Irrigation control with feedback loops

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Abstract

Applying excessive irrigation amounts is common. There is a need for a common tool which indicates sufficiency of added amount of water. Sufficient irrigation amounts is that amount that which would result in wetting the soil profile down to the bottom of the active root zone up to the water content of field capacity. Use of this definition as a control objective is problematic since this result is reached only after cessation of irrigation.

We define an irrigation objective as the depth of the wetting front to stop irrigation so that the final depth of the redistribution front would stop at the bottom of the root zone. We developed algorithms that form a closed feedback loop with a learning trial and error procedure that helps to find the optimal depth of the wetting front to stop irrigation. An input to the system is the planned final depth of the redistribution front. The system then conducts a series of trial and error field tests where a wetting front depth to stop irrigation is selected and retested. The measured final depth of the redistribution front is compared with the planned final depth. Successive corrections of next depth of the wetting front are made until the planned final redistribution depth is reached.

A dedicated wetting depth probe to track the location of the wetting and drainage fronts is presented. Also, the logic sequence for selection of the optimal wetting depth to stop irrigation and the results from a series of field trials are presented. The irrigation control with feedback was tested under real conditions during the last four years in a avocado plantation, an olive grove, a paulownia tree plantation and in selected urban sites. Savings of irrigation water in the range of 30 to 50 percent in comparison to irrigation amount using conventional practices were measured. Results from these field trials are presented and analyzed.

Introduction

The practice of water application for the irrigation of plants often results in the application of excessive amounts of water because of a number of reasons. First, the estimate of the amount of water to apply involves a number of errors. Second, the location of the depth of the bottom of the active root zone in real time is often a wild guess. Above all, a procedure to verify whether the amount of water applied is sufficient, deficient or excessive, is practically non existent.

Irrigation amount was traditionally estimated on the basis of direct soil water sampling. Presently, it is sometimes estimated using dedicated soil water sensors but mainly by estimating irrigation amounts based on the measurements of weather parameters related to water evaporation. Clearly, all methods involve significant errors often resulting in the application of excessive or deficient amounts of water.

We examine here the possibility of replacing the irrigation amount as an irrigation control parameter with the final depth of the redistribution front. The justification for this substitution is that the final depth of the redistribution front in a given soil profile is closely related to the amount of water applied during irrigation. At a first glance this alternative is impractical because the redistribution front reaches its stable depth hours or even days after irrigation is terminated. In addition, we presently lack the methodology to estimate in real time two closely related parameters, the final depth of the drainage following irrigation and the depth of the bottom of the active root zone.

The conceptual, technological and practical solution to the realization of this alternative is the heart of our irrigation control with feedback loops system and is the objective of this presentation.

Theory

Final depth of the redistribution front as an irrigation control parameter

The water balance of a soil profile, following wetting at its surface by rain or irrigation, involves three stages, the wetting stage, the redistribution and the drying stage.

During the wetting stage water reaching the soil surface moves downward in a piston like movement, wetting each layer to a maximal value before advancing to the next layer. Under conditions when the water is being applied to the soil surface at a constant rate, the rate of advance of the often visible wetting front moves down the soil profile at an essentially constant rate. The actual rate of advance depends on soil texture, initial soil water content and on the water application rate. The velocity of advance of the wetting front is normally in the range of 5 to 20 cm. per hour and the duration of wetting stage is in the range of fractions to full hours.

The redistribution stage starts when water application stops. It is characterized by two processes taking place at the same time. Soil layers above the final wetting front are gradually draining as a result of the downward movement of excess water in response to gravitational forces. Soil layers below the location of the final wetting front are being wetted up in response to the movement of the drainage water from the wetted soil depths. Both the rates of the drainage of the previously wetted soil layers as well as the rates of wetting of the deeper soil layers are gradually diminished.

The downward movement of the redistribution front below the final location of the wetting front is of special interest since it determines the final depth of the wetted soil profile following irrigation.

The redistribution front is identified as a soil layer, below the wetting front, where its soil water content gradually increases following cessation of irrigation. Its rate of downward advance decreases with time and reaches a practical stop at deeper soil layers. The final, stable, depth of the redistribution front is influenced by soil properties and by the location of the wetting front at the end of irrigation.

The stage of soil drying, as a result of water uptake by roots (or evaporative drying), takes place all the time. It becomes the major process responsible for changes in the soil water content along the soil profile, when the redistribution stage is reaching a relatively slow rate in comparison to the drying rate. The relative rate of soil drying is related to the rate of water loss by the canopy and to the density of roots in the soil layer.

The soil drying front is identified by a significant decrease in the water content of a soil layer. It was reported to move downward in field crops in parallel to the downward movement of new active roots. For fruit trees with a relatively stable root distribution, the rate of soil drying is closely related to the density of active roots and to climatic conditions.

Based on the above analysis, it is proposed to control the final depth of the redistribution front (the final depth of the wetted profile and thus the irrigation amount) by the selection of the correct depth of the wetting front to stop irrigation.

When to stop irrigation

A search for a depth of the wetting front to stop irrigation that would bring to a stop the drainage front at the known bottom of the active root zone.

It is assumed here that the final depth of the redistribution front, for a given soil profile, Z_F, depends mainly on the depth of the wetting front at the end of irrigation, Z_I, (which is function of the quantity of water applied). Initial attempts to develop a theoretical relationship between, Z_I, and, Z_F, were unsuccessful, especially when tested experimentally under realistic conditions. Clearly, the relationships between these two parameters is rather complex and is being influenced by a large number of factors that could not be quantified (soil texture, soil structure, profile uniformity, presence of less permeable soil layers etc.). Thus, the theoretical estimation of an optimal value of, Z_I, to stop irrigation, so that the resulting final depth of the redistribution front, Z_F, would reach the bottom of the active root zone in real time is not a realistic control objective.

The solution to this interesting problem was to develop a series of algorithms that would function as a question and answer learning system that could play a guessing game in order to find the correct value of Z_{Ii}. As a first step, the planned final depth of the redistribution front, Z_F, based on real time knowledge of the location of the bottom of the active root zone is established. Than, a first test value of Z_{Ii} is selected, irrigation is initiated and than stopped when the wetting front reaches the first test depth Z_{Ii}. The location of the redistribution front is tracked in real time until its final stable depth Z_{Fi}, is reached. A comparison is made between the planned and the measured values. If Z_{Fi} is deeper than Z_F, too much water was applied. Then, the next test wetting front depth to stop irrigation, Z_{Ii+1} will be shallower than the first one, less water to apply. If Z_{Fi} is shallower than Z_F , too little water, then the next wetting front test depth to stop irrigation would be deeper than the first test value.
These trial and error tests are repeated until the optimal value of Z_{Ii} is found (it takes two to three iterations). This learning process is repeated prior to each irrigation cycle.

When to start irrigation

The time to start irrigation determines the maximum value of water deficit developed in the crop. The relationships between the level of crop deficit and the various yield expressions are complex. Thus, it is presently quite difficult to time irrigation based on a specific measure of crop water deficit. In our present irrigation control system we take advantage of the detailed information concerning root activity as a function of soil depth (slope of water extraction by the sensors along the probe). Accordingly, we have developed a start irrigation algorithm where the soil layer-sensor depth-where maximum root activity takes place is an input to the system. A start irrigation command is issued when change in the sensor's reading, since the end of the drainage stage, is a predetermined percent value .The higher the percent the longer is the time to start next irrigation.

Logic of the control irrigation system with feedback

1. Input value of Z_F, planned final depth of redistribution front at bottom of active root zone.
2. Input value of Z_{RM}, depth of layer with maximum root activity.
3. Input value of threshold percent change in resistance value during drying stage of sensor at depth Z_{RM} since end of drainage stage to start irrigation
4. Input value of delta R, threshold percent change in resistance of sensor reading to identify arrival of wetting or drainage fronts.
5. Select first value of Z_{Ii}, depth of wetting front to stop irrigation.

