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Design of Rain Water Harvesting System for Efficient Water Scarcity and Flood Management in India

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Author's contribution

Author SK designed the study, performed the statistical analysis, wrote the protocol, analysis of the study, literature searches, wrote the first draft of the manuscript, read and approved the final manuscript.

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ABSTRACT

Areas experiencing extensive floods during the rainy season and water scarcity in winter require efficient water resource management. Economical water-harvesting structures such as drystone masonry and upstream-wall cement masonry, with heights ranging from 1 to 2.5 meters, are constructed for catchments smaller than 10, 10 to 20, and 20 to 30 hectares, respectively, utilizing locally sourced materials. These constructions offer significant cost-effectiveness for the location, boasting a B:C ratio of 3.5:1. In certain areas of Assam, Garh structures are constructed, featuring large and lengthy embankments on both sides with an open central section for water flow. Within paddy fields, the entire area is partitioned into small square segments, creating small embankments known as "Dara." which store rainwater for cultivation. Across the entire Western Himalayan region, encompassing Jammu, Himachal Pradesh, and Northern Uttaranchal, Guhl serves as a standardized water harvesting technique. Notably, in Akola and Chittoor districts, the establishment of farm ponds has significantly boosted crop and livestock productivity, along with farm income. Additional irrigation has notably enhanced the yield of various rainfed crops such as pigeon pea, chickpea, groundnut, cotton, and vegetables, as well as mango and coconut plants, with improvements ranging from 5 to 72%. With the availability of harvested rainwater for supplemental

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irrigation, farmers have also planted additional fruit trees, resulting in increased productivity of existing fruit trees, such as mango (39%) in Chittoor district and coconut (51%) in Vellore district. Expanding the number of rainwater harvesting structures could potentially reduce runoff within the basin by up to 60%. The implementation of Doha Models, involving percolation tanks dug along the length of lower-order seasonal streams in Jalna district of Maharashtra, has increased cropping intensity from 129% to 132%. Remarkably, five out of seven crops have demonstrated a relatively higher percentage increase in yields. The optimal productivity of harvested water is achieved when efficient application methods such as micro-irrigation are employed, targeting high-value crops.

Keywords: Watershed management, flood protection, rain water harvesting; supplemental irrigation; doha models.

1. INTRODUCTION

Water plays a crucial role in ecosystems, essential for sustaining biodiversity. The scarcity of freshwater for agricultural, industrial, and domestic needs isn't limited to arid regions; it also impacts regions with high rainfall. Factors contributing to water scarcity include limited water storage capacity, slow infiltration rates, high evaporation demands, and significant fluctuations in annual precipitation [1-3]. The term "water harvesting" was coined by Geddes from the University of Sydney, defining it as the collection and storage of any water form, including runoff or creek flow, for irrigation. Meyer of USDA, USA, expanded this definition to include the practice of collecting rainfall water from treated areas to increase runoff. More recently, Currier from the USA defined it as the process of collecting natural precipitation from prepared watersheds for beneficial use. Today, water harvesting encompasses collecting and storing runoff water or creek flow resulting from rainfall in both surface and subsurface soil profiles [4,5]. While initially prevalent in arid and semi-arid regions, water harvesting is now increasingly used in sub-humid and humid areas. In India, water harvesting involves utilizing erratic monsoon rainfall for crop cultivation in dry regions and conserving excess runoff water for drinking and groundwater recharge. When water harvesting techniques are applied to runoff farming, the soil itself serves as the storage reservoir [6,7]. However, for purposes like livestock, supplementary irrigation, or human consumption, additional storage facilities are required. In countries with abundant land, water harvesting entails capturing and storing rainwater for various uses.

In India, relying solely on land area for rainwater harvesting is impractical. Therefore, water harvesting in the Indian context involves maximizing the utilization of rainwater where it falls and collecting any excess water for reuse within the same area [8]. Hence, the concept of water harvesting varies across different regions and countries. Water harvesting techniques serve both agricultural purposes and contribute to increasing groundwater availability. Household water harvesting has been practiced worldwide for many years. In rural areas, people traditionally collect rooftop water during rainy days for various household needs, including drinking. In South East Asian nations, individuals place large earthen pots at the corners of their houses to collect rooftop water for domestic use [9-11]. For instance, the Agricultural College building in Coimbatore, constructed a century ago, employed a rainwater harvesting system. Rainwater from the rooftop was collected through pipes and stored in large underground tanks beside the building. Thus, rainwater harvesting has been an age-old practice, evolving over time and serving various purposes worldwide. However, the systematic implementation of rainwater harvesting remains a concern in many places. Today, there is a growing need to adopt rainwater harvesting to address water issues not only in arid regions but also in sub-humid and humid areas. Rainwater harvesting dates back over a thousand years in South India, evidenced by the construction of irrigation tanks, temple tanks, and farm ponds. In the modern era, organizations such as ICRISAT in Hyderabad, the Central Arid Zone Research Institute in Jodhpur, CRIDA in Hyderabad, State Agricultural Universities, and other dryland research centers across India are actively engaged in rainwater harvesting initiatives.

