Accuracy and uniformity of measured irrigation

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Abstract

This paper describes a method of irrigation called Measured Irrigation (MI). One decides in advance how much water each plant requires and MI delivers the required volume of water. MI is an unpressurised gravity-feed irrigation system that directly controls the volume of water emitted from each nozzle in each sector during the irrigation event without the need to control the flow rate or the length of the irrigation event. Trials compare the accuracy and uniformity of MI with drip irrigation products.

Introduction

In many locations, particularly in poorer countries, access to mains water supply and mains power is either unavailable or too expensive for irrigation use. In such locations MI can provides water-efficient irrigation from a water tank with power provided by a solar panel. Pressurised irrigation is impractical in such locations because of the power required for the pump.

Pressurised drip irrigation systems are able to control the volume of water emitted from a dripper during the irrigation event by controlling both the flow rate from the dripper and the length of the irrigation event. The flow rate is controlled by pressure compensating drippers. This approach requires the control of two parameters, flow rate and time.

MI is an unpressurised gravity-feed irrigation system that controls a single parameter only, namely the volume of water emitted from each nozzle in each sector during the irrigation event. The flow rate and the length of the irrigation event adjust automatically to ensure that the correct volume of water is emitted by each nozzle. MI uses the nozzle formula to predict the volume of water delivered to each sector during the irrigation event, and to predict the volume of water delivered by each emitter nozzle within each sector.

The results of some preliminary trials of MI were presented at the 7th Asian ICID Regional Conference in June 2012. Omodei (2012) demonstrated accuracy and uniformity in excess of 90%. Trials conducted by Chand (2012) in a Major Industry Project at the School of Natural and Built Environments at the University of South Australia also confirmed levels of accuracy and uniformity in excess of 90%. The results of further trials were published in Omodei (2013) and these trials demonstrated accuracy of approximately 95% and uniformity between 90% and 95%.

This paper presents the results of more extensive research trials designed to evaluate MI and to compare MI with pressure compensating drippers and pressure compensating dripline.

Measured irrigation

Lamm et al. (2007) state that microirrigation, the slow and targeted application of irrigation water to prescribed soil volumes, has become synonymous with modern and efficient irrigation practices that conserve precious water resources and maximize plant performance. Among microirrigation technologies, drip irrigation is the most efficient because of its ability to minimize evaporation and runoff by wetting a relatively small area (Capra and Scicolone 2007). However, drip irrigation has a relatively high maintenance cost due to the clogging of drippers by organic and non-organic materials (Capra and Scicolone 2007, Taylor et al. 2006).

According to International Development Enterprise a majority of smallholders in developing countries are deprived of this technology due to its high capital cost and non-adaptability to small land holdings (IDE 2011).

The vast majority of microirrigation systems are pressurised with pressures in excess on 100 kPa. For unpressurised (or gravity feed) systems the pressure at the emitters need to be at least 10 kPa (IDE 2011). Based on field trials in India, Ella et al. (2007) conclude that low-cost gravity feed irrigation is one of the best options for smallholders in developing countries. They also conclude that the irrigation system functions best with pressure of 30 kPa. The results of the trials reported in this paper demonstrate that on level ground MI provides accurate and uniform irrigation with pressures as low as 1 kPa.

Any pressurised microirrigation system that attempts to control the volume of water discharged from an emitter during an irrigation event does so by controlling both the flow rate at the emitter and the length of the irrigation event. MI uses a different approach in that it directly controls the volume of water discharged from an emitter during the irrigation event without the need to control the flow rate or the length of the irrigation event. Both the flow rate and the length of the event are allowed to vary automatically to ensure that the correct volume of water is discharged. Because there is no need to control the flow rate, the cost of installing an irrigation system may be significantly reduced.

The *principle of measured irrigation* states that:

For any two nozzles at the same pressure, the ratio of the flow rates is independent of the pressure

A nozzle is a short cylindrical tube for restricting the flow. For the pressure range used in gravity feed irrigation, it is assumed that the principle of measured irrigation is applicable. Research trials for this paper at pressures of 2 kPa, 4 kPa and 6 kPa support the principle of measured irrigation.

We will describe the following three implementations of the principle of measured irrigation:
Unpowered single-sector measured irrigation
Solar-powered single-sector measured irrigation
Solar-powered multi-sector measured irrigation

Unpowered single-sector measured irrigation

A water tank can be converted into a simple low-cost irrigation system by attaching the outlet tap on the tank to a network of polypipe (LDPE) with emitter nozzles attached to the polypipe. The nozzles should be at the same level and lower the outlet on the tank.

