An Improved Weighing Lysimeter Facility for Citrus Evapotranspiration Studies

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Abstract

An improved weighing lysimeter facility, designed to fulfil a definite need for better daily and seasonal information on water use by citrus orchards is described and evaluated. The facility consists of three lysimeters each containing a single tree and having a total mass of approximately 50 tons.

Mass changes of 2 kg (equivalent to 0,15 mm of water over the 13,4 m^2 lysimeter surface area) can be resolved without difficulty and errors in successive measured mass increments during typical calibration runs are hardly ever in excess of this value. In addition to this very satisfactory resolution and accuracy, a considerable degree of uniformity in evapotranspirational response between similarly treated lysimeters was revealed in measurements of monthly water use over a season, and of daily water use over periods of several weeks.

Direct measurements of the diurnal march of transpiration, needed for progress in modelling the mechanism of water uptake and flow in citrus trees, can be satisfactorily accommodated by the lysimeters in summer when transpiration rates are high. Winter and spring rates are generally low. The resolution limit of 2 kg is then not entirely adequate for describing diurnal curves on the basis of hourly transpiration rates. However, by frequent sampling within the hour and mathematical smoothing of the data, it seems possible to improve such diurnal curves to the point of acceptability, at least until more sensitive methods of measuring hourly transpiration rates from mature orchard-grown citrus trees can be developed.

Detailed and consistent evapotranspiration measurements such as provided by the lysimeters are unique in the study of citrus water relations and provide a rare opportunity of analysing the seasonal and daily water use characteristics in response to the annual physiological growth cycle, local climatic variations and varying conditions of water supply.

Introduction

Most research on citrus water relations under orchard conditions (Hashemi and Gerber, 1967; Van Bavel, Newman and Hilgeman, 1967; Kalma and Stanhill, 1969; Kaufmann and Elfving, 1972; Elfving, 1971) has been severely restricted by a lack of knowledge of the instantaneous, or even the daily mean, rate of water consumption per tree. Green, Burger and Conradie (1974) described a prototype weighing lysimeter of dimensions 3,66 m x 3,66 m x 1,8 m intended to correct this deficiency. Though performance of this low-cost prototype was not satisfactory there was ample evidence that additional effort and expenditure, aimed at improving the accuracy and resolution of the lysimeter, would be well justified.

This paper reports on the results of modifications and extensions to the lysimeter system, presents some typical calibration and water use data and describes research objectives which the lysimeter facility may help to achieve.

Materials and Methods

Orchard Material

The prototype lysimeter (Green *et al.*, 1974) was installed in 1970 in a normal tree position within a block of Valencia trees planted in 1963. This orchard block was initially double-planted (spacing 6,1 m x 3,55 m) with the intention of eventually achiev-

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ing a normal 6,1 m x 6,1 m spacing by removing every alternate tree in every row. The technique of transplanting a mature tree had first to be mastered before one of the double-planted trees earmarked for removal could successfully be transplanted into the lysimeter. This transplanting procedure was repeated in the winter of 1972 directly after the masonry work and installation of steel tanks for two additional lysimeters had been completed. Soil was packed into the tank around the roots in layers, in the same order and to the same bulk density as in the surrounding orchard soil. Fig. 1 illustrates the current orchard layout with the three lysimeters adjacent to one another in an "L" configuration. Lysimeter trees are well-representative of surrounding trees in the orchard, though the tree in C, the prototype, is noticeably larger than those in A and B, the two newer lysimeters.

Construction

Though essentially similar, some structural changes with reference to the prototype construction (Green *et al.*, 1974) were made to the steel tanks and concrete-lined pits of the new installations. The tanks then had the channel-iron wall supports on the inside instead of the outside, permitting a smaller gap between the steel walls and the surrounding concrete retaining wall. Inner surfaces of the tank were coated with fibreglass to counteract the effects of rusting.

The inspection space beneath the two new lysimeters was reached through a single manhole providing access to a centrally-placed passageway which extended in opposite directions into the concrete platform area under each lysimeter tank. The load cells and outer bolted-down brackets of the horizontal stabilisation system were supported on this concrete platform. As before (Green *et al*, 1974), the steel I-beam platform supporting each tank rested directly on the load cells and provided anchorage for the inner brackets of the horizontal stabilizers. The home-made stabilizers of the prototype were discarded in favour of a commercial type.

