Accuracy and uniformity of a gravity-feed method of irrigation

Bernard Omodei

Dot2dot, 5/50 Harvey Street, Woodville Park, SA 5011, Australia

Abstract

This paper describes a method of irrigation called Measured Irrigation (MI). MI is a gravity-feed irrigation system that directly controls the volume of water emitted from each emitter nozzle in each sector during the irrigation event without the need to control the flow rate or the duration of the irrigation event. Three implementations of MI are described: unpowered single-sector MI, solar-powered single-sector MI and solar-powered multi-sector MI. For solar-powered MI the irrigation frequency is proportional to the evaporation rate minus the precipitation rate. MI does not require access to electricity grid power or to an urban water supply. Trials compare the accuracy and uniformity of MI with pressure compensating drip irrigation products.

Introduction

Measured Irrigation (MI) is a gravity-feed irrigation system that directly controls the volume of water discharged by each emitter in each sector during the irrigation event.

In many locations, particularly in poorer countries, access to an urban water supply and electricity grid power is either unavailable or too expensive for irrigation use. In such locations Measured Irrigation can provide water-efficient irrigation from a water tank with power provided by a solar panel. Pressurised irrigation is often impractical in such locations due to limited access to sufficient power to operate a suitable 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 duration of the irrigation event. The flow rate is controlled by pressure compensating drippers that are designed to produce a constant output pressure for a range of input pressures This approach requires the control of two parameters, flow rate and time.

An *irrigation sector* is defined as an irrigation area where the amount of water delivered to the area during the irrigation event can be adjusted without affecting any irrigation outside the area. The term *gravity-feed* in relation to irrigation systems is used in this paper to refer to irrigation systems where the pressure is less than 20 kPa. The term *pressurised* in relation to irrigation systems is used in this paper to refer to irrigation systems where the pressure is greater than 20 kPa.

Because MI is a gravity-feed irrigation system that directly controls the volume of water emitted from each emitter nozzle in each sector during the irrigation event, there is no need to control the flow rate or the duration of the irrigation event. MI controls a single parameter only, namely the volume of water emitted from each emitter nozzle in each sector during the irrigation event. The flow rate and the duration of the irrigation event adjust automatically to ensure that the correct volume of water is emitted by each emitter 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.

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).

According to International Development Enterprise (IDE) 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 of 100 kPa. According to IDE (2011) for gravity-feed systems the pressure at the emitters need to be at least 10 kPa. 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 most popular method of low-cost gravity-feed irrigation for smallholders in developing countries o uses microtube emitters (Bhatnagar and Srivastava 2003, IDE 2011). The hydraulics of microtube emitters has been well established (Katri et al. 1979, Wu et al. 2010).

The results of some preliminary trials of MI were presented at the 7th Asian ICID Regional Conference in June 2012. Omodei (2012) reported 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%. Note that accuracy, or AM (Accuracy of the Mean) to be more precise, is defined as

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

where M is the mean emitter volume and P is the predicted emitter volume.

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. The MI trials were conducted at pressures of 2 kPa, 4 kPa and 6 kPa.

Although this paper describes measured irrigation from a water tank, measured irrigation can be adapted to an urban water supply.

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 duration 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 duration of the irrigation event. Both the flow rate and the duration 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.

In the context of measured irrigation, a nozzle is defined as a short cylindrical tube for restricting the flow.

The following three implementations of measured irrigation are described:

- 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 emitter nozzles should all be at the same level and this level must be below 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 emitter 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 manually and all the nozzles commence flowing including the control nozzle. When the water level reaches the level line the tap is turned off manually. 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 and/or dry 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. These nozzles are short blunt stainless steel dispensing needles used in the electronics industry.

Fig. 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:

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

where

V_m is the estimated volume of water discharged 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.

The distance between the level line on the evaporator and the overflow level determines the maximum amount of water that must evaporate before the next irrigation event commences after heavy rainfall. Without overflow there may be no irrigation for more than a month of dry weather after a very heavy rainfall.

Solar-powered single-sector measured irrigation

Unpowered single-sector MI can be automated and all the power required can be provided by a solar panel. The solar panel is needed for the solenoid-actuated valve and for the control circuit.

