution of available iron (Fe) in the Parbhani-Gangakhed watershed (Table 4.21; Fig. 4.16) indicates that very high Fe content (>10.5 mg kg^{-1}) dominates the region, covering 3931.8 ha, which represents 81.1% of the total geographical area. Areas with high (8.5-10.5 mg kg^{-1}) and moderately high (6.5-8.5 mg kg^{-1}) Fe levels account for 7.4% and 6.0% of the area, respectively, suggesting adequate iron availability in most soils. The spatial pattern of manganese (Mn) (Table 4.22; Fig. 4.17) shows that very high Mn content (>9.0 mg kg^{-1}) occupies 4397.3 ha (90.7%), while high Mn levels (7.0-9.0 mg kg^{-1}) occur in 184.4 ha (3.8%). Similarly, the distribution of copper (Cu) (Table 4.23; Fig. 4.18) reveals that almost the entire watershed has very high Cu content (>1.0 mg kg^{-1}), covering 4581.7 ha (94.5%), indicating sufficient copper availability in the soils. In contrast, zinc (Zn) availability (Table 4.24; Fig. 4.19) shows some variation. The medium Zn category (0.6-0.9 mg kg^{-1}) covers the largest area (53.5%), followed by moderately high Zn (22.1%) and low Zn (14.1%) classes. Smaller areas fall under high Zn (4.8%). Overall, the soils generally have adequate micronutrient levels, although zinc availability varies across the area.

Table 4.21: Available Fe content in the soils of Gangakhed watershed

Sr. No.	Available Fe (mg kg^{-1})	Area (ha)	TGA (%)
1	Moderately High (6.5 - 8.5)	289.3	6.0
2	High (8.5 - 10.5)	360.5	7.4
3	Very High (> 10.5)	3931.8	81.1
4	Habitation	94.5	1.9
5	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

Table 4.22: Available Mn content in the soils of Gangakhed watershed

Sr. No.	Available Mn (mg kg^{-1})	Area (ha)	TGA (%)
1	High (7.0 - 9.0)	184.4	3.8
2	Very High (> 9.0)	4397.3	90.7
3	Habitation	94.5	1.9
4	Waterbody	170.8	3.5
5	**Total**	**4846.9**	**100.0**

Table 4.23: Available Cu content in the soils of Gangakhed watershed

Sr. No.	Available Cu (mg kg^{-1})	Area (ha)	TGA (%)
1	Very High (> 1.0)	4581.7	94.5
2	Habitation	94.5	1.9
3	caWaterbody	170.8	3.5
	Total	**4846.9**	**100.0**

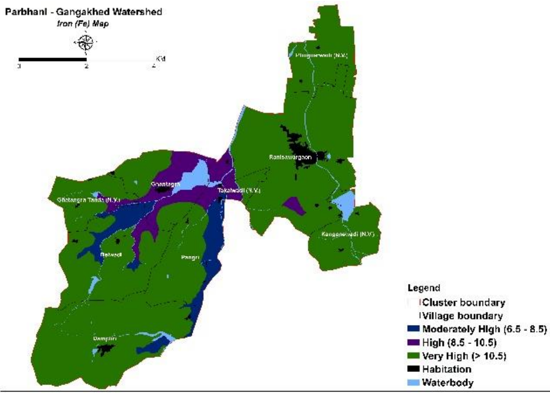


Fig. 4.16: DTPA-extractable soil Fe map of Gangakhed watershed

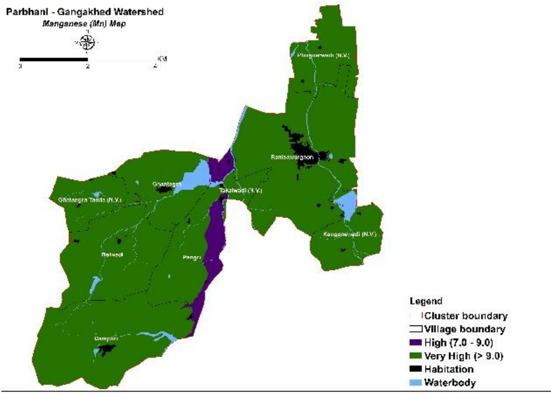


Fig. 4.17: DTPA-extractable soil Mn map of Gangakhed watershed

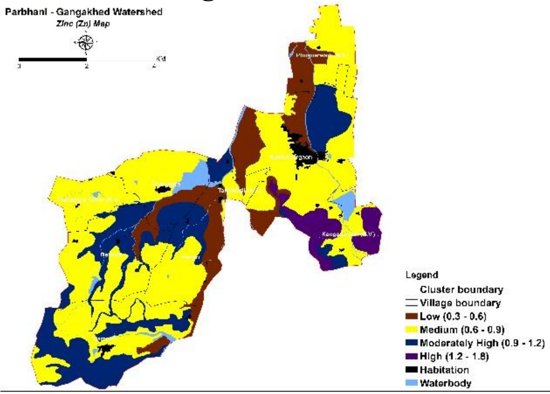


Fig. 4.18: DTPA-extractable soil Cu map of Gangakhed watershed

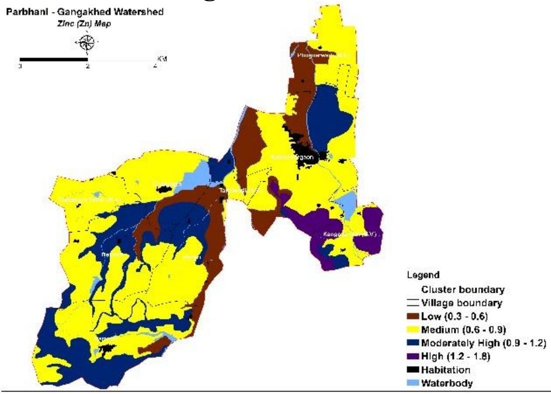


Fig. 4.19: DTPA-extractable soil Zn map of Gangakhed watershed

Table 4.24: Available Zn content in the soils of Gangakhed watershed

Sr. No.	Available Zn (mg kg^{-1})	Area (ha)	TGA (%)
1	Low (0.3 - 0.6)	684.5	14.1
2	Medium (0.6 - 0.9)	2593.2	53.5
3	Moderately High (0.9 - 1.2)	1072.2	22.1
4	High (1.2 - 1.8)	231.8	4.8
5	Habitation	94.5	1.9
6	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

4.6 Surface Runoff

Surface runoff is a key factor influencing water availability and watershed functioning in Gangakhed Taluka. The region receives an average annual rainfall of about 842 mm (2014-2024), yet the hydrological response across the landscape varies significantly due to differences in slope, land use and soil conditions. The nine study villages fall within mixed terrain-from river-adjacent low-lying plains to upper upland zones which results in varying runoff behaviour and water retention characteristics.

Field assessments indicate that water availability near valley regions and river-side settlements is comparatively better, owing to improved recharge and access to surface water. However, upland areas and hilly locations face persistent challenges such as limited infiltration, seasonal drying of water sources, loss of fertile topsoil, and rapid movement of rainwater due to insufficient bunding and slope control. These site-specific constraints highlighted the need for systematic runoff estimation to understand the scale of water lost as direct surface flow and to identify areas requiring priority intervention.

The runoff estimation study was carried out using the SCS-Curve Number (CN) method, utilizing actual rainfall records from 2014-2024 along with verified land use and soil characteristics. Rainfall data was compiled daily and analysed seasonally, and CN values were assigned after considering ground conditions informed by satellite interpretation and field verification. Based on these inputs, annual and seasonal runoff was computed for each monsoon period.

Surface runoff in the watershed exhibits clear seasonality and is closely linked to the timing and intensity of monsoon rainfall. Analysis of the monthly data for the period 2014-2024 (Table 4.25) indicates that July and September consistently generate the highest runoff, reflecting periods of concentrated rainfall and saturated soil conditions. Runoff during June is generally low, as early monsoon rains are absorbed by dry soils, while October runoff is minimal due to reduced rainfall and declining soil saturation. August runoff remains moderate across most years.

Table 4.25: Details of Monthly (June-Oct) runoff (mm) for the period 2014-2024

Year/Month	June		July		Aug		Sept		Oct	
	Rainfall (mm)	Runoff (mm)	Rainfall (mm)	Runoff (mm)	Rainfall (mm)	Runoff (mm)	Rainfall (mm)	Runoff (mm)	Rainfall (mm)	Runoff (mm)
2014	49.9	0.0	96.8	13.9	222.8	31.5	82.4	9.3	9.6	0.0
2015	72.4	0.0	34.7	0.0	75.7	0.0	116.5	0.0	9.1	0.0
2016	202.2	15.6	228.7	32.2	87.9	8.2	407.4	149.6	138.1	75.5
2017	231.3	64.3	41.5	0.0	283.4	76.3	117.5	12.2	160.8	65.0
2018	203.7	30.5	67.3	0.7	257.9	53.2	72.5	8.4	0.3	0.0
2019	124.5	0.6	113.8	18.4	224.6	64.2	285.5	49.6	270.6	106.1
2020	228.7	23.3	216.9	20.0	165.4	15.7	223.1	58.3	54.9	0.7
2021	249.7	64.0	228.5	42.4	128.7	7.1	331.2	132.7	119.0	19.0
2022	259.1	63.3	368.8	155.9	39.3	0.0	206.1	45.8	92.2	1.6
2023	85.0	4.0	249.0	22.1	48.8	0.0	156.0	8.7	7.3	0.0
2024	126.3	7.9	419.1	162.6	171.8	16.8	260.2	102.7	35.0	0.2
Average	**166.6**	**24.9**	**187.7**	**42.6**	**155.1**	**24.8**	**205.3**	**52.5**	**81.5**	**24.4**

Year-to-year variations, as summarized in Table 26, show significant fluctuations in total runoff depending on annual rainfall and rainfall distribution. Deficit rainfall years, such as 2015 and 2023, experienced negligible runoff, whereas high-intensity rainfall years, including 2016, 2021, 2022, and 2024, produced substantial runoff. This demonstrates the watershed’s high sensitivity to rainfall intensity and distribution patterns.

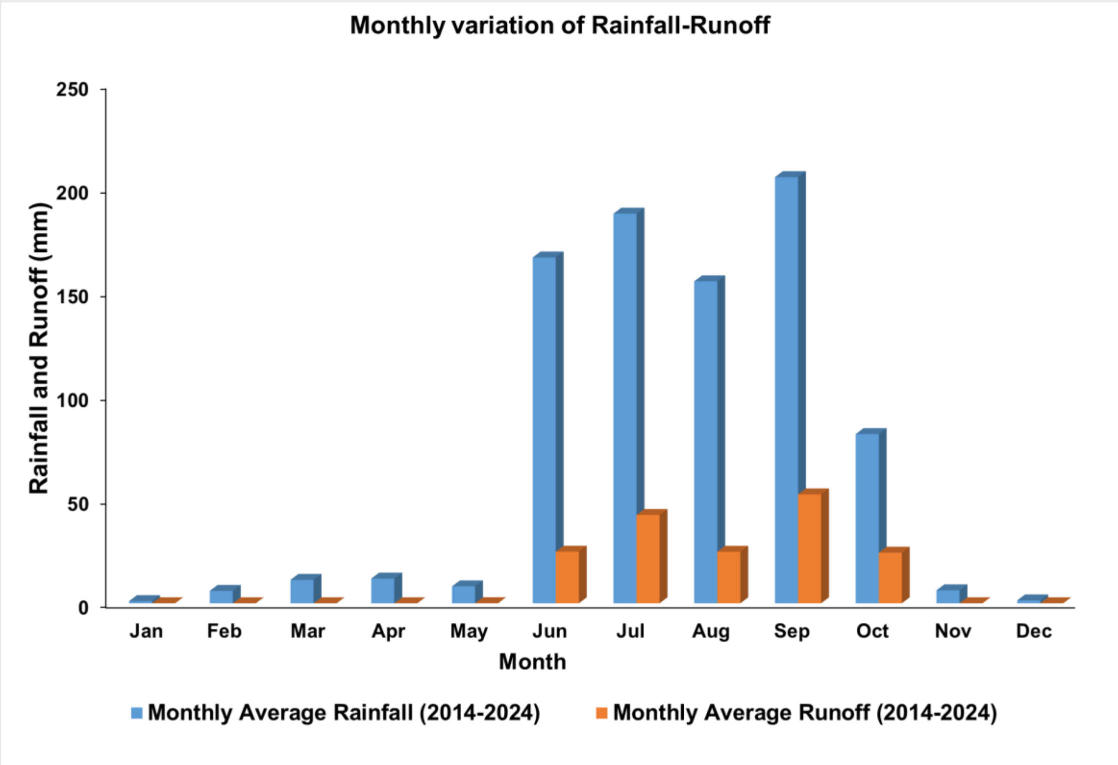


Fig. 4.20: Monthly variation of rainfall-runoff

Table 4.26 Relationship between Rainfall and Runoff Gangakhed watershed

Year	Rainfall (mm)	Runoff (mm)	No. of Runoff Events	Runoff (%)
2014	573.3	54.7	7	9.5
2015	389.5	0.0	0	0.0
2016	1116.2	281.0	25	25.2
2017	836.0	217.8	16	26.0
2018	642.8	92.6	15	14.4
2019	1041.3	238.9	19	22.9
2020	912.2	117.9	21	12.9
2021	1122.1	265.2	25	23.6
2022	965.5	266.6	22	27.6
2023	649.0	35.1	12	5.4
2024	1017.6	290.2	18	28.5
Average	**842.3**	**169.1**	**16**	**20.1**

The study indicates that, on average, 20.1% of the total annual rainfall is lost as surface runoff, with the remainder infiltrating into the soil, being used by crops, or lost through evaporation. Runoff is highly seasonal, with approximately 56% of the total annual runoff occurring during July and September, when soils are saturated and rainfall intensity is at its peak. Early monsoon rainfall in June is mostly absorbed by dry soils, while runoff in October is minimal due to reduced rainfall and lower soil saturation.

