Watershed Ecology and the Environment 7 (2025) 159–177

Contents lists available at ScienceDirect

Watershed Ecology and the Environment

journal homepage: www.keaipublishing.com/en/journals/watershed-ecology

Integrated watershed management for transforming dryland livelihoods: A climate-smart strategy for sustainable dryland agriculture in India

Ram A. Jat [a], Dinesh Jinger [b,*], Anita Kumawat [a], Saswat Kumar Kar [c], Indu Rawat [d], Suresh Kumar [e], Venkatesh Paramesh [f], Vijay Singh Meena [g], Rajesh Kaushal [d], Kuldeep Kumar [a], Hari Singh Meena [h], S.P. Wani [i], Rajbir Singh [j], M. Madhu [d]

[a] ICAR-Indian Institute of Soil and Water Conservation, Research Center, Kota 324002 Rajasthan, India
[b] ICAR-Indian Institute of Soil and Water Conservation, Research Center, Vasad 388306 Gujarat, India
[c] ICAR-Indian Institute of Soil and Water Conservation, Research Center, Koraput 763002 Odisha, India
[d] ICAR-Indian Institute of Soil and Water Conservation, Dehradun 248 195 Uttarakhand, India
[e] ICAR-Central Soil Salinity Research Institute, Karnal 132001 Haryana, India
[f] ICAR-Central Coastal Agricultural Research Institute, Ela-403402, Goa, India
[g] ICAR-Indian Agricultural Research Institute, Regional Station, Pusa 848125 Bihar, India
[h] ICAR-Indian Grassland and Fodder Research Institute, Regional Station, Avikanagar 304501 Rajasthan, India
[i] Formerly with, International Crops Research Institute for the Semi-arid Tropics, Patancheru 502324 Telangana, India
[j] Indian Council of Agricultural Research, New Delhi 110012, India

ARTICLE INFO

Keywords:
Ecosystem services
Dryland
Hydrology
Soil health
Sustainability

ABSTRACT

In India, 51 % of the net sown area relies on rainfed agriculture, with 40 % of landholdings unirrigated and 13 % partially irrigated. Rainfed farming produces 40 % of food grains and supports two-thirds of the livestock population but faces challenges like land degradation, low productivity, and biodiversity loss due to erratic monsoons and extreme weather. Additionally, India's water scarcity is worsening, with per capita availability expected to reduce from 802 cubic meters in 2022 to 677 cubic meters by 2050. Therefore, to meet the diverse food requirements of the burgeoning population of the country, conservation of natural resources, and improving the living standard of the resource-poor small and marginal farmers is imperative. Integrated watershed management (IWM) has emerged as a climate-smart strategy to address these challenges by enhancing soil and water conservation, agricultural productivity, and livelihoods in dryland systems. This study assesses the impact of IWM on dryland agriculture in India by analyzing various interventions such as *in-situ* and *ex-situ* water conservation, soil health management, and the use of modern technologies like remote sensing (RS) and geographic information systems (GIS). The results revealed that the adoption of IWM practices has led to significant improvements in soil moisture retention (20–25 %), soil organic carbon (22–32 %) agricultural productivity (30–45 %), and water use efficiency (15–25 %). Additionally, soil conservation techniques have reduced soil loss and runoff by 25–50 % and 50–60 %, respectively. Furthermore, the cultivation of lemon grass (*Cymbopogon flexuosus*), anjan grass (*Cenchrus ciliaris*), and bamboo (*Bambusa spp.*) could be the nature-based solutions for mitigating the impact of climate change due to their soil binding capacity and carbon sequestration potential. Moreover, this review indicates the potential of fast-growing trees (*Melia dubia*) under the agroforestry system in

Abbreviations: AICRP-CS, All India Coordinated Research Project on Cropping Systems; ASTER, The Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer; BCR, Benefit Cost Ratio; CAM, Crassulacean acid metabolism; CID, Crop Diversification Index; CPE, Cumulative Pan Evaporation; CRIDA, Central Research Institute for Dryland Areas; CSWCRTI, Central Soil and Water Conservation Research and Training Institute; DAS, Days after Sowing; DEM, Digital Elevation Model; DI, Deficit irrigation; DVC, Damodar Valley Corporation; ES, Ecosystem Services; ET, Evapo-transpiration; FAO, Food and Agriculture Organization; FYM, Farm Yard Manure; GPS, Global Positioning System; GIS, Geographic Information Systems; GOI, Government of India; HR, Himalayan Region; ICRISAT, International Crop Research Institute for Semi-Arid Tropics; IISWC, Indian Institute of Soil and Water Conservation; IMSD, Integrated Mission for Sustainable Development; IRR, Internal Rate of Return; IW, Irrigation Water; IWM, Integrated Watershed Management; IWRM, Integrated Water Resources Management; NGOs, Non Government Organization; NPK, Nitrogen, Phosphorus, and Potassium; NRAA, National Rainfed Area Authority; NUE, Nitrogen Use Efficiency; ORPs, Operational Research Project; RS, Remote Sensing; RUSLE, Revised Universal Soil Loss Equation; SDGs, Sustainable Development Goals; SRTM, Shuttle Radar Topography Mission; WEPP, Water Erosion Prediction Project; WUE, Water Use Efficiency; ZT, Zero Tillage.

* Corresponding author.
E-mail address: dineshjinger28@gmail.com (D. Jinger).

https://doi.org/10.1016/j.wsee.2025.03.006
Received 14 June 2024; Received in revised form 21 March 2025; Accepted 24 March 2025
Available online 1 April 2025
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enhancing carbon sequestration by >100 % over sole cultivation. These results demonstrate that IWM is a sustainable solution to mitigate the adverse effects of climate change on dryland farming systems and improve rural livelihoods. Further, the study suggests that IWM practices helps to achieve sustainable development goals (SDGs) such as zero hunger, no poverty, and climate action etc., particularly in the face of climate change in water-scarce regions.

Introduction

Rainfed farming supports 80 % of the world's cropland, produces over 60 % of global cereal grains, and creates jobs in rural areas (Reynolds et al., 2007; Ghassemi-Golezani et al., 2023). In India, a large part of the agricultural production comes from rainfed areas, like 44 % of rice, 87 % of coarse cereals (sorghum, pearl millet, maize), 85 % of food grain legumes, 72 % of oilseeds, 65 % of cotton, and 90 % of minor millets (Jinger et al., 2017a; Jinger et al., 2017b). Overall, rainfed agriculture produces 40 % of the food grains, supports two-thirds of the livestock population, and is critical to food security, equity, and sustainability (Rao, 2021). Despite its potential for rapid agricultural growth, rainfed systems face severe challenges such as land degradation, water scarcity, low productivity, and loss of biodiversity (Bhan, 2013; Srinivasa Rao et al., 2015; Ren, 2022). In India, 120.7 million hectares (36.6 % of the total area) are degraded, posing risks to food security, livelihoods, and environmental sustainability (Jinger et al., 2024; Kaushal et al., 2024). India faces severe water stress, with per capita water availability projected to drop from 802 cubic meters in 2022 to 677 cubic meters by 2050 due to poor water management, population growth, and climate change. With water availability projected to decline drastically by 2050, effective planning and implementation of Integrated Watershed Management (IWM) are crucial to enhance productivity and secure sustainable development in rainfed and degraded areas (Singh et al., 2009a; 2009b; Wani et al., 2013; Dass et al., 2013; Mukherji, 2022).

A watershed can be defined as a geo-hydrological unit that drains all its runoff through a common point, called the outlet of the watershed (Wang et al., 2016a; Wang et al., 2016b; Pandey et al., 2021). The watershed above any point on a drainage channel is, therefore, all of the land and water areas that drain through that point. A watershed is not merely a geo-hydrological unit as defined by the hydrologist; rather, it is a land mass that is bordered horizontally by the water that drains into a point in the channel and vertically by the region affected by human activity (Uniyal et al., 2020; Orke and Li, 2021). This area is home to a complex system of physical, social, and economic elements that are all highly dynamic and interconnected. In terms of resource development, it covers the development and collective, effective, and efficient management of natural resources (Wang et al., 2016; Reddy et al., 2017; Mosaffaie et al., 2021; Singh et al., 2021). A network of streams or drainage lines of different orders is found in the watersheds. A method of area planning for natural resources, particularly land, water, and vegetation, is called "*watershed management*" (Shiferaw et al., 2008; Reddy et al., 2017; Apruv and Cai, 2020). Its goal is to meet the socio-economic demands of the local community or human society in question. According to ecological principles, it must be sustainable, meaning

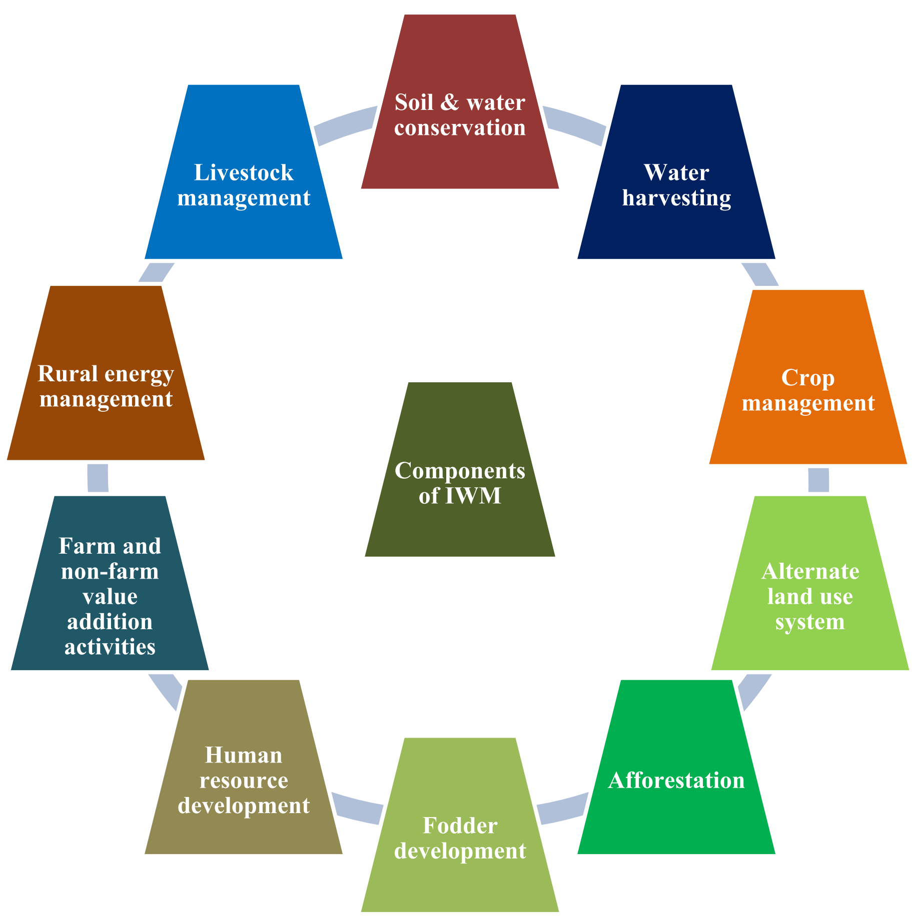

Fig. 1. Components of Integrated watershed management.

that the treated watershed must allow for the greatest amount of stability during the processes of production, consumption, and regeneration (both artificial and natural) (Nerker et al., 2016; Dey et al., 2023). It must be able to provide for the members' livelihoods and meet their demands for sustenance over the long run (Nerker et al., 2015; Peterson et al., 2021; Narendra et al., 2021). Different components of integrated watershed management are mentioned in Fig. 1.

