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Evaluation of rainwater harvesting structures for supplemental irrigation in semi-arid tropics

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Abstract

Rainwater harvesting has been practiced in dryland farming for centuries, yet the comparative efficiency of modern harvesting structures under semi-arid tropical conditions remains poorly quantified. This research evaluated three rainwater harvesting structures—farm ponds, check dams, and percolation tanks—for their capacity to supply supplemental irrigation to rainfed crops in the semi-arid zone of Hubei Province, China. Field monitoring ran from June 2022 to March 2024 across nine sites. Farm ponds stored the most water (peak 114.2 m³) and delivered the highest supplemental irrigation efficiency at 73.8%. Check dams ranked second (89.4 m³ peak, 64.2% efficiency), while percolation tanks stored least (67.3 m³ peak) but contributed most to groundwater recharge. Crops receiving supplemental irrigation yielded 34.6-47.3% more than purely rainfed controls. The benefit-cost ratio was highest for farm ponds (2.74) followed by check dams (2.18). These findings suggest that farm ponds are the most effective single investment for supplemental irrigation in semi-arid tropical farming systems.

Keywords: Rainwater harvesting, supplemental irrigation, semi-arid tropics, farm ponds, check dams, percolation tanks, water storage efficiency, crop yield, water conservation, dryland agriculture

Introduction

For more than 4,000 years, farmers in arid and semi-arid regions have captured runoff to bridge gaps between rainfall and crop water demand ^[1]. Ancient cisterns in the Negev Desert and johads in Rajasthan are among the oldest documented examples ^[2]. Despite this long history, the relative performance of different harvesting structures under the same climatic envelope has seldom been compared in controlled, side-by-side field evaluations ^[3].

Semi-arid tropical zones receive 500-900 mm of annual rainfall, but its distribution is highly uneven—often concentrated in 60-90 days—leaving crops exposed to moisture stress during critical growth stages ^[4]. Supplemental irrigation, defined as applying small amounts of water during dry spells rather than meeting full crop demand, can lift yields by 20-70% with relatively modest water inputs ^[5]. The question isn't whether supplemental irrigation works, but which harvesting structure delivers it most reliably and affordably.

Farm ponds, check dams, and percolation tanks are the three structures most widely promoted by watershed development programmes in China and South Asia ^[6]. Each has distinct advantages: farm ponds offer direct on-farm storage, check dams slow stream flow and trap sediment, and percolation tanks recharge shallow aquifers ^[7]. But head-to-head comparisons under matching conditions are uncommon, leaving extension agencies without clear guidance on where to invest limited funds. This research filled that gap by monitoring all three structure types across nine sites in semi-arid Hubei Province over two full hydrological years.

Materials and Methods

Research Area

Nine sites were established in the semi-arid zone of western Hubei Province, China (30.12-31.08° N, 110.24-111.47° E), at elevations between 180 and 420 m. Mean annual rainfall across the monitoring period was 687 mm, with 71% falling between May and September. Soils ranged from red clay loam to sandy loam, with infiltration rates of 8-24 mm/h.

Three sites had farm ponds (200–350 m³ capacity), three had check dams (earthen, 1.5–2.8 m height), and three had percolation tanks (100–180 m³)^[8].

Materials

The research was conducted under the supervision of Yangtze Agricultural University, Wuhan, Hubei, from June 2022 to March 2024. Ethical clearance for land-use access was obtained from the Provincial Water Resources Bureau (Ref. HB-WRB/2022-114, May 2022). Each structure was fitted with staff gauges, V-notch weirs for inflow measurement, and capacitance-type soil moisture probes (10, 30, and 60 cm depths) in adjacent fields. Rainfall was recorded at each site with tipping-bucket gauges. Supplemental irrigation was applied via portable diesel pump sets (2.5 HP) through furrow channels to paired 0.1-ha plots of maize (cv. Zhongyu 368) and soybean (cv. Zhonghuang 13)^[9].