6. Start first irrigation.

7. Scan sensors along depth probe every two minutes during wetting stage to track Z_{Ii} the location of the wetting front.

8. Scan probe until sensor Z_{Ii} is identified.

9. Stop irrigation.

10. Scan sensors below depth of wetting front every eight minutes for Z_{Fi}, redistribution front position.

11. Locate probe with Z_{Fi} actual final depth of redistribution front.

12. If depth of Z_{Fi} is larger than the planned final depth Z_F, excess irrigation, than next depth of wetting front to stop irrigation, Z_{Ii+1} would be shallower than Z_{Ii} . If Z_{Fi} is smaller than Z_F , deficient irrigation , than Z_{Ii+1} would be deeper than Z_{Ii} . If $Z_{Fi} = Z_F$ than $Z_{Ii+1} = Z_{Ii}$.

13. Scan resistance value of sensor at Z_{RM} , depth of maximal root activity.

14. If threshold value of resistance of sensor at Z_{RM} is reached than start irrigation.

This sequence is being repeated during each irrigation cycle

Experimental

A major requirement for the realization of this plan is the experimental ability to track the location of both the wetting front and the drainage front during an irrigation cycle. In addition, a procedure to obtain a measure of root activity as a function of soil depth must also be developed.

We have designed, constructed and field tested a depth probe capable of tracking the wetting and redistribution fronts as well as the rates of soil drying in real time. The depth probe, **Fig 1,** consists of a plastic cylindrical rod, 25mm outside diameter, on which metal rings, 10mm wide are imbedded at 50mm intervals. Each ring is connected by a conductive wire to a control box outside the probe. Each pair of rings makes up a sensor, the top of the first sensor is 4cm from the soil surface, the second at 10cm cm and top of the eights and last sensor is located 46cm from the soil surface. Using a dedicated circuit in the control box measures the electrical resistance between the adjacent pair of rings. When the depth probe is inserted into the soil, each sensor (adjacent pair of rings) measures the soil electrical impedance between the two rings. The soil electrical impedance is sensitive to its clay content, its water content, salt concentration in the soil solution and soil temperature. Clearly, we are not interested in an exact estimate of the water content of the surrounding soil. Rather, our interest is in the relative change in the impedance reading as a result of a relative change in the soil water content as a result of the arrival of the wetting front, the redistribution front as well as the soil drying as a result of water extraction by roots.

The sequence of data collection by the depth probe following irrigation is as follows:

Tracking the wetting front

Once a signal to start irrigation is outputted, the wetting stage stats. Because of the short time constant of the wetting process the sensors along the probe are scanned every two minutes and the system looks for a sudden five percent decrease in the impedance readings of each sensor indicating the arrival of the wetting front to the top of the sensor.
A realistic example of the tracking of the wetting front during the wetting stage – irrigation - is presented in **Figure 2.** A number of characteristics are apparent. First, the movement of the wetting front is orderly layer after layer and practically at a constant velocity. The time it takes for the wetting front to advance through a sensor for this soil is about one hour. During that time the reading of the impedance decrease at a constant rate and once the front reaches the bottom of a sensor the impedance value remains constant until the end of the wetting stage.

Tracking the redistribution front

When a command to stop irrigation is outputted, the scanning system moves to the drainage of the sensors above the wetting front and then to the redistribution stage in the layers below the wetting front where the probe is being scanned every eight minutes.
A realistic example of impedance readings of the sensors for a 12 hour period during the wetting and for about eight hours after irrigation stopped is presented **in Figure 3.** The impedance reading of the sensors along the probe after irrigation stop could be divided into two groups. For sensors located above the location of the final depth of the wetting front, 22cm, their impedance gradually increase indicating soil drying as a result of drainage of excess water. For sensors located below the depth of 22cm,(lower graph) their impedance readings decrease with time indicating that the surrounding soil layers ate being wetted as a result of redistribution. The process of wetting of the lower soil layers continues for some times after irrigation stopped until it reaches a practical end. The final wetting depth during redistribution, Z_{li} , was 40cm. When Z_{Fi} is located, the system reaches the end of the redistribution stage and the start of the drying stage. This stage lasts until the beginning of the next irrigation. The main data collection at this stage is scanning of the sensor located at the depth of the maximal root activity to indicate the time the threshold increase in its

impedance was completed. Once this point is reached a signal to start irrigation is issued by the control box to the solenoid valve.

Examples of the type of data being collected by the sensors along the depth probe during a conventional, non controlled, irrigation cycle for a heavy soil irrigated with mini sprinkles are presented in Figure 4 and with drippers in Figure 5.
The time changes of the eight sensors along the depth probe inserted in an avocado plantation during an irrigation cycle every two days using mini sprinklers are presented in **Figure 4.** All eight sensors, down to a depth of 52cm, responded to the irrigation event. Following irrigation cessation a slight decrease in the impedance readings of all sensors, as a result of drainage of excess water from all soil layers can be observed. About six hours after irrigation stopped the impedance readings of the sensors started to increase as a result of a decrease in the soil water content of the adjacent soil layers. For the sensors down to the depth of 28 cm the drying of the soil layers was mainly a result of water uptake by the avocado root system. The slow increase in the impedance readings of sensors below the depth of 34cm is probably due mainly to continuous slow drainage of soil water to deeper layers.
Based on these results it is suggested that most of active root system of the avocado tree extended down to a depth of about 34m only. Clearly, this avocado plantation was irrigated in a considerable excess of water.
An additional important conclusion from present result is the maximal activity of the avocado root system was located at the 10 to 16 cm depths.

Result from a wetting depth probe, inserted in the soil of an adjacent avocado field daily irrigated by a drip system, are presented in **Figure 5.** Generally, the time changes in the impedance readings of the eight sensors along the probe are similar to those presented in Figure 4. All the eight sensors respond to the advance wetting front every day. Because of the daily application of water, the slight decrease in the impedance readings of the sensors is not apparent and the soil drying process begins almost immediately. The soil drying pattern of all sensors down to the depth of 34 cm appears to be the result of water uptake by the active root system of the avocado trees. The impedance readings of the deeper sensors continue a pattern of additional decrease in their impedance readings as a result of continuous wetting of the soil layers down to the depth of 52cm. No doubt the drip irrigated soil is receiving excessive amounts of irrigation water. Based on the impedance readings of the sensors, slope of the time changes, the bottom of the active root zone is at 34cm. as observed in the section irrigated with mini sprinklers. The soil layers with the most active roots are located at the soil depth range of 28 to 34cm, deeper than that under mini sprinkler irrigation.

Using the results of frequent scanning the sensors along the depth probe, both the depth of the bottom of the active root zone as well as the depth range inhabited by the most active roots was demonstrated using the field results presented in Figures 4 and 5.

Results and Discussion

The irrigation control system with feedback loops has been under field testing since 2004. Normally the tests were conducted in cooperation with the local farm advisers and the measured weekly and seasonal water use in the test plots were compared with measured values from neighboring plots irrigated using local best practices. The amounts of water used by the test control areas were taken from records accumulated in the irrigation computer controlling the irrigation of the whole plantation. Field trials were conducted in an avocado plantation on a clay soil in kibbutz Yechiam, Western Galilee, an olive grove on a sandy loess soil, in kibbutz Revivim Southern Negev and a Paulownia tree plantation, on a sandy loam soil, kibbutz Givat Haim, coastal plane. The test plots were under the control of a solenoid valve which was normally operated by a central irrigation computer. The test area varied from one to four hectares. The sensors along the depth probes were frequently scanned, depending on the stage of soil wetting, and the data was stored in the control box and downloaded once a week to a lap top, analyzed and plotted. The figures showing field results normally cover a period of about 7 days only, this in order to demonstrate as many details as possible of the events taking place in real time. .

