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Rainwater management for sustainable production of citrus in central India

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A study was conducted involving (i) continuous trench (CT), (ii) CT with rainwater harvesting tank (RWHT) and basin irrigation (BI), and (iii) CT with RWHT and drip irrigation (DRI) to identify a suitable rainwater management strategy for citrus orchards in central India. CT with RWHT and DRI was found most suitable under which fruit production, net profit and economic water productivity were enhanced by 3.19, 3.98 and 2.30 times respectively, compared with rainfed treatment. The energy use efficiency improved by 87% with a 49% increase in sustainability yield index in CT with RWHT and DRI than the rainfed treatment.

Keywords: Citrus, rainwater harvesting, micro-irrigation, water productivity, yield.

CITRUS is extensively grown in tropical climates. Water for irrigation becomes a limiting factor in citriculture in the tropics[1]. The excessive overland flow of rainwater during the wet season and shortage of available soil moisture during the dry period affect the productivity and productive life of citrus plantations[2]. Thus conservation of rainwater using appropriate measures and reuse of conserved water effectively are imperative for sustainable citriculture.

'Nagpur' santra (*Citrus reticulata* Blanco), a globally recognized loose-skin citrus cultivar, is extensively grown in 0.25 m ha of central India. The cultivar is mainly planted and grown in a climate with soil enriched with clay (45–60%)[3]. Inadequate soil moisture during the non-rainy period affects productivity and causes the drying of mandarin plantations[1]. The underground water level in the aquifers has declined at an alarming rate due to overuse during last few decades in the region[4]. Despite water scarcity, a favourable climate and higher economic return help boost the cultivation of citrus in this region[5]. Drip irrigation (DRI) has also promoted cultivation of the crop in sloped and rolling lands[6]. Adoption of appropriate rainwater harvesting techniques such as continuous trench (CT) and water harvesting tank, and use of harvested water through DRI could increase the productivity of citrus in the region. Energy use analysis in crop production is crucial for sustainable agriculture. However, studies on run-off harvesting and reuse of water utilizing DRI and input–output energy analysis in citriculture are limited. The present study was therefore conducted to assess the response of citrus orchards to rainwater conservation and its reuse through DRI in a hot, sub-humid region of central India.

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Prediction of surface run-off based on rainfall quantity in citrus plantations has also been explored in this study.

The experiment was conducted for seven years (2004–2010) at ICAR-Central Citrus Research Institute, Nagpur (lat. 21°09′N, long. 79°02′E and 340 m amsl), India. The Nagpur mandarin orchard established at 6 m plant spacing was taken for experimentation. Soil at the study site was clayey with sand : silt : clay in the ratio 32 : 24.5 : 43.5. The slope of the orchard was 12%. The climate of the study area was hot, sub-humid and tropical in nature. Minimum (13.8°C) and maximum (45.2°C) daily temperatures were recorded in December and May respectively. Similarly, minimum (2.4 mm) and maximum (12.8 mm) daily evaporation occurred in December and May respectively. Out of the total rainfall (860 mm), 84% occurred during July–October (rainy period) at the study site. Groundwater was 20 m low from the ground.

The performance of rainwater conservation measures (RWCM) such as (i) CT, (ii) CT + rainwater harvesting tank (RWHT) + basin irrigation (BI) and (iii) CT + RWHT + DRI was evaluated against rainfed treatment (RT). The experimental layout of the treatments was randomized block design (RBD). For each treatment, 320 plants in a plot of 240 m in length and 48 m in breadth were selected. The shape of CT was trapezoidal, having a wider top (0.6 m) and narrow bottom (0.15 m) with a 0.30 m depth. RWHT (35 m × 35 m × 3 m dimension) was constructed at the drainage exit of the plot, considering the coefficient of drainage as 42.70 mm in the orchard[3].

Water application under both DRI and BI was done using water in RWHT. Irrigation under different treatments was performed during the drought period in the wet season (July–October) and the critical crop growth stage (fruit development) during the dry season (December–February). Fertilizer application was done uniformly (N, 260 kg ha^{-1}; P, 185 kg ha^{-1} and K, 72 kg ha^{-1}) to the experimental plants according to an earlier recommendation[7]. The general cultural practices were followed uniformly for all treatments of the orchard.