The watershed approach originated from the late 19th century Alps restoration movement in Europe and the 1930s conservation movement in the U.S., focusing on preserving downstream habitats (Anselmetto et al., 2024). In India, it began in the 1950s with the establishment of the Damodar Valley Corporation (DVC) in Jharkhand. The ICAR-Indian Institute of Soil and Water Conservation (formerly CSWCRTI) and ICAR-Central Research Institute for Dryland Areas (CRIDA) later advanced watershed research, establishing 42 small research watersheds and 47 model watersheds (Kumar et al., 2022a,b; Walia et al., 2024). Initially, these programs were land and water resource-based with a technical focus, but success was limited (Bhandari et al., 2007; Wani et al., 2009). Today, a participatory approach emphasizes community involvement, gender equity, and institution building (Nagaraja and Ekambaram, 2015; Biswas et al., 2017). The Indian government continues to invest heavily in watershed projects through initiatives like the WARASA-Jan Sahabhagita and Hariyali guidelines, with common guidelines from the National Rainfed Area Authority (NRAA) adopted in 2008 (Raju et al., 2008).

Previous studies on watershed management have predominantly focused on high-rainfall or irrigated regions, leaving a significant gap in understanding how Integrated Watershed Management (IWM) can be adapted and scaled for dryland systems, which are particularly vulnerable to water scarcity, land degradation, and the impacts of climate change. Additionally, while there has been some research on the short-term benefits of soil and water conservation, few studies have provided long-term, quantitative assessments of IWM's effects on groundwater recharge and soil health. This gap is addressed in the current study by offering specific data on increases in groundwater levels and soil organic carbon. Furthermore, although the potential of modern tools like Geographic Information Systems (GIS) and remote sensing for watershed delineation and management is well recognized, their systematic application in enhancing the efficiency of IWM interventions has been under-explored. This study bridges that gap by leveraging these tools to optimize resource use and identify erosion-prone areas. Another limitation in existing literature is the inadequate exploration of the socio-economic benefits of IWM, with most studies focusing on environmental outcomes. This research expands the scope by presenting how IWM interventions can significantly improve livelihoods, crop productivity, and poverty reduction in rainfed areas. Additionally, previous research has produced inconsistent findings regarding the impact of water conservation practices on water-use efficiency and crop yields, which this study clarifies by providing comprehensive data across diverse agroecological regions. Finally, while the importance of community participation in watershed management is acknowledged, few studies have systematically evaluated its role in the success of IWM projects. This research highlights the crucial role of participatory approaches in ensuring the effective implementation and long-term sustainability of IWM interventions.

Rainfed agriculture, which supports a significant share of food production, suffers from soil degradation, erratic rainfall, and declining productivity, threatening food security and livelihoods. IWM has emerged as a climate-smart approach to address these challenges by enhancing water conservation, soil health, and agricultural resilience. While watershed programs in India have evolved from technical interventions to participatory models under initiatives like the National Rainfed Area Authority (NRAA), research on IWM's long-term impact on groundwater recharge, soil health, and socio-economic benefits remains limited, particularly in dryland regions. This review synthesizes evidence on IWM's effectiveness, highlighting its role in sustainable resource management, the application of modern tools like GIS and remote sensing, and the importance of community participation in ensuring long-term success. By bridging these research gaps, the study provides insights into how IWM can enhance climate resilience, support rural livelihoods, and contribute to achieving Sustainable Development Goals (SDGs) in water-scarce regions. Further, this study highlights IWM as a climate-smart strategy for addressing water scarcity, enhancing agricultural productivity, and improving rural livelihoods in dryland regions. By integrating modern tools like GIS and Remote Sensing, IWM optimizes water conservation, soil health, and erosion control, leading to a 30–45 % increase in crop yields and improved water-use efficiency. The study emphasizes IWM's role in climate change adaptation, biodiversity conservation, and socio-economic development by reducing land degradation, boosting groundwater recharge, and creating employment opportunities. Furthermore, its findings provide valuable insights for policymakers to implement sustainable water resource management strategies aligned with the Sustainable Development Goals (SDGs). The success of IWM, exemplified by case studies like the Sukhomajri watershed, makes it a scalable and replicable model for promoting environmental sustainability, food security, and community resilience.

Methodology

We systematically searched for scientific literature using the following search terms in Google Scholar: "Dryland AND Watershed AND Integrated Watershed Management AND Climate smart strategies AND Erosion control AND Water Conservation AND Food Production AND Land rehabilitation," of which the first 235 results were selected. Studies were selected if they included the watershed and any of the keywords searched. We collected further records from the reference lists of review articles and research articles meeting the initial eligibility criteria. Targeted searches of governmental and independent agricultural research organizations were also performed in India where medium-to large-scale, watershed studies have taken place (Fig. 2).

- The study scope was extended to watershed management practices or IWM;
- The study was original research, a dataset, or a dissertation, i.e., not a review, book chapter, or conference proceeding was considered.
- Both on-farm (farmer's field) and on-station (research station) trials were considered;

Planning, delineation, and execution of watershed work using modern tools (RS and GIS)

Need for delineation of watershed

Watershed delineation is critical for planning and managing natural resource conservation projects (Pande, 2020). A watershed is considered a basic unit for organizing developmental activities, consisting of an outlet, drainage network, drainage divide, and sub-basin boundary. Delineating these features is essential for effective watershed management, classification, and analysis (Lai et al., 2016). Proper delineation simplifies monitoring and economic analysis, providing greater returns on investments in watershed development (Johnson & Baltodano, 2004).

Methods for delineation of watershed based on RS and GIS approach

Delineation using GIS and Remote Sensing (RS) enhances watershed management by identifying drainage patterns and stream features. Advanced techniques like the ArcGIS model builder and outlet repositioning approaches have simplified the process (Kraemer & Panda, 2009; Chowdary et al., 2009). Comparisons of TOPODATA, ASTER, and SRTM-DEM datasets found TOPODATA the most accurate for watershed delineation (Mantelli et al., 2011; Pande, 2022). Modern methods

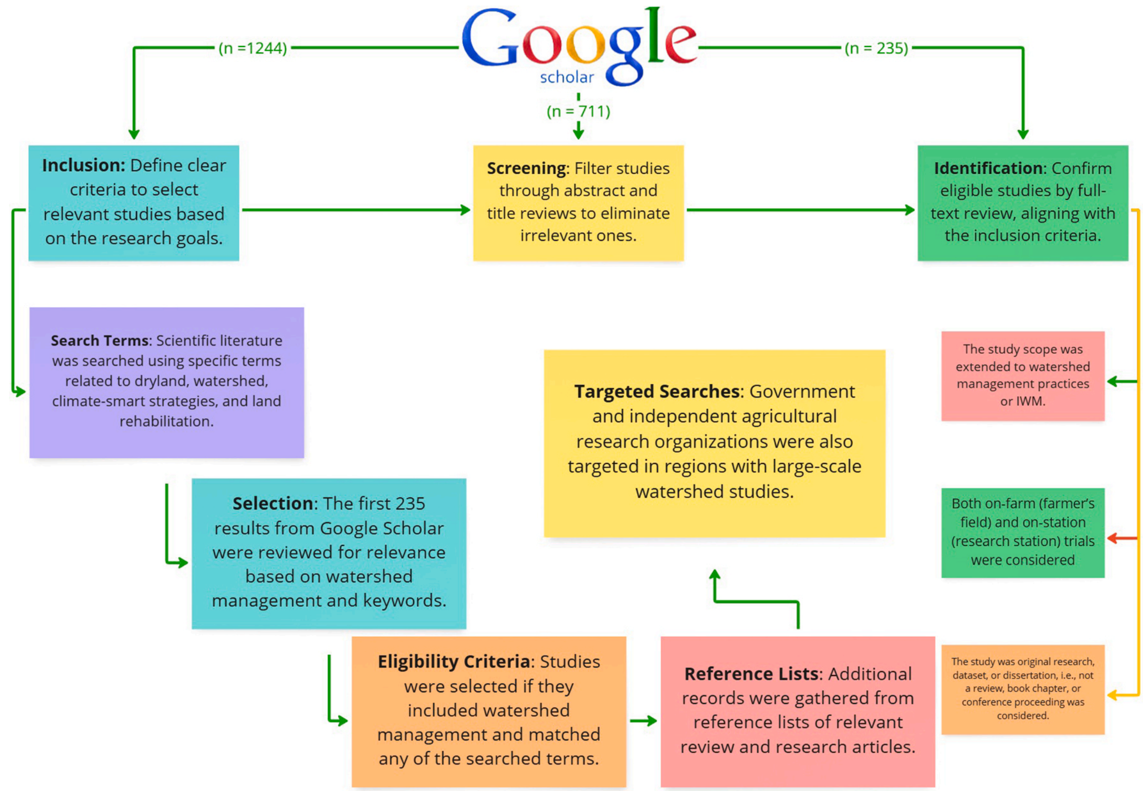

Fig. 2. Methodological flowchart of the present study.

combining digital elevation models (DEM) with hydrographic features provide better results in plain areas (Lai et al., 2016; Shekar and Mathew, 2024).

