Irrig Sci (1990) 11: 189–195

Irrigation Science

Design and evaluation of an irrigation system for creating water gradients under an automatic rain shelter

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Received May 31, 1989

Summary. This paper reports on the design and performance of an irrigation system associated with a rain shelter. The shelter is used in the closed position as a platform for multiple spray lines. This system automatically supplies, at a specified time, water of specified depth and delivery rate, either uniformly or on a specified gradient across the sheltered area. Variations in crop water deficits and yields have conformed closely to imposed water gradients.

Modern rainshelters for crop research are structurally sophisticated, enabling a shelter to be light, strong, easily moved, have high clearance, and cover remarkably large areas. This is matched by the electronic sensing, logging, and control technology used in automation of the shelter movement and environmental monitoring (Foale et al. 1986; Upchurch et al. 1983).

In studies of water stress it is usually valuable to have multiple treatment levels. However, the greater the number of plots, the greater the loss of expensive experimental land as border areas. This loss is due mainly to the combination of the lack of (a) practical means of preventing interference above ground among plants in neighbouring treatments and (b) practical means of creating sharp boundaries between irrigation treatments with sprinkler systems.

Gradients of water, such as are supplied by a line source spray system (Hanks et al. 1976), offer an attractive means of avoiding both these problems. However, one of the requirements for uniformity of water distribution longitudinally is that the spray line extends beyond the experimental area the distance of a wetted spray radius minus 1 spray interval (Hanks et al. 1976). For rain shelter installations such as that in Fig. 1, with a line source running along one side of the study area, the shelters in their "off" positions would intercept water from sprays in the terminal sections of the line and reduce application to the ends of the study area.

This paper reports on the design and performance of an irrigation system that produces any specified water gradient within the confines of a rain shelter by time-programmed switching of overhead spray lines mounted in the shelter.

Description of rain shelter

The shelter consists of two sheds which are drawn together to cover a single experimental area. Shed construction and drive system are much as described by Foale et al. (1979). A clearance of 2.7 m was achieved by mounting rails at 1 m and extending wheel struts to 1.7 m, and end walls were added. The layout of the facility is shown in Fig. 1. There are two alternative study areas, each 13 × 18 m, which share one shelter "off" position (shown with shelter on study area 1).

Design of the irrigation system

The system was designed to meet the following criteria:

1. Convenient and accurate control of both depth of water applied and gradient across the area,
2. Ability to adjust rate of application to not exceed the soil infiltration rate,
3. Automatic operation, allowing unattended irrigation at night when wind is minimal, with the ability to suspend irrigation on power failure and to resume when power is restored.
4. Small uncontrolled variation in water application, and
5. Low cost.

The type of system which seemed to offer most promise in providing these features is one in which operation of closely-spaced parallel overhead irrigation lines is controlled by solenoid valves. These and the pump are controlled by software on a small computer via a logic controller. Information for a particular irrigation is entered from the keyboard in response to prompts.

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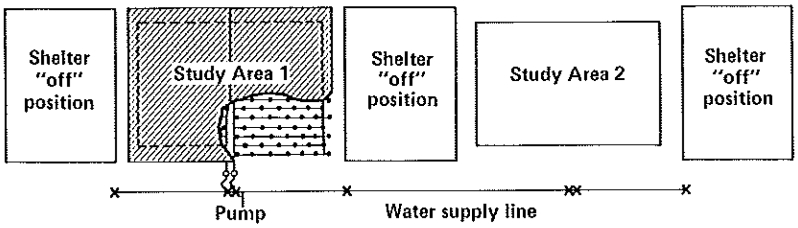

Fig. 1. Layout of rainshelter facility with shelter covering one of two study areas. The cutaway shows the headline and lateral irrigation spray lines of the irrigation system suspended from the shelters. Taps on the water supply line are indicated by (x), with hose connections to the shelters as located