Conventional irrigation systems use a computer controller to control the opening and closing of solenoid-actuated valves in order to control the duration of the irrigation event and the frequency of irrigation. Solar-powered MI uses an evaporator and level sensor to control the volume of water delivered during the irrigation event and the frequency of irrigation. The controller for MI measures the voltage difference between the high probe and the reference probe, and the voltage difference between the low probe and the reference probe.

Fig. 3 Level sensor with the low probe on the left (in the water), the reference probe in the middle, and the high probe on the right (out of the water)

The level sensor has three probes as shown in Fig. 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 starts. 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 can be 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.

The schematic diagram in Fig. 4 illustrates the relationship between the various components of solar-powered single-sector measured irrigation.

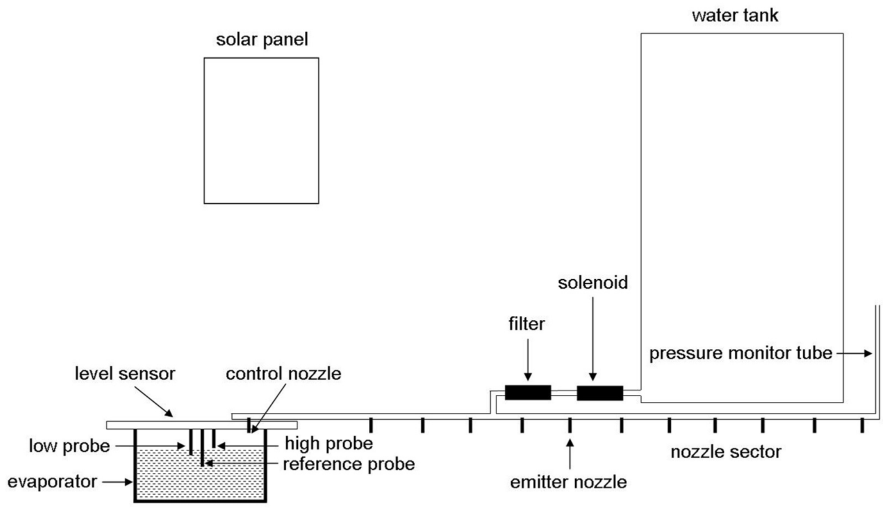

Fig. 4 Schematic diagram for solar-powered single-sector measured irrigation

Solar-powered multi-sector measured irrigation

This implementation is suitable for much larger applications that require many separate sectors and much more water. Note that the irrigation in any sector is independent of the irrigation in the other sectors. In order to deliver water to all the sectors simultaneously, a *flow-splitter* is required.

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 flow-splitter 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 measured volumes of water to the irrigation sectors. All nozzles should be open to the atmosphere at all times.

Fig. 5 Flow-splitter and solar panel

Fig. 6 Flow-splitter nozzles with the control nozzle on the left

In Fig. 5 the water level in the flow-splitter has stabilized so that the outflow rate matches the inflow rate. Suppose that the inflow rate 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 ensures that all flow-splitter nozzles are at the same pressure.

The schematic diagram in Fig. 7 illustrates the relationship between the various components of solar-powered multi-sector measured irrigation. Note that the irrigation system is gravity-feed after the water has entered the flow-splitter. The irrigation system may be pressurised before the water enters the flow-splitter.