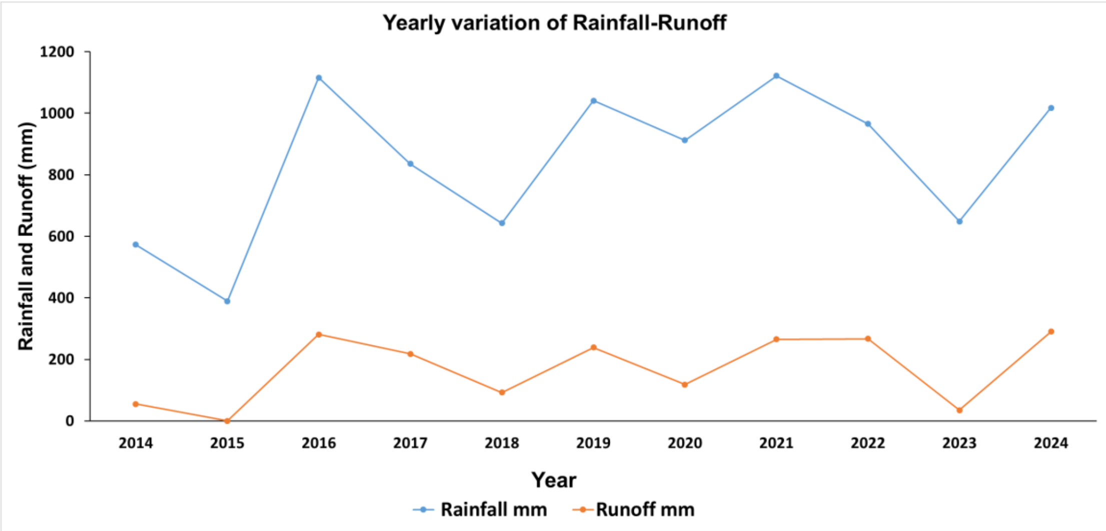


Fig. 4.21: Yearly variation of rainfall-runoff in Gangakhed watershed

4.7 Mapping of Groundwater Potential Zones

Groundwater is a crucial source of water supply in Gangakhed Taluka, sustaining domestic needs, drinking water requirements, and agricultural irrigation. In upland and non-command areas, where surface water is either scarce or unreliable, dependence on groundwater is particularly high. The region receiving an average annual rainfall of 842.3 mm, which is relatively low, the recharge of groundwater remains insufficient to meet the overall demand. The limited rainfall, coupled with variations in soil types, landforms, and the complex hydrogeological framework, results in uneven distribution of groundwater across the study area. Certain areas, particularly those with steep slopes, rocky outcrops, and shallow soils, experience minimal recharge, while other low-lying and gently undulating terrains have moderate potential for water storage. This uneven availability presents significant challenges for sustainable water management and highlights the need for a detailed spatial understanding of groundwater potential.

In response to these challenges, a comprehensive assessment was undertaken to delineate groundwater potential zones for the nine-village cluster watershed of Gangakhed Taluka. The study adopted a multi-criteria spatial analysis approach, integrating eight key thematic layers that influence groundwater occurrence and movement: lithology, land use and land cover (LULC), drainage density, soil type, slope, elevation, landform, and rainfall distribution. Each of these parameters plays a significant role in determining the capacity of the terrain to store and transmit groundwater. Lithology controls the subsurface porosity and permeability, while soil type influences infiltration and runoff characteristics. Similarly, slope and drainage patterns dictate the flow of surface water, impacting the areas that are more favorable for recharge. Landforms and elevation contribute to natural water retention zones, and rainfall, although low, is a critical factor in replenishing shallow aquifers. Integrating all these factors provides a robust framework for assessing groundwater potential in a systematic and scientific manner.

The analysis was carried out using a weighted overlay technique within a Geographic Information System (GIS) environment. Each thematic layer was assigned a weight according to its relative influence on groundwater potential, determined through the Analytical Hierarchy Process (AHP). This method was supported by expert consultation and a review of relevant scientific literature to ensure that the assigned weights realistically reflected local hydrogeological conditions. Data for the layers were sourced from remote sensing imagery, field surveys, and secondary datasets from government and research publications. Each layer was standardized and classified into sub-categories, which allowed the study to capture subtle variations in recharge potential across the watershed. By combining these weighted layers, a detailed Groundwater Potential Zonation (GWPZ) map was developed, categorizing the landscape into five classes: Very Good, Good, Moderate, Poor, and Very Poor.

The final map provides clear spatial insights into groundwater distribution. Approximately 19.3% of the watershed is classified as "Very Poor," representing areas with steep terrain, and shallow soil cover, where natural recharge is highly limited. Around 24.7% of the area falls under the "Poor" category, typically characterized by high runoff and low infiltration. An additional 23%, is identified as "Moderate" potential, reflecting gently undulating terrains that allow moderate recharge of shallow aquifers. Areas with "Good" and "Very Good" potential together cover approx. 33% of the watershed, indicating that high-yield groundwater zones are limited. These findings highlight that the majority of the taluka, approximately 67%, requires careful management interventions to sustain groundwater resources and meet future water demands.

The delineation of groundwater potential zones has significant implications for planning and implementing water resource management strategies in Gangakhed Taluka village cluster watershed. The map serves as a scientific basis for designing groundwater recharge structures, promoting soil and moisture conservation, and implementing land treatment measures, especially under programs like the Pradhan Mantri Krishi Sinchayee Yojana - Watershed Development Component 2.0 (PMKSY-WDC 2.0). By identifying priority micro-watersheds with poor groundwater potential, interventions can be focused where they are most needed, ensuring optimal utilization of resources. Conversely, areas identified with good to very good potential can be prioritized for sustainable groundwater extraction and irrigation planning. The integration of these spatial insights into watershed management ensures that both surface and groundwater resources are effectively harnessed, minimizing water scarcity risks for domestic, agricultural, and ecological needs.

The low rainfall of the region, combined with its varied terrain and complex hydrogeology, makes sustainable groundwater management particularly challenging. Therefore, an integrated approach, combining scientific mapping, field validation, and strategic interventions, is essential. Enhancing recharge in moderate and poor potential zones through, percolation tanks, farm ponds, and contour bunding can improve groundwater availability and help stabilize water supply in critical areas. Furthermore, protection of recharge zones from encroachment and over-extraction, along with careful monitoring of groundwater levels, can ensure the long-term sustainability of aquifers. The insights derived from the GWPZ mapping not only guide immediate water management decisions but also contribute to long-term planning for climate resilience and food security in Gangakhed Taluka village cluster watershed.

In conclusion, the Groundwater Potential Zonation provides a detailed understanding of the spatial distribution of groundwater resources, emphasizing areas of scarcity and zones suitable for sustainable exploitation. While high-yield groundwater areas are limited, strategic management and targeted interventions can improve recharge, optimize groundwater utilization, and enhance water security across the area. This comprehensive assessment forms the foundation for evidence-based decision-making, ensuring that groundwater resources continue to support domestic, agricultural, and ecological needs in Gangakhed Taluka for years to come.

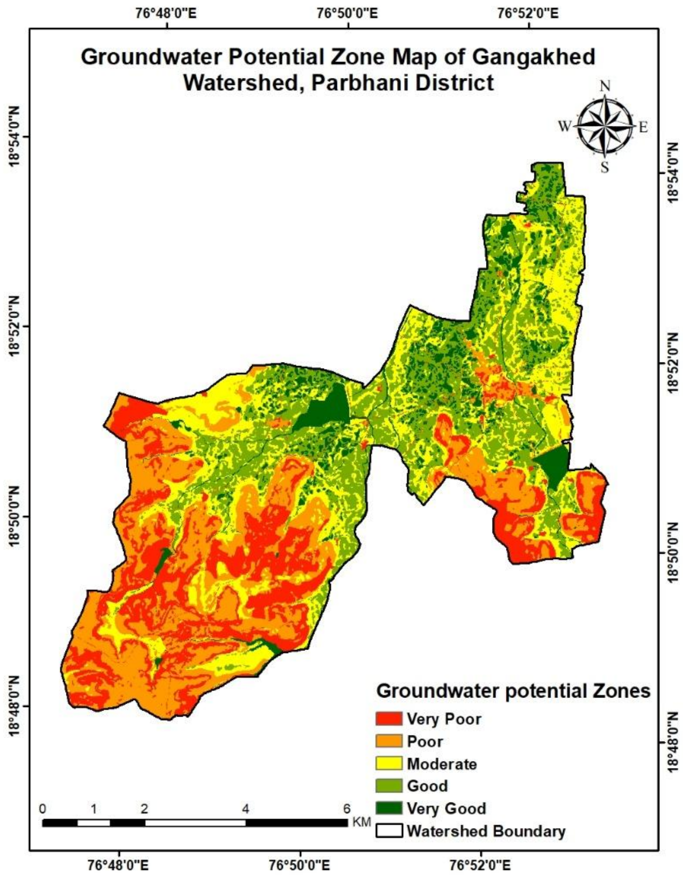


Fig. 4.22. Ground water potential zones in Gangakhed watershed

4.8 Evaluation of Soil-Site Suitability for Crops

Soil and climate are the prime factors governing optimum crop growth. Soil physicochemical properties and crop micro-environment control the availability of water and essential plant nutrients. Therefore, key soil attributes, *viz.* soil depth, texture, fertility status and drainage conditions are carefully assessed during soil-site evaluation. This enables meaningful interpretation of soil maps in terms of their suitability for field and horticultural crops and contributes to the formulation of scientific land-use plans for watershed development.

The suitability of soils for crop cultivation was determined based on the criteria proposed by Naidu et al. (2006). The concept of land utilization types and the classification system for land evaluation categorizes land into different hierarchical levels, namely orders, classes, sub-classes, and units. Two major orders are recognized: 'S' (Suitable) and 'N' (Not suitable), representing the general suitability status of land. Under the suitable order (S), three classes S1, S2, and S3 indicate high, moderate, and marginal suitability, respectively, while the not suitable order (N) includes two classes N1 and N2 representing current and permanent unsuitability. The assignment of these classes is based on the degree of land limitations affecting crop production.

The major land limitations considered in this evaluation exercise include those imposed by climate (c), topography (t), wetness (w), soil fertility (f), and physical soil constraints (s). These limitations were graded on a scale from 0 to 4, where 0 indicates no limitation and optimal conditions for crop growth; 1 denotes slight limitation with nearly optimal conditions; 2 indicates moderate limitation with noticeable effects on crop performance; 3 represents severe limitation rendering the land uneconomical for the proposed use; and 4 reflects very severe limitation, where crop yields fall below economically viable levels, making the land unsuitable for the intended use.

Several soil-site parameters, including climatic variables (rainfall, temperature); topographic features (slope, landscape position, and erosion susceptibility); wetness conditions (drainage, flooding risk and soil aeration); physical soil properties (texture, depth, structure and available soil moisture); fertility attributes (soil pH, nutrient availability, organic matter content, cation exchange capacity, base saturation) and groundwater table were examined to determine land suitability for agricultural crops and other land uses. Based on the integration of these parameters, the watershed area was evaluated for its suitability for the following commonly cultivated and potential-for-introduction crops.

4.8.1 Soil-Site Suitability for Cotton Cultivation

The soil-site evaluation for cotton cultivation shows areas categorized as highly suitable (S1) cover 474.7 ha, accounting for about 9.8% of the total geographical area, indicating favorable soil and site conditions for achieving good crop performance. 128.9 ha (2.7%) of the total geographical area is classified as moderately suitable (S2), these areas provide acceptable conditions for cotton cultivation, though certain soil and site constraints may affect crop performance.

A large portion of the watershed, covering 2279.4 ha (47.0%), falls under the marginally suitable (S3) category (Table 4.27, Fig. 4.23), indicating the presence of moderate limitations that may restrict yield potential. Around 1698.6 ha (35.0%) of the area is categorized as not suitable (N) for cotton cultivation due to severe soil and site-related constraints. Overall, the assessment indicates that major portion of the watershed is moderately suitable for cotton cultivation.