2. MATERIALS AND METHODS

2.1 Design of Rain Water Harvesting

The construction of rainwater collection systems is relatively straightforward, typically comprising a catchment area, storage tank, and connecting pipework. These systems are categorized as direct, indirect, or gravity feed based on how rainwater is stored and distributed. The materials used for the catchment area significantly impact the amount of runoff water and its quality in terms of physical, chemical, and biological aspects. Initial rainwater runoff is typically more polluted than subsequent runoff. For non-potable uses, rainwater only needs treatment before entering the storage tank, typically with a cross-flow or screen filter with a permeability of 0.2 to 1.00 mm. Additional treatment may occur within the storage tank through flotation and settling. Underground storage is preferred to limit exposure to sunlight and maintain lower water temperatures, reducing microbiological activity such as algal growth. The capacity of the rainwater storage tank is crucial as it affects both the economics and operation of the system.

2.2 Rainwater Harvesting System

Rainwater harvesting entails the capture and storage of rainwater, usually from roofs or other man-made surfaces, along with gathering sheet runoff from natural catchment areas. This harvested water serves various purposes in domestic, industrial, agricultural, and environmental settings. Water harvesting systems are categorized as small, medium, or large scale, usually determined by the size of the catchment area. This approach has been widely adopted and promoted in numerous developing countries like the USA, Japan, China, India, Germany, and Australia to meet the growing water demand across sectors such as agriculture and industry. The main components of a rainwater harvesting system include the catchment area, gutter and downspout, filtration system, storage system, delivery system, and treatment/purification.

2.2.1 Process for rainwater harvesting

2.2.2.1 Calculation of water harvesting potential and match with the water demand

$$Total\ volume\ of\ water = Area \times runoff\ coefficient\ \times rainfall$$

Water loss occurs through evaporation or absorption by catchment surfaces and other forms of loss. The runoff coefficient of a catchment indicates the fraction of rainfall that can be collected as harvestable rainwater from the total precipitation.

2.2.2.2 Decide the type, capacity and location of structures

Below are the two primary methods of rainwater harvesting.

i. Storage of rainwater on surface for future use
ii. Recharge to ground water.

3. RESULTS AND DISCUSSION

3.1 Whether to Store Rainwater or Use it for Recharge?

The decision of whether to store rainwater for future use or to recharge groundwater depends on the rainfall pattern and the region's capacity to do so. The sub-surface geology of the area also influences this decision-making process. Delhi, Gujarat, and Rajasthan, where the entire annual rainfall is concentrated within 3 or 4 months, predominantly focus on groundwater recharge. Conversely, regions like Tamil Nadu, Kerala, Bangalore, and Mizoram, where rainfall is spread throughout the year with intermittent dry periods, utilize small-scale tanks to store rainwater for use during dry spells. For instance, in Ahmedabad, which experiences a limited number of rainy days similar to Delhi, traditional rainwater storage structures known as 'tanks' are still employed in residential areas, hotels, and temples. In areas where groundwater is saline, alternative systems may be used for rainwater storage.

3.2 Traditional Water Harvesting Techniques

3.2.1 Ponds / tanks

These are the predominant techniques for gathering and retaining rainwater. Many ponds have their own catchment areas, ensuring sufficient water during the rainy season. If the catchment area is inadequate, water from nearby streams is redirected through open channels to replenish the pond. Alternatively, water from irrigation canals may also be utilized. Ponds are dug in various shapes and sizes, determined by factors such as soil type, land availability, and the water needs of the local community. These ponds are referred to by different names depending on the region (Table 1).