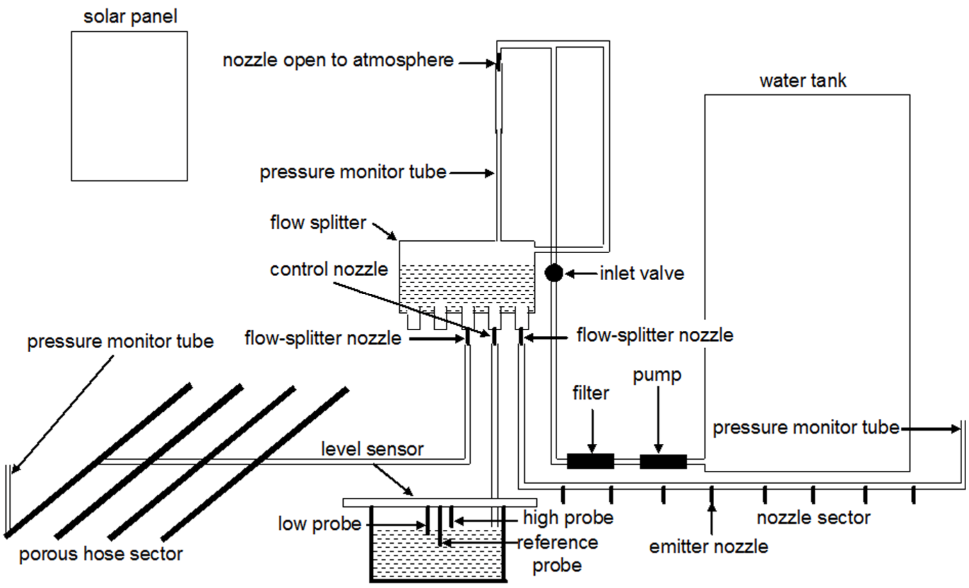

Fig. 7 Schematic diagram of solar-powered multi-sector measured irrigation showing one nozzle sector and one porous hose sector

The Nozzle Formula

The nozzle formula states that:

$$\textit{measured volume} = \textit{control volume} \times \textit{nozzle ratio} \qquad (2)$$

where

measured volume is the volume of water delivered by a flow-splitter nozzle 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 flow-splitter 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 flow-splitter 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.

Once the control nozzle has been selected, the nozzle formula allows one to select the appropriate flow-splitter nozzle to deliver the desired volume of water to sector.

The accuracy and uniformity of pressurised drip irrigation depends on the fabrication of accurate and uniform pressure compensating drippers. With MI, pressure compensating emitters are not required, but the emitters must all be located at the same elevation in each sector.

For drip irrigation, pressure compensating drippers are effective within a pressure range specified by the manufacturer. For MI, pressure compensation is not required provided that the emitters are at the same elevation and the distance from the first to the last emitter is small enough to avoid significant pressure differences at the emitters when they are flowing.

Nozzle sector

The nozzle formula is used to predict the volume of water delivered to a sector during the irrigation event. The *extended nozzle formula* is derived below and it predicts the volume of water emitted by an emitter nozzle within a sector.

Applying the nozzle formula (2) to a sector

$$V = V_c R \qquad (3)$$

where

V is the measured volume of water delivered to the sector during the irrigation event,

V_c is the control volume and

R is the nozzle ratio for the flow-splitter nozzle for the sector.

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

Assume that all the emitter 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 an emitter nozzle is proportional to its nozzle ratio, and hence

$$V_i = VR_i / (R_1 + R_2 + \ldots + R_N) \qquad i = 1, 2, \ldots, N \qquad (4)$$

Substituting equation (3) into equation (4) the *extended nozzle formula* is derived

$$V_i = V_c RR_i / (R_1 + R_2 + \ldots + R_N) \qquad i = 1, 2, \ldots, N \qquad (5)$$

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 flow-splitter nozzles on the top level flow splitter, and the extended nozzle formula is used to determine the volumes of water emitted by the flow-splitter 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 conventional porous hose at low pressure MI porous hose is made from a mixture of rubber and plastic where the percentage of plastic is reduced to increase the porosity of the hose. MI porous hose is available commercially from Dot2dot Post Pty Ltd.

Single outlet sector

For some sectors porous hose or emitter 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 could be 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 or 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

It can be shown that 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 as shown in Table 1. The control volume is 1.7 litres.

Table 1 Water requirement and corresponding flow-splitter nozzle for each sector at the Prospect Community Garden

