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M Manikandan
ICAR-All India Coordinated Research Project for Dryland Agriculture, Kovilpatti Main Centre, Agricultural Research Station, Tamil Nadu Agricultural University, Kovilpatti, Tamil Nadu, India

N Anandaraj
Agricultural College and Research Institute, Thanjavur, Tamil Nadu, India

M Rajeswari
Agricultural College and Research Institute, Maduari, Tamil Nadu, India

S Manoharan
ICAR-All India Coordinated Research Project for Dryland Agriculture, Kovilpatti Main Centre, Agricultural Research Station, Tamil Nadu Agricultural University, Kovilpatti, Tamil Nadu, India

V Sanjivkumar
ICAR-All India Coordinated Research Project for Dryland Agriculture, Kovilpatti Main Centre, Agricultural Research Station, Tamil Nadu Agricultural University, Kovilpatti, Tamil Nadu, India

G Guru
ICAR-All India Coordinated Research Project for Dryland Agriculture, Kovilpatti Main Centre, Agricultural Research Station, Tamil Nadu Agricultural University, Kovilpatti, Tamil Nadu, India

K Baskar
ICAR-All India Coordinated Research Project for Dryland Agriculture, Kovilpatti Main Centre, Agricultural Research Station, Tamil Nadu Agricultural University, Kovilpatti, Tamil Nadu, India

G Ravindracharry
Project Coordination Unit, ICAR-All India Coordinated Research Project for Dryland Agriculture, Central Research Institute for Dryland Agriculture, Hyderabad

Corresponding Author:
M Manikandan
ICAR-All India Coordinated Research Project for Dryland Agriculture, Kovilpatti Main Centre, Agricultural Research Station, Tamil Nadu Agricultural University, Kovilpatti, Tamil Nadu, India

Enhancing rainfed cotton production through supplemental irrigation in the vertisols tract of Southern Tamil Nadu, India

M Manikandan, N Anandaraj, M Rajeswari, S Manoharan, V Sanjivkumar, G Guru, K Baskar and G Ravindracharry

Abstract
Uncertain dry periods and rainfall shortfalls pose serious obstacles to rainfed crop production. In-situ rainwater harvesting methods are employed within the farm to retain soil moisture and meet crop needs. However, these methods prove insufficient during prolonged dry periods lasting 2-3 weeks. Supplemental irrigation through ex-situ rainwater harvesting offers a solution to mitigate the impact of dry spells on crop growth and reduce yield loss. In semi-arid regions like the Vertisols tract of Kovilpatti, India, Rainfed crops are largely cultivated during the North East Monsoon (NEM) season occurring from October to December and typically brings about 400 mm of rainfall. Monsoon failures and prolonged dry spells frequently occur in these areas. A continuous long-term research study conducted between 2011 and 2021 at the black soil farm of Agricultural Research Station in Kovilpatti, Tamil Nadu, aimed to assess runoff potential, losses, and the feasibility of supplemental irrigation (SI) from a farm pond for rainfed cotton production. By analyzing runoff-causing rainfall and runoff generated from one-hectare catchment area, the runoff coefficient of 0.24 was determined. On average, a quantity of 250 m^3 of water can be collected in a farm pond. This amount is sufficient for a single application of supplemental irrigation (SI) on an area of 0.4 hectares at a depth of 50 mm. This study documented a yield increase ranging from 12.7% to 17% and a rainwater use efficiency of 1.52 to 3.13 kg/ha/mm in cotton through the implementation of SI during critical moisture stress periods. The combined use of in-situ and ex-situ rainwater harvesting at the farm level, along with modern micro irrigation, will enhance the productivity of rainfed crops.

Keywords: Cotton, farm pond, rainwater use efficiency, supplemental irrigation, soil moisture

1. Introduction
India holds the top rank globally in terms of both land area and production in rainfed cultivation. From an estimated net cultivated area of 140.3 million hectares, approximately 79.44 million hectares (57%) are under rainfed conditions, making a significant contribution of 44% to the total food grain production (Sharma 2011) [24]. Rainfed agriculture plays a crucial role in supporting nearly 40% of India's population, 80% of horticulture, and 60% of livestock. (Rao *et al.* 2017) [18]. Coarse cereals, pulses, oilseeds, and cotton are the primary crops cultivated in rainfed regions.

Although rainfed agriculture holds substantial potential for crop production, it encounters various challenges. These challenges include low soil moisture, inadequate field practices, uneven rainfall distribution, poor utilization of high-yielding varieties, limited adoption of advanced technologies, high cultivation costs, and migration. Other constraints related to soil that hinder crop yields encompass high soil temperatures, soil degradation, low water infiltration rates, poor water retention capacity, substantial surface runoff, and significant losses due to soil evaporation (Lal 2008) [8]. A mere deviation of one standard deviation from the average annual rainfall can lead to a complete crop failure (Rockstrom and Falkenmark 2000) [20].

Rainwater management stands as a crucial component within rainfed agriculture. Research indicates that only a fraction of rainfall say 10 to 30% is optimally utilized for plant transpiration and growth (Rockstrom 2001; Oweis and Hachum 2001) [21, 11]. Achieving desirable crop yields in rainfed areas depends on efficient rainwater harvesting within soil profiles or storing excess surface runoff water for future use. Various soil moisture conservation techniques are implemented at the farm level to enhance rainfall utilization and improve rain-fed crop production.