Measuring system

Installation of the improved measuring system was completed in June 1975. Improvements comprised the following:

1. removal of the old load cells (nominal accuracy 0,1 %) from the prototype and the equipping of all three lysimeters with commercially obtainable precision load cells (nominal accuracy 0,02 %);
2. intentional overloading of the load cells in the interests of improved sensitivity; three 10-ton instead of three 20-ton load cells per lysimeter were used to support an approximate load of 50 tons;
3. replacing the strip chart recording system with a high quality, commercially obtainable digital mass indicator with an electronic taring capability, together with a three-channel switching unit capable of either manual or remote operation; and
4. carefully making final fine adjustments to load cell positions to achieve a high degree of positional stability even when lysimeters were free-standing on load cells only;

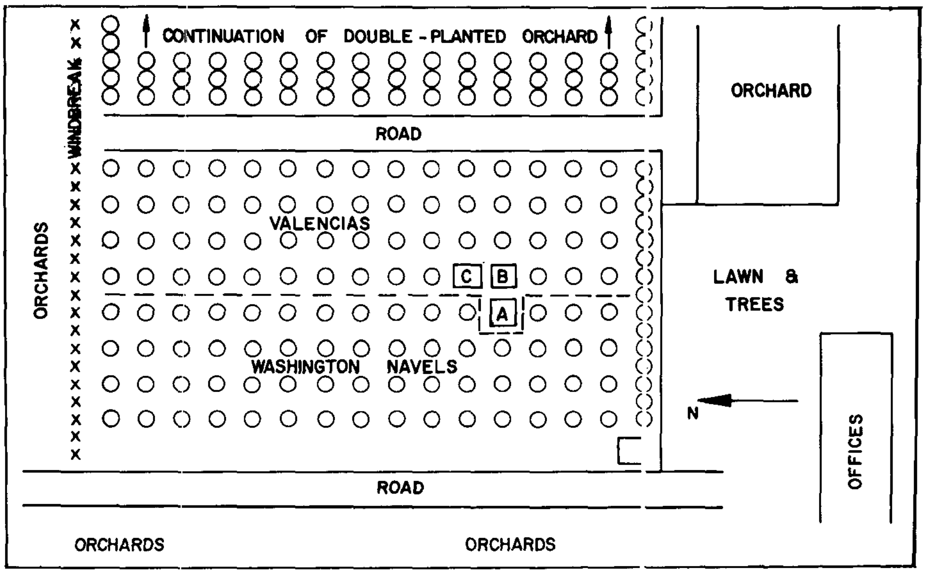

Figure 1
Positions of lysimeters A, B and C in relation to the rest of the orchard and immediate surroundings

slight departures from the stable equilibrium position due, e.g. to windiness, were then purely temporary. The horizontal stabilisers were in fact adjusted to allow a small measure of free movement in a horizontal plane. They were there mainly as a precautionary measure, to check whether systematic sliding of the tank was taking place and to prevent gross horizontal shifts which might result from, say, gale force winds.

Recording

Initially, displayed readings had to be recorded manually but more recently an automatic timing control and a digital printer was installed to provide a routine half-hourly printout of the mass of each lysimeter.

Drainage

With the multiple ceramic cup drainage system of the prototype virtually inoperative because of the gradual blockage of pores, the two new lysimeters were provided with a drainage system consisting of a coiled perforated pipe. Ends were connected to drainage outlets to which suction could be applied. Pipes were laid in a horizontal plane 1,7 m below the lysimeter soil surface and embedded in coarse sand to provide a measure of filtration. Suction was provided by modified aquarium pumps, capable of almost −20 kPa but adjusted to provide −10 kPa at the drainage outlet. This proved to be adequate for rapidly removing at least all the free water collecting at the bottom of the 1,8 m profile, and for closely simulating orchard soil water conditions in the top 1,2 m of soil where nearly all citrus roots are concentrated.

Results and Discussion

Construction

The observed tendency of the walls and floor of the tank to bulge and the I-beam supports to buckle when lysimeters were lifted under load, suggests that greater strength will be needed in future installations of this kind. Fortunately these faults have as yet in no way affected the sensitivity or accuracy of the system.

