A Computer Simulation of Soil Water Distribution Using the Pulsed Drip Irrigation Method at Low and High Discharge Rates on a Sandy Soil

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Abstract

A previously verified computer simulation model was used with properties of a regic sand as input data. Continuous and pulsed drip irrigation at rates of 1,5 *l*, 3 *l* and 9 *l*/h were compared with respect to vertical and horizontal soil water distribution. Results indicate that 3 *l*/h pulsed drip irrigation can successfully replace 1,5 *l*/h continuously applied, allowing a larger emitter orifice and reduced blocking problems, but still maintaining sufficient water above 0,6 m soil depth. At 9 *l*/h the differences between pulsed and continuous treatments were small.

Introduction

Irrigation from point source systems are now used extensively. The principal advantages of these systems are numerous when well planned, installed, maintained, and correctly exploited. These advantages may be classed as follows:

Accuracy of water application

Water is applied directly to the root system, thereby excluding disadvantages such as system and evaporation losses, overlapping applications from sprinkler systems and sensitivity to wind. Perennial plants are frequently individually irrigated.

General economy

When point-source systems are adapted to local conditions they are virtually automatic, eliminating expensive labour costs. Secondly, the low operating pressures and low discharge rates frequently minimize pumping costs. Economy as far as volume of water is concerned is a known fact, and high production levels per unit water applied are obtained.

Efficiency of water utilization

Water is supplied to the plant at a high soil moisture potential, lowering energy inputs for physiological uptake processes. With the added advantage that water is supplied only as needed, the high yields obtained with trickle irrigation is self evident. The simultaneous application of water and fertilizer adds to the general efficiency of these systems.

Cultivation practices

Because the soil remains virtually dry at the surface, cultivation is seldom hampered and weed control becomes both easier and less expensive.

A similar list of possible disadvantages could also be compiled. These include high cost, necessity to filter the water, accompanying blocking problems and deep percolation losses below the root zone in light textured soils when high discharge rates are employed.

It has been shown (Bar-Yosef and Sheikholslami, 1976; Levin, *et al.*, 197[illegible]; Bresler, *et al.*, 1971) that a saturated zone with a varying radius develops beneath the trickle source, the extent of this zone depending mainly on trickle discharge rate

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*Present address: Oenological and Viticultural Research Institute, Stellenbosch, 7600, South Africa and soil characteristics. A gradual decrease of water content was also observed from the saturated zone up to the wetting front boundary.

In the present study the phenomenon of water loss below the root zone in a coarse-textured soil (and an implicit loss of nutrients) was studied as a function of discharge rate and application method. Because low discharge rates are necessary to prevent deep percolation losses in sandy soils (with the accompanying disadvantages of frequent stoppages), a pulsed application method was evaluated. According to previous investigations (Levin and Van Rooyen, 1977), this method theoretically eliminates both deep percolation losses and blocking problems associated with high and low discharge rates, respectively. It appeared important to study the effect of discharge rate and pulse irrigation on the soil moisture distribution at varying times after initiation of the irrigation, to properly evaluate the practical applicability of such methods. This paper therefore reports the results of such an intensive investigation which was done with the aid of a simulation model.

Materials and Methods

Soil characteristics

A regic sand typical of large areas of the Western Cape was considered in the study. The drip irrigation system is used extensively on this soil. The physical characteristics of the soil are given in Table 1. Other characteristics needed for the study included the relationship between soil water conductivity K (cm/min) and the volumetric water content θ (cm^3/cm^3), as well as the diffusivity D (cm^2/min) as a function of θ. These characteristics were determined as reported previously (Levin, Van Rooyen and Van Rooyen, 1977).

Solving the flow equation

As the present article involves only the application of a computer simulation model previously calibrated and verified (Levin, *et al.*, 1977), no laboratory experiments are involved. Owing to the excellent agreement between experimental and theoretical calculations at low discharge rates found in the above study, pulsed irrigation (switching the discharge from the emitters on and off at regular intervals) was applied at both intermediate and higher discharge rates in the present study. As pulsed applications of not more than 2*l*/h were modelled previously for this soil, pulsed application rates of 1½, 3 and 9*l*/h were compared with applications continuously applied at the same discharge rates. Calculations of soil water distribution were made employing a two-dimensional water transport model developed by Brandt, *et al.* (1971) and expanded to include salt transport by Bresler (1975). The latter model was modified by Levin, *et al.* (1977) to accommodate pulsed irrigation and to perform calculations of water distribution patterns in the vertical and horizontal plane. This version of the model was also used in the present study. Briefly, the calculations are made by solving the transient flow equation for the plane flow case:

$$\frac{\delta\theta}{\delta t} = \frac{\delta}{\delta x}\left[K(\theta)\frac{\delta P}{\delta x}\right] + \frac{\delta}{\delta z}\left[K(\theta)\frac{\delta H}{\delta z}\right] \ldots\ldots\ldots (1)$$

where x is the horizontal co-ordinate, z the vertical (considered positive downward), K(θ) the hydraulic conductivity of the soil as a function of θ, and H is the hydraulic head (sum of pressure head P, and gravitation head z). K and P must be single-valued continuous functions of θ, and the hydraulic gradient the only force causing water to flow. The time (min) from the start of irrigation is indicated by t. In the axisymmetric cylindrical flow model, however, a single trickle nozzle is considered (Brandt, *et al.*, 1971). The origin is at the centre of the trickle source, and assuming radial axis symmetry, equation 1 takes the form

$$\frac{\delta\theta}{\delta t} = \frac{\delta}{\delta r}\left[K(\theta)\frac{\delta P}{\delta r}\right] + \frac{K(\theta)}{r}\frac{\delta P}{\delta r} + \frac{\delta}{\delta z}\left[K(\theta)\frac{\delta H}{\delta z}\right] .. (2)$$

where r is the radial distance from the point source.

Equation 2 was solved numerically by an approach which combines the noniterative alternating-direction-implicit (ADI) difference method with Newton's method (Brandt *et al.*, 1971). All calculations were performed with a FORTRAN program executed on a Burroughs 7700 computer.

Treatments

Irrigation application rates of 1,5 *l*/h, 3 *l*/h and 9 *l*/h (pulsed and continuous) were simulated with this model. In all cases a total of 12 *l* of water were added to the soil, in the first instance continuously, i.e. all were applied in one irrigation at the prescribed discharge rate, and secondly as a pulsed irrigation where the water was applied at the same discharge rate at half hourly intervals for 30 min at a time, therefore needing double the time for a 12 *l* application. The longest irrigation period therefore amounted to a total of 16 h (1,5 *l*/h pulsed) and the shortest 1,33 h (9 *l*/h continuous). All applications were simulated up to a time of 24 h, including varying time intervals of redistribution after terminating water application. Test values for initial moisture content (θ_i) were taken as 0,03 cm^3/cm^3) and 0,08 cm^3/cm^3. These values represent the permanent wilting point and field capacity values respectively for the experimental soil.

