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Integrating land resource inventory and hydrology to transform rainfed agriculture towards sustainable intensification

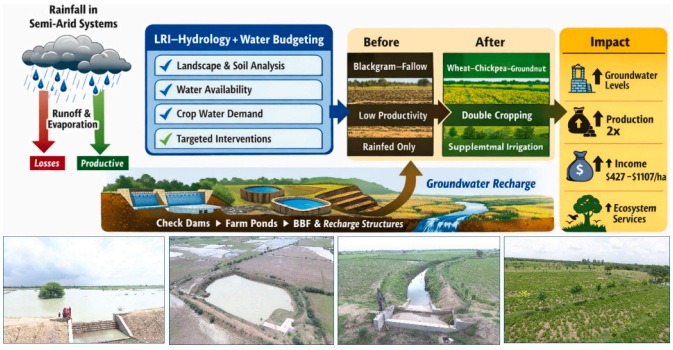
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HIGHLIGHTS

- Integrated LRI–hydrology framework links soil, water, and cropping systems.
- Rainfall partitioning, not rainfall amount, governs water availability
- Landform interventions reduced runoff by ~20–40% and improved soil moisture.
- Water budgeting enabled alignment of crop demand with available water supply.
- Landscape application doubled production and increased farm income substantially.

GRAPHICAL ABSTRACT



ARTICLE INFO

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ABSTRACT

Context: Rainfed agriculture in semi-arid regions is constrained not only by rainfall scarcity but also by inefficient conversion of rainfall into plant-available water. Large yield gaps persist because of poor rainfall partitioning, limited soil-moisture storage, and weak integration of land, water, and cropping-system management.
Objective: This study aimed to develop and validate an integrated Land Resource Inventory (LRI)–hydrology framework for improving water availability and guiding sustainable cropping-system intensification in semi-arid rainfed systems.
Methods: The framework was developed using long-term experimental evidence from ICRISAT's heritage watersheds in Alfisols and Vertisols, integrating soil–water characterization, rainfall–runoff relationships, landform management, and water budgeting. It was subsequently applied in Bundelkhand, central India, across a ~ 5000-ha geographical landscape (~3000 ha agricultural land), using LRI-based planning, hydrological analysis, and targeted natural resource management interventions.

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Results and conclusions: Heritage watershed results demonstrated strong contrasts in soil–water dynamics, with Vertisols (150–200 mm plant-available water) providing greater moisture-buffering capacity than Alfisols (80–120 mm). Raised-bed landform interventions reduced runoff by ~20–40% and improved rainfall retention and soil-moisture availability. At landscape scale, targeted interventions created ~731,000 m^3 of additional water-storage capacity and substantially improved shallow groundwater availability. The landscape-equivalent supplemental irrigation requirement increased from ~35 to ~78 mm as cropping systems intensified; the incremental demand (~43 mm) was comparable to the estimated additional annual runoff-harvesting opportunity (~40–45 mm), complemented by in-situ moisture conservation. Improved water availability enabled a transition from moisture-limited systems, including blackgram-based systems and seasonal fallows, towards more intensive and diversified systems involving groundnut, wheat, and chickpea. Agricultural production more than doubled, while net returns increased from USD 427 to 1107 ha^{-1} $year^{-1}$ (approximately USD 854 to 2214 $household^{-1}$ $year^{-1}$). The results demonstrate that integrating soil, hydrology, water availability, and crop-water demand can support sustainable intensification through improved management of available landscape resources.
Significance: The LRI–hydrology framework provides a scalable and replicable approach for translating soil and hydrological understanding into landscape-level decisions on water harvesting, cropping-system design, and resource management. It offers a pathway for improving water productivity, strengthening climate resilience, and supporting land degradation neutrality across semi-arid rainfed agro-ecologies in Asia and Africa.

1. Introduction

Rainfed agriculture dominates global agricultural systems, accounting for nearly 60–65% of the world's cultivated land and contributing about 40% of total food production (Rockström et al., 2009). It supports the livelihoods of nearly two billion people, particularly in semi-arid regions of Asia and sub-Saharan Africa, where farming systems are highly dependent on variable and uncertain rainfall (FAO, 2021; Rosegrant et al., 2009). Despite its global significance, rainfed agriculture continues to face persistent and widening yield gaps, often producing only a fraction of its potential due to soil degradation, nutrient depletion, poor infiltration, limited water retention, and increasing climate variability (Mueller et al., 2012; Godfray et al., 2010).

In rainfed systems, the primary challenge is not just water scarcity, but how effectively rainfall is partitioned into productive and non-productive components (Rockström et al., 2003; Rockström et al., 2010). Studies indicate that nearly 50–70% of rainfall in rainfed landscapes is lost as unproductive runoff or evaporation, leaving only a limited proportion available for crop uptake and groundwater recharge (Falkenmark and Rockström, 2006). This inefficient rainfall partitioning compounded by land degradation and climate variability, resulted in low water-use efficiency, production risks, and greater vulnerability to drought, particularly in semi-arid regions of Asia and Africa (Li et al., 2014). Together, these factors highlight the urgent need for approaches that enhance rainwater capture and productive use while restoring soil and hydrological functions at the landscape scale (Sishodia et al., 2016; Wani et al., 2017; Wable et al., 2021).

Over the past several decades, watershed-based natural resource management (NRM) interventions have been widely promoted to address these constraints. Evidence shows that such interventions can bridge yield gaps by 30–60%, improve water-use efficiency, enhance groundwater recharge, and increase farm incomes without expanding cultivated land (Rao et al., 2007; Ravula et al., 2020; Anantha et al., 2021a; Anantha et al., 2021b; Garg et al., 2020a; Dev et al., 2022). In addition to agronomic benefits, watershed programs generate multiple ecosystem services, including improved water availability, reduced soil erosion, enhanced soil carbon and strengthened resilience to climate variability (Millennium Ecosystem Assessment, 2005). However, despite these successes, watershed programs often remain infrastructure and intervention-driven (Wani et al., 2009; Wani et al., 2011), with limited integration of spatial variability in soil and landscape characteristics, hydrological processes, water availability and cropping system requirements within a unified planning framework.

A key limitation of current approaches is the lack of systematic integration between Land Resource Inventory (LRI), hydrological processes, and cropping system planning. LRI provides detailed spatial information on soil depth, texture, slope, and land capability, which fundamentally govern infiltration, runoff generation, and soil water storage. These processes determine how rainfall is partitioned into soil moisture, runoff, and groundwater recharge, thereby influencing the effective water available for crop production (Prasad et al., 2022). Despite this process-level understanding, soil–hydrology relationships are rarely integrated with quantitative water budgets to determine how much water is available and which cropping systems can be sustainably supported.

Long-term experimental watershed studies, often referred to as heritage watershed datasets, provide a strong scientific basis for understanding rainfall–runoff relationships, infiltration dynamics, erosion processes, and seasonal water balances (Garg and Wani, 2012; Green et al., 2020). These datasets offer valuable insights into soil–water–crop interactions under controlled conditions (Pathak et al., 2004; Pathak et al., 2013; Garg et al., 2022). However, a key limitation in the literature is that such process-level hydrological knowledge often remains confined to experimental or academic analysis, with limited translation into actionable frameworks for agricultural and landscape planning (Karlberg et al., 2015). Bridging this gap requires converting process-based understanding into operational frameworks that can guide cropping system design and resource allocation in real-world farming systems (Nune et al., 2021).

Water budgeting provides a practical pathway to operationalize this integration. By quantifying the balance between rainfall inputs, runoff losses, soil water storage, and groundwater recharge, water budgets enable direct estimation of water available for crop production (Garg et al., 2011; Garg et al., 2013; Garg et al., 2020b). When combined with LRI and hydrological information, water budgeting can align crop water demand with available water supply, thereby improving water productivity, economic returns and resilience to rainfall variability (Molden et al., 2010; Anantha et al., 2022; Anantha et al., 2023a, 2023b). However, the application of water budgeting as a decision-support tool for cropping system optimization remains limited, particularly at landscape and community scales. Such an integrated approach has broader relevance for semi-arid regions of Asia and sub-Saharan Africa, where rainfall variability, degraded soils, and limited irrigation infrastructure constrain sustainable agricultural intensification.

This study addresses these gaps by developing and validating an integrated framework that links LRI, hydrological processes, water budgeting, and cropping system design, and demonstrates its applicability from experimental research to real-world landscapes. The framework combines long-term experimental evidence from ICRISAT's heritage watershed in Alfisols and Vertisols with landscape scale application in the Bundelkhand region of central India. This experimental-to-landscape approach enables process-level understanding of rainfall partitioning and soil–water–crop interactions to inform water budgeting, targeted NRM interventions, and cropping-system

planning under real-world farming conditions.

Specifically, the objectives of this study are to: i) quantify how contrasting soil properties, infiltration behaviours and landform management regulate rainfall partitioning and water availability through rainfall partitioning and plant-available water in Alfisols and Vertisols; (ii) evaluate how differences in water availability influence cropping-system performance under contrasting rainfall regimes; (iii) integrate LRI, hydrological assessment, and water budgeting to identify landscape-level water supply–demand gaps and guide the spatial targeting of NRM interventions; and (iv) assess changes in groundwater availability, cropping systems, agricultural production, and farm income following landscape-scale implementation of the framework. By linking process understanding with field-scale implementation, this study advances a systems-based and scalable approach for sustainable intensification of rainfed agriculture, with strong relevance for broader application across Asia and Africa.

2. Materials and methods

2.1. Integrated LRI–hydrology framework for water budget–based cropping system design

This study employs an integrated Land Resource Inventory (LRI)–hydrology framework to guide water budgeting, cropping system design, and landscape-scale natural resource management in rainfed environments. The framework is designed to translate process-based understanding of soil–water interactions into actionable planning and decision-support tools. It was operationalized using long-term experimental evidence from ICRISAT's heritage watershed sites and subsequently applied at landscape scale in the Bundelkhand region (Jhansi district, central India).

The framework consists of four interlinked components: (i) landscape characterization, (ii) resource availability assessment, (iii) resource demand estimation, and (iv) bridging the supply–demand gap (Fig. 1). Together, these components provide a systematic approach for aligning land and water resources with crop water requirements under variable rainfall conditions.

The first component, landscape characterization, involves detailed assessment of the biophysical and socio-economic attributes of the system. This includes soil properties (depth, texture, structure, water-holding capacity and nutrient availability), land slope, land use, existing cropping systems, and available infrastructure related to water harvesting and irrigation. In addition, socio-economic aspects such as farm size, population, livestock, access to resources, and management practices are considered. This component, largely derived from LRI, provides the spatial foundation for understanding variability in runoff generation, infiltration potential, and soil moisture storage across the landscape.

The second component focuses on resource availability, which is quantified through water budgeting. Water availability is primarily a function of LRI-derived land characteristics and meteorological parameters, particularly rainfall and temperature. Using hydrological measurements, rainfall is partitioned into key components including surface runoff, soil water storage, and groundwater recharge. This enables estimation of the effective water available for crop use at seasonal and annual scales. The water budgeting approach thus provides a quantitative measure of supply, reflecting both natural resource endowment and hydrological behavior of the system.

The third component addresses resource demand, which represents the water requirements of different cropping systems, domestic and other sectors. Crop water demand is determined based on crop type, growth duration, rooting depth, and climatic conditions. This component enables estimation of water requirements at crop and system levels, allowing comparison between available water (supply) and crop water needs (demand). Such assessment is critical for identifying mismatches between existing cropping patterns and the hydrological capacity of the landscape.