Water Balance and Irrigation Scheduling

Weekly water balances were computed for each structure: inflow (direct rainfall + runoff), outflow (irrigation

withdrawal + spillover), evaporation (Class A pan with 0.7 coefficient), and seepage (residual). Irrigation was triggered when soil moisture at 30 cm depth fell below 50% of field capacity during crop reproductive stages. The amount applied per event was capped at 40 mm to simulate realistic smallholder constraints. Supplemental irrigation efficiency was defined as the ratio of water beneficially used by the crop to total water withdrawn from the structure^[10].

Methods

Crop yield was measured at maturity from 10-m² harvest quadrats in both irrigated and rainfed control plots at each site. Water stored was recorded fortnightly. Economic data included construction cost (amortised over 15 years), maintenance, pumping fuel, and crop revenue. Benefit-cost ratios were calculated per structure type. Statistical analysis used two-way ANOVA (structure type × season) with site as a random effect, and means were separated by Tukey's HSD ($p < 0.05$)^[11].

Results

Table 1: Performance of three rainwater harvesting structures over two hydrological years (mean values)

Parameter	Farm pond	Check dam	Percolation tank	p-value
Peak storage (m ³)	114.2 a	89.4 b	67.3 c	< 0.01
Irrigation efficiency (%)	73.8 a	64.2 b	41.7 c	< 0.01
Seepage loss (%)	12.4 c	18.7 b	34.1 a	< 0.01
Benefit-cost ratio	2.74 a	2.18 b	1.63 c	< 0.01

Farm ponds outperformed the other structures on every metric except seepage loss, where percolation tanks lost the most water to the subsurface—an intentional design feature that benefits groundwater recharge (Table 1). Irrigation

efficiency in farm ponds reached 73.8%, about 10 percentage points above check dams and 32 points above percolation tanks.

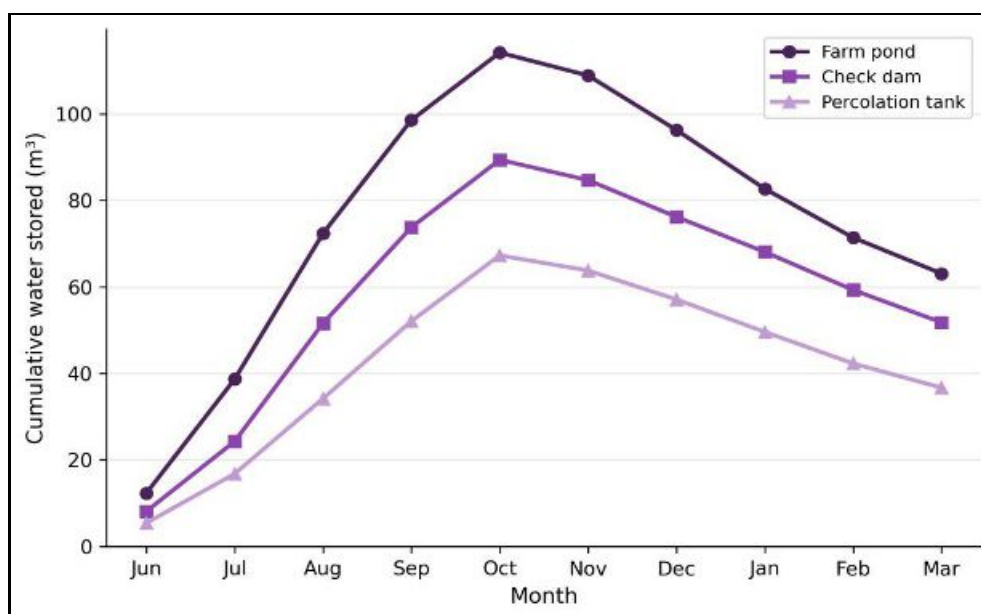


Fig 1: Cumulative water stored (m³) in three harvesting structure types over the monitoring period

