IRRIGATION AND DRAINAGE
Irrig. and Drain. **63**: 621–627 (2014)
Published online 11 September 2014 in Wiley Online Library (wileyonlinelibrary.com) **DOI**: 10.1002/ird.1870

INTEGRATED IRRIGATION AND DRAINAGE MANAGEMENT FOR CITRUS ORCHARDS IN VERTISOLS†

PRAVUKALYAN PANIGRAHI*
Directorate of Water Management, Chandrasekharpur, Bhubaneswar, Odisha, India

ABSTRACT

Efficient irrigation and drainage are a prerequisite for sustainable citriculture. Citriculture in vertisols often faces the twin problem of waterlogging in the rainy season and water shortage during the post-rainy period, leading to suboptimal productivity and decline of citrus orchards in central India. With this in mind, the integrated impact of irrigation methods (drip and basin) and surface drainage (parallel trenches) was studied in citrus orchards of the region. Drip irrigation (DI) produced 23% higher fruit yield than basin irrigation (BI) under drainage. Drainage was an important consideration for both DI and BI. However, drainage was much more important for BI than DI to achieve higher fruit yield. Conjunctive use of DI and drainage (DI_D) reduced the soil and nutrient losses through runoff and produced 90% higher yield with better quality fruit, using 30% less irrigation water (171% improvement in irrigation water use efficiency) than BI without drainage. Citrus production with DI_D was also found to be economically superior to other treatments, generating more net return (INR 225 000 ha^{-1} yr^{-1})[1] with higher benefit–cost ratio (5.2). Overall, the study demonstrates that adoption of DI_D could be a viable option for commercial citriculture on clay soil in water-scarce central India. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS: citrus; surface drainage; drip irrigation; clay soil; water shortage; irrigation efficiency

Received 30 September 2013; Revised 21 April 2014; Accepted 22 April 2014

RÉSUMÉ

L'irrigation et le drainage efficace est la condition sine qua non pour l'agrumiculture durable. L'agrumiculture dans les vertisols est souvent confronté au double problème de l'exploitation de l'eau en saison des pluies et le manque d'eau pendant la période post-pluies conduisant à une productivité sous-optimale et le déclin des vergers d'agrumes dans le centre de l'Inde. Compte tenu de cela, l'impact intégré des méthodes d'irrigation (goutte à goutte et bassin) et le drainage de surface (des tranchées parallèles) a été étudiée dans le verger d'agrumes de la région. L'irrigation goutte à goutte (DI) a produit un rendement de fruits 23% de plus que l'irrigation du bassin (BI) en vertu de drainage. Le drainage était une considération importante pour les DI et BI. Cependant, le drainage était beaucoup plus important pour la BI de DI pour atteindre le rendement élevé en fruits. L'utilisation conjointe de DI et de drainage (DI_D) a réduit les pertes par ruissellement éléments nutritifs et a produit un rendement de 90% supérieur avec des fruits de meilleure qualité, avec 30% de moins d'eau d'irrigation (amélioration de 171% dans l'irrigation utilisation de l'eau) par rapport à BI sans drainage. La production d'agrumes avec DI_D a également été constaté économiquement supérieur à d'autres traitements, générant plus de revenu net (INR 225 000 ha^{-1} an^{-1}) avec plus ratio avantages–coûts (5.2). Globalement, l'étude montre que l'adoption de DI_D pourrait être l'option viable pour l'agrumiculture commerciale sur le sol lourds du centre de l'Inde dans un contexte de rareté de l'eau. Copyright © 2014 John Wiley & Sons, Ltd.

MOTS CLÉS: agrumes; drainage de surface; irrigation goutte à goutte; sol argileux; pénurie d'eau; efficacité de l'irrigation

*Correspondence to: Pravukalyan Panigrahi, Directorate of Water Management, Chandrasekharpur, Bhubaneswar, Odisha-751 023, India. E-mail: pravukalyan@rediffmail.com
†L'irrigation et la gestion intégrée du drainage pour les vergers d'agrumes dans des vertisols.

INTRODUCTION

Water is a critical input for commercial citriculture. The citrus tree is highly sensitive to both excess and shortage of soil moisture during any phase of its growth (Davies and Albrigo, 1994). Efficient water management resulting in optimum water content in the *rhizosphere* of the crop is a prerequisite for sustainable citriculture.