Table 4.27 Area under suitability sub-classes for Cotton cultivation

Sr. No.	Suitability class	Area (ha)	Percent (%)
1	Highly Suitable (S1)	474.7	9.8
2	Moderately Suitable (S2)	128.9	2.7
3	Marginally Suitable (S3)	2279.4	47.0
4	Not Suitable (N)	1698.6	35.0
5	Habitation	94.5	1.9
6	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

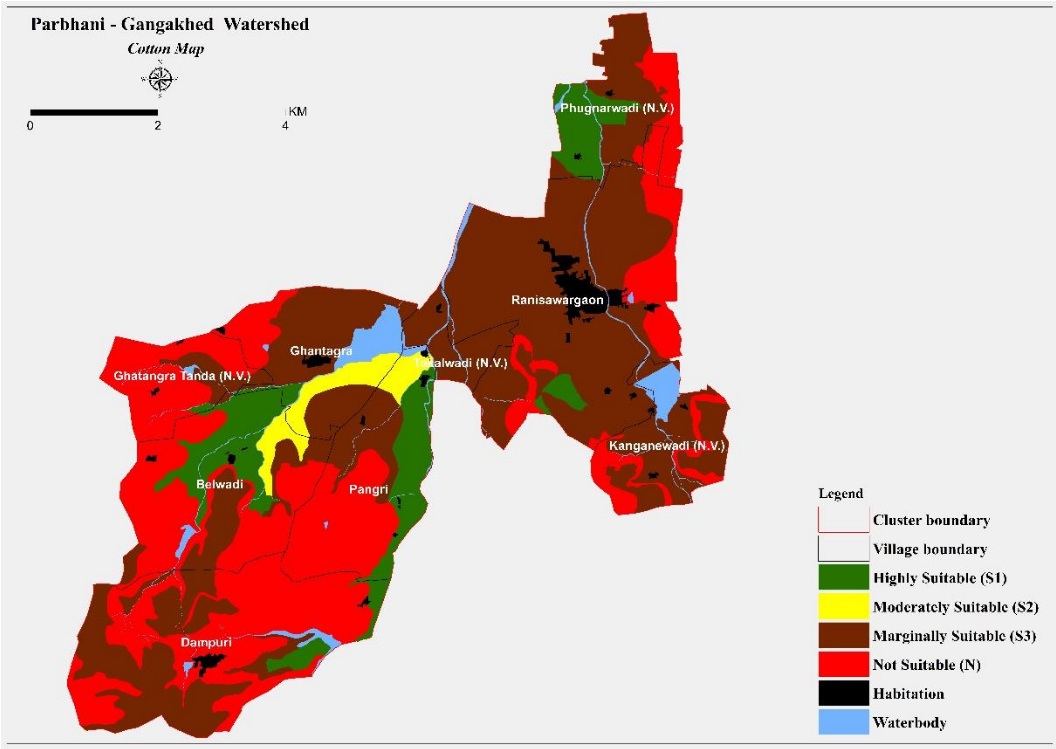


Fig. 4.23 Soil site suitability map for Cotton cultivation

4.8.2 Soil-Site Suitability for Soybean Cultivation

Soil-site evaluation results for soybeans show a varied distribution of suitability classes across the watershed (Table 4.28, Fig. 4.24). Areas categorized as moderately suitable (S2) class is covering area 1566.2 ha (32.3%), representing zones where soybean cultivation is feasible, although certain soil or site constraints may influence yield levels. 2205.2 ha (45.5%) of the watershed area is occupied under the marginally suitable (S3) category, suggesting the presence of noticeable limitations that may restrict optimum crop growth. About 16.7% of the watershed is not suitable (N) for soybean cultivation. These results most favorable for soybean cultivation in the watershed by following recommended package of practices.

Table 4.28 Area under suitability sub-classes for Soybean cultivation

Sr. No.	Suitability class	Area (ha)	Percent (%)
1	Moderately Suitable (S2)	1566.2	32.3
2	Marginally Suitable (S3)	2205.2	45.5
3	Not Suitable (N)	810.2	16.7
4	Habitation	94.5	1.9
5	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

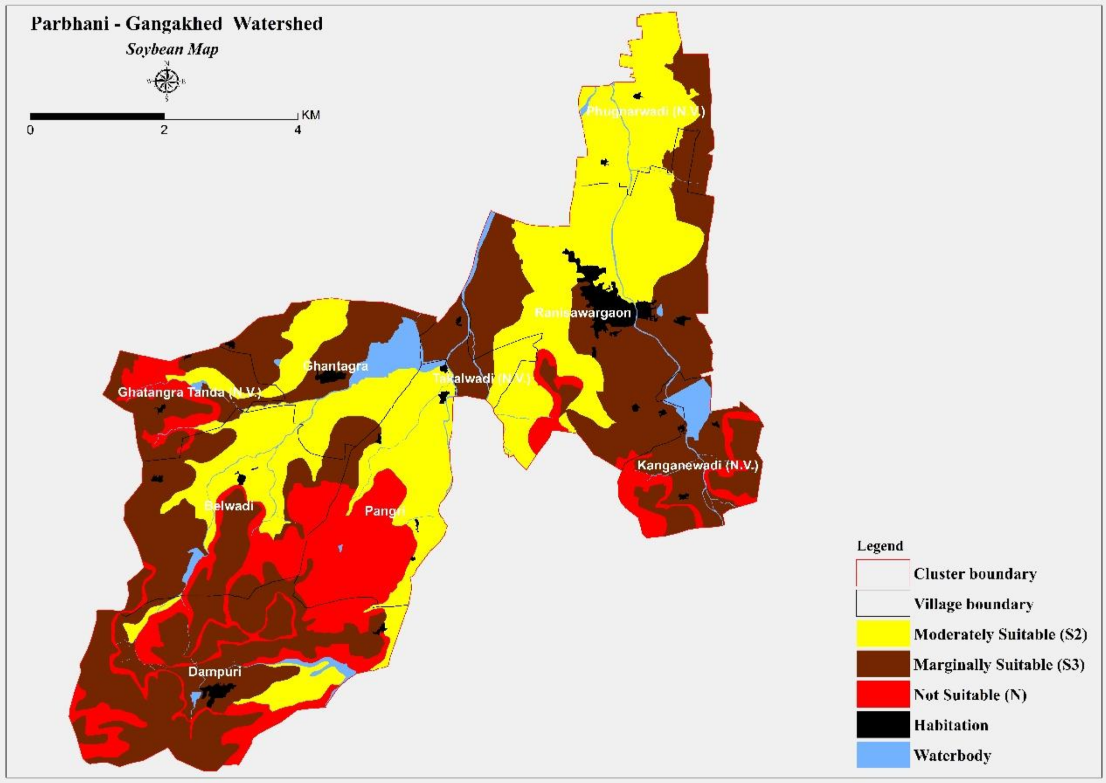


Fig. 4.24 Soil site suitability map for Soybean cultivation

4.8.3 Soil-Site Suitability for Groundnut Cultivation

1566.2 ha (32.3%) of the watershed area is moderately suitable (S2), and another 2205.2 ha (45.5%) is marginally suitable(S3) for Groundnut cultivation. While the former class represents areas with more acceptable conditions for crop growth, the latter would permit cultivation after following recommended conservation or ameliorative measures. About 16.7% of the watersheds was identified as not suitable (N) for Groundnut cultivation due to severe soil and site limitations (Table 4.29, Fig. 4.25). These results marginally to moderately suitable for groundnut cultivation in the watershed by following recommended package of practices.

Table 4.29 Area under suitability sub-classes for Groundnut cultivation

Sr. No.	Suitability class	Area (ha)	Percent (%)
1	Moderately Suitable (S2)	1566.2	32.3
2	Marginally Suitable (S3)	2205.2	45.5
3	Not Suitable (N)	810.2	16.7
4	Habitation	94.5	1.9
5	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

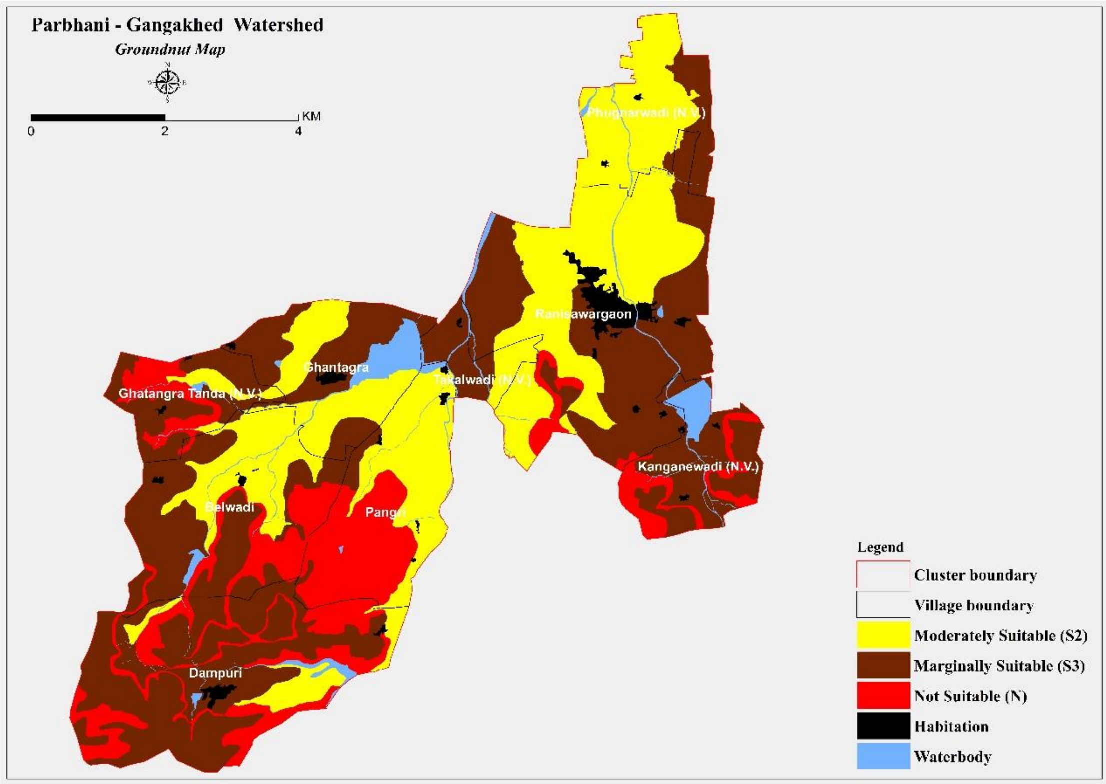


Fig. 4.25 Soil site suitability map for Groundnut cultivation

4.8.4 Soil-Site Suitability for Sorghum (Jowar) Cultivation

The soils of the watershed were evaluated for sorghum cultivation based on crop-specific requirements. The distribution of suitability classes is presented in Table 4.30, Fig.4.26. The results indicate that about 603.6 ha (12.5%) of the watershed area provides favorable soil and site conditions for optimal crop growth and is highly suitable (S1) for sorghum. The moderately suitable (S2) category covers 962.6 ha (19.9%), wherein minor soil and environmental constraints may reduce crop productivity. Around 45.5% of the watershed was found to be marginally suitable (S3) for the crop, reflecting moderate to severe limitations related to soil and terrain parameters that may restrict yield potential unless appropriate agronomic management practices are adopted. 16.7% of the watershed area is not suitable (N) for sorghum cultivation due to severe soil and site constraints.

Table 4.30 Area under suitability sub-classes for Sorghum (Jowar) cultivation

Sr. No.	Suitability class	Area (ha)	Percent (%)
1	Highly Suitable (S1)	603.6	12.5
2	Moderately Suitable (S2)	962.6	19.9
3	Marginally Suitable (S3)	2205.2	45.5
4	Not Suitable (N)	810.2	16.7
5	Habitation	94.5	1.9
6	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

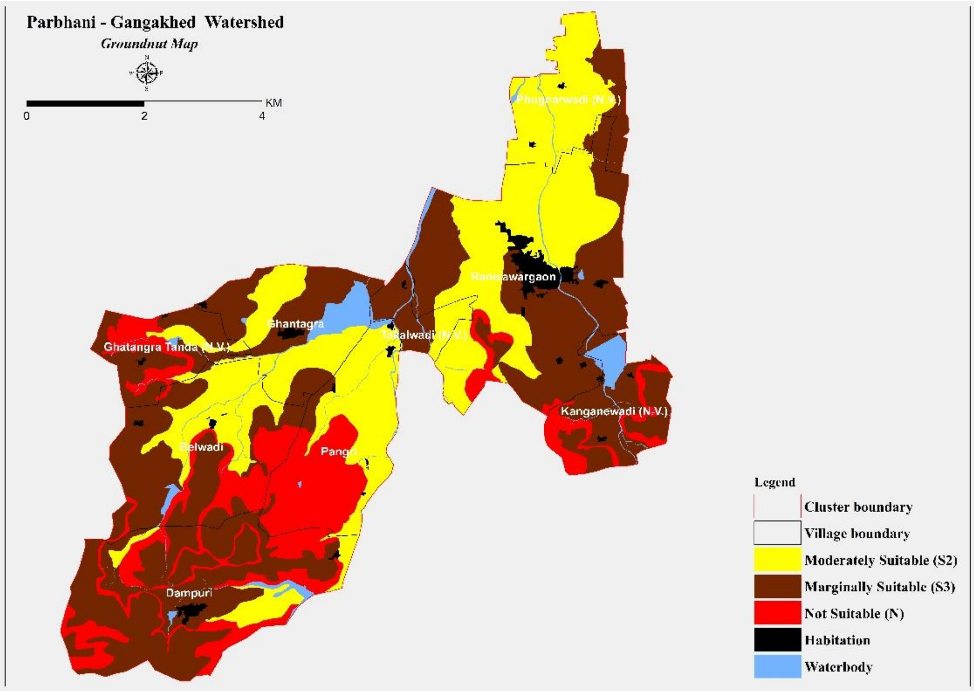


Fig. 4.26 Soil site suitability map for Sorghum (Jowar) cultivation

4.8.5 Soil-Site Suitability for Onion Cultivation

The suitability assessment for onion cultivation across the watershed reveals a broad range of suitability classes (Table 4.31, Fig. 4.27). Areas covering 2919.5 ha (60.2%) and 2919.5 ha (34.3%) have been classified under moderately suitable (S2) and marginally suitable (S3) categories, respectively. Overall report indicated that watershed area is marginally to moderate suitable for onion cultivation.