3.2.2 Ground water harvesting

In the hilly regions of Uttaranchal, locals gather groundwater by constructing stone walls across groundwater streams, known as Naula or Hauzi. However, there has been a gradual decrease in the construction of these structures, likely due to the depletion of underground streams caused by extensive deforestation and increased human activities in the hills. A similar practice is observed in certain parts of Kerala, where groundwater is collected by digging long, deep trenches along gentle slopes, known as Surangam. In Punjab, shallow wells are dug near streambeds to capture seepage water, referred to as Jhalars. In Rajasthan, these wells are called Beris and were historically constructed by kings. In Gujarat, shallow wells known as Virdas are excavated in depressions to access groundwater. In Tamil Nadu, similar structures known as Ooranis were built in the past.

3.2.3 Hill slope collection

In numerous mountainous regions with ample rainfall, constructed lined channels run across hill slopes to intercept rainwater. These channels provide water for irrigating terraced fields and are also utilized for domestic purposes, with excess water stored in small ponds. This approach is observed in states like Himachal Pradesh, Uttarakhand, Meghalaya, and Arunachal Pradesh.

3.3 Modern Structures for Water Harvesting

3.3.1 Roof top harvesting

This method primarily serves the purpose of providing drinking water. Rainwater from the roofs of buildings is collected and stored in tanks, either above or below ground level. This practice is prevalent at the individual household level in remote hilly areas with high rainfall and some semi-arid regions on the plains. It is observed in northeastern states such as Arunachal Pradesh, Assam, Meghalaya, Manipur, and Nagaland, as well as in districts like Bikaner, Jaisalmer, and Jodhpur in Rajasthan. In recent years, spurred by initiatives from both Central and State Governments, this practice has gained traction in numerous cities and towns across the country.

3.3.2 Check Dams

These structures, made of concrete or masonry, are constructed across small streams to store surface water and facilitate incidental groundwater recharge. Their design considers factors such as the water volume that can be stored upstream, the safe evacuation of surplus flood discharge, structural stability against different forces, and potential groundwater recharge. Typically, these structures are built by State Government agencies like the Departments of Irrigation/Water Resources, Agriculture, and Forests. They represent enhanced versions of the traditional temporary or semi-permanent structures typically constructed by villagers across natural streams or drainage channels.

3.3.3 Percolation tanks

These structures are primarily constructed to retain monsoon runoff over a vast area, thereby enhancing groundwater recharge. The selection of percolation tanks is based on the moderate to high porosity of the soil and underlying rocky layers. Ponding is carried out similarly to check dams, albeit with longer bunds and lower heights. The design aims to fill the pond multiple times during the rainy season, allowing most of the impounded water to percolate into the ground before subsequent rainfall. However, achieving this ideal operation is rarely feasible in real-world conditions. These tanks are typically erected by government agencies due to the specialized hydrogeological skills required for their construction.

3.3.4 Sub-surface dykes

These are impermeable structures constructed below the stream bed level using materials like masonry, concrete, or clay. They aim to intercept sub-surface water flow in natural streams, thereby enhancing the productivity of wells and hand pumps upstream. Additionally, alongside these direct water harvesting techniques, various indirect methods have also been devised. These aim at augmenting soil moisture retention and preventing soil erosion and land degradation. These are:

(i) **Contour bunding:** These are low earthen ridges constructed horizontally in rows across hill slopes. They aid in retaining soil moisture and mitigating topsoil erosion.
(ii) **Gully plugging:** These are erosion control structures erected across gullies in mountainous regions, constructed using indigenous materials such as stone boulders, soil, and brushwood.

Contour bunding and gully plugging are integral components of watershed improvement projects. The other works in this category are:

- Bench Terracing
- Contour Cropping
- Contour

Table 1. Local name of pond in in different states of India

State	Local name of pond
Nagaland	Zabo
Gujarat	Kunda, Jheel
Gujarat	Kunda, Jheel
Orissa	Katas, Mundas
Maharashtra	Bandharas
Karnataka	Volakere, Katte or Kunte
Andhra Pradesh	Tank
Kerela	Tank
Ladakh	Zing
Jammu	Chhapris
Sikkim	Khup

