

Final Report

LongStop: a more sensitive Wetting Front Detector
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LongStop: a more sensitive Wetting Front Detector

Background

The FullStop Wetting Front Detector was designed to be a simple, inexpensive and robust device that gives a yes/no response to whether a wetting front has reached a particular depth. When searching for simplicity and low cost, tradeoffs need to be made with sensitivity; in the case of FullStop the decision was made to detect a 2 kPa strength wetting front.

From a theoretical perspective, the FullStop Wetting Front Detector is not well suited to furrow irrigation, deep placement, cracking soils or where soil disturbance must be minimized. The LongStop Wetting Front Detector has been specifically designed for the above applications. Working prototypes have been built and have undergone limited field testing in sandy soils. This pilot study evaluates the performance of the LongStop under a furrow irrigated cotton crop on a cracking grey clay soil.

Objectives

1. Field test a simple device that alerts growers that drainage of water below the rootzone has reached unacceptable levels.
2. Compare versions of the Wetting Front Detector with different sensitivity limits.
3. Evaluate different fill materials for the LongStop that ensure the instrument remains in hydraulic equilibrium with the soil.
4. Provide guidelines as to how to deploy a wetting front detector on a cracking clay soil
5. Utilise the Cotton and Grains Knowledge Project (CRD1), the CRCIF and CRC cotton extension networks for communicating the project results to irrigators.

Rationale

The FullStop Wetting Front Detector (WFD) comprises a specially shaped funnel that distorts the downwards flow of water through the soil, producing saturation (free water) from an unsaturated soil. The shape of the detector determines the sensitivity. The minimum sensitivity of the FullStop in cm of suction is set by the height of the funnel; additional sensitivity is gained through convergence by the funnel, which is soil type dependant. The minimum sensitivity is around 2 kPa (20 cm suction), which corresponds to fluxes between 0.2 to 0.4 mm/h in most soils.

The strength of wetting fronts weakens with depth. This is best visualized by thinking of a wave. The water content rises quickly over a short period in the near surface soil after irrigation – similar to a wave with high amplitude and narrow base. As the wetting front propagates into the subsoil, a greater depth of soil is wetted, but the change in water content is less than at the surface. In other words the short duration steep wave turns into a low amplitude wave that moves more slowly. If the soil was near the upper drained

limit before irrigation and there is no evapotranspiration, the volume of water in each wave is approximately the same. The sensitivity of wetting front detectors relates to the amplitude of the wave that can be detected. The deeper the placement, the harder it becomes to detect the front.

Put another way, irrigation may be applied at 5 mm per hour for 5 hours. At a depth of 50 cm, the water may be moving at a rate of 0.5 mm/h over a period of 50 hours. At a depth of 100 cm, the water may be moving at a rate of 0.1 mm/h over a period of 250 hours. The FullStop WFD would record this front if it was placed above 50 cm, but not if it were placed at 100 cm depth, even though a similar amount of water passed each depth.

When fluxes are low, convergence by the funnel is less important than the need to counteract capillary emptying by the surrounding soil. In these cases, a pipe-like design is more appropriate than a funnel. Hence we developed the LongStop version of the wetting front detector.

There are three aspects to the sensitivity of a WFD.

1. the weakest front that they can detect, hence the minimum flux required to trigger
2. the speed of response to an arriving front
3. the rate at which the WFD equilibrates with the surrounding soil as the soil starts to dry

Convergence by the FullStop funnel gives it a very rapid response time to an approaching front (point 2), as long as the front is within its sensitivity range. The funnel also empties quickly as the soil dries, as there is a large cross sectional area and shallow depth (point 3). The FullStop is therefore suited to automatic control (rapid response), shallow placement (strong fronts) and solute monitoring (described later).

The sensitivity of LongStops has been shown to be related to its length, at least in the 3 to 6 kPa range, and is therefore much more sensitive than the FullStop (point 1). In theory we could detect any strength fronts, but there are practical limitations. We must keep the LongStops as short as possible – in other words define the minimum sensitivity that gives acceptable results. For example a 100 cm LongStop is more sensitive than a 60 cm one, but it is harder to install (a deeper hole is required) and it may require a more specialized fill material. This is because the material that fills the LongStop must have a high unsaturated conductivity at a suction equal to its length, so that it remains in hydraulic equilibrium with the surrounding soil during drying.

LongStops may suit flood irrigation better than the FullStops for two reasons. First, flood irrigators tend to apply a large amount of water at one time, so fairly deep placement is necessary. Second, when the soil is flooded, the structure of the soil plays a greater role in the infiltration speed and pattern compared to sprinkler and drip systems, which generally apply water at rates below the saturated hydraulic conductivity of the soil. LongStops can be installed with minimum impact on soil structure.

