



## Assessment of Hydrological Intervention for Hallur (4d4d4b) Sub Watershed of Rattihalli Taluk, Haveri District, Karnataka

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### Abstract

The Halluru sub-watershed in Rattihalli taluk, Haveri district, demonstrates complex hydrological and agro-ecological dynamics shaped by topography, land use, soil properties and climatic variability. DEM analysis reveals elevations ranging from 450 to 808 m. Actual evapotranspiration (AET) exhibits considerable spatial and seasonal variation, from 542 to 988 mm, with lower values in high-elevation rainfed areas and higher values in low-lying irrigated zones with deeper soils and denser vegetation. Land use was predominantly agricultural ( $\approx 50.7\%$  cropland; 6.1% plantations), with minimal forest cover (0.2%) and moderate wasteland (3.3%), water bodies, and built-up areas (4.6%). Surface soils vary widely, with clayey soils dominating central and southern regions (infiltration  $\sim 2$  mm/hr), clay loam in scattered patches ( $\sim 7$  mm/hr) and sandy clay/loamy soils in uplands ( $\sim 10$ – $14$  mm/hr), influencing runoff. Rainfall analysis (2014–2022) showed that average annual rainfall of 826 mm, with kharif rainfall ( $\approx 60\%$ ) deficient in 2015, 2016 and 2018, rabi rainfall ( $\approx 20.29\%$ ) severely deficient in 2016 and 2017 and summer rainfall ( $\approx 19.37\%$ ) contributing to pre-monsoon soil moisture. The annual number of rainy days ranged from 12–25, with 0–9 days producing runoff (20–30 mm), and  $>30$  mm events recorded only in 2021–2022. Satellite-derived soil moisture maps indicate high heterogeneity, with Kharif values up to  $0.28 \text{ m}^3/\text{m}^3$  in valleys and Rabi values declining to  $0.10$ – $0.16 \text{ m}^3/\text{m}^3$  in uplands, highlighting seasonal moisture stress. Groundwater levels (2014–2023) showed seasonal fluctuations with a long-term declining trend, exacerbated during 2019–2020 by low rainfall and intensive pumping. Budyko analysis indicated predominantly water-limited regime, with Rabi PET/P and AET/P ratios emphasizing dependence on soil moisture and groundwater, while Kharif is energy-limited. The watershed conservation plan integrates graded bunding, contour trenches and rock-out structures to reduce erosion, enhance infiltration, stabilize soils, and protect downstream areas.

**Keywords:** Groundwater dynamics: Rainfall variability: Soil moisture distribution: Budyko analysis.

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### Introduction

Agriculture and allied sectors continue to form the backbone of the Indian economy, remaining heavily dependent on natural resources such as rainfall, surface and groundwater, soil and forest vegetation. However, increasing demographic pressure, land-use change, and climate variability have intensified the depletion and degradation of these finite resources, threatening

long-term agricultural sustainability and rural livelihoods. Integrated watershed management has therefore emerged as a key framework for conserving land and water resources and enhancing ecosystem resilience in semi-arid regions like Karnataka (Poonia and Singh, 2025). A watershed is defined as a topographically delineated hydrological unit that drains runoff through a network of streams to a



common outlet and serves as an integrated biophysical system influenced by interactions among climate, soil, vegetation, water and socio-economic activities.

Unscientific land-use practices, deforestation, excessive extraction of water resources and inadequate soil conservation measures accelerate watershed degradation, often intensified by human interventions. Participatory watershed management involving local communities has been shown to significantly improve conservation outcomes and socio-economic benefits, especially in water-scarce agro-ecosystems. Watershed management aims to improve water availability and quality, enhance soil fertility, support appropriate cropping patterns tailored to local resources, generate employment and improve livelihoods (Jain et al., 2022). Scientifically, watershed management is the integrated and sustainable utilization of land and water resources to achieve optimal productivity with minimal environmental vulnerability. It involves the application of soil and water conservation measures, regulation of surface runoff, reduction of soil erosion, enhancement of groundwater recharge and efficient use of irrigation water. Hydrological studies at the watershed scale are fundamental for understanding water balance, runoff generation, infiltration processes, and the impacts of land-use change (FAO, 2023). At the field level, hydrological assessments guide the implementation of soil conservation structures, water quality monitoring and supply evaluation. State-wide hydrological observations show that between November 2023 and November 2024, approximately 86.9% of monitored wells in Karnataka registered rising shallow aquifer levels (0–4 m), while only about 13.1% recorded a decline, reflecting variable groundwater responses to recent recharge efforts (CGWB, 2024). Seasonal fluctuation data from November 2024 to January 2025 indicates that 67% of wells exhibited declining water levels, with only a small proportion showing increases, emphasizing the importance of temporal monitoring in hydrological assessments.