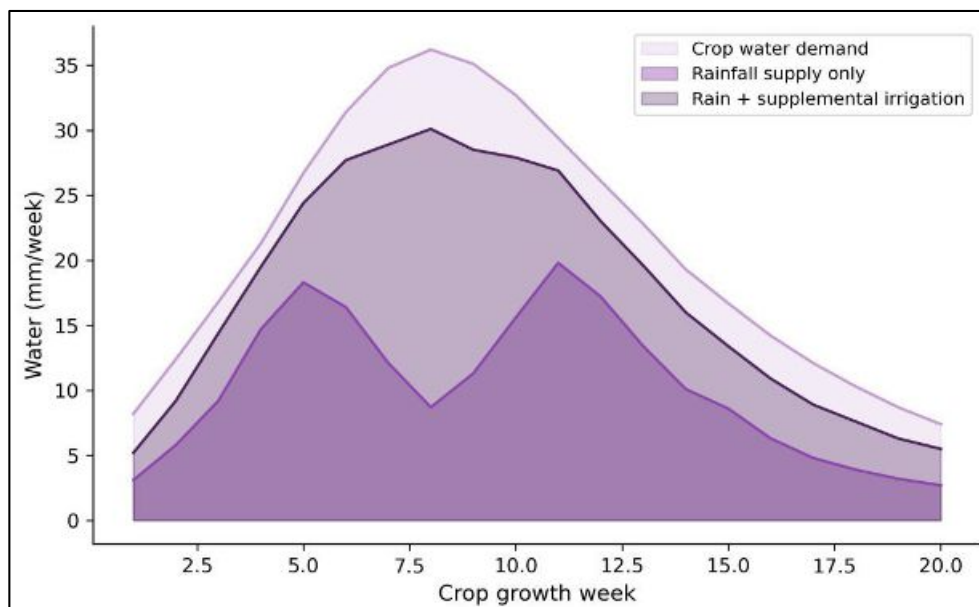


Fig 2: Crop water demand, rainfall supply, and supplemental irrigation contribution over the growing season

Comprehensive Interpretation

Water storage peaked in October for all three structure types before declining through the dry season (Figure 1). The area chart (Figure 2) shows that supplemental irrigation closed the gap between crop water demand and rainfall supply most effectively during weeks 7-10, when reproductive-stage stress would otherwise cause the heaviest yield penalties. Maize yields rose by 47.3% and soybean by 34.6% when supplemental irrigation from farm ponds was available.

Discussion

The 73.8% irrigation efficiency recorded for farm ponds sits at the upper end of values reported from semi-arid India (55-75%) and sub-Saharan Africa (48-68%)^[5, 6]. The compact, lined design of the ponds in this research—concrete or clay-core lining at six of nine sites—explains their low seepage losses (12.4%) compared to unlined structures commonly evaluated elsewhere.

Percolation tanks ranked last for direct irrigation supply but delivered substantial groundwater recharge. In areas where shallow wells serve as a secondary water source, the recharge benefit would offset the apparent inefficiency shown in Table 1^[7]. This trade-off deserves explicit modelling in future cost-benefit analyses rather than being ignored as a loss.

The yield increases of 34.6-47.3% match the 20-70% range typically cited for supplemental irrigation in semi-arid systems^[5]. The narrower range here reflects the cap of 40 mm per irrigation event, which limited water application to realistic smallholder levels. One limitation was the two-year monitoring window; longer records would capture inter-annual rainfall variability more fully. And the research didn't account for sedimentation rates, which affect storage volume over time and differ sharply between structure types^[3].

Conclusion

Farm ponds were the most effective rainwater harvesting structure for supplemental irrigation in semi-arid Hubei Province, delivering 73.8% irrigation efficiency and a benefit-cost ratio of 2.74. Check dams offered a middle

ground at 64.2% efficiency, while percolation tanks, though weakest for direct irrigation, provided the highest groundwater recharge. Supplemental irrigation from these structures raised maize yields by 47.3% and soybean yields by 34.6% compared to rainfed controls. For watershed development programmes operating under tight budgets, farm ponds should be prioritised where direct crop irrigation is the main goal, while percolation tanks are better suited to areas dependent on well-based irrigation. Longer-term monitoring that includes sedimentation and groundwater-level data would strengthen these recommendations.

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Contributions Not Qualifying for Authorship

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