Calculation and interpretation of soil moisture distribution

Instead of the usual calculation of soil moisture distribution in terms of mass or volume fractions, the amount or volume of water present in layers at different distances from the source were determined. The following assumptions were made:

TABLE 1
PHYSICAL CHARACTERISTICS OF THE EXPERIMENTAL SOIL

clay %	silt %	coarse sand %	medium sand %	fine sand %	PWP cm^3/cm^3	FWC cm^3/cm^3	Ksat. cm/min	bulk density g/cm^3
1,25	0,89	9,05	62,66	26,24	0,023	0,087	0,75	1,5

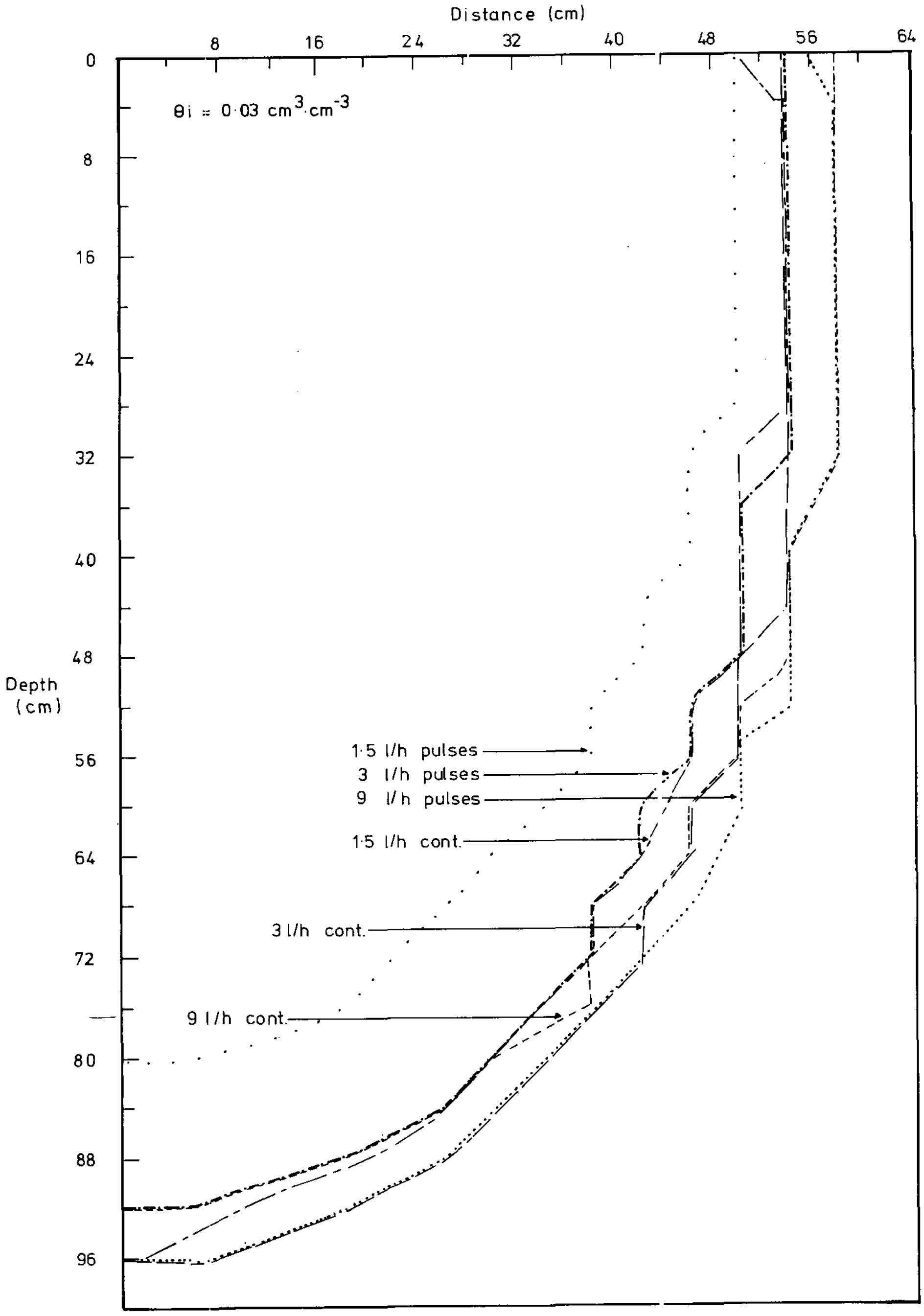

Figure 1
Wetting front boundaries after 12 h, $\theta_i = 0{,}03\ cm^3/cm^3$

1. The soil moisture at a point directly under the source has an equal chance to distribute in all directions. The wetted volume of the soil was, for the purpose of the investigation, divided into groups of concentric rings around the source, 10 mm deep and 40 mm in the horizontal direction.

2. To calculate the volume of water that had accumulated in each ring, the initial water content was subtracted from the water content found at time t, and the result multiplied by the volume of the ring (Levin, *et al.*, 1977).

3. A two-dimensional grid of water volumes with columns denoting distance and rows denoting depth, was then drawn up; the total sum of columns or rows had to approximate the total volume applied, 12 *l* in this case.

4. To enable graphical representation of water distribution in the wetted soil volume, the total volumes present in each column or row of the grid were expressed as percentage of the total sum.

Results and Discussion

The following treatment abbreviations are used:

9 *l*/h continuous/pulses = 9C/9P
6 *l*/h continuous/pulses = 6C/6P
3 *l*/h continuous/pulses = 3C/3P
1,5 *l*/h continuous/pulses = 1,5C/1,5P

Wetting front boundaries

The positions of the wetting fronts 12 h from the start of irrigation for all treatments, relative to the point source at position zero, can be seen for an initial water content (θ_i) of 0,03 cm^3/cm^3 in Fig. 1, and for θ_i = 0,08 cm^3/cm^3 in Fig. 2. In both cases it is evident that higher discharge rates resulted in a greater advance of the wetting front (WF) in both the vertical and horizontal directions. The wetted soil volume is much smaller in the case of θ_i = 0,03 cm^3/cm^3 than with the higher θ_i, and the differences between treatments were much greater in the latter case. With θ_i = 0,08 cm^3/cm^3 the higher discharge rates 9C, 9P and the 3C application differed from the lower discharge rates in that a greater advance of the WF in all directions was evident, whereas the 1,5P treatment separated from the low discharge rates at a depth of about 0,9 m. At deeper levels this treatment showed a strong decrease in vertical distribution, resulting in the smallest WF advance of all treatments. The 3P and 1,5C treatments showed identical distribution patterns. In the case of θ_i = 0,03 cm^3/cm^3 the differences were much smaller, except for the 1,5P treatment, which again resulted in a much smaller wetted soil volume than the rest of the treatments.

At the same θ_i the smaller soil volume obtained with the lower discharge rates would logically result in a higher average soil water content, as the same amount of water (12 *l*) was added in all cases.