Basin and/or furrow are the most widely adopted methods of irrigation in fruit crops including citrus (Fereres *et al.*, 2003). However, drip irrigation has proved its worth by producing higher yield with better fruit quality under reduced water supply in citrus (Germanà *et al.*, 1992). Moreover, drainage has been found effective in improving the productivity of citrus in sandy soil under shallow groundwater condition (Minessy *et al.*, 1970; Boman and Tucker, 2002). Schaffer and Moon (1990) observed that intermittent flooding for 35 days causes considerable tree mortality of 'Tahati' lime on sandy loam soil. Unbalanced nutrient uptake (Minessy *et al.*, 1971), poor rooting (Iyengar *et al.*, 1996) and suboptimum plant growth (Marathe *et al.,* 2000) either alone or in combination contribute towards the suboptimum productivity and decline of citrus in waterlogged areas.

'Nagpur' mandarin (C*itrus reticulata* Blanco) is commercially cultivated as an irrigated crop on 0.2 Mha (million hectares) of central India. Use of groundwater through the basin method is a common irrigation practice for the crop. The overexploitation of groundwater in the last few years has caused the drying-up of wells resulting in a water crisis in the region (Singh and Srivastava, 2004). The shortage of irrigation water in the critical growth stages during January–June has become one of the major *abiotic* constraints to optimum production of citrus. On other hand, the intense and high rainfall (550–630 mm) occurring in 12–15 rainy days during four months (July–October) of the year (the rainy season) coupled with smectite-rich black clay soil (35–60% clay content) generates a substantial amount of runoff in the citrus orchards (Mohanty *et al.*, 2000; Panigrahi *et al.,* 2012). However, the mild land slope (<0.5%) and basins created for irrigation purposes prevent the free passage of runoff to outlets in orchards. As a result, ponding and prolonged saturation of the soil take place which cause heavy fruit drops and suboptimal nutrient uptake by citrus plants (Marathe *et al.*, 2000). In spite of such water management constraints, acreage under the crop is increasing exponentially each year due to cultivar suitability and higher production economics compared to other crops in the region (Gangwar *et al.*, 1999). The orchard growers are more focused on enhancing the productivity as well as the longevity of citrus orchards by utilizing less water. This could be possible by using efficient irrigation and drainage practices in the crop.

In black clay soils, surface drainage has been found to be very effective in eliminating ponding, and preventing prolonged saturation caused by slow infiltration and low hydraulic conductivity coupled with the shrink–swell properties of these soils (Sevenhuijsen, 1994; Marathe *et al.*, 2000). However, information on the performance of the integrated use of irrigation methods (drip, basin) and surface drainage in citrus orchards in clay soil is scarce worldwide. Keeping this in mind, a study was conducted to evaluate the feasibility of drip and basin irrigation methods with and without a surface drainage system (parallel trench) in citrus orchards in a black clay soil (vertisol) of the subhumid, subtropical climate of central India.

MATERIALS AND METHODS

The experiment was started with 4-year-old 'Nagpur' mandarin plants and carried out for 3 consecutive years (2006–2009) in the research orchard of the National Research Centre for Citrus, Nagpur (latitude 21° 08′ 45″ N, longitude 79° 02′ 15″ E, 340 m above mean sea level), Maharashtra state, India. The plant-to-plant spacing in a row and row-to-row spacing were maintained at 6 m. The experimental soil was clay in texture (32% sand, 25% silt and 43% clay). The volumetric soil water content at field capacity (0.033 MPa) and permanent wilting point (1.5 MPa) were 29.8 and 18.7%, respectively. The soil was alkaline (pH 7.8) with cation exchange capacity of 42.8 cmol (p^+) kg^{-1}. The available N, P and K in the soil were 115, 12 and 142 ppm, respectively. The saturated hydraulic conductivity of the soil was 7.2 mm h^{-1}. The climate of the study region is categorized as subhumid (annual rainfall 780 mm) tropical with hot and dry summer (mean temperature, 35.7 °C) and cold winter (mean temperature, 14.1 °C). Rainfall in the monsoon period (June–September) is more than 90% of the annual rainfall. The mean daily pan evaporation rate varied from 2.4 mm (December) to 13.2 mm (May). The groundwater depth near to the experimental site varied in the range 20–30 m from the ground surface.

