WATER AND SALT TRANSPORT, WATER UPTAKE, AND LEAF WATER POTENTIALS DURING REGULAR AND SUSPENDED HIGH FREQUENCY IRRIGATION OF CITRUS*

CHRISTIAAN DIRKSEN**, J.D. OSTER and P.A.C. RAATS***
U.S. Salinity Laboratory, U.S.D.A., Riverside, Calif. (U.S.A.)

*This work was supported in part by EPA Interagency Project IAG-D4-0370.
**Present address: Department of Soils and Fertilizers, Agricultural University, Wageningen (The Netherlands)
***Present address: Institute for Soil Fertility, Haren (Gr.) (The Netherlands)

(Accepted 19 June 1979)

ABSTRACT


High frequency irrigation of citrus was interrupted for up to 2 months to study the dynamics of salt and water transport in soil, water uptake distributions and leaf water potentials. Irrigation water was applied to less than half the surface area per tree. Water content profiles and chloride distributions indicated that of the water uptake below the irrigated area, about 80% took place above 0.60-m depth, and that considerable water was taken up from outside the irrigated area. The water for the latter was supplied by lateral flow, as evidenced by the hydraulic gradients, the relative extent of the lateral flow in summer and winter, and the fact that at 0.90-m depth water contents were uniform. In summer, the citrus showed signs of stress after about 4 weeks of suspended irrigation. At that time leaf water potentials did not recover any longer during the night. This study indicates that high frequency irrigation of citrus is not too vulnerable to temporary system breakdown and that deficit-irrigation could be practiced.

INTRODUCTION

High frequency irrigation provides a continuous supply of low-salinity water near the soil surface or around a source. With frequent applications at rates controlled by the irrigation system rather than by the soil, soil water contents or pressure heads can be maintained above field capacity (Rawlins, 1973) while maintaining leaching fractions as low as 0.05. Such low leaching fractions reduce soil mineral dissolution and enhance precipitation of gypsum and lime (Rhoades et al., 1974). These and other aspects of high frequency irrigation and minimum leaching, such as salt tolerance of crops, reduced salt loads of irrigation return flows, and energy and fertilizer savings, have been discussed in more detail by Van Schilfgaarde et al. (1974) and Rawlins and Raats (1975).
The potential of modifying irrigation management to obtain higher water use efficiency and to reduce the adverse effects of irrigation on the salt load of irrigation return flow, without decreasing crop yields, is being evaluated in two field experiments with citrus and alfalfa in southwestern Arizona. These experiments were described and initial results were given by Hoffman et al. (1977), and the U.S. Salinity Laboratory Staff (1977). This study concerns one short and two long interruptions of high frequency irrigation of citrus irrigated at an average leaching fraction of about 0.3. The purpose of this was to study the dynamics of water and salt transport in the soil and water uptake distributions during irrigation, as well as the response of citrus when irrigation was interrupted. The latter is of particular interest with regard to the vulnerability of trees to temporary breakdown of high frequency irrigation systems, and the prospects for deficit-irrigation (Fischbach and Somerhalder, 1974; Miller and Aarstad, 1976).

EXPERIMENTAL

We give only a summary of the experimental set-up, described in detail by Hoffman et al. (1977), as it pertains to this particular study. The citrus orchard was established in 1963 near Tacna, Arizona, on Dateland fine sandy loam (Typic Hapludalf, coarse loamy, mixed hyperthermic). For a complete profile description, see U.S. Salinity Staff (1977, Table A-1). The Valencia orange trees (Citrus sinensis L.) are Campbell Nucellar budwood grafted on rough lemon rootstock and are planted at a spacing of 4.9 × 6.7 m. Until December 1973, the trees were irrigated by conventional border flooding at a leaching fraction of about 0.50. Since then they have been irrigated automatically up to five times per day, at average leaching fractions ranging between 0.05 and 0.30. The irrigation water is from the Mohawk Canal and has a typical concentration of total dissolved solids of 940 g/m³. The water is applied at a rate of 1.9 l/min per tree for 15–30 min per irrigation, which amounts to 0.9–1.8 mm over the total surface area per tree. The water is applied to only about half the total surface area — a circular area with a radius of about 2.1 m — with a 35-m-long spiral of dual-chamber, drip irrigation tubing with outlets every 0.3 m along its length. Irrigation is controlled by light-emitting diodes and phototransistors placed directly opposite each other on mercury manometers of tensiometers (Austin and Rawlins, 1977). Their location on the manometers is chosen so that the desired amount of water is applied according to soil salinity and pan evaporation.