Among the notable practices in rainfed agriculture, rainwater harvesting through farm ponds holds significant promise for productivity enhancement. Studies demonstrate that collecting on-farm runoff into excavated farm ponds and providing supplemental irrigation can enhance the yield and stabilize crop production (Krishna *et al.* 1987) [6]. Farm ponds assist farmers in managing dry periods during the season by utilizing stored water (Reddy *et al.* 2012) [19]. Determining pond capacity is based on design rainfall and considerations of crop water requirements during critical stages, seepage, and evaporation losses. For regions with mean annual rainfall ranging from 500 to 750 mm, farm ponds with a capacity of 500 cubic metre are recommended. In areas with mean annual rainfall exceeding 750 mm in black soil regions, farm ponds of 500-1000 cubic metre capacity without lining can be constructed (Adhikari *et al.* 2010; Reddy *et al.* 2012) [1, 12]. Opportunities for harnessing excess runoff in rainfed regions exist across various states in the country (Wani *et al.* 2003; Sharma *et al.* 2010) [25, 23].

The primary cause of crop failure or reduced yields in rainfed crop production is the occurrence of mid-season and terminal dry periods lasting 1 to 3 weeks during crop growth. These periods adversely affect soil moisture profiles. Supplemental irrigation (SI) involves providing a small amount of water through some micro irrigation devices to rainfed crops during periods of insufficient rainfall to maintain enough moisture in the rootzone for regular growth and yield stability (Nangia and Oweis 2016) [9]. SI utilizes water stored in small ponds constructed near the fields. Harvesting a portion of surplus rainfall and storing it in ponds during the rainy season, then using this water for SI alongside improved agronomic practices, enhances agricultural production in rainfed areas (Pathak *et al.* 2009) [17]. This approach mitigates the impact of severe dry spells and offers opportunities in vulnerable rainfed regions (Rockstrom 2001) [20].

As rainfall serves as the primary water source for crop production in rainfed ecosystem, the depth of water added through SI alone cannot fully support economic crop production. Unlike regular irrigation, the timing and depth of SI cannot be predetermined due to rainfall uncertainty. However, SI reduces the impact of critical water shortages. SI not only boosts yield but also enhances water productivity when used in conjunction with rainwater (Oweis *et al.* 2000; Oweis *et al.* 1998) [13, 14]. Evidence suggests that SI ranging from 50 to 200 mm per season (500-2000 cubic m per hectare) sufficiently mitigates yield-reducing dry spells in most years and rainfed systems (Wani *et al.* 2003) [25].

Studies reveal that providing SI during dry periods at different crop growth stages improved yields by 29% to 114% for various crops (Sharma *et al.* 2006; Wani *et al.* 2008). Ilbeyi *et al.* (2006) [22,25,26] reported that applying a cubic meter of water through SI at the optimal time with appropriate management could yield an additional 2.0-3.5 kg of grain compared to rainfed production. Osman *et al.* (2013) [10] concluded that small brick and cement mortar lined ponds are suitable for small farmers with two hectares of land, enabling up to 30% additional net income through SI for tobacco cultivation. Panigrahi *et al.* (2005) [16] stated that SI in a rice-mustard cropping system in India is an economically viable option for improving smallholder farmer livelihoods.

Despite the proven effectiveness of SI as a practice to alleviate dry spell effects, it faces several challenges. These challenges include difficulties in accurately planning the timing and depth of water application in advance, lack of a fixed schedule due to reliance on rainfall, and practical feasibility of retaining water in the presence of significant seepage and evaporation losses (Oweis and Hachum 2012) [12]. This study aims to explore potential solutions to these challenges, particularly for farmers with small land holdings in rainfed agriculture. Pandey *et al.* (2006) [15] reported higher yield increments by developing smaller ponds for dry spell mitigation. Despite numerous studies on runoff harvesting, few published data specifically address supplemental irrigation for rainfed cotton.

Recognizing the importance of enhancing crop productivity in rainfed regions and acknowledging the need for supplemental irrigation during critical stages to prevent crop failures and minimize soil moisture deficits, this study aims to assess the feasibility of using farm pond water for providing supplemental irrigation to rabi cotton in the Vertisol tracts of Southern Tamil Nadu, India. The specific objectives of this study are threefold: firstly, to ascertain the runoff coefficient by establishing relationships between rainfall and runoff; secondly, to document the availability of soil water within the soil profiles; and finally, to analyze the crop response in terms of yield and rainwater use efficiency through the application of supplemental irrigation (SI).

2. Materials and Methods

2.1 Study area

This long-term research was conducted at the Agricultural Research Station in Kovilpatti, Tamil Nadu, India, spanning from 2011 to 2021. Kovilpatti stands as a unique representative location for dryland agriculture in Tamil Nadu, primarily comprising around 70% Vertisols. The soil depth varies between 110 and 150 cm, and the infiltration rate measures 0.9 cm/hr. During moisture-stress periods, the soil develops distinctive cracks, at least one centimeter wide and extending over 50 centimeters in depth. In terms of soil texture, the soil leans toward clayey, with clay content ranging from 46.4% to 61.2%, silt content between 10.0% and 17.5%, and coarse sand content ranging from 12.6% to 24.5%. The soil bulk density ranges from 1.21 to 1.36 kg/m³, with a field capacity of 35% and a permanent wilting point of 14%. The soil exhibits a subangular blocky structure, with a generally neutral to slightly alkaline pH (7.8 to 8.2) at lower depths. The soil's nutrient levels are characterized by low available KMnO4-N, low to medium available Olsen's-P, and high available NH4OAc-K. Taxonomically, this soil is classified under the USDA system as fine, smectitic, isohyperthermic, belonging to the Typic Haplusterts family (AICRPDA Kovilpatti 2021) [2].