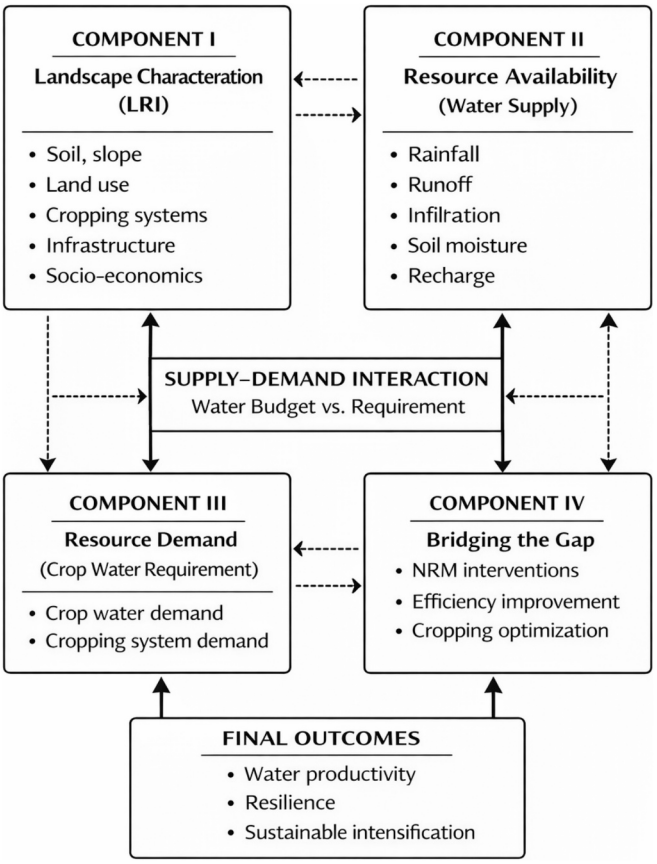


Fig. 1. Integrated LRI–hydrology framework for water budget–based cropping system design.

The fourth component focuses on bridging the gap between resource availability and demand. At the landscape scale, rainfall availability was partitioned into surface runoff, groundwater recharge, and soil-moisture storage. Surface runoff was estimated using the rainfall–runoff relationships derived from the long-term heritage watershed experiments, while groundwater recharge was estimated from changes in groundwater levels. The remaining fraction represented water retained within the landscape, primarily as soil moisture available during and following the monsoon season. This water-supply assessment was then linked with the existing spatial and seasonal cropping pattern and associated water demand.

Crop water demand was estimated from reference evapotranspiration (ETo) and crop coefficients (Kc) for the respective crops and growing periods (*Eq.1*). The estimated crop water requirement was compared with water available from rainfall-derived soil moisture to determine the extent to which crop demand could be met by landscape itself (through available residue moisture) and the additional water requirement that would need to be supplied from groundwater. This supply–demand assessment explained the observed seasonal cropping pattern, where some fields supported only kharif crops, others supported rabi crops using residual soil moisture and/or groundwater, while fields with sufficient water availability supported both kharif and rabi crops. Fields where available water was inadequate to meet crop demand remained seasonally or permanently fallow.

Crop water requirement was estimated as:

$$CWR = \sum_{t=1}^{n} Kc_t \; x \; ET0_t \tag{1}$$

where CWR is Crop Water Requirement over the entire crop-growing

season (in mm); ET_0 is Reference evapotranspiration. It represents the atmospheric demand for water from a reference surface and is estimated using the FAO Penman–Monteith method (Allen et al., 1998); *Kc* is Crop coefficients at various crop stages (shown by time step, t); t is time step used in the calculation at 10-days interval based on crop-growth-stage (NWDA, 2019).

Resource-use efficiency was therefore assessed in terms of the productive utilization of available landscape water. Seasonal and permanent fallows were considered indicative of underutilized landscape moisture, where a larger fraction of available water could be lost through non-productive evaporation rather than crop transpiration. The framework consequently evaluated opportunities to convert runoff into additional soil-moisture storage and groundwater recharge through targeted NRM interventions. This augmented water supply was first allocated to bridging the water deficit of existing cropping systems and, where additional water was available, to supporting crop intensification through expansion of cultivated area, double cropping, and supplemental irrigation.

The identified demand-supply gap was addressed through three complementary pathways: (i) resource augmentation, including in-situ soil and water conservation, runoff harvesting, and groundwater recharge; (ii) improving resource-use efficiency by reducing non-productive evaporation losses and increasing productive use of available soil moisture and groundwater; and (iii) cropping system adaptation and intensification by selecting crop and crop sequences (cropping systems) that better matched the available water source. The choice of interventions depends on site-specific conditions derived from LRI and hydrological assessment.

The integrated framework thus establishes a structured linkage between land characteristics, hydrological processes, water availability, and cropping system decisions. By explicitly quantifying both supply and demand components and identifying pathways to bridge their gap, the approach enables informed planning of natural resource management interventions and cropping strategies. The framework also facilitates scaling from experimental watershed-level understanding to landscape-level application, providing a basis for improving water productivity, enhancing resilience, and supporting sustainable intensification of rainfed agriculture.

2.2. Long term experiment at ICRISAT heritage watershed

The long-term experiments were conducted at ICRISAT's heritage watershed research site located at Patancheru, Telangana, India (17°27′N, 78°16′E). The site represents a semi-arid tropical environment characterized by high rainfall variability and predominantly rainfed agricultural systems. The mean annual rainfall is 850 mm with most precipitation received during the southwest monsoon season (June–October). The heritage watershed experiments at ICRISAT represent one of the longest-running datasets on soil–water–crop interactions in semi-arid regions. These experiments were initiated in 1975 for Vertisols and in the early 2000s for Alfisols and have evaluated the effects of landform management and cropping systems on hydrological processes and agricultural productivity under rainfed conditions.

For the present study, a consistent 10-year analysis period (2000−2010) was selected from the long-term experimental records to ensure comparability across soil types, treatments, and hydrological variables. While the experiments span multiple decades, only data within this defined period were used for detailed analysis of rainfall partitioning, soil moisture dynamics, and crop performance. The experimental setup comprises paired micro-watersheds of approximately 3.5 to 5.0 ha each, established to evaluate the impact of landform and cropping system interventions on hydrological processes (Pathak et al., 2016; Anantha et al., 2022). The study includes contrasting soil types, primarily Alfisols and Vertisols, which represent dominant soil groups across semi-arid regions of India and similar agro-ecologies in Asia and Africa.

To characterize soil physical properties, detailed profile-wise soil sampling was undertaken at five representative locations within the experimental watersheds to capture spatial variability. Soil samples were collected at multiple depths (15 cm interval) and analyzed for particle size distribution (% sand, silt and clay), bulk density, and soil water retention characteristics including field capacity and permanent wilting point (Table 1A**)**. These measurements enabled estimation of plant-available water and supported interpretation of soil moisture dynamics across soil types. A paired watershed approach was adopted, wherein one watershed was managed under an improved landform system and the other under conventional farmer practice. The improved system consisted of Broad Bed and Furrow (BBF raised-bed) landform, designed to enhance infiltration, reduce runoff velocity, and improve soil moisture storage. The control watershed was maintained under flatbed conditions, representing traditional management practices. Cropping treatments included intercropping (e.g., sorghum–pigeonpea, groundnut–pigeonpea) and sequential systems (e.g., maize–chickpea) under improved landform conditions, while traditional systems largely followed fallow–post-rainy season cropping patterns (Table 1B and Table 1C). Crop yields were determined using standard crop-cutting methods at harvest with measurements undertaken at a minimum of three representative locations within each treatment during the respective cropping season to account for spatial variability. Soil-moisture measurements were similarly undertaken at three representative locations within each treatment at each sampling interval.

To understand soil hydraulic behavior, tension disc infiltrometer measurements were conducted to assess infiltration characteristics (by applying suction at −15, −10, and − 5 cm) and near-saturated hydraulic conductivity for different soil types (Garg et al., 2022). Soil moisture dynamics were monitored at multiple depths (0–15, 15–30, and 30–45 cm) using gravimetric measurements at three representative locations within each treatment at each sampling interval, thereby capturing both spatial and temporal variability in soil-water availability during the cropping seasons.

Runoff was monitored using H-flumes installed at the outlet of each experimental watershed, coupled with stage recording systems to measure runoff at high temporal resolution. Runoff depth and discharge were computed using calibrated rating curves. As runoff represents the integrated hydrological response of the entire contributing watershed, measurements were made at a single outlet for each experimental watershed; however, multiple rainfall–runoff events were recorded within each season and across years to characterize temporal variability. Thus, crop and soil-moisture measurements incorporated spatial

Table 1A
Summary of measured soil, hydrological, and crop indicators; their measurement methods used in the ICRISAT heritage watershed experiments.

Parameters	Measurement method	Reference
Per cent sand, silt, clay	Hydrometer method;	Beverwijk, 1967
Bulk density	core-cutter method	Cresswell and Hamilton, 2002
Soil water retention (Field capacity (FC), permanent wilting point (PWP)	Pressure-plate apparatus at −0.3 and − 15 MPa;	Richards, 1948
Infiltration and hydraulic conductivity,	Tension-disc infiltrometer at different suction heads	Watson and Luxmoore, 1986
Soil moisture (Profile/ root-zone soil water)	Gravimetric sampling	Periodic measurements (10 days interval) during crop seasons
Surface runoff	H-flume with stage recorder	Daily/event-based long-term monitoring (Chow, 1959; Garg et al., 2022)
Grain yield	Crop-cutting at harvest; yields converted to sorghum-equivalent yield	Plot-wise and season-wise (Anantha et al., 2023b)

Table 1B
Experimental details of Vertisols between 1976 and 2010.

System	Improved system				Traditional practice	
Watershed area (ha)	3.48				3.41	
Land slope (%)	1.8–2.0%				1.8–2.0%	
Landform	Raised Bed (Plot 1 and Plot 2)				Flat land (plot 3 and plot 4)	
Cropping system	i) Sorghum/ Pigeon pea		ii) Maize-Chickpea		iii) Fallow-Sorghum	iv) Fallow-Chickpea
Experimental years	1976–2009		1976–2009 (Alternate)		1979–2009	1979–2009
No of year experiments undertaken	11 Years		24 Years		35 Years	35 Years
Crops cultivated	Sorghum	Pigeon pea	Maize	Chickpea	Rabi Sorghum	Chickpea
Sowing Months	June	June	June	Oct	Oct	Oct
Harvesting Months	Oct	Feb	Oct	March	March	March
Fertilizer application	60 Kg N/ha 20 Kg P/ha		60 Kg N/ha 20 Kg P/ha		10 t ha^{-1} of farmyard manure (alternate year)	

Table 1C
Experimental details of Alfisols between 2002 and 2009.

Cropping system	Land form	1. Sole Sorghum	2. Groundnut intercrop pigeon pea		3. Sole Castor	4. Sorghum intercrop Pigeon pea	
Experimental years		2002–2006	2002–2006		2007–2009	2007–2009	
No of year experiments undertaken		5	5		3	3	
Fertilizer application	Raised bed (Plot 1 and 2)	40 kg N/ha; 40 kg P_2O_5/ha	20 kg N/ha; 40 kg P_2O_5/ha		40 kg N/ha; 40 kg P_2O_5/ha	40 kg N/ha; 40 kg P_2O_5/ha	
	Flat land (plot 3 and 4)	10 ton/ha FYM (every alternate year)	10 ton/ha FYM (every alternate year)		10 ton/ha FYM (every alternate year)	10 ton/ha FYM (every alternate year)	
Crops cultivated		Sorghum (Kharif)	Groundnut	Pigeonpea	Castor (Kharif)	Sorghum ((kharif)	Pigeonpea
Sowing months		June	June	June	June	June	June
Harvesting months		Oct	Oct	Feb	Oct	Oct	Feb

Land slope = 1.6%.

replication within the experimental watersheds, whereas runoff was monitored as an integrated watershed-scale response with repeated observations across rainfall events and years.