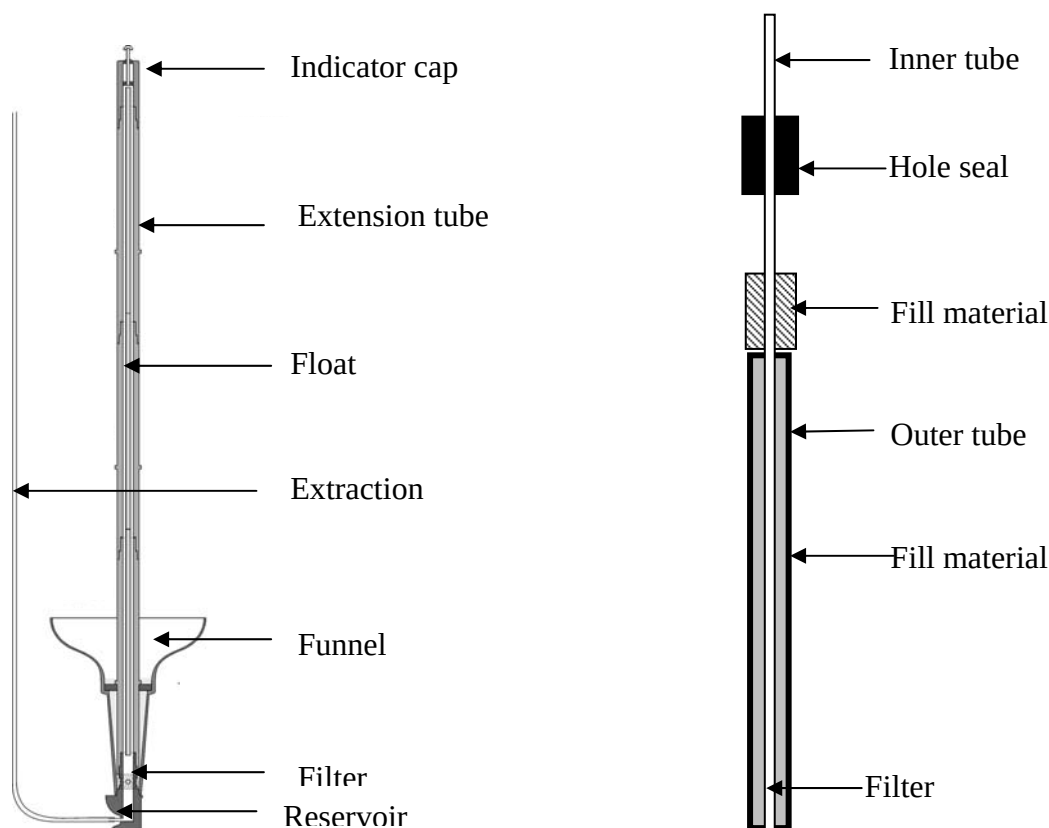


Fig. 1. Schematic of FullStop (left) and LongStop (right) Wetting Front Detectors. The FullStop is comprised of a 200 mm diameter x 250 depth funnel with extension tubes to the surface housing a float which activates a magnetically latched indicator above the soil surface. The LongStop is comprised of two concentric tubes, the outer 50 mm in diameter and the inner 20 mm in diameter. The length of the outer tube depends on the desired sensitivity and is filled with a porous material. The inner tube runs to the surface and shows the level of the watertable in the outer tube. In both designs saturation occurs at the base and water moves through a screen filter into a reservoir.

The experiment

The experiment was carried out at the Australian Cotton Research Institute research station (ACRI), Myall Vale, NSW. The soil is a self mulching grey Vertosol (clay percentage 50% dominated by smectites). The furrows were 200 m long. Cotton was planted in October 2005 and harvested in April 2006.

Two lengths of LongStop were compared, 60 and 100 cm, equating to sensitivities of 6 and 10 kPa respectively. These are referred to as LS_60 and LS_100. Each length LS was either filled with diatomaceous earth (d.e.) or a fine sand material. LongStops were

installed to monitor fronts passing depths of 50 and 100 cm at the head and tail end of the furrow. A total of thirty-two LongStops were installed (2 lengths x 2 fill materials x 2 depths x four replicates).