Macro-scale statistics from the National Compilation on Dynamic Ground Water Resources of India (2024) report that Karnataka's annual groundwater extraction stands at 58.4% of recharge, below the national average, but with pronounced over-exploitation in several districts, highlighting spatial heterogeneity in resource stress (GoK, 2024). Moreover, improved management measures such as extensive recharge structures under state and central schemes have contributed to rising water levels in many taluks, with an average rise of up to 13.2 m in parts of 347 rural gram panchayats and significant aquifer recovery in previously critical areas.

Such data highlight both progress and the fragility of hydrological systems under climatic and anthropogenic pressures. In this context, the present study focuses on the hydrological intervention and sustainable management of the Halluru sub-watershed (4D4D4B), located in Rattihalli taluk of Haveri district, Karnataka. By integrating recent rainfall runoff groundwater statistics with land-use analyses and community based conservation strategies, this research aims to support evidence-based watershed development and resource sustainability in a region facing significant seasonal water variability and socio-economic challenges.

## Material and Methods

### Study Area

The Hydrological intervention of the Halluru sub-watershed located in Ratteehalli taluk of Haveri district, Karnataka, India. Haveri district is situated in the northern part of Karnataka and occupies a central geographical position within the state, falling under the Northern Transitional Agro-climatic Zone (Zone-8). The district extends over an area of approximately 4,848 km<sup>2</sup> and lies between 14°32'00" and 14°34'00" N latitude and 75°27'00" and 75°28'30" E longitude (Fig. 1). Geologically, the district is predominantly characterized by schist formations with limited occurrences of granite-gneiss. Agriculture in the region comprises both irrigated and rainfed systems, with major crops including sugarcane, paddy, ragi, maize, wheat, soybean, jowar, cotton, pulses, chilli, groundnut, horse gram, sunflower, along with various vegetable and horticultural crops.

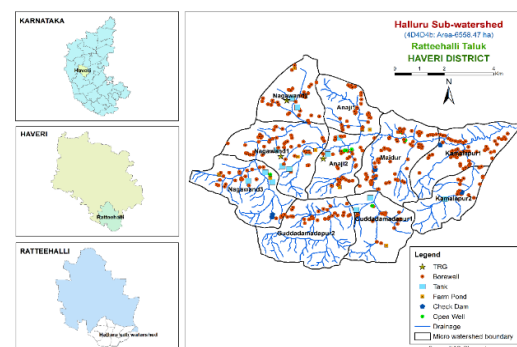


Fig. 1 Location of the study area

### Geoprocessing

Kriging is an advanced geostatistical interpolation technique used to estimate values at unsampled locations by accounting for both the spatial distance and the statistical correlation among observed data

points. It generates a continuous surface from discrete point measurements by modeling spatial variability through variogram analysis and applying a fitted mathematical function to quantify spatial dependence. The kriging process involves exploratory data analysis, variogram modeling, surface estimation, and evaluation of prediction uncertainty (Prasad et al., 2023). Estimated values are derived using a weighted linear combination of neighboring sample points, where weights are assigned to ensure unbiased predictions with minimum estimation variance. Depending on the analytical requirements, either a fixed or variable search radius may be employed, and predicted values may extend beyond the observed data range. Fundamentally, kriging is based on the principles of zero bias and minimum mean square error and is capable of estimating values over an entire spatial domain, within finite blocks, or at specific point locations by utilizing spatially structured sample information.