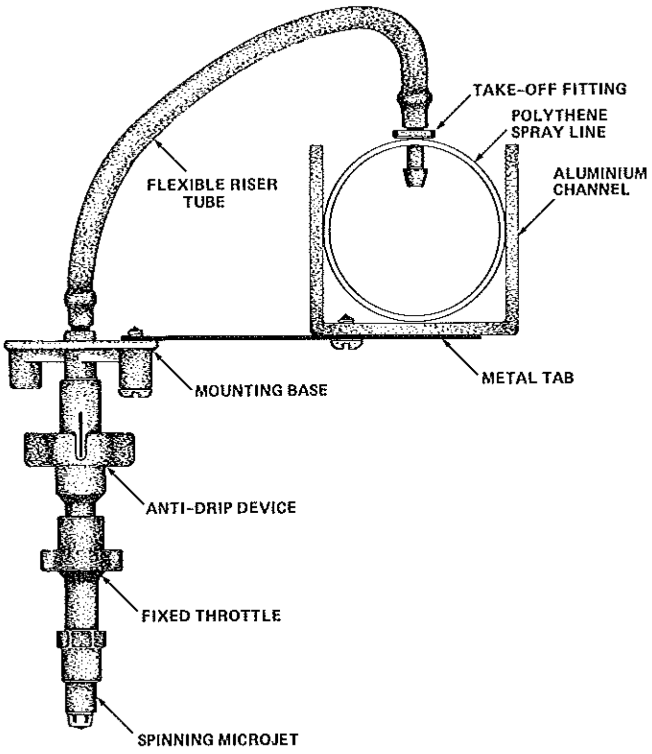

Fig. 2. The spray assembly. (The channel is mounted to the bottom of, and normal to, trusses in the shelter)

The following sections describe the design and testing of such a system.

Spray assemblies

Uniform water application from radial spray units can be achieved only with a high degree of overlap. In the rain shelter, obstructions within a short distance beyond the borders of the experimental area prevent sprinklers being placed much beyond these borders. These two constraints make necessary a system of closely-spaced, small, spray units. An evaluation was made of a range of Micro-jet[1] units, which have a nominal coverage of about 2 m radius. A rotating type (Series 'X') provided more uniform application than the stationary type. Although the nominal discharge of 150–250 L per hour would result in an application rate exceeding the maximum infiltration rate, this is prevented by adjusting the durations for which lines are switched on and off. The spray assembly is shown in Fig. 2. The rotating jet is mounted at the end of an assembly consisting of a mounting base, an anti-drip device[2], and an anti-misting device[2]. Mounting on easily bendable metal tabs (Fig. 2) facilitates level adjustment.

Optimizing spray unit positioning

The starting point for designing the layout of spray units was firstly that units would be on a "diamond" pattern, and that they would be 150 cm or 75 cm apart in the lines. To achieve the latter with a 150 cm in-line spacing would require only that application of water be split over time and the mobile shelter be moved 75 cm for the second application. The main design task was to determine the optimum line spacing for spray units at 150 cm and 75 cm. The approach taken was to document water distribution patterns of a prototype module of the eventual system at various heights in windless conditions. A module consisting of more than one spray unit is needed so that performance reflects interaction between droplets from adjacent spray jets on the line. It was not necessary to consider interaction between spray units in adjacent lines since adjacent lines would never operate simultaneously.

An appropriate measurement area in a module of 5 sprays in one line is shown in Fig. 3. Collection cups were positioned on a 25 cm × 30 cm grid. The overlap patterns indicate that two spray units are needed on each side of the centre unit. Figure 4 compares variation along transects perpendicular to the spray line at 25 cm intervals along the line. Benefits of 75 cm over 150 cm spacing in reducing variation were substantial.

Numerical simulation of water distribution as a function of line spacing

Figure 5 shows two adjacent spray lines, each with a grid of water distribution data in the space between them. They are part of an array covering the irrigated area. At the spacing shown, water from other lines in the array will not reach the area between the lines shown, but as the spacing is reduced the overlapping of grids from adjacent lines into this region will occur. If we take the case of uniform water application (i.e. no gradient), it is sufficient to examine the distribution between two lines only, since the pattern repeats.