Economic performance of the cropping systems was assessed in terms of net returns (NR), calculated as the gross value of crop production minus the corresponding cost of cultivation, following *Eq. 2*:

$$NR = Y\,x\,P - CoC \tag{2}$$

where NR is net returns (USD ha^{-1}), Y is crop yield (t ha^{-1}), P is the corresponding crop price (USD t^{-1}), and COC is the cost of cultivation (USD ha^{-1}). The cost of cultivation included major variable costs associated with crop establishment and management, including seed, land preparation, fertilizers and other crop inputs, labour and field operations, together with the additional cost of raised-bed preparation (Anantha et al., 2023b). For intercropping and sequential cropping systems, net returns from individual component crops were summed to estimate annual system-level net returns.

To enable comparison of productivity among cropping systems comprising different crops, individual crop yields were converted to sorghum-equivalent yield (SEY, refer *Eq. 3*) based on their relative market prices (Anantha et al., 2023b):

$$SEY = \frac{Y\,x\,P}{P_s} \tag{3}$$

where SEY is sorghum-equivalent yield (t ha^{-1}), Y is crop yield (t ha^{-1}), P is the corresponding crop price (USD t^{-1}), and Ps is the price of sorghum (USD t^{-1}). For intercropping and sequential cropping systems, the SEY of individual component crops was summed to estimate annual system-level productivity.

Analysis of variance (ANOVA) was applied to variables with replicated observations, including soil physical properties (soil texture and bulk density), to assess differences between the contrasting soil types. ANOVA was also used to evaluate differences in runoff response between landform treatments across rainfall-intensity classes, based on the replicated rainfall–runoff events. Statistical significance was evaluated at $p < 0.05$. Soil water-retention characteristics, infiltration characteristics, and associated hydrological responses were interpreted primarily through their measured magnitudes and process relationships, as these variables were used to characterize the contrasting water-storage and moisture-supplying capacities of Alfisols and Vertisols.

2.3. Landscape-scale application in Jhansi cluster

The integrated LRI–hydrology framework was applied at landscape scale in the Bundelkhand region of central India, specifically in Sutta and Singar villages of Jhansi district, covering a geographical area of approximately 5000 ha (Fig. 2). The region represents a semi-arid agro-ecosystem characterized by erratic rainfall, degraded land resources, and chronic water scarcity (Dev et al., 2022). Bundelkhand is widely recognized as one of the most drought-prone regions in India, where agriculture is predominantly rainfed and highly vulnerable to monsoon variability. A substantial proportion of cultivable land remains fallow either during monsoon (kharif) or the post-monsoon (rabi) season, primarily due to limited soil moisture storage and inadequate groundwater availability. High-intensity rainfall events often result in rapid runoff and low infiltration, leading to inefficient rainwater utilization and reduced cropping intensity. These conditions have historically constrained agricultural productivity and livelihood security (Garg et al., 2020b).

To address these challenges, the integrated LRI–hydrology framework was implemented during 2018–2022 with support from the Government of Uttar Pradesh. Detailed Land Resource Inventory (LRI) and hydrological assessments were undertaken to delineate landscape units based on soil depth, slope, land use, and hydrological response, while the baseline biophysical and agricultural characteristics of the study landscape are summarized in Table 1D. These assessments enabled identification of runoff generation zones, recharge potential areas, and suitable locations for targeted interventions, forming the basis for spatial planning.

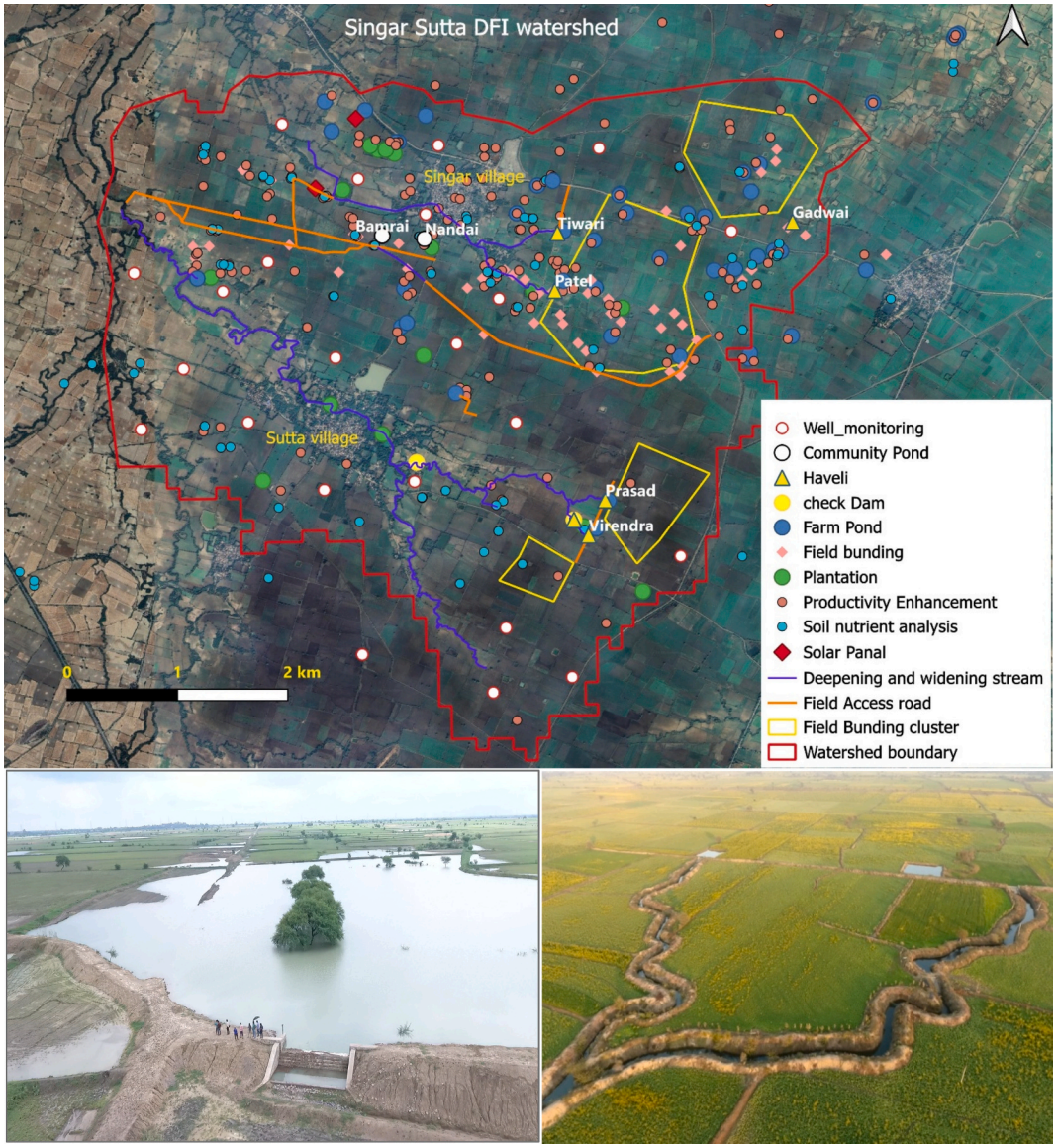


Fig. 2. Location of the Jhansi cluster showing the implementation of natural resource management (NRM) and resource use efficiency interventions; (bottom left) harvested water in a haveli structure; and (bottom right) deepening and widening of the stream network with check plugs.

Based on this assessment, a range of natural resource management (NRM) interventions was implemented to enhance water availability and improve landscape hydrological functioning (Fig. 2). These included large-scale rainwater harvesting structures (i.e., *haveli* cultivation), deepening and widening of existing stream networks, and construction of farm ponds and check dam structures to promote groundwater recharge.

The selection, type, location, and capacity of NRM interventions followed a water demand–supply assessment combined with LRI and hydrological analysis. Crop water requirement represented the total water demand of a crop or cropping system over its growing period, whereas supplemental irrigation requirement represented the additional water needed after accounting for the moisture-supplying capacity of the landscape. The latter was estimated by integrating process understanding and rainfall–runoff relationships derived from the heritage watershed experiments with site-specific rainfall characteristics of the Jhansi landscape. The heritage watershed relationships were not transferred directly; rather, rainfall amount, event characteristics, and temporal distribution at Jhansi were considered together with local soil and landscape characteristics to estimate runoff generation and the proportion of rainfall retained within the landscape. For a representative seasonal rainfall of approximately 600 mm, this assessment estimated about 90–100 mm of surface runoff and approximately 20–30 mm of groundwater recharge, with the remaining effective rainfall, after accounting for other hydrological losses, providing the principal source of soil-moisture supply to crops. This estimated landscape moisture-supplying capacity was then considered in determining the supplemental irrigation requirement of the prevailing and targeted cropping systems.

For landscape-scale assessment, the supplemental irrigation requirement of individual cropping systems was multiplied by their respective cultivated areas, and the aggregated water demand was expressed as an equivalent water depth over the total geographical area of 5000 ha. This enabled direct comparison between landscape-level supplemental water demand and the additional water-harvesting potential required to bridge the identified demand–supply gap.

Interventions followed an upland-to-downstream and decentralized treatment approach. Upland areas were prioritized for in-situ soil and water conservation to retain rainfall near its point of occurrence, reduce erosive runoff and sediment movement, and enhance infiltration and

Table 1D
Soil biophysical and nutrient characteristics along with demographic details of the Jhansi cluster.

Parameters	Values	Methods/Source
Village names	Sutta and Singar, Jhansi district, Uttar Pradesh, India	
Geographical area (ha)	4550	Village census
Agricultural land (ha)	2995	Village census
No of Households (–)	1450	Village census
Average land holding (HH/ha)	2.05	
No. of samples collected for undertaking soil biophysical and nutrient analysis	200	
Coarse sand, %	7.07	hydrometer method (Sarkar and Haldar, 2005).
Fine sand, %	34.5	hydrometer method
Clay, %	33.4	hydrometer method
pH	8.19	1:2 soil:water slurry: pH meter
EC, dS m^{-1}	0.23	1:2.5 soil:water slurry: EC meter
SOC, %	0.4	chromic acid digestion method (Walkley and Black, 1934)
Av. P (mg/kg)	8.4	Olsen's and Bray's method using a continuous auto-analyser (Olsen and Sommers, 1982)
Ex. K (mg/kg)	137	The ammonium acetate method to extract available cations (Ca, Mg, Na, and K (Hanway and Heidel, 1952).
Ex. Ca (mg/kg)	4517	
Ex. Mg (mg/kg)	346	
Ex. Na (mg/kg)	126	
Av. S (mg/kg)	10.7	0.15% $CaCl_2$ extraction (Tabatabai, 1996)
Av. B (mg/kg)	0.56	The hot-water extraction method was followed for available B (Keren, 1996)
Av. Fe (mg/kg)	3.35	A flame photometer (Systronics India Ltd., Ahmedabad, India) was used to measure exchangeable cation concentrations. Micronutrients such as Fe, Mn, Cu, and Zn were analyzed using the diethylenetriamine penta-acetic acid (DTPA) extraction method and an inductively-coupled plasma spectrometer (Model: HD prodigy; Teledyne Leeman Labs, USA)
Av. Zn (mg/kg)	0.18	
Av. Cu (mg/kg)	0.62	
Av. Mn (mg/kg)	3.35	

groundwater recharge. Ex-situ rainwater-harvesting structures were subsequently located along suitable drainage pathways to capture the remaining runoff and support surface storage, groundwater recharge, and downstream baseflow. Combining in-situ and ex-situ measures was also considered important for the sustainability of storage structures, as treatment of contributing uplands reduces sediment delivery and subsequent loss of storage capacity. Decentralized interventions were preferred, where technically feasible, to distribute hydrological and agricultural benefits across a larger number of farmers and landscape positions rather than concentrating benefits only in middle and downstream areas. Final intervention selection and sizing therefore considered not only biophysical and hydrological suitability, but also available investment, land availability, farmer acceptance, expected number of beneficiaries, and hydrological performance under high-runoff events, rather than relying solely on average runoff conditions. Details of the interventions, including structure type, location, dimensions, and storage capacity are summarized in Supporting **Tables A–B**.