The present study employed an integrated geospatial and hydrological approach to assess rainfall characteristics, groundwater status, evapotranspiration, satellite-derived soil moisture and to formulate a conservation plan for the study watershed. Rainfall index, spatial rainfall distribution, and seasonal rainfall (Kharif and Rabi) were analysed using long-term rainfall data obtained from IMD and state rain-gauge stations, and spatial interpolation was carried out using the Kriging technique in ArcGIS 10.8.1. Groundwater status was assessed using pre- and post-monsoon water-level data sourced from the Central Ground Water Board (CGWB) to evaluate seasonal fluctuations and recharge conditions. Evapotranspiration index was estimated using remotely sensed climatic datasets and standard FAO-based approaches to understand atmospheric water demand (Mustafaa et al., 2023). Satellite-retrieved soil moisture for Kharif and Rabi seasons was derived from passive microwave satellite products (Sentinel-based datasets) to analyse seasonal soil moisture dynamics and crop water availability. Digital Elevation Model (DEM) data obtained from KRSRAC, Bengaluru, were used to delineate watershed boundaries, drainage networks, slope, and terrain parameters (KRSRAC, 2023). All thematic layers were generated, integrated, and analysed in ArcGIS 10.8.1 to identify hydrologically sensitive zones. Based on the spatial integration of rainfall variability, groundwater conditions, evapotranspiration stress, soil moisture status, slope and land use, a watershed-based conservation plan was proposed, recommending

suitable soil and water conservation measures such as check dams, contour bunds, recharge structures and land management practices to enhance water availability, reduce runoff and soil erosion, and improve overall watershed sustainability.

### Statistical Analysis

Statistical analysis was carried out using ArcGIS 10.8.1 to perform comprehensive quantitative assessments for the generation of Groundwater status, AET, LULC and Soil moisture maps. Descriptive statistical analysis of seasonal rainfall and rainfall events was conducted using Microsoft Excel (2021) and SPSS Statistics (Version 27) to summarize and interpret the data (Pallant, 2007).

## Results and Discussion

The Digital Elevation Model (DEM) analysis of the Hallur sub-watershed indicates that elevation ranges from approximately 450 m to 808 m above mean sea level, reflecting a moderately undulating to hilly terrain (Fig 2). The higher elevation zones, predominantly located along the watershed divides, are characterized by steeper slopes and act as runoff generation areas, contributing to rapid surface flow during rainfall events. The lower elevation areas represent valley floors and drainage corridors where runoff accumulation and groundwater recharge potential are relatively higher (Kumar et al., 2023). This variation in elevation strongly influences drainage density, slope gradients, soil erosion susceptibility and land-use suitability within the sub-watershed.

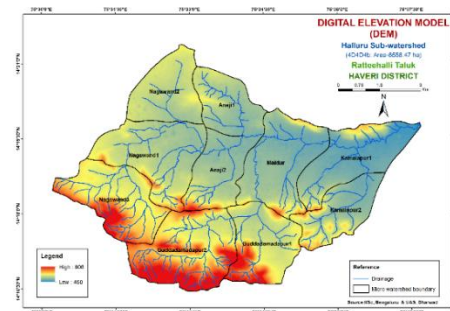


Fig. 2 Digital elevation model (DEM) map

The Annual Actual Evapotranspiration (AET) map of the Hallur sub-watershed reveals pronounced spatial variability, with AET values ranging approximately from 542 mm to about 988 mm, reflecting the combined influence of topography, land use, soil moisture availability, and vegetation cover (Fig 3). Lower AET values ( $\approx 542$ – $621$  mm) were predominantly observed in the north-western and upper reaches of the watershed,

which are characterized by relatively higher elevations, shallow soils, lower soil moisture retention and rainfed agricultural practices, thereby limiting actual water loss through evapotranspiration. Moderate AET zones ( $\approx 622\text{--}770$  mm) dominate the central parts of the watershed, corresponding to gently sloping terrain with mixed land use and moderate soil moisture conditions. Higher AET values ( $\approx 771\text{--}988$  mm) were observed in the southern and south-eastern portions of the watershed, where lower elevations, deeper soils, better moisture availability, irrigated agriculture and denser vegetation cover enhance evapotranspiration rates (Sharma et al., 2023). This spatial pattern indicates that areas with higher AET are likely associated with greater water consumption and agricultural intensity, while low-AET zones experience moisture stress and limited crop water use. The observed AET distribution highlights the importance of watershed-specific water management strategies, emphasizing the need for moisture conservation and recharge interventions in low-AET areas and efficient irrigation and water-use practices in high-AET zones to ensure sustainable water resource management.