The performance of three treatments: (i) drip irrigation (DI) with drainage (parallel trench): DI_D (ii) DI without drainage: DI_{WD} and (iii) basin irrigation (BI) with drainage: BI_D were compared with traditional BI without drainage (BI_{WD}) practised in citrus orchards of the region. The treatments were laid out in randomized complete block design with five replications. Each replicated plot (48 × 42 m) had 56 trees in 7 adjacent rows. Irrigation was scheduled at 100% crop evapotranspiration ($ET_{c.}$) with DI, whereas in BI (circular basin) 50% available soil water content in the effective root zone was used for irrigating the trees. The effective root zone depth of 'Nagpur' mandarin trees was considered as 0–0.40 m, as observed by Autkar *et al.* (1988). The $ET_{c.}$ was estimated based on the FAO Penman–Monteith method (Allen *et al.*, 1998) and the volume of water applied with DI was worked using the formula (Germanà *et al.*, 1992)

$$V_{id} = \pi\left(D^2/4\right)\times K_c\times (ET_{c.} - R_e)/(E_i\times 1000) \qquad (1)$$

where V_{id} is the volume of irrigation water applied (m^3 $tree^{-1}$), D the mean tree canopy spread diameter (m), K_c the crop coefficient: 0.7 (Allen *et al.*, 1998), R_e the effective rainfall (mm) and E_i the efficiency of the drip irrigation system (90%). The effective rainfall was observed to be equal to the total rainfall during the irrigation period, as drainage was found to be negligible in the orchard (Panigrahi *et al.*, 2009). DI was imposed through four online 4 l h^{-1} pressure-compensated emitters per tree.

The irrigation water quantity under BI was calculated using the formula

$$V_{ib} = (FC - RSM)\times d\times \pi\left(D^2/4\right) \qquad (2)$$

where V_{ib} is the irrigation water volume (m^3 $tree^{-1}$), FC the field capacity of soil (%, volume basis), RSM the required soil water content at 50% depletion of available soil water (%, volume basis), d the effective root zone depth (0.4 m) of 4–6-year-old 'Nagpur' mandarin trees and D the mean diameter of tree canopy spread (m). After each irrigation season, the basins were filled with soil to restrict water stagnating in the rainy season. The watering period and drainage period were from December to June and from July to October, respectively. The water applied under both DI and BI was recorded.

For efficient drainage design, the drainage coefficient (42.7 mm day^{-1}) suggested by Mohanty *et al.* (2000) based on 30 years' daily rainfall analysis and crop tolerance period (4 days) to standing water in the orchard was considered. The drainage system was designed based on a 10-year return period of rainfall in the region. Trapezoidal trenches of 0.3 m depth, 0.3 m bottom width and 1: 1.5 side slopes were made with 12.0 m drain spacing across the slope (0.3%) between the tree rows. Runoff from the plot (48 × 12 m) having two tree rows was quantified under each treatment using a multi-slot divisor, as suggested by Suresh (1997). Well- stirred runoff samples (1000 ml) were collected after each rainfall and the samples were filtered to determine the soil loss (sediment) in different treatments. The sediment samples were kept at 4 °C and subjected to analysis for available N, P and K after each rainy season by following standard procedures (Tandon, 2005).

The soil water content (SWC) at 0.2, 0.4, 0.6 and 1.0 m depths was monitored twice per week with the help of a neutron moisture meter (Troxler, USA). Tensiometers (four in number per tree and three trees in each treatment) were used to measure soil water tension at 0.2, 0.4, 0.6 and 1.0 m soil depths.

The number of fruits harvested and their weight in each treatment were recorded. The yield was calculated considering 278 trees per hectare. Irrigation water productivity (WP) was calculated as the ratio of fruit yield to irrigation water used. Five fruits from each experimental tree were selected randomly and their internal quality (juice content, total soluble solids and acidity) were determined following the procedures mentioned by Ranganna (2001). The maturity index (MI) was calculated as the ratio of total soluble solids (TSS) to acidity (Ballester *et al.,* 2011).