Calibration

Three separate calibration runs were undertaken:

1. in June 1975, when test masses (concrete blocks of known mass), applied in increments of approximately 47 kg over a range of 1 875 kg were used;

2. in September 1976, when standard assize test masses were applied in increments of 40 kg over a range of 2 000 kg; and

3. in August 1977, when cut lengths of steel rail of known mass (each approximately 14 kg) were used over a range of 1 200 kg.

Particularly encouraging was the 1976 calibration, the only one of the three which had test masses of undisputed accuracy. Results are shown in Fig. 2 as the error accumulated in response to successive 40 kg increments over a 2 000 kg loading and unloading cycle. Such a cycle took between 45 and 60 min

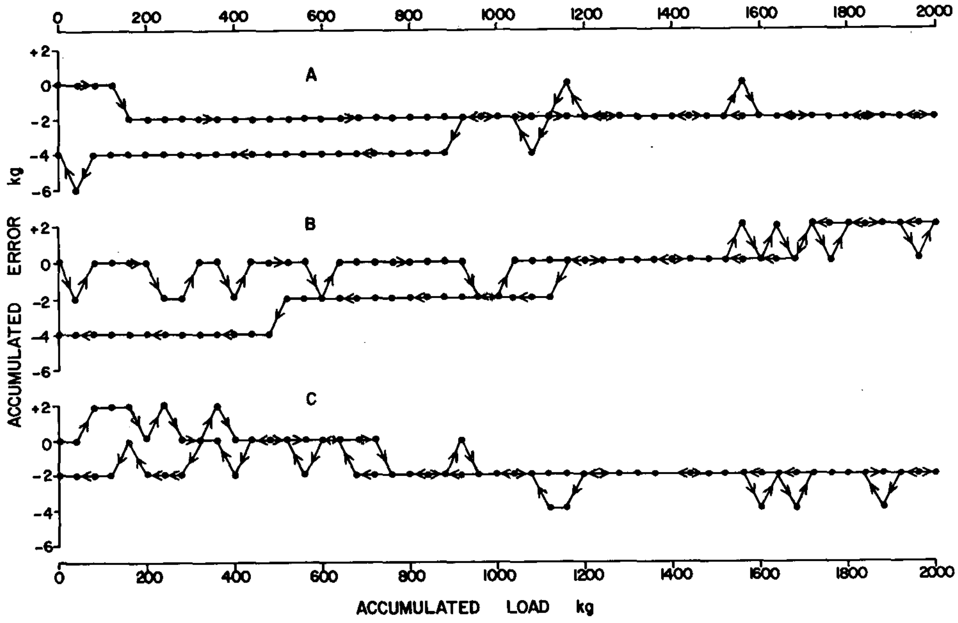

Figure 2
Responses of lysimeters A, B and C to cycles of loading and unloading as measured over a total range of 2 000 kg during a calibration run on 20 September 1976

to complete during which time the two "resting" lysimeters had lost from 2 to 4 kg of water through evapotranspiration. A large proportion of the small accumulated error was in effect due to this loss rather than inaccuracy in the measuring system. It can therefore safely be stated that at no time was the accumulated error in excess of 4 kg, or the error from one reading to the next in excess of 2 kg. Furthermore, there was no evidence of hysteresis.

During calibration heavily overcast sky conditions prevailed with windiness varying from calm for calibration of A to a fresh breeze for the calibration of B and C. Windiness had no effect on the measurement of mass other than increasing the time taken to obtain a stable reading. A stable reading was clearly indicated by a brightening of the digital display which occurred when successive signal integrations over short time intervals (± 2 s) were repeatedly in agreement. Even during windy conditions it was possible to increment mass 100 times and obtain as many stable readings within an hour.

Cumulative errors recorded during calibration runs of 1975 and 1977, despite reservations regarding the absolute accuracy of the calibration masses, never exceeded 9 kg over a total range between 1 and 2 tons, confirming that no significant sensitivity changes had taken place over a period of several years.

Zero drift unfortunately could not be readily assessed because of the gradually increasing mass of the system due to tree growth. It is, however, possible to report that no abnormal responses are on record which could be attributed to this factor.