Rainfall serves as a critical hydrological input parameter for designing farm ponds. Daily rainfall data from 1974 to 2021 were utilized to understand the rainfall patterns in the study area (Fig. 1 and 2). The long-term average annual rainfall for the study area was 725.2 mm over 41 rainy days. For seasonal breakdown, the North East monsoon (October to December), which aligns with Kovilpatti's cropping season, recorded a normal rainfall of 393 mm, while the South West monsoon (June to September) received 158.2 mm. The agro climate of the Agricultural Research Station in Kovilpatti is characterized as semi-arid tropics, with maximum and minimum temperatures of 35.4 °C and 22.4 °C, respectively.

2.2 Experiment details

The experiment involved cotton cultivation with two distinct treatments: (i) providing supplemental irrigation to the rainfed crop and (ii) maintaining a pure rainfed crop. Cotton variety KC3 was cultivated using a seed rate of 20 kg/ha, and a spacing of 45 x 15 cm was adopted. The crops were grown in gross plots measuring 750 m² (50 x 15 m) and net plots of 540 m². Prior to cultivation, the fields were well-prepared through one round of disc ploughing followed by two rounds of cultivation using a cultivator. Ridges and furrows were established with a spacing of 45 cm, forming 10 m-long rows using a ridger. Seeds were manually dibbled at a depth of 3-5 cm, placed on the side of the ridge at 2/3 of the ridge height, maintaining recommended row-to-row and seed-to-seed distances. Throughout the cultivation, practices were carried out in adherence to the crop production guide of the Tamil Nadu State.

Prior to commencing cultivation, soil samples were collected from the study area and subjected to analysis of initial physical and chemical properties, as outlined in Table 1.

Table 1: Initial soil physical and chemical properties of study plot

Soil physical properties		Soil chemical properties	
Texture	Clayey	pH	8.0
Depth (cm)	190-200	EC	0.19
Field capacity (%)	35	Av. N (kg ha^{-1})	115-136
Wilting point (%)	14	Av. P (kg ha^{-1})	10.2 -11.2
Infiltration rate	9 mm/hr	Av. K (kg ha^{-1})	410 -472
		Organic carbon (g kg^{-1})	2.8

2.3 Farm Pond and harvestable runoff water

A rectangular farm pond measuring 25 meters in length and 13 meters in width, with a depth of 1.5 meters, was utilized for capturing runoff from a catchment area of 1 hectare. The pond was lined with random rubble masonry. For pumping water from the pond, a 5 HP diesel engine was employed. A single raingun with a tripod stand, capable of discharging 3 liters per second and covering a wetted diameter of 12 meters, was used to sprinkle water over the growing crop.

Runoff water generated from the 1-hectare catchment area was directed into the farm pond after accounting for soil infiltration, interception, and local depressions. The increase in water level within the farm pond was observed incrementally during the rainy season, allowing for the calculation of runoff. The components of the water balance for the farm pond were determined by considering the stored water's availability, evaporative losses, and seepage losses. To evaluate the viability of providing supplemental irrigation from the farm pond, an assessment was conducted based on critical stages of crop growth during different periods and the water availability within the farm pond.

2.4 Soil sampling

To assess the soil moisture content throughout the cotton cropping period, samples were gathered at distinct stages: the initial stage (1-10 days), vegetative stage (11-44 days), flowering stage (45-87 days), and maturity stage (88-145 days). The samples were obtained at depths of 0-15 cm, 15-30 cm, and 30-45 cm, taken during the midpoint of each stage, irrespective of rainy days. Soil moisture content was determined through gravimetric measurement. This involved recording the initial and final weights of soil samples after they were oven-dried.

2.5 Cotton response to supplemental irrigation

The study's objective was to observe how crops responded to supplemental irrigation from the farm pond during periods of moisture deficit. To achieve this, cotton yield was recorded for each treatment, and the calculation of rainwater use efficiency was undertaken. As the crops are cultivated in rainfed regions without any additional irrigation apart from rainwater, the rainwater use efficiency (RWUE) serves as a measure of water productivity or efficiency for a specific treatment. Calculating RWUE involved considering the total rainwater utilized by the crops throughout the entire growing season and its impact on crop yield for the given treatment (Sharma *et al.* 2010). In scenarios where supplemental irrigation was applied, the depth of the supplemental irrigation would be added to the cumulative depth of rainfall. The calculation of rainwater use efficiency (RWUE) follows this formula: RWUE (kg/ha/mm) = Yield (kg/ha) / Cumulative rainfall (mm) from sowing to harvest. This calculation accounts for the yield achieved in kilograms per hectare and the cumulative amount of rainfall in millimeters from the point of sowing to harvest.

3. Results and Discussion

3.1 Rainfall Characteristics

The annual and seasonal rainfall series for Kovilpatti are visually represented in Fig. 1 and 2, respectively. Statistical analysis of the rainfall data is summarized in Table 2. The average annual rainfall for Kovilpatti is determined to be 725.2 mm, occurring over 41 rainy days. Among the recorded years, the highest annual rainfall of 1309.7 mm (across 68 rainy days) was documented in 2018, while the lowest annual rainfall of 199.6 mm (spanning 15 rainy days) was recorded in 2016. In terms of seasonal distribution, the North East monsoon (NEM) accounts for the maximum rainfall, followed by the South West monsoon (SWM). Notably, the NEM brought about 393 mm of rainfall across 21 rainy days, while the SWM contributed 158.2 mm over 9 rainy days. On the other hand, the winter season experienced the least rainfall at 37.2 mm, followed by the summer season with 136.6 mm.

Examining the data for the highest and lowest annual one-day maximum rainfall, the year 2006 (specifically, October 28) observed the highest amount at 154.6 mm, while the year 1991 (September 12) recorded the lowest amount at 39.2 mm. Over the span of 48 years, the average annual one-day maximum rainfall was calculated to be 83.4 mm. Notably, during 11 years (constituting 23% of the total), the daily maximum rainfall exceeded 100 mm. However, no consistent trend in the occurrence of heavy rainfall was observed during these years. The distribution of one-day maximum rainfall across the months of the year is visually depicted in Fig 3. This representation highlights that October received the highest share of one-day maximum rainfall (29%), closely followed by November (27%). The majority of the one-day maximum rainfall events were associated with the North East monsoon season.