constitutes nearly 13.5% of the area, suggesting seasonal cropping patterns, soil moisture limitations, or temporary land abandonment during the Rabi season. Forest cover was minimal (around 0.2%), indicating significant reduction of natural vegetation and limited ecological buffering capacity. Wastelands account for about 3.3%, representing degraded or less productive areas that may be prone to erosion and require reclamation measures (Patil and Das, 2024). Water bodies and built-up areas together cover roughly 4.6%, reflecting limited surface water storage and moderate rural settlement expansion. The predominance of agricultural land coupled with low forest cover underscores the pressure on land and water resources within the watershed, emphasizing the need for sustainable land management practices, crop diversification, soil and water conservation measures, and protection of remaining natural and water resources to enhance agricultural productivity and environmental sustainability in the Hallur sub-watershed.

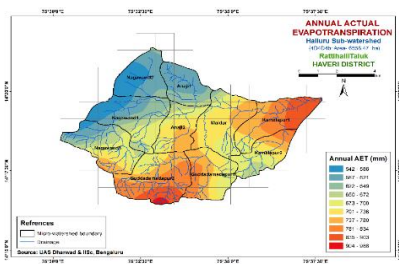


Fig. 3 Annual actual evapotranspiration map

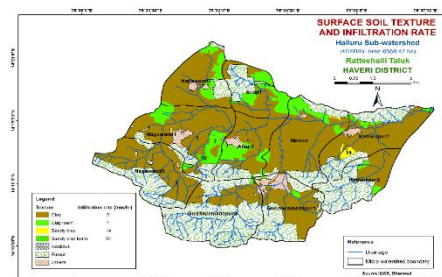


Fig. 5 Soil texture and infiltration rate

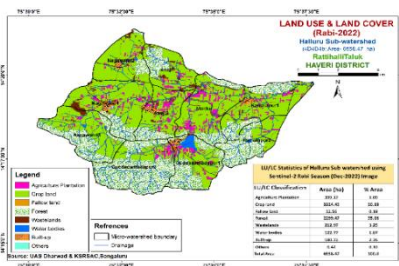
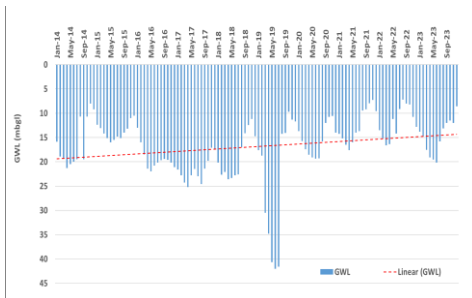


Fig. 4 Land use land cover (LULC) map (rabi season)

The Land Use and Land Cover (LULC) map of the Hallur sub-watershed derived from Sentinel-2 imagery for the Rabi season (2022) indicated that agriculture was the dominant land use, reflecting the agrarian nature of the region (Fig 4). Cropland occupies the largest share of the watershed (approximately 50.7%), followed by agricultural plantations (about 6.1%), highlighting intensive agricultural activity supported by both rainfed and irrigated practices. Fallow land

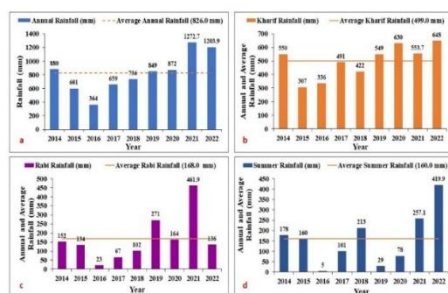
The surface soil texture and infiltration rate map of the Hallur sub-watershed reveals clear spatial variability that strongly influences hydrological response and water availability. Clayey soils dominate a major portion of the watershed, particularly in the central and southern regions, exhibiting low infiltration rates of approximately 2 mm/hr, which promote higher surface runoff and increase susceptibility to waterlogging and soil erosion during intense rainfall events (Fig. 5). Clay loam soils with moderate infiltration rates around 7 mm/hr occur in scattered patches, offering comparatively better moisture retention and suitability for agricultural crops. Sandy clay and sandy clay loam soils, characterized by higher infiltration rates of about 10-14 mm/hr, were mainly observed in the upper and peripheral parts of the watershed, facilitating rapid percolation and enhanced groundwater recharge but also posing a risk of moisture stress under prolonged dry conditions. Rocky and forested patches show limited infiltration capacity and contribute to quick