Table 4.31 Area under suitability sub-classes for Onion cultivation

Sr. No.	Suitability class	Area (ha)	Percent (%)
1	Moderately Suitable (S2)	2919.5	60.2
2	Marginally Suitable (S3)	2919.5	34.3
3	Habitation	94.5	1.9
4	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

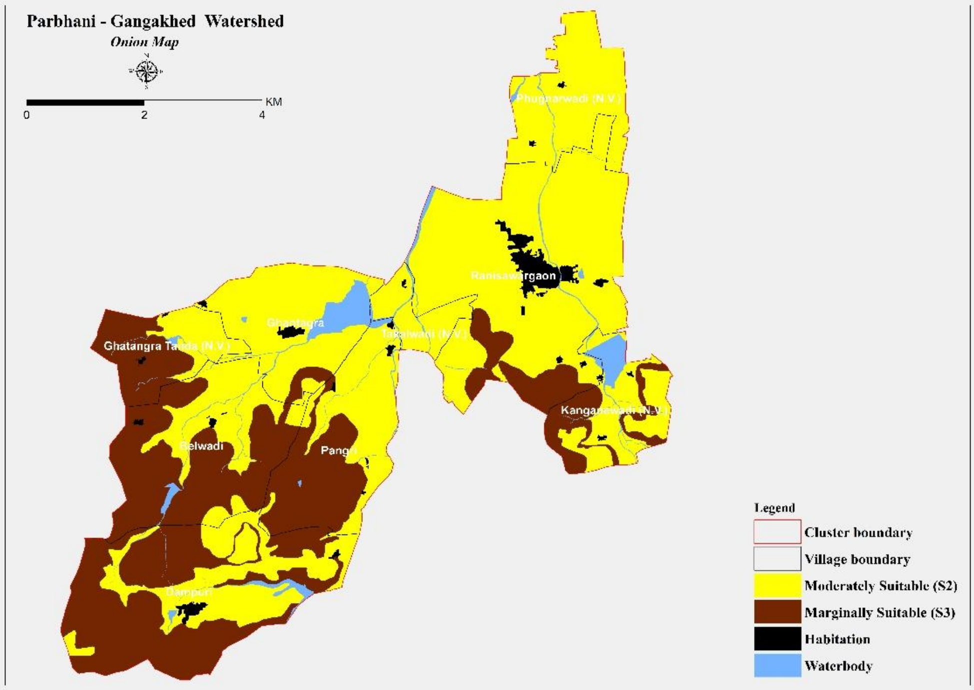


Fig. 4.27 Soil site suitability map for Onion cultivation

4.8.6 Soil-Site Suitability for Chickpea Cultivation

1566.2 ha (32.3%) of the watershed area were categorized under moderately (S2) suitable, respectively, for Chickpea cultivation, whereas 2205.2 ha (45.5%) of area was found to be marginally suitable (S3), reflecting moderate to severe constraints primarily associated with soil and environmental factors, which may restrict yield potential without appropriate management practices. Only 16.7% area of watershed is not suitable(N) for Chickpea. Chickpea is recommended for cultivation in major portion of the watershed (Table 4.32, Fig. 4.28).

Table 4.32 Area under suitability sub-classes for Chickpea cultivation

Sr. No.	Suitability class	Area (ha)	Percent (%)
1	Moderately Suitable (S2)	1566.2	32.3
2	Marginally Suitable (S3)	2205.2	45.5
3	Not Suitable (N)	810.2	16.7
4	Habitation	94.5	1.9
5	Waterbody	170.8	3.5
Total		**Total**	**4846.9**

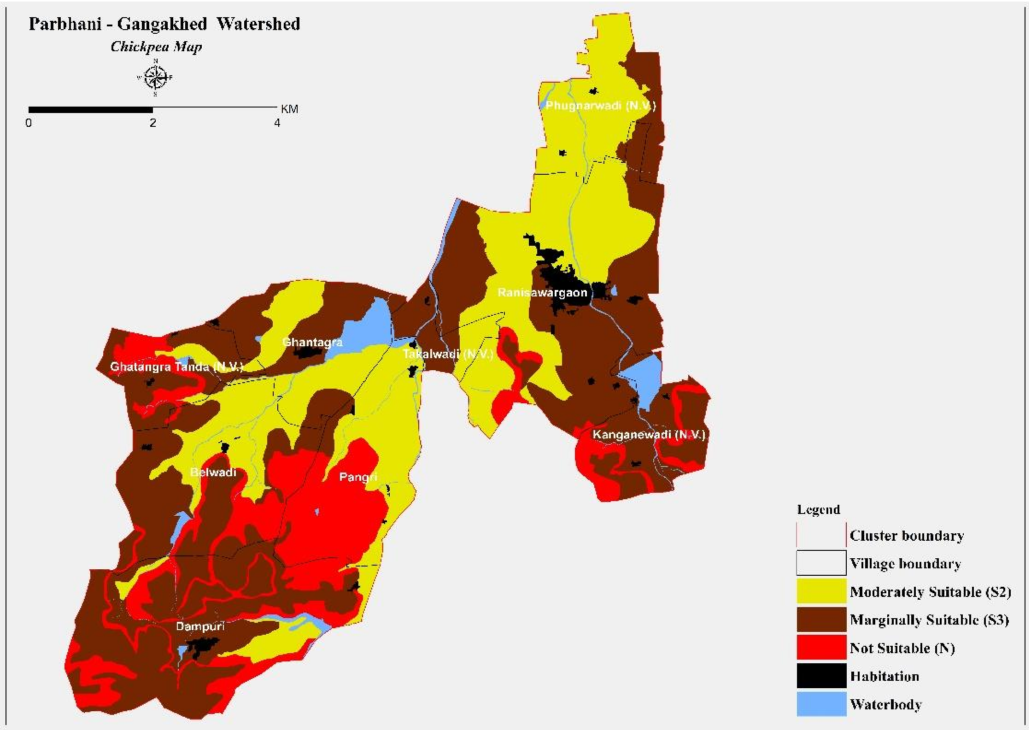


Fig. 4.28 Soil site suitability map for Chickpea cultivation

4.8.7 Soil-Site Suitability for Sugarcane Cultivation

The soil-site suitability analysis for sugarcane cultivation reveals a wide variation in land capability across the watershed. Area 603.6 ha (12.5%) of the watershed area is moderately suitable for sugarcane (Table 4.33, Fig. 4.29). These areas represent zones where sugarcane cultivation can be practiced with moderate limitations. Another 962.6 ha (19.9%) of the area is marginally suitable (S3), indicating the presence of noticeable constraints that may affect crop establishment and productivity. In contrast, a primarily share of the watershed, accounting for 62.2% cannot be put under sugarcane due to severe soil and site limitations.

Table 4.33 Area under suitability sub-classes for Sugarcane cultivation

Sr.No	**Suitability class**	**Area (ha)**	**Area (%)**
1	Moderately Suitable (S2)	603.6	12.5
2	Marginally Suitable (S3)	962.6	19.9
3	Not Suitable (N)	3015.4	62.2
4	Habitation	94.5	1.9
5	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

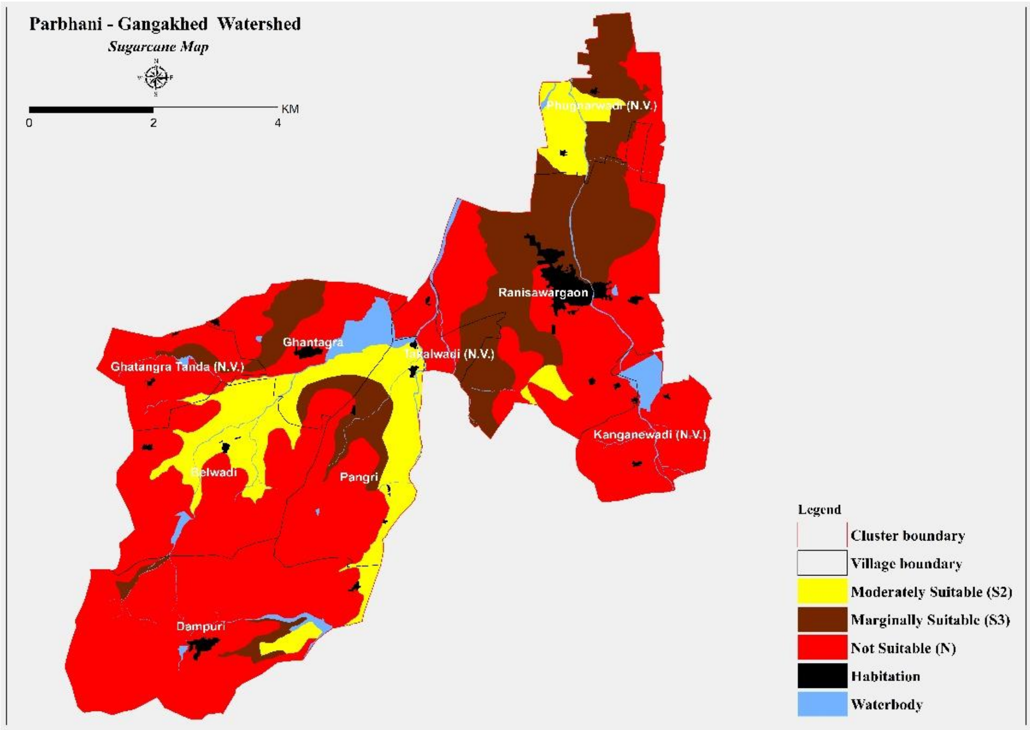


Fig. 4.29 Soil site suitability map for Sugarcane cultivation

4.8.8 Soil-Site Suitability for Black Gram (Urad) Cultivation

The soil-site suitability analysis for black gram cultivation reveals a wide variation in land capability across the watershed. Areas identified as moderately suitable (S2) extend over 1566.2 ha, constituting 32.3% of the total geographical area, indicating with manageable limitations for crop establishment and growth. Around 2205.2 ha (45.5%) area of the watershed is categorized as marginally suitable (S3), indicating the presence of noticeable constraints that may affect crop establishment and productivity. Only 16.7% area of watershed is not suitable(N) for black gram. Black Gram is recommended for cultivation in major portion of the watershed (Table 4.34, Fig. 4.30).

Table 4.34 Area under suitability sub-classes for Black Gram (Urad) cultivation

Sr.No	Suitability class	Area (ha)	Area (%)
1	Moderately Suitable (S2)	1566.2	32.3
2	Marginally Suitable (S3)	2205.2	45.5
3	Not Suitable (N)	810.2	16.7
4	Habitation	94.5	1.9
5	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

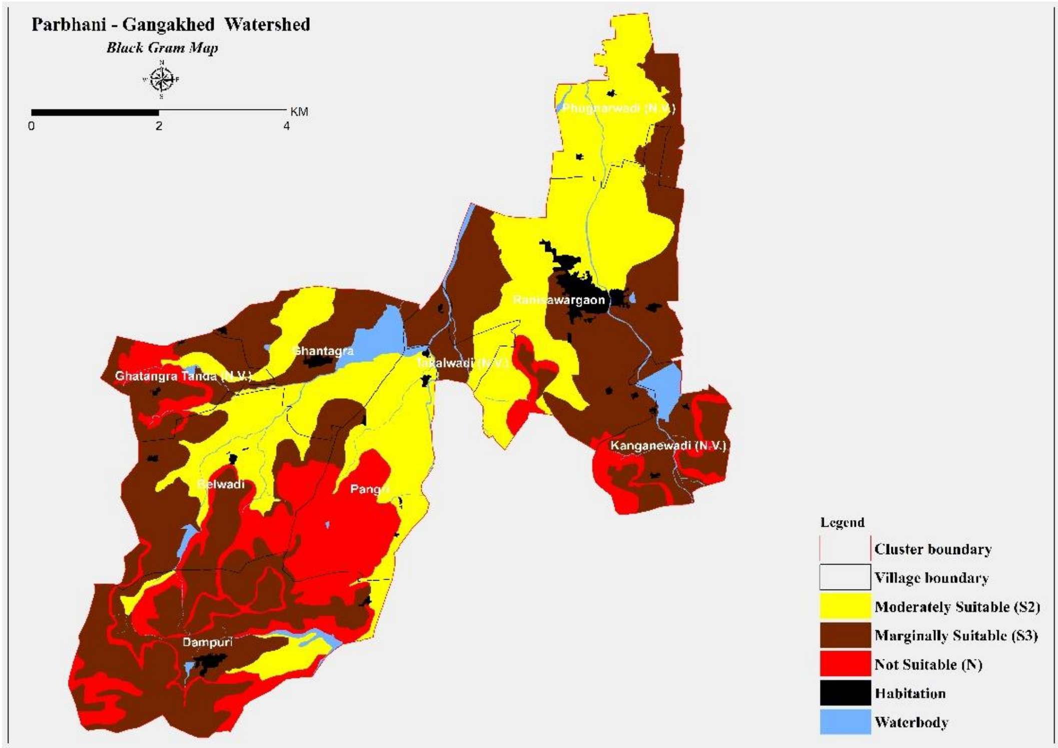


Fig. 4.30 Soil site suitability map for Black Gram cultivation

4.8.9 Soil-Site Suitability for Green Gram Cultivation

A larger proportion of the watershed, 1566.2 ha (32.3%), is categorized as moderate suitable (S2), wherein crop yields would be manageable limitations, as these areas provide relatively stable conditions for crop establishment and growth. Green Gram can be cultivated in about 45.5% of the watershed area (2205.2ha) with constrained by soil and site factors, resulting in reduced productivity under normal management practices. Only 16.7% area of watershed are not suitable(N) for crop cultivation (Table 4.35 and Fig. 4.31.). The major land emphasizes the need for careful site selection when planning green gram cultivation within the watershed.