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[1] Southern Cross

[2] Distributed by Dan Sprinklers, Australia

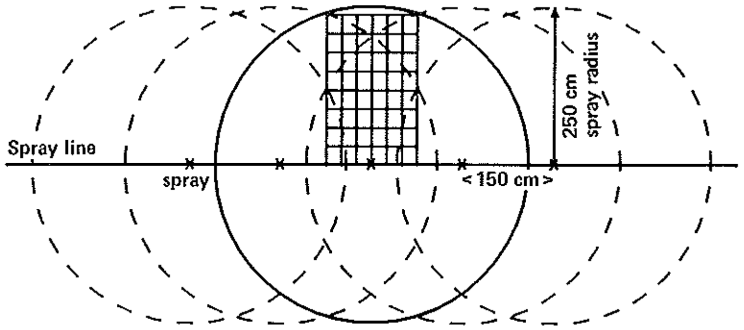

Fig. 3. The sampling grid (25 cm × 30 cm) for characterizing water distribution from a line with sprays at a spacing of 150 cm

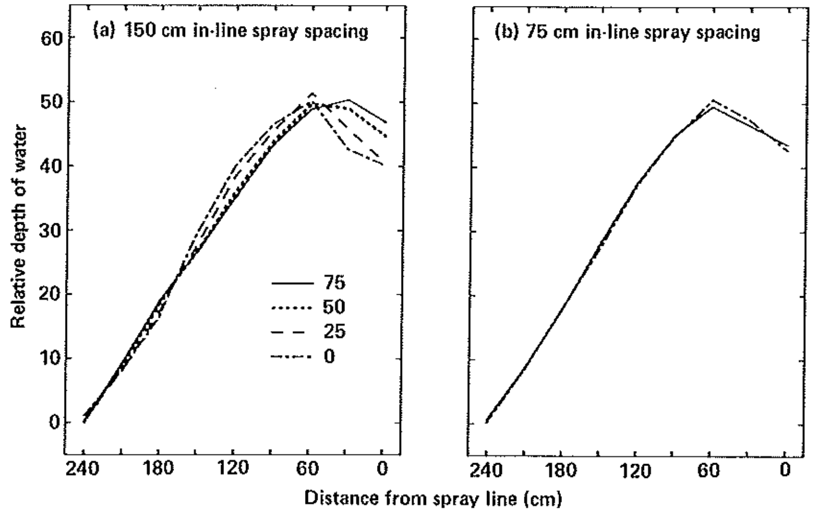

Fig. 4a, b. Patterns of water distribution along transects perpendicular to the spray line at 25 cm intervals. **a** As measured according to Fig. 5. **b** Simulated 75 cm spacing using data from **a**

The process of summing the contributions of the several lines can be simplified by considering only the transects at 0 and 75 cm in Fig. 5. Here the variability will be greatest. Also, when the within-line spacing of spray units is 150 cm the transect through the spray unit (0 cm) on one line is the 75 cm transect for the adjacent line (Fig. 5). Summation was done at 25 cm intervals along each transect, for line spacings from 40 cm to 210 cm, and the results are summarised in Fig. 6. (The 75 cm within-line spacing, achieved in practice by splitting water applications and applying half with the shelters displaced 75 cm, was simulated by averaging the central transect and the 75 cm transects.)

At line spacings closer than 80 cm there was little deviation from mean irrigation amount at either 150 or 75 cm in-line spacings. In the range 80–120 cm, errors in the 75 cm spray spacing (Fig. 6b) were much lower than at 150 cm. As line spacing increases, the upwards trend in variation is evident, but superimposed on this is a cyclic pattern, more pronounced at the 75 cm in-line spacing, due to interaction between the patterns of individual units. By selecting a line spacing at one of the minima in this cyclic pattern, it is possible to get good uniformity with a moderate number of lines. The 100 cm spacing between lines gives an excellent result with 75 cm in-line spacing, and this configuration was selected.