To evaluate hydrological impacts, groundwater dynamics were monitored monthly in 26 existing farmer-owned dug wells spatially distributed across the study watershed to capture spatial and temporal variability in groundwater response. These wells had historically been developed by farmers for domestic and agricultural water supply and represented the locally utilized shallow groundwater system within the weathered and fractured hard-rock aquifer. The monitored dug wells were approximately 5–10 m in diameter and 8–15 m deep. Total well depth was determined through physical measurements and cross-checked with information obtained from well owners. Depth to groundwater was measured manually from the ground surface using a water-level indicator. To minimize the influence of pumping-induced drawdown, farmers were informed in advance of the monitoring schedule, and measurements were undertaken only when pumping had remained suspended for approximately 24–48 h. The same wells were monitored at monthly intervals throughout the assessment period to maintain spatial and temporal consistency.

For interpretation of groundwater availability, measured depth-to-water was converted to hydraulic head, defined in this study as the available water column within the dug well (*Eq*. 4):

$$H = D–DTW \quad (4)$$

where H is the hydraulic head (available water column, m), D is the total depth of the well (m), and DTW is the measured depth to groundwater from the ground surface (m).

Thus, a higher hydraulic head represents a greater water column available in the well. Hydraulic head was subsequently classified into five categories (dry, 0–3.0 m, 3.1–6.0 m, 6.1–9.0 m, and > 9.0 m) to evaluate temporal changes in well-functioning status and groundwater availability. The standardized non-pumping period, repeated monitoring of the same wells, and consistent monthly measurement procedure were used to minimize measurement variability and short-term pumping effects. In addition, land use and cropping system dynamics were assessed through field surveys capturing changes in cropped area, cropping intensity, and reduction in fallow lands.

3. Results

3.1. Soil physical properties at ICRISAT heritage watershed

The soil physical characteristics of Alfisols and Vertisols at the ICRISAT heritage watershed presented in Fig. 3. In Alfisols, the surface layers (0–20 cm) were dominated by sand fractions, with total sand (coarse + fine) exceeding 60–70%, while clay content remained relatively low (approximately 10–20%). With increasing depth, clay content increased gradually, reaching about 20–30% in deeper layers (>60 cm), indicating a weakly developed argillic horizon. In contrast, Vertisols exhibited consistently high clay content (typically 40–60%) throughout the soil profile, with relatively minor variation across depths. This uniform clay-rich structure contributed to higher water retention across all layers. The sub-surface layers (30–90 cm) in Vertisols showed particularly high clay fractions (>50%), which play a dominant role in storing soil moisture and sustaining crops during dry periods. Bulk density profiles further reflected differences in soil structure and compaction (Fig. 4). In Alfisols, bulk density increased with depth, ranging from approximately 1.4–1.5 g cm^{-3} in surface layers to 1.5–1.6 g cm^{-3} in deeper layers (60–100 cm). In Vertisols, bulk density values were comparatively lower in surface layers (~1.2–1.3 g cm^{-3}) and increased moderately with depth (~1.3–1.5 g cm^{-3}), reflecting better aggregation and structural development despite higher clay content. ANOVA confirmed significant differences in soil texture between Alfisols and Vertisols across comparable profile depths (15–90 cm), with sand, silt, and clay contents differing significantly between the two soil types ($p < 0.001$). Profile-average bulk density was also significantly higher in Alfisols (1.53 ± 0.05 g cm^{-3}) than in Vertisols (1.29 ± 0.08 g cm^{-3}; $p < 0.001$).

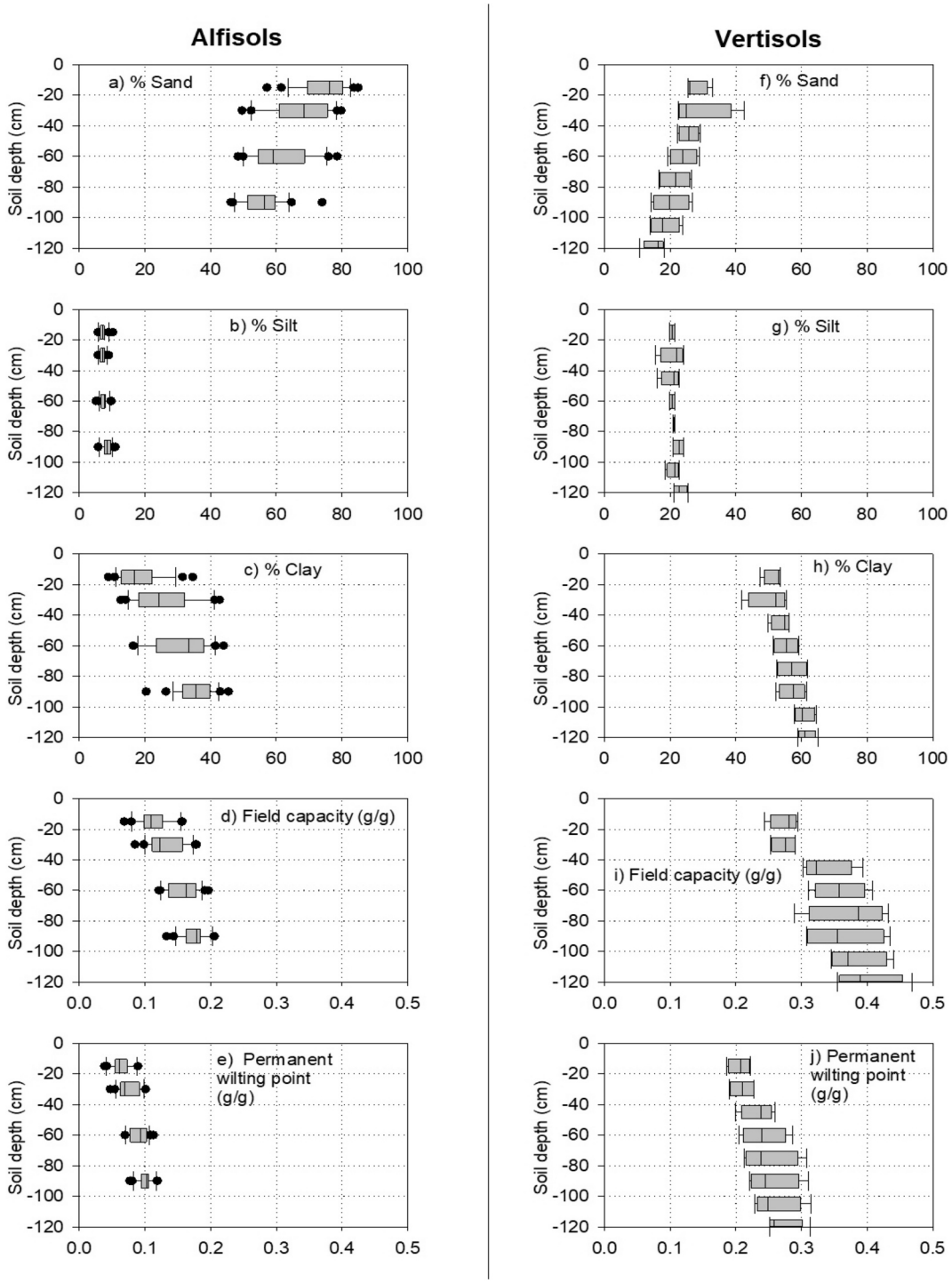


Fig. 3. Depth-wise distribution of soil texture (sand, silt, and clay fractions) and water retention properties (field capacity and permanent wilting point) in Alfisols and Vertisols at the ICRISAT heritage watershed.

Soil water retention characteristics, expressed through field capacity (FC) and permanent wilting point (PWP), showed pronounced differences between the two soil systems (Fig. 3). In Alfisols, FC values ranged from approximately 0.18–0.22 m^3 m^{-3} in surface layers and increased slightly with depth, while PWP values ranged between 0.08 and 0.12 m^3 m^{-3}, indicating limited plant-available water. In contrast, Vertisols exhibited substantially higher FC values (approximately 0.35–0.40 m^3 m^{-3}) and higher PWP values (approximately 0.18–0.22 m^3 m^{-3}) across the profile. Importantly, the difference between FC and PWP, representing plant-available water (PAW), was substantially greater in Vertisols across all depths, particularly in the 30–90 cm layer. Based on these retention characteristics, the estimated water storage for a 1 m soil profile of Vertisols is 350–400 mm of water at field capacity, with about 150–200 mm of plant-available water (FC–PWP). In comparison, Alfisols stored about 180–220 mm of water at field capacity, with 80–120 mm of plant-available water.

3.2. *Hydrological characteristics of Alfisols and Vertisols*

The infiltration behavior of Alfisols and Vertisols measured through

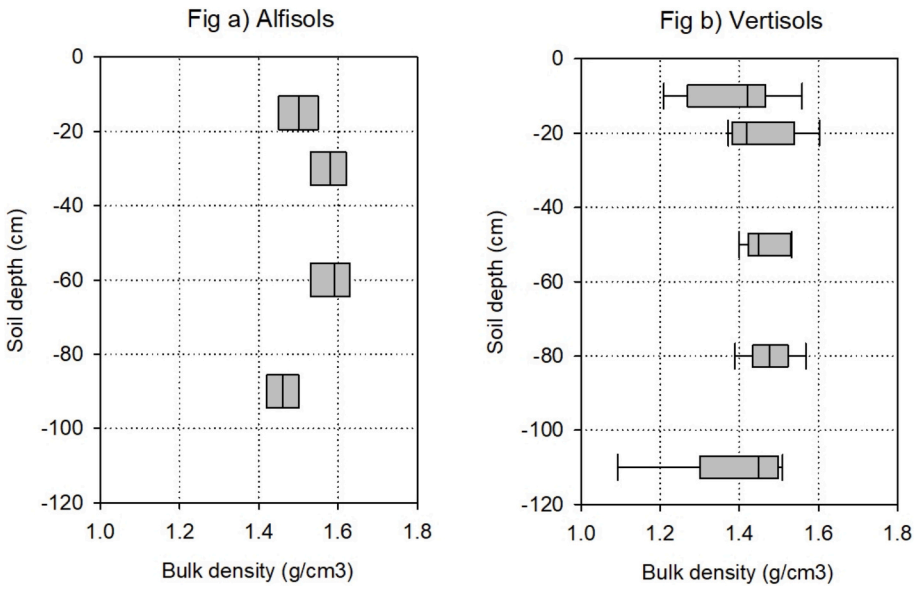


Fig. 4. Depth-wise variation in bulk density in Alfisols and Vertisols at the ICRISAT heritage watershed.

tension disc infiltrometer showed a clear and systematic decline in steady-state infiltration rates with increasing suction, reflecting the progressive exclusion of larger pores and transition from macropore-dominated to matrix-controlled flow (Fig. 5). At near-zero tension, representing near-saturated conditions, infiltration rates were highest in both soil types. In Vertisols, median steady-state infiltration rates were approximately 80–100 mm h^{-1}, with a wide range extending up to ~350 mm h^{-1}, indicating substantial variability and strong contribution of macropores. In Alfisols, infiltration rates were comparatively higher at saturation, with median values around 150–170 mm h^{-1} and maximum values reaching ~330 mm h^{-1}. In Vertisols, infiltration reduced from ~80–100 mm h^{-1} at saturation to approximately 20–40 mm h^{-1} at −50 mm, representing a reduction of nearly 60–70%. Further increases in suction (−100 to −150 mm) reduced infiltration rates to below 10 mm h^{-1}, indicating that most flow at saturation was governed by macropores. This sharp decline confirms the dominance of preferential flow pathways, likely associated with cracks and structural pores typical of Vertisols. In Alfisols, infiltration rates also declined with increasing suction but followed a relatively different pattern. From ~150–170 mm h^{-1} at saturation, infiltration decreased to approximately 30–50 mm h^{-1} at −50 mm, indicating a reduction of about 70–75%. At higher tensions (−100 to −150 mm), infiltration rates dropped to below 10–15 mm h^{-1}, similar to Vertisols.