Results from an avocado field irrigated with mini sprinkles under our irrigation control with feedback system during October 2005, are presented **Figure 6.**
On the upper part of each figure are the time and duration of irrigation. Also in each parenthesis, the left number represents the sensor number located at the planned final wetting depth, Z_{Fi} , and the right figure represents the selected sensor number that will stop irrigation when detecting the arrival of the wetting front , Z_{Ii}. During the present test the planned final depth of wetting was at sensor number 5 – 34cm. The sensor number to stop irrigation was changing between 3 and 4 representing stopping depth of 22 and 28 cm. The lower figure highlights the behavior of the deeper sensors- soil layers.

At the end of first irrigation the impedance readings of sensor 5 indicate that the surrounding soil was not wetted by the redistribution front, see lower figure. The feedback system reacted and the sensor to stop irrigation changed to a deeper one, number 4. The immediate result was an increase in the duration of irrigation from 2.35 hours to 2.49 hours and the sensor at the planned final wetting depth indicated the redistribution front reached it, a significant decrease of its impedance reading. The wetting of sensor 5 was excessive and as a result the stopping sensor for next irrigation the sensor to stop irrigation was changed back to number 3 and the duration of next irrigation dropped accordingly.. This feedback control pattern repeated itself a number of times. The end result, see lower figure, is that the impedance readings of the deeper sensors at the 40 and 46 cm depths were

practically constant, with changes less then five percent in their value. This stability is the result of the feedback loop system and indicates that the leakage of soil water to deeper soil layers as a result of the application of excessive amounts of water was avoided. The percent saving of the measured water amounts applied under the irrigation control with feedback system compared to the measured water amounts applied to adjacent area irrigated using recommended practices was 35 percents.

The time changes in the sensor readings along the depth probe in a test area planted with olives and irrigated with drippers are presented in **Figure 7**. The solenoid valve of this area was under the control of our irrigation control with feedback system. The period presented in this Figure was that of 6 days at the end of October 2005. The planned final wetting depth was at sensor number 4 – 28cm and the sensor to stop irrigation was at sensor number 3 – 22cm. throughout the reported test period. The control system resulted in irrigation every two days during the test period.

The impedance reading of the sensor at 28cm, final wetting depth, and of the sensor at 34cm were practically stable with a slight tendency to dry. Under this situation the feedback control system did not see any reason to change the depth of the sensor that stops irrigation. The impedance readings of the sensors at 40cm and 46cm depths, see lower figure, were practically stable. Thus, no drainage of excess irrigation water was detected. The percent of saving of the measured water amounts in the test area under the control of the irrigation control with feedback loops during the test period was 42 percent compared to that measured in an adjacent area that was irrigated according to the best practices recommended by irrigation extension personnel.

Figure 8 presents the time changes in the impedance readings of sensors along a wetting depth probe inserted in a Paulownia tree plantation on a sandy loam soil during the first part of May 2007. The trees were irrigated with a drip system and irrigation was managed by the irrigation control with a feedback loop. Irrigation was initiated by the system every 4 days. The planned final wetting depth was by sensor number 4 at a depth of 28cm. The sensor to stop irrigation was changed by the control system between numbers 2 and 1 equivalent to depths of 10 and 16 cm.

During the first irrigation water application was stopped when sensor number 2 detected the arrival of the wetting front, irrigation lasted for one hour. The impedance reading of sensor number 4 dropped slightly as a result of the arrival of the redistribution front. Thus, next irrigation, the sensor to stop irrigation changed to a shallower soil depth, number 1. The result was that sensor 4 hardly sensed any change in its impedance and a fast correction to sensor number 2 was made and an additional irrigation followed. The total duration of water application was 75 minute. The impedance reading of sensor 4 decreased somewhat. For the next irrigation the feedback loop system changed the sensor to stop irrigation to the sensor at 10 cm. number 1. The duration of irrigation was 36 minutes and the impedance reading of the planned last stopping depth, sensor number 4, did not change.

The impedance readings of sensors at 40 and 46 cm along the depth probe hardly changed during the eight day test period indicating that the amounts of water applied were just enough to wet the planned last wetting depth. The percent saving of the measured irrigation amounts during the month of May by the test area compared to the irrigation amounts applied to the neighboring areas irrigated following the practices recommended by the local extension service was 47 percent.

Summary and Conclusions

The concept of using the planned final depth of the redistribution front following irrigation as a control objective was introduced and the difficulties discussed. Relationship between the location of the wetting front at the end of irrigation and the final depth of the redistribution front at the end of an irrigation cycle were analyzed. A set of algorithms forming a learning trial and error system was developed in order to select an optimal depth of the wetting front to stop irrigation. This choice should result in a final location of the redistribution front at the depth of the bottom of the active root zone.
Accordingly, sensors, equally spaced along a depth probe, capable of tracking the locations of the wetting front during irrigation and the locations of the redistribution front following irrigation were designed constructed and tested. In addition, a logical sequence of algorithms for the control with feedback of irrigation was developed.

The combination of a wetting depth probe and a control box was tested under realistic conditions. We have demonstrated the ability of the sensors along the probe to track in real time the position of the wetting front during irrigation and the location of the redistribution front following the end of irrigation. In addition, we have shown that by daily scanning of the sensors along a probe inserted in an irrigated soil with a growing crop, it is possible to locate the location of the bottom of the active root zone as well as the depths where the activity of the root system is at its maximal rate.

In Figures 4 and 5, measurements of the time changes of sensors placed along depth probes inserted in locations in an avocado plantation irrigated by mini sprinklers (fig.4) and irrigated by drippers (fig.5) during an irrigation cycle. The results demonstrate the ability of the data logging system to analyze the distribution of the active root system based on its ability to extract soil water as a function of soil depth. Also, the sufficiency of the application of irrigation amounts could be independently analyzed.

The time changes of the measured impedance readings of sensors along depth probes inserted in plots irrigated under the control of the irrigation control with feedback system were presented in Figure 6, avocado irrigated with mini sprinklers, in Figure 7, olive grove irrigated with drippers and in Figure 8, Paolownia tree plantation irrigated by drippers. In all presented field examples the effectiveness of the irrigation control with feedback system was apparent. First, in establishing a effective maximal final wetting depth at the bottom of the active root system. This

final wetting depth was maintained using the feedback loops by controlling the time, and thus the amount, to stop irrigation by the control of the optimal depth of the wetting front to stop irrigation. In all examples the depth of the sensor to stop irrigation was changed when needed in response to whether the redistribution front arrived or passed the planned final depth of wetting. As expected the induced changes in the depth of the location of the sensor to stop irrigation immediately affected the duration of the water application.