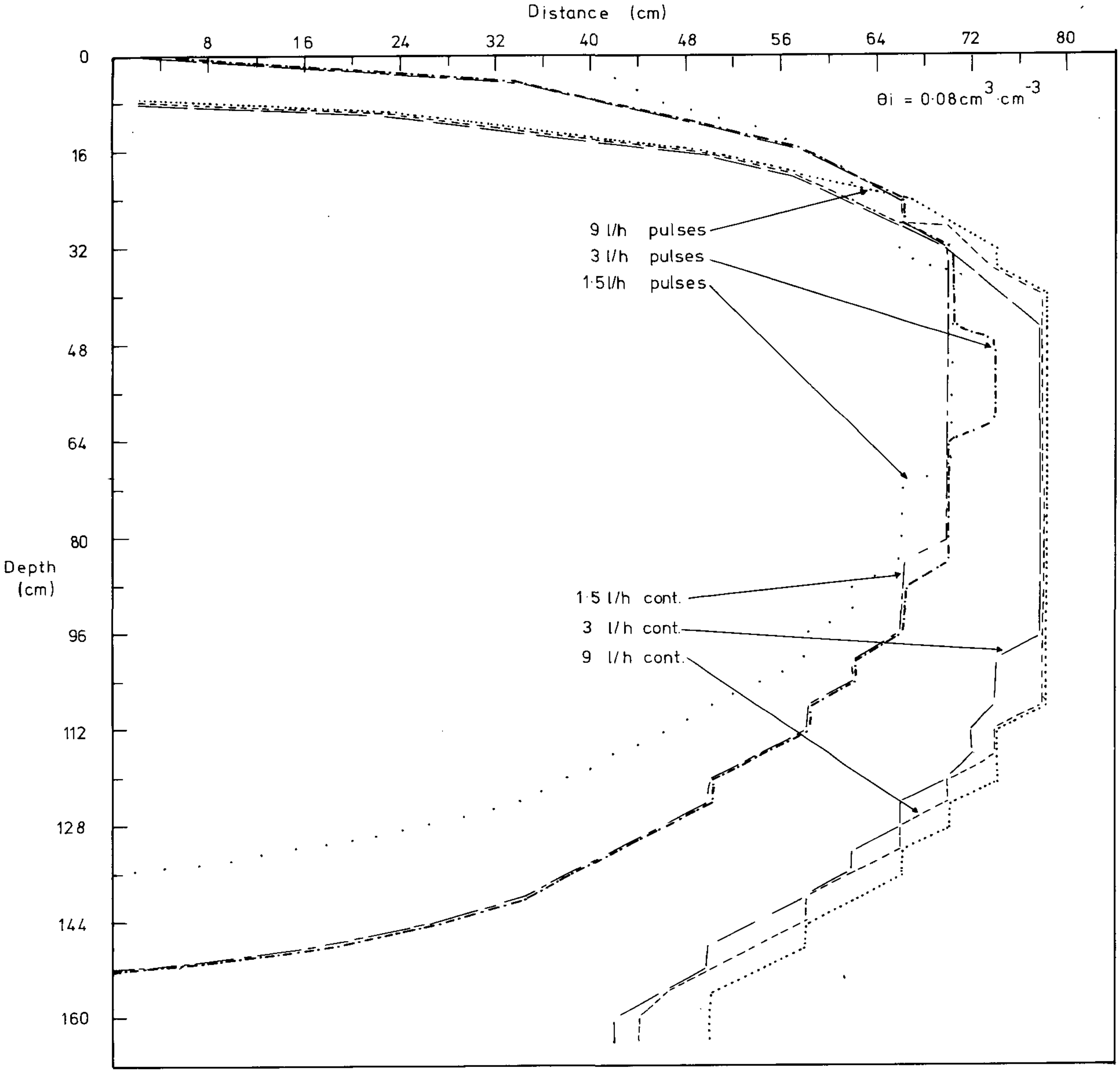

Figure 2
Wetting front boundaries after 12 h, θ_i *= 0,08 cm^3/cm^3*

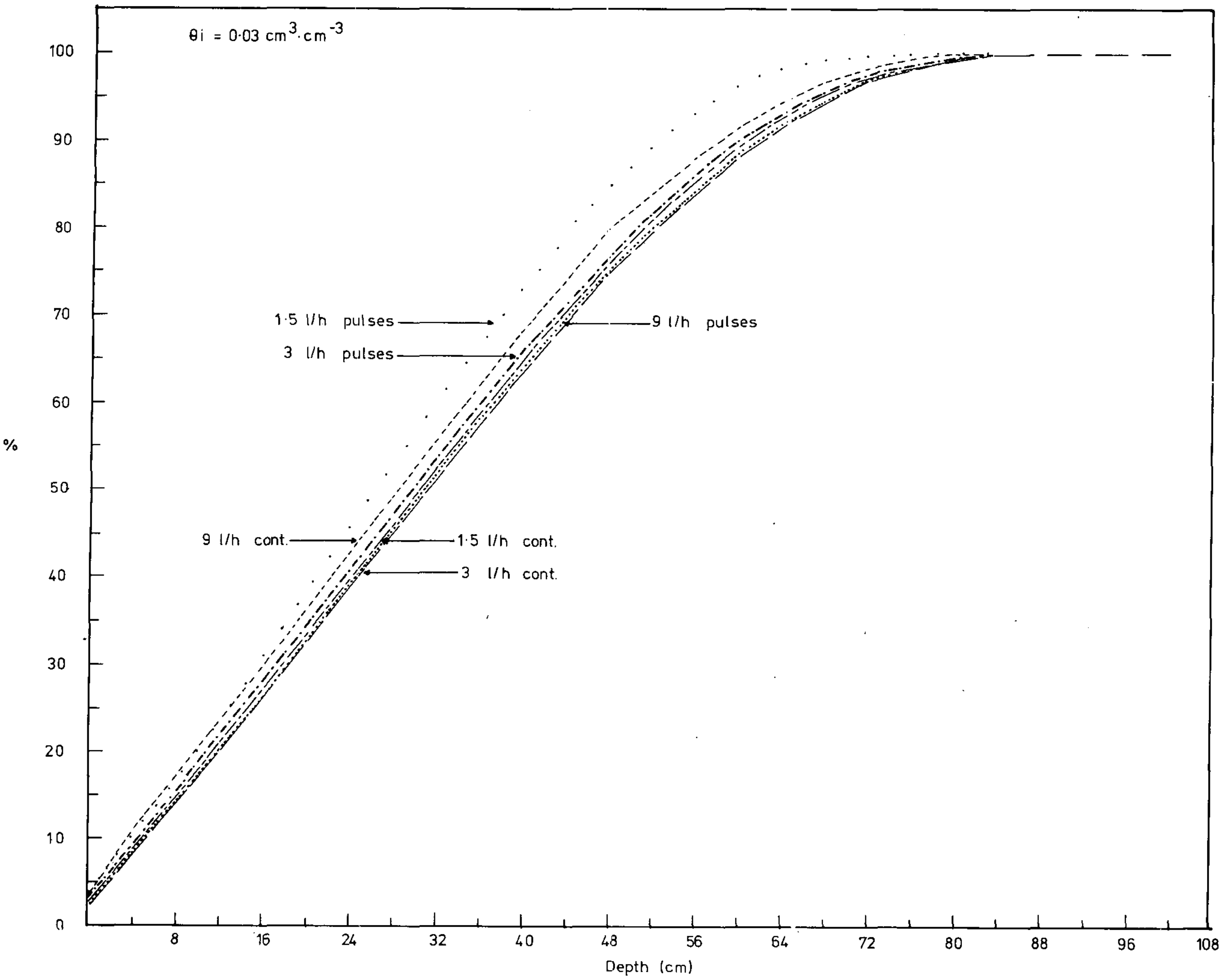

Figure 3
Cumulative percentages of water found in the wetted soil as a function of depth at $\theta_i = 0,03\ cm^3/cm^3$ for different treatment. after an application of 12 l

Although the WF concept is widely used as an indication of soil moisture distribution under a point source, the method has serious limitations in that no indication is given of the *quantitative* water accumulation at different depths and distances from the source. Such information is logically of great importance with respect to the quantitative extraction pattern of the plant roots. The results also show (Figs 3 to 6) that as far as availability to plant roots is concerned, water contents at an appreciable distance behind the WF were not significantly different from θ_i. This resulted in the use of the quantitative approach to soil water distribution adopted for this study, as discussed under materials and methods.