Financial analysis was carried out by estimating net income (NI) and benefit–cost ratio (BCR) for each treatment. Both the indices were determined adopting the same procedures followed by Panigrahi *et al.* (2013). The actual price paid for the DI system including its installation (INR 48 000 ha^{-1}) was considered in the economic analysis. The cost of energy (electrical, INR 5 per kWh) was determined based on the actual charges paid for operating the irrigation pump under different irrigation methods. For basin irrigation, the charges paid for making circular basins (diameter, 1.0 m) keeping the tree at the centre and application of water to the basins through flexible pipes were considered. The cost of cultivation of citrus includes cost of planting material and its establishment, inter-cultivation, irrigation, application of fertilizers and manure, weeding, plant protection and fruit harvesting. For drainage treatment, the actual charges paid for making the drains and their maintenance were considered under the operating cost. Drains were constructed every year after the rainy season using drainage machinery. The annual interest rate during the experimental period was 12%. Subsequently, the gross income (GI) and NI were estimated based on the wholesale price (in Indian rupee, INR) of Nagpur mandarin fruits (INR 15 500 t^{-1} in December and INR 11 700 t^{-1} in January) in the region during the experimental years, as quoted by the National Horticulture Board (NHB) (2012). The economic water productivity (EWP) was worked out as the NI per unit volume of water applied in different treatments.

The data were subjected to statistical analysis for a test of significance and the Duncan multiple range test (DMRT) was used for separation of means, following the methods given by Gomez and Gomez (1984).

RESULTS AND DISCUSSION

Runoff, soil and nutrients loss

Table I shows that the quantity of runoff generated along with soil and nutrient (available N, P and K) losses in different treatments varied significantly. The maximum runoff (295 mm) was recorded with BI_D. However, the runoff generated in DI_D (288 mm) was statistically ($P > 0.05$) on a par with that in BI_D. Similarly, the runoff produced in BI_{WD}

Table I. Runoff, soil and nutrients loss under different irrigation treatments with and without drainage in 'Nagpur' mandarin* (mean annual rainfall during 2006–2009 = 750 mm)

Treatment	Runoff (mm)	Soil loss (t ha^{-1})	Available nutrients (kg ha^{-1})		
			N	P	K
DI_D	288[†b]	1.92[a]	0.389[a]	0.072[a]	0.617[a]
DI_{WD}	130[a]	2.51[b]	0.503[b]	0.090[b]	0.802[b]
BI_D	295[b]	2.02[a]	0.393[a]	0.073[a]	0.641[a]
BI_{WD}	138[a]	2.64[b]	0.512[b]	0.096[b]	0.843[b]

*Mean annual data during the year 2006–2009.
†Data within a column followed by different letters differ significantly at $P < 0.05$.
DI: drip irrigation; D: with drainage; WD: without drainage; BI: basin irrigation.

(138 mm) and DI_{WD} (130 mm) were at par. The higher runoff under BI_D was attributed to the drains laid out between the tree rows. However, the loss of soil and available N, P and K followed the reverse trend of runoff under drained and undrained treatments with the corresponding irrigation method. The reduction of soil and nutrient loss under drainage was due to low concentration of sediment in runoff which was caused by deposition of soil in the drainage trenches.

Soil water variation

Figure 1 shows the mean monthly SWC at 0.2, 0.4, 0.6 and 1.0 m depth under various treatments. The SWC decreased in the month of November, due to water extraction by the citrus trees to compensate for their evapotranspiration (ET) demand in that month. However, SWC improved in December due to starting of irrigation which was required to break the stress for induction of flowering in the trees in this month. In top 0.4 m soil, SWC was consistently maintained during January–June with DI (27–28.1% v/v), whereas with BI the SWC varied significantly between two irrigations (24.2–29.8% v/v). The SWC was observed to be higher in the treatments without drainage during November–January. However, the drainage did not influence the SWC during January–June under corresponding irrigation methods, probably due to the higher ET of the trees with higher SWC in these months. The SWC at 0.6–1.0 m depth under DI was lower than that at 0.4–0.6 m depth, indicating the shallow wetted soil volume under the system which is desirable for efficient irrigation in the crop. On the other hand, the SWC at 1.0 m depth under BI showed an increasing trend in spite of irrigating the top 0.4 m soil under this treatment. This happened due to percolation of water from the upper 0.4 m soil through preferential pathways (cracks and fissures) in this cracking type of clay soil at low SWC under BI (Rycroft and Amer, 1995). Moreover, the increase in SWC at 1.0 m depth under BI was relatively higher during April–June than November–March. This was due to higher percolation of water under higher irrigation application in summer months (April–June) in BI. During the rainy season (July–October), all the treatments except DI_D resulted in significantly higher SWC (≥field capacity) in the top 0.4 m soil in the orchard. However, the intermittent