A plastic hobby box or similar container is placed at a central location in a garden and one of the nozzles drips water into the box. This nozzle is called the *control nozzle*. A level line is marked on the inside of the box about 7 cm below the overflow level.

When the water level is about 1 cm below the level line the outlet tap is turned on, and when the water level reaches the level line the tap is turned off. Due to evaporation the water level will fall and so the cycle continues indefinitely. The box is called the *evaporator*.

When it is very hot the water evaporates more quickly and so the tap is turned on sooner. And when it rains extra water enters the evaporator and so the start of the next watering is delayed.

Fig 1. Colour-coded nozzles for MI

Fid 2. Yellow control nozzle delivering water to the evaporator

For single-sector MI one can derive the following formula for estimating the month by month volumes delivered by an emitter nozzle:

$$V_m = RA(e_m - r_m) \quad m = 1, 2, \ldots , 12$$

where

V_m is the estimated volume of water emitted by an emitter nozzle in month *m*,

R (or *nozzle ratio*) is the ratio of the flow rate of the emitter nozzle to the flow rate of the control nozzle when both nozzles are at the same pressure,

A is the cross-sectional area of the evaporator,

e_m is the average monthly evaporation in month *m*, and

r_m is the average monthly rainfall in month *m*.

The above estimates assume that the evaporator does not overflow or run dry. Note that V_m is independent of when the tap is turned on and off.

Solar-powered single-sector measured irrigation

Unpowered single-sector MI can be automated using a solar panel.

Conventional irrigation systems use a computer controller to control the opening and closing of solenoids in order to control the length of the irrigation event and the frequency of irrigation. Solar-powered MI uses an evaporator and level sensor to control the length of the irrigation event and the frequency of irrigation.

Fig. 3 Level sensor with the low probe on the left, the reference probe in the middle, and the high probe on the right

The level sensor has three probes as shown in Figure 3. During the irrigation event the water level rises as water slowly drips into the evaporator from the control nozzle. When the water level reaches the high probe on the right the irrigation stops. The water level then falls due to evaporation until the water level is below the low probe on the left at which point the irrigation recommences. This cycle continues indefinitely.

The volume of water required to raise the water level from the low probe level to the high probe level is called the *control volume*. It is also the volume of water that must evaporate between irrigation events.

All the power required for single-sector MI is provided by a 10 watt solar panel.

By choosing the appropriate emitter nozzles every plant receives a measured volume of water during the irrigation event. The volume of water delivered to each plant is simply the control volume multiplied by the relevant nozzle ratio.

The irrigation frequency responds to the prevailing weather conditions. During very hot weather the evaporation rate will be much greater and so the irrigation down time will be shorter. On cool overcast days, the evaporation rate will be quite small and so the irrigation down time will be longer. And when it rains the water level in the evaporator rises and delays the start of irrigation.

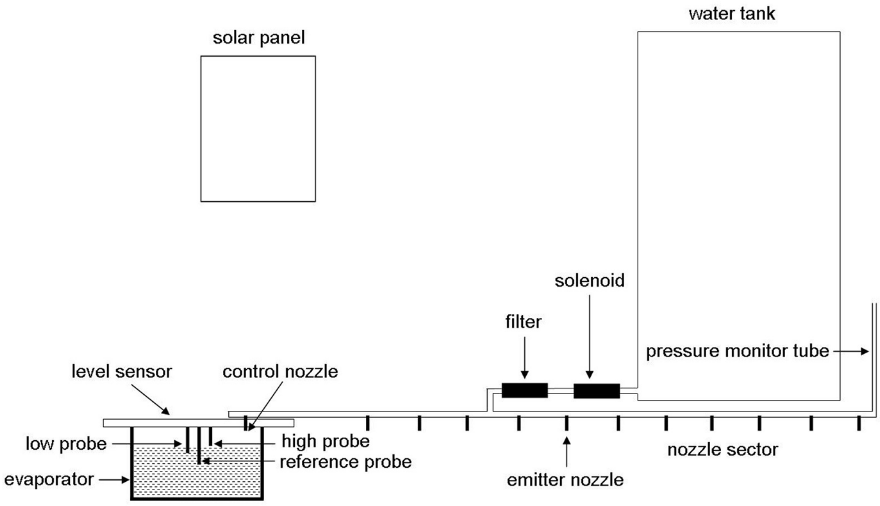

Fig 4. Schematic diagram if solar-powered single-sector measured irrigation

Solar-powered multi-sector measured irrigation

This implementation is suitable for much larger applications that require many separate sectors and much more water. In order to deliver water to all the sectors simultaneously, a *flow splitter* is needed.