The results in all the field tests of the activity of the irrigation control with feedback system were:

1. The water content of the soil layers below the planned final wetting depth remained unchanged indicating that no excessive amounts of irrigation water were applied.
2. Substantial saving of irrigation water was achieved as a result of the application of our control system, 35% under the avocado plantation, 42% under the olive grove and 45% under the Paolownia tree plantation.
3. The danger of leaching of soluble salts to the water table as a result of the application of excessive amounts of irrigation water was minimized.
4. No damage to the test plants was apparent as a result of applying the irrigation control with feedback system

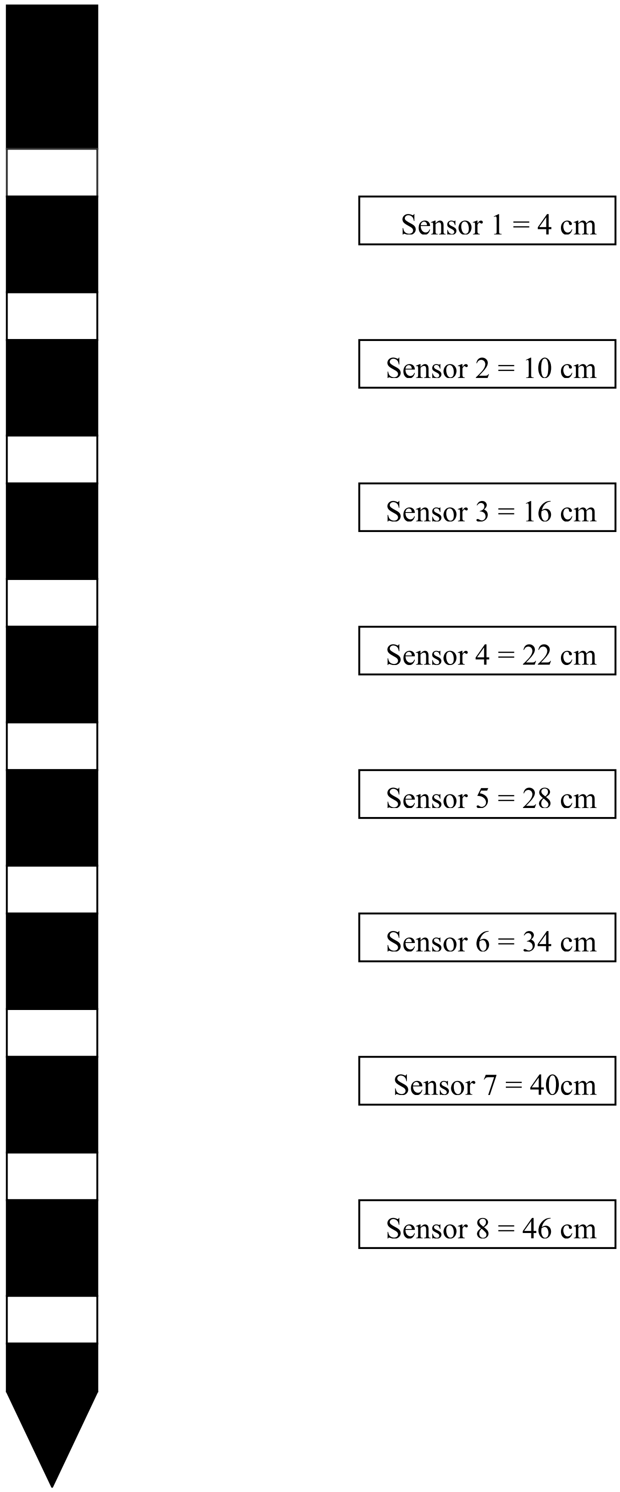


Fig. 1 – Wetting fronts depth probe

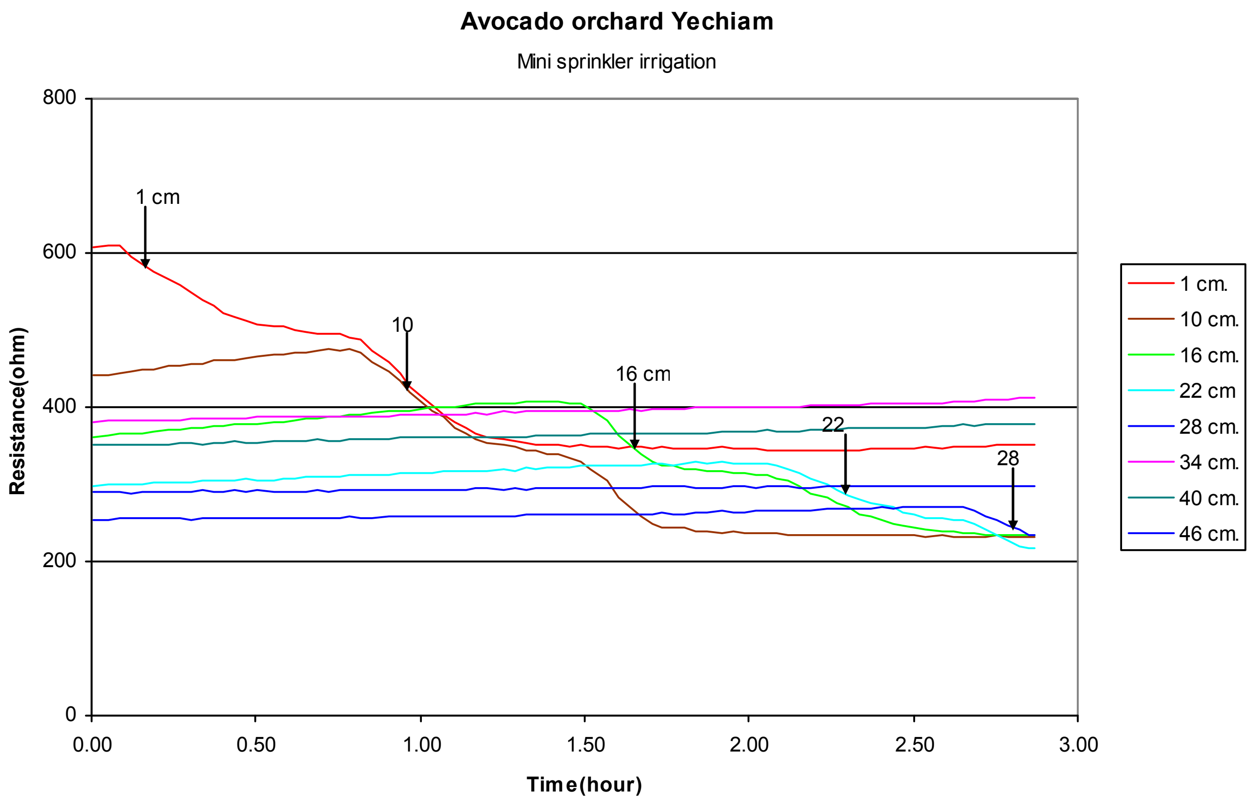
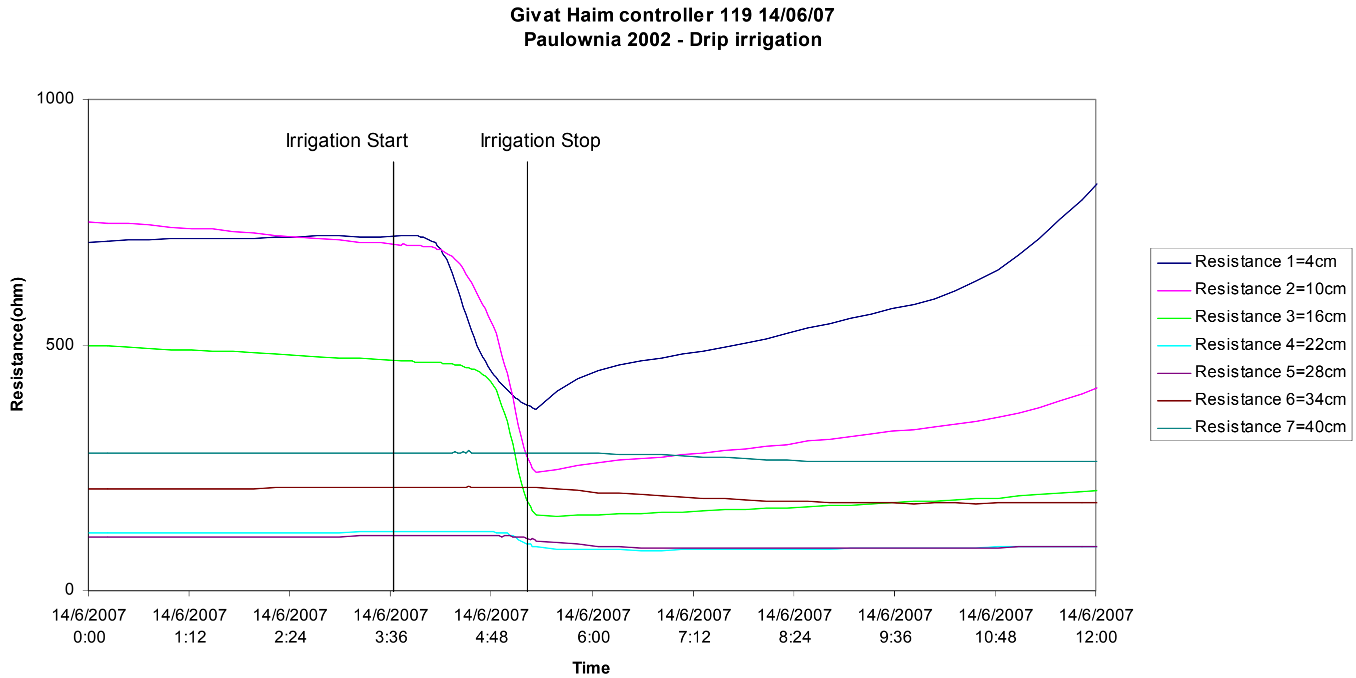