runoff generation (Manjunatha et al., 2024a). Overall, the dominance of low-infiltration clayey soils indicates a need for soil and water conservation measures such as contour bunding, field bunds, and surface drainage in runoff-prone areas, while recharge structures and moisture conservation practices are more appropriate in zones with higher infiltration rates to improve groundwater recharge and sustainable agricultural productivity in the Hallur sub-watershed (Addisie, 2022).



**Fig. 6** Groundwater status of Hallur sub watershed

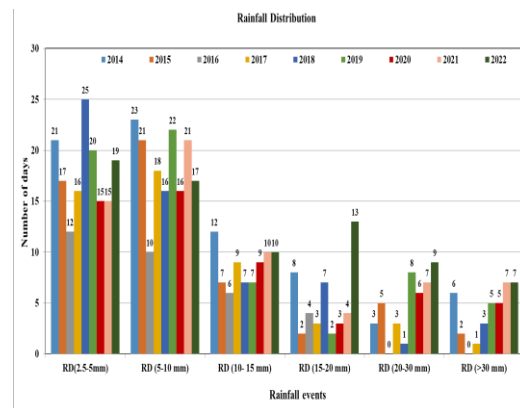
The monthly groundwater levels (GWL) from January 2014 to September 2023 exhibit clear seasonal and inter-annual variations, marked by occasional sharp declines (Fig. 6). Despite these fluctuations, the linear trend line reveals a gradual long-term lowering of the water table, indicating progressive groundwater depletion at the site. Temporary rises in GWL correspond to recharge periods, likely driven by monsoon rainfall or reduced extraction, while repeated troughs most notably the extreme drops in 2019–2020 suggest the combined effects of deficient rainfall and intensified irrigation pumping (Manjunatha et al., 2024b). Over time, the lower peaks observed in recent years compared to earlier ones indicate that the aquifer’s recovery after recharge events is incomplete, pointing to cumulative overdraft, diminished storage capacity, and potential impacts from changing land-use practices.



**Fig. 7** Rainfall index of Hallur sub watershed

The analysis of rainfall at Hallur station (2014–2022) indicates significant variability in both annual and seasonal precipitation, with an average annual rainfall

of 826 mm (Fig. 7). The kharif season, contributing approximately 60% of the annual rainfall, exhibited prominent deficits in 2015 (38%), 2016 (32%) and 2018 (15%), reflecting its strong influence on overall annual rainfall deficiencies observed in 2015–2018. Such kharif deficits are likely linked to weak southwest monsoon activity, which was the primary driver of rainfall during this period. Rabi rainfall, accounting for about 20.29% of annual rainfall, also showed considerable deficits, particularly in 2016 (86%) and 2017 (60%), suggesting a delayed or insufficient northeast monsoon and possible soil moisture stress affecting post-monsoon cropping. Summer rainfall, contributing roughly 19.37% of the annual total, though minor, plays a crucial role in pre-monsoon soil moisture recharge (Manjunatha et al., 2024c). The observed inter-annual variability across seasons indicates that Hallur experiences both monsoon-related and post-monsoon hydrological stress, which can adversely affect agricultural planning, water resource management, and crop yield stability. The deficits in specific years can be attributed to broader climatic fluctuations, including weak monsoon systems, erratic rainfall distribution and potential regional dry spells (Cholo and Tolossa, 2023).