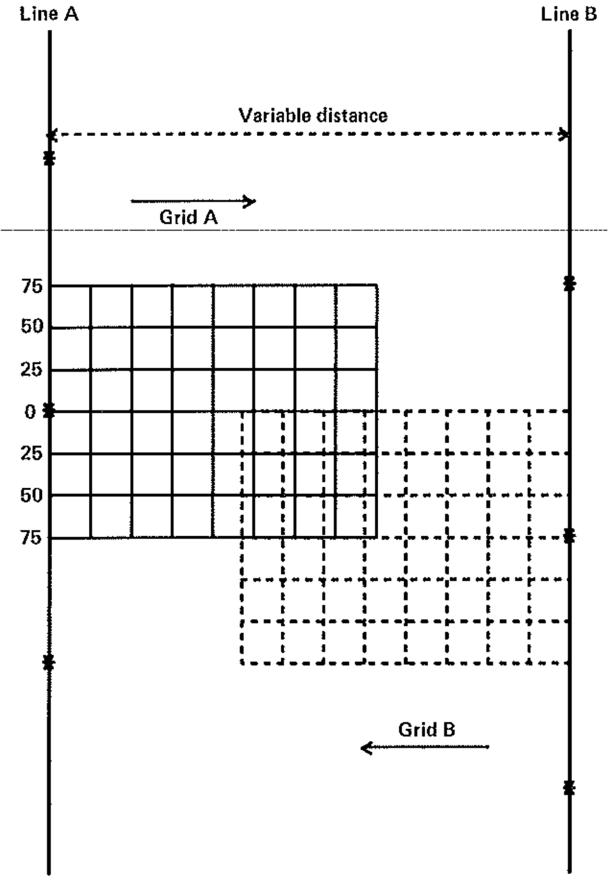

Fig. 5. Example of a sample grid overlay with sprays on a "diamond" pattern and at 150 cm spacings along two lines