For this study the automated irrigation of the nine trees of replicate H4, which was being operated at an average leaching fraction of about 0.3, was interrupted three times. First there was a brief interruption from 24 to 29 August 1976, during which only tensiometric measurements were made. The two major interruptions were from 1 November 1976 to 6 January 1977, and from 14 June to 13 July 1977. During the first major period 6.6 mm precipitation fell on 13 November and some water was applied accidentally about
16 November. These events temporarily affected the water contents to a depth of about 40 cm. Throughout the two major periods, volumetric soil water contents were measured at 0.10-m depth intervals with a dual-access tube γ-ray attenuation probe with automatic temperature compensation by a pulse height discriminator module (Troxler Model 2376, Raleigh, N.C.)\textsuperscript{1}. Leaf water potentials were measured with a pressure chamber during the last period. Relative humidity was determined from wet and dry bulb temperatures. To eliminate effects of neighboring trees on other irrigation schedules, we instrumented only the center tree of the nine trees of H4, as indicated in Fig. 1. Six tensiometers were installed between 0.30- and 1.80-m depth at 0.30-m intervals at each of the 14 locations. During the installation of the access tubes on 13–15 October 1976, soil samples were taken at 0.1-m intervals down to

\begin{center}
\textbf{Fig. 1. Geometry of areas and measuring sites for center tree of H4.}
\end{center}

\textsuperscript{1} Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the U.S. Department of Agriculture.
1.50 m for determination of soil bulk density, volumetric water content, and chloride concentration. Soil samples for chloride determinations were also taken on three other dates at 0.10-m or 0.20-m depth intervals to a depth of 1.80 m at the sites shown in Fig. 1. The chloride concentrations were expressed in moles per cubic meter of soil water at the field water content at the time of sampling.

RESULTS

Fig. 2 shows water content profiles on 13–15 October 1976. They are averages for each pair of access tube sites. These water contents represent conditions under regular, automated frequent irrigation. Near the soil surface the water contents ranged from 0.075 to 0.265 m³/m³, yet at the 0.90-m depth all profiles had about the same water content of 0.16 m³/m³. The two profiles within the irrigated area had the highest water content near the surface. Not shown is a profile taken midway between the trees, at 4.3 m on the diagonal. The water content there increased from 0.07 m³/m³ at the 0.10-m depth to 0.16 m³/m³ at the 0.90-m depth. Thus, at the 0.90-m depth soil water contents no longer reflected that the irrigation water was applied to less than half the

![Fig. 2. Water content profiles in west, south, and southeast radials obtained by gravimetric sampling on 13–15 October 1976. Each curve is average for pair of access tubes used with γ probe.](image-url)
surface area. About 16 mm of precipitation received 3 weeks prior to the sampling could be responsible for the water close to the soil surface midway between the tree rows, but the steep increase in water content with depth does indicate nearly horizontal flow to 2.2 m beyond the wetted perimeter. This horizontal flow masks the influence of gravity one would expect in a homogeneous soil. This suggests that the hydraulic conductivity was larger in the horizontal than in the vertical direction, similar to observations in laboratory experiments with fine sand (Dirksen, 1978).

Although the decrease in water uptake with depth tends to increase water contents, it is not clear why they should increase so much below 1.0 m when the groundwater table is deeper than 4 m. Tensiometer data of 12 October 1976 in Fig. 3 show a change from a decreasing to an increasing pressure head with depth at about 0.9 m. However, the pressure heads do not increase as much below this depth as would be consistent with the upper part of the water content profiles. The pressure head distributions correspond to total head gradients of less than unity below 0.9 m. This could be due to hysteresis if the bottom was recently drying while the top was wetting; but, it is more

Fig. 3. Pressure head distribution in kPa on 12 October 1976 for the north (a), east (b), and northeast (c) radials.
likely that the water retentivity curve (soil texture) differs between the upper and lower part of the profile. Thus below 0.9 m there must be layers, such as a sand layer, that impede drainage and have higher water contents for the same pressure head than the soil above.

Water contents at the start of the two major interruption periods showed some quantitative differences between summer and fall that indicated the extent of lateral movement. Fig. 4. shows water content profiles below the irrigated area (west 1.22–1.52 m) on 1 November 1976 and 6 January, 14 June, 20 June and 13 July 1977. From 0 to 0.80 m, the water content at the start of the interruption period was higher in the summer than in the fall. Below 0.80 m the differences were small between summer and fall. During the summer, nine times more water was applied than during the fall and thus the hydraulic conductivities and water contents were higher near the water supply. This was not true outside the irrigated area. Between 3.35 and 3.66 m in the southeast radial (Fig. 5), the water content was higher in the fall than in the summer down to 0.70 m. The highest water content was measured on 8 November, 1 week after the irrigation was stopped. Thus, the water content between the rows increased during the transition from summer to winter while the trend underneath the trees was just the opposite. This indicates that lateral flow is more extensive in winter than in summer, in spite of the
higher water content gradients in summer. Apparently, the larger lateral flow beyond the wetted perimeter in summer is mostly dissipated by root water uptake and evaporation from the soil surface.