Further, rainfall–runoff relationships at the ICRISAT heritage watershed sites showed strong dependence on soil type, landform, and rainfall characteristics, reflecting the combined influence of soil physical properties and infiltration behavior. Runoff dynamics were analyzed at three levels: event scale, rainfall category, and seasonal/yearly scale, providing a comprehensive understanding of rainfall partitioning.

Event-wise analysis revealed a strong positive relationship between daily rainfall and runoff generation in both Alfisols and Vertisols (Fig. 6). In Alfisols, runoff increased sharply with increasing rainfall, particularly beyond 40–50 mm rainfall events, indicating limited infiltration capacity and rapid saturation of surface layers. The regression relationships (Fig. 6a) showed stronger runoff response under flatbed conditions, with higher slopes compared to raised bed (BBF) systems, indicating greater runoff generation for the same rainfall magnitude.

In contrast, Vertisols exhibited relatively lower runoff response for comparable rainfall events, particularly under raised bed systems (Fig. 6b). Although Vertisols have lower inherent infiltration, the presence of cracks and macropores allows partial transmission of water, reducing immediate runoff under moderate rainfall conditions. However, under high-intensity rainfall events (>80–100 mm), both soil types showed sharp increases in runoff. Across both soils, the raised bed system consistently reduced runoff compared to flatbed conditions, with the difference becoming more pronounced at higher rainfall magnitudes. This highlights the effectiveness of landform modification in regulating rainfall partitioning at event scale.

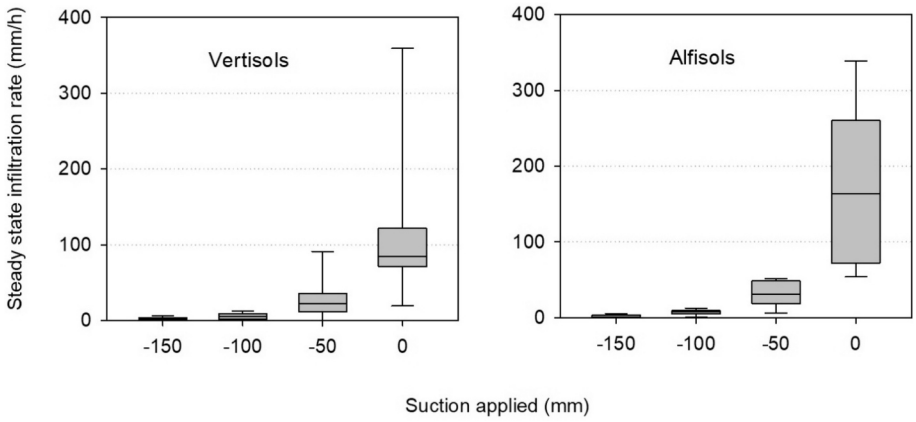


Fig. 5. Infiltration characteristics under varying tension levels showing pore-scale hydraulic behavior in Alfisols and Vertisols.

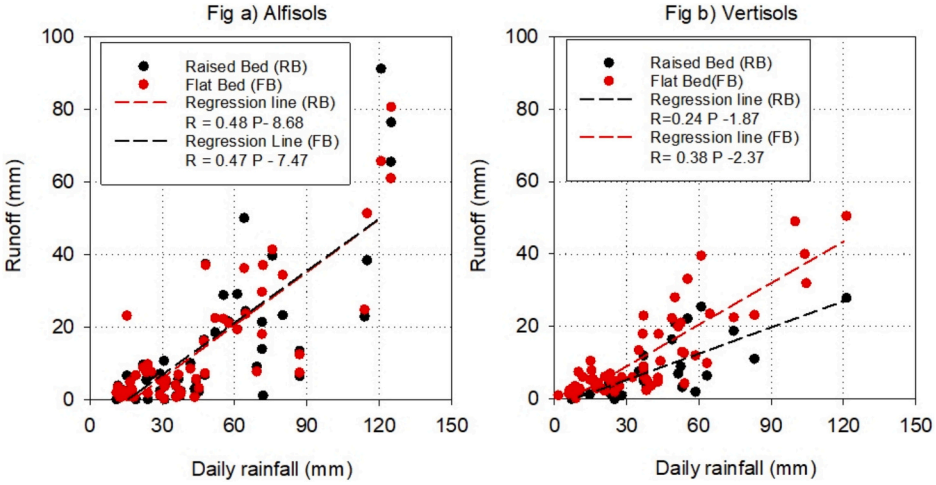


Fig. 6. Event-scale rainfall–runoff relationships under raised bed and flat bed systems in (a) Alfisols and (b) Vertisols.

Rainfall category analysis (Fig. 7) further illustrates how runoff varies with increasing rainfall intensity across soil types and landforms. In Alfisols, runoff increased progressively across rainfall categories, with relatively low runoff (<10 mm) for events below 30 mm rainfall, but rising sharply to 30–80 mm runoff for rainfall events exceeding 80–100 mm, particularly under flatbed conditions. The BBF system significantly reduced runoff across all rainfall categories, although the effect was more pronounced at higher rainfall intensities. In Vertisols, runoff response was comparatively moderated under BBF conditions, with most rainfall categories showing lower runoff values compared to Alfisols. Under flatbed conditions, however, runoff increased substantially with rainfall, reaching 40–50 mm for high rainfall categories (>80 mm).

Across all rainfall regimes (dry, normal, and wet years), runoff generation varied considerably between soil types and management systems (Table 2). In Alfisols, total seasonal runoff ranged from 9 mm (2%) to 213 mm (17–22%) of seasonal rainfall, depending on rainfall conditions and landform. During dry years (573 mm rainfall), runoff

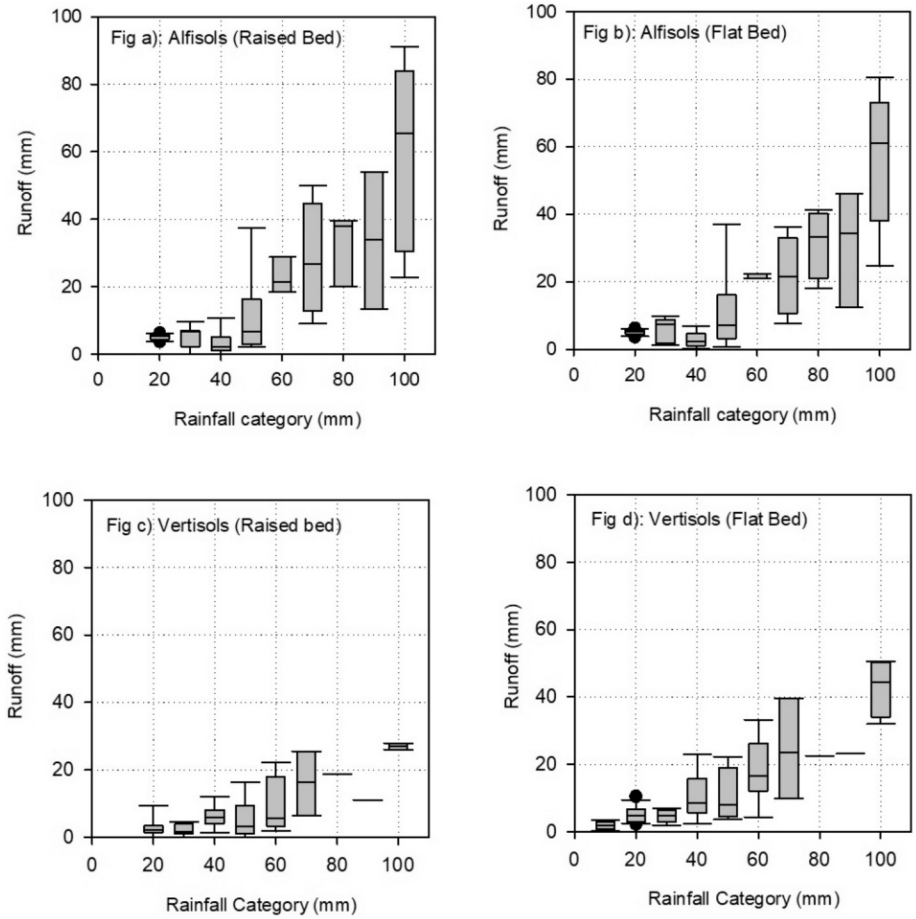


Fig. 7. Runoff response across rainfall categories under raised bed and flat bed systems in Alfisols and Vertisols.

Table 2
Rainfall–runoff response in Alfisols and Vertisols under raised bed and flat bed systems during dry, normal, and wet years at the ICRISAT heritage watershed.

Site	Year	Rainfall (mm)	Runoff (mm)	
			Raised bed	Flat bed
Alfisols	Dry	573	9 (2%)	6 (1%)
	Normal	722	115 (16%)	126 (17%)
	Wet	986	186 (19%)	213 (22%)
Vertisols	Dry	530	2 (0.1%)	9 (2%)
	Normal	729	53 (7%)	77 (11%)
	Wet	1101	215 (20%)	258 (23%)

remained relatively low, accounting for 2–6% of rainfall, whereas in wet years (986 mm rainfall), runoff increased substantially to 186–213 mm (19–22%), particularly under flatbed conditions.

In Vertisols, seasonal runoff ranged from 2 mm (0.3%) in dry years under raised bed conditions to 258 mm (23%) in wet years under flatbed conditions. During normal years (729 mm rainfall), runoff was 53 mm (7%) under raised bed system compared to 77 mm (11%) under flatbed conditions, indicating a substantial reduction associated with improved landform. In wet years (1101 mm rainfall), runoff reached 215 mm (20%) under raised bed system and 258 mm (23%) under flatbed conditions, highlighting the increased runoff potential under high rainfall conditions.

At the event scale, ANOVA further indicated that the effect of landform on runoff varied with rainfall intensity, with raised-bed systems showing significantly lower runoff than flat-bed systems particularly under light-to-moderate rainfall events ($p < 0.05$), whereas differences generally diminished under high- and very-high-intensity rainfall events (Garg et al., 2020a, 2020b). This reduction in runoff increased the opportunity for rainfall to enter and move through the soil profile; however, the amount subsequently retained as plant-available water depended on soil depth and water-retention characteristics.