The coefficient of variation (CV) for annual rainfall stands at 30.1, indicating that there is not considerable variation in the overall amount of rainfall over time. The series for summer and winter rainfall exhibit higher CV values. In order to assess whether the annual and seasonal rainfall data adhere to a normal distribution, skewness and kurtosis were calculated. Skewness measures symmetry or the lack thereof in a dataset. A dataset is considered symmetric when it appears the same on both sides of the central point. For a normal distribution, the skewness is zero, and symmetric data should exhibit skewness close to zero. Positive skewness values for all rainfall series indicate right-skewed data, implying a tail towards the right. The coefficient of skewness for monsoon seasons and annual rainfall is nearly zero, suggesting a nearly normal distribution of rainfall. Rainfall during winter and summer seasons demonstrates more pronounced skewness compared to the monsoon season.

Kurtosis, on the other hand, gauges the peakness or flatness of data relative to a normal distribution. High kurtosis in datasets typically results in a distinct peak near the mean, followed by a rapid decline and heavy tails. Conversely, low kurtosis indicates a flatter top near the mean, rather than a sharp peak. The standard normal distribution has a kurtosis of zero. The positive kurtosis observed in the annual rainfall dataset for Kovilpatti indicates a peaked distribution. On the other hand, the negative kurtosis seen in the South West monsoon (SWM) dataset indicates a flatter distribution.

Table 2: Statistical properties of annual and seasonal rainfall series of Kovilpatti

Sl. No	Time series	Mean (mm)	Maximum (mm)	Minimum (mm)	Standard Deviation	Coefficient of Variation, %	Skewness	Kurtosis
1	January	18.9	212.0	0.0	43.5	229.9	3.4	11.6
2	February	18.4	145.8	0.0	31.2	169.7	2.2	5.5
3	March	21.9	208.7	0.0	37.6	172.0	3.5	14.5
4	April	52.2	163.8	0.0	40.6	77.8	0.6	-0.2
5	May	62.6	193.9	3.1	43.9	70.2	0.8	0.4
6	June	15.3	99.4	0.0	21.4	140.4	2.0	4.6
7	July	23.0	149.0	0.0	30.8	133.9	2.1	5.4
8	August	40.1	158.6	0.0	35.8	89.2	1.0	1.2
9	September	79.8	224.2	0.8	57.0	71.5	0.6	-0.6
10	October	177.3	503.1	20.8	103.1	58.2	1.3	2.2
11	November	154.1	614.0	14.0	116.7	75.7	1.6	3.9
12	December	61.6	228.3	0.0	55.6	90.1	1.3	1.4
13	Annual	725.2	1309.7	199.6	218.1	30.1	0.2	0.4
14	SWM	158.2	321.4	18.6	76.5	48.3	0.1	-0.8
15	NEM	393.0	822.7	80.2	167.0	42.5	0.4	0.0
16	Winter	37.3	223.6	0.0	55.9	149.7	2.1	3.9
17	Summer	136.6	381.4	6.3	77.0	56.3	0.8	1.0

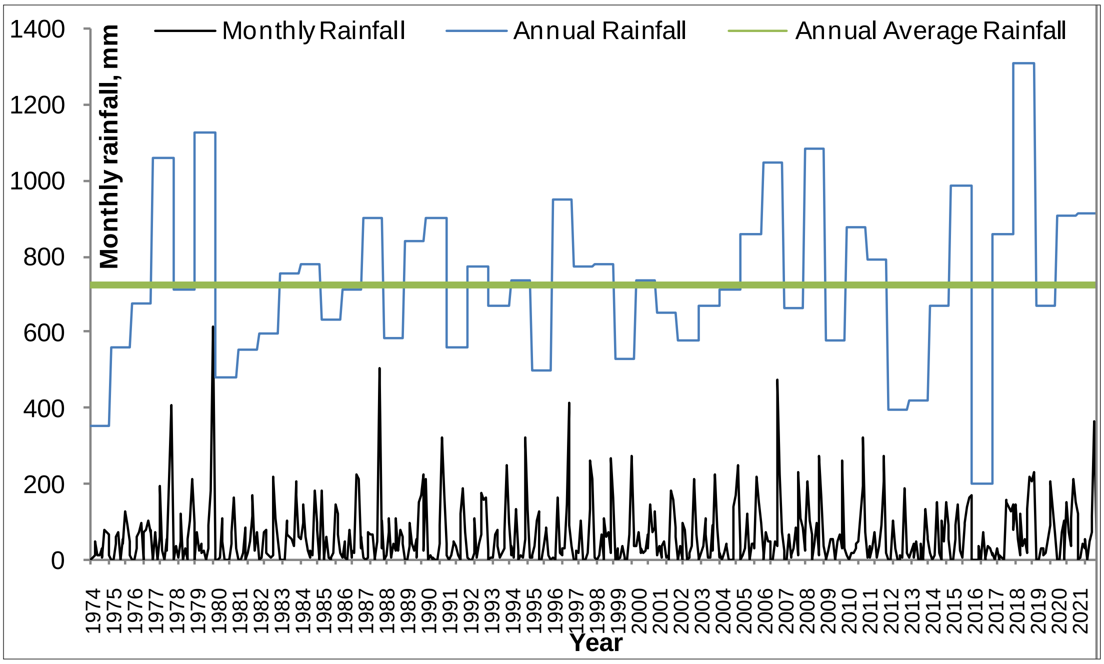
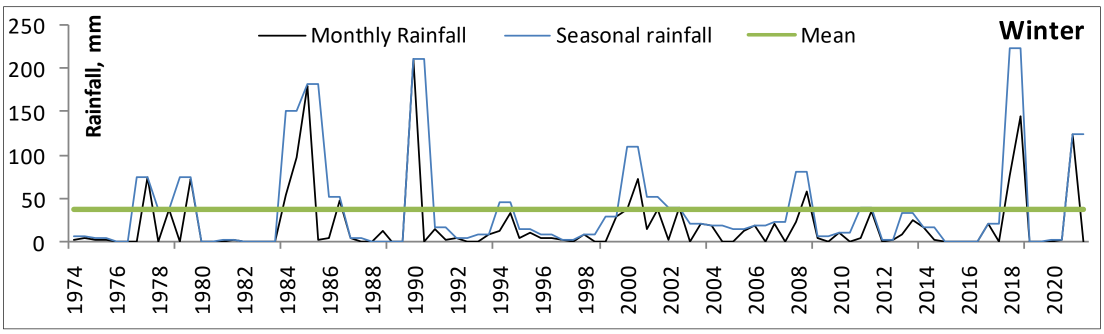