Soil moisture distribution in the vertical direction

The cumulative distribution of soil water 12 h after starting a 12 *l* irrigation, was plotted against depth for the two θ_i values (Figs 3 and 4). It is noticeable that the differences between treatments were much larger in the case of the higher θ_i as compared to the lower θ_i. At the latter initial boundary condition (θ_i = 0,03 cm^3/cm^3) there were no significant separation of curves, except in the case of the 1,5P treatment which had a generally higher water content at any depth than any of the other treatments. From Fig. 1 it can be deduced that 80% of all water added to the system is retained in the 0—1 m depth range for the treatments 1,5C and 3P as compared to the 0—1,16 m layer for the higher discharge rates (θ_i = 0,08 cm^3/cm^3). The corresponding depth range for the 1,5P treatment was 0—0,84m. An interesting observation is that at both θ_i conditions the 3P treatment contained more water than the 9P application at any depth. This situation is however reversed with the continuous applications for the respective treatments, the 3 *l*/h application rate containing slightly less water at any depth. At the lower θ_i much more water was retained in the 0—0,6 m layer (85%) than for θ_i = 0,08 cm^3/cm^3 (25—35%) for any of the treatments (Figs 3 and 4). This is of course predictable due to the lower initial water content resulting in a lower soil water conductivity, especially near the wetting front.

From Fig.4 the differences between the 1,5C and 3P treatments on the one hand and the 3C, 9C and 9P treatments

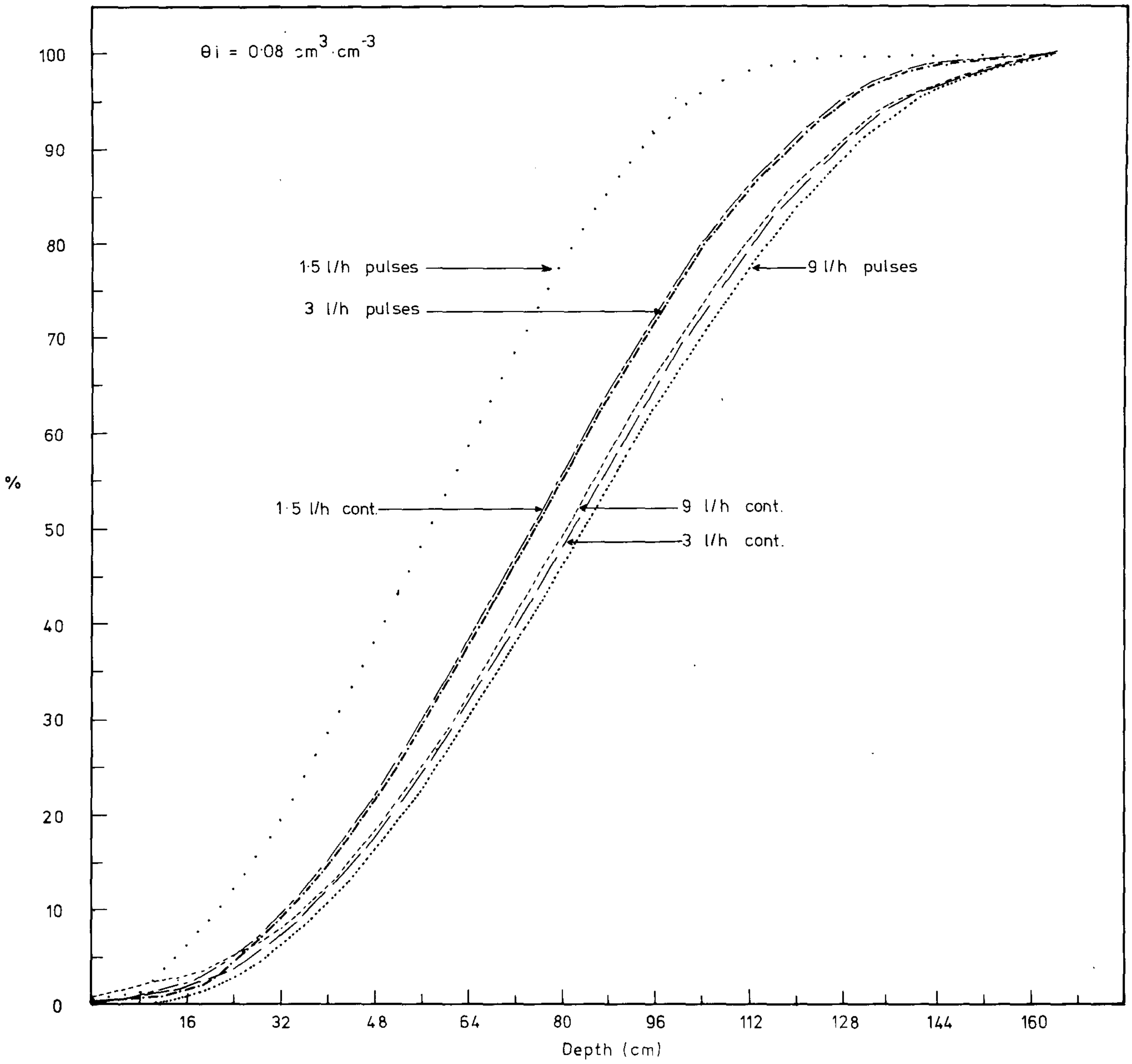

Figure 4
Cumulative percentage of water found in the wetted soil as a function of depth at θ_i *= 0,08 cm^3/cm^3 for different treatments after application of 12 l*

on the other hand can be clearly seen. The former contained appreciably more water at any depth deeper than 40 cm, than the higher discharge rates. To a depth of 0,6 m (root depth) the higher discharge rates retained an average of 27% of the applied water, while the 1,5C and 3P treatments contained 33%. The 1,5P treatment retained 56% of the total water. The corresponding figures for θ_i = 0,03 cm^3/cm^3 were generally much higher, but with small inter-treatment differences, i.e. 97% for 1,5P and an average of 93% for the rest.

Figures 7 and 8 show the cumulative percentage of the added water to a depth of 0,6 m depth plotted against time. Figure 8 again demonstrates the large differences between the 1,5C and 3P on the one hand, and the higher discharge rates on the other. As before, the 1,5P treatment was greatly different from the rest of the treatments. The high discharge rate treatments (9C and 9P)as well as the 3C application were grouped together and retained much less water above 0,6 m at any time than the 1,5C and 3P treatments, which in their turn fell far below that of the 1,5P treatment at any time up to 24 h. Figure 7 shows the same situation at the lower θ_i. The water distribution pattern stayed much the same as with the higher θ_i, but the differences between treatments were smaller. As in Figures 3 and 4