Fig. 2 – Tracking the position of the wetting front, field results.



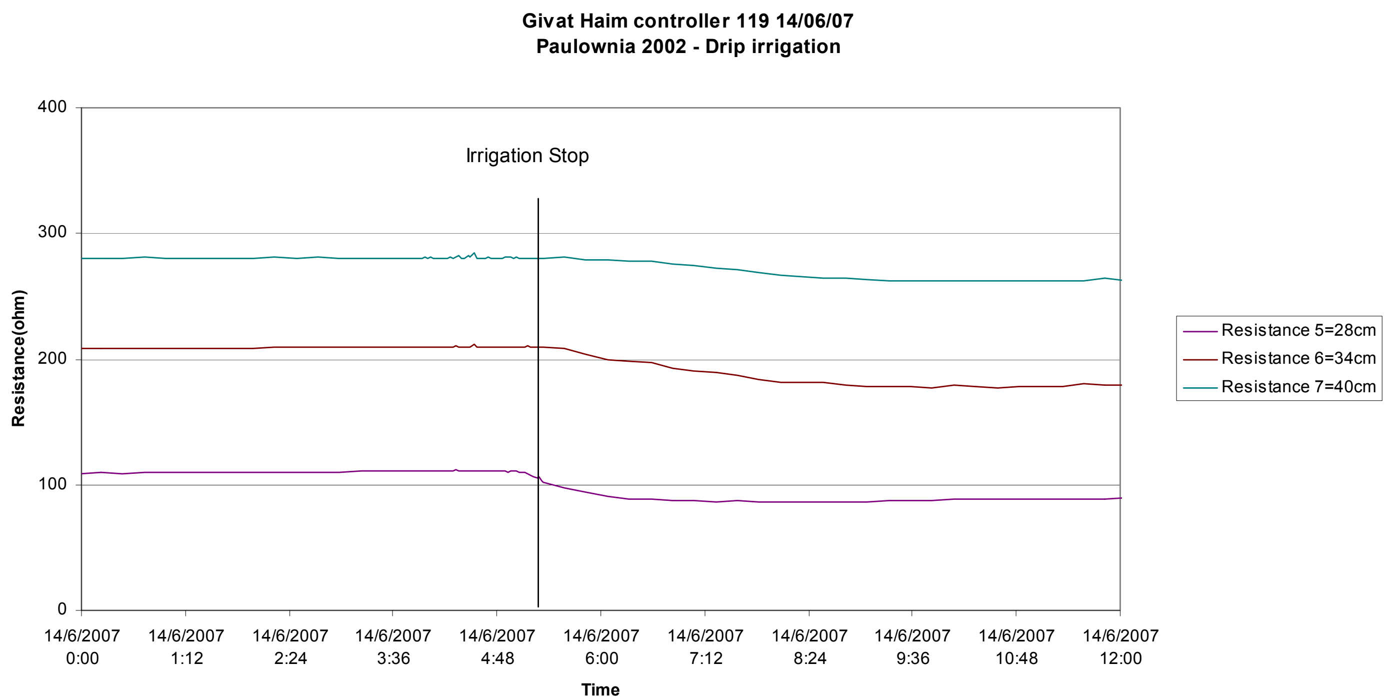
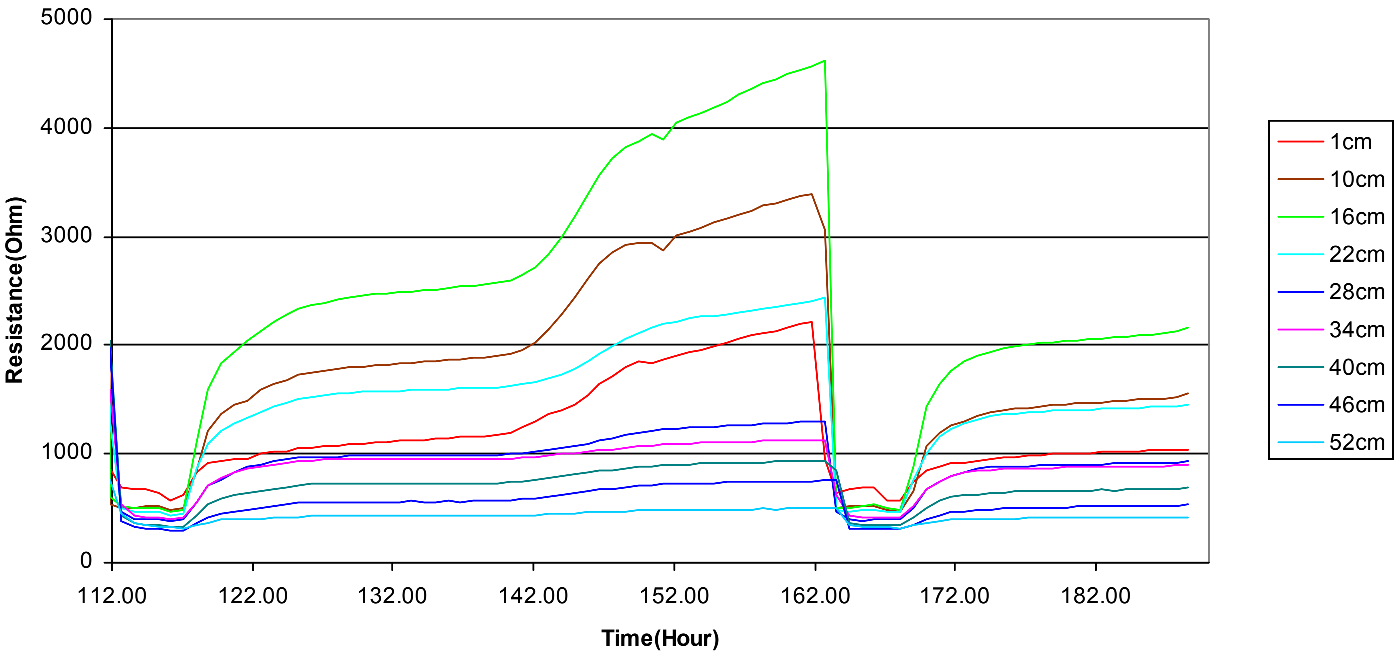


Fig. 3 – Tracking the drainage and redistribution fronts, field results.