Fig 1: Annual rainfall distribution from 1974 to 2021 at Kovilpattiraingauge station



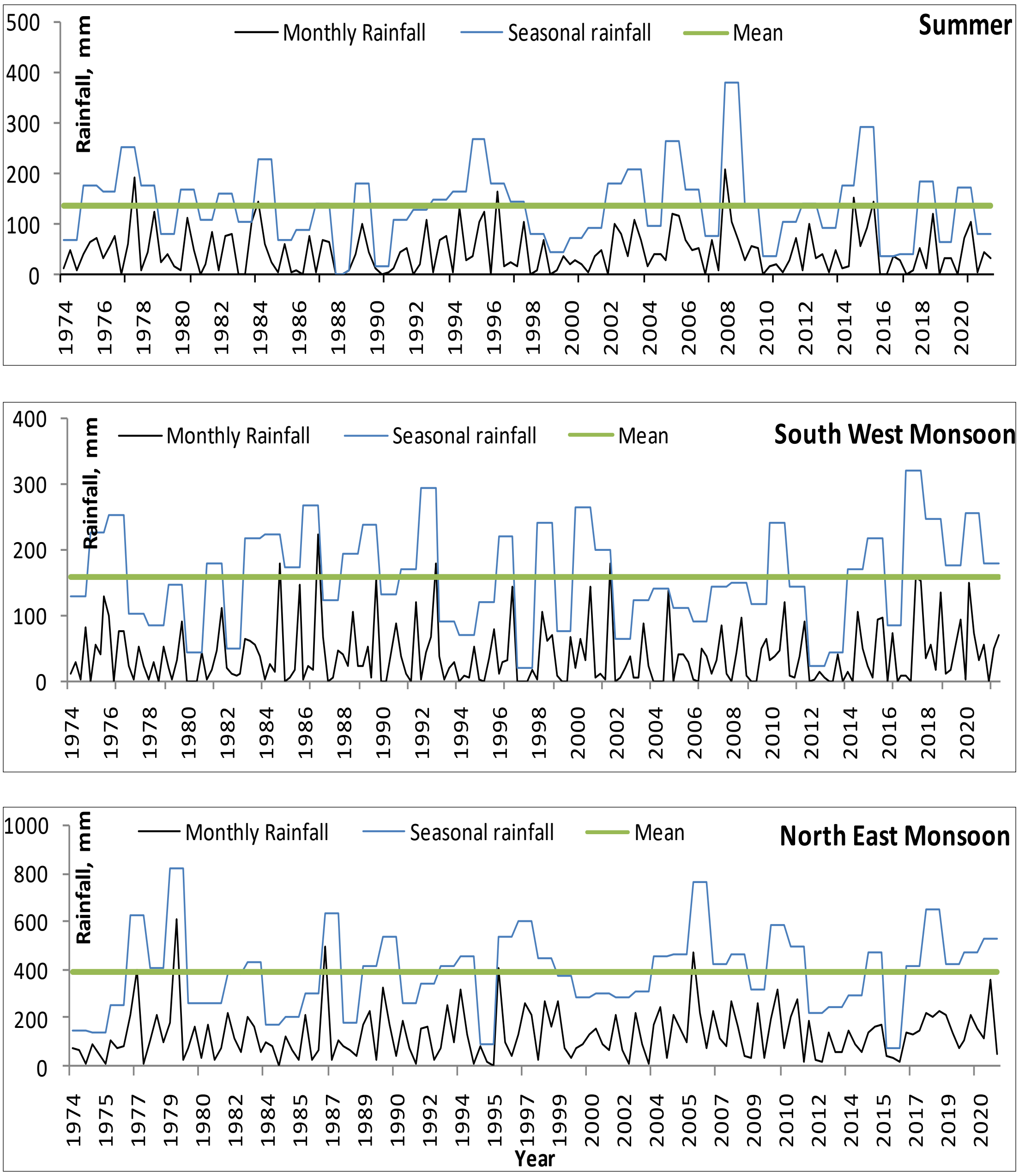


Fig 2: Seasonal rainfall distribution from 1974 to 2021 at Kovilpattiraingauge station