The profile for 20 June in Fig. 4 shows that the relatively abundant supply of water near the surface was taken up rapidly in 6 days, but that little was taken up from below 1.0 m. During the following 23 days, water uptake was much slower and decreased only slightly with depth down to 1.50 m. On 13 July the water content, about 0.11 m³/m³, was nearly uniform to 1.20 m. The much greater ET in the summer caused the water content to decrease more in 6 days than it did in 2 months in the fall. The final water contents were about 0.02 to 0.03 m³/m³ greater in the fall than in the summer. Outside the irrigated area (Fig. 5) there was no excess water near the soil surface. Water loss was nearly uniform down to the 1.50-m depth during both periods at rates which differed by a factor of four or more between summer and fall. Again, the final water contents were lower in the summer.

Fig. 6 shows the average change per day of the water content as a function of depth and time for the irrigated area (south 1.22—1.52 m) during four periods within the summer interruption. The changes became less and shifted downward with time. From 14—16 June the soil below 0.60 m was wetting up as a result of vertical redistribution, and there also must have been lateral flow. Both types of flow complicate the interpretation of the initial changes
Fig. 6. Profiles of average water content change per day between 1.22 and 1.52 m of south radial for four periods during summer interruption of irrigation.

in water content due to water uptake, but they probably become small within 2 days after irrigation. Lateral flow should be the smallest and vertical redistribution the largest in the tree rows (south radial), because it is there that the irrigated areas are closest together. The west radial (not shown) did exhibit less redistribution than the south radial.

Since a 2- to 4-day interruption in the irrigations is not uncommon under the automated control, and considering the arguments above, the curve for the second period in Fig. 6 should provide a conservative estimate of the steepness of the water uptake distribution under the normal frequent irrigation regime. The cumulative distribution with depth, given in the last column of Table I, agrees qualitatively with the water uptake distribution shown in the third column of Table I. It is based on the chloride concentrations in column 2, which are the averages for the seven sites sampled in March 1976 within the irrigated area shown in Fig. 1. Since chloride does not precipitate and negligible quantities are taken up by the plant roots, the relative water uptake distribution is calculated according to

\[
RWU = \frac{1 - (C_{iw}/C_{sw})}{1 - LF}
\]

where \( C_{iw} = 3.3 \) mole/m³, is the chloride concentration of the irrigation water and \( C_{sw} \) is the chloride concentration of the soil water at a given depth.
TABLE I

Cumulative relative water uptake derived from chloride distribution (Eqn. 1) and from water content profiles (Fig. 6)

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Cl conc. (mole/m³)</th>
<th>From Eqn. 1</th>
<th>From Fig. 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>6.0</td>
<td>0.65</td>
<td>0.43</td>
</tr>
<tr>
<td>0.6</td>
<td>8.3</td>
<td>0.87</td>
<td>0.74</td>
</tr>
<tr>
<td>0.9</td>
<td>9.4</td>
<td>0.94</td>
<td>0.87</td>
</tr>
<tr>
<td>1.2</td>
<td>10.2</td>
<td>0.98</td>
<td>0.94</td>
</tr>
<tr>
<td>1.5</td>
<td>10.6</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

The RWU values are based on the assumption that root activity ceases at the 1.50-m depth, which corresponds with an overall leaching fraction (LF) of 0.31. Thus, both calculations indicate that under the irrigated area about 80% of the water uptake takes place above the 0.60-m depth.

It is also of interest to look at the spatial distribution of water uptake. For this, the water contents for each position were smoothed individually in time, and the total loss of water between days of measurement was calculated for each of the six 1.50-m-deep profiles (Fig. 7). Water uptake took place from

Fig. 7. Total loss of water per day for each of six profiles during summer interruption of irrigation and estimated ET based on weighted average of these water losses.
the beginning at all six radial distances. At the largest radial distance, south-east-out, the initial uptake was larger than at two other locations. All locations showed a rapid decline of the uptake to about the same value by about 26 June, then an increase before they all declined toward the end of the period. The increase resulted from increased root activity in the lower part of the root zone (see Fig. 6). Two of the profiles are within the irrigated area; three are just beyond the wetted perimeter and one is far beyond it. By assigning weights of 2/5, 2/5, and 1/5, respectively, to the averages of the calculated water losses for each of these three groups (proportional to the fraction of the area per tree they represent, Fig. 1) the total water uptake for the tree was calculated and is also plotted in Fig. 7. The total water uptake during the first 2 days was thus estimated at 7.8 mm/day, which was equal to the measured evaporation from a pan located within the orchard. This agrees well with other data of the entire citrus experiment which show that the ratio between ET and the pan evaporation was close to unity. This ratio may be somewhat high compared with what is generally found, because the pan is within the orange orchard, which reduces pan evaporation.