sector	sector description	water requirement	Flow-splitter nozzle
1	9 m of porous hose, high level garden bed	120 L	6.4 rivet
2	10 m of porous hose, high level garden bed	120 L	6.4 rivet
3	9 m of porous hose, low level garden bed	120 L	6.4 rivet
4	10 m of porous hose, low level garden bed	120 L	6.4 rivet
5	9.5 m porous hose, low level garden bed	120 L	6.4 rivet
6	10 m of porous hose, two low level garden beds	120 L	6.4 rivet
7	7.5 m of porous hose, high plastic garden bed	90 L	5.4 rivet
8	3 m of porous hose, high plastic garden bed	30 L	olive
9	7.5 m of porous hose, high plastic garden bed	90 L	5.4 rivet
10	6 m of porous hose, 6 large barrel pots	60 L	4.2 rivet
11	18 m of porous hose, herb garden beside tanks	200 L	5/32 inch washer
12	32 m of porous hose, fruit trees and vines beside southern fence	380 L	5 mm washer
13	60 m 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 a travelling boom. The system is pressurized before the top level flow-splitter and gravity-feed thereafter. Every seedling receives a predetermined volume of water, and there is a major reduction in water consumption compared to overhead sprinklers. Water usage measurements indicate a reduction in water consumption of at least 50%. All the power required is provided by a 20 W solar panel mounted on the boom. Fig. 8 illustrates the application of solar-powered multi-sector MI to boom irrigation.

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

Fig. 8b Emitter nozzles for boom irrigation

Methods and materials

The accuracy and uniformity of MI were compared with the accuracy and uniformity of drip irrigation with pressure compensating drippers and pressure compensating dripline. The pressure compensating drip irrigation products evaluated were purchased from retail irrigation outlets in Adelaide. The drip irrigation products have 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. Note that the tolerances in the manufacture of the stainless steel nozzles are shown in brackets (Jensen Global Inc 2014).

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 0.79 (±0.02) mm
- Pink stainless steel nozzle with internal diameter 0.99 (±0.02) mm
- White stainless steel nozzle with internal diameter 1.17 (±0.02) mm
- Purple stainless steel nozzle with internal diameter 1.35 (±0.02) mm
- Orange stainless steel nozzle with internal diameter 1.51 (±0.02) mm
- Olive stainless steel nozzle with internal diameter 1.77 (±0.02) 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. Without loss of generality, the predicted volume of water emitted was standardised to one litre. For drippers and dripline the duration of the irrigation event was adjusted so that the predicted volume of water emitted from each dripper was one litre. For MI the control volume was adjusted to ensure that the predicted volume of water emitted from each emitter nozzle was one litre. All trials used 13 mm diameter dripline or polypipe.

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 the 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.

For drippers and dripline, the pressure was measured by a standard inline water pressure gauge. For MI the pressure was measured by an inline pressure monitor tube. All volumes were measured by collecting the water from the emitters in catch cans and weighing the water in the catch can (it is assumed that 1 ml of water weighs 1 gram).

For completeness the definitions of AM (Accuracy of the Mean), DU (Distribution Uniformity), SU (Statistical Uniformity) and CU (Christensen Uniformity) are given below and are equivalent to those used in Lamm et al. (2007).

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

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

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

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.

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

$$CU = 100 (1 - (\sum|V_i - M|) / 20 / M)$$

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

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..

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

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

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

Fig. 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 Figs. 9, 10 and 11.

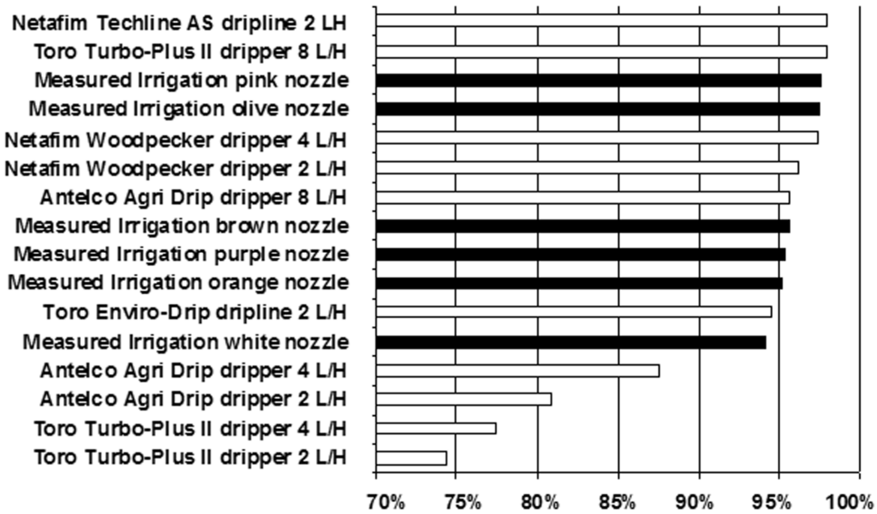

Fig. 9 Ranked summary of the accuracy of the mean **AM** for all 16 products listed in Table 2. The accuracy of the mean is the average across the relevant 3 pressures. The black bars are for MI.