A 'push tube' was used to create a 50 mm diameter hole, which in the case of a LS₁₀₀ measuring at 100 cm depth, needed to be 200 cm deep. The LongStop was then inserted into the hole. Diatomaceous earth or fine sand (the same as the material filling the LS) was then poured down the hole to fill any gaps when the LS and the wall of the hole and to provide a 10 cm 'wick' above the LS. The role of the wick was to keep the LS and the soil in hydraulic equilibrium. Bentonite clay was added above the wick, so that no water could enter the LS via the soil disturbed soil. The water had to enter the LS radially via the wick immediately above it.

Six of the LongStop installations were monitored with Watermark capillary matrix sensors, so that soil water potential could be monitored on a four hourly basis. For each LS, one sensor was placed in the wick material just above the LS, and the other in the soil about 50 cm away at the same depth.

16 FullStop WFDs were also installed in the centre of the beds at depths of 25 and 50 cm below the depth of the furrow. Half the FullStop wetting front detectors were filled with the same fine sand as used in the LongStops and the other half were filled with soil. The reason for filling the FullStop funnels with fine sand was to prevent water moving down cracks and activating the FS without wetting the full soil profile above. The fine sand has a very high affinity for water, so if water was delivered to the funnel via a crack, the fine sand would wet up and transmit water to the surrounding soil, so that saturation would not occur at the base of the funnel until all the surround soil was wetted to about 2 kPa suction.

The FullStops were installed shortly after planting and six irrigation events were monitored through the season. It was not possible to get access to the fields for a day or two after irrigation. The position of the FullStop float was recorded (up/down) and the electrical conductivity of the water sample from the FullStop measured. The float was then reset before the next irrigation. Generally the float would not reset for several days, as the FullStops continued to hold water until the soil suction rose above 2 kPa suction.

The LongStop installation was completed later, and the last four irrigation events were monitored in the same way as the FullStops, except the volume of water captured by the LongStop was measured. The volume of water in the LongStop is related to the water level in the inner tube, hence the actual soil suction in the wick. After measurement of EC the water was returned to the LongStop.

Results

FullStop response:

All FullStop wetting front detectors responded to each irrigation event at both the 25 and 50 cm depths (Table 1). This was contrary to our expectations, as we did not expect strong fronts at 50 cm depth in the centre of the cotton beds.

Table 1. The number of FullStops activated for each depth and fill class at each of the six irrigations. The maximum number in each class is 4.

WFD Type	FullStop			
Depth	25 cm		50 cm	
Fill	Soil	Sand	Soil	Sand
14 Dec 05	4	4	4	4
29 Dec 05	4	4	4	4
14 Jan 06	4	4	4	4
30 Jan 06	4	4	4	4
14 Feb 06	4	4	4	4
1 March 06	4	4	4	4

The possibility of preferential flow to the detector is the most obvious reason for a ‘false positive’. Preferential flow was most likely early in the season, before the soil had settled after installation. The elapsed time between the water in the furrow reaching the position of the FullStop down the row, and the FullStop triggering, was measured for the first irrigation. On average it took almost the same time for the water to trigger the 25 and 50 cm FullStops (33 and 35 minutes respectively), but it should be noted that the water had to move horizontally towards the centre of the row, which may account for the similar response times. Filling the funnel with fine sand slightly lengthened the response time, and the response time was much faster at the head compared to the tail end (Table 2).

Table 2. The elapsed time between the water in the furrow reaching the position of the FullStop down the row, and the FullStop response as a function of depth, fill material and position in the row

		Time to trigger (minutes)
Depth	25 cm	33
	50 cm	35
Fill material	Fine sand	37
	Clay Soil	31
Position	Head	26
	Tail	42

The time it takes for the FullStop to empty of water after irrigation tells us something about how waterlogged the soil is. The FullStop only starts to empty by capillarity once the soil suction rises above 2 kPa. At the start of the season, when evapotranspiration was low, 6 of the 8 shallow FullStops could not be reset 5 days after irrigation i.e. they still contained more than 20 ml water. None of the FullStops at 50 cm depth could be reset. In contrast, 1 FullStop at 25 cm and 6 at 50 cm depth could not be reset after 3 days following the final irrigation.

FullStop Electrical Conductivity:

The electrical conductivity of the water sampled by the FullStop fell from around 1.5 dS/m to around 0.6 dS/m between December and March. Slightly higher EC was recorded at 50 cm during the middle period (Figure 2a), and slightly higher EC at the tail end of the furrow (Figure 2b). We did not analyse the composition of the samples. Another researcher using FullStops on the research station recorded similar EC levels containing nitrate in the range of 250 to 500 mg/l.