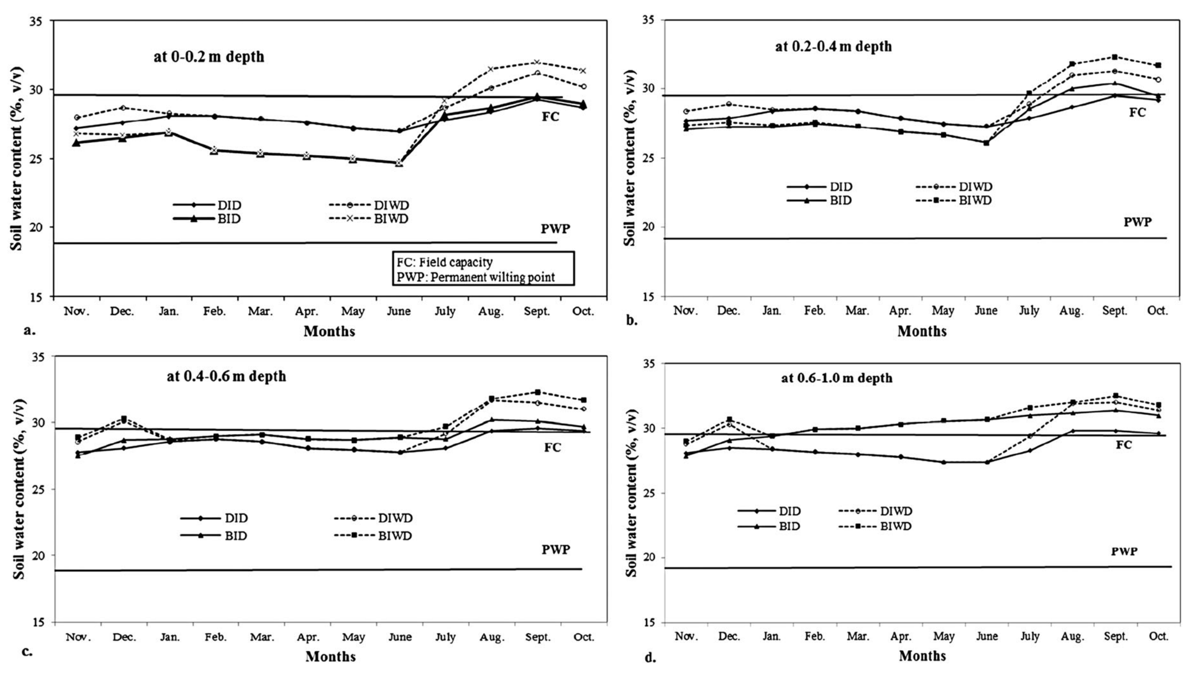

Figure 1. Soil water content at (a) 0–0.2 m, (b) 0.2–0.4 m, (c) 0.4–0.6 m and (d) 0.6–1.0 m depth under different irrigation and drainage treatments in 'Nagpur' mandarin

accumulation of water in the orchard (for 5–7 days) due to intense rainfall resulted in a saturated soil condition in most of the period in undrained treatments (BI_{WD} and DI_{WD}).

Yield and irrigation water use efficiency

Table II shows the number of fruit harvested, fruit drop, average fruit weight, fruit yield, WP and fruit quality under different irrigation and drainage treatments. The maximum number of fruit was harvested in DI_D (523 tree^{-1}), followed by BI_D (450 tree^{-1}). BI_{WD} produced the minimum number of fruit (310 tree^{-1}), due to maximum fruit drop (235 tree^{-1}) in this treatment. The higher fruit drop under BI_{WD} was due to water stress in the trees caused by high soil water fluctuation in the irrigation season and saturated SWC in most of the period during the rainy season in this treatment.