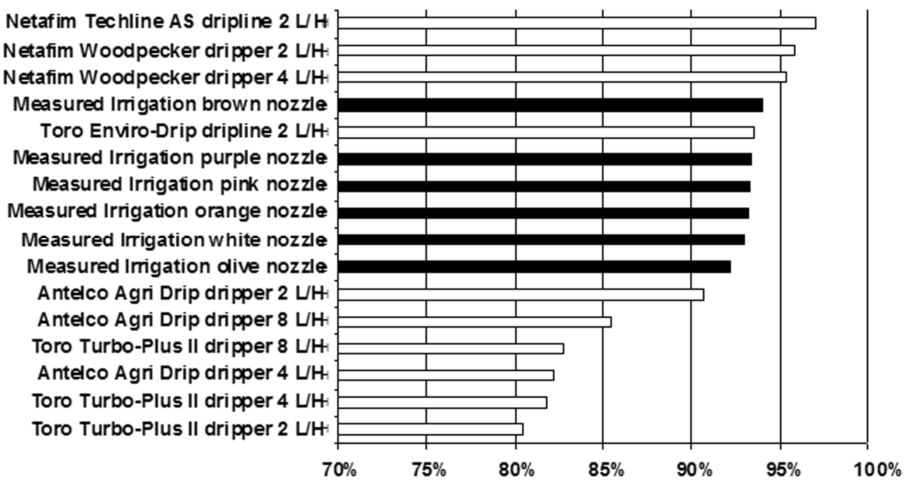

Fig. 10 Ranked summary of the distribution uniformity **DU** for all 16 products listed in Table 2. The distribution uniformity is the average across the relevant 3 pressures. The black bars are for MI.

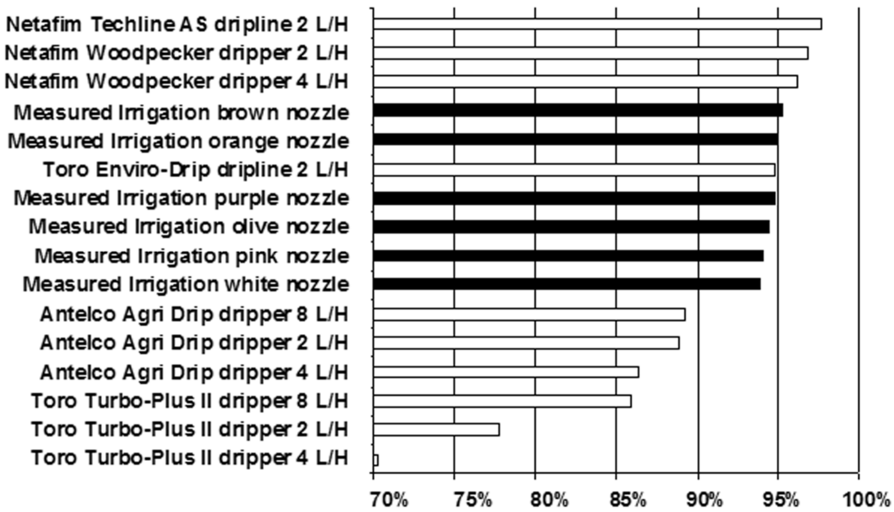

Fig. 11 Ranked summary of the statistical uniformity **SU** for all 16 products listed in Table 2. The statistical uniformity is the average across the relevant 3 pressures. The black bars are for MI.

Conclusions

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 it performed better than most of the pressure compensating drippers evaluated.

Automated MI may be installed anywhere that has access to sunlight and stored water. Pressurised irrigation systems may often be impractical in such locations unless there is access to either an urban water supply or electricity grid power.

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 and so the number of sectors may need to be increased.

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