Soil moisture dynamics in Alfisols and Vertisols further showed distinct temporal and depth-wise patterns in response to rainfall events (Fig. 8). In Alfisols, soil moisture remained relatively low and fluctuated within a narrow range, with values in the 0–15 cm layer typically between 0.05 and 0.18 cm^3 cm^{-3}, while deeper layers (16–45 cm) maintained comparatively higher moisture levels of 0.20–0.30 cm^3 cm^{-3}. Vertisols exhibited higher soil moisture content across all depths, particularly during the monsoon and post-monsoon periods (Fig. 8). The 16–45 cm layers maintained moisture levels between 0.25 and 0.45 cm^3 cm^{-3}, while surface layers (0–15 cm) showed greater variability, ranging from near saturation (~0.40–0.45 cm^3 cm^{-3}) following rainfall events to below 0.10 cm^3 cm^{-3} during dry periods. Compared to Alfisols, Vertisols showed slower depletion of soil moisture, especially in sub-surface layers. The depth-wise distribution indicates that in Vertisols, moisture was retained in deeper layers (16–45 cm) for extended periods, whereas in Alfisols, soil moisture was largely confined to shallow depths and depleted rapidly between rainfall events.

3.3. Cropping system performance under varying moisture regimes

The performance of cropping systems in the ICRISAT heritage watershed was strongly governed by landscape-level moisture availability and its temporal dynamics, which are controlled by soil physical properties, infiltration behavior, and rainfall–runoff partitioning (**Table 3** and Table 4). In Vertisols, higher plant-available water (approximately 150–200 mm within a 1 m soil profile) enabled relatively stable cropping system performance across rainfall regimes. Sorghum-based systems, including sole sorghum and sorghum+pigeonpea intercropping, performed consistently under rainfed conditions. In dry years (535 mm rainfall), sole sorghum yielded about 3.91 t ha^{-1}, while sorghum+pigeonpea systems yielded approximately 3.52 t ha^{-1}, with net returns ranging from USD 889 to 1241 ha^{-1}. During normal years (750 mm rainfall), yields increased to 3.52–4.33 t ha^{-1}, and net returns improved to USD 1037–1284 ha^{-1}. In wet years (1100 mm rainfall), system productivity further increased to 4.09–4.78 t ha^{-1}, with net returns exceeding USD 1134–1311 ha^{-1}.

In Alfisols, cropping system performance was more sensitive to rainfall variability due to lower plant-available water (80–120 mm) and rapid moisture depletion. In dry years (573 mm rainfall), sole sorghum yields were relatively low (2.14–2.47 t ha^{-1}), while groundnut+pigeonpea intercropping systems yielded 1.67–1.87 t ha^{-1}, but generated higher net returns (USD 1637–1821 ha^{-1}) compared to sole

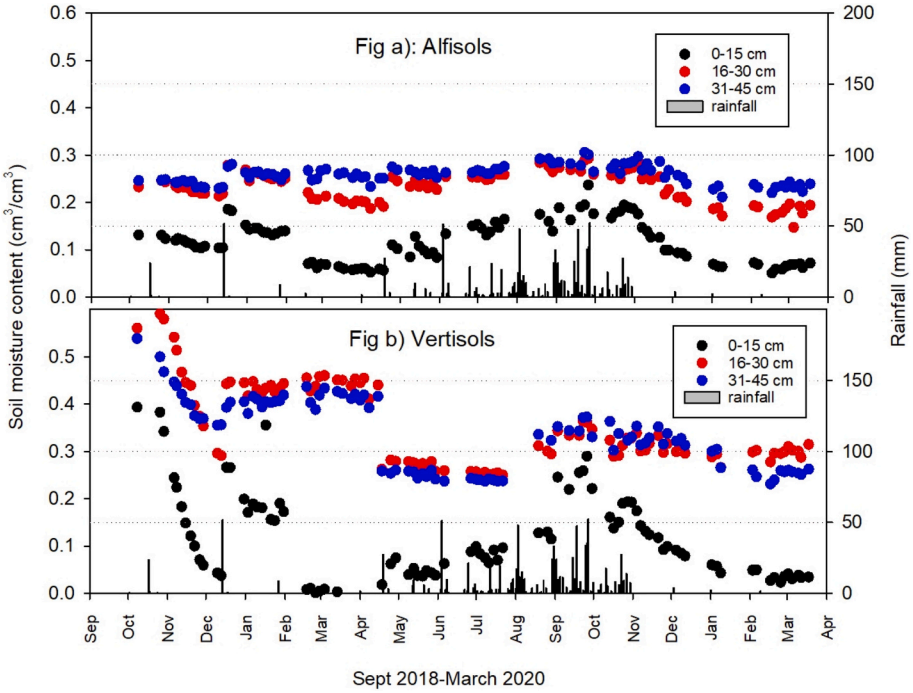


Fig. 8. Temporal and depth-wise soil moisture dynamics under contrasting soil types: (a) Alfisols and (b) Vertisols.

Table 3
Performance indicators of vertisols production system for dry, normal and wet years.
Note: Figures in parentheses indicate standard deviation.

System		Dry Years ($n = 5$)		Normal years ($n = 21$)			Wet Years ($n = 9$)
		Improved Practice	Farmer Practice	Improved Practice	Farmer Practice	Improved Practice	Farmer Practice
Rainfall		535 (48)	535	750 (117)	750	1100 (78)	1100
Runoff		12 (14)	47 (46)	80 (64)	152 (84)	250 (56)	379 (59)
Effective rainfall		523 (38)	488 (36)	670 (81)	598 (73)	850 (61)	721 (47)
Measured crop yield (t ha^{-1})							
	Sorghum	3.91 (0.77)	–	3.52 (0.38)	–	3.11 (1.03)	–
i) Sorghum/PP	Pigeonpea	0.70 (0.45)	–	1.05 (0.33)	–	1.34 (0.18)	–
	Maize	4.79 (1.83)	–	4.33 (0.88)	–	4.09 (0.93)	–
ii) Maize-Chickpea	Chickpea	1.15 (0.50)	–	1.42 (0.37)	–	1.57 (0.39)	
iii) Fallow-Sorghum	Rabi Sorghum	–	1.10 (0.67)	–	1.16 (0.57)	–	1.08 (0.48)
iv) Fallow-Chickpea	Chickpea	–	1.15 (0.18)	–	1.20 (0.41)	–	0.99 (0.33)
Sorghum Equivalent yield (t ha^{-1})							
i) Sorghum/PP		5.93 (1.27)	–	6.58 (1.23)	–	7.00 (1.51)	–
ii) Maize-Chickpea		6.47 (2.48)	–	6.66 (1.31)	–	6.78 (1.43)	–
iii) Fallow-Sorghum		–	1.10 (0.67)	–	1.16 (0.57)	–	1.08 (0.48)
iv) Fallow-Chickpea		–	2.48 (0.38)	–	2.59 (0.88)	–	2.13 (0.71)
Net return (US$/ha)							
i) Sorghum/PP		889 (119)	–	1037 (280)	–	1134 (344)	–
ii) Maize-Chickpea		1241 (563)	–	1284 (298)	–	1311 (324)	–
iii) Fallow-Sorghum		–	87 (172)	–	150 (130)	–	134 (109)
iv) Fallow-Chickpea		–	333 (87)	–	358 (200)	–	252 (162)

Note: Figures in parentheses indicates standard deviation.

Table 4
Performance indicators of Alfisols production system for dry, normal and wet years.

Particulars		Dry years ($n = 1$)		Normal years ($n = 5$)		Wet years ($n = 2$)	
Landform treatment		Flat Land	Raised Bed	Flat Land	Raised Bed	Flat Land	Raised Bed
Rainfall (mm)		573	573	752	752	1070	1070
Runoff (mm)		6	9	130	115	274	257
Effective rainfall (mm)		566	563	622	637	795	812
Measured Crop yields							
1. Sole Sorghum	Sorghum yield (t ha^{-1})	2.14	2.47	1.71 (0.73)	2.16 (0.88)	2.63	2.80
	GN yield (t ha^{-1})	1.67	1.87	0.31 (0.08)	0.40 (0.03)	1.14	1.23
2. GN/PP intercrop	PP yield (t ha^{-1})	1.30	1.51	0.65 (0.57)	0.87 (0.79)	0.94	1.03
3. Sole Castor	Castor yield (t ha^{-1})	–	–	1.52 (0.27)	1.75 (0.43)	–	–
	Sorghum yield (t ha^{-1})	–	–	2.06 (1.11)	2.48 (1.04)	–	–
4. Sorghum/PP intercrop	Pigeonpea yield (t ha^{-1})	–	–	1.52 (0.33)	1.82 (0.52)	–	–
Sorghum equivalent yield (t ha^{-1})							
1. Sole Sorghum		2.14	2.47	1.71 (0.73)	2.16 (0.88)	2.63	2.80
2. GN/PP intercrop		7.99	9.12	2.67 (1.45)	3.53 (2.26)	5.62	6.11
3. Sole Castor		–	–	3.84 (0.68)	4.45 (1.09)	–	–
4. Sorghum/PP intercrop		–	–	6.49 (0.40)	7.79 (0.75)	–	–
Net return (US$/ha)							
1. Sole Sorghum		375	377	275 (167)	308 (199)	485	452
2. Groundnut/Pigeonpea intercrop		1637	1821	429 (329)	553 (512)	1099	1139
3. Sole Castor		–	–	766 (154)	831 (248)	–	–
4. Sorghum/Pigeonpea intercrop		–	–	1345 (90)	1569 (171)	–	–

Note: Figures in parentheses indicates standard deviation.

cropping systems (USD 375–377 ha^{-1}). During normal years (752 mm rainfall), groundnut+pigeonpea systems achieved 2.67–4.35 t ha^{-1} (equivalent yield basis), while sole sorghum remained relatively less productive (1.71–2.60 t ha^{-1}), with net returns ranging from USD 429–553 ha^{-1}. In wet years (1070 mm rainfall), cropping systems responded positively, with groundnut+pigeonpea systems reaching 5.62–6.11 t ha^{-1} equivalent yield and net returns of USD 1099–1139 ha^{-1}, although increased runoff losses limited proportional gains in productivity.

3.4. Impact of LRI–hydrology framework on water availability and profitability in Jhansi cluster

Implementation of LRI–hydrology-based interventions between 2018 and 2022 led to substantial improvements in water availability at the landscape scale. A combination of rainwater harvesting structures, drainage line treatments, and in-situ conservation measures resulted in the creation of 731,000 m^3 of additional water storage capacity (Table 5A). This static storage capacity was equivalent to 14.6 mm of water when expressed over the 5000-ha geographical landscape. Previous field studies from the region have shown that decentralized water-harvesting structures fill, on average, approximately three times during

Table 5A
Impact of LRI–hydrology–based natural resource management interventions on key indicators before and after implementation.

SN	Resource availability, production, and net returns	2019 (before)	2021 (after)
1	Storage capacity created (m^3)	–	731,000
2	Functioning dug/bore wells (no.)	20	220
3	Total production from landscape (Field pea equivalent in tons/year)	5698	12,350
4	Net returns generated from entire cluster during *kharif* (Million USD)	0.512	1.383
5	Net returns generated from entire cluster during rabi (Million USD)	0.800	1.935
6	Net returns generated from entire cluster from agriculture (Million USD)	1.312	3.318
7	Net returns from agriculture (USD/ha/year)	427	1107

a monsoon season (Garg et al., 2020b). Accordingly, the created storage capacity represents an annual runoff-harvesting opportunity of approximately 40–45 mm at the landscape scale. In addition, in-situ soil and water conservation measures implemented in 10–15% of total area improved rainfall retention, infiltration and groundwater availability, which was reflected in a sharp increase in the number of functioning wells from 20 to 220.