The meteorological parameters, including rainfall, were measured at the weather station established at the site near the experimental field. A five-slot multi-slot divisor was used at the outlet to quantify the surface run-off generated in each experimental plot. After every erosive rainfall, run-off quantity was quantified from a plastic tank (3000 litre capacity) which harvested run-off from one slot of the divisor. The total run-off was determined by multiplying the run-off quantity from one slot by 5. The soil moisture content (SMC) at 0–1.0 m depth was determined fortnightly using a neutron moisture probe (Troxler, USA). Fruit yield in each experimental plot was estimated by measuring the value in each plant.

The fruits yield per unit quantity of water used was taken as water productivity (WP) under different treatments. The sustainable yield index (SYI), which reflects the continuity of yield of a crop in future years, normally ranges from 0 to 1 (ref. 8). SYI values approaching 1 indicate a higher scope of sustaining crop yield. The value of SYI was worked out using the formula[9]

$$\text{SYI} = \frac{(\bar{Y} - \sigma)}{Y_m},$$

where $\bar{Y}$ is the average yield, σ the annual standard deviation of yield and Y_m is the highest yield. The standard procedure was followed to estimate energy input (EI), energy output (EO) and energy use efficiency (EUE) in various treatments[10,11]. The ratio of EO to EI was taken as EUE. Financial analysis for gross income (GI) and net income (NI), including benefit–cost ratio (BCR), was done following standard methodology[5].

The data were analysed for least significant difference (LSD) and Duncan's multiple range test (DMRT) was performed for mean separation following the standard statistical procedure[12]. The relationship between run-off and rainfall was developed using Microsoft Excel 2010.

Figure 1 presents the volume of run-off produced and reused in the citrus plantation under various conservation practices and rainfed treatments (RTs). RT induced the highest run-off, followed by CT. The maximum conservation (29.2–31.4%) of surface run-off resulted in lower run-off in CT. Furthermore, infiltration of higher amounts of water in the soil caused by higher retention time due to reduced overland flow velocity resulted in lower run-off under CT[13]. The run-off quantity generated in CT was at par with that in CT + RWHT. Earlier, 23% of rainfall was observed as run-off in citrus planted on a 12% land slope in sandy loam soil[14]. Another experiment with young pre-bearing citrus plants grown on 8–14% land slope showed that 33% of rainfall exited as run-off[15]. The difference in magnitude of run-off generated under different experiments was ascribed to the difference in land factors (soil type, land gradient and area of the experimental plot), weather parameters (precipitation trend, evaporation rate, etc.) and plant factors (plant height, canopy coverage) of

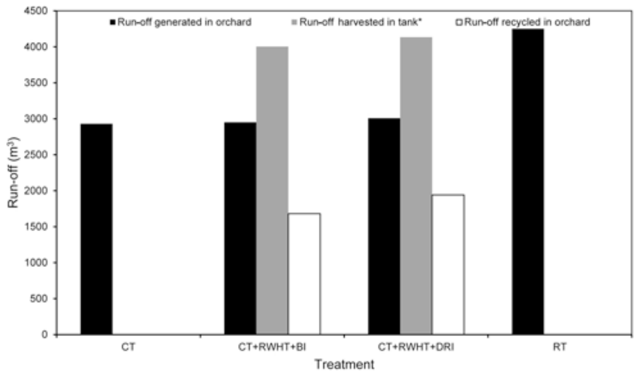

Figure 1. Run-off generated, harvested and recycled under various treatments in a citrus orchard. *Run-off collected in tank: run-off induced at the outlet + rainfall (1053 m^3).