Resolution and accuracy of measured mass changes far exceeded manufacturers specifications and guarantees for the load-cell and mass-indicator combination used. Two possible reasons for this are the following:

1. The intentional overloading, made safer by particularly gentle operating conditions (total absence of mechanical shock), effectively doubled the output signal from the load cells in terms of mV/kg. The larger output was more readily accomodated by the measuring system which does not have an unlimited resolution capability.

2. The use of a relatively small proportion of the load cell operating range tended to reduce the hysteresis and non-linearity errors quoted for full-scale operation while not affecting resolution, the load-cell being an infinite-resolution transducer.

Evapotranspiration (ET) measurement

Lysimeter performance with regard to evapotranspiration measurement is assessed in three ways:

1. by comparing monthly evapotranspiration totals from three similarly treated lysimeters;

2. by examining daily evapotranspiration responses over periods when lysimeters were irrigated simultaneously and at staggered intervals of a few days;

3. by examining typical diurnal curves of evapotranspiration.

Fig. 3 illustrates the results of evapotranspiration measurement over a 12-month period from July 1975 to June 1976. Values are presented in depth units relating to the surface area of the lysimeters For the most part, lysimeters were similarly irrigated, i.e. when soil water deficits of between 75 and 100 mm had been accumulated. Irrigation was not necessarily simultaneous; in fact, months with the most scatter in ET values (January and March) were the months with the largest variations in timing of irrigation.

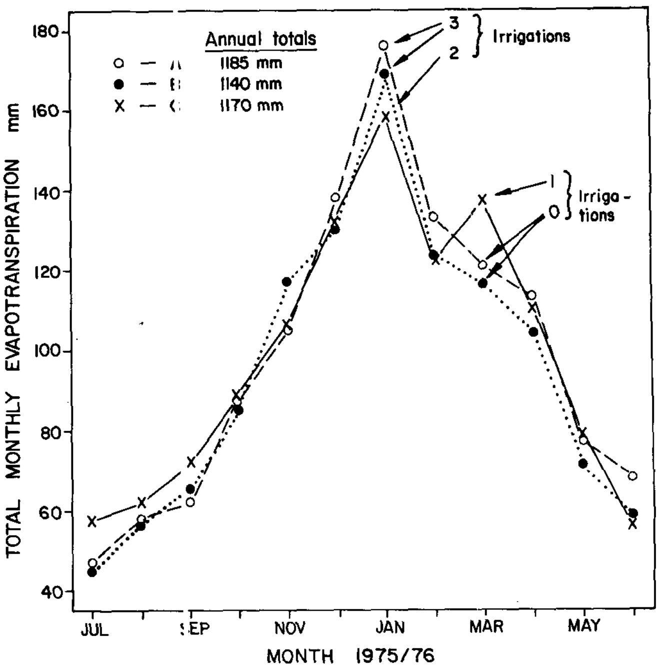

Figure 3

Variation of monthly evapotranspiration totals for lysimeters A, B and C during one growing season. Totals for January and March are shown in relation to the number of irrigations applied during these months

Over the year there was less than 4 % difference in total ET, with lysimeters A, C and B ranked in descending order of water use. Lysimeter C at that stage contained a tree discernably larger than those in lysimeters A and B, and would have been expected to record the highest evapotranspiration rates. However, being the oldest, lysimeter C also had the longest history of irrigation, in the absence of leaching, with moderately saline water. Suspected salinity stress was confirmed by soil analysis, and remedied by the application of leaching irrigations to all lysimeters in July 1976. This had the effect of changing the ranking (in order of decreasing water use) from A,C,B to C,A,B for the period September to November 1977. From being about equal to the mean evapotranspiration from A and B, evapotranspiration from C increased to an excess of some 13 % over the mean from A and B during the latter half of 1976. This excess was more consistent with the difference in tree size mentioned previously.

Fig. 4 reproduces two three-week extracts from the daily evapotranspiration record of each lysimeter. Fig. 4a represents a period over which the three lysimeters received identical treatment. Fig. 4b on the other hand illustrates the effect of staggering irrigations, i.e. irrigating lysimeter B two days after lysimeter C and lysimeter A four days after B.