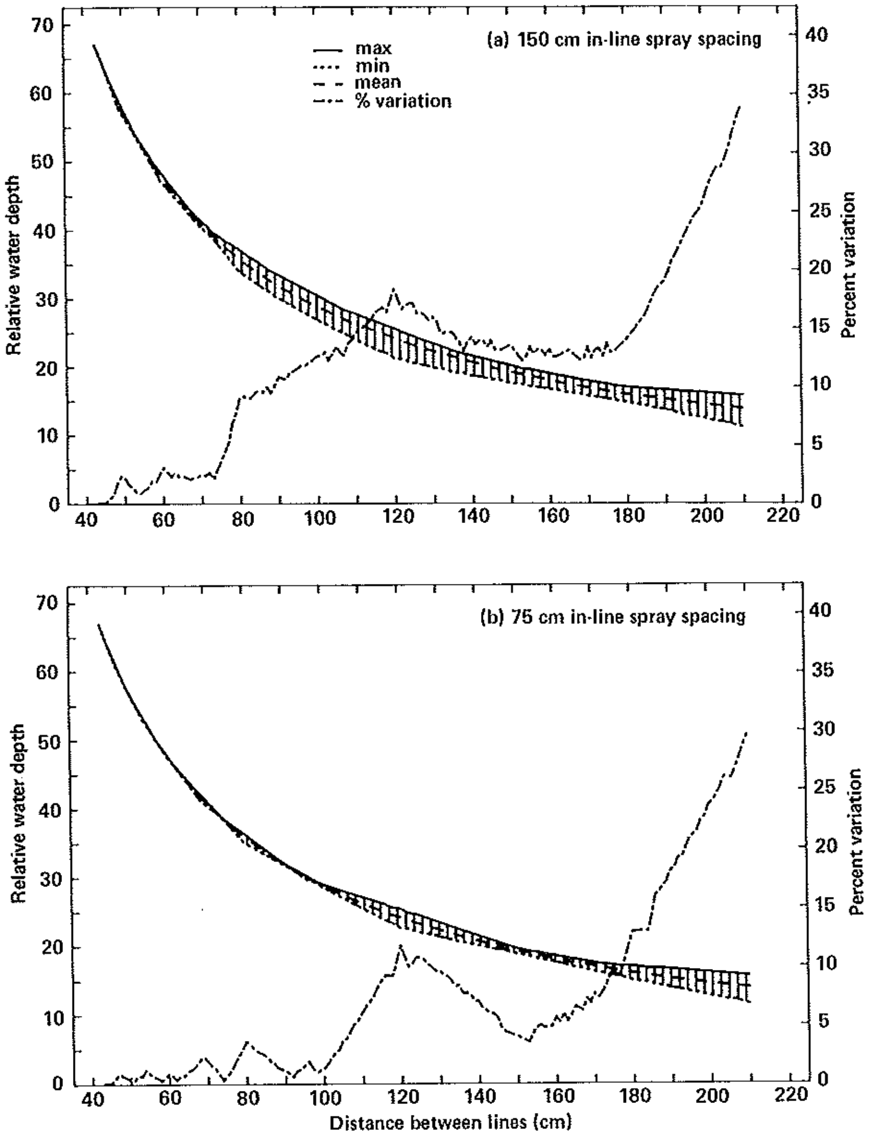

Fig. 6a, b. Simulated quantity and variation of water as distance between spray lines increases. a In-line spray spacing 150 cm and b 75 cm

Figure 7 shows a simulated water application with a 100 cm line spacing for a gradient from 30 mm to 0. Halving the 150 cm spray spacing greatly improved simulated uniformity of water distribution (Fig. 7b).

Electronic control of water application

The interface hardware was designed for use with personal computers with an RS232c serial communications port and a programming language that allows input of a single ASCII character via the RS232c port without the need of an end of line character. Any BASIC language having the INPUT$ (n, n) statement is suitable for communicating with the interface electronics.

A modular approach was chosen in designing the electronics. The circuit functions were separated into two units: CODING/DECODING and POWER CONTROL. The former contains the RS232c serial communications, address decoding, memory, digital input encoding and 20 mA current loop circuits. Solenoid power switching and its associated power supply are contained in the POWER CONTROL module. Control signals to this unit are via the 20 mA current loop.

Performance of the irrigation system

Aims

The testing of the irrigation system in the rainshelter was aimed mainly at quantifying the uniformity at which water could be applied to the experimental area (a) at a single depth for the entire area or (b) on a specified gradient. A secondary objective was to compare the spatial distribution with the expected values from the simulations conducted in designing the system.