The temporal dynamics of groundwater recovery further demonstrate the effectiveness of LRI-hydrology framework in addressing seasonal water scarcity (Fig. 9). During the pre-monsoon period (June), the proportion of dry wells reduced substantially to about 50–60%, with the remaining wells showing measurable water column (>0–3 m and deeper categories). After the monsoon (October), a shift towards higher hydraulic head categories was observed, with nearly 80–90% of wells becoming functional, and a substantial proportion falling within 3–6 m and 6–9 m water column ranges. Importantly, this improvement persisted into the post-monsoon period (March), where approximately 60–70% of wells remained functional, indicating enhanced groundwater storage and reduced seasonal depletion.

The improvement in water availability was accompanied by substantial changes in cropping systems, agricultural productivity, and livelihoods across the study area. The most visible impact was the transformation of cropping patterns and reduction in fallow lands (Fig. 10). During the kharif season, the area under groundnut expanded from 240 ha (before intervention) to 2100 ha (after intervention), while fallow land reduced from 600 ha to 200 ha. Similarly, diversification into blackgram and sesame was observed.

In the rabi season, which was previously constrained by moisture availability, significant intensification was observed. Wheat cultivation increased from 225 ha to 900 ha, chickpea remained stable but more productive, and lentil cultivation expanded from 338 ha to 450 ha, while fallow land reduced from 750 ha to negligible levels. These changes indicate a clear shift towards double cropping systems and increased cropping intensity. At the landscape scale, total agricultural production (expressed as field pea equivalent yield) increased from 5698 tons/year to 12,350 tons/year, representing more than a two-fold increase (Table 5A).

The water implications of this cropping-system transition were further evaluated by comparing crop-water and supplemental-irrigation requirements before and after intervention (Table 5B). When expressed over the total 5000-ha geographical landscape, the estimated supplemental irrigation requirement of the pre-intervention cropping systems was approximately 35 mm. This represents the estimated irrigation requirement rather than the quantity of irrigation water actually supplied. Under the prevailing water-limited conditions, farmers had adapted their cropping systems to available soil-moisture and groundwater resources following local experience and traditional knowledge, including substantial area under single-season cropping and seasonal fallows. Nevertheless, inadequate water availability during critical crop-growth stages resulted in moisture stress and associated yield penalties, as also indicated through farmer consultations and crop cutting studies. Following LRI-hydrology framework, the landscape-equivalent supplemental irrigation requirement increased to approximately 78 mm as cropping systems shifted towards more intensive crop sequences, representing an incremental supplemental-water requirement of approximately 43 mm. This incremental requirement was comparable in magnitude to the additional annual runoff-harvesting opportunity of approximately 40–45 mm generated through the ex-situ interventions, with further enhancement of rainfall retention and infiltration through in-situ conservation measures. Importantly, this additional harvested

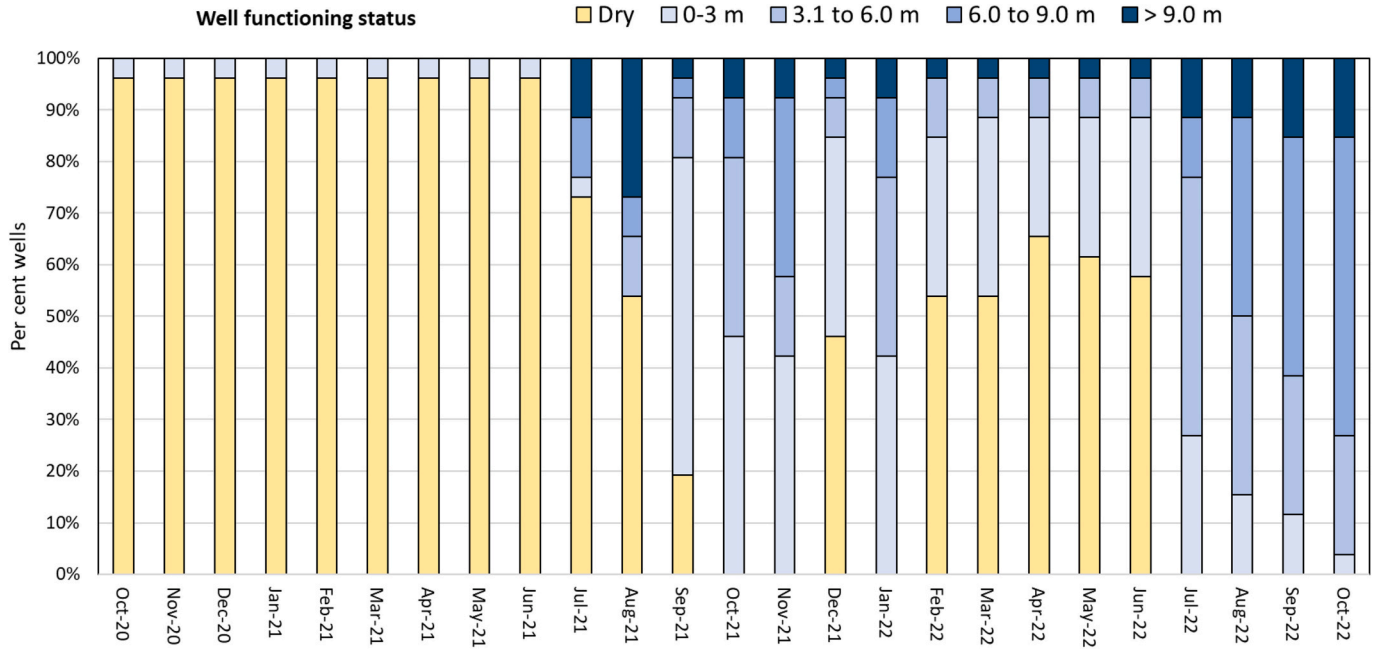


Fig. 9. Impact of rainwater harvesting (RWH) interventions on well functioning status in the Jhansi cluster: monthly distribution of wells across hydraulic head (available water column within the dug well) categories (Dry, 0–3.0 m, 3.1–6.0 m, 6.1–9.0 m, and > 9.0 m).

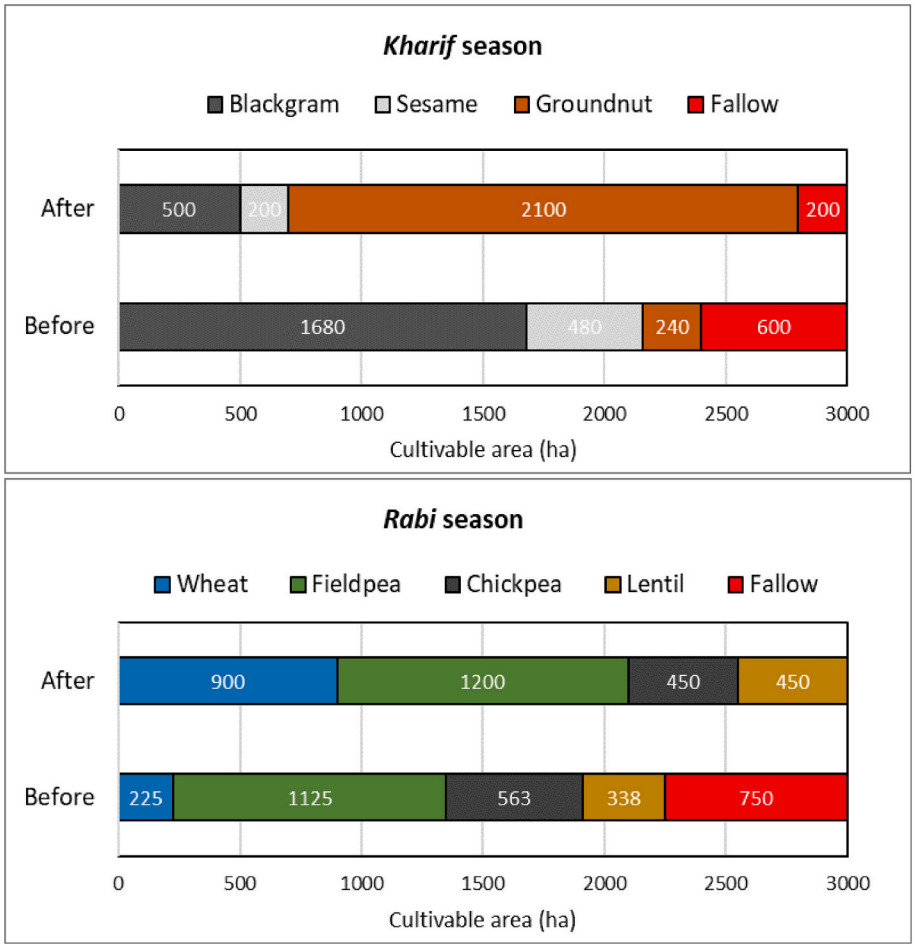


Fig. 10. Changes in cropping systems and crop intensification following LRI–hydrology based landscape interventions in the Jhansi cluster.

Table 5B
Cropping-system transitions and associated crop-water and supplemental-irrigation requirements before and after LRI–hydrology-based interventions in the Jhansi landscape.

SN	Cropping system	Area under cultivation (ha)		System water requirement (mm)	Supplemental irrigation* requirement (mm)
		Before interventions	After interventions		
1	Groundnut-wheat	120	–	650	230
2	Groundnut-fallow	120	–	300	–
3	Black gram-Chickpea	68	–	490	70
4	Black gram-Lentils	338	–	470	50
5	Black gram-Field pea/Mustard	1125	–	520	100
6	Fallow-Chickpea	495	–	420	–
7	Sesame-Fallow	480	–	210	–
8	Fallow-Wheat	105	200	550	130
9	Black gram-Fallow	149	–	270	–
10	Groundnut-Chickpea	–	450	520	100
11	Groundnut-Field pea	–	1200	550	130
12	Groundnut-Lentils	–	450	500	80
13	Black gram-wheat	–	500	620	200
14	Sesame-wheat	–	200	560	140

* Supplemental irrigation requirement represents the additional crop-water demand after accounting for the estimated moisture-supplying capacity of the landscape. Landscape-equivalent supplemental irrigation requirement was calculated by weighting the supplemental irrigation requirement of each cropping system by its respective cultivated area and expressing the aggregated demand over the total geographical area of 5000 ha; landscape-equivalent supplemental irrigation requirement was ≈35 mm before and ≈78 mm after intervention.

water did not meet the entire crop-water requirement; rather, it complemented rainfall-derived soil moisture and groundwater resources and provided supplemental water during critical crop-growth periods, thereby creating conditions for reducing seasonal fallows and expanding double-cropping systems.

Economic benefits were equally significant. Net returns generated from the cluster increased from USD 0.512 million to 1.383 million during kharif and from USD 0.800 million to 1.935 million during rabi, resulting in total agricultural income increasing from USD 1.312 million to 3.318 million. At the household level, considering an average landholding of 2.0 ha, net returns increased from approximately USD 854 to 2214 per household per year, indicating substantial livelihood

improvement. The enhanced economic opportunities also contributed to return migration of 350 families, reflecting improved rural resilience and employment generation.

4. Discussion

4.1. Integrating soil, infiltration and runoff processes in rainfed landscapes

The results demonstrate that rainfall partitioning in rainfed systems is governed by the interaction of soil physical properties, pore-scale hydraulic behavior, soil water retention capacity and landform configuration. Alfisols exhibited higher near-saturated infiltration rates; however, infiltration declined by approximately 70–75% in Alfisols and 60–70% in Vertisols at −50 mm suction and fell below 10–15 mm h^{-1} at higher suctions (−100 to −150 mm). This sharp decline indicates that larger, hydraulically connected pores make a substantial contribution to near-saturated flow in both soil types, while matrix flow becomes increasingly dominant as larger pores are excluded. Thus, high near-saturated infiltration should not be interpreted directly as greater water storage within the soil profile (Nimmo, 2021).