The flow splitter accurately divides a single inflow of water into multiple outflows with one outflow for each irrigation sector. The proportion of water delivered to each outlet is determined by the size of the irrigation nozzle attached to outlet on the flow splitter. The control nozzle is connected to one of the outlets on the flow splitter and a tube delivers water from the control nozzle to the evaporator. The irrigation event stops when the control volume of water has been delivered to the evaporator. The other outlets deliver water to the irrigation sectors.

Fig 5. Flow splitter and solar panel

Fig 6 . Irrigation nozzles and the control nozzle on the left

In Figure 5 the water level in the flow splitter has stabilized so that the outflow rate matches the inflow rate. Suppose that the inflow is increased by adjusting the inlet valve. The water level in the flow splitter will rise until the outflow rate matches the increased inflow rate. However, the volume of water delivered to the evaporator (namely, the control volume) does not change, and so the volume of water delivered to any sector does not change.

Note that a flow splitter can be any shape or size provided that all the outlets on the flow splitter are at the same level. This is important because the principle of measured irrigation requires that all nozzles be at the same pressure.

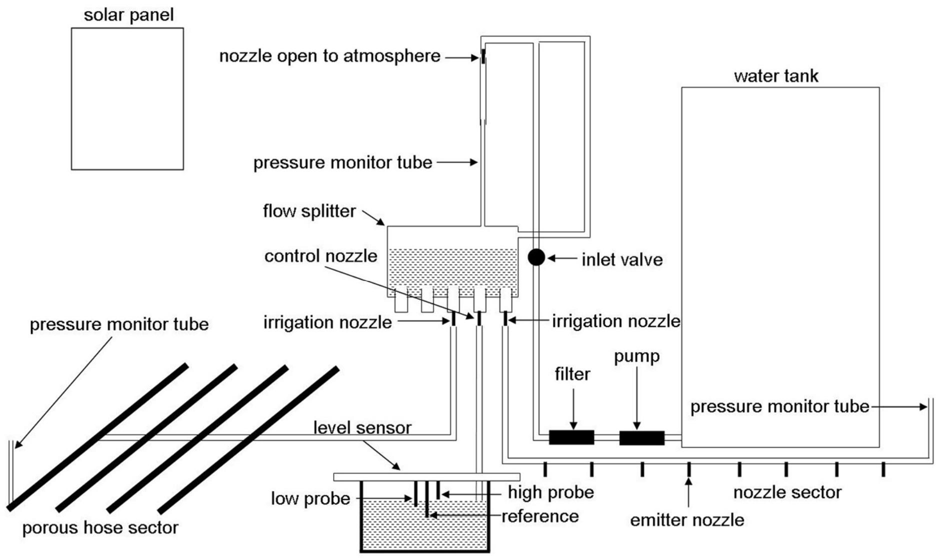

Fig 7. Schematic diagram of solar-powered multi-sector measured irrigation showing one nozzle sector and one porous hose sector

The Nozzle Formula

The nozzle formula states that:

measured volume = *control volume* × *nozzle ratio*

where

measured volume is the volume of water delivered by the irrigation nozzle on the flow splitter during the irrigation event,

control volume is the volume of water delivered by the control nozzle to the evaporator during the irrigation event, and

nozzle ratio is the ratio of the flow rate of the irrigation nozzle to the flow rate of the control nozzle when both nozzles are at the same pressure.

A simple way to measure the nozzle ratio is to collect water from the irrigation nozzle in one container and water from the control nozzle in another container. The nozzle ratio is simply the ratio of the two volumes.

The nozzle ratio is a characteristic of the nozzles and independent of the flow rate. Therefore the volume of water delivered to any irrigation sector during the irrigation event is independent of the flow rate. The water level in the flow splitter can rise and fall without affecting the irrigation volumes.

The accuracy and uniformity of pressurised drip irrigation depends on the fabrication of accurate pressure compensating drippers. For MI no pressure compensation is required.