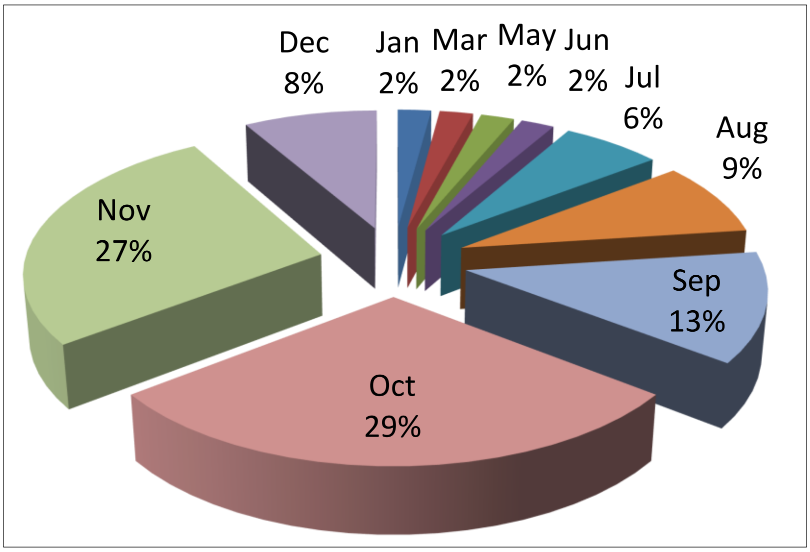


Fig 3: Distribution of one day maximum rainfall at Kovilpatti raingauge station

3.2 Rainfall - Runoff relationship

Table 3 presents data covering the period from 2011 to 2021, including annual rainfall, North East monsoon (NEM) rainfall, rainfall leading to runoff, actual runoff generated, and runoff water harvested in the pond.

Table 3: Runoff generated and rainwater harvested in the farm pond

Year	Annual Rainfall		NEM		Runoff causing rainfall, mm	Runoff, mm	Water harvested in pond
	Rainfall, mm (rainy days)	Deviation from normal rainfall %	Rainfall, mm (rainy days)	Deviation from normal rainfall, %			
2011	787.6 (42)	+ 7.0	503.4 (22)	+ 26.0	244.6	46.5	480
2012	392.9 (23)	- 46.0	228.3 (14)	- 42.4	81.8	32.6	326
2013	421.3 (28)	- 42.0	252.8 (17)	- 35.4	105.8	41.0	410
2014	666.8 (48)	- 7.7	301.2 (21)	- 23.0	63.6	20.3	215
2015	988.6 (52)	+ 35.3	475.8 (21)	+ 21.0	59.4	18.8	188
2016	199.6 (15)	- 72.0	80.2 (7)	- 79.8	0	0	No runoff
2017	801.7 (36)	+ 12.3	421.4 (17)	+ 6.2	282.4	26.8	268
2018	410.6 (34)	- 42.5	213.9 (19)	- 46.0	0	0	No runoff
2019	668.1 (46)	- 5.2	426.4 (28)	+ 9.2	108.9	25.8	258
2020	905.6 (47)	+ 29.5	473.3 (26)	+ 21.2	125.6	27.4	274
2021	914.7 (60)	+ 28.7	532.3 (29)	+ 33.9	151.9	48.0	481

Excess (+) /Deficit (-)

During the study period, there were five years characterized by excessive annual rainfall, ranging from 7% to 35% over normal rainfall, and seasonal rainfall ranging from 6.2% to 33.9% over normal rainfall. On the contrary, six years recorded deficit annual rainfall, with the maximum reaching 72%. In the year 2016, a mere 80.2 mm of NEM rainfall was recorded, which was a substantial 80% below the normal rainfall.

One of the most promising in-situ soil moisture conservation techniques, involving the use of ridges and furrows, was employed in the catchment area where cotton crops were cultivated. Runoff water was directed into the farm pond after ensuring adequate water retention in the field. However, the farm pond did not receive runoff water in 2016 and 2018 due to these years experiencing a deficit of more than 46% in NEM rainfall. The precipitation that contributed to runoff was measured at 95.8 mm, resulting in a runoff of 31.9 mm from a catchment area of 1 hectare. The accumulated amount of water collected in the farm pond summed up to 250 m³. The pond attains its maximum capacity when the NEM rainfall reaches 450 mm. For the practice of supplemental irrigation (SI), it was implemented when the runoff water that flowed into the pond exceeded 250 m³.

The rainfall-runoff relationship yielded a runoff coefficient of 0.24, which was derived and is depicted graphically in Fig 4. To elaborate on the water balance of the black soil farm pond, the analysis considered the quantity of runoff water entering the pond during the season (inflow), as well as the quantity of water lost through evaporation and seepage. From the total water stored in the farm pond, approximately 38.3% was lost through evaporation, while about 29.8% was lost due to seepage.

The runoff coefficients are specific to each site, and estimating them is essential for areas without flow measurement data. This estimation aids in designing pond dimensions. Studies have shown that black soils with gentle to moderate slopes (1-10%), and a catchment area of 1-5 hectares, tend to have an average runoff coefficient of 10-20% (Adhikari *et al.* 2010; Reddy *et al.* 2012; Rao *et al.* 2017) [1, 20, 18]. Although our findings yielded higher values compared to previous studies for black soil, these results will certainly contribute to increased runoff water collection in the farm pond. This opens up the possibility of expanding the scope for additional supplemental irrigation.