Fig. 8. Total head distribution in kPa in east radial on 1 November, 15 November, and 6 December 1976.
After 12 days the rate of water uptake had decreased to 2.0 mm/day, followed by an increase to 3.0 mm/day after 18 days. The final value after 29 days was 1.0 mm/day. These rates are not corrected for upward flow or water uptake below 1.50 m. The latter is not known, but based on the observed rates of change of water content just above 1.50 m, it is likely insignificant except possibly toward the end of the stress period. As to upward flow from below 1.50 m, the tensiometric measurements taken during both stress periods indicated that this also was negligible.

Fig. 8 shows contours of equal total soil water potential $H$ in the east radial on 1 November, 15 November, and 6 December 1976, respectively. The reference level is $H = 0$ for saturation (pressure head $h = 0$) at the 0.3-m depth. On 1 November, just before the irrigation was turned off, all hydraulic gradients were directed downward and away from the irrigated area. By 15 November, the hydraulic gradients began to reverse; on 6 December all gradients were vertically upward and inward toward the tree. However, steady-state measurements on undisturbed cores showed that the hydraulic conductivity drops be-

Fig. 9. Total head distribution in kPa in east radial on 24 August, 29 August, and 1 September 1976.
low 0.1 mm/day at pressure heads of about $-20$ kPa. Consequently, the upward water flux was negligible. Instead, the gradients reflect the progression of water uptake with radial distance and depth.

The quality of tensiometer data obtained during June and July 1977 was insufficient to determine hydraulic head contours. However, good data were obtained during a 6-day interruption in August 1976. Fig. 9 shows total hydraulic head contours for the east radial just before this interruption (a), and just before the irrigation was resumed (b). Comparison of Figs. 8a and 9a shows again that the pressure heads (and thus water contents) are higher in the summer than in the fall. The contours of Fig. 9b indicate that most of the root uptake occurred above the 0.60-m depth. A steep upward hydraulic gradient in the top is separated from a downward gradient in the bottom by the plateau between the two $-20$ kPa contours. Fig. 9c shows total head contours about 3 days after the irrigation was resumed. The top soil has reached near normal potentials, but probably due to drainage, and maybe some root uptake, the lower $-20$ kPa contour has vanished. These contours indicate a rather sharp wetting front with little redistribution, which supports the arguments made earlier in connection with the water uptake distribution (Table I). These data are representative for the first 6 days in June 1977. For the rest of the interruption period, the total heads shown in Table II, which are averages for all radial distances for each depth in June and July of 1977, give a good picture

<table>
<thead>
<tr>
<th>TABLE II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total potentials* in kPa for center tree from 9—13 June 1977 (averages per depth)</td>
</tr>
<tr>
<td>Date</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>North: radial distance 0.61—2.44 m</td>
</tr>
<tr>
<td>Depth</td>
</tr>
<tr>
<td>0.30 m</td>
</tr>
<tr>
<td>0.60 m</td>
</tr>
<tr>
<td>0.90 m</td>
</tr>
<tr>
<td>1.20 m</td>
</tr>
<tr>
<td>1.50 m</td>
</tr>
<tr>
<td>1.80 m</td>
</tr>
<tr>
<td>East: radial distance 0.61—3.05 m</td>
</tr>
<tr>
<td>Depth</td>
</tr>
<tr>
<td>0.30 m</td>
</tr>
<tr>
<td>0.60 m</td>
</tr>
<tr>
<td>0.90 m</td>
</tr>
<tr>
<td>1.20 m</td>
</tr>
<tr>
<td>1.50 m</td>
</tr>
<tr>
<td>1.80 m</td>
</tr>
<tr>
<td>Northeast: radial distance 1.83—4.27 m</td>
</tr>
<tr>
<td>Depth</td>
</tr>
<tr>
<td>0.30 m</td>
</tr>
<tr>
<td>0.60 m</td>
</tr>
<tr>
<td>0.90 m</td>
</tr>
<tr>
<td>1.20 m</td>
</tr>
<tr>
<td>1.50 m</td>
</tr>
<tr>
<td>1.80 m</td>
</tr>
</tbody>
</table>

* All potentials are negative. The — sign has been omitted for convenience.
of the shift in the water uptake with depth and time. Again, by the time the
gradient reverses from downward to upward, the pressure head has decreased
to the point that the hydraulic conductivity is very small. The estimated maxi-
mum upward flux at any place or time was only 0.3 mm/day and most were
much smaller.