Nozzle sector

The nozzle formula is used to predict the volume of water delivered to a sector during the irrigation event. To predict the volume of water emitted by a nozzle within a sector we need to derive the *extended nozzle formula*.

For a particular sector assume that there are N emitter nozzles with nozzle ratios $R_1, R_2, \dots, R_N$ and that the volumes of water emitted by the nozzles are $V_1, V_2, \dots, V_N$.

Assume that all the nozzles are at the same level and there is no head loss between the nozzles within the sector.

Therefore the volume of water emitted by a nozzle is proportional to its nozzle ratio.

The nozzle formula tells us the total volume of water emitted within the sector, and hence we derive the extended nozzle formula

$$V_i = V_c R R_i / (R_1 + R_2 + \dots + R_N) \qquad i = 1, 2, \dots, N$$

where

V_c is the control volume and

R is the nozzle ratio for the irrigation nozzle for the sector.

For some applications it may be appropriate to use a hierarchy of flow splitters where the output from a flow splitter at one level becomes the input for a flow splitter at a lower level. The nozzle formula is used to determine the volumes of water emitted by the nozzles on the top level flow splitter, and the extended nozzle formula is used to determine the volumes of water emitted by the nozzles on the lower level flow splitters.

MI porous hose sector

For some applications MI porous hose may be the preferred method of delivering water to the plants. MI porous hose should not be used in pressurised systems, and conventional porous hose for pressurised systems should not be used with measured irrigation. Conventional porous hose is more than 50 times less porous than MI porous hose and so hardly any water will weep from the hose at low pressure

Single outlet sector

For some sectors porous hose or nozzles may not be the preferred method of delivering water to the plants. For example, a large deep rooted tree may be better irrigated with a watering spike that reaches the root zone. This is a single outlet sector where all the water for the sector is delivered to the watering spike. If there is an individual plant that is much higher of much lower than all the other plants, then a single outlet sector may be appropriate for such a plant.

A single outlet sector may be small tank or container that receives a fixed volume of water during the irrigation event. Hence MI has other applications besides irrigation. For example it can be used to efficiently deliver measured volumes of water to drinking containers for animals.

Irrigation frequency

The irrigation frequency is proportional to the evaporation rate minus the precipitation rate in the vicinity of the evaporator. Therefore the evaporator should be located so that it is exposed to the same weather conditions as the plants to be irrigated. The irrigation frequency can be changed by adjusting the gap between the low probe level and the high probe level. This will also change the control volume. However, the monthly water usage does not change. For example, if the gap between the low probe and the high probe is halved, then the volume of water used during the irrigation event is halved, but the irrigation frequency is doubled.

Example 1. Community garden

The Prospect Community Garden was constructed in 2011 on a 1500 square metre block of land owned by the City of Prospect. Every plant in the garden is irrigated by solar-powered multi-sector MI. The site uses 14 of the 25 outlets on the flow splitter. There are 13 porous hose sectors using 13 of the flow splitter outlets, and one flow splitter outlet is used for the control nozzle. The control volume is 1.7 litres. See Table 1 for further details.

Table 1. Water requirement and corresponding nozzle for each sector at the Prospect Community Garden

sector	sector description	water requirement	nozzle
1	9 metres of porous hose, high level garden bed	120 L	6.4 rivet
2	10 metres of porous hose, high level garden bed	120 L	6.4 rivet
3	9 metres of porous hose, low level garden bed	120 L	6.4 rivet
4	10 metres of porous hose, low level garden bed	120 L	6.4 rivet
5	9.5 metres porous hose, low level garden bed	120 L	6.4 rivet
6	10 metres of porous hose, two low level garden beds	120 L	6.4 rivet
7	7.5 metres of porous hose, high plastic garden bed	90 L	5.4 rivet
8	3 metres of porous hose, high plastic garden bed	30 L	olive
9	7.5 metres of porous hose, high plastic garden bed	90 L	5.4 rivet
10	6 metres of porous hose, 6 large barrel pots	60 L	4.2 rivet
11	18 metres of porous hose, herb garden beside tanks	200 L	5/32 inch washer
12	32 metres of porous hose, fruit trees and vines beside southern fence	380 L	5 mm washer
13	60 metres of porous hose, fruit trees and vines beside western and northern fences, and nearby garden beds	750 L	2 x 5 mm washer
	Total water requirement	2320 L	

Example 2. Measured irrigation on a boom

The flow splitters are mounted on the boom and the system is pressurized before the top level flow splitter and gravity feed thereafter. Every plant receives a predetermined volume of water, and hence there is a major reduction in water consumption. All the power required is provided by a 20 watt solar panel mounted on the boom.