Mini sprinkler irrigation



Mini sprinkler irrigation

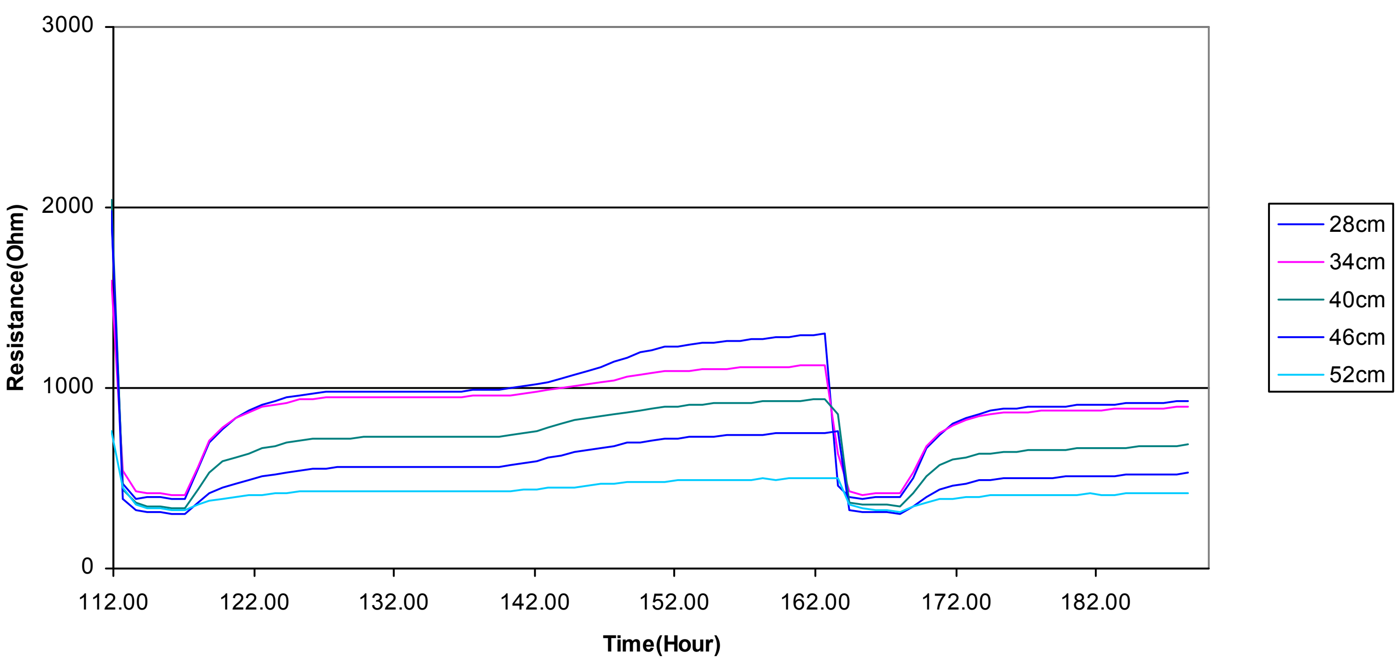
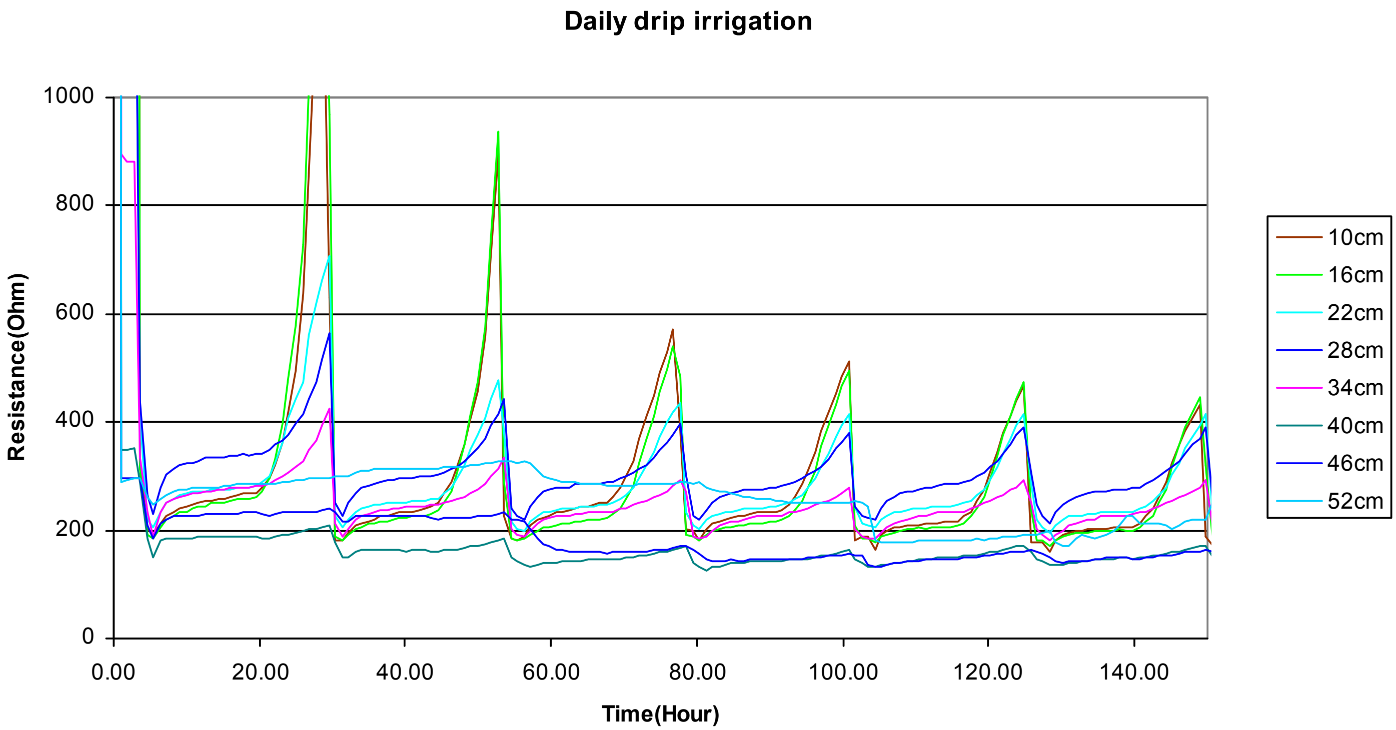


Fig. 4 – Time changes of the impedance by sensors along the probe.
Avocado, mini sprinkles, no control