The fruit weight was higher in DI_D (123 g fruit^{-1}), followed by DI_{WD} (118 g fruit^{-1}). However, the fruit weight in DI_{WD} was at par ($P > 0.05$) with that in BI_D. The highest fruit yield was observed with DI_D (17.9 t ha^{-1}), followed by BI_D (14.5 t ha^{-1}). The higher yield under drainage with the corresponding irrigation method indicated the greater impact of drainage on productivity than irrigation system in the crop. The minimum fruit yield was recorded with BI_{WD} (9.4 t ha^{-1}). Overall, twice the improvement (54%) in yield under BI compared with DI due to drainage indicates the greater necessity of drainage in basin-irrigated orchards than in drip-irrigated ones.

The irrigation water used (IWU) under DI_D was 30% less than that under BI_D. The water saving under DI was ascribed to low evaporation due to partial wetting, less deep percolation in the tree basins and reduced conveyance losses under the system compared with BI. The highest WP was estimated with DI_D (9.5 kg m^{-3}), followed by DI_{WD} (7.5 kg m^{-3}). The higher WP in DI was attributed to higher fruit yield using a relatively lower amount of irrigation water compared to BI. The minimum WP was estimated with BI_{WD} (3.5 kg m^{-3}).

Fruit quality analysis showed that the juice percentage was higher in DI (38.4–40.2%) than BI (35.2–38.2%). However, drainage produced higher juice content (1.8–3% more) in the fruits with the corresponding irrigation method. The acidity of juice was minimum in DI_D (0.79), followed by DI_{WD} (0.81). The TSS followed the same trend of juice content in the treatments. The increase in TSS with some decrease in acidity in the fruits with DI_D and DI_{WD} might be due to enhanced conversions of acids to sugars under optimum SWC in these treatments (Huang *et al.,* 2000). The higher TSS of fruits under deficit SWC conditions was also reported earlier in citrus (Ballester *et al.,* 2011). The maturity index (MI), which determines the time of harvesting of the fruits, was observed to be higher in DI_D

Table II. Yield, irrigation water productivity (WP) and fruit quality of 'Nagpur' mandarin as affected by various irrigation treatments with and without drainage*

	Yield parameters					Quality parameters			
Treatment	No. of fruits tree^{-1}	Average fruit weight (g)	Fruit yield (t ha^{-1})	IWU (m^3 ha^{-1})	WP (kg m^{-3})	Juice (%)	Acidity (%)	TSS$^+$ (^{0}Brix)	Maturity index
DI_D	523^{†d} (77)^β	123^c	17.9^d	1890	9.5^d	40.2^c	0.79^a	10.2^c	12.9
DI_{WD}	430^b (150)	118^b	14.1^c	1890	7.5^c	38.4^b	0.81^b	9.7^b	12.0
BI_D	450^c (110)	116^b	14.5^b	2700	5.4^b	38.2^b	0.84^c	9.6^b	11.4
BI_{WD}	310^a (235)	109^a	9.4^a	2700	3.5^a	35.2^a	0.89^d	8.4^a	9.4

*Mean annual data during 2006–2009; IWU: irrigation water used; DI: drip irrigation; D: with drainage; WD: without drainage; BI: basin irrigation; +TSS: total soluble solids.
†Data within a column followed by different letters differ significantly at $P < 0.05$; β: values in parentheses ( ) indicate the number of fruit dropped.

Table III. Economics of 'Nagpur' mandarin production under different irrigation treatments with and without drainage*

Treatments	Gross income ($^+$INR ha^{-1})	Fixed cost (INR ha^{-1})	Operating cost (INR ha^{-1})	Total cost (INR ha^{-1})	Net income (INR ha^{-1})	B/ C	Economic water productivity (INR m^{-3} irrigation water)
DI_D	278 000 ^{†d}	20 000^b	33 500^b	53 500^b	225 000^d	5.2^d	119.0^d
DI_{WD}	166 000^c	20 000^b	28 000^a	48 000^a	118 000^b	3.4^b	62.2^c
BI_D	225 000^b	3 300^a	56 000^d	59 300^c	166 000^c	3.8^c	61.5^b
BI_{WD}	110 000^a	3 300^a	50 500^c	53 800^b	56 600^a	2.1^a	21.0^a

*Mean annual data during 2006–2009; +INR: Indian rupee; DI: drip irrigation; D: with drainage; WD: without drainage; BI: basin irrigation.
†Data within a column followed by different letters differ significantly at $P < 0.05$; B/C: benefit–cost ratio.

with a minimum value in BI_{WD}. Due to higher MI, the fruits under DI_D were harvested one month earlier than that with BI_{WD}.