Morphometric analysis and identification of erosion-prone areas for prioritization of watershed

Soil erosion, a major cause of land degradation, requires location-specific conservation measures. Morphometric analysis using GIS and RS helps prioritize vulnerable areas (Balasubramanian et al., 2017; Sutradhar and Mondal, 2023; Sharma et al., 2023). DEM data from SRTM, Cartosat, and ASTER is essential for understanding hydrological performance (Rai et al., 2017; Shekar and Mathew, 2023). Techniques like the Revised Universal Soil Loss Equation (RUSLE) quantify soil erosion and guide conservation measures (Balasubramani et al., 2015). Integrating local community participation in the planning and execution of conservation projects ensures successful outcomes, particularly in semi-arid regions (Mansuri & Rao, 2004).

Nature of soil and water conservation interventions in different watershed regions

Engineering or mechanical measures are known as the first line of defense with regard to runoff and soil erosion control, followed by agronomical measures in order to add strength to the structure (Kumar et al., 2020). Generally, for land having a slope less than 2 %, numerous agronomical measures are usually preferred for land stabilization and control of soil erosion, and in the case of land having a slope more than 2 %, engineering measures or bioengineering dealings are recommended (Jinger et al., 2019; Singh et al., 2020). Bioengineering measure is the integration of engineering design and technology into living systems for achieving a lot more stability and durability in structure. Various site-specific bioengineering actions are utilized in order to trim down the eroding effects of runoff streams, protect the riverbank from erosion, and this could possibly be broadly categorized as drainage line treatment structures and slope stabilization structures (Sharda et al., 2007). The drainage line treatment structures are constructed across the stream flow direction to reduce flow velocity and bring it down to non-erosive velocity and also create sediment deposits behind the structure (Singh et al., 2023). The Impact of soil and water conservation technologies at three sites revealed that the adoption of such technologies increased yield and profitability and reduced the cost of cultivation, which was justified by higher IRR and BCR (Rao et al., 2005; Sikka et al., 2014). Techniques of different watershed programs have been depicted in Fig. 3.

In-situ soil and water management measures

The location-specific *in-situ* soil and water management measures, depending upon local soil type, climate, cropping pattern, etc., are advised to improve soil moisture level and to control loss of soil nutrient by runoff water, which ultimately helps in achieving sustainable crop production (Singh et al., 2014).

These measures are preferred to aid in controlling the erosion of soil by various causing agents and also to retain the maximum possible water in the field itself, which will be available to plants during the - subsequent period (Wani et al., 2011; Nayak et al., 2019; Jinger et al., 2023). Detailed techniques were discussed in Table 1.

Ex-situ water management to augment blue/green water

Ex-situ water management measures are implemented to capture runoff away from its source and increasewater retention time. To address growing global food demand, location-specific strategies for runoff harvesting and soil moisture enhancement are essential, especially during dry spells (Rockström and Falkenmark, 2015). These measures not only recharge groundwater but also create additional irrigation potential (Wani et al., 2011; Kurothe et al., 2018; Garg et al.,

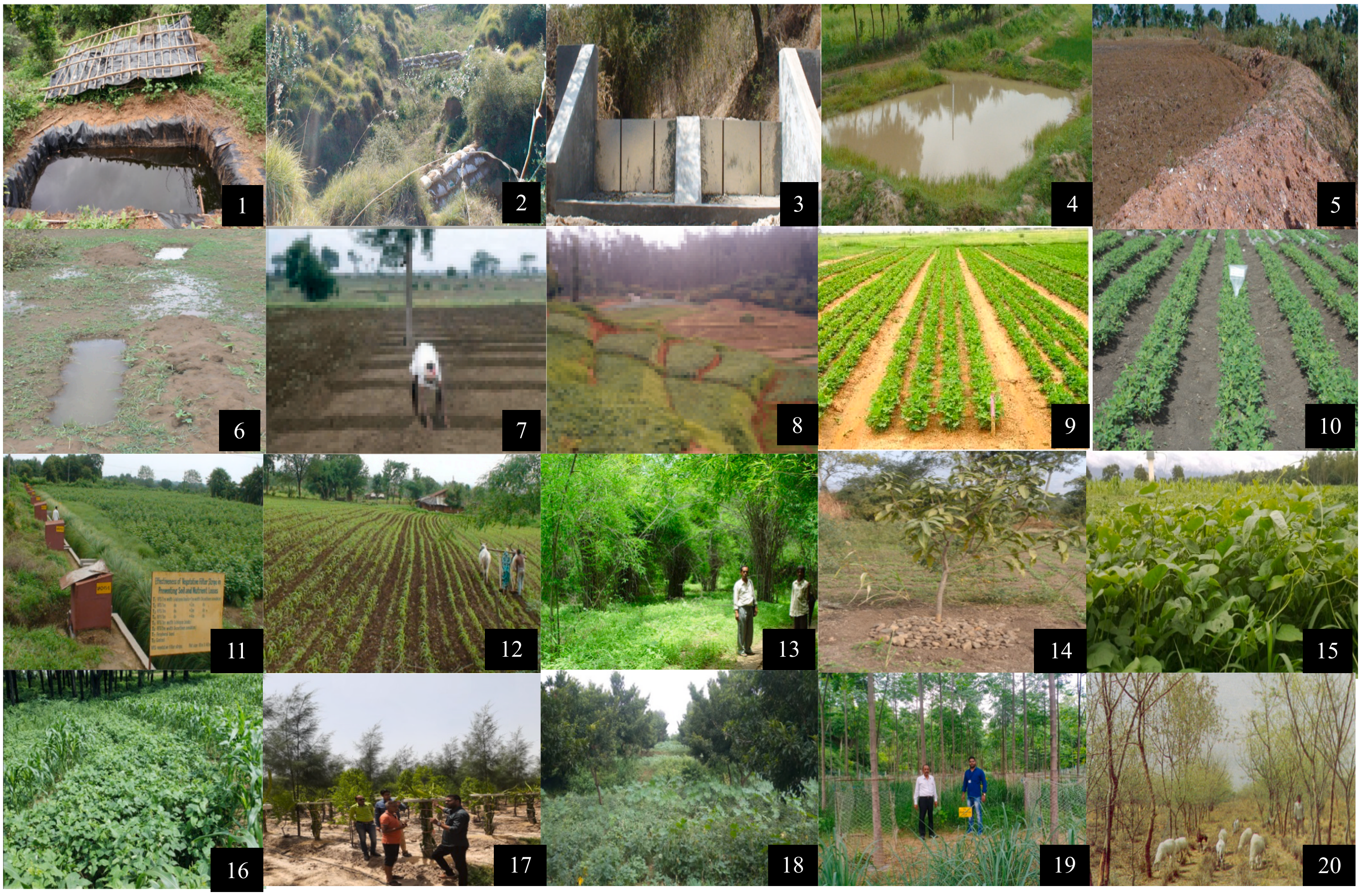

Fig. 3. Various soil and water conservation techniques implemented in different watershed program. 1: Jalkund; 2: bouribund; 3: checkdam; 4: dugout pond; 5: peripheral bund; 6: staggered trenches; 7: compartmental bunding; 8: bench terracing; 9: broad bed & furrow; 10: ridge & furrow; 11: grassfilters; 12: conservation furrow; 13: bamboo live checkdam; 14: stone mulching; 15: cover cropping; 16: strip cropping; 17: horti-silviculture system; 18: agri-horticulture system; 19: silvo-aromatic system; 20: silvi-pasture system.

2019). Research conducted in the Adarsha watershed, Kothapally, India, demonstrates that the adoption of water and soil conservation techniques significantly boosted groundwater recharge and reduced runoff by 30–45 % (Wani et al., 2002). Additionally, farmers in the watershed improved crop yields and net returns by utilizing advanced agronomic practices such as intercropping, high-yielding cultivars, and integrated nutrient and pest management (Wani et al., 2003). Yield increases of 2.0–2.5 times for maize-pigeon pea systems and 4.0 times for sole maize were observed, alongside a 2.0–3.0-fold expansion in areas cultivated with maize, pigeon pea, and chickpea (Srinivas et al., 2020; Garg et al., 2012). These improvements led to a 10–30 % rise in green water availability, crop productivity, and net returns, ultimately enhancing water use efficiency (Wani et al., 2006). The effectiveness of IWM structures relies on various socio-economic and physical factors, which can be analyzed using GIS to identify suitable sites (Al-Adamat et al., 2010; Shashilila and Patra, 2018). The subsequent sections discuss popular *ex-situ* water conservation measures in detail.

Check dams

The check dams are artificial barriers built across the stream that collect water, trap sediment, and reduce the velocity of flow. Small-sized water harvesting structures like check dams possess vast potential for storing water and irrigating nearby areas (Agoramoorthy et al. 2008; Palsaniya et al., 2012). Check dams have an important role in fulfilling the water needs and hence affect the agricultural production and livelihood of beneficiary farmers (Abbasi et al. 2019). It has been reported that low-cost plastic check dams made up of polypropylene (PP) and high-density polyethylene (HDPE) are found to be equivalent in terms of water harvesting and groundwater recharge at Mahi Ravine lands of Central Gujarat (Kurothe et al., 2018). Moreover, live bamboo check dams and bori bund check dams supported by bamboo + Anjan grasses were found to be promising in slop stabilization, reducing the velocity of runoff water, trapping silt, and groundwater recharge (Singh et al., 2020).

Percolation tanks

The percolation tanks are the surface runoff harvesting structures spread over an area having a high permeability rate with the purpose of recharging the groundwater storage. The artificial recharge of groundwater is widely done by constructing percolation tanks across the stream (Srivastava et al. 2007; Agarwal et al. 2013). The second or third-order streams having optimum catchment area and fractured surface are preferred for the construction of a percolation tank (CGWB, 2007). GIS and RS technology can be used for the assessment of the suitable site of artificial groundwater recharge (Srivastava et al. 2007; Kadam et al. 2012), and various available software may be used for deciding the -optimum dimensions of percolation tanks for harvesting water.

Farm ponds

Water harvesting structures like farm ponds are most necessary to harvest water and supply during the deficit period to mitigate the drought effects during erratic rainfall situations. It is generally constructed in low-lying areas to collect a large amount of water. The site selected for farm pond construction should not have any impervious layer or heavy soil deposition; rather, it should have a moderate to low infiltration rate for better pondage (Singh et al. 2009). As per IMSD

Table 1
Soil and water management practices used in watershed management programmes.