Table 1. Rainfall–run-off relations (2004–08) and relationship between observed and predicted run-off (2009 and 2010) under different rainwater conservation measure in citrus

Treatment	Empirical model for rainfall–run-off relations	R^2		
CT	Y = 0.328, X – 1.343	0.82		
CT + RWHT + BI	Y = 0.414, X – 1.267	0.89		
CT + RWHT + DRI	Y = 0.548, X – 1.064	0.91		
RT	$Y = 4.50e^{0.026X}$	0.86		
	Relationship between observed and predicted run-off			
	2009		2010	
	R^2	RMSE	R^2	RMSE
CT	0.84	0.52	0.87	0.35
CT + RWHT + BI	0.86	0.41	0.90	0.14
CT + RWHT + DRI	0.87	0.37	0.92	0.11
RT	0.89	0.16	0.94	0.08

Y, Run-off; X, Rainfall; RMSE, Root mean square error.

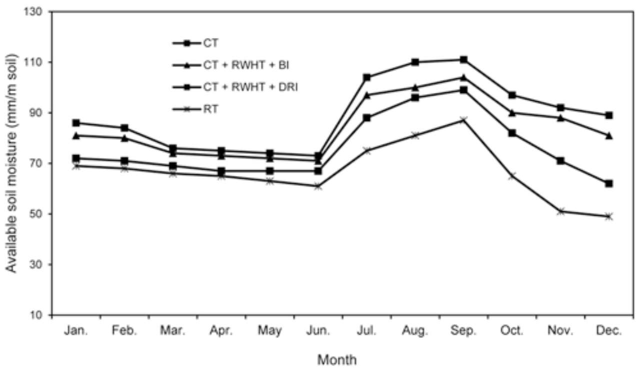

Figure 2. Monthly average soil moisture content (0–1.0 m) in the study under various treatments.

citrus orchards considered in the study. The quantity of run-off induced under DRI was at par with that under BI. However, the amount of run-off reused in the orchard under DRI was higher than that in BI. The higher available run-off under DRI was attributed to lower loss of water as seepage and evaporation from RWHT with higher frequency (once in 2–3 days) of water application under DRI than BI (once in 7–9 days). Overall, the conjunctive use of CT and RWHT was found as a better option for water conservation, and DRI was an efficient method for water application in the orchard.

A linear relationship was established between rainfall and run-off in CT and CT + RWHT during 2004–2008 (R^2 = 0.82–0.91), whereas with RT the relationship was exponential in nature (R^2 = 0.86) (Table 1). This exponential relationship between rainfall and run-off indicated that the run-off quantity produced in RT was higher than in other treatments for any change in the amount of rainfall. In a study, it was also observed that rainfall had an exponential relationship with run-off induced in citrus orchards (R^2 = 0.84–0.88)[15]. Moreover, the developed rainfall–run-off relationships reasonably predicted run-off amounts (R^2 = 0.84–0.94) under different conservation practices and RT treatment in 2009 and 2010 (Table 1). The good relationships developed between observed and predicted run-off indicate that the proposed model will help in the planning and implementation of conservation practices in citrus belts of central India and other regions with hot sub-humid tropical climate and Vertisol.

Figure 2 presents the monthly soil moisture content under different treatments. In January and February, the highest moisture content was recorded in CT + RWHT + DRI, followed by CT + RWHT + BI. The higher soil water content was due to run-off conservation and frequent irrigation to citrus plantations under CT + RWHT + DRI. In the past, it has also been observed that *in situ* conservation practices improved soil water content up to 20% in citrus[16]. From March to June, marginally higher (8–13%) soil water content was observed under conservation measures than RT. The soil water content under different treatments from July to December followed the same trend as from January and February. The higher soil water content from July to December has been attributed to the harvesting and reuse of rainwater under conservation treatments. The available soil water content in RT diminished from October to December. However, soil water content progressively decreased from October to December. Moreover, the reduction in available soil water content in RT from October to December has been ascribed to inadequate rainfall, which could not fulfil the water requirements of the plants during this period. However, the decrease in available soil water content from October to December reflected the lower water requirement of citrus plants in December than in October in the growing region. In the past, the minimum water requirement of mandarin plants in central India was also reported in December[2].