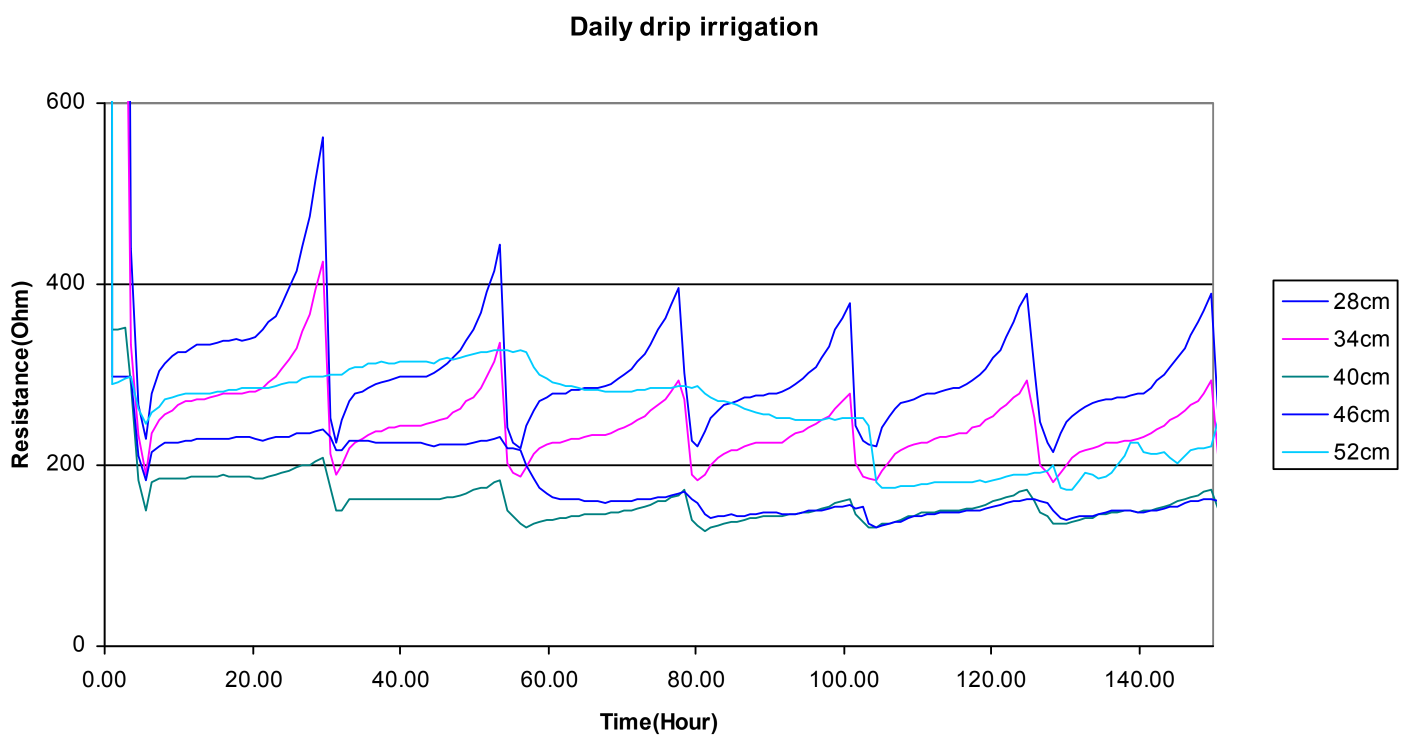
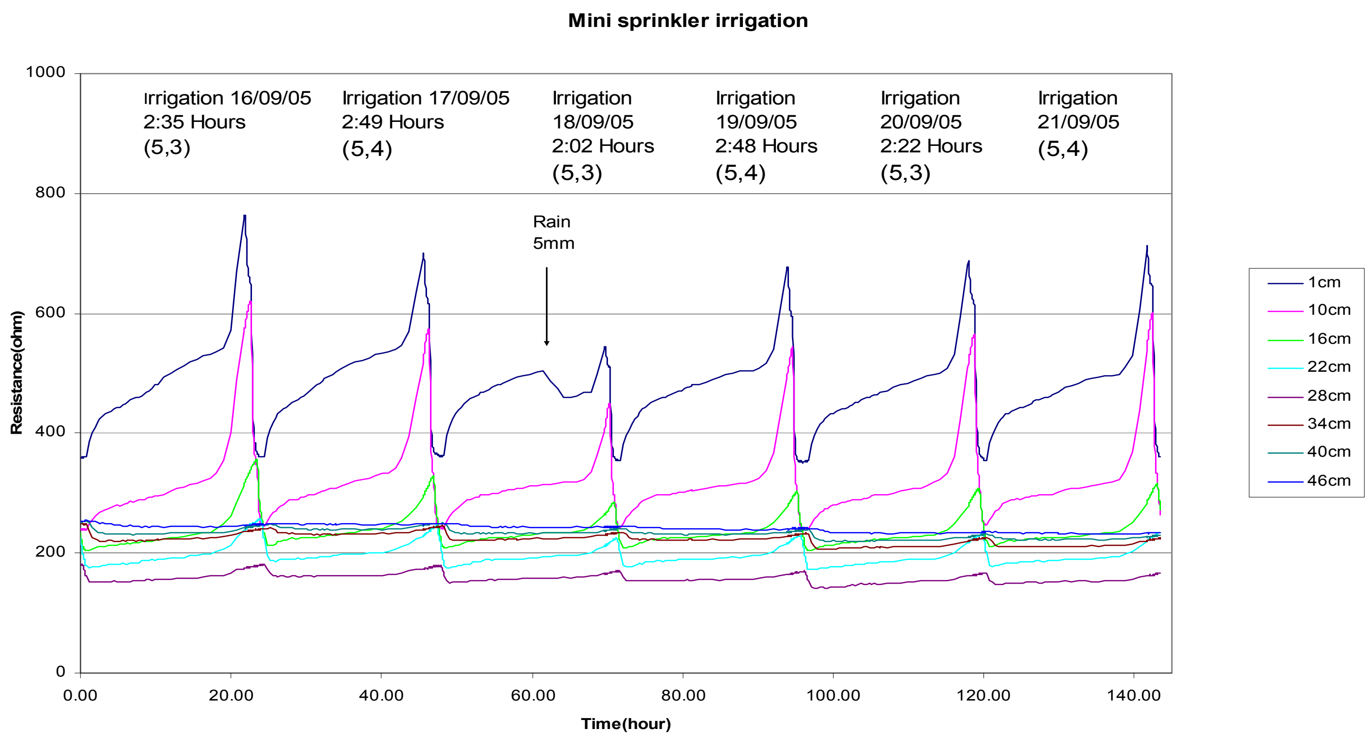


Fig. 5 – Time changes of the impedance by sensors along the probe.
Avocado, drippers, no control