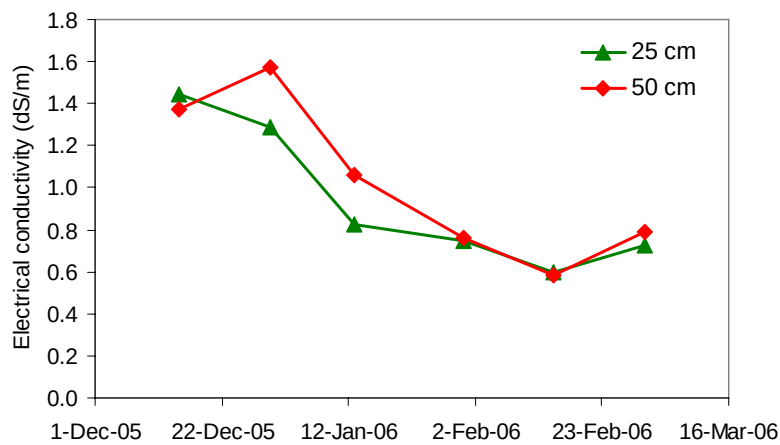


Figure 2 a. The change in electrical conductivity at 25 and 50 cm depths through the season

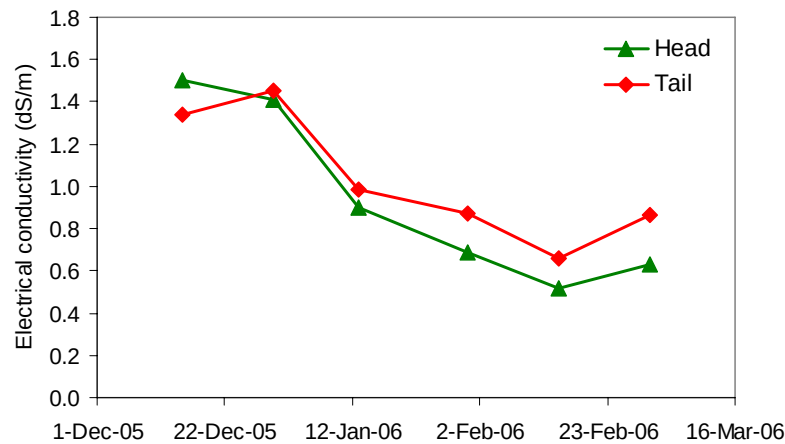


Figure 2 b. The change in electrical conductivity at head and tail ends of the furrow through the season

LongStop response:

Unlike the FullStops, the response rate of LongStops at 50 cm depth was not 100%. Ignoring the final irrigation event, which was a ‘small irrigation’, the response rate of diatomaceous earth LSs was just over 75% and considerably lower for the sand filled LSs. At 100 cm depth about one third of the LSs were triggered by irrigation.

Table 3. The number of LongStops activated for each depth, length and fill class at each of the four irrigations. The maximum number in each class is 4.

WFD Type	LongStop							
Depth	50 cm				100 cm			
Length	60 cm		100 cm		60 cm		100 cm	
Fill	d.e.	sand	d.e.	Sand	d.e.	Sand	d.e.	sand
14 Jan 06	3	1	3	2	0	0	0	0
30 Jan 06	3	1	3	3	1	1	1	2
14 Feb 06	3	2	4	4	2	1	2	2
1 March 06	0	0	1	1	2	0	1	1

A more detailed analysis of LS performance can be gained from comparing the minimum suction in the wick of the LongStop with the volume of water collected by the LongStop at the time of sampling. According to theory, if the suction in the wick of as LS_60 is less than 6 kPa, it should contain water. Similarly, if the suction in the wick of a LS_100 is less than 10 kPa, it should contain water, with the volume of water increasing as the suction tends towards zero. Although Watermark capillary matrix sensors are not considered to be very accurate in the 0-10 kPa range, the comparison of suction and volume does give a clearer picture (Table 4).

Table 4. The minimum suction in the wick material and the volume of water in the three instrumented LongStops at the time of sampling after irrigation at 50 cm depth. The shaded zone is described in the text. The numbers in parenthesis are the suction at the time the LS was monitored.

Irrigation	LS_60 d.e. fill		LS_60 sand fill		LS_100 sand fill	
	Suction (kPa)	Volume (ml)	Suction (kPa)	Volume (ml)	Suction (kPa)	Volume (ml)
1	2	65	4 (11)	2	2	70
2	3	22	5 (15)	0	3	45
3	3	35	5 (18)	0	3	90
4	11	0	25 (25)	0	17	2

Relatively strong fronts passed the 50 cm depth at all three locations, dropping the suction below 5 kPa, at least for the first three irrigation events. At the second site (LS_60 sand fill), the Watermark revealed that the minimum soil suction after irrigation was within LS sensitivity range, but no water was found in the LS (shaded area in Table 4). Although the logged soil suction record showed the soil at 50 cm depth fell below 6 kPa shortly after irrigation, the site could not be visited until two days after irrigation, by which time the soil suction had risen to between 11 and 18 kPa. At this suction all the water would be removed from the LS. Thus it is possible that the LS filled and emptied before it could be sampled. This problem was not experienced with the FullStop because of the magnetic latching of the indicator, which remains in the ‘up’ position after all the water has been removed by capillarity.