**Fig. 8** Rainfall distribution of Hallur sub watershed

The annual number of rainy days exceeding 2.5 mm ranged between 12 and 25, while days likely to generate significant runoff (20–30 mm) averaged 0 to 9 per year, showed moderate inter-annual variability. Exceptionally high-intensity events (>30 mm) were recorded only in 2021 and 2022, which is critical information for designing watershed conservation and water-harvesting structures (Fig 8). Analysis of rainfall distribution from 2014 to 2022 indicates that most precipitation occurred as light to moderate showers (2.5–10 mm), whereas higher-intensity events ( $\geq 15$  mm) were relatively infrequent. Years such as 2014 and 2017



were dominated by frequent low-intensity rainfall, while 2018 experienced more 15–30 mm events, reflecting occasional intense convective storms. The scarcity of >30 mm events suggest limited potential for rapid runoff, whereas the predominance of smaller rains favours gradual soil moisture replenishment, though deep percolation and substantial groundwater recharge remain limited unless rainfall occurs consecutively or on already moist soils, consistent with the moderate responses seen in groundwater trends (Manjunatha et al., 2024d).

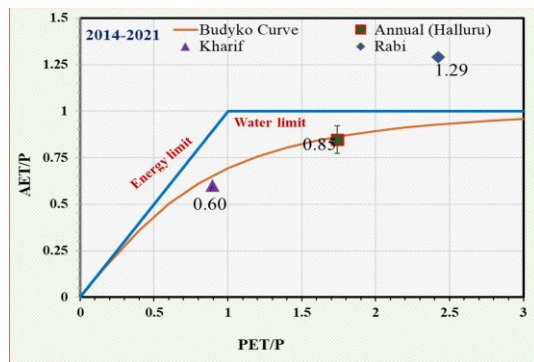


Fig. 9 Evapotranspiration index of Hallur sub watershed

The Budyko plot for 2014–2021 indicated that the catchment operates under a predominantly water-limited regime, with the annual point lying above the Budyko curve at a PET/P ratio of about 1.8 and an AET/P of roughly 0.85, suggesting relatively high evaporative indices despite limited rainfall (Fig 9). The Rabi season shows an even higher PET/P of about 2.6 but an AET/P close to 1.29, implying that during this dry season atmospheric demand far exceeds precipitation and much of the evapotranspiration is likely sustained by soil moisture storage and groundwater abstraction, which can intensify water stress and deplete subsurface reserves (Manjunatha et al., 2024c). The Kharif season point, with PET/P around 0.9 and AET/P near 0.60, plots closer to the energy-limited side, indicated that during the monsoon months water availability was relatively better and evapotranspiration was constrained more by available energy than by rainfall, supporting enhanced crop growth and partial replenishment of soil and groundwater stores, though not enough to fully compensate the high dry-season demand.

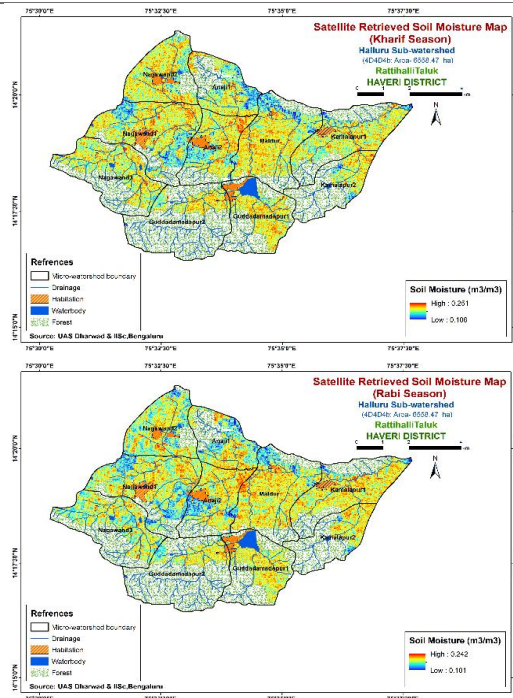
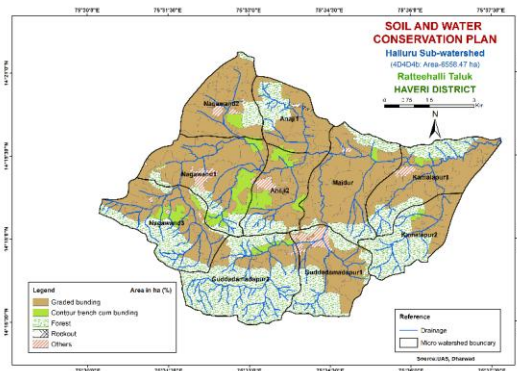