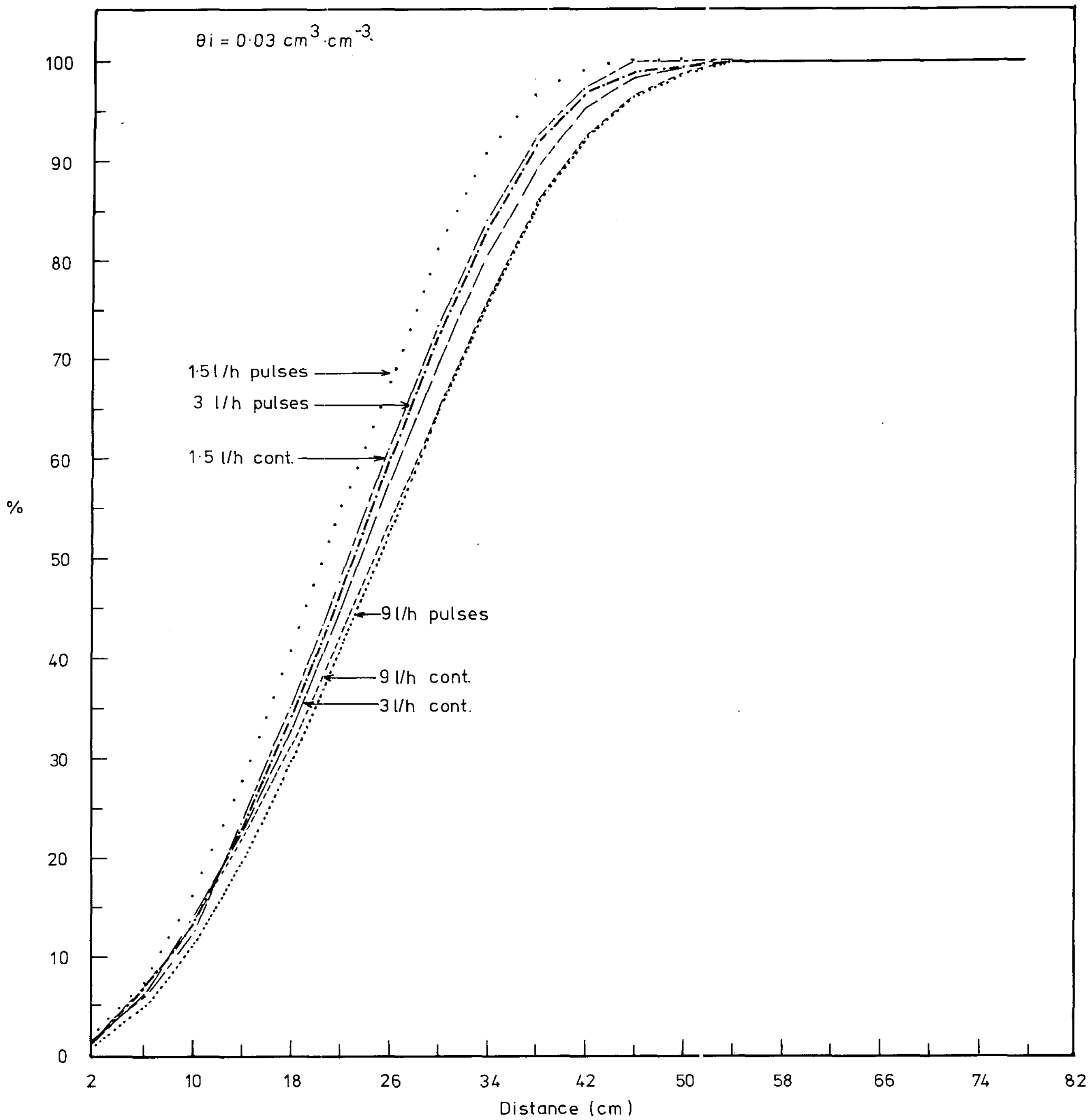

Figure 5
Cumulative percentage of water found in the wetted soil as a function of horizontal distance from the source plane, 12 h after start of irrigation for an application of 12 l (θ_i = 0,03 cm^3/cm^3)

it will be noted that at higher θ_i (0,08 cm^3/cm^3) less water was retained above 0,6 m, resulting from higher soil water conductivity at higher water contents. The conditions at θ_i = 0,08 cm^3/cm^3 are however more relevant, being the field capacity of the soil in question.

The differences illustrated in Fig. 8 indicate the possibility of avoiding water and nutrient losses below the root zone by making use of low discharge emitters, or more favourably, higher discharge emitters (to avoid blocking problems) combined with intermittent irrigation. The advantage of this approach is more pertinent under wet conditions, which is normally the case where drip irrigation is implemented and the soil water kept in the region of the field capacity (FC) value.

The partial inhibition of the downward movement of soil water with low discharge rates did not result in an accompanying increase in horizontal distribution. This suggests a higher