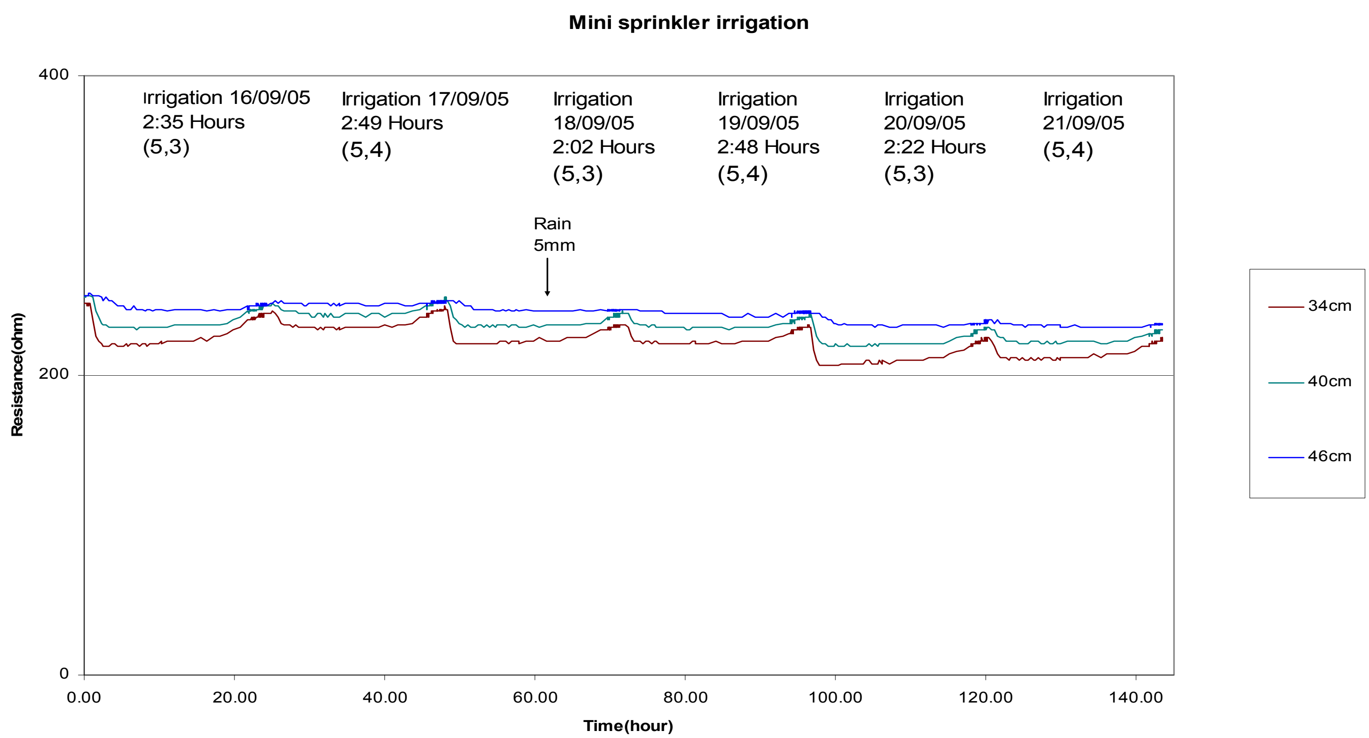
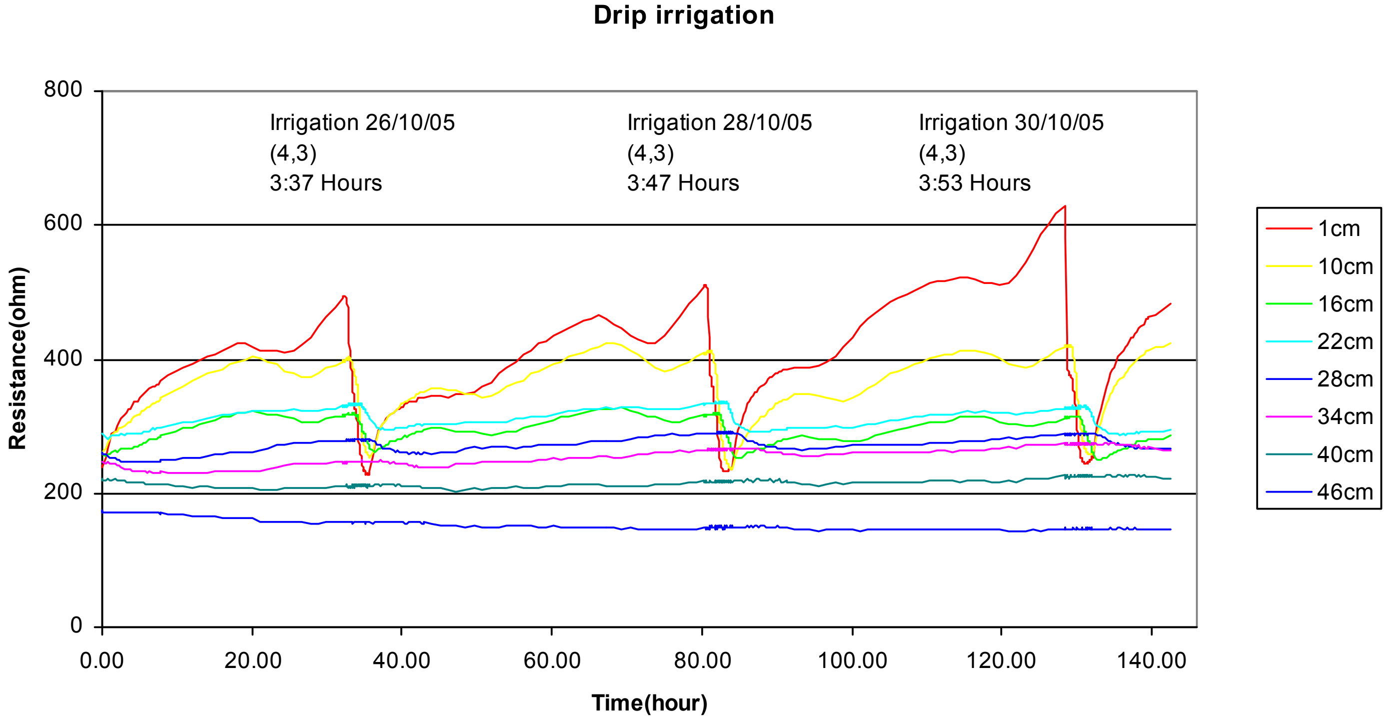


Fig. 6 – Time changes of the impedance by sensors along the probe.
Avocado, mini sprinklers, irrigation control with feedback.



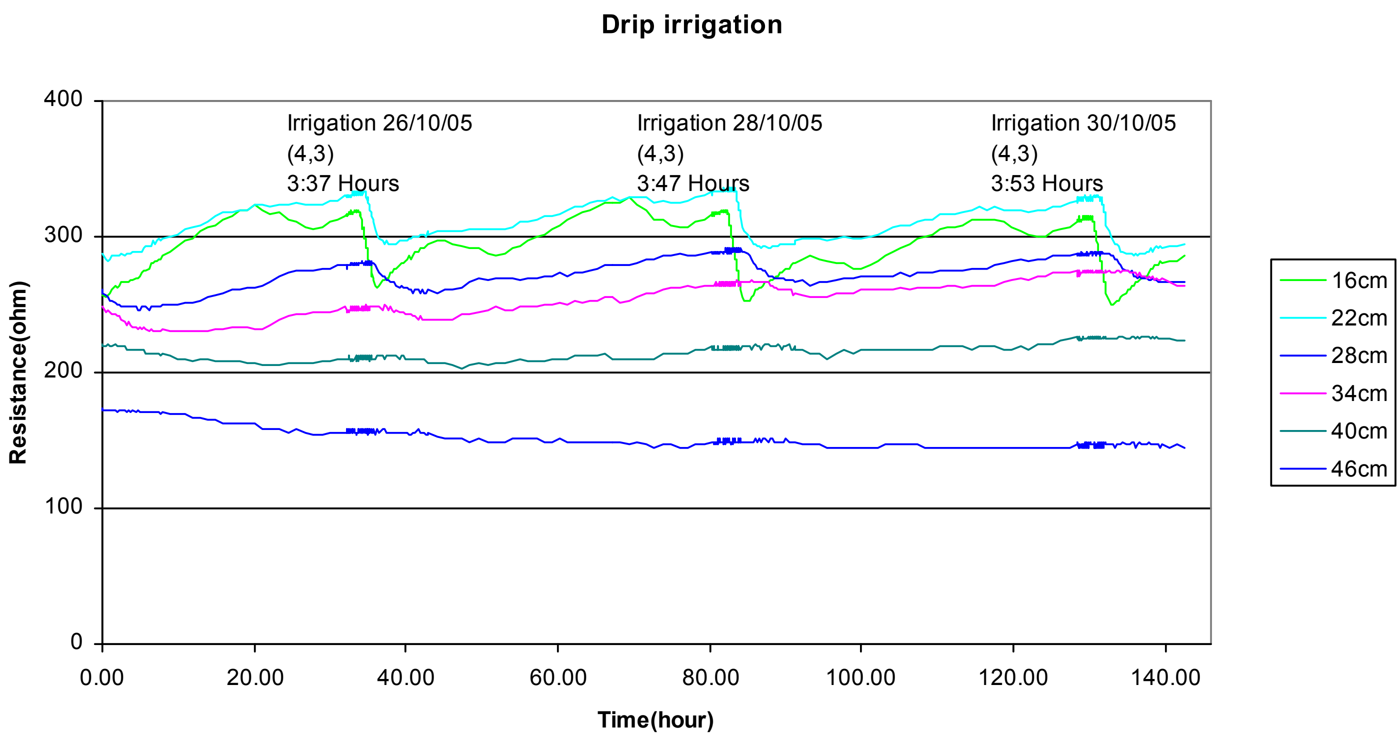