Table 2. Examples of traditional water harvesting systems in India

Regions	Water Harvesting Techniques
Trans-Himalayan Region	Zing: Tanks for collecting melted ice water in Ladakh.
Western Himalayas	Kul: Water channels to collect and store water in mountain areas of Jammu and Himachal Pradesh. Naula: Small ponds to collect rainwater in Uttaranchal.
Eastern Himalayas	Apatani system: Terraced plots connected by inlet and outlet channels in Arunachal Pradesh. Zabo: Impounding runoff water in Nagaland. Bamboo drip irrigation: In the hilly areas of Meghalaya, water from streams is brought to the plains via bamboo pipes for drip irrigation.
Brahmaputra Valley	Dongs: Ponds in Assam to collect and store rain water. Dungs or Jampois: Small irrigation channels linking rice fields to streams in the Jalpaiguri district of West Bengal.
Indo-Gangetic Plain	Dighis: Small square or circular reservoir fed by canals from rivers in Delhi. Baolis: A baoli is a reservoir in which rain water can be stored from which everyone could draw water for use.
Thar Desert	Baoris / Bers: Community wells in Rajasthan that capture and conserve rainwater. Tankas: Underground tank to store rain water in Rajasthan. Kund: A circular underground tank or small natural or artificial lake, having a saucer-shaped catchment area that gently slopes towards the center, where water that has fallen as rain is collected.
Central Highlands	Johads: Johads are small earthen check dams that capture and conserve rainwater, improving percolation and groundwater recharge, found in Alwar district of Rajasthan.

3.4 Some Case Studies of Rain Water Harvesting

3.4.1 Makkowal project - A case study

Makkowal, located in Punjab, India, approximately 30 km from Hoshiarpur at the foothills of Shivaliks, encompasses 300 houses and spans an area of 243 hectares. To the north lies hilly terrain, while the western part features leveled lands with a moderate slope. The sandy to sandy loam soils are suitable for agriculture, yet productivity is hampered by limited irrigation water availability. Despite an average rainfall of around 1000 mm, precipitation is irregular, with about 80% occurring during the monsoon months. Severe soil erosion from flash floods and heavy rainfall, coupled with frequent drought-induced crop failures, are common challenges. The village faces acute water scarcity; Even a 100-meter-deep open well failed to provide sufficient drinking water. Villagers must traverse 2 to 3 km across hilly terrain to access wells along stream banks, where perennial flow is present for much of the year. A drainage line treatment sketch map for the Makkowal watershed is depicted in Fig. 1.