When similarly treated, lysimeters yielded data which on only 4 days out of 21 showed a spread exceeding 1 mm. Where a greater spread did occur, lysimeter values were however consistently ranked. The way this consistent response pattern is disturbed following irrigations at different times is contrasted in

Fig. 4b. Immediately after irrigation, the most recently irrigated lysimeter registered ET losses which exceeded ET from drier lysimeters by from 1,5 to 5 mm/d, depending on atmospheric evaporative demand and on the extent of soil surface shading by the canopy and consequent suppression of surface evaporation.

Fig. 4 thus clearly illustrates that in their day-to-day operation, the lysimeters are sufficiently sensitive to

1. register small systematic differences in evapotranspiration from different citrus trees, and
2. suggest that the immediate boost to the ET rate following irrigation falls away fairly rapidly and can no longer be observed after 6 to 7 days.

The capacity of the lysimeters to reveal diurnal trends in evapotranspiration must be restricted to some extent by the 2 kg (2ℓ) resolution limit, even though from the calibration data in Fig. 2, one would seldom expect an error in excess of 2 kg to occur from one reading to the next. Figs. 5 and 6 illustrate two examples of diurnal evapotranspiration curves from trees sub-

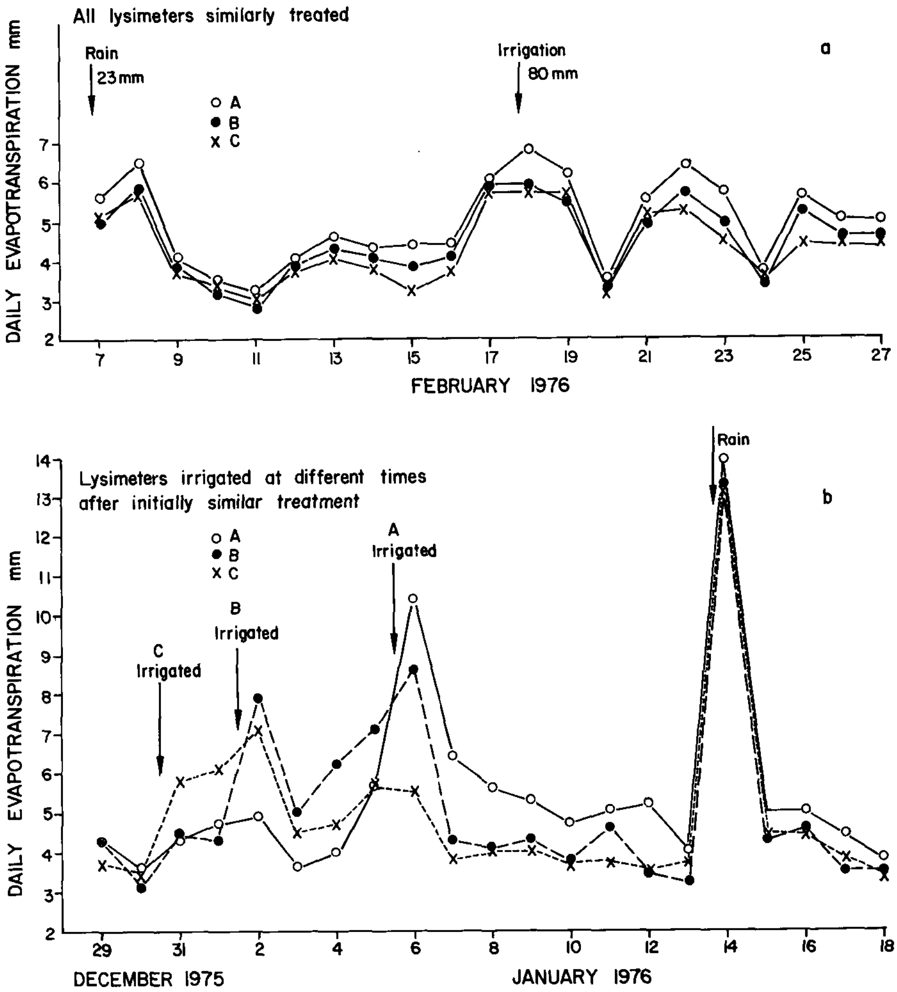

Figure 4
Comparison of daily evapotranspiration totals from three lysimeters over a period of three weeks: (a) irrigation applied simultaneously; and (b) irrigations staggered