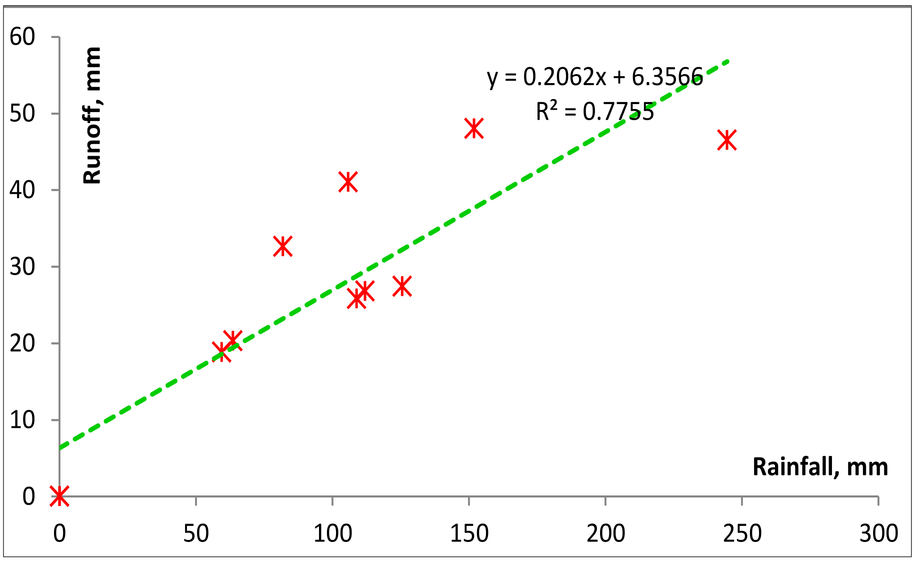


Fig 4: Rainfall-Runoff relationship for the study area

3.3 Soil water content at different depth during crop period

Ensuring a good yield in rainfed crops hinges on maintaining adequate soil water content within the soil profiles from the vegetative to the maturity stages of cotton production. Monitoring the soil water content at the rootzone depth of cotton throughout the crop's growth period offers valuable insights into the timing for providing supplemental irrigation.

Graphical representation of soil water content at various crop growth stages and depths for rainfed cotton is presented in Fig 5, focusing solely on different scenarios involving supplemental irrigation (SI). Notably, soil water content fluctuates in response to varying levels of rainfall. The depth at which samples are collected notably influences the observed soil moisture content. Surface layers experience greater soil water loss, particularly up to a depth of 15 cm, due to the higher rate of water evaporation from this exposed surface layer. Comparatively higher soil moisture content was detected at a depth of 30-45 cm in comparison to the 15-30 cm depth. In certain years, such as 2015/16, 2019/20, and 2021/22, ample moisture was retained in the subsoil surface, rendering supplemental irrigation unnecessary. However, during 2016/17 and 2018/19, the distribution of rainfall in the NEM was below normal, leading to insufficient soil moisture retention to meet the crop's demand.

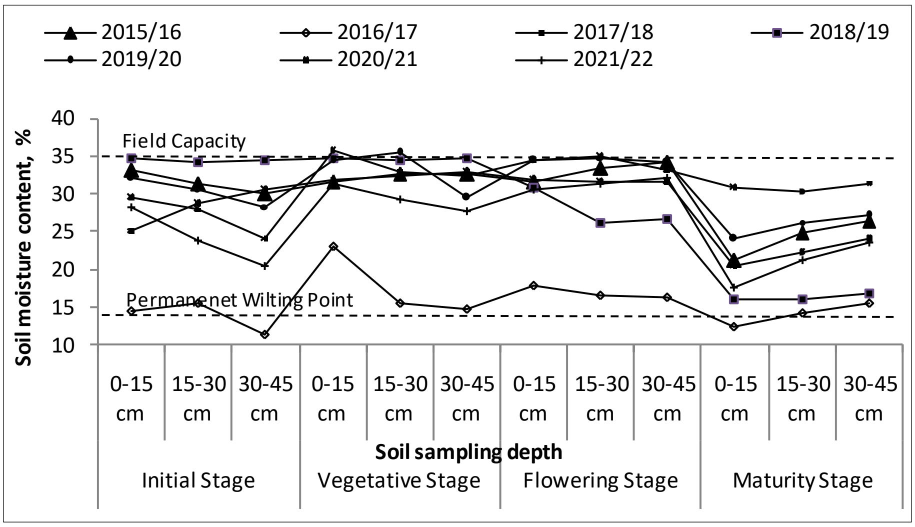


Fig 5: Vertical distribution pattern of soil water content for different crop growth stages

3.4 Effect of supplemental irrigation in cotton production

Table 4 outlines the impact of supplemental irrigation on the yield and rainwater use efficiency of cotton production. The runoff water that was stored within the farm pond was utilized to provide supplemental irrigation to a designated area of 0.4 hectares during the water-stressed phases of the crop. To facilitate supplemental irrigation, a 5 HP diesel engine with a sprinkler irrigation system fixed with high volume raingun was utilized. The pond's stored water was harnessed for irrigation purposes when dry spells persisted for over 15 days during the active growth stages of the crop.

Table 4: Effect of supplemental irrigation in yield and rainwater use efficiency of cotton production

Year	NEM Rainfal, mm	Yield, Kg/ha			SI, mm	Crop stages	RWUE, kg/ha mm	
		Pure rainfed	Pure rainfed + SI	Increase in yield, %			Pure rainfed	Pure rainfed + SI
2011/12	503.4	1515	1730	14.2	50	Maturity stage	3.01	3.13
2013/14	252.8	790	820	3.8	44	Vegetative stage	3.13	2.76
2015/16	475.8	940	965*	-	-	-	1.98	-
2017/18	421.4	876	987	12.7	25	Flowering stage	2.08	2.21
2019/20	426.4	938	954*	-	-	-	2.20	-
2020/21	473.3	677	793	17.1	50	Boll formation stage	1.43	1.52
2021/22	532.3	912	928*	-	-	-	1.71	-

*No treatment effect

The cotton crops exhibited positive responses to supplemental irrigation (SI) in the years when SI was given. Moreover, when SI was used in conjunction with the rainwater stored in the ridges and furrows, higher cotton production per unit of water was achieved compared to using rainwater alone. The application of SI utilizing harvested rainwater during periods of moisture stress in various years and crop stages led to yield increases of 3.8% to 17.1% in cotton, surpassing the yield of pure rainfed production.