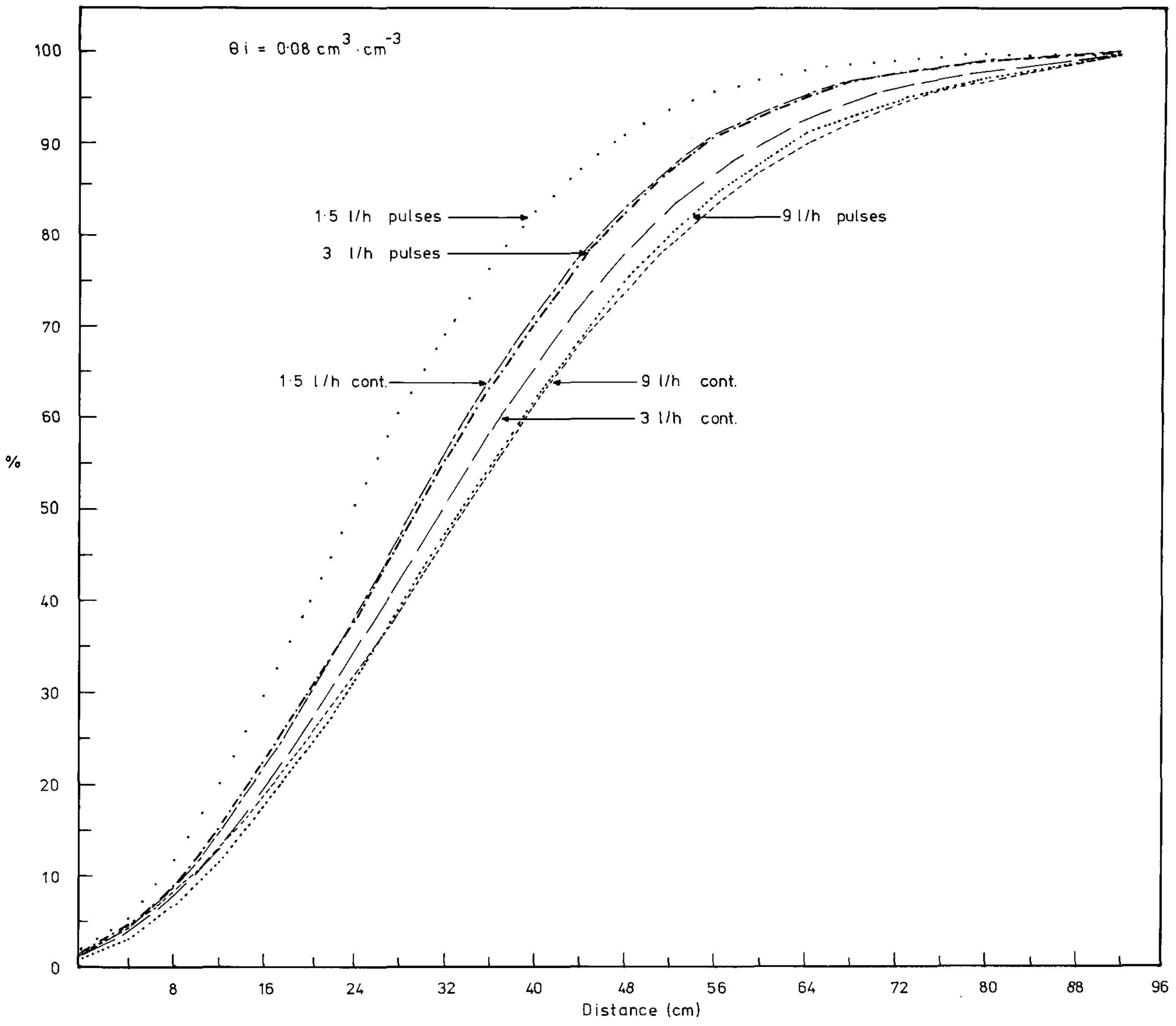

Figure 6
Cumulative percentage of water found in the wetted soil as a function of horizontal distance from the source plane, 12 h after start of irrigation for an application of 12 l (θ_i = 0,08 cm^3/cm^3)

water content in the wetted soil volume as compared to the higher discharge rates. This effect is however expected to decrease through redistribution after termination of irrigation. Figures 7 and 8 show that such a redistribution process did take place in all cases as manifested in the corresponding decrease in percentage water found above 0,6 m depth, the slope of these lines indicating the rate of re-distribution in each case. It is noteworthy that the rate of redistribution decreases with time (except 1,5 *l*/h pulsed) and, more important, that the lines tend to converge. However, even at 24 h after starting the irrigation, the 1,5C and 3P treatments still retained 7 – 8% more water above 0,6 m than the group of high discharge rate treatments, in the case of θ_i = 0,08 cm^3/cm^3.

Soil water distribution in the horizontal plane

In Figs 5 and 6 the cumulative percentages of the total water volume in the full soil depth were plotted against distance from the source on the abscissa, 12 h after starting irrigation. Similar to the vertical distribution pattern, the high discharge treatments advanced further from the source, and separated into similar groups as mentioned previously, i.e both the 1,5C and

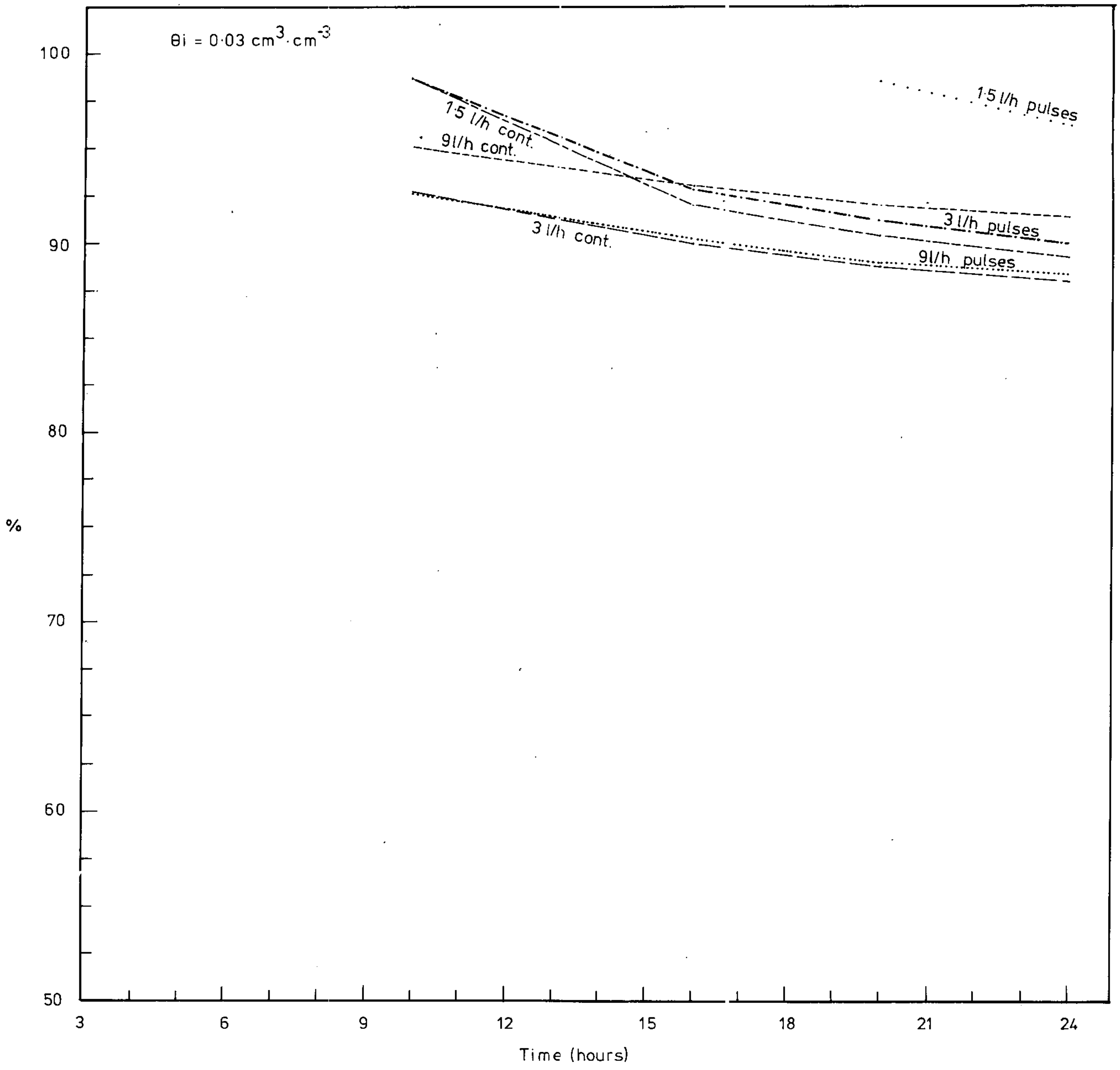

Figure 7
Percentages of total amount of applied water found in the 0—60 cm layer of the wetted soil, versus time from the start of irrigation for an application of 12 l (θ_i = 0,03 cm^3/cm^3)

3P treatments advanced to a lesser extent than the high discharge treatments. The 1,5P treatment resulted in the least horizontal spread. In general differences were appreciably smaller compared to vertical distribution and those between treatments much smaller for θ_i = 0,03 than for θ_i = 0,08 cm^3/cm^3.