Table 4.35 Area under suitability sub-classes for Green Gram cultivation

Sr. No	Suitability class	Area (ha)	Area (%)
1	Moderately Suitable (S2)	1566.2	32.3
2	Marginally Suitable (S3)	2205.2	45.5
3	Not Suitable (N)	810.2	16.7
4	Habitation	94.5	1.9
5	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

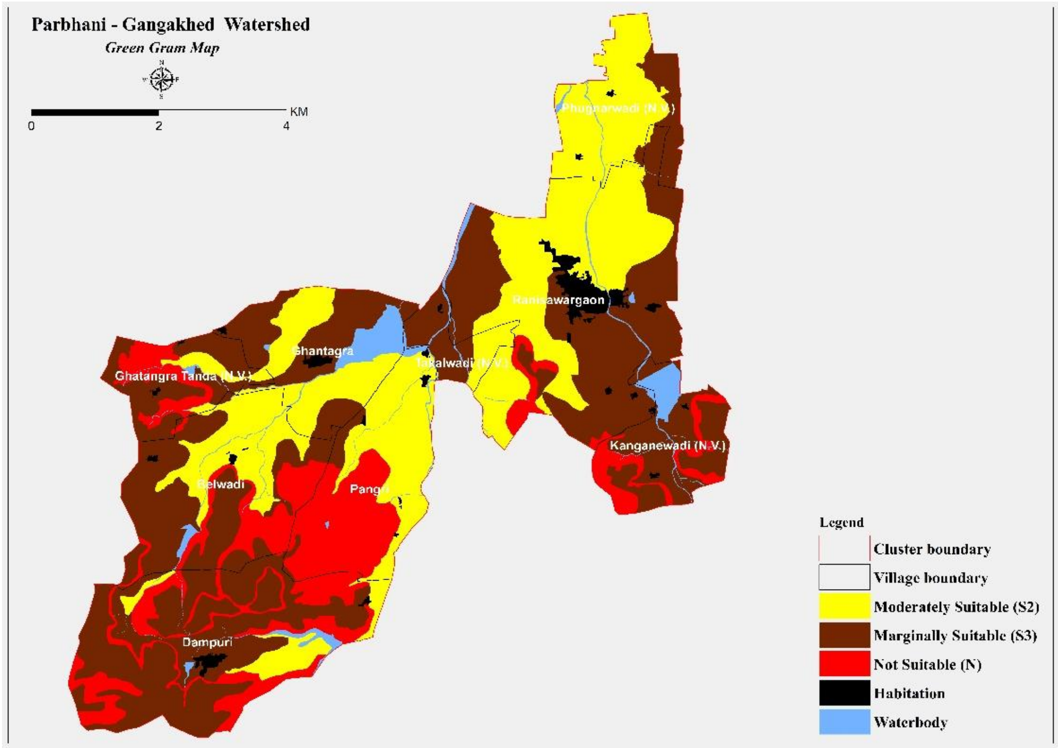


Fig. 4.31 Soil site suitability map for Green Gram Cultivation

4.8.10 Soil-Site Suitability for Mango Cultivation

About 9.8% of the watershed area were categorized under moderately suitable(S2) occupy 474.7 ha respectively, for Mango cultivation, whereas 2.7% of area was found to be marginally suitable (S3), reflecting moderate to severe constraints primarily associated with soil and environmental factors, which may restrict yield potential without appropriate management practices. 82.1% area of watershed are not suitable(N) for crop cultivation (Table 4.36 and Fig. 4.32).

Table 4.36 Area under suitability sub-classes for Mango cultivation

Sr.No	Suitability class	Area (ha)	Area (%)
1	Moderately Suitable (S2)	474.7	9.8
2	Marginally Suitable (S3)	128.9	2.7
3	Not Suitable (N)	3978.1	82.1
4	Habitation	94.5	1.9
5	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

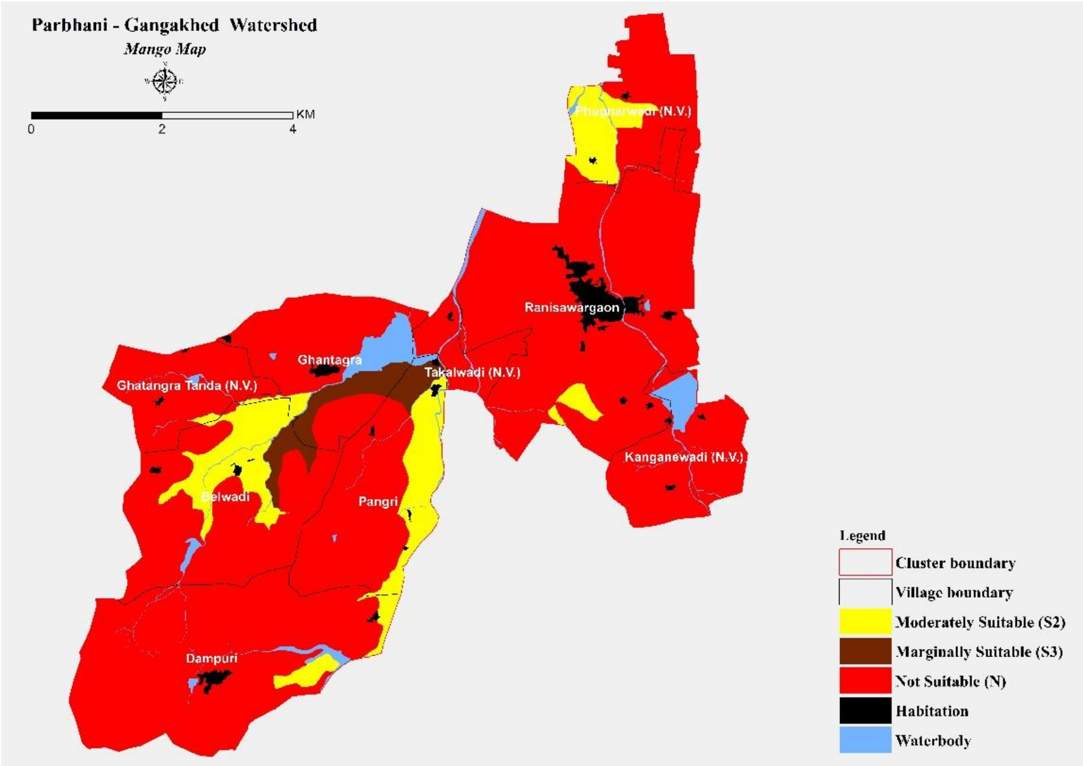


Fig. 4.32 Soil site suitability map for Mango cultivation

4.8.11 Soil-Site Suitability for Custard Apple Cultivation

About 12.5% of the watershed area were categorized under moderately (S2) suitable occupy 603.6 ha, respectively, for custard apple cultivation, whereas 19.9% of area was found to be marginally suitable (S3), reflecting moderate to severe constraints primarily associated with soil and environmental factors, which may restrict yield potential without appropriate management practices. 62.2% of the watershed area is not suitable (N) for custard apple cultivation due to severe limitations (Table 4.37, Fig. 4.33).

Table 4.37 Area under suitability sub-classes for Custard Apple cultivation

Sr.No	Suitability class	Area (ha)	Area (%)
1	Moderately Suitable (S2)	603.6	12.5
2	Marginally Suitable (S3)	962.6	19.9
3	Not Suitable (N)	3015.4	62.2
4	Habitation	94.5	1.9
5	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

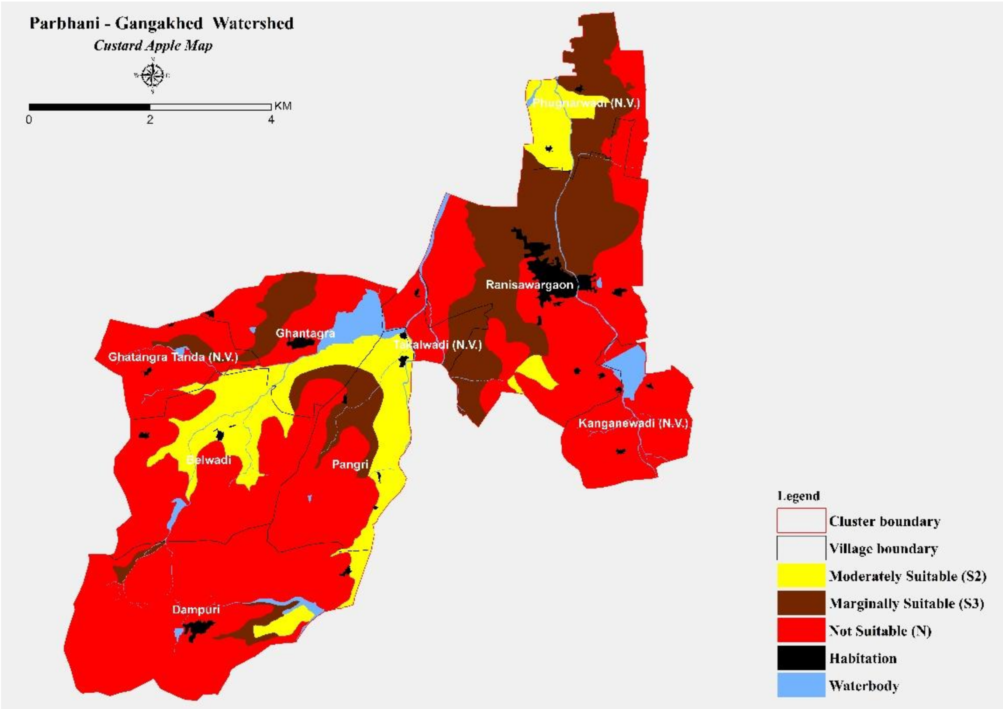


Fig. 4.33 Soil site suitability map for Custard Apple cultivation

4.8.12 Soil-Site Suitability for Guava Cultivation

The soils of the watershed were evaluated for Guava cultivation based on crop-specific requirements. The distribution of suitability classes is presented in Table 4.38, Fig.4.34. The results indicate that about 603.6 ha (12.5%) of the watershed area is classified as moderately suitable (S2), certain limitation for Guava growth and productivity. 962.6 ha (19.9% of the total geographical area of the A considerable portion of the watershed area is categorized as marginally suitable (S3), reflecting moderate to severe constraints related to soil properties and terrain slope, which may restrict yield potential unless appropriate management practices are adopted.

62.2% of the watershed area is not suitable (N) for Guava cultivation due to severe limitations associated with rocky soil, topography, waterlogging, steep slope and alkalinity of soil. Overall, the evaluation suggests that more than half of soil is not suitable for Guava cultivation.

Table 4.38 Area under suitability sub-classes for Guava cultivation

Sr. No	Suitability class	Area (ha)	Area (%)
1	Moderately Suitable (S2)	603.6	12.5
2	Marginally Suitable (S3)	962.6	19.9
3	Not Suitable (N)	3015.4	62.2
4	Habitation	94.5	1.9
5	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

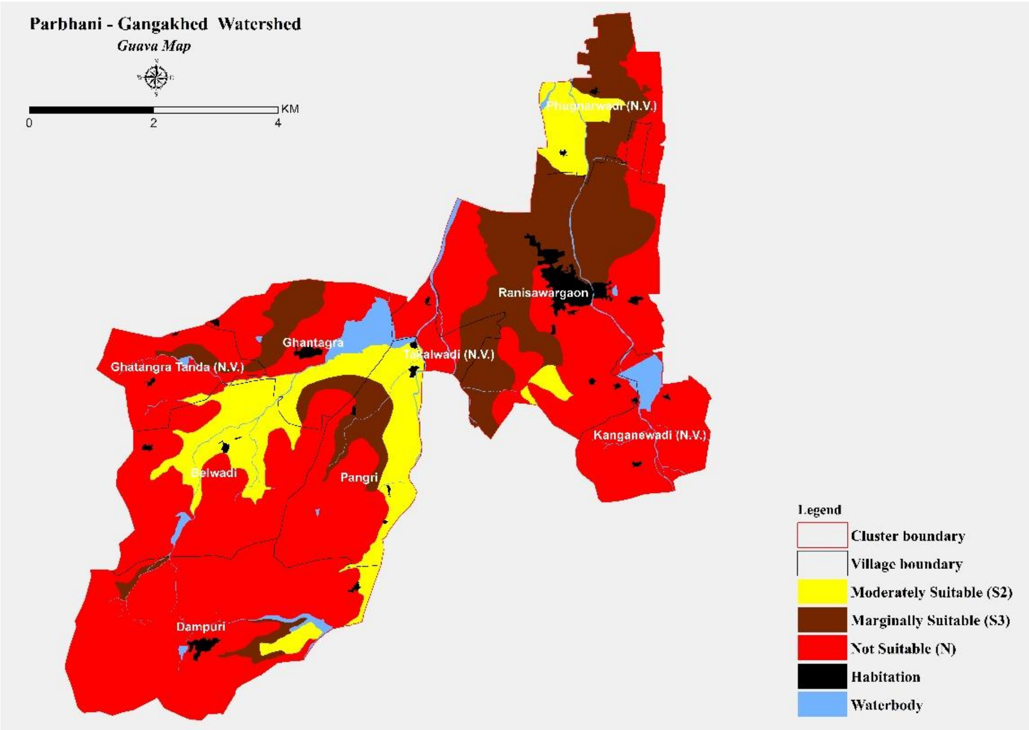


Fig. 4.34 Soil site suitability map for Guava cultivation

4.8.13 Soil-Site Suitability for Tomato Cultivation

The soils of the watershed were evaluated for tomato cultivation based on crop-specific requirements. The distribution of suitability classes is presented in Table 4.39 and Fig. 4.35. The results indicate that only 1566.2 ha (32.3% of the total geographical area of the watershed) is classified as moderately suitable (S2), providing certain limitations for tomato growth and productivity. A considerable portion of the watershed around 45.5% of the area is categorized as marginally suitable (S3), reflecting moderate to severe constraints related to soil properties and terrain slope, which may restrict yield potential unless appropriate management practices are adopted.