Fig 8. Boom irrigation for thousands of seedlings in a commercial seedling nursery using MI

Methods and materials

The accuracy and uniformity of MI was compared with the accuracy and uniformity of drip irrigation with pressure compensating drippers and pressure compensation dripline. The pressure compensating drip irrigation products evaluated were purchased from retail irrigation outlets in Adelaide. The drip irrigation products had high volume sales worldwide and were manufactured by three large multinational irrigation companies. The companies selected were Toro (head office in USA), Netafim (head office in Israel) and Antelco (head office in Australia).

A complete list of the products evaluated for accuracy and uniformity is as follows.

Toro:
Enviro-Drip pressure compensating dripline 2 L/H, 50 cm spacing
Turbo-Plus II pressure compensating dripper 2 L/H
Turbo-Plus II pressure compensating dripper 4 L/H
Turbo-Plus II pressure compensating dripper 8 L/H

Netafim:
Techline AS pressure compensating dripline 1.6 L/H, 50 cm spacing
Woodpecker pressure compensating dripper 2 L/H
Woodpecker pressure compensating dripper 4 L/H

Antelco:
Agri Drip pressure compensating dripper 2 L/H
Agri Drip pressure compensating dripper 4 L/H
Agri Drip pressure compensating dripper 8 L/H

Measured Irrigation:
Brown stainless steel nozzle with internal diameter 0.838 mm
Pink stainless steel nozzle with internal diameter 0.965 mm
White stainless steel nozzle with internal diameter 1.219 mm
Purple stainless steel nozzle with internal diameter 1.346 mm
Orange stainless steel nozzle with internal diameter 1.499 mm
Olive stainless steel nozzle with internal diameter 1.753 mm

For each trial water was collected from 20 emitters spaced 50 cm apart. For each trial the water was filtered by a 120 mesh inline filter. In all cases the predicted volume of water emitted was 1 litre. For drippers and dripline the length of the irrigation event was adjusted so that the predicted volume of water emitted from each dripper was 1 litre. For MI the control volume was adjusted to ensure that the predicted volume of water emitted from each emitter nozzle was 1 litre. All trials used 13 mm diameter dripline.

For each product 3 different water pressures were tested. For the drippers and dripline the pressures selected were 100 kPa, 200 kPa and 300 kPa. These pressures are within the recommended pressure range for all drip irrigation products tested. For MI the pressures selected were 2 kPa, 4 kPa and 6 kPa. Note that the pressures for MI are 2 of the corresponding pressures for drip irrigation.

Results

A complete list of results is presented in Table 2 where AM is the Accuracy of the Mean for the 20 emitters, DU is the Distribution Uniformity for the 20 emitters, SU is the Statistical Uniformity for the 20 emitters and CU is the Christensen Uniformity for the 20 emitters. For completeness the definitions are given below and are equivalent to those used in Lamm et al. (2007).

$$\mathrm{AM} = 100\,(1 - |M - P| / P)$$

where M is the mean emitter volume and P is the predicted emitter volume (1 litre in our case).

$$\mathrm{DU} = (100\, M_{25}) / M$$

where M_{25} is the mean emitter volume for the lowest 25 of measurements, and M is the mean emitter volume for all the measurements.

$$\mathrm{SU} = 100\,(1 - (\textstyle\sum(V_i - M)^2) / 20)^{1/2} / M)$$

$$\mathrm{CU} = 100\,(1 - (\textstyle\sum|V_i - M|) / 20 / M)$$

where the summation is for all emitter volumes V_i for $i = 1, 2, \ldots, 20$.

For MI the low pressure is 2 kPa, the medium pressure is 4 kPa and the high pressure is 6 kPa. For all other products the low pressure is 100 kPa, the medium pressure is 200 kPa and the high pressure is 300 kPa.