The Watermark sensors showed irrigation water did not penetrate to 100 cm in two of the three locations monitored at 100 cm depth, and correspondingly the LS at these two sites collected no water. At the third site the Watermark sensors recorded very weak fronts after irrigations one and four and fairly strong fronts after irrigation events two and three. These ‘stronger’ fronts were within the range of the adjacent LS, and it was triggered on both occasions (Table 5).

Table 5. The minimum suction in the wick material and the volume of water in the three instrumented LongStops at the time of sampling after irrigation at 100 cm depth.

Irrigation	LS 60 sand fill		LS 100 d.e. fill		LS 100 sand fill	
	kPa	ml	kPa	ml	kPa	ml
1	15	0	20	0	17	0
2	14	0	18	0	1	30
3	17	0	37	0	1	15
4	25	0	37	0	43	0

The complete suction and LS response over time is shown in Figures 3 and 4 on the following pages.

Depth 50 cm; LS_100; fill sand; Tail

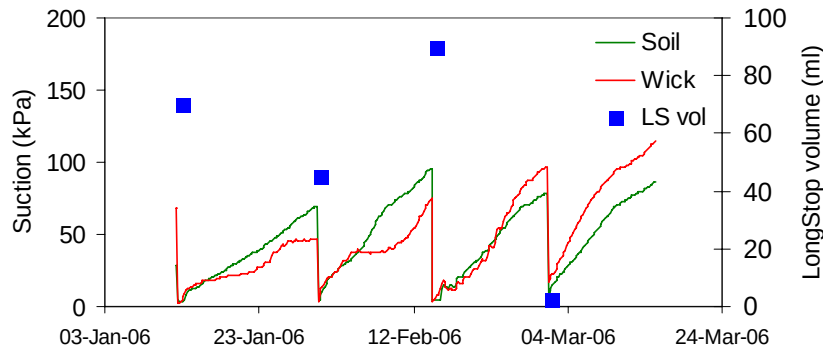


Figure 3a. Strong fronts recorded at 50 cm depth, with slight differences in the rate of soil drying in the soil and sand wick. LongStop (length 100 cm) collected water after the first three irrigation events but not the fourth.

Depth 50 cm; LS_60; fill sand; Tail

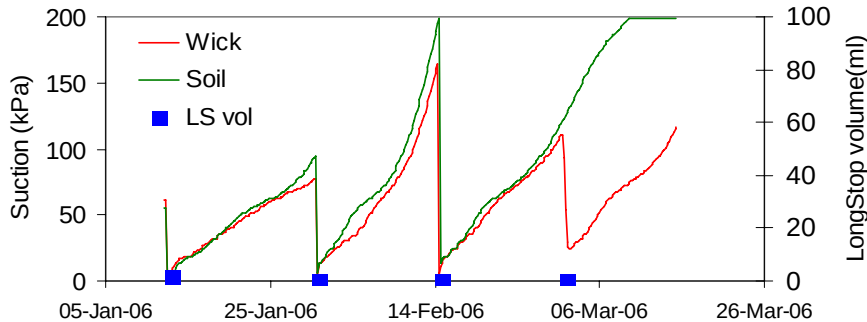


Figure 3b. Strong fronts observed at 50 cm depth, with similar rate of drying in the soil and sand wick. Last irrigation event recorded in wick not soil. No water collected in LongStop (length 60 cm).

Depth 50 cm; LS_60; fill d.e.; Head

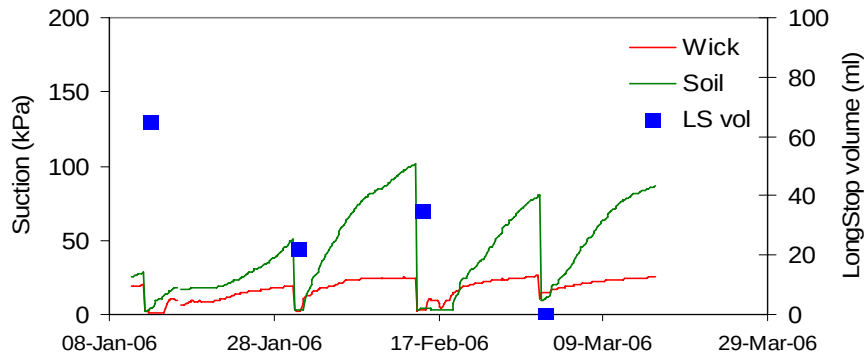


Figure 3c. Soil wetter in diatomaceous earth wick than soil. LongStop (length 60 cm) collected water for first three irrigation events but not the fourth.