In a previous study (Levin *et al.*, 1977) it was shown that wetting front advance does not give a clear picture of the quantitative distribution of the soil water, which is of extreme importance in practice, the soil water in the vicinity of the wetting front being relatively unavailable for uptake by plant roots. The distance from the source at which 80% of the water had accumulated was considered a more suitable criterion of the lateral distribution patterns of the different treatments. Thus the distance between the 80% level and the point source versus time since the initiation of irrigation was plotted (Figures 9 and

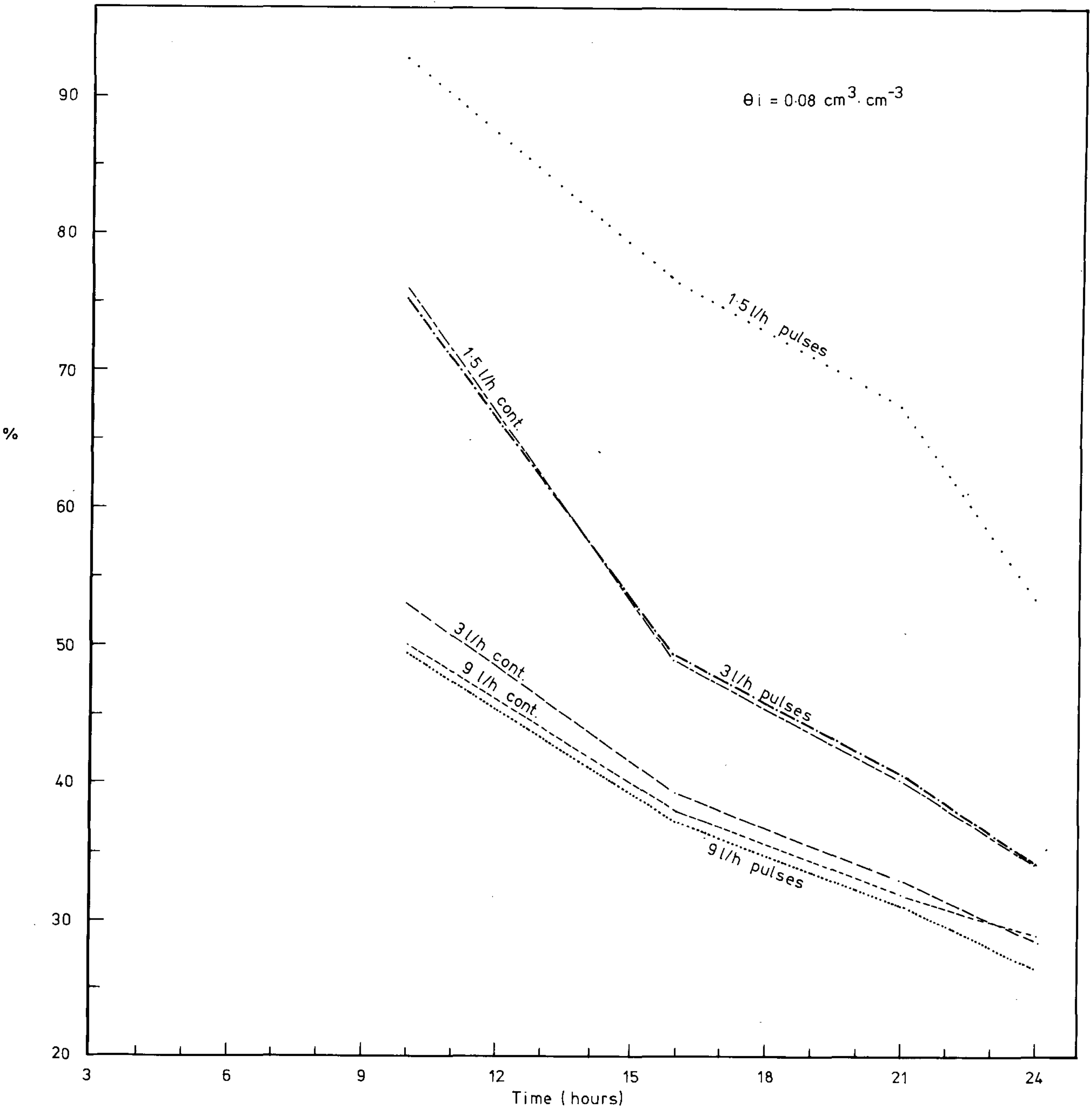

Figure 8
Percentage of total amount of applied water found in the 0—0,6 m layer of the wetted soil, versus time from the start of irrigation for an application of 12 l(θ_i = 0,08 cm^3/cm^3)

10). It will be observed that the distance at any specific time is greater in the case of θ_i = 0,08 cm^3/cm^3 than for the lower θ_i, as would logically be expected. The "80% front" distances at θ_i = 0,08 cm^3/cm^3 and t = 12 h were 0,33 m for the 1,5C and 3P treatments, 0,37 m for the 3C, and ca 0,43 m for the 9C and 9P treatments. The corresponding distances for θ_i = 0,03 cm^3/cm^3 were 27,31 and 0,34 m respectively.

It is generally accepted that lateral soil water distribution under point-source irrigation practices can be augmented by increasing the discharge rate of the emitter (Bresler *et al.*, 1971). As pointed out previously (Levin, *et al.*, 1977), the extent of redistribution after termination of irrigation was not taken into account in the above case. Figures 9 and 10, however, show that a convergence of these lines can be expected, and somewhat