About 16.7% of the watershed area is not suitable (N) for tomato cultivation. Overall, the evaluation suggests that while soil is marginally suitable to moderately suitable for tomato cultivation.

Table 4.39 Area under suitability sub-classes for Tomato cultivation

Sr.No	Suitability class	Area (ha)	Area (%)
1	Moderately Suitable (S2)	1566.2	32.3
2	Marginally Suitable (S3)	2205.2	45.5
3	Not Suitable (N)	810.2	16.7
4	Habitation	94.5	1.9
5	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

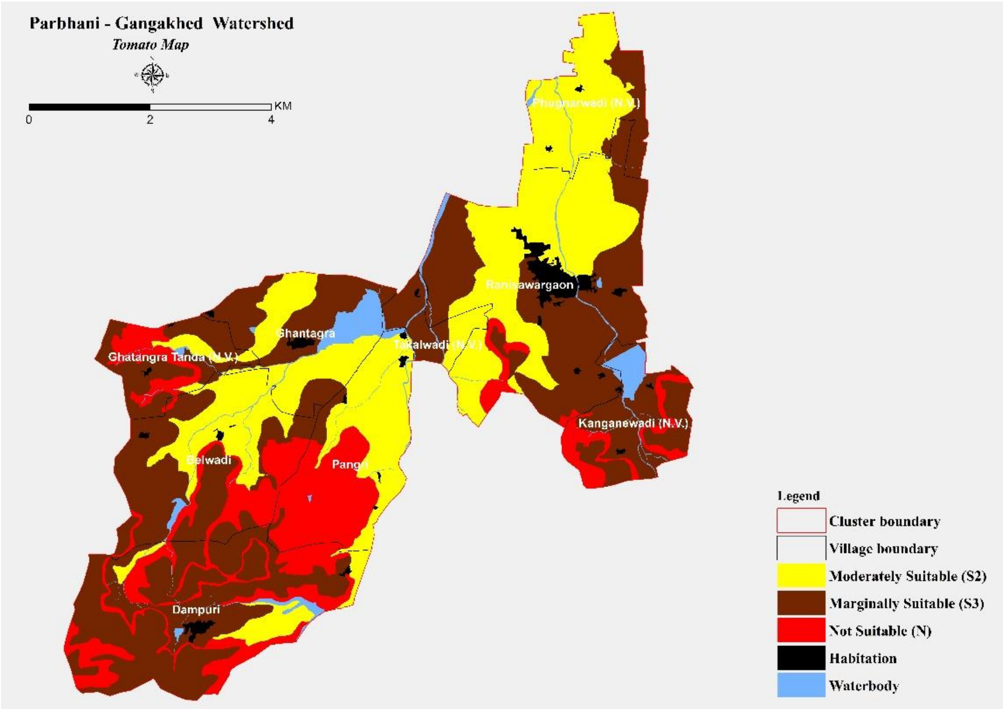


Fig. 4.35 Soil site suitability map for Tomato cultivation

4.8.14 Soil-Site Suitability for Chilli Cultivation

The soils of the watershed were evaluated for Chilli cultivation based on crop-specific requirements. The distribution of suitability classes is presented in Table 4.40 and Fig. 4.36. The results indicate that only 603.6 ha (12.5% of the total geographical area of the watershed) is classified as moderately suitable (S2), providing certain limitations for Chilli growth and productivity. A considerable portion of the watershed around 65.4% of the area is categorized as marginally suitable (S3), reflecting moderate to severe constraints related to soil properties and terrain slope, which may restrict yield potential unless appropriate management practices are adopted.

About 16.7% of the watershed area is not suitable (N) for Chilli cultivation. Overall, the evaluation suggests that while soil is marginally suitable to moderately suitable for Tomato cultivation.

Table 4.40 Area under suitability sub-classes for Chilli cultivation

Sr. No	Suitability class	Area (ha)	Area (%)
1	Moderately Suitable (S2)	603.6	12.5
2	Marginally Suitable (S3)	3167.9	65.4
3	Not Suitable (N)	810.2	16.7
4	Habitation	94.5	1.9
5	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

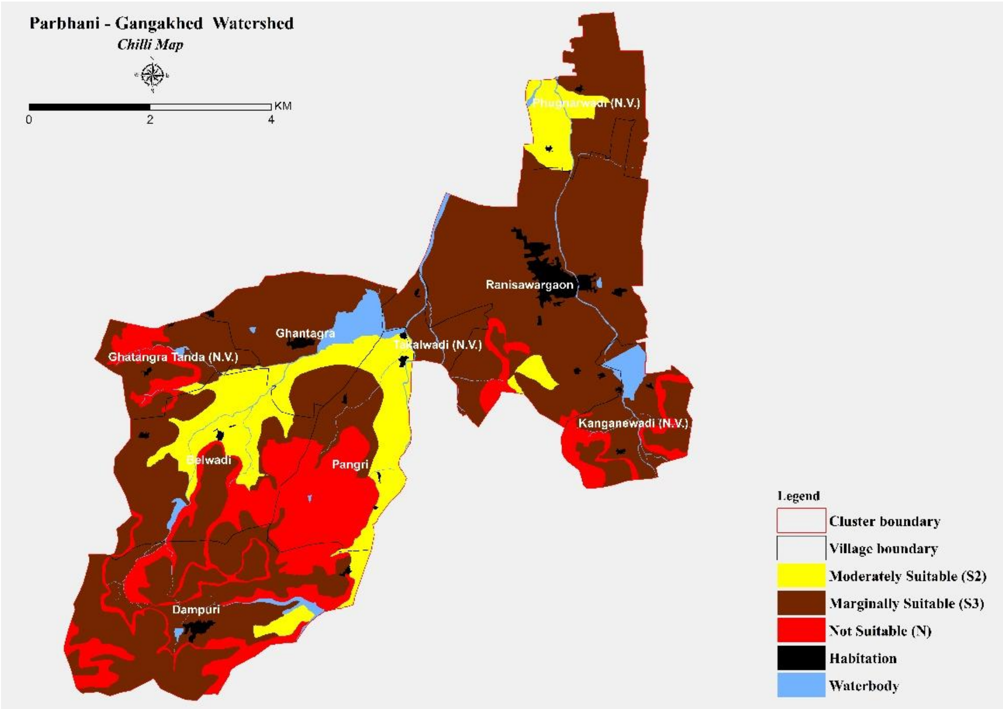


Fig. 4.36 Soil site suitability map for Chilli cultivation

4.8.15 Soil-Site Suitability for Lady Finger (Bhindi/Okra) Cultivation

The soils of the watershed were evaluated for lady finger cultivation based on crop-specific requirements. The distribution of suitability classes is presented in Table 4.41 and Fig.4.37. The results indicate that only 1566.2 ha (32.3% of the total geographical area of the watershed) is classified as moderately suitable (S2), providing certain limitations for lady finger growth and productivity. A considerable portion of the watershed around 42.3% of the area is categorized as marginally suitable (S3), reflecting moderate to severe constraints related to soil properties and terrain slope, which may restrict yield potential unless appropriate management practices are adopted.

About 19.9% of the watershed area is not suitable (N) for lady finger cultivation. Overall, the evaluation suggests that while soil is marginally suitable to moderately suitable for lady finger cultivation.

Table 4.41 Area under suitability sub-classes for Lady Finger (Bhindi) cultivation

Sr. No	Suitability class	Area (ha)	Area (%)
1	Moderately Suitable (S2)	1566.2	32.3
2	Marginally Suitable (S3)	2052.5	42.3
3	Not Suitable (N)	962.9	19.9
4	Habitation	94.5	1.9
5	Waterbody	170.8	3.5
	Total	**4846.9**	**100.0**

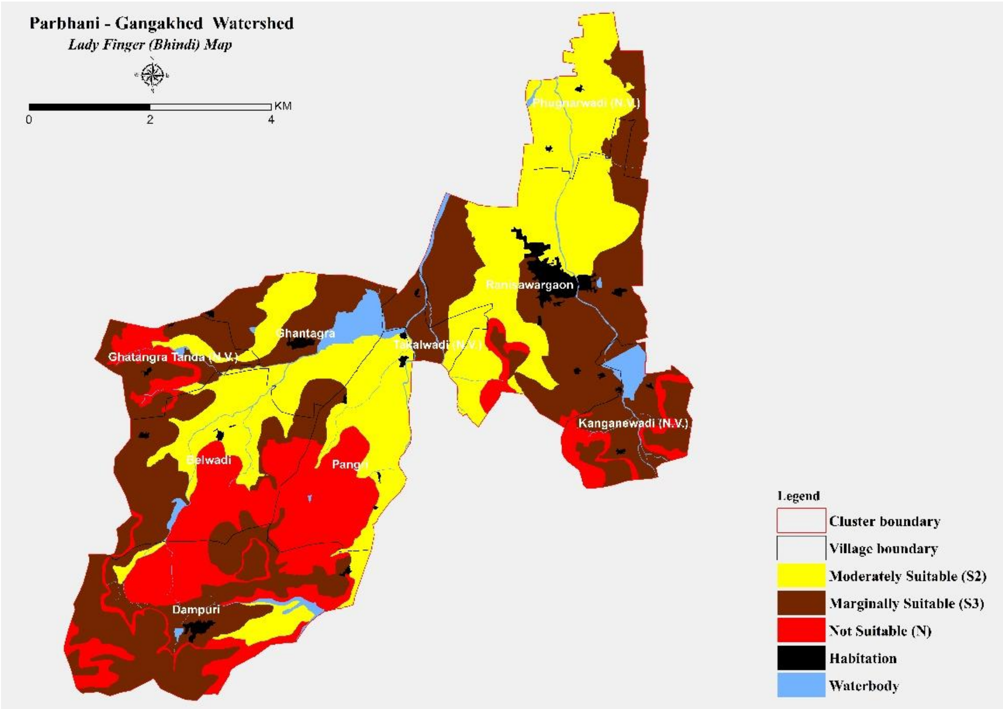


Fig. 4.37 Soil site suitability map for Lady Finger (Bhindi/okra) cultivation

4.9 Soil and Water Conservation measures

Soil and Water Conservation (SWC) is essential for sustaining soil fertility, controlling erosion, enhancing water availability, and supporting long-term agricultural productivity. In regions like Gangakhed Taluka, where soils are predominantly clay and clay loam with varying depths and slopes, and rainfall is relatively low, effective SWC interventions are critical to prevent land degradation, improve groundwater recharge, and maintain ecological balance. The diverse landforms of the taluka including escarpments, plateaus, pediments, valleys, rivers, and waterbodies require site-specific conservation measures tailored to local soil, slope, and land use conditions.

The SWC plan for the cluster watershed in Gangakhed has been developed through detailed analysis of landform, soil texture, soil depth, slope, and land use/land cover (LULC). Each intervention has been strategically allocated to address the conservation needs of cultivated lands, open scrublands, wastelands, urban areas, and waterbodies. The measures integrate both engineering and vegetative approaches to maximize effectiveness, enhance moisture retention, reduce surface runoff, and support sustainable land use.

On escarpments, where soils are shallow to very shallow and slopes are generally steep, afforestation and in-situ moisture conservation measures have been extensively applied in open scrublands and wastelands. These interventions help stabilize soils, improve infiltration, and reduce surface runoff. Cultivable lands in few parts of escarpments are treated with protection terraces, conservation bench terraces, and strengthening of existing field bunds with safe disposal of runoff, minimizing topsoil loss and improving moisture availability. In areas with very shallow soils, pure protection terraces have been deployed on steeper slopes to further reduce erosion risks.

Pediments and plateaus, characterized by moderate to shallow clay and clay loam soils, have received a combination of field bunds, bench terraces, conservation terraces, and pure protection terraces, particularly in cultivable lands. Open scrublands and wastelands in these areas are treated with afforestation and in-situ moisture conservation measures to enhance vegetation cover, improve soil structure, and maintain surface moisture. Farm ponds are integrated with field bunds at selected sites to enhance water storage and support irrigation. In valleys and deeper soil zones of pediments, broad bed and furrow (BBF) systems combined with field bunds and farm ponds have been implemented extensively. These measures facilitate water storage, reduce runoff velocity, and promote groundwater recharge. Stream-adjacent areas and nala channels have been stabilized through cement and earthen nala bunds, desilting, and stream bank plantations, reducing erosion and sedimentation. Cultivable lands on gentle to moderate slopes are strengthened with field bunds and conservation bench terraces to protect soil and retain moisture.