SWC measures	Location	Crop/Cropping system	Impact	References
Agronomic practices and vegetative measures				
Cover crops	*Kuchchh* (Gujarat)	Greengram and clusterbean	Soil loss was reduced by 77 % and 73 % by greengram and cluster bean over fallow.	Machiwal et al. (2021)
Strip cropping	Bikaner (Rajasthan)	Clusterbean+anjan grass (*Cenchrus ciliaris*), mothbean+anjan grass, pearmillet+anjan grass	Soil loss reduced by 4.5 to 9 folds over sole cropping	Soni et al. (2013)
Intercropping	Dehradun (Uttarakhand)	Maize+sweet potato	Soil loss decreased by 56 % and soil moisture improved by 19.3 % over maize-wheat system	Yadav et al. (2023)
Contour farming	Siddipet (Telangana)	Mungbean + pigeonpea	Mungbean and pigeonpea yield increased by 45 % and 12 % over up and down cultivation	Ramanjaneyulu et al. (2020)
Mulching	Nawanshahr (Punjab)	Maize	Reduced runoff (35 %) and soil loss (90 %)	Bhatt and Khera (2006)
Conservation agriculture	Dehradun (Uttarakhand)	Maize-wheat	Wheat equivalent yield (+47 %)	Ghosh et al. (2015)
Configuration techniques	Kalburgi (Karnataka)	Pigeonpea	Ridge and furrow protected the crops from dry spells and enhanced crop production by 300 kg/ha over peasant practices.	Rejani et al. (2022)
Agri-horticulture	Anand (Gujarat)	Cowpea + castor + sapota	This system decreased soil loss (37.7 %) and runoff (19.1 %) and sequestered 9.79–11.3 Mg C (CO_2 eq.) ha^{-1}.	Jinger et al. (2022)
	Dehradun (Uttarakhand)	Litchi + cowpea + turmeric	Soil available nitrogen, phosphorus, and potassium improved by 19.9 %, 75.3 %, and 36.8 %, respectively over mono culture.	Rathore et al. (2024)
Horti-pasture system	Shivalik hills (Chandigarh)	Aonla + *Chrysopogon fulvus*	Horti-pasture system saved water (4.9–30.7 cm) and soil (862–2,818 kg ha^{-1})	Prasad et al. (2012)
Alley cropping (Hedgerow intercropping)	Koraput (Odisha)	Fingermillet + gliricidia	Hedgerows intercropping decreased run-off (29 %), soil loss (45 %)	Hombegowda et al. (2020)
Silvo-pasture system	Anand (Gujarat)	*D. strictus* + anjan grass	Reduction of soil (90 %) and nutrient loss (70 %)	Rao et al. (2012)
Bamboo cultivation	Dehardun (Uttarakhand)	*D. strictus*, *D. hamiltoni*, *D. asper*, *Bamboosa bambos*, *B. nutans*, and *B. balcooa*	Fine and coarse roots of bamboo infiltration, reduced runoff and protected the gully land from further expansion.	Kaushal et al. (2020; Kaushal et al., 2021)
Horticulture intervention with conservation practices	Dehardun (Uttarakhand)	Aonla, guava, mango, litchi, and citrus with mulching and profile modification	These systems enhanced the SOC by 22–32.6 % over farmer's practices.	Rathore et al. (2023)
Horti-silviculture system	Anand (Gujarat)	Dragon fruit + *Melia dubia* + half-moon terrace	The biomass and carbon sequestration increased by 183.2 % and 82.8 % respectively, compared to sole Melia plantation without half-moon terrace.	Jinger et al. (2024)
Silvo-aromatic system	Anand (Gujarat)	Lemon grass + *Melia dubia* + soil moisture conservation measure	The silvo-aromatic system significantly improved the total tree biomass and total CO_2-sequestration with a 255 % increase over sole Melia.	Jinger et al. (2025)
Engineering measures				
Geotextiles	Udhagamandalam (Tamil Nadu)	–	Jute geotextiles reduced the soil loss by 75 % and saved total nutrients by 46 to 62 %.	Manivannan et al. (2018) Adhikary and Sankar (2018)
	West bengal (India)	Groundnut	Crop yield and SOC increased by 64.2 % and 53 %, respectively.	
Bench terracing (BT)	Ravine land (Gujarat)	Sapota	Decreased overflow (34 %) and soil loss (25 %)	Kumar et al. (2020a)
Conservation bench terraces (CBT)	Dehardun (Uttarakhand)	Rice (recipient area) Maize + cowpea (donor area)	CBT reduced the runoff (80 %) and soil loss (88 %)	Sharda et al. (2013)
Contour bunding	Pali-Marwar (Rajasthan)	Mustard	Economic and biological yield improved by 14.4 % and 15.3 % over no bunding	Regar et al. (2007)
Conservation ditching	Ballary (Karnataka)	Sorghum	Reduced runoff and soil loss by 80 % and 64.3 % and increased yield by 36 %,	Mishra and Patnaik (2008)
Compartmental bunding (CP)	Sholapur (Maharashtra)	–	CP led to 4.3 % runoff over flat sowing (27 %).	Sharda and Ojasvi (2005)
Contour trenching	Puttur (Karnataka)	Cashew	Reduced runoff (45 %) and soil loss (50 %)	Rejani and Yadukumar (2010)Ali et al. (2017)
	Kota (Rajasthan)	Aonla + Anjan grass + *D. strictus*	Reduced runoff (86 %) and soil loss (125 %)	
Peripheral bund	Agra (Uttar Pradesh)	Green gram	Increased yield (164 %)	Singh et al. (2016)
Drop Spillway	Bundi (Rajasthan)	Soybean, mustard, and chickpea	Enhanced soil moisture by 15–20 %.	Ali and Jayaraman (2021)
Vegetative barrier (VB)	Anand (Gujarat)	Pigeon pea	VB reduced the runoff (20 %) and soil loss (51 %)	Kurothe et al. (2013)
Grass waterways	Dehardun (Uttarakhand)	Para grass	Reduced the outflow up to 22 %	Mahapatra et al. (2018)
Gully plug	Agra (Uttar Pradesh)	–	Stabilized the gully head and acted as barriers for further gully expansion	Soni et al. (2018)
Bori bund	Vasad (Gujarat)	Bamboo and Anjan grass	Reduced runoff velocity and soil loss to a great extent.	Singh et al. (2020, 2021)
Check dams	Jhalawar and Banswara (Rajasthan)	–	Reduced runoff by 35 % and improved infiltration by 27 %.	Agoramoorthy et al. (2008)

guidelines, the site having a 0–5 % slope, low permeability, and located on a first-order stream is most preferred for farm pond construction (Naseef and Thomas, 2016). The farm ponds have shown a significant impact on farmers' fields in terms of increasing cropping intensity, crop yield, and improving average annual income (Chavai et al., 2015). The farm pond-based irrigation system to the adjoining *Ziziphus mauritiana* orchard in the arid region was found to be effective in sustaining the production system with a benefit-cost ratio of 1.672 (Goyal et al., 1995; Bouma et al., 2016). A study by ICRISAT on farm ponds across 7 locations and 5 states (Chittoor, Anantapur in Andhra Pradesh, Akola in Maharashtra, Bangalore rural in Karnataka, Vellore in Tamil Nadu, and Bhilwara and Jodhpur in Rajasthan) revealed substantial benefits accruing from the investment made (Pathak et al., 2013). Due to the availability of additional water, not only was cropping intensity and crop diversity increased but also diverse portfolios like horticulture, dairy, sheep rearing, etc., were added to the farm. Further, gross cropped area and water use efficiency was maximized using efficient sprinkler irrigation system. Farm ponds are instrumental to increasing productivity, net returns, and groundwater recharge, thus resilience to climate change-induced shocks (Kumar et al., 2016).

Efficient use of water resources under watersheds and enhancing water use efficiency

Water is essential for life, food production, energy, and economic development. However, freshwater supplies are increasingly strained due to global population growth, industrialization, and urbanization. By 2050, water withdrawals are expected to rise by 50–250 %, with 6 billion people facing clean water scarcity (Florke et al., 2018; Boretti & Rosa, 2019). This scarcity threatens food security and livelihoods, especially for small farmers in developing regions. To combat this, efficient water-use methods like micro-irrigation, irrigation scheduling, mulching, *in-situ* moisture conservation, and improved cropping systems must be adopted. Watershed management offers a climate-smart solution to conserve water, enhance soil fertility, and sustain agricultural productivity in dry regions.

Due to the lack of adoption of effective water management techniques, agricultural water usage efficiency is still quite poor (Deng et al., 2006). Hence, the adoption and development of novel water management approaches are needed to address the declining water availability and enhance WUE. The implementation of land configuration, mulching, irrigation techniques, tillage, soil–water conservation practices, cropping systems, soil, crop, and nutrient management practices, etc., can enhance WUE (Raes et al., 2013). Many studies demonstrated that the adoption of advanced agronomic water management practices increased the WUE (Zhuo and Hoekstra, 2017). Nangia et al. (2008) reported that improved management of N fertilizers resulted in increased WUE. Improved water and nutrient management has been shown to enhance WUE by 10–25 % in wheat-maize crop rotation (Fang et al., 2010).

Reducing evaporation

To enhance the use efficiency of stored water and maximize productive uses, checking evaporation losses is very important. The integration of agronomic interventions—such as mulching, intercropping, relay cropping, conservation tillage, vegetative cover, and integrated crop management—within watershed development programs offers viable solutions for minimizing evaporative losses and runoff, improving soil health, and enhancing soil infiltration, green water storage, groundwater recharge, water use efficiency, and agricultural productivity (Kurothe et al., 2018; Kader et al., 2019; Singhal et al., 2020; Rao et al., 2022). Moreover, interculture or weed management is also reported to be helpful in reducing evaporation losses besides improving crop yield from the cropland (Jinger et al., 2016a, Wang et al., 2016b, 2017).

Mulching

Mulching is a highly effective agronomic practice that enhances water-use efficiency (WUE) by reducing evaporation, regulating soil hydrothermal properties, and improving soil health (Jinger & Kakade, 2019; Jat et al., 2021a). It also suppresses weeds, reduces runoff, and increases crop productivity (Kumawat et al., 2020). Organic mulches like crop residue improve microbial activity, soil fertility, and moisture retention (Yadav et al., 2021). Residue mulching (3–6 Mg ha^{-1}) can reduce soil evaporation by 21–40 %. Other mulches like newspaper and plastic can improve WUE and reduce evapotranspiration losses (Ranjan et al., 2017; Zhang et al., 2018), with plastic mulching increasing WUE by up to 64 % (Zegada-Lizarazu & Berliner, 2011).