Fig. 5 and 7 show that water is taken up not only directly below the ir-
rigated area, but also outside that area, even during the first 2 days after irri-
gation and thus during regular frequent irrigation. This is also evident from
the chloride distributions as a function of radial distance and depth. Fig. 10
shows the chloride distribution after 1, 2, and 3 years of automated frequent
irrigation. Where more than one value was available for a particular radial
distance, chloride concentrations were averaged over the radial directions
(Fig. 1). Chloride concentrations were highest beyond the wetted perimeter.
The extent of the higher concentrations increased with time outside the
wetted perimeter and above about the 1.5-m depth.

![Diagram showing chloride concentration distributions](image)

**Fig. 10.** Chloride concentration distributions in the soil solution at field water content
after 1, 2, and 3 years of automated, frequent irrigation.

In the fall and winter the trees did not appear to be under stress during the
entire interruption of irrigation, but in the summer they began to show signs
of stress after 4 weeks without irrigation. In the summer, leaf water potentials
(LWP) of 12 individual leaves and relative humidity (RH) were measured early
in the morning and in the afternoon. They are shown in Fig. 11, along with
daily rates of pan evaporation (PE). The LWP in the afternoon generally reflect
the variations in the PE. The main exception is on 22 June, when all the LWP
measurements were lower than at any other time. This may have been caused by a short-term, high evaporative demand, that did not significantly affect pan evaporation for the entire day. However, it also coincides with the time the tree ran out of easily available water directly under the canopy (see Fig. 4). The higher LWP values later, as well as the water uptake data in Figs. 6 and 7, suggest that the tree needed some time to adjust before it could take up water elsewhere in the root zone; it probably also regulated LWP with the stomates. The LWP values in the afternoon decreased with time toward the end of the interruption period, but on 13 July they were still not as low as on 22 June. It appears that the signs of stress were caused by the lack of recovery of the LWP during the night rather than the LWP during the day. The LWP in the early morning decreased steadily throughout the period and was only \(-1800\) kPa on 13 July. This stress did not appear to adversely affect yields in 1978. The yields, both in kg/tree and the number of fruits/tree, averaged over the nine trees of the H4 replicate, were within the range of differences among the averages of all the high leaching replicates observed in the previous four years.
CONCLUDING REMARKS

Except during the suspensions, the citrus was irrigated several times per day at a leaching fraction of about 0.3. The water was applied to less than half the surface area. About 80% of the water uptake under the irrigated area took place above 0.6-m depth. Water uptake also occurred outside the wetted perimeter. The water for this was supplied by lateral flow. Frequent irrigations can keep soil water contents higher than field capacity without undue drainage (Rawlins, 1973). The water thus stored in the soil profile is then available for root uptake when irrigation is diminished or suspended. In the fall, irrigation could be suspended for more than 2 months without apparent ill effects on the citrus. In the summer, water stored below the irrigated area supplied the trees for about 6 days, while the ET was decreasing.

After this easily available water was exhausted, the citrus adjusted by taking up water at more uniform and much reduced rates down to at least 1.50 m. It appeared to keep its LWP high during the day by regulating the stomates. Serious stress developed when LWP failed to recover during the night, after about 30 days.

These results indicate that even in extremely hot climates, citrus under frequent irrigation is not too vulnerable to temporary breakdowns of the irrigation system. If only a fixed amount of water can be used per year, the water for leaching in the winter could possibly be made available by practicing deficit-irrigation during the summer (Fischbach and Somerhalder, 1974; Miller and Aarstad, 1976). Under deficit-irrigation, water stored in the soil profile in the spring is used gradually throughout the summer, or during periods of extremely high ET. The main advantage of deficit-irrigation during periods of high demand is, of course, that the capacity of the irrigation system, and with it the initial and operating costs, can be reduced.

ACKNOWLEDGEMENTS

The work reported here was supported in part by the U.S. Environmental Protection Agency under EPA-IAG-D4-0370. We also wish to express our appreciation to W.J. Alves, D.F. Handley, R.T. Pine, C.L. Webber, III and J.D. Wood who have made significant technical contributions to this work.

REFERENCES