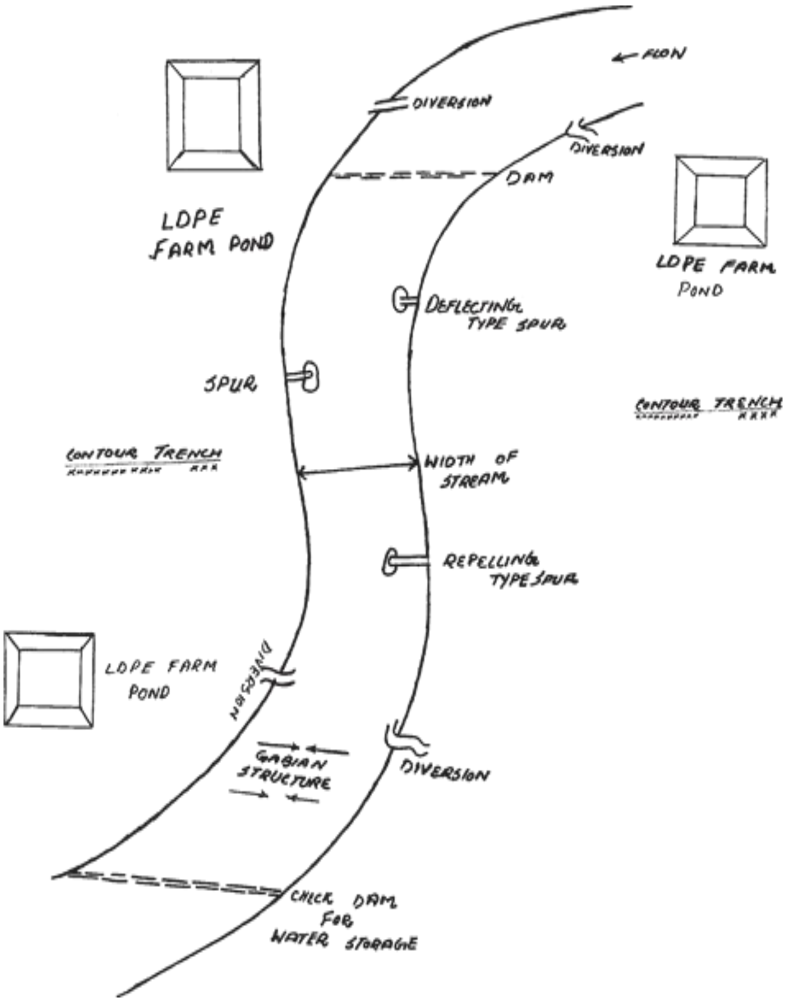

Fig. 1. Layout map of drainage line treatment of Mokkowal and Takaral Watersheds

The project commenced in 1986 and functioned for seven years, aimed at harnessing surface flow from the hill seepage located 3 km from the village. Three existing shallow open wells along the stream bank were replenished with seepage water and interconnected using cement concrete pipes. The village pond underwent deepening, widening, and renovation, increasing its storage capacity to 2.4 hectare-meters. A network of underground cement concrete pipelines was laid from the pond to convey water for agricultural irrigation. Separate taps for drinking, bathing, washing, and cattle were installed just before the village pond, with surplus arrangements made on the opposite side. The entire catchment area of choes was treated with various engineering and biological conservation measures. The cost and effective lifespan of earthen check dams depend on location, proper design, and maintenance. Construction costs for earthen dams in the area ranged from Rs 2.5 to Rs 27.0 per cubic meter of capacity. Prior to the project implementation, farmers used only FYM (Farm Yard Manure) without fertilizers, high-yielding varieties, or weedicides. Subsequently, farmers began using high-yielding varieties of maize and wheat seeds, as well as chemical fertilizers, weedicides, and pesticides. This transition led to increased fertilizer usage, crop yields (including wheat, maize, gram, and fodder), and overall returns, as depicted in Figs. 2,3.

3.4.2 Takarla project-A case study

The Takarla surface flow harnessing project, resembling the Makkowal project with slight modifications, is situated in the foothills of the Indian Shiwaliks, approximately 13 km from Balachaur in Nawashahar district, Punjab. Operating for seven years, the area features undulating slopes with loamy sand to sandy loam soils, occasionally silt loam, and erodible in nature. Being rainfed, the region is prone to torrential rainfall, leading to surface runoff

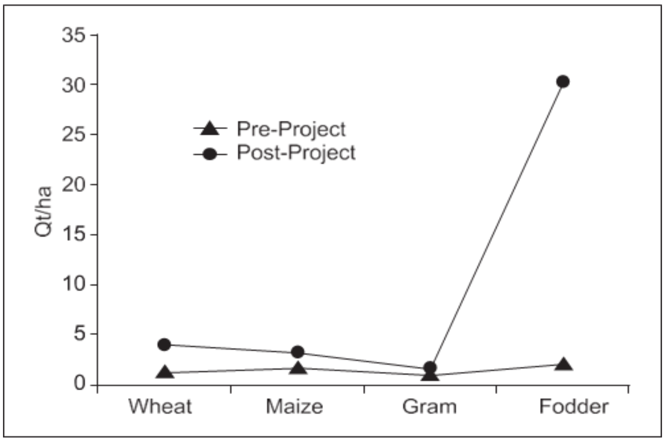

Fig. 2. Pre and post-project average yields (qt ha^{-1})

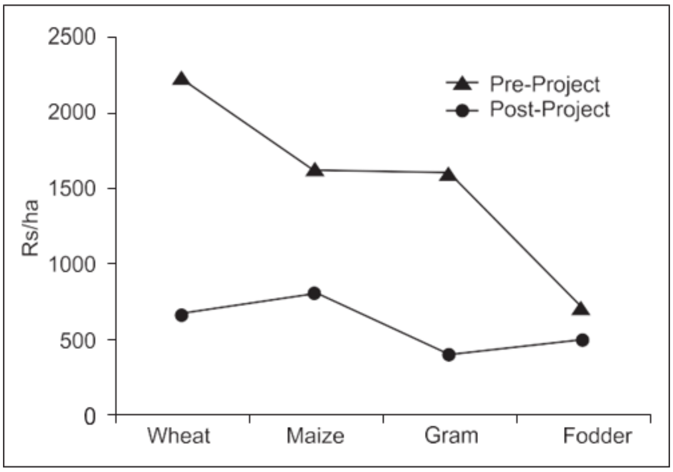

Fig. 3. Pre and post-project average returns (Rs. ha^{-1})

caused by seepage from the hillsides. Despite the rainy season lasting 3-4 months, seepage continues for an extended period, albeit at reduced rates, remaining in the sub-surface sand bed of choe. The project involved constructing a concrete toe wall in the channel at the stream bed, along with a weir on the barrier wall to release flow close to the water pool. A stilling basin was created on one side of the stream to generate a water head, connected to the inlet via a pipe. Additionally, a filter of local stones and grits was placed above the weir in the choe bed to aid water infiltration during lean periods. An underground pipeline from the stilling basin delivers water, via gravity flow, to agricultural fields situated at a lower elevation, providing supplemental irrigation for approximately 100 hectares of farmland in the village. The study area's major crops, along with their pre- and post-project yields and returns, are detailed in Table 3 and Figs 4,5 illustrating increasing gross returns from adopting new water-saving techniques. Furthermore, a case study examining water resources in Shaheed Bhagat Singh Nagar was conducted by R. Agrawal et al. [8].