Economics

Table III shows that the mean annual GI, fixed cost (FC), operating cost (OC), total cost (TC), NI, BCR and EWP in the irrigation-cum-drainage treatments were affected significantly ($p < 0.05$). The maximum GI was generated in DI_D (INR 278 000 ha^{-1}) followed by BI_D (INR 225 330 ha^{-1}), whereas BI_{WD} generated the minimum GI (INR 110 000 ha^{-1}). The higher GI from the treatments with drainage was attributed to not only higher fruit yield, but the higher market price (INR 3 800 t^{-1}) of the fruits due to early harvest (1 month early) in these treatments compared with undrained treatments.

The FC was found to be higher in drip-irrigated treatments (INR 20 000 ha^{-1}) than basin-irrigated treatments (INR 3300 ha^{-1}), due to the cost of the DI system installed in the orchard. However, the TC was found to be higher in basin-irrigated treatments (INR 53 800–59 300 ha^{-1}), due to the relatively higher increase in OC over FC in BI (INR 47 200–52 700 ha^{-1}) compared to DI (INR 8000–13 500 ha^{-1}). The higher OC under BI was caused by higher power costs and labour charge involved in this irrigation method. The OC and TC were found to be higher under drainage in the corresponding irrigation method, due to labour charges involved in construction and maintenance of the drainage system in the orchard.

The maximum NI (INR 225 000 ha^{-1}) with higher BCR (5.2) was estimated in DI_D, followed by BI_D (NI, INR 166 000 ha^{-1}; BCR, 3.8). However, the highest EWP was found with DI_D (INR 119 m^{-3} water), followed by DI_{WD} (INR 62.2 m^{-3} water). The higher EWP in DI_D was due to a relatively higher enhancement in NI with using less water in this treatment compared to other treatments. The lowest EWP was observed with BI_{WD} which was 82% lower than that with DI_D.

CONCLUSIONS

Drip irrigation is found to be a potential water-saving technique, conserving 30% irrigation water over basin irrigation in citrus production of central India. Adoption of drip irrigation could reduce groundwater use and consequently improve irrigation water availability throughout the year in citrus orchards in the region. Further, drainage (parallel trenches) enhanced the fruit yield by reducing the fruit drop in the rainy season in both drip- and basin-irrigated orchards. However, the impact of drains on crop productivity was superior under basin irrigation than drip irrigation. Parallel trenches also conserved a substantial amount of available nutrients (N, P and K) in the soil by trapping the sediment lost through the surface runoff in the drains. Overall, the combined use of drip irrigation and parallel trenches produced the highest fruit yield, with 171% improvement in irrigation water use efficiency over that in traditional basin irrigation without drainage in citrus orchards. It was also found economically superior by generating the highest profit per unit water used, due to higher fruit production and savings of labour and power under this treatment. Overall, we conclude that adoption of drip irrigation and parallel trenches is a viable option against traditional basin irrigation without drainage for citrus cultivation in clayey soils under similar agro-climatic conditions such as those found in central India. Further study to evaluate the techno-economic feasibility of drainage-water harvesting and its reuse through micro-irrigation in citrus is suggested.

NOTE

1. INR = Indian rupee; 1US$ = INR 44.7, mean price level 2006–2009.

REFERENCES

Allen RG, Pereira LS, Raes D, Smith M. 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56. Rome, Italy.

Autkar VN, Kolte SO, Bagade TR. 1988. Distribution of active rooting zones in Nagpur mandarin and estimates of water requirement for Vertisols of Maharashtra. *Annals of Plant Physiology* **2**(2): 219–222.

Ballester C, Castel J, Intrigliolo DS, Castel JR. 2011. Response of Clementina de Nules citrus trees to summer deficit irrigation. Yield components and fruit composition. *Agricultural Water Management* **98**: 1027–1032.

Boman B, Tucker D. 2002. Drainage Systems for Flatwoods Citrus in Florida. Circular 1412, Agricultural and Biological Engineering Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, http://edis.ifas.ufl.edu.

Davies FS, Albrigo LG. 1994. Citrus. CAB International: Wallingford, UK.