Intercropping

Intercropping enhances WUE by optimizing soil moisture use, reducing water losses, and mitigating water stress (Chimonyo et al., 2016; Jat et al., 2021b). It reduces runoff by 17–26 % and increases productivity by improving soil structure and moisture retention (Sharma et al., 2017a; Singh et al., 2020a). Maize + pigeon pea intercropping, for example, reduces runoff by 19.3 % and increases WUE by 48 % over monoculture systems (Coll et al., 2012; Singh et al., 2014a; Singh et al., 2014b). The improved and complementary rooting pattern, increased root density and biomass, and good canopy development under intercropping facilitate increased spatiotemporal utilization of green water and reduced erosion, runoff, and soil evaporation losses (Maitra et al. 2020). The synergistic regulation of water supply and complementary patterns of roots in maize + pea strip intercropping led to 14 % and 17 % higher WUE than the pure stand of maize and pea, respectively (Mao et al. 2012; Gitari et al. 2019). Higher green water conservation under the intercropping system was due to lower evaporation and runoff losses over a single crop (Stomph et al. 2020; Yin et al. 2020).

Relay cropping

Relay cropping improves resource use efficiency, productivity, and sustainability by extending the growing season and improving water use through complementary root systems (Gao et al., 2009). It enhances WUE by 13.3–53.5 %, as shown in studies on prosomillet (Gong et al., 2020), and helps conserve water through improved physiological processes such as stomatal regulation (Tang et al., 2005). Gong et al. (2020) demonstrated that strip relay cropping of prosomillet resulted in significantly ($P < 0.05$) increased green WUE by 13.3–53.5 % as compared to sole cropping. The improved physiological metabolism, soil environment, and resource availability contributed to higher grain yield, which consequently led to higher WUE of relay cropping. Meixiu et al. (2020) developed a model with water limitation to simulate water acquisition efficiency in wheat-maize relay cropping in the Northwest. The results indicate that relay strip intercropping of wheat and maize achieved an increase of land use efficiency of 59% and of WUE of 14%.

Irrigation methods

Irrigation scheduling at critical growth stages is key for efficient water use in water-scarce conditions (Ram et al., 2013). The alternate furrow irrigation method reduces water consumption by 15.3–16.1 % compared to flood irrigation in wheat + maize systems (Wang et al., 2015). In bed-planted wheat, water savings of 30–49 % were achieved, while ridge-planted cotton saved 20–42 % using alternate furrow irrigation, which improved WUE by 23.9–43.2 % for wheat and 2.1–19.5 % for cotton without significant yield losses (Thind et al., 2010). Furrow irrigation saves 12–24 % of water, with similar or higher yields compared to conventional methods (Sarkar et al., 2010). Advanced methods like drip and sprinkler irrigation minimize evaporation, runoff, and nutrient loss, achieving 98–99 % WUE, saving 12–84 % of irrigation water, and increasing crop yields (Abd El-Wahed et al., 2017; Jain et al., 2021a). Drip irrigation applied at 0.8–1.0 IW/CPE was economically viable, saving 40 % more water than check basin methods (Kaur & Brar, 2016; Jain et al., 2021b). Subsurface drip irrigation further enhances

WUE by distributing water and nutrients more uniformly in the root zone (Adetoro et al., 2020). Deficit irrigation (DI) also improves WUE by applying less than full crop requirements, reducing water consumption and production costs, especially in arid regions (Haghverdi et al., 2017). Computerized irrigation systems have been shown to reduce water use by 21 % and increase irrigation WUE by 29–36 % (Bryant et al., 2017).

Water budget-based water scheduling

Water budget-based irrigation scheduling has emerged as a more precise method for determining irrigation needs (Kirnak et al., 2019). A study in deep Vertisols in Bhopal, India, showed that applying 8 cm of water at sowing and 14 cm at the crown root initiation stage using sprinkler irrigation, followed by flooding, resulted in the highest wheat yield and improved water and nitrogen use efficiency (Pradhan et al., 2017). Efficient water management requires determining optimal irrigation thresholds for each crop (Lemay et al., 2012). Soil matric potential is a direct measure of soil water availability, and using it for irrigation scheduling reduced water usage by 40–49 % in fall-winter and 42–46 % in spring-summer seasons, while increasing WUE by 65–96 % and 14–73 %, respectively (Buttaro et al., 2015). Studies have shown that irrigation thresholds of −10 to −15 kPa improve yield by 20 % and WUE by 33 % under dry climates (Letourneau et al., 2015). Higher WUE was achieved at thresholds of −15 to −30 kPa (Hoppula & Salo, 2007; Bergeron, 2010). Drip irrigation at 50–70 % of field capacity saved 17–33 % of water and increased wheat yield by 0.3–16.7 %, while WUE improved by 29–79.9 % (Jha et al., 2019). A 20 % water deficit using a crop water stress index in drip-irrigated pumpkin enhanced WUE without significantly reducing yields in semi-arid conditions (Kirnak et al., 2019).

Water efficient crops/cultivars and management practices

Developing water-efficient genotypes and modifying sowing dates, crop geometry, and seed rates are effective strategies to enhance crop WUE (Xu et al., 2016). Water-efficient cultivars outperform others under water-deficit conditions by mitigating stress and producing higher yields (Ul-Allah et al., 2018). C_4 crops like maize and sorghum are generally more water-efficient than C_3 crops, while CAM crops like cactus and pineapple are the most efficient (Sharma et al., 2015). Studies have shown that medium spike wheat cultivars (e.g., JM 22) have 4.2–9.3 % higher WUE due to better post-anthesis biomass and water uptake from deeper soil profiles (Wang et al., 2016). In sweet sorghum, CSH 22 SS was found to be the most water-efficient (Sawargaonkar et al., 2013). Other agronomic practices like subsoil tillage, integrated nutrient management, and mulching also contribute to improved WUE (Ma et al., 2018; Jain et al., 2021c). Subsoil tillage reduces water use by 6.3–7.8 % and increases WUE by 12.7–15.2 % compared to rotary tillage (Tao et al., 2015). Early sowing combined with zero tillage has been shown to boost water productivity by up to 25 % (Brouziyne et al., 2018).

Integrated soil test-based nutrient management

According to Hatfield et al. (2001), there is a possibility to increase crop WUE by 15–25 % by means of better nutrient management approaches and by 25–40 % through soil management practices. The higher WUE through fertilizer application has been shown both under irrigated and water-limited conditions, but more under later conditions (Singh et al., 2010a). Several researchers indicated that balanced application of macro- and micronutrients resulted in increased WUE in several crops, *viz.*, paddy, maize, wheat, chickpea, green gram, and potato (Martineau et al., 2017; Sharma et al., 2017b; Jat and Balyan, 2004). The importance of K and Zn in coping with drought and enhancing WUE is well recognized under water availability and water deficit (Hussain et al., 2018). The balanced application of K in maize under normal and 30 % water deficit conditions led to lower transpiration and improved leaf rolling, which consequently saved irrigation water, increased drought tolerance, and enhanced the WUE by 30.0 % compared to without K application (Martineau et al., 2017). Li et al. (2004) suggested that pre-sowing irrigation with P application and pre-sowing irrigation alone in wheat increased the WUE by 150 % and 119 %, respectively, compared to the control. Likewise, the application of N at high rates increased the WUE of high-yielding rice under flooded as well as alternate wetting and drying irrigations (Zhang et al., 2012).

Crop diversification with high-value crops

In several regions of India, cropping systems have been diversified by introducing new crops to sustain and improve the productivity (Reddy and Suresh, 2009). Wheat was introduced in the rice-based system to utilize residual soil moisture and economize irrigation requirements of wheat in West Bengal (Prasad et al., 2014). Studies carried out by All India Coordinated Research Project on Cropping Systems at different locations in India documented 100–200 % higher WUE in different cops (Ramesh et al., 2009). Singh et al. (2005) concluded that the introduction of high-value crops such as cabbage, snake gourd, colocasia, pointed gourd, and papaya in the existing rice-rice system improved the WUE by 600 %. The increased WUE with diversification has also been reported by Lenssen et al. (2014) and Miller et al. (2003). Crop diversification through intercropping (groundnut+pigeon pea) and double cropping (maize-horsegram/sesamum) was suggested as a very useful approach for enhancing rainwater use efficiency together with drought mitigation and yield stabilization in the upland rice ecosystem of Odisha (Kar et al., 2004).

Recycling of community wastewater for safe reuse

Reusing cleaned wastewater for a variety of uses, including residential consumption, groundwater recharge, industrial operations, and landscape and agricultural irrigation, is known as water recycling (Tortajada, 2020). Moreover, wastewater recycling and reuse prevent the water pollution by decreasing nutrient loads from wastewater that discharges into the waterways (Saad et al., 2017). Conservation and reuse of wastewater reduce water diversions from sensitive ecosystems and impact on water quality by reducing wastewater discharge and thus provide considerable environmental benefits (Smol et al., 2020). Hence, recycling of domestic wastewater for reuse is a critical component of sustainable water management in several water-stressed countries (Saliba et al., 2018). Mekala et al. (2008) estimated that around 73,000 ha of land in India are directly watered with wastewater. About 1700 ha of land is irrigated with wastewater to grow vegetables like brinjal, ladyfinger, and cucurbits in summer and cabbage, cauliflower, mustard, and spinach in winters by 12,000 farmers in New Delhi, India. Likewise, wheat is largely irrigated with wastewater in Ahmadabad and Kanpur, India (Winrock International India 2007). Flower production is also practiced by the farmers of Kanpur, India, with wastewater irrigation. Jasmine cultivation with wastewater irrigation in Hyderabad, India, generated employment for 8–9 months per year and provided a profit of about Rs. 15,000–20,000 per ha (Buechler et al. 2002). However, direct use of city wastewater for growing food crops, especially vegetables poses significant threat to human health, Hence, further research on feasible solutions for treating city wastewater is needed.

Kitchen gardening

Kitchen gardening involves growing vegetables and fruits in small areas near the home, providing fresh, organic produce to the family while saving money and time (Dhakal et al., 2020). It ensures food and nutritional security, creates a healthy hobby, and promotes environmental sustainability (Ghosh & Maharjan, 2014). Rainwater catchment and domestic rooftop harvesting are key water sources, making kitchen gardening economically viable and enhancing rural livelihoods (Chowdhury et al., 2016). Wastewater from kitchens can also be reused for growing crops, saving water and increasing output (Gunawardana et al., 2018). Properly managed kitchen gardens improve quality of life, generate income, and support economic growth (Chawla et al., 2016).

Benefits accrued through integrated watershed management

Tangible benefits

Different resources are provided by watershed management, creating interdependent benefit flows. A few of these advantages are material goods like wood, food, and fodder, which can be utilized to construct homes, meet farmers' needs for sustenance, and feed animals, respectively (Fig. 4). Next we have discussed on food production in detail.