Table 2 gives the fruit yield, crop water use (CWU), WP, EUE and SYI under different conservation treatments and RT. The highest CWU was observed under CT +

Table 2. Water use, fruit yield, water productivity (WP), sustainability and energy utilization under different conservation treatments in citrus

Treatment	Crop water use (m^3 ha^{-1})	Fruit yield (t ha^{-1})	WP (kg m^{-3})	SYI	EUE (MJ t^{-1})
CT	4675[b]	9.74[b]	2.08[b]	0.66[b]	1.13[b]
CT + RWHT + BI	6342[c]	17.25[c]	2.71[c]	0.79[c]	1.65[c]
CT + RWHT + DRI	6565[d]	22.81[d]	3.47[d]	0.88[d]	1.91[d]
RT	3790[a]	7.14[a]	1.88[a]	0.59[a]	1.02[a]

Data in a column with the same letters are non-significantly affected ($P < 0.05$).
SYI, Sustainable yield index; EUE, Energy use efficiency.

Table 3. Financial analysis and economics of water use under different conservation treatments in citrus

Treatment	Gross income (INR ha^{-1} yr^{-1})	Net income (INR ha^{-1} yr^{-1})	Benefit–cost ratio	Gross economic water productivity (INR m^{-3} yr^{-1})	Net economic water productivity (INR m^{-3} yr^{-1})
CT	132464[b]	86767[b]	2.89[b]	28.33[b]	18.55[b]
CT + RWHT + BI	234600[c]	173175[c]	3.81[c]	36.99[c]	27.30[c]
CT + RWHT + DRI	310216[d]	237916[d]	4.29[d]	47.25[d]	36.24[d]
RT	97104[a]	59704[a]	2.59[a]	25.62[a]	15.75[a]

Data in a column with the same letters are non-significantly affected ($P < 0.05$).

RWHT + DRI. The reuse of harvested rainwater in citrus plantations has been attributed to higher CWU in CT + RWHT + DRI treatment compared with other treatments. The negligible loss of water through seepage, deep percolation and evaporation was the reason for higher water use under DRI than BI[3]. The highest fruit yield recorded in CT + RWHT + DRI was 219% higher than RT. The increased fruit number and heavier fruits improved fruit yield under CT + RWHT + DRI than RT. The enhanced blooming of flowers accompanied by reduced fall of flowers and fruits (104 nos) brought maximum fruits under CT + RWHT + DRI. The improved plant physiology under optimum available soil moisture and nutrients in the root zone might have reduced the fall in flowers and fruits and produced heavier fruits under conservation measures. In the recent past, more fruit falling along with smaller fruits under sub-optimum soil moisture content was observed in citrus groves[17]. CT + RWHT + DRI produced maximum WP among the treatments. The increased yield in CT + RWHT + DRI resulted in higher WP in this treatment compared to other treatments. The rainfed treatment produced minimum WP. Previous studies also observed the improvement in WP by 78% under rainwater conservation in citrus orchards[3,16]. The highest SYI was observed in CT + RWHT + DRI, whereas RT produced the lowest SYI. The lower SYI in RT indicates better efficacy of rainwater conservation measures in sustainable citrus production under CT + RWHT + DRI. EUE in different treatments also followed the same trend as SYI. A previous study indicated higher EUE due to *in situ* water harvesting in maize[18].

Financial analysis indicated that the highest gross income (GI) was in CT + RWHT + DRI due to maximum fruit yield in this treatment (Table 3). Maximum net income (NI) was also generated in CT + RWHT + DRI, despite higher cost of constructing the RWHT and installation of DRI system in the orchard. More returns accrued than the expenditure increased NI under CT + RWHT + DRI. BCR under different treatments followed the same trend as that of NI. Minimal BCR due to lower GI was registered in RT. The gross economic water productivity (GEWP) and net economic water productivity (NEWP) were reported to be higher in CT + RWHT + DRI (Table 3). The improved GI and NI in CT + RWHT + DRI boosted GEWP and NEWP in this treatment compared to the other treatments.

Rainwater harvesting and its efficient management have brought considerable improvement in fruit production, water productivity, net profit, energy use efficiency and sustainability under various conservation treatments in citrus orchards. Forecasting surface run-off from rainfall amount using the models proposed in this study may help design soil and water conservation structures in the citrus-growing pockets of central India. Overall, adoption of continuous trench in conjunction with run-off recycling tank-based drip irrigation is recommended for sustainable production of citrus in central India.

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