Depth 100 cm; LS_60; fill sand; Head

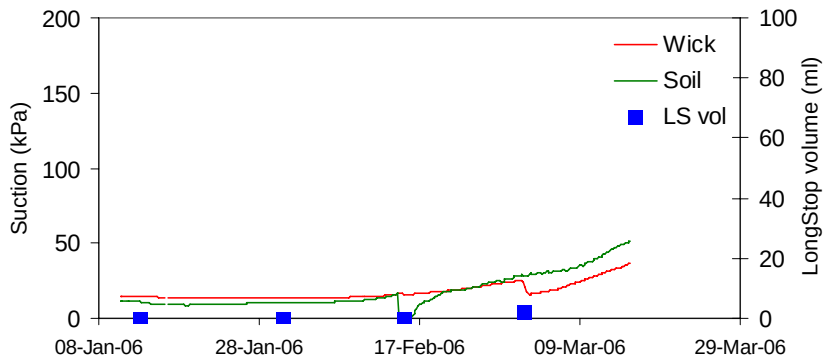


Figure 4a. One front recorded in soil and one weak front in sand wick material at 100 cm depth. Wet in both sand wick and soil and slow root extraction towards the end of the season. No water recorded in LongStop (length 60 cm)

Depth 100; LS_100; fill sand; Tail

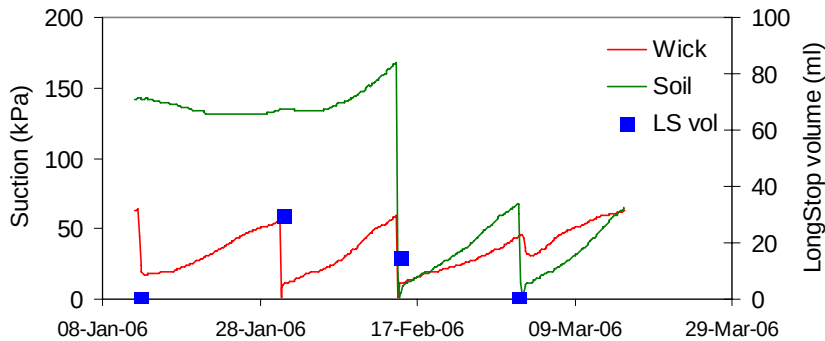


Figure 4b. Two strong fronts recorded at 100 cm depth in sand wick and two in soil. LongStop collected water on two occasions.

Depth 100 cm; LS_100; fill d.e.; Head

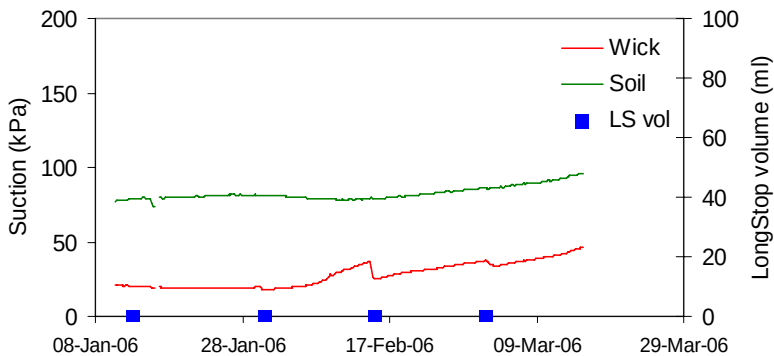


Figure 4c. No front recorded at 100 cm depth and soil wetter in diatomaceous wick than soil. No water recorded in LongStop (length 100 cm)

Discussion

The FullStop WFD responded to every irrigation event, which was not expected. Although preferential flow may have contributed to this, there are reasons why it is matrix flow appears to dominate. First, the FullStops filled with fine sand contained almost 2000g of material that needed an 18% change in water content to move from 10 kPa to saturation – or 360 ml. If a crack delivered water to the sand in the funnel, then the wet sand would be in contact with 300 cm² of dry soil, which would effectively remove water from the funnel. Second, the FullStops could not be reset for several days after irrigation. If the FullStops were triggered by preferential flow, they should self empty quickly after irrigation because the soil around them would not be saturated. Third, the EC in the water collected by the FullStop was 2 to 5 times higher than the irrigation water, suggesting that nutrients or salt were mobilized by matrix flow.