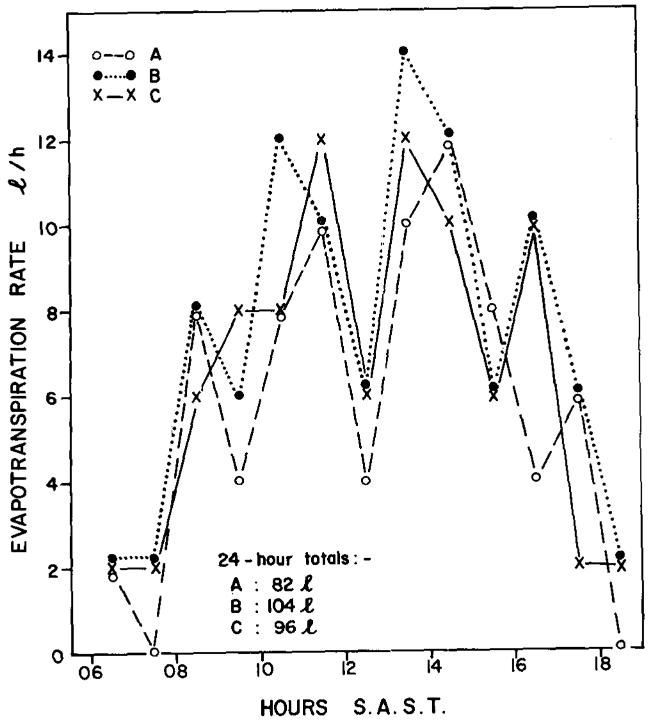

Figure 5
Diurnal march of evapotranspiration based on unsmoothed data from three lysimeters for a day (8 Mar. 1978) of high water consumption when soil water deficits below field capacity were as follows:
A, 123 mm; B, 14 mm; C, 41 mm

jected (since January 1977) to treatments producing widely ranging conditions of soil water deficit. Fig. 5 is an unsmoothed plot of hourly ET rates recorded manually, prior to the installation of a printer, on a late summer day with a relatively high evaporative demand (Class A-pan Eo = 8,0 mm). The plot reveals oscillations in the hourly ET rate which are considerably in excess of the resolution. Particularly striking in this example are the late morning (10h00 — 12h00) and early afternoon (13h00 — 15h00) peaks separated by a midday drop, a pattern more or less consistent for all lysimeters. In the absence of supporting data for this day, it may be speculated that the midday drop arose either from a general closure of stomates or a sharp decline in radiation around midday. While such agreement between lysimeters should not be taken as evidence that diurnal ET curves from differently-treated lysimeters are necessarily always alike, the likeness in this instance does promote confidence in the ability of the lysimeters to register correctly the diurnal evapotranspiration response. Even full allowance for possible resolution errors in each observation would not materially affect the observed trend.

Figure 6 demonstrates the results of measurements on an early summer day which despite a similar evaporative demand (Eo = 8,1 mm) as in the previous example, reveals a much lower and more variable ET rate, reflecting a lesser ability of the tree to conduct water at this time of the year (Green & Moreshet, 1979) as well as possible treatment effects. Treatment A in fact registered only 44 ℓ for the entire day which in absolute terms is not much greater than the 30 ℓ recorded on a typical cloudless day in winter. Inadequate resolution must severely restrict the obtaining of good diurnal curves when ET rates are this low, but this effect may be somewhat reduced by more frequent sampling and mild smoothing of data. In preparing Fig. 6, adjacent half-hourly ET values were summed to obtain consecutive overlapping half-hourly values of total ET for an hour. Finally, running means of 3 consecutive half-hourly values of ET (in ℓ/h) are plotted to generate the diurnal curve. Of the three lysimeters, B, the only one with a wet soil surface, yielded the curve with the sharpest peak, which may be a reflection of the larger soil evaporation component not subject to any physiological restrictions. The other two curves are in many ways similar to those in Fig. 5. These display the very common feature of a plateau being reached fairly early in the day after which there is a tendency for ET to oscillate about this plateau until mid-afternoon, when the radiant energy load drops decisively and ET declines accordingly.