Food Production

In the Kokriguda watershed, Koraput, Odisha, the agronomical intervention included crop diversification through cash crops like vegetables, improved crop varieties, double cropping, and improved cropping systems and crop production practices. Collective efforts of the above interventions resulted in a sixfold increase in overall watershed productivity in terms of rice equivalent yield. The nutrition of villagers also improved as evidenced by the increase in vegetable consumption from 15.4 g to 33.0 g/capita/day (Dass et al., 2014). The construction of anicuts and afforestation in the Bhind and Morena watersheds of Madhya Pradesh prevented farmers from cultivating ground descending in two villages, Bindwa and Himmatpur, while simultaneously reclaiming the ravine area. According to the results, the net cultivated area grew by 6.5 % in Himmatpur and 13 % in Bindwa village. The water table rose in both villages, which led to an increase in the irrigated area and cropping intensity of 73 % in Bindwa village and 45 % in Himmatpur village (Singh et al., 2018). The implementation of agroforestry (castor + cowpea + sapota) has a remarkable effect on crop productivity in the Mahi ravine watershed area of Gujarat. The agroforestry system produced the highest system productivity measured in cowpea equivalent yield (CEY), increasing it by 162 % and 81.9 %, respectively (Jinger et al., 2022).

In the Salaiyur watershed, Coimbatore, Tamil Nadu, integrated watershed management practices were implemented, monitored, and finally evaluated. Improved crop diversification and a package of measures in the Dhoti watershed, Rajasthan, yielded 17–80 % more grain during the *rabi* and *kharif* seasons, respectively, than the watershed's traditional cropping system. Similarly, in the Vejalpura-Rampura watershed, Gujarat, construction of dugout ponds for life-saving irrigation increased the yield of rainfed paddy crops by 42 %. Odisha interventions, including lined ponds, jhola kundi, check dams, and dugout ponds, were also implemented in the Lachhaputraghati watershed. According to Dhyani et al. (2016), the area under cereal, pulse, and oilseed crops grew to a total of 45 ha.

Intangible ecosystem services from watershed

Many benefits are less tangible services but important from an environmental point of view, like reducing erosion, conservation of moisture, and cycling nutrients (Swallow et al., 2001). These benefits are very difficult to measure and value. However, we have collected the data from research conducted at various institutes on soil and water conservation and discussed it below.

Erosion control and soil conservation

In the Netrenahalli watershed of Karnataka's Chitradurga district, soil and moisture conservation measures preserved 685 cubic meters of soil from 165 ha within agricultural lands, increasing in-situ moisture and slightly boosting crop yields in rainfed areas. Additional water storage of 4657 cubic meters was created through pond construction, tank de-siltation, and nala deepening (Raizada et al., 2018). In the Babina watershed of Bundelkhand, *Saccharum munja* vegetative barriers were the most effective soil conservation technique, followed by land leveling, field bunding, and contour bunding (Kumar et al., 2016). In Gujarat's Mahi Ravine Watershed, bench terracing and contour bunding significantly reduced runoff and soil loss in sapota orchards (Kumar et al., 2020a; Kumar et al., 2020b; Kumar et al., 2020c). The Eastern

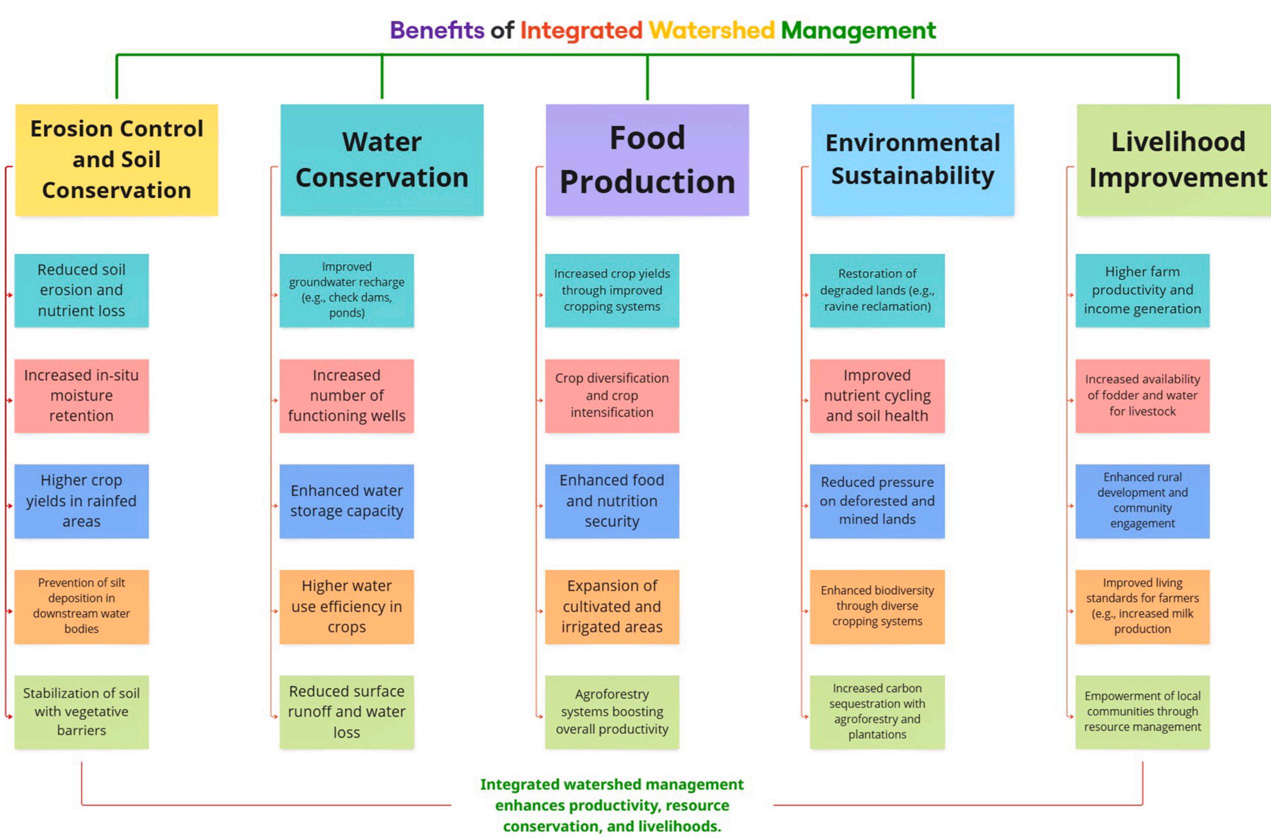

Fig. 4. Benefits from integrated watershed mangement.

Ghats face land degradation from shifting cultivation and deforestation. Watershed management, including intercropping of papaya and gliricidia, reduced soil loss to 0.5–1.4 t ha^{-1}, and gliricidia's nitrogen fixation and resource conservation enhanced system stability (Jhakhar et al., 2010). In sloping lands of Odisha, bioengineering measures like earthen bunding with broom grass effectively reduced runoff to 11.6 % compared to 24.5 % under traditional farming (Sahoo et al., 2018).

Water conservation

In Maharashtra's Shekta watershed, check dams were constructed to collect 28,950 m3 of runoff water and prevent erosion. This intervention increased the total number of wells by 48 %, seasonally functioning wells by 51 %, and perennially functioning wells by 128 % to 223 % over 4–8 months (Wani et al., 2011a). In Gujarat's Rajasamadhiyala watershed, similar measures resulted in a 20.8 % increase in open wells and a 96.1 % growth in bore wells from 1995 to 2004, with the mean water column increasing by 6.6 m during the rainy season (Wani et al., 2011). In the Bundelkhand region of Central India, in-situ moisture conservation techniques, such as contour staggered trenches, enhanced soil moisture content by 49–51 % at depths of 0–30 cm (Singh et al., 2015). In Karnataka's Hegadekhatta watershed, moisture conservation in *Acacia* plantations increased soil moisture by 20 % compared to controls (Dass et al., 2013). Moisture conservation practices in ridges and furrows with crop residue also improved water use efficiency, with the maize-mustard system achieving 12.27 kg ha^{-1} -mm due to reduced evapotranspiration (Jhakhar et al., 2017). In Hiware Bazar, an integrated watershed program improved water availability, fodder supply, and milk production, elevating the farmers' standard of living (Phand et al., 2007) (Fig. 5).

Ecosystem Services (ES) are the benefits provided to humans through the conservation of natural resources, thereby ensuring the sustained supply of essential goods and services (MEA, 2005). Therefore, an ecosystem through the supply of need-based ecosystem services establishes a linkage between ecosystems and societies (MEA, 2005). Similarly, watershed management is also a social-ecological system (Cabello et al., 2015), wherein a hydrologically connected geographical area is managed by the local community. On the contrary, if the flow of any of the ecosystem services declines, it is an indicator of the degradation of the natural resource base of that system (Tamire et al., 2023). Therefore, in the case of watershed management, the concept of ecosystem services and payment for it is being increasingly used as a management approach for sustaining the watersheds and establishing harmonious economic linkages between the upstream and downstream areas.

Integrated watershed development interventions provide both tangible goods and intangible ecosystem services (ESs), including improved soil health and ecological benefits (Rao, 2000; Joshi et al., 2005; Singh et al., 2010a) (Table 2). Well-managed watersheds enhance supporting services, such as increased soil health, and regulating services like groundwater recharge, leading to expanded irrigated areas, increased cropping intensity, and restored traditional water harvesting structures (Chandru et al., 2015; Sikka et al., 2020). These effects, especially in drought-prone regions, improve resilience (Wani et al., 2007). Cultural services from watersheds include the formation of local institutions and gender equity, promoting collective action and resource conservation. For instance, in the Sukhomajri watershed, local pastoralists stopped open grazing and implemented "social fencing," leading

Fig. 5. Success story of integrated watershed management program in Hiware Bazar village of Maharashtra (Source: DownToEarth, 2020).

Table 2
Ecosystem services from watershed.