Fig. 10 Satellite retrieved soil moisture (Kharif and Rabi season) of Hallur sub watershed

The satellite-derived soil moisture maps for the Hallur sub-watershed revealed marked seasonal and spatial variability (Fig. 10). During the Kharif season, moisture was highest along drainage channels, valley bottoms and around the central waterbody (up to  $\sim 0.28 \text{ m}^3 \text{ m}^{-3}$ ), while upland and mid-slope areas remain relatively dry ( $\sim 0.11 \text{ m}^3 \text{ m}^{-3}$ ), reflecting the influence of topography, soil texture and land use on water distribution. Valleys benefit from runoff accumulation and shallow groundwater, whereas well-drained, coarse-textured, or intensively cultivated uplands experience rapid water loss through infiltration and evapotranspiration. In the Rabi season, surface moisture generally declines, with most areas ranging between  $0.10\text{--}0.16 \text{ m}^3 \text{ m}^{-3}$  and wetter pockets (up to  $\sim 0.24 \text{ m}^3 \text{ m}^{-3}$ ) confined to low-lying zones and waterbody fringes. Limited post-monsoon rainfall, high evaporative demand, ongoing crop water uptake and irrigation practices exacerbate drying in upland and mid-slope areas, leaving large portions of the watershed susceptible to moisture stress (Hussain et al., 2024). These patterns indicate that while low-lying and valley regions maintain relatively better water availability, upland fields require targeted soil moisture conservation, mulching and supplemental irrigation to sustain crop growth and productivity during the dry season (Juma et al., 2024).



**Fig. 11** Proposed conservation plan of Hallur sub watershed

The soil and water conservation plan for the Halluru sub-watershed in Rattihalli taluk, Haveri district, identifies priority zones for interventions such as graded bunding, contour trench-cum-bunding and rock-out structures (Fig. 11). These measures are primarily concentrated along cultivated hill slopes and upper catchment areas, while forested patches remain limited to small central and northern sections. Graded bunds on gently sloping agricultural lands were designed to control sheet erosion, retain soil moisture and enhance groundwater recharge by reducing runoff velocity (Manjunatha et al., 2024b). Contour trenches and bunds on steeper mid-catchment slopes intercept surface flow, increase infiltration and stabilize erodible soils. Rock-out structures and other similar interventions along drainage channels help prevent gully formation, mitigate peak flows and protect downstream fields and settlements from sedimentation and flooding. Overall, the spatial distribution of these conservation measures reflects careful integration of land use, topography, and drainage patterns to optimize hydrological benefits and support sustainable agricultural productivity across the watershed.

## Conclusions

The comprehensive analysis of the Halluru sub-watershed highlights its complex interplay of topography, soil, land use, rainfall variability and hydrological processes, which collectively influence water availability, soil moisture dynamics and agricultural productivity. Steep upper catchments generate rapid runoff, while lower valleys favour water accumulation and groundwater recharge, further modulated by heterogeneous soil infiltration rates and seasonal evapotranspiration patterns. Rainfall deficits during kharif and rabi seasons, combined with limited high-intensity rainfall events, contribute to seasonal moisture stress, particularly in upland and mid-slope

areas, while satellite-derived soil moisture and groundwater trends confirm long-term depletion and incomplete aquifer recovery. The predominance of agricultural land, low forest cover and intensive water use exacerbate pressure on soil and water resources, emphasizing the vulnerability of the watershed to climatic fluctuations and anthropogenic impacts. Implementation of targeted soil and water conservation measures including graded bunds, contour trenches and rock-out structures aligned with topography and land use, can mitigate erosion, enhance infiltration, improve moisture retention and support sustainable groundwater recharge.

## Statements and Declarations

### Data Availability Statement

Raw data supporting this study are available from the corresponding author upon request.

### Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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