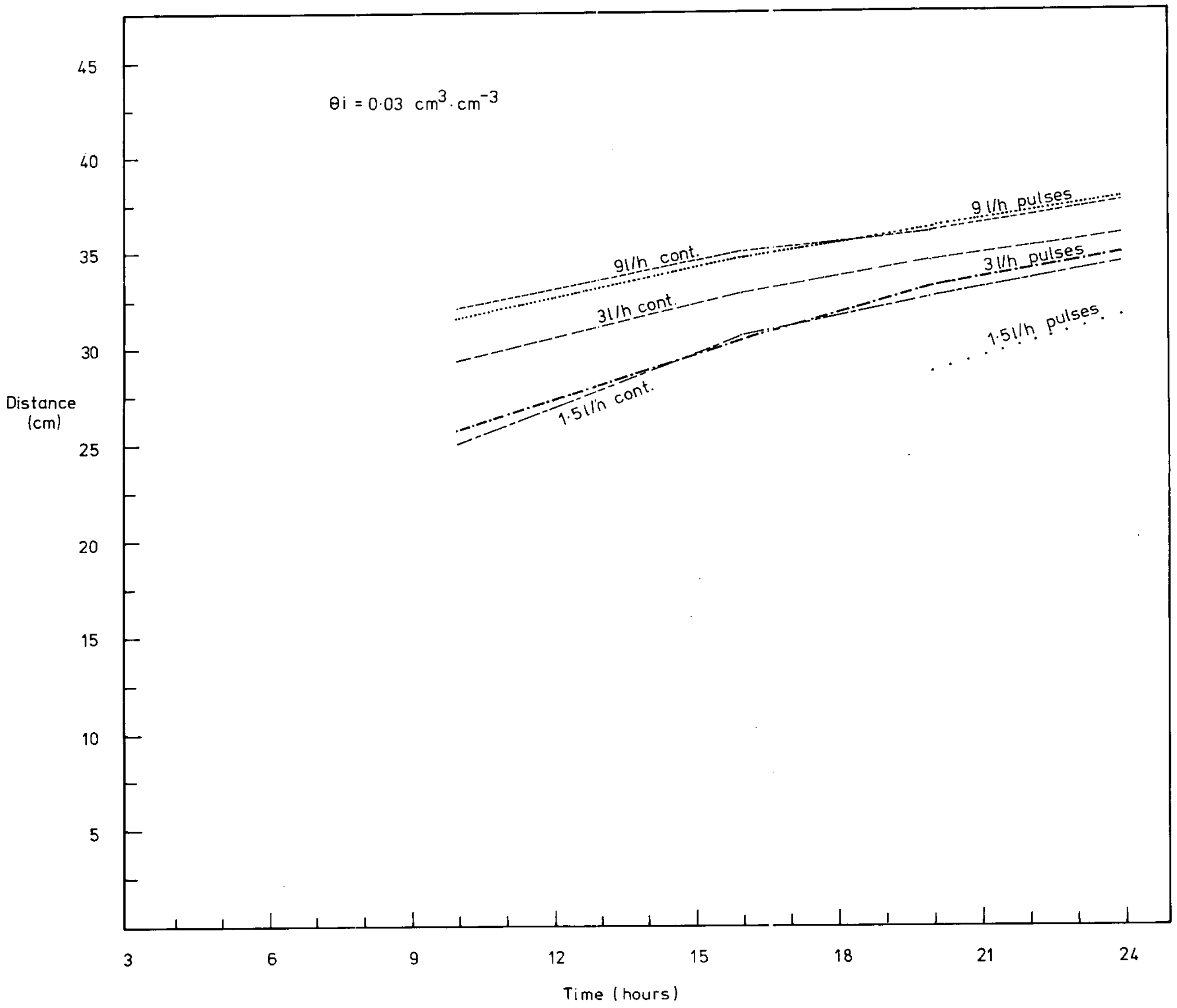

Figure 9
Horizontal progression of 80% of the water found as a function of time from the start of an irrigation of 12 l (θ_i = 0,03 cm^3/cm^3)

faster at lower θ_i values. The slopes of these lines (rate of redistribution) indicate that significant redistribution continues even 24 h after ceasing water application. In the case of θ_i = 0,08 cm^3/cm^3 a more rapid redistribution is indicated by steeper slopes in this case.

Conclusions

The simulation model studies clearly point out that the differences between pulsed and continuously applied trickle irrigation decreases with increasing discharge rate. It was furthermore shown that for the soil in question, a 3 *l*/h pulsed irrigation gave the same results as 1,5 *l*/h continuously applied in terms of deep percolation losses below the 0,6 m depth. At a 9 *l*/h discharge rate, the difference between pulsed and continuous application was insignificant for the experimental soil. With all treatments, differences were smaller at the lower initial moisture content.

At a peak water consumption (experimentally determined for vines and fruit trees in the Western Cape) of 20 to 40 *l* per plant, the 3 *l*/h pulsed irrigation method can cope with the evapotranspiration rate and retain as much water in the 0—0,6 m depth as the method whereby 1,5 *l*/h is continuously applied. This permits a trickler with a larger aperture with accompanying advantages. At 1 *l*/h continuous and higher discharge rates as much as 70% of the applied water could be lost through deep

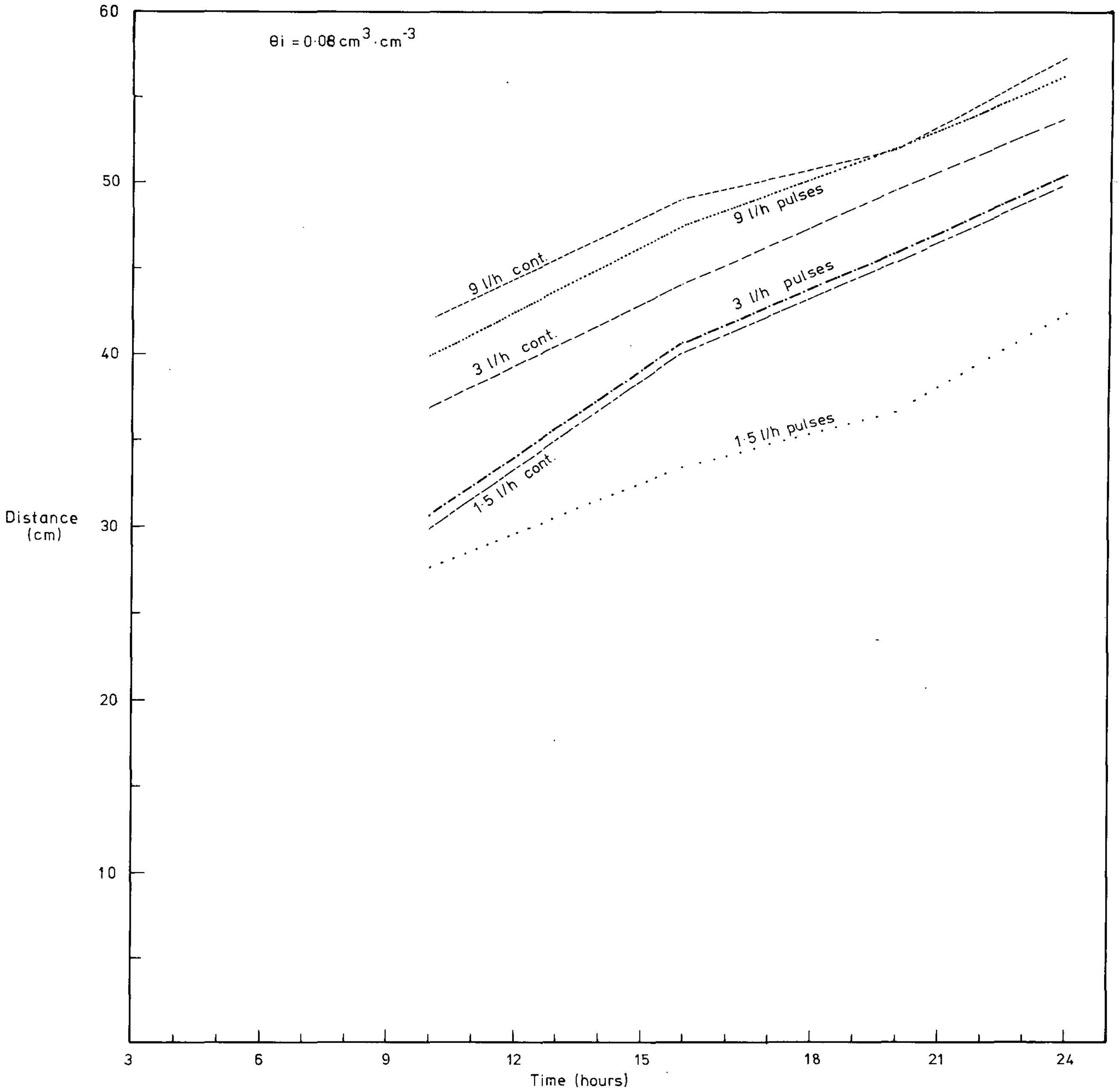

Figure 10
Depth above which 80% of applied water is found as a function of time from the start of an irrigation of 12 l (θ_i = 0,08 cm^3/cm^3)

percolation in 24 h under zero consumptive use. Increasing the discharge rate did not promote lateral spread of water to the same extent as vertical flow to deeper levels.

The results show that the 3 *l*/h pulse treatment would be the most suitable method of irrigation in this case. It must be stressed, however, that although similar differences between treatments might be found for other textural soil types, it is conceivable that the optimum treatment might have a quite different absolute value than in the present case, due to different conductivity and diffusivity relationships. The advantages of a pulse treatment would probably still hold good, however. It is proposed that each soil type (or textural class) would have a different optimum pulsed discharge rate, which would result in the most advantageous 3-dimensional soil water distribution pattern.

Although the model produced excellent results, predicting accurately field as well as laboratory conditions, the extension of its capabilities to include simultaneous water extraction by plant roots would be a great advantage, and add greatly to its value. Optimum discharge rates and method of application for different irrigated soil types could then be determined with increased accuracy, leading to realistic input data for system design and accompanying optimum use of irrigation water.

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