It is not clear why fewer LongStops were activated at a depth of 50 cm than FullStops. Where Watermark sensors were placed next to the LongStops, the results were in agreement, apart from the one case where it appears that the LongStop self-emptied before it could be sampled. In the LS_60 class at 50 cm depth, the diatomaceous earth fill appeared superior to the sand fill, possibly because it is slower to empty. A second reason for non-response of certain LSs may be due to the fact that the push tube smeared the soil surrounding the hole at installation. This smeared surface may present a barrier to the movement of water between the soil and LS. As the soil undergoes wetting and drying cycles, the impact of smearing should be reduced.

The performance of LongStops at 100 cm depths was consistent with the Watermark Soil water potential sensors. Wetting fronts reached 100 cm depths on about one third of occasions and the response rate was approximately 30%.

Conclusion:

The trial demonstrated a successful ‘proof of concept’ for WFDs under furrow irrigated cotton on cracking clay soils. The utility of the FullStop WFD is likely to lie more in the solute monitoring capability than wetting front monitoring. This is because large, infrequent irrigations are given, which penetrate well below 50 cm depth. FullStops are not ideally suited to deep placements. The value of the FullStop as an indicator of waterlogging could also be of importance to the cotton industry, as this is known to limit yields.

The LongStops performed according to theory and were able to detect weak wetting fronts at depth. They could be used to show irrigators the time period when the soil is wetter than a given suction. The variable tension lysimeter at ACRI will provide the relationship between drainage rate and suction for these soils, from which a ‘threshold’ suction can be derived. The LongStop length could then be set as a ‘switch’, to show the irrigator when they had passed this threshold suction.

APPENDIX: Properties of fill materials:

A LongStop is essentially two concentric tubes. The outer tube is filled with a porous material and the inner tube is filled with air, with the tubes connected via a screen filter near the base. If both tubes were filled with water, the porous material in the outer ring would be saturated and the water in the inner tube would be level with the top of the instrument.

If the LS was buried in the soil, the drier soil would ‘suck’ water out of the porous material in the outer ring, and the water level in the inner tube would fall. The amount of water the surrounding soil could remove from the LS depends on the matric potential or suction of the soil. Suction is measured in pressure units or height (1 kPa = 10 cm). Therefore if the soil is at 5 kPa suction, it can drop the watertable inside the LS by 50 cm. If the soil was drier than 100 cm, it could remove all the free water from inside the LS. This is why the measuring range or sensitivity of the LS is set by its length.

The LS must be filled with a material with a high hydraulic conductivity. If the soil is drying rapidly around the LS, the material in the LS must be able to remove water sufficiently fast such that the suction in the soil equals the depth to the water level in the inner tube. Since the hydraulic conductivity decreases rapidly as suction increases, it is important that the fill material has a high conductivity at a suction equal to its length.

Two fill materials were used. Diatomaceous earth is well known for its high hydraulic conductivity. Although the particle size is quite large, it has a micro-structure giving a dense network of fine interconnecting pores. The fine sand material contained 50% particles less than 100 micron by mass (Figure 5).

The water release characteristics of the fill material influence the response time. Diatomaceous packs at a very low bulk density earth having a porosity of around 83%. When the LS_100 was saturated, the volumetric water content was $0.82 \text{ m}^3/\text{m}^3$, and fell to only $0.80 \text{ m}^3/\text{m}^3$ as the suction falls to 100 cm. Thus the d.e. remains almost completely saturated over the 0-100 cm suction range, meaning that only a small amount of water needs to be collected for a large change in volume in the inner tube (Figure 6).

The volumetric water content of the fine sand falls from $0.45 \text{ m}^3/\text{m}^3$ to $0.19 \text{ m}^3/\text{m}^3$ over the 0-100 cm suction range, so much more water needs to enter and fill the material to give a corresponding change in the level of water in the inner tube. This may delay the response time of the instrument and account for the differences observed in the field.

If the soil dries much more than 100 cm, then there is a large reservoir of water inside a d.e. LS, which may keep the soil artificially wet around the wick. This would not be such an issue for the fine sand. The suction measured by Watermark sensors certainly differed between the d.e. wick and the bulk soil, although this may also be due to the salinity of d.e.

Diatomaceous earth is difficult to pack and may shrink on drying in the tube, leaving air gaps that would break the hydraulic continuity required for the instrument to operate properly. A sand replacement with suitable hydraulic properties would be required if there is going to be widespread use of the device. This study suggests that the fine sands used does not have the optimal hydraulic properties.