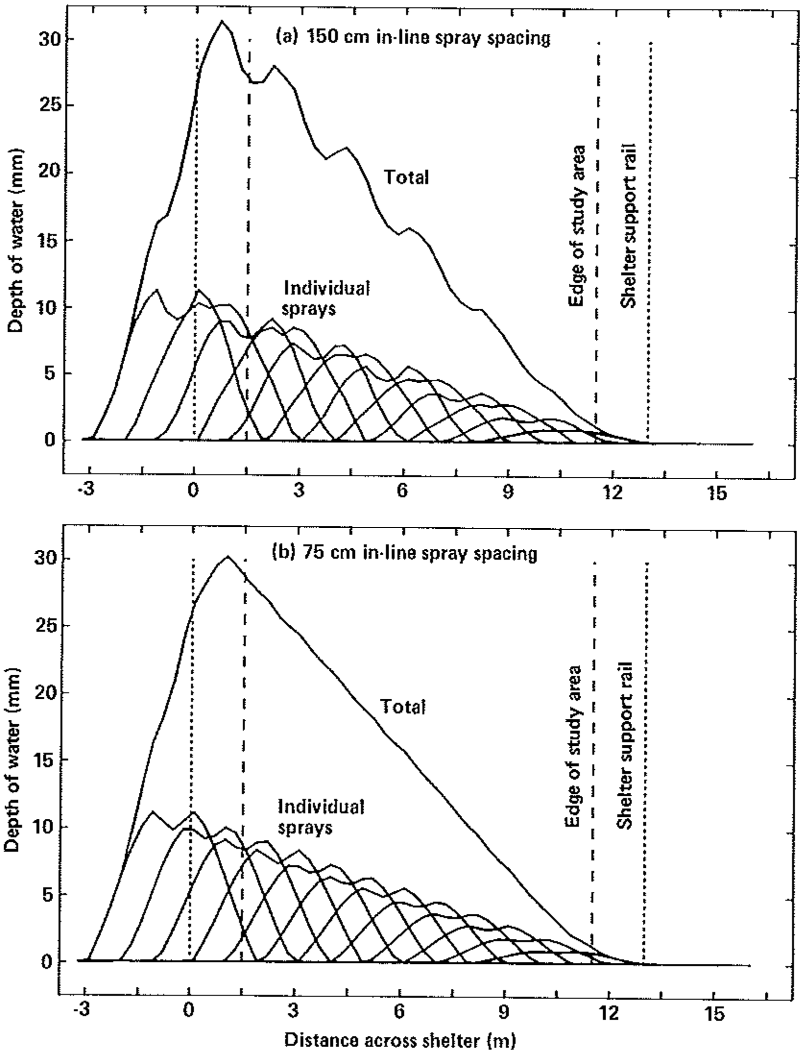

Fig. 7. Simulated water distributions for a designated gradient across the sheltered area for two in-line spray spacings (150 cm, 75 cm) with lines 100 cm apart

Procedure

Within the rainshelter, four quadrats 150 × 200 cm (two to each half) were randomly selected on each irrigation day. On each quadrat a rain gauge assembly of 63 gauges 25 cm apart was placed. On four different days, a nominal 30 mm irrigation was applied with gauges at ground level (2.7 m below the sprays). This procedure was repeated on four subsequent days with the gauges 1.0 m above ground. To minimize the effects of wind, irrigations were applied on calm nights between 04.00 and 06.30 h.

The effect of moving the spray array 75 cm, halfway through an irrigation (effectively halving the in-line spray unit spacing) was investigated by superimposing the distribution pattern within a quadrat upon itself, with a displacement of 75 cm, and dividing water depths by two.

Actual transects of water distribution across the shelter were measured using gauges at 25 cm intervals. At each irrigation, two transects 75 cm apart and each directly under spray units on alternate lines were sampled in each half of the shelter. A gradient across the shelter from 30 mm to 0 mm was applied and measured on the four transects on each of four irrigation occasions.

Results and discussion

The amount and variability in depth of water for each irrigation event are shown in Table 1. Mean irrigation amount ranged between 29.6 mm and 26.1 mm for 7 of the 8 events. The CV at ground level averaged about 6% and was about double this value at 1 m. When in-line unit density was doubled, CV at ground level was reduced from 5.9% to 4.7% and at 1 m, from 13.7% to 10.8%. Variability increased with proximity to the spray jets because of a reduction in size of the base of the spray "cone" and consequent reduced spray overlap. The effect on variability of doubling in-line unit density by repositioning spray units for the second half of the irrigation was modest because the effect of improved geometry was small in relation to random variation.

The results of the test of the irrigation system's ability to apply a gradient across the rainshelter are shown in Fig. 8, where measured gradients were compared to simulated. Since the average depth of water applied was 28.5 mm (Table 1), the range used in the simulation in Fig. 8 was 0–28.5 mm. At the 150 cm spacing the measured curve did not have the regular sinusoidal pattern as