Waterbodies, rivers, and urban infrastructure have been integrated into the plan to ensure comprehensive watershed management. Renovation of waterbodies has been carried out according to site-specific conditions to improve water storage, while stream bank plantations protect riverbanks and prevent erosion. Roads have been treated with slope management and runoff control measures to reduce soil loss. Rooftop rainwater harvesting has been introduced in built-up areas to capture and utilize rainfall efficiently. At the time of execution of conservation measures, farmers' opinion may be opted and appropriate design may be done. If the site condition is not appropriate for suggested measures, alternative measures may be opted. The suggested polygon wise soil and water conservation measure is individual or combination of different conservation measures and each polygon is considered as independent unit.

Table 4.42 Proposed soil and water conservation (SWC) plan for Gangakhed watershed

Sr. No.	Proposed SWC Plan
1	Field bund/Strengthening of existing bund with safe disposal of runoff water, Farm pond
2	Puretocion Terrace
3	Conversation Bench Terrace in Unbunded Field/Field bund/Strengthening of existing bund with safe disposal of runoff water
4	Afforestation, In-situ Moisture Conservation Measures
5	Field bund/Strengthening of existing bund with safe disposal of runoff water
6	Renovation of Waterbody as per the site condition
7	Rooftop Rainwater Harvesting
8	Stream Bank Plantation
9	Broad Bed and Furrow (BBF) system/Field bund/Strengthening of existing bund with safe disposal of runoff water, Farm pond
10	Field bund/Strengthening of existing bund with safe disposal of runoff water, Grass waterway

11	Road
12	Horticultural Plantation, In-situ Moisture Conservation Measures
13	Broad Bed and Furrow (BBF) system/Field bund/Strengthening of existing bund with safe disposal of runoff water
14	Cement Nala Bund, Earthen Nala Bund / Repairing of Cement Nala Bund and Desilting of Nallas
15	Afforestation, In-situ Moisture Conservation Measures, Farm pond
16	In-situ Moisture Conservation Measures

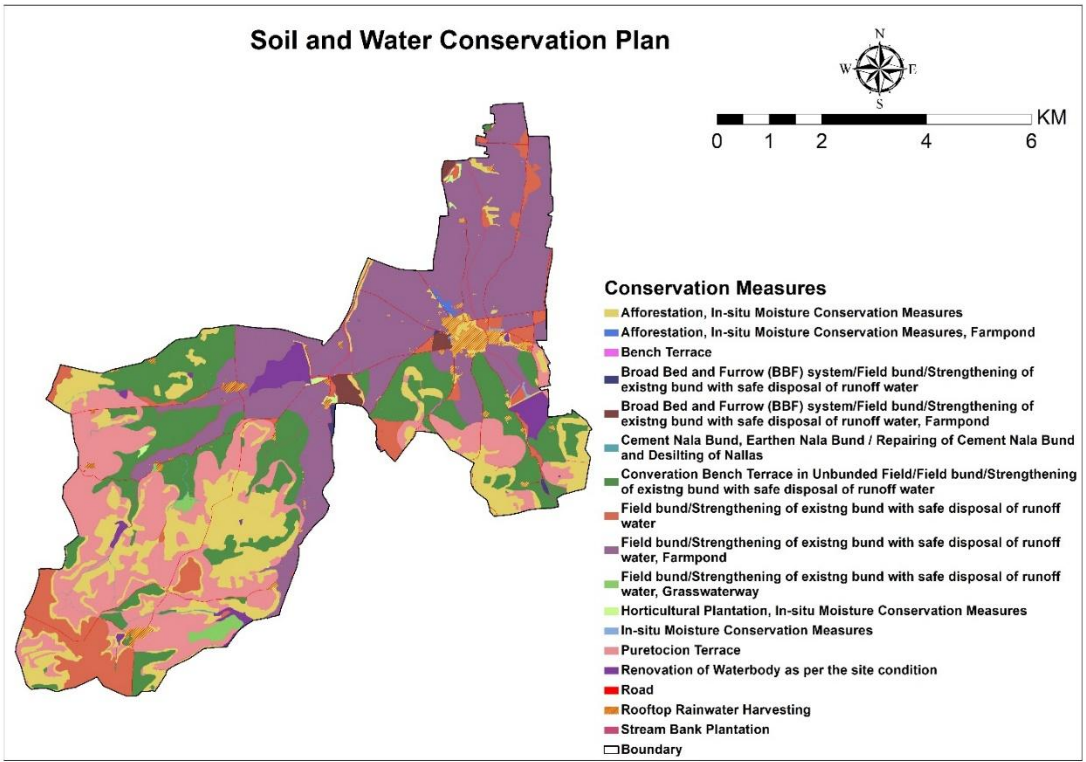


Fig. 4.38: Soil and water conservation measures proposed for Gangakhed watershed

This integrated SWC plan ensures that soil erosion is minimized, water retention is improved, and land degradation is controlled across watershed. By applying interventions appropriate to each landform and soil type, the plan supports sustainable agriculture, enhances groundwater recharge, strengthens ecosystem resilience, and contributes to the long-term socio-economic development of the region.

CHAPTER 5

SUMMARY AND CONCLUSION

5.1 SUMMARY

- The cluster has clay soils (86.3%) which offer good moisture retention but are highly prone to erosion on slopes.
- Soils are non-saline, neutral to alkaline, and strongly calcareous (74% high $CaCO_3$ content).
- The cluster features adequate micronutrients but suffers from widespread nitrogen deficiency across 76.9% of the area.
- Agriculture is largely rainfed but however, groundwater provides over 84% of seasonal irrigation needs.
- 20.1% of rainfall is lost as runoff, while over-extraction causes declining groundwater tables.
- 67% of the area requires careful management interventions to sustain groundwater resources and meet future water demands.
- 77.3% of the watershed is cultivable, with a high cropping intensity of 160.1%.
- Cotton (52.4%) and soybean (26.6%) are primary Kharif crops; sorghum and gram dominate Rabi.
- Soil site suitability evaluations indicate that the watershed is primarily moderately to marginally suitable for major crops like cotton, soybeans, and chickpeas. However, fruit crops (mango, guava, custard apple) and sugarcane are deemed not suitable over 60% of the land due to severe site limitations.
- The agricultural economy relies heavily on small (1–2 ha) and marginal (<1 ha) farmers, who together make up 66.6% of the farming population, bringing the average landholding size to just 1.7 ha.
- Educational attainment is inconsistent across the cluster; for example, Kanganewadi village suffers from an 82% illiteracy rate, while villages like Phugnarwadi and Ranisawargaon show better primary and higher education levels.
- A comprehensive Soil and Water Conservation plan is proposed to combat erosion and degradation. Key measures include field bunds, farm ponds, BBF systems, and afforestation for wastelands.

5.2 CONCLUSION

The comprehensive assessment of the Gangakhed Taluka watershed in Parbhani District highlights a region with strong agricultural potential that is currently constrained by significant hydrological and soil-related challenges.

The watershed's agricultural economy is heavily dependent on the erratic southwest monsoon and is characterized by a high concentration of small and marginal farmers. While there has been a notable shift towards cash crops like cotton and soybean, land suitability evaluations reveal that the region's soils are primarily only marginally to moderately suitable for these crops, and highly unsuitable for water-intensive or fruit crops like sugarcane, mango, and guava due to severe site limitations.

Soil health in the region is a mix of strengths and weaknesses. The predominantly clay soils offer good moisture retention but are highly susceptible to erosion on slopes. While the soil is non-saline with moderate to high organic carbon and adequate micronutrients (iron, manganese, copper), it suffers from widespread nitrogen deficiency and strongly calcareous conditions, requiring careful nutrient management to sustain crop productivity.

The most pressing issue in the watershed is water scarcity and management. With traditional flood irrigation practices and an over-reliance on groundwater through borewells, the region is experiencing declining pre-monsoon water tables and severe water wastage. Furthermore, approximately 20.1% of the annual rainfall is lost as surface runoff, particularly during the peak monsoon months of July and September. This is compounded by spatial mapping which indicates that 67% of the watershed area possesses poor to moderate groundwater potential, meaning high-yield groundwater zones are severely limited.

To secure the region's agricultural and ecological future, the implementation of a targeted Soil and Water Conservation (SWC) plan is critical. By applying site-specific interventions such as field bunds, farm ponds, conservation bench terraces, broad bed and furrow (BBF) systems, and afforestation, the watershed can effectively reduce surface runoff, control soil erosion, and enhance groundwater recharge. Ultimately, integrating these scientific conservation measures will stabilize the water supply, build climate resilience, and ensure long-term socio-economic development for the farming communities of Gangakhed Taluka.

ANNEXURE -1

Methodology for Morphometric Analysis

Morphometric analysis was carried out to understand the drainage characteristics and hydrological behavior of the study area. A Digital Elevation Model (DEM) was used as the primary dataset to derive terrain and drainage information. The DEM was processed in a Geographic Information System (GIS) environment to remove sinks and generate flow direction and flow accumulation grids. Based on the flow accumulation threshold, the drainage network was extracted and stream orders were assigned using the Strahler stream ordering method.

Using the derived drainage network and flow direction layers, watershed and sub-watershed boundaries were delineated by identifying outlet points along the main drainage channels. The resulting hydrologically closed units were used as the basis for morphometric analysis. Linear, areal, and relief morphometric parameters were computed using standard equations widely adopted in geomorphological studies (e.g., Horton, 1945; Strahler, 1964; Schumm, 1956). Linear parameters such as number of streams, stream length, bifurcation ratio, channel length, and basin perimeter were calculated from the extracted stream network. Areal parameters including basin area, drainage density, stream frequency, form factor, elongation ratio, circularity ratio, compactness coefficient, and length of overland flow were derived to evaluate watershed shape, drainage efficiency, and runoff potential. Relief parameters such as basin relief, relief ratio, ruggedness number, and Melton ruggedness number were estimated using elevation data from the DEM to assess terrain characteristics and erosion susceptibility.

The morphometric analysis was conducted at the watershed and sub-watershed scale, as these parameters depend on natural drainage boundaries rather than administrative limits. The derived indices were subsequently interpreted to understand runoff generation, erosion susceptibility, and groundwater recharge potential within the watershed system. The results were further used to support soil and water conservation planning and watershed management strategies for the study area.

Morphometric analysis Gangakhed cluster, Parbhani

In this study, runoff estimation, groundwater potential zone (GWPZ) mapping, and soil and water conservation (SWC) planning were performed at the village-cluster level to facilitate site-specific evaluation and practical implementation. In contrast, morphometric analysis was carried out at the watershed level because morphometric parameters are governed by natural drainage boundaries rather than administrative limits.

Morphometric analysis involves the quantitative assessment of drainage network characteristics, basin geometry, slope, and relief, all of which directly influence runoff generation, soil erosion, and groundwater recharge. These parameters must be derived from a hydrologically closed unit defined by natural divides. A watershed represents such a unit, where streams develop in a hierarchical order and converge toward a common outlet, enabling accurate computation of indices such as drainage density, bifurcation ratio, stream frequency, form factor, and relief ratio.

Village clusters, being administrative units, do not correspond to complete drainage systems. As streams frequently traverse village boundaries, conducting morphometric analysis at the cluster level would produce truncated stream networks and distorted basin geometry, thereby leading to unreliable hydrological interpretation. Therefore, morphometric analysis was intentionally performed at the watershed level to maintain hydrological accuracy, while runoff estimation, GWPZ mapping, and SWC planning were undertaken at the village cluster level for effective local implementation. This integrated framework links natural hydrological processes with decentralized planning for sustainable water resource management. The Gangakhed cluster, Parbhani, Maharashtra, comprises nine villages. Together, these villages constitute the study cluster having one sub-watershed Fig.1

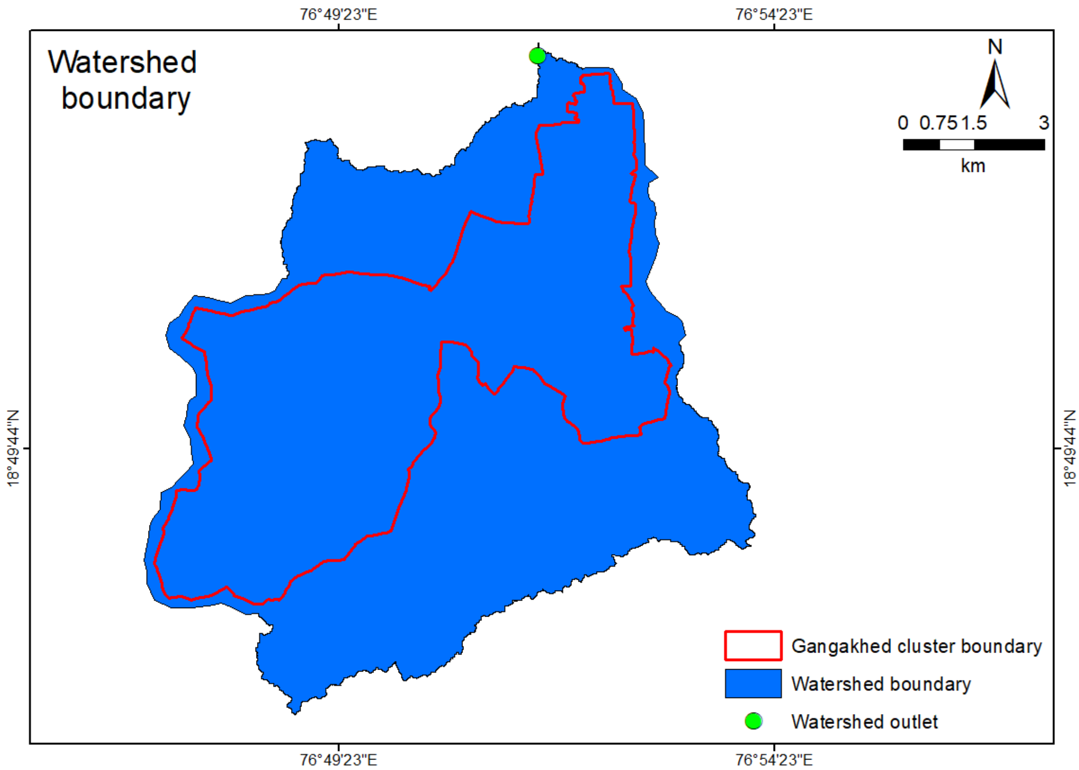


Fig. 1: Map of Gangakhed Cluster depicted through sub-watershed

Table 1: Distribution of area under different sub-watershed, Gangakhed cluster, Parbhani

Sr. No.	Sub-watershed name	Sub-watershed order	Elevation (m)	Area (km^2)	Flow origination
1	W1	5^{th}	316-498	101.24	South-north
		Total		**101.24**	

The watershed wise area, their order, elevation range and drainage network are presented in Table. 1 and in Fig 2. The morphometric characteristics of sub-watershed are analyzed under three aspects: linear, areal, and relief.