Table 2. Results of all trials where AM is Accuracy of the Mean, DU is Distribution Uniformity, SU is Statistical Uniformity and CU is Christensen Uniformity

	low pressure				medium pressure				high pressure			
	AM %	DU %	SU %	CU %	AM %	DU %	SU %	CU %	AM %	DU %	SU %	CU %
Toro Enviro-Drip dripline 2 L/H	89.3	95.3	96.5	97.1	98.1	93.1	94.4	95.4	95.9	91.9	93.3	95.0
Toro Turbo-Plus II dripper 2 L/H	68.0	75.9	70.3	74.4	79.7	83.5	79.4	82.7	75.3	82.0	83.3	85.5
Toro Turbo-Plus II dripper 4 L/H	87.2	81.1	65.8	76.9	65.6	76.6	64.3	70.6	79.6	87.7	81.0	88.1
Toro Turbo-Plus II dripper 8 L/H	98.5	86.3	89.1	92.9	98.2	89.0	87.7	94.5	97.0	72.8	80.9	86.4
Netafim Techline AS dripline 1.6 L/H	99.3	97.7	97.8	98.2	95.4	97.7	98.2	98.6	99.1	95.7	96.7	97.8
Netafim Woodpecker dripper 2 L/H	93.3	94.4	97.5	98.2	95.9	94.8	96.1	97.2	99.3	96.1	96.7	97.0
Netafim Woodpecker dripper 4 L/H	98.7	94.2	95.1	96.7	96.9	95.7	96.4	97.4	96.4	96.0	96.8	97.5
Antelco Agri Drip dripper 2 L/H	93.9	90.7	91.3	93.6	78.2	91.9	90.9	93.3	70.4	89.3	84.4	91.1
Antelco Agri Drip dripper 4 L/H	85.1	72.7	77.7	86.1	93.3	84.5	88.6	91.8	84.0	89.3	91.7	94.3
Antelco Agri Drip dripper 8 L/H	98.7	82.0	87.0	90.6	96.1	86.2	89.8	92.2	92.1	88.1	90.7	92.3
MI brown nozzle	92.7	94.8	95.1	96.1	94.5	95.4	96.6	97.3	99.4	91.9	93.9	95.4
MI pink nozzle	99.3	94.6	95.8	96.5	99.8	92.1	91.8	95.8	93.8	93.1	94.5	96.3
MI white nozzle	89.5	95.5	96.5	97.1	98.7	91.8	92.9	95.4	94.3	91.8	92.2	95.8
MI purple nozzle	93.8	94.2	95.6	96.6	94.6	94.9	96.1	96.8	97.5	91.1	92.5	95.0
MI orange nozzle	94.5	91.8	93.8	95.4	95.9	93.0	95.1	96.3	94.8	94.6	96.0	97.1
MI olive nozzle	98.8	89.1	92.3	93.9	96.4	93.8	95.3	96.1	97.2	93.8	95.5	96.1

Figure 9 is a chart showing the ranked results for the accuracy of the mean AM for all products.

Figure 10 is a chart showing the ranked results for the distribution uniformity DU for all products.

Figure 11 is a chart showing the ranked results for the statistical uniformity SU for all products.

Note that the results for MI are indicated by solid bars in Figures 9, 10 and 11.

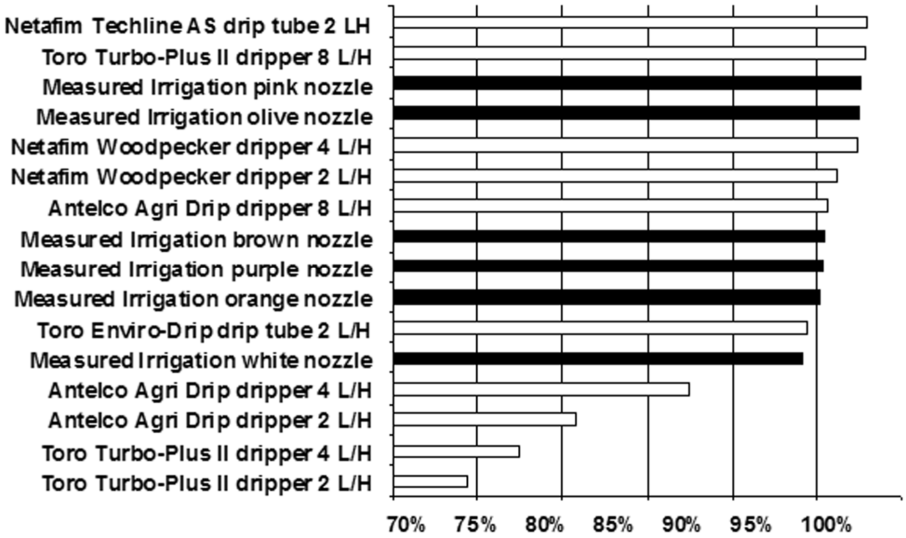

Fig 9. Ranked summary of the accuracy of the mean for all 16 products listed in Table 2. The accuracy of the mean is the average across the relevant 3 pressures.