Ecosystem Services	Definition	Indicator	Example and Impact	References
Provisioning	Products/ goods obtained from ecosystems (*e.g.*, fodder, wood, biofuels)	Food production	Increased productivity of various crops by 15 to 66 % in Bundelkhand Region, Madhya Pradesh	Mondal et al. (2013)
	These can be directly consumed and traded, and commonly valued at market price	Fruits production	Increased area under horticultural crops Zunheboto watershed, Nagaland	Singh et al. (2010a) Singh et al. (2010b)
		Drinking water	Improved the access to drinking water in watershed project areas	Rao, 2000
		Employment opportunities	On average the employment opportunities increased to the extent of 182 man-days per ha per year in different watersheds in India	Joshi et al. 2005
Supporting	Functions and processes which are essential to produce other ecosystem services (Provisioning, Regulatory and Cultural services)	Reduction in waste land	Cultivable wastelands declined by 60 % in various watersheds in Himachal Pradesh	Singh et al., 2010b
		Reduction in soil loss	On average reduction in soil loss by 0.82 tonnes per ha in various parts of India	Joshi et al. 2005
		Reduction in run-off	Significant reduction in runoff in Garhkundar–Dabar watershed, Bundelkhand	Reddy et al., 2017a; Reddy et al., 2017b
		Improvement in soil fertility	Improved availability of macro and micro nutrients in different watersheds of Bundelkhand Region	Kumar et al., 2020a; Kumar et al., 2020b; Kumar et al., 2020c
		Carbon sequestration	Kwalkhad Watershed in Western Himalayan region	Goswami et al. (2014)
Regulating	The functions which help in regulating the phenomena such as flood mitigation, water quality, carbon sequestration and long-term storage etc.	Groundwater Recharge	Augmented groundwater in Saliyur watershed, Tamil Nadu Totaganti micro-watershed, Haveri Karnataka	Sikka et al. 2020Chandru et al. (2015)
		Drought proofing	Fakot watershed, Uttarakhand	Wani et al. 2007
Cultural	Nonmaterial benefits arising from the interaction between human-being and ecosystems	Reduction on women Drudgery	Reduced time for water collection in Dudhi watershed, Madhya Pradesh	Hope, 2007; Sharma et al. 2012
		People participation and strengthening of local institutions	Improve social participation and collective actions	Joshi et al. 2005

to vegetation restoration and solving the lake's siltation problem (Arya, 2023). Watershed management also empowers women by increasing their participation in decision-making, reducing migration, and alleviating drudgery through improved access to drinking water (Grewel et al., 1999; Sharma et al., 2012). Programs often promote financial empowerment *via* self-help groups (Khatibi & Indira, 2011). Fig. 6

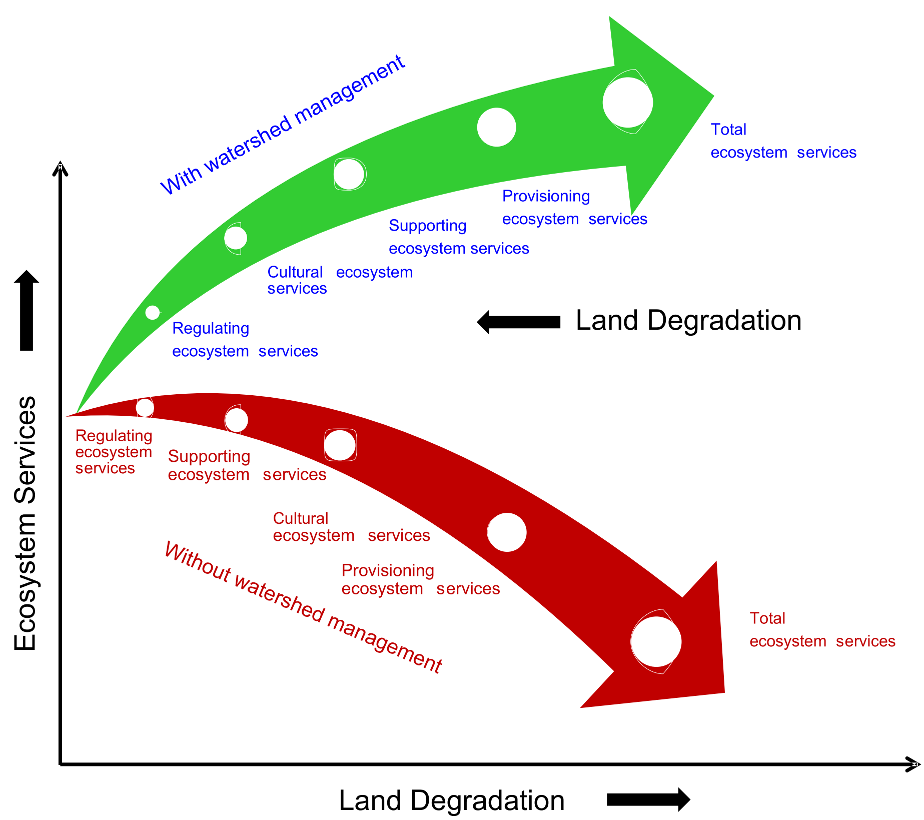

Fig. 6. Level of ecosystem services with and without watershed scenarios.

illustrates that land degradation causes a downward spiral of ecosystem services, but well-managed watersheds can reverse degradation and increase overall ESs. Systematically measuring these services and incorporating them into management strategies ensures a sustainable ES supply and supports the livelihoods of resource-poor farmers in ecologically fragile regions. Similarly, the impacts of IWM on five capitals have been illustrated in Fig. 7.

Watershed success story: Sukhomajri watershed

A parched village in the Shivalik foothills, *Sukhomajri* was located in the Panchkula district, close to Chandigarh. Significant ecological issues plagued it in the 1970s. Groundwater levels were extremely low, despite 1100 mm of rainfall falling there. That tale of misfortune was cyclical. There was little vegetation because of the soil's state, which exacerbated runoff and erosion. The villagers had begun removing hill slopes to make room for the plow because of the lack of land due to economic instability. The land's ability to retain water and its rich topsoil were diminished as a result, and the annual rains carried the fertile soil away, even though the output was minimal. About 15 km from Sukhomajri, the man-made Sukhna Lake had lost about 68 % of its storage capacity due to sedimentation by 1976, just 13 years after it was first formed. To investigate the reason for the excessive sediment rate, the CSWCRTI team was dispatched to examine the lake's catchment. The slopes close to Sukhomajri have seen severe degradation, as was quickly found out. There was very little vegetative cover on the hills, only 5 %. The peasants had historically kept herds of animals to reduce risk because agriculture was fraught with uncertainty. The hills that surrounded the settlement were open for the livestock to graze on. Severe erosion and low grass yield were caused by uncontrolled grazing without breaks. The village's economy was in complete disarray. Only emaciated individuals and poverty filled the houses. Pre- and post-scenario of *Sukhomajri* watershed has been depicted in Fig. 8.

Major components of the Sukhomajri model

- Blocking the catchment area from grazing and trimming the grasses and trees.
- In order to improve the moisture regime of the poor soil, approximately 200 staggered contour trenches per hectare were built in the 4.3 ha of badly eroded watershed region.
- A number of check dams, grade stabilizers, and debris basins made of locally accessible stones were built in the degrading catchment area to manage silt from the gullies.
- The implementation of vegetative measures involved the planting of tree species such as Shisham (*Dalbergia sisso*) and Khair (*Acacia catechu*) in the pits, Bhabbar grass (*Eulaliopsis binata*) at the trench mounds, and *Agave americana* and *Ipomea cornea* at critical areas to prevent soil erosion. The species were chosen based on their economic worth and degree of adaptation.
- Building of clay reservoirs to hold surplus monsoon rainwater for use in gravity-flow supplemental irrigation of agricultural fields.

Lessons from Sukhomajri

- It is imperative to guarantee people's participation from the start.
- It is necessary to first identify the demands and issues facing the populace.
- A project might not succeed if its goals are not to satisfy their needs, address their issues, and lessen their suffering.
- Incorporating regional expertise and customs into an enhanced framework.

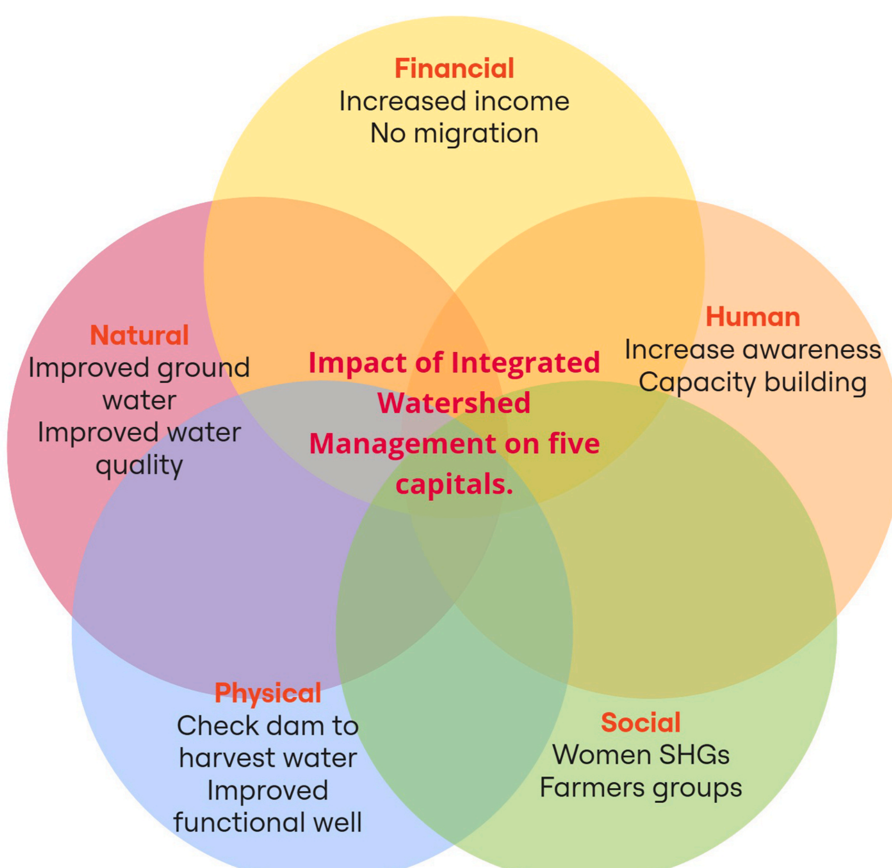

Fig. 7. Impact of Integrated Watershed Management on Five Capitals.

Fig. 8. Impact of Sukhomajri watershed program on water availability and vegetation.

- Projects for watershed management ought to have a brief gestation time.
- Benefits must be accessible as soon as feasible.
- A village society's constitution must be in place before beginning such projects.
- Sustainability and equity—that is, ensuring that all resources belonging to common property are accessible to all societal segments—should be prioritized.
- Project managers must be aware of the distinctions between the roles and duties that apply to men and women when it comes to using natural resources to support livelihood systems.