Table 3. Pre and post project average yields of major crops

Name of Crop	Pre-project Yield (q ha^{-1})	Post-project Yield (q ha^{-1})
WHEAT	10.0	25.0
MAIZE	5.0	12.5
GRAM	2.5	7.5
FODDER	40.0	100.0

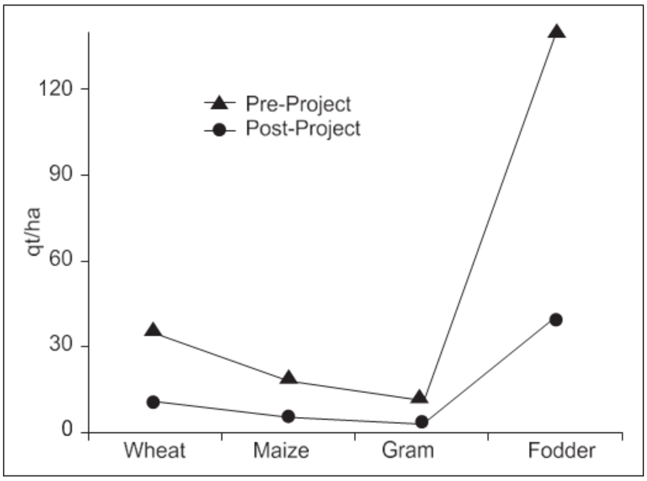

Fig. 4. Pre and post-project average yields (q ha^{-1}) of majorcrops

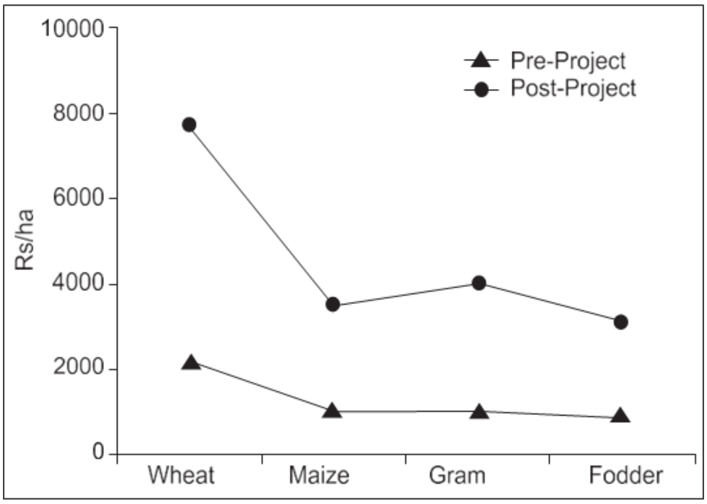

Fig. 5. Pre and post-project gross returns (Rs. ha^{-1}) of majorcrops

4. CONCLUSION

The irregular and uneven distribution of rainfall, both spatially and temporally, highlights the significance of rainwater harvesting in enhancing and sustaining agricultural productivity. Excavated dug-out pond tanks, characterized by an inverted truncated pyramid shape with 1:1 side slopes and lined with a 200-micron polyethylene sheet buried at a depth of 20 cm and pitched with bricks, are recognized as the most suitable method for storing runoff in cultivated lands. The earthen embankments designed for rainwater harvesting offer a cost-benefit ratio of approximately 1.38:1. Utilizing rainwater collected during the monsoon for irrigation during periods of scarcity has been shown to increase crop yields by 25-35% during the Rabi season and provide additional water for domestic use to 55% of the area's population. There is an urgent requirement for flood protection and irrigation on farmlands below the hills through the control and utilization of runoff, as well as the rehabilitation of upper watersheds to reduce runoff and erosion from the hills through soil conservation measures. Strengthening the capacity of project implementing agencies is vital for the successful implementation of traditional and new on-farm rainwater harvesting techniques, enabling them to conduct investigations and research on surface hydrology, groundwater, and micro-watershed studies.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models

(ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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