In certain years, specifically 2012/13, 2014/15, 2016/17, and 2018/19, rainfall deficits were recorded. Non-uniform distribution of rainfall during monsoons was a key factor contributing to poor crop growth response. For instance, in the rabi season of 2012/13, runoff occurred from a single rainfall event, with the pond reaching 67% of its capacity. The stored water remained available until the second week of November 2012 (45thstandard week), eliminating the need for SI. Similarly, the lack of runoff water in the pond during 2016/17 and 2018/19 prevented the application of SI during critical crop stages.

In 2015/16, 2019/20, and 2021/22, surplus monsoon rainfall years were observed, resulting in adequate soil water retention in the vertical soil profiles throughout the crop stages. As a result, SI was not required. In rabi 2015/16, despite an excess of 21% rainfall during the NEM season, runoff water collected in the farm pond accounted for only 38% of its total capacity due to low runoff-producing events. Frequent light rainfall, though well-distributed over the crop period, was sufficient, rendering SI unnecessary.

During rabi 2019/20, the collected runoff water in the farm pond amounted to 53% of the pond's volume. The well-distributed NEM rainfall of 426.4 mm over 28 rainy days eliminated the need for SI, as no moisture stress was observed in the plants during the growth period. Likewise, in rabi 2021/22, the farm pond reached its maximum storage capacity due to a 21% excess in NEM rainfall across 29 rainy days, effectively ensuring adequate soil water content and alleviating moisture stress in the crops. Studies have revealed that supplemental irrigation during critical growth stages of crops can lead to increased grain yield (Sharma *et al.* 2010) [23]. An impact analysis of farm ponds was conducted in three districts - Adilabad (Telangana), Anantapur and Chittoor (Andhra Pradesh), India. The results indicated that crops such as sorghum, groundnut, and soybean demonstrated a notable increase in yield upon the adoption of farm pond technology in the Adilabad District. The yield of groundnut increased by 25.4% due to additional irrigation from farm ponds constructed in the Anantapur district. Furthermore, in the Punganurmandal of the Chittoor district, crops including cotton, bajra, chilli, and maize exhibited enhanced yield as a result of the farm pond construction (Rao *et al.* 2017) [18]. These results align with the findings reported in the present study.

3.5 Rainwater use efficiency for cotton production

The central goal of rainfed crop production at the farm level is to ensure the efficient utilization of rainwater. This is measured by the production of economic biomass in relation to the amount of water available, commonly expressed as more crop yield per unit of rainfall or harvested water (comprising both rain and collected runoff water). The combination of in-situ rainwater harvesting, which maximizes soil infiltration and water retention, along with ex-situ rainwater harvesting and storage systems for supplemental irrigation, can enhance rainwater utilization and consequently boost crop production.

Table 4 presents the rainwater use efficiency (RWUE) calculated for different years. The data underscores that rainfed crops benefiting from supplemental irrigation exhibit higher RWUE than those under pure rainfed conditions. Specifically, pure rainfed cotton displayed RWUE ranging from 1.43 to 3.13 kg/ha/mm. However, the inclusion of SI with pure rainfed cotton resulted in elevated RWUE, spanning from 1.52 to 3.13 kg/ha/mm. In cases where SI was applied to a depth of 44 mm during the vegetative stage of cotton in 2013/14, the yield differences between treatments were minimal, leading to a similar effect on RWUE. Sharma *et al.* in 2010[23], estimated rainwater use efficiency (kg/ha/mm) for different crops under both traditional practices and improved technologies in the primary rainfed crop districts of India. This estimation was based on long-term on-farm data from the national network on rainfed agriculture. For cotton, the estimated value was 0.38 kg/ha/mm (ranging from 0.17 to 1.52) under traditional practices and 1.60 kg/ha/mm (ranging from 1.23 to 1.97) under improved technologies. Our findings also align with the results presented in AICRPDA (2011-2021) [3]. The combined use of rainwater and supplemental irrigation has not only increased crop production but has also enhanced RWUE, demonstrating improved water utilization efficiency in rainfed agriculture. Enhanced productivity resulting from the provision of supplemental irrigation can also lead to increased income, which can be utilized beneficially in various ways, such as purchasing livestock or acquiring new modern equipment (Falkenmark *et al.* 2001; Kumar *et al.* 2016) [4, 7]. Rainwater harvesting through farm ponds and its utilization as supplementary irrigation with modern micro irrigation equipment is an economically feasible option, even at the farm scale. This approach is particularly appealing for rainfed crops such as cotton, maize, pulses, minor millets, and oilseed crops.

4. Conclusions

In regions facing water scarcity, the primary objective in dryland crop production systems is to maximize production per unit of available rainwater on the farm. This study specifically investigated the feasibility of applying supplemental irrigation during periods of moisture stress in cotton production. For this purpose, a farm pond with a catchment area of 1 hectare and a storage capacity of 487.5 m³ was utilized, resulting in an actual water harvest of 250 m³. The derived runoff coefficient from the rainfall-runoff relationship was 0.24. The application of supplemental irrigation from the farm pond to cotton during critical stages such as vegetative, flowering, and boll formation led to significant yield increases ranging from 12.7% to 17.1%. By combining rainwater with supplemental irrigation, a higher rainwater use efficiency (RWUE) of 1.52 to 3.13 kg/ha/mm was achieved. This study has demonstrated that the combined utilization of in-situ rainwater harvesting and ex-situ rainwater harvesting with supplemental irrigation from farm ponds yields a more pronounced positive impact on crop production. This integrated approach holds immense potential for enhancing crop productivity in rainfed areas at the farm level.

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6. References

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