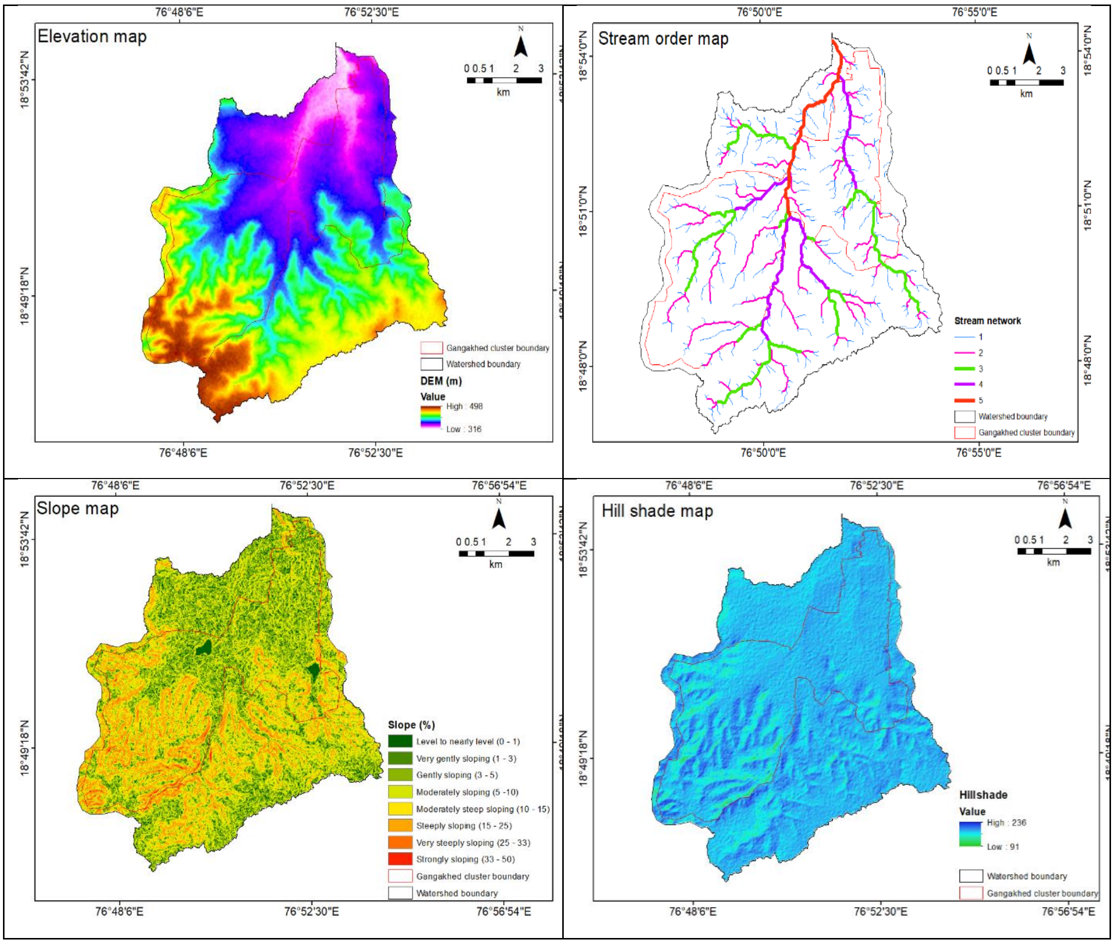


Fig. 2: Elevation, stream network, slope and hill shade map of sub-watershed

Linear aspect

Linear morphometric parameters focus on the stream network characteristics and its influence on runoff and watershed behavior. The morphometric analysis of the sub-watersheds shows clear variation in drainage characteristics.

W1 has the number of streams (445) and total stream length (233.6 km), indicating a well-developed drainage network Table 2. The bifurcation ratio indicated as 4.4, suggesting relatively greater structural influence watershed. Mean channel length and valley length of watershed, reflecting more mature channel development. Channel index of watershed W1 (1.40), indicating greater sinuosity. Basin perimeter of W1 (63.21 km), confirming it as the most extensive sub-watershed.

Table 2: Linear morphometric parameters of sub-watersheds, Gangakhed Cluster, Parbhani

Sr. no.	Morphometric parameter	Symbol	Unit	W1
1	No. of streams	Nu	No	445
2	Stream length	Lu	km	233.6
3	Bi-furcation ratio	Rb	-	4.4
4	Mean channel length	Cl	km	18.11
5	Valley Length	Vl	km	15.20
6	Channel Index	Ci	-	1.40
7	Minimum areal distance	Adm	km	13.2
8	Valley Index	Vi	-	1.15
9	Basin perimeter	P	km	63.21

Areal Aspects

Areal parameters describe the two-dimensional properties of the watershed, including shape, size, and drainage efficiency, which directly influence runoff and groundwater recharge. Basin area of watershed W1 (101.24 km²) and mean basin width is 5.3 km. Form factor (Ff) and elongation ratio (Re)in W1 (0.28 and 0.6), suggesting a comparatively more circular basin. Circularity ratio (Rc) of W1 is 0.32, while compactness coefficient (Cc) as 1.78, reflecting greater basin irregularity. Standard sinuosity index (Ssi) as 1.19, indicating relatively higher channel sinuosity in W1.Drainage parameters show that stream frequency (Fs) is 4.4 per km² and Drainage density (Dd) as 2.3 km/km². Drainage intensity (Di) follows a similar trend, with the highest value as 1.9.Length of overland flow (Lg) as (0.24 km) indicating shorter runoff travel distance in W1.

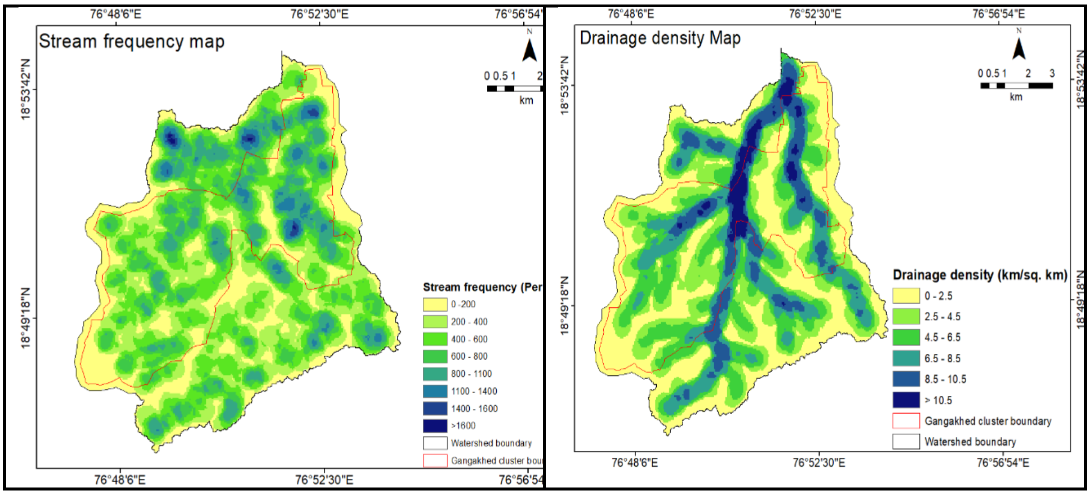


Fig. 3: Steam frequency and drainage density map of sub-watershed

Table 3: Areal morphometric parameters of sub-watersheds, Gangakhed cluster, Parbhani

Sr. No.	Parameter	Symbol	Method/ Formula	Unit	W1
1.	Mean basin width	Wb	Wb=A/Lb	km	5.3
2.	Basin area	A	GIS Analysis	km2	101.24
3.	Relative perimeter	Pr	Pr= A/P	km	1.6
4.	Length area relation	Lar	Lar = 1.4*A0.6	km2	22.35
5.	Lemniscate's	k	K = Lb2/A	-	3.6
6.	Form factor	Ff	Ff = A/Lb2	-	0.28
7.	Elongation ratio	Re	Re = 2/Lb*(A/π)0.5	-	0.6
8.	Circularity ratio	Rc	Rc = 12.57*(A/P2)	-	0.32
9.	Compactness coefficient	Cc	Cc = 0.2841*P/A0.5	-	1.78
10.	Standard sinuosity index	Ssi	Ssi = Ci/Vi	-	1.19
11.	Stream frequency	Fs	Fs = Nu/A	Per km2	4.4
12.	Drainage Density	Dd	Dd = Lu/A	km/km2	2.3
13.	Drainage Intensity	Di	Di = Fs/Dd	-	1.9
14.	Length of Overland Flow	Lg	Lg = A/2*Lu	km	0.24

Relief Aspects

The maximum basin height (Z) of W1 (498m) and total basin relief (H) is also maximum as (182 m) Table 4. Relief ratio (Rhl) as W1 (9.6), indicating steeper terrain conditions, while Relative relief ratio (Rhp) of W1 (287.9)suggesting higher relief intensity in W1. The ruggedness number (Rn) of watershed W1 (0.35), reflecting more dissected and erosion-prone terrain. Similarly, the Melton ruggedness number (MRn) is shown in W1 (18.1), indicating comparatively higher susceptibility to runoff and erosion processes.

Table 4: Relief morphometric parameters of sub-watersheds, Gangakhed Cluster

Sr. no.	Parameters	Symbol	Methods/Formula	W1
1.	Height of at basin mouth (m)	z	DEM	316
2.	Maximum height of the basin (m)	Z	DEM	498
3.	Total basin relief (m)	H	H = Z - z	182
4.	Relief ratio	Rhl	Rhl = H / Lb	9.6
5.	Relative relief ratio	Rhp	Rhp = H * 100 / P	287.9
6.	Ruggedness number	Rn	Rn = Dd*(H/1000)	0.35
7.	Melton Ruggedness number	MRn	MRn = H / A^0.5	18.1

The slope distribution of watershed W1 shows that the terrain is predominantly moderately undulating to sloping. The moderately sloping class (5-10%) occupies the largest share of the watershed, covering 34.29 km^2 (33.87%), indicating that a major portion of the area experiences moderate runoff potential. This is followed by the gently sloping class (3-5%), which accounts for 24.08 km^2 (23.79%), representing relatively stable terrain suitable for agricultural activities. The moderately steep slope class (10-15%) covers 16.15 km^2 (15.96%), while steep slopes (15-25%) occupy 13.05 km^2 (12.89%), suggesting the presence of erosion-prone areas in parts of the watershed. The very gently sloping (1-3%) and level to nearly level (0-1%) categories cover 6.69 km^2 (6.61%) and 5.58 km^2 (5.51%), respectively, indicating limited flat terrain mainly located in valley bottoms or lower reaches. In contrast, very steep slopes (25-33%) and strongly sloping areas (33-50%) are minimal, covering only 1.24 km^2 (1.23%) and 0.15 km^2 (0.15%) of the watershed.

Based on the morphometric characteristics and slope distribution, an integrated soil conservation and land use planning strategy is essential for watershed W1. The well-developed drainage network, high drainage density (2.3 km/km^2), high stream frequency (4.4 per km^2), and relatively high bifurcation ratio (4.4) indicate rapid runoff generation and greater susceptibility to soil erosion. In addition, the higher relief (182 m), steep terrain conditions, and ruggedness parameters further increase the erosion risk in the watershed. The slope analysis shows that a considerable portion of the area falls under moderately sloping (5-10%) and steep slopes (10-25%), which require appropriate conservation interventions. Therefore, field bunds, and vegetative barriers should be implemented in gently sloping agricultural lands (1-5%) to reduce runoff and enhance soil moisture retention. In moderately sloping areas (5-10%), terracing, contour trenching, and strip cropping can effectively minimize soil loss and improve water infiltration. For steep slopes (>10%), afforestation, agro-forestry, and pasture development are recommended to stabilize the soil and control erosion. Along the drainage lines and lower reaches of the watershed, check dams, gully plugs, and percolation tanks should be constructed to reduce flow velocity, enhance groundwater recharge, and manage sediment transport. Overall, land use planning based on morphometric and slope analysis suggests prioritizing soil and water conservation measures, sustainable agriculture, and vegetation cover to improve watershed stability, reduce erosion risk, and promote long-term land productivity in watershed W1.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