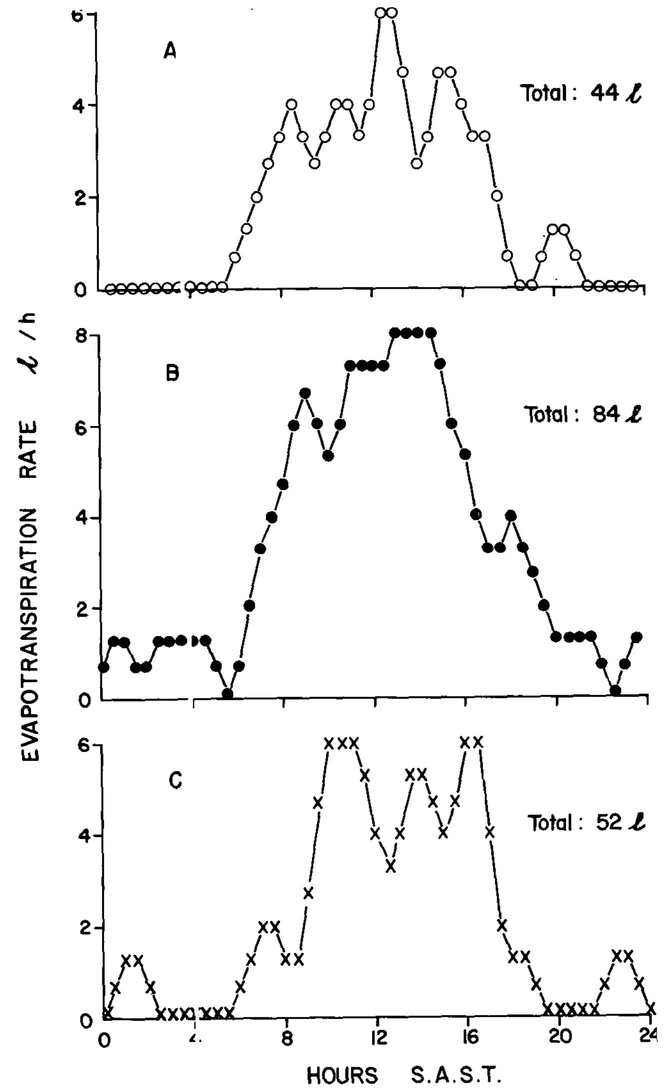

Figure 6
Diurnal march of evapotranspiration based on smoothed data from three lysimeters for a day (26 Nov. 1978) of low water consumption when soil water deficits below field capacity were:
A, 140 mm; B, 9 mm; C, 49 mm

Conclusions

Despite certain obvious deficiencies in tank construction, the lysimeters have surpassed expectations in regard to general performance. Three calibration runs at yearly intervals have demonstrated that the system is highly stable. Considering the large total mass of the system, the resolution of 2 kg, and accuracy of the same order, can be regarded as most satisfactory. On the strength of this performance, daily ET totals can be measured to within an accuracy of 10 % in winter and 3% in summer. The agreement between lysimeters and the similar appearance between lysimeter and surrounding orchard trees suggest that the former are highly representative of healthy trees of similar age under the same growing conditions. The measurement of diurnal transpiration trends would have benefitted decidedly by greater resolution, especially during periods of low transpiration rate. It is however questionable whether improved resolution would be obtained by further improvements to the measuring system, however costly these may be. Despite drawbacks, useful diurnal transpiration curves may be obtained through frequent sampling and mathematical smoothing when necessary.

By providing the only known direct measurements of short-term water use by mature citrus trees under field conditions, the lysimeters have opened up new possibilities for research into many facets of citrus water relations, all of which are now receiving attention to a greater or lesser extent. Firstly, it is possible to study the seasonal response of daily ET to weather conditions, soil water status and the ability of the tree itself to conduct water. This is essential to the development of more universally acceptable models for predicting orchard water requirements. Secondly, the lysimetric measurements of daily and even shorter term transpiration rates provide the necessary background for investigating the physiological basis for citrus tree conductance which appears to be so important in controlling the rate of water use. Finally, several possible alternative indirect methods of measuring the transpiration rates from citrus trees can only be properly standardised if independent measurements such as lysimetric values are available.

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