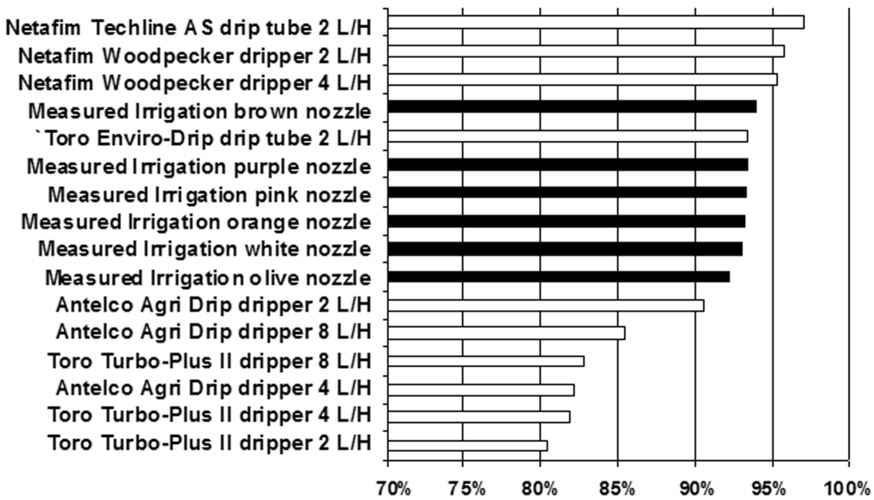

Fig 10. Ranked summary of the distribution uniformity for all 16 products listed in Table 2. The distribution uniformity is the average across the relevant 3 pressures

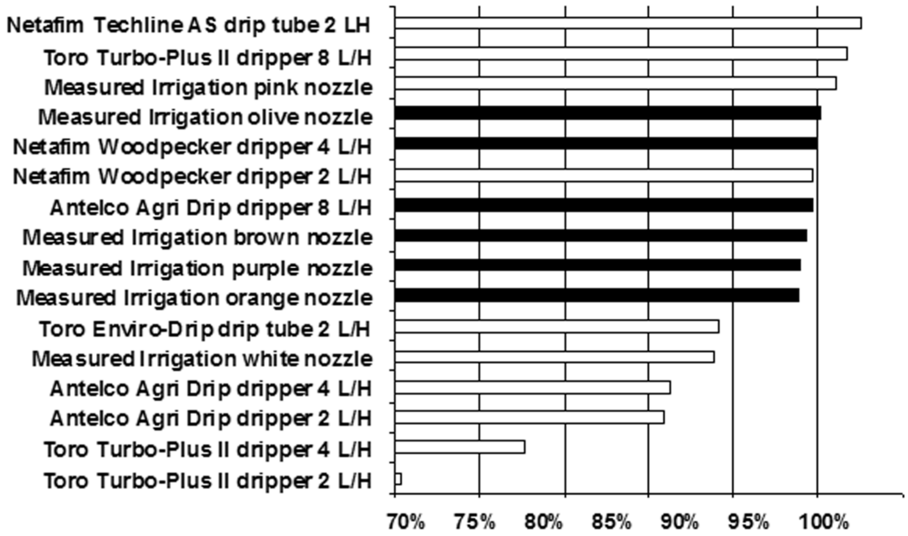

Fig 11. Ranked summary of the statistical uniformity for all 16 products listed in Table 2. The statistical uniformity is the average across the relevant 3 pressures.

Conclusion

Based on the products evaluated, pressure compensating dripline exhibited higher levels of accuracy and uniformity than pressure compensating drippers. MI nozzles exhibited accuracy of approximately 95% and uniformity between 90% and 95%. MI did not perform as well as the two dripline products evaluated, but if performed better than most of the pressure compensating drippers evaluated.

Automated MI may be installed anywhere that has access to sunlight and stored water.

A major advantage of solar-powered MI is that the irrigation frequency is proportional to the evaporation rate minus the precipitation rate in the vicinity of the evaporator.

A significant disadvantage of MI is that all the emitters within a sector need to be at approximately the same level. Hence on sloping ground the sectors would need to follow the contours.

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