Implication of the study

The findings of this study hold significant implications for both policymakers and practitioners working in the fields of water management, agriculture, and climate resilience. The demonstrated improvements in groundwater recharge, soil health, and agricultural productivity through IWM practices provide a robust framework for sustainable agricultural practices in water-scarce and dryland regions. These results highlight the potential of IWM as a key strategy for addressing water scarcity and land degradation, which are critical challenges in India and other semi-arid regions globally. Additionally, the use of modern tools like Geographic Information Systems (GIS) and Remote Sensing (RS) in watershed planning can be adopted by local governments and non-governmental organizations to optimize resource management and prioritize interventions in the most erosion-prone and vulnerable areas. The participatory approach utilized in this study, which involves local communities in both the planning and implementation of watershed projects, also highlights the importance of community engagement in ensuring the long-term success and sustainability of these initiatives. From a broader perspective, the current study's insights into WUE and increased crop productivity can guide the development of climate-smart agricultural policies, helping countries achieve their Sustainable Development Goals (SDGs) related to zero hunger, reduced poverty, and environmental sustainability. Furthermore, the IWM framework can be promoted and adapted for use in other developing countries facing similar challenges, providing a viable solution for enhancing food security and improving rural livelihoods in the face of climate change.

Challenges

The integrated watershed approach, which aims to manage water resources, land use, and ecosystem health holistically and sustainably, faces a number of challenges. These challenges might arise from a variety of technical, institutional, socio-economic, and environmental factors. Some of the primary challenges are as follows (Kerr et al. 2000; Arya and Samra, 2001; Sharma, 2002; Sharma and Scott, 2005): Poor planning and design: The limited knowledge of watersheds often leads to poor planning and design which results in ineffective interventions and inequitable benefit distribution. Lack of knowledge of hydrology, land use, and community participation needs may fail to achieve the desired objectives. Climate change has increased risk and unpredictability for farmers and has emerged as a major threat to ensuring water supplies and maintaining the productivity of watersheds. These challenges need to be addressed through proper planning, redesigning conservation and water harvesting structures etc.. There is an immediate need to integrate traditional knowledge and modern techniques to improve the stakeholders' watershed productivity and livelihood security. Agroforestry and horticultural technologies have also great potential for contingency planning. These technologies also need to be suitably modified to address the problem of climate change.

Complex terrains and resource constraints: Due to complex terrains and resource constraints, scaling up watershed projects remains a challenge. In the recent past, small-scale models have shown success with the involvement of communities, social organizations, and appropriate site selection. In some of the states, a "mission mode" approach was followed for the development of watersheds. However, large-scale replication of such effective watershed models and success stories still remains a challenging issue.

Weak monitoring and inadequate data: In the past, many watersheds have been developed. However, monitoring and impact assessment in these watersheds in terms of hydrology, soil health, and biodiversity has been inadequate or poorly attempted. Without reliable data, it is difficult to assess changes and implement the watershed interventions. Poor data collection and lack of real-time monitoring further reduce efficiency. The challenge therefore is to develop and refine methodologies for data collection and long-term monitoring of watersheds in a scientific manner so that progress of these watersheds can be tracked in the long term. Such type of monitoring is essential for informed decision-making, ensuring accountability, transparency, and long-term sustainability for watershed initiatives.

Socioeconomic disparities and land ownership issues: Watersheds provide many benefits in terms of food, fodder, wood, water etc., which have a direct impact on the agriculture and livelihoods, of the community. However, equitable sharing of the benefits among the intended population of the watershed remains a major challenge. It has been observed that farmers with large landholdings or having more influential groups have better access to resources and decision-making and benefit more from watershed interventions while the landless people, small and marginal farmers and weaker sections of society receive fewer benefits only. In some of the watershed projects the women and landless people were worse due to limited access to resources that support their livelihoods. This issue requires immediate attention and policy support.

Upstream and downstream conflicts: Upstream and downstream conflicts are very common in watershed programs. Soil water conservation measures like afforestation or dam construction etc. adopted upstream have a beneficial impact on water availability downstream and thus benefit the one group while the population in the upstream gets no major benefits. Therefore, there is a need to provide a compensation mechanisms to the upstream residents who get no direct benefits of conservation despite the fact that their land holdings are involved in watershed interventions.

Use of modern tools and techniques: The new tools like remote sensing, GIS, drones, and real-time monitoring have huge potential for planning and monitoring land use changes. These tools can also be successfully used to improve water resource management. However, lack of technical expertise, high costs, and inadequate infrastructure are major challenges that prevent the use of these tools and techniques. Therefore, there is a strong need for integrating digital tools for sustainable and data-driven watershed management.

Capacity building: The success of watershed initiatives largely depends on farmers and communities in the watersheds. However, due to limited awareness, communities may find it hard to adopt sustainable land management practices which can lead to inefficient resource use. Moreover, weak institutional capacity at local, state, and national levels makes it difficult for the effective implementation of watershed programs. Strengthening capacity building is therefore crucial to ensure the effectiveness of watershed management initiatives. For this, there is a strong need to upgrade the skills of communities and local farmers through training and exposure visits. Strengthening the capacity of the institutions is also important for ensuring the long-term success of watershed programs.

Lack of Coordination: It has been observed that multiple agencies (government agencies, NGOs, and local communities etc.) are involved in watershed management and hence, may lead to conflicts and inefficiencies in watershed management. Due to this sometimes there is poor coordination and overlapping of responsibilities among these agencies which can delay the implementation of various activities. A common policy framework and integrated approach are therefore required for decision making. Moreover, strengthening collaboration among different agencies with well-defined roles can improve the sustainability and efficiency of the work.

Lack of participation: The lack of participation by the community due to lack of awareness about rights and benefits is one of the major challenges that weakens project sustainability. There is low adoption and maintenance of scientific interventions without the active participation of stakeholders. This also results in inequitable benefit distribution. Moreover, the failure of government schemes in the past makes the community afraid to participate in the new initiatives. To ensure equitable benefit-sharing, participation involving all stakeholders in decision-making processes is required. Encouraging community participation can ensure resilience and the long-term success of watershed initiatives. Strengthening institutions through transparent governance mechanisms can also ensure equitable benefits.

Lack of legal and regulatory framework: Due to poor monitoring, lack of accountability, and fragmented regulations, the watersheds are not properly managed which results in poor coordination among stakeholders. In the absence of a unified legal framework, the enforcement and outcome of interventions remain weak which results in reducing project effectiveness. Strengthening legal frameworks and strict enforcement can help in ensuring equitable resource distribution and streamlining community participation funding and monitoring mechanisms in the watersheds.

Lack of funding and resources: Limited funds restrict watershed intervention, capacity building, and technology adoption in watershed programs and hampers the effectiveness of the project. The Government of India's focus under the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) has placed more emphasis on irrigation and water use efficiency. The funding and implementation for the Watershed Development Component (WDC-PMKSY) are not strong enough for large-scale impact. The challenge therefore is to strengthen the watershed component through increased funding to enhance the impact of watershed interventions which can be supported through increased government investment, participation of the private sector, and funding from international donors.

Way forward

The innovative and inclusive approaches from successful watershed programs should be scaled across India, focusing on sustainable, synergistic, and socially acceptable IWM practices. While soil erosion has been a historical focus, modern challenges such as sewage contamination and eutrophication now threaten the water quality. These issues require integrated approaches with comprehensive monitoring and adaptive management. Effective watershed management demands institutional capacity building, integrated water resources management, robust monitoring, strategic partnerships, climate adaptation stratagies, economic valuation, and advocacy. Institutions must be equipped with resources and expertise to govern effectively. Advanced monitoring systems, like remote sensing and IoT sensors, are crucial for assessing watershed health, water quality, and land use changes. Incorporating climate adaptation strategies is essential to mitigate floods and droughts. Economic valuation of watershed initiatives will guide funding and policy, highlighting socio-economic benefits. Capacity building for stakeholders, including farmers and officials, is necessary to promote IWM adoption. Collaboration between governments, NGOs, academia, and the private sector is the key for effective implementation of of interventions and get desired outcomes and impacts. Training programs should focus on advanced water management, soil health techniques, and spatial technologies. Government policies should incentivize water-efficient technologies, support research, and align various development programs. Community participation in watershed management is crucial for sustainability. Local communities must be empowered to take ownership of initiatives. Continued research and collaboration between research institutions, government agencies, and international organizations are vital to developing innovative water conservation and soil health practices. Establishing robust monitoring and evaluation frameworks will ensure data-driven decision-making, identify gaps, and scale successful practices.

Conclusion

Integrated Watershed Management (IWM) is a proven and effective climate-smart approach for ensuring sustainable livelihoods in dryland regions, particularly in India. Evolving from basic soil and water conservation to holistic, participatory strategies, IWM addresses critical challenges like water scarcity, land degradation, and climate change. This study demonstrates that IWM has significantly improved agricultural productivity by 30–45 %, reduced soil erosion by 25–50 %, increased groundwater recharge by 10–30 %, and boosted water-use efficiency by 15–25 %. The integration of modern tools like Geographic Information Systems (GIS) and Remote Sensing (RS) has enhanced resource management and ensured equitable benefit distribution among communities. These results highlight IWM's potential to mitigate climate change impacts and contribute to achieving Sustainable Development Goals (SDGs) in water-scarce regions. Moreover, this model offers valuable lessons for scaling similar initiatives in other developing regions, promoting both environmental sustainability and socio-economic upliftment.

While this study highlights the positive impacts of IWM, further research is needed to assess the long-term sustainability of these interventions across various agroecological zones. Moreover, there is a need to explore the socio-economic dimensions of IWM, particularly in terms of equity and gender participation, to ensure that the benefits are equitably distributed among all stakeholders. Future studies should also focus on integrating climate change adaptation measures into IWM to address emerging challenges such as the increased frequency of extreme weather events. Finally, the scaling up of IWM practices across other regions in India and globally requires robust policy frameworks and institutional support, which should be prioritized in future research and implementation strategies.

CRediT authorship contribution statement

Ram A. Jat: Writing – original draft, Conceptualization. **Dinesh Jinger:** Writing – original draft, Conceptualization. **Anita Kumawat:** Data curation. **Saswat Kumar Kar:** Formal analysis. **Indu Rawat:**

Methodology. **Suresh Kumar:** Writing – original draft. **Venkatesh Paramesh:** Writing – review & editing. **Vijay Singh Meena:** Writing – review & editing. **Rajesh Kaushal:** Writing – original draft. **Kuldeep Kumar:** Software. **Hari Singh Meena:** Validation. **S.P. Wani:** Conceptualization. **Rajbir Singh:** Writing – review & editing. **M. Madhu:** Writing – review & editing.

Declaration of competing 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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