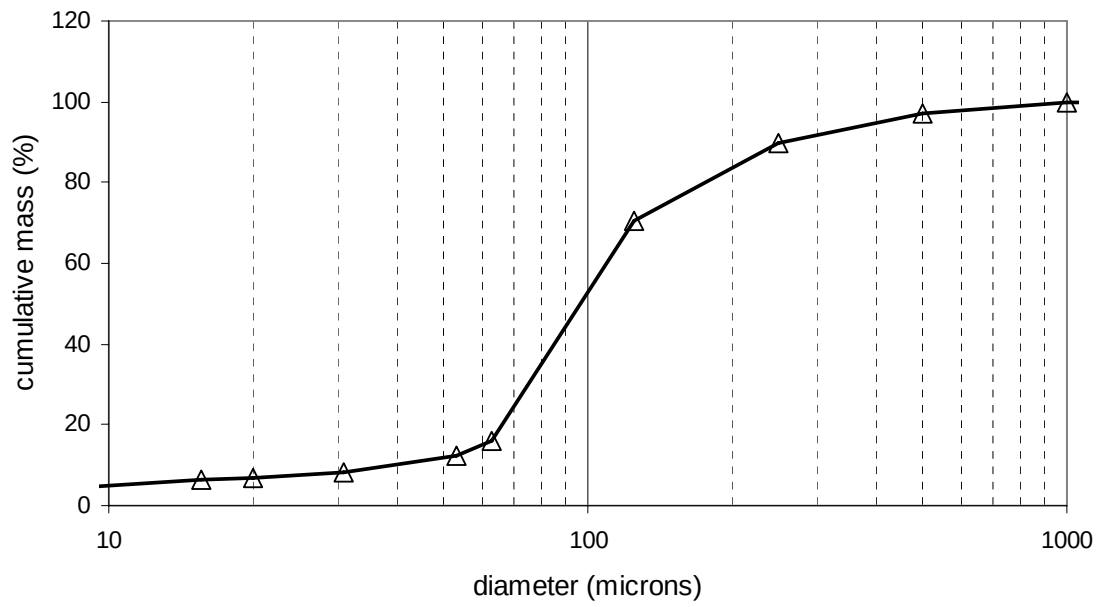


Figure 5. Particle size of the fine sand used in the LongStops

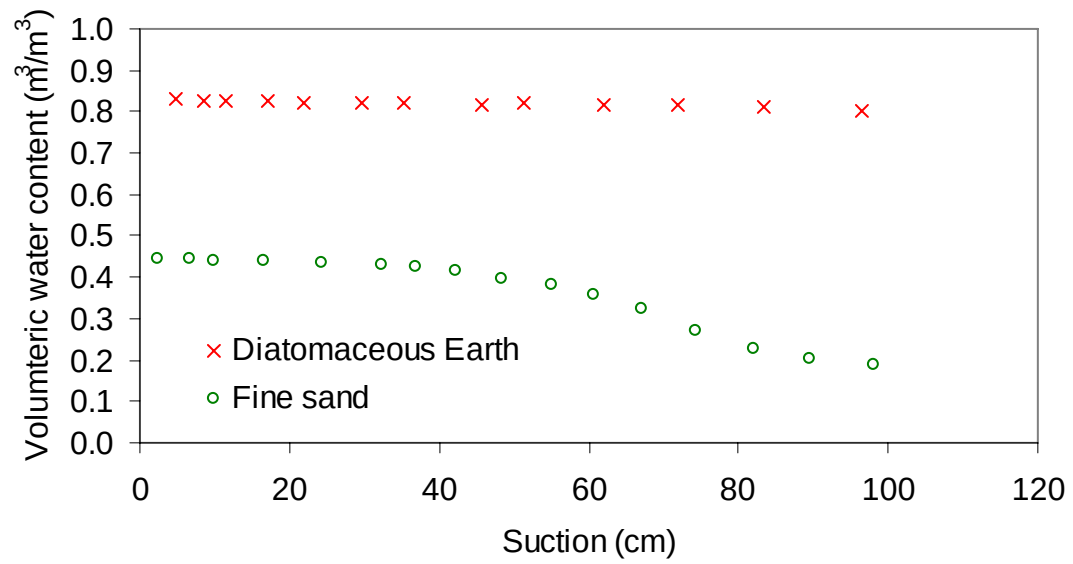


Figure 6. The volumetric water content of fine sand and diatomaceous earth over the 0 to 100 cm suction range