Fereres E, Goldhamer DA, Parsons LR. 2003. Irrigation water management of horticultural crops. *HortScience* **38**(5): 1036–1042.

Gangwar LS, Shirgure PS, Singh S. 1999. Economic viability of investment on adoption of drip irrigation system in Nagpur mandarin orchards. In *Proceedings of National Symposium on Citriculture*, 17–19 November 1997, Nagpur, India; 246–250.

Germanà C, Intrigliolo F, Coniglione L. 1992. Experiences with drip irrigation in orange trees. In *Proceedings of the VII International Citrus Congress of the International Society of Citriculture*, 8–13 March, Acireale (Catania), Italy; 661–664.

Gomez KA, Gomez AA. 1984. Statistical Procedures for Agricultural Research. John Wiley & Sons: New York.

Huang X, Huang HB, Gao F. 2000. The growth potential generated in citrus fruit under water stress and its relevant mechanisms. *Scientia Horticulturae* **83**: 227–240.

Iyengar BVR, Keshavamurthy SV, Shivananda TN. 1996. Increasing fertilizer use efficiency in citrus. *Indian Horticulture* **41**(3): 21–23.

Marathe RA, Mohanty S, Singh S. 2000. Soil drainage characteristics and its effect on the performance of Nagpur mandarin orchards of central

India. In *Proceedings of International Symposium on Citriculture,* 23–27 November 1999, Nagpur, India; 442 – 447.

Minessy FA, Barakat MA, El-Azab EM. 1970. Effect of water table on mineral content, root and shoot growth, yield and fruit quality in 'Washington Navel' orange and 'Balady mandarin'. *Journal of American Society of Horticulture Science* **95**: 81–85.

Minessy FA, Barakat MA, El-Azab EM. 1971. Effect of some soil properties on root and top growth and mineral content of Washington Navel orange and Balady mandarin. *Plant and Soil* **34**: 1–15.

Mohanty S, Marathe RA, Singh S. 2000. Drainage coefficients for different Nagpur mandarin growing regions of central India. In *Proceedings of International Symposium on Citriculture*, 23–27 November 1999, Nagpur, India; 598–603.

National Horticulture Board (NHB). 2012. Price and annual arrival of fruits, vegetables and flowers. www. nhb.gov.in/online client/moth wise annual price and arrival report. aspx (last accessed 20 September 2013).

Panigrahi P, Srivastava AK, Huchche AD. 2009. Influence of in-situ soil and water conservation measures on performance of Nagpur mandarin. *Journal of Agricultural Engineering (ISAE)* **46**(3): 37–40.

Panigrahi P, Huchche AD, Srivastava AK. 2012. Various inter-row water harvesting techniques in acid lime orchards. *Journal of Soil and Water Conservation* **11**(1): 49–52.

Panigrahi P, Sharma RK, Parihar SS, Hasan M, Rana DS. 2013. Economic analysis of drip irrigated Kinnow mandarin orchard under deficit irrigation and partial root-zone drying. *Irrigation and Drainage* **62**: 67–73.

Ranganna R. 2001. Handbook of Analysis and Quality Control for Fruit and Vegetable Products, 2nd edn. Tata McGraw-Hill: New Delhi.

Rycroft DW, Amer MH. 1995. Prospects for drainage of clay soils. FAO Irrigation and Drainage Paper 51. Rome, Italy.

Schaffer B, Moon PA. 1990. Influence of rootstocks on flood tolerance of Tahiti lime trees. *Proceedings of the Florida State Horticulture Society* **103**: 18–21.

Sevenhuijsen R J. 1994. Surface drainage systems. In Drainage Principles and Applications, Publication No. 16, 2nd edn, Ritzema HP (ed.). International Institute for Land Reclamation and Improvement: Wageningen, the Netherlands; 799–826.

Singh S, Srivastava AK. 2004. Citrus industry of India and overseas. In Advances in Citriculture, Singh S, Shivankar VJ, Srivastava AK, Singh IP (eds). Jagmander Book Agency: New Delhi, India; 8–67.

Suresh R. 1997. Soil and Water Conservation Engineering, 2nd edn. Standard Publishers: New Delhi, India.

Tandon HLS. 2005. Methods of Analysis of Soils, Plants, Waters, Fertilizers and Organic Manures, 2nd edn. Fertilizer Development and Consultancy Organization: New Delhi, India.