This distinction is further supported by the contrasting soil water-retention characteristics (Gupta et al., 2023). Despite their relatively higher near-saturated infiltration rates, Alfisols stored only about 80–120 mm of plant-available water within a 1-m profile, compared with 150–200 mm in Vertisols. The greater plant-available water storage in Vertisols was also reflected in the observed soil-moisture dynamics, with higher and more persistent moisture in deeper layers, whereas Alfisols showed relatively rapid moisture depletion following rainfall events. These results demonstrate that rainfall availability to crops depends not only on the rate at which water enters the soil, but also on pore-mediated flow, profile depth, and the capacity of the soil to retain infiltrated water within the root zone.

Landform modification through raised bed systems emerged as a key intervention that restructured these hydrological processes (Asewar et al., 2021). By altering micro-topography, raised bed systems reduce runoff velocity, increase infiltration opportunity time, and improve rainfall retention within the field (Srinivas et al., 2022). Importantly, the effectiveness of raised bed systems is soil-dependent: in Vertisols, it primarily improves drainage and reduces waterlogging constraints, whereas in Alfisols, it enhances infiltration and reduces rapid runoff losses. This dual functionality underscores the importance of context-specific landform interventions. From a broader perspective, these findings reinforce that rainfall partitioning is not solely a climatic function but a landscape property, shaped by soil–structure–management interactions. This has important implications for hydrological modelling and watershed planning, where simplified assumptions about infiltration and runoff may fail to capture field realities (Bauser et al., 2022).

Soil moisture dynamics represent a critical link between hydrological processes and agricultural outcomes by determining the amount and temporal availability of water accessible to crops. In rainfed systems, crop performance is therefore influenced not only by rainfall amount and distribution, but also by the capacity of the soil profile to capture, retain, and supply water during different stages of crop growth (Bal et al., 2024). While the heritage watershed experiments primarily focused on rainfed soil moisture processes, the landscape-scale application demonstrated that captured runoff and increased infiltration can translate into shallow groundwater availability, providing an important buffer during subsequent dry periods. Similar multi-year observations from semi-arid Bundelkhand showed that rainwater-harvesting interventions increased shallow groundwater levels by 2–5 m, with recharge generated during wet years remaining available during subsequent dry years (Garg et al., 2020b). These findings highlight that soil moisture should not be viewed in isolation but as part of a continuum of water availability spanning soil storage and groundwater systems (Vereecken et al., 2022; Liu et al., 2022).

4.2. Cropping system adaptation to soil–water regimes

The differential performance of cropping systems across soil types and rainfall regimes highlights that cropping system suitability is fundamentally governed by soil–water interactions rather than rainfall alone. Vertisols, with higher moisture storage and sustained availability, support relatively stable and higher biomass systems, including long-duration crops and intercropping combinations. In contrast, Alfisols require adaptive, short-duration, and diversified systems that can cope with rapid moisture depletion. The consistent performance of intercropping systems across both soil types suggests that diversification enhances system resilience by spreading risk across crops with different water-use strategies. Increasing seasonal rainfall therefore does not necessarily translate into proportional gains in crop productivity when rainfall is poorly distributed or a substantial fraction is lost as runoff. Recent field evidence from semi-arid systems similarly demonstrates that rainfall distribution and the proportion of rainfall effectively retained for crop use are critical determinants of crop productivity and water productivity (Ponakala et al., 2024). These findings reinforce the importance of effective rainfall, rather than total rainfall alone, in determining crop performance.

An important insight emerging from this study is the observed adaptation of cropping systems along a gradient of moisture availability, linking the controlled experimental evidence from the heritage watershed with the landscape-scale application in Jhansi. The before–after comparison at Jhansi showed that changes in cropping systems occurred alongside substantial improvements in water availability following implementation of the LRI–hydrology framework. Before interventions, cropping systems such as blackgram–fallow, blackgram–field pea, and sesame–chickpea were prevalent under limited and uncertain water availability. After interventions, increased rainwater harvesting, improved groundwater availability, and greater access to supplemental irrigation were accompanied by expansion of groundnut-based systems during kharif and wheat, chickpea, and field pea during rabi. The observed transition is therefore consistent with a shift from predominantly soil moisture-limited systems towards cropping systems increasingly supported by both stored soil moisture and supplemental groundwater. The temporal correspondence between improved water availability and cropping intensification, together with the process understanding derived from the heritage watershed experiments, suggests that enhanced water security was an important enabling factor in this transition. Similar evidence from semi-arid Bundelkhand showed that improved groundwater availability following rainwater-management interventions increased cropping intensity and brought fallow lands into productive cultivation (Singh et al., 2021; Singh et al., 2014).

Although the landscape-scale assessment did not include a comparable untreated control area, cropping decisions may also be influenced by socioeconomic factors such as market opportunities, crop prices, food requirements, and farmer preferences (Agrawal et al., 2021; Baccar et al., 2023). For example, the observed expansion of groundnut and wheat may partly reflect their economic and food-security importance, with groundnut serving as an important cash crop and wheat as a major staple crop in the region. However, such socioeconomic opportunities alone do not overcome the underlying biophysical constraint of inadequate water availability. The before–after evidence therefore suggests that improved water availability was an important enabling factor for intensification, while market, policy, and household considerations may have influenced the specific crops selected once water constraints were reduced.

4.3. Ecosystem-based intensification and replicability of the LRI–hydrology framework

A key insight emerging from this study is that sustainable

intensification of rainfed systems does not necessarily require high external resource inputs, but rather a resource-conscious and system-level approach that improves the harvesting, storage, and efficient use of available water resources. Sustainable intensification therefore requires agricultural production to be aligned with locally available resource thresholds and their temporal variability (Prasad et al., 2022). The results demonstrate that strategic resource augmentation through NRM interventions, combined with enhanced resource use efficiency, can elevate production systems to higher levels of productivity while promoting more sustainable resource use.

The principal advantage of the LRI–hydrology framework is that management decisions are guided by a systematic assessment of resource availability, crop-water demand, and the resulting demand–supply gap, rather than beginning with predetermined interventions. Similar water-centric approaches emphasize that sustainable agricultural intensification requires explicit consideration of available water resources, agricultural water demand, landscape heterogeneity, and context-specific management options (Taye et al., 2022; Haileslassie et al., 2022). The framework first quantifies rainfall partitioning into soil moisture, runoff, and groundwater recharge and evaluates these resources against the water requirements of existing cropping systems. The identified demand–supply gap then provides the basis for determining the extent of resource augmentation required and for selecting appropriate combinations of in-situ conservation, runoff harvesting, groundwater recharge, and resource-use-efficiency measures. At landscape scale, this demand–supply linkage was reflected in the close correspondence between the incremental supplemental irrigation requirement associated with cropping intensification (~43 mm) and the additional annual runoff-harvesting opportunity created through the interventions (~40–45 mm). The augmented resource availability is subsequently evaluated against cropping-system water requirements to identify opportunities for reducing seasonal fallows, providing supplemental irrigation, and sustainably intensifying cropping systems. Thus, the framework links resource assessment, intervention planning, and productive water use within a single system-level decision process. This approach aligns with the concept of "vapor shift" described by Rockström (2003), which emphasizes increasing the productive use of rainfall (green water) by reducing non-productive losses such as runoff and evaporation. An important implication of this work is its potential applicability across semi-arid regions of Asia and Africa for sustainable crop intensification opportunities and building system resilience.

5. Conclusion

This study demonstrates that effective management of rainfed systems requires a shift from rainfall-centric perspectives to a soil–water–crop integrated framework, where water availability is governed by landscape properties rather than rainfall alone. By combining long-term experimental evidence from ICRISAT heritage watersheds with landscape-scale application in Jhansi cluster, Bundelkhand, the study provides a clear pathway for translating process-based hydrological understanding into actionable solutions for sustainable intensification. The results show that soil type and landform play a decisive role in regulating rainfall partitioning, soil moisture storage, and crop performance. Vertisols, with higher plant-available water and deeper storage, supported relatively stable and higher productivity systems, whereas Alfisols required adaptive cropping strategies due to limited storage and rapid moisture depletion. Importantly, landform interventions such as broad bed and furrow systems significantly reduced runoff by ~20–30% and improved rainfall retention and soil moisture availability across both soil types.

At the landscape scale, the integration of LRI and hydrology framework enabled systematic assessment of resource availability, crop water demand, and the resulting demand–supply gap, thereby guiding the location and scale of interventions. The application of this framework in Jhansi cluster led to substantial augmentation of water resources, including creation of ~731,000 m^3 of water-storage capacity and improved shallow groundwater availability. The incremental landscape-equivalent supplemental irrigation requirement associated with cropping intensification (~43 mm) was comparable in magnitude to the additional annual runoff-harvesting opportunity created through the interventions (~40–45 mm), demonstrating the linkage between resource augmentation and cropping-system water demand. These hydrological improvements were accompanied by enhanced irrigation access, expansion of cropped area, and intensification of cropping systems. A key outcome of the study is the demonstrated linkage between water availability and cropping system transitions. Under moisture-limited conditions, agricultural systems remained constrained to low-risk, short-duration crops; however, improved soil moisture regimes combined with groundwater recharge and supplemental irrigation supported a transition towards more productive and diversified agricultural systems, including double cropping and higher-value crops. This shift was associated with a more than two-fold increase in total agricultural production and significant improvements in farm income at both household and landscape scales.

Beyond productivity gains, the study highlights that sustainable crop intensification can be supported through ecosystem-based management, where resource augmentation and improved efficiency enhance productivity while maintaining the natural resource base. The framework operationalizes the concept of improving productive use of rainfall by reducing non-productive losses, thereby strengthening the link between hydrological processes and agricultural outcomes. The integrated LRI–hydrology approach developed in this study provides a potentially replicable and scalable framework for semi-arid regions facing similar challenges of rainfall variability, degraded soils, and limited water resources. By aligning cropping systems with landscape hydrology and resource availability, the approach offers a scientifically robust pathway for enhancing water productivity, strengthening resilience, and contributing to land degradation neutrality in rainfed agro-ecosystems.

CRediT authorship contribution statement

Kaushal K. Garg: Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **K.H. Anantha:** Validation, Methodology, Formal analysis, Conceptualization. **Venkata Radha Akuraju:** Methodology, Formal analysis, Data curation. **Nagaraju Budama:** Methodology, Data curation. **Anjaneyulu Akula:** Methodology, Data curation. **Sunil Niranjan:** Validation, Methodology, Data curation. **Asha Ram:** Validation, Methodology, Data curation. **Ashok Shukla:** Methodology, Data curation. **Nagarjuna N. Reddy:** Methodology, Data curation. **Israr Majeed:** Methodology, Data curation. **Niranjan Padhan:** Methodology, Data curation. **Debi Prasad Sahoo:** Methodology, Data curation. **Aiendrila Dey:** Methodology, Data curation. **Sourav Roy:** Methodology, Investigation. **R.K. Uttam:** Resources, Methodology. **Shailendra Soni:** Data curation. **Bhabani S. Das:** Validation, Methodology, Data curation, Conceptualization. **Ramesh Singh:** Validation, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

We (Kaushal K Garg, Anantha KH, Venkataradha A, Nagaraju B, Anjaneyulu A, Sunil Niranjan, Asha Ram, Ashok Shukla, Nagarjuna N Reddy, Israr Majeed Reshi, Niranjan Padhan, Debi P Sahoo, Aiendrila Dey, Sourav Roy, RK Uttam, Shailendra Soni, Bhabani S Das, Ramesh Singh), hereby declare that there is no conflict of interest among us and partners on submitted manuscript.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2026.105021.

Data availability

Data will be made available on request.

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