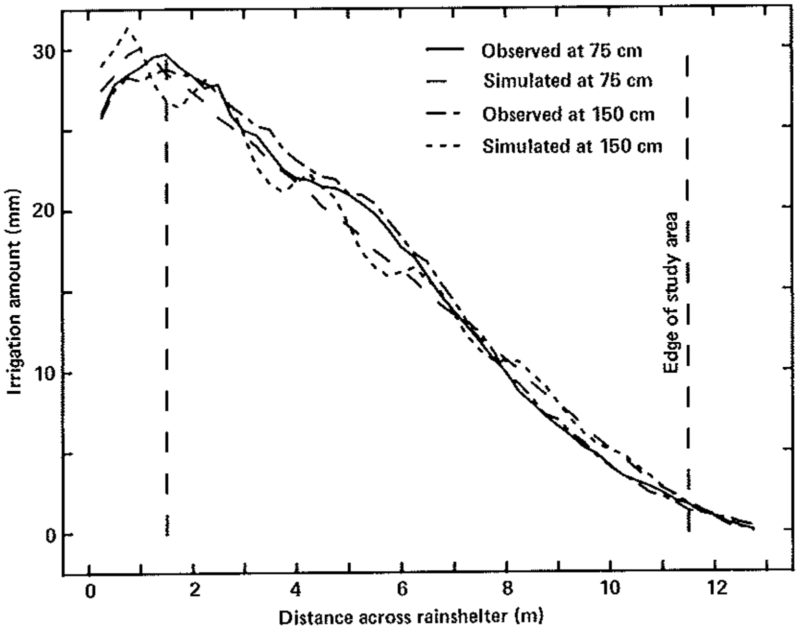

Fig. 8. Simulated and observed irrigation at two in-line spray spacings

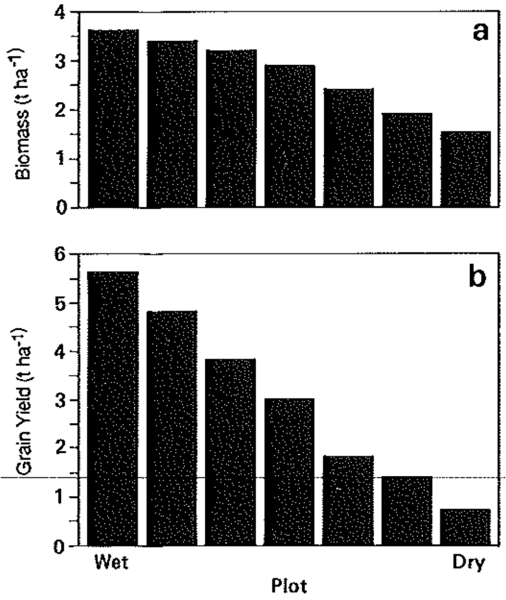

Fig. 9a, b. Patterns of **a** biomass and **b** grain yield across the gradient of applied water from two experiments. Each plot is two rows

in the simulations. The normalized slopes of the simulated and observed gradients were not significantly different ($P < 0.05$). Thus there seems to be no need to implement the strategy for eliminating the sinusoidal variations, as per Fig. 7, using split irrigations with the shelter repositioned 75 cm from the original.

The linearity of the measured gradient ($r^2 = 0.90$), while satisfactory, can be improved. A slight "hump" in the measured gradients can be seen at the mid to high application depths. Cause for this has been traced to higher water pressure in this region of the shelter due to a solenoid switching pattern that results in fewer lines being on simultaneously when this area is being irrigated.

Table 1. Variation in water application when distance between sprays in the line was 150 cm and 75 cm

Height of rain gauges above ground (m)	Irrigation event	150 cm		75 cm	
		Mean depth (mm) (N=252)	CV (%)	Mean depth (mm) (N=144)	CV (%)
0.1	1	29.2	4.5	29.1	3.8
0.1	2	29.5	8.0	29.6	6.3
0.1	3	28.5	5.0	28.5	3.8
0.1	4	27.5	6.2	27.4	5.0
0.1	mean	28.5	5.9	28.7	4.7
1.0	5	27.4	13.2	27.4	10.2
1.0	6	29.1	12.0	29.1	9.7
1.0	7	26.1	12.3	26.1	8.7
1.0	8	23.4	17.4	23.3	14.9
	mean	26.5	13.7	26.5	10.8

This is readily corrected by altering the software to provide a switching pattern in which the number of lines operating is constant.

In experiments conducted using this system, crop yields have followed closely the linear gradient of water application. Figure 9a shows maize biomass yields at tassel initiation from one experiment and Fig. 9b maize grain yields for another experiment.

Conclusions

This irrigation system provides a very versatile, convenient, and cost effective means of controlling water application for studies of crop response to water deficits in confined areas. High precision in both water application and plant growth responses can be achieved.

Schematic diagrams

Further documentation containing all schematics, construction details and parts list can be obtained from the authors.

Acknowledgements. The authors gratefully acknowledge our colleague, Doug Abrecht, for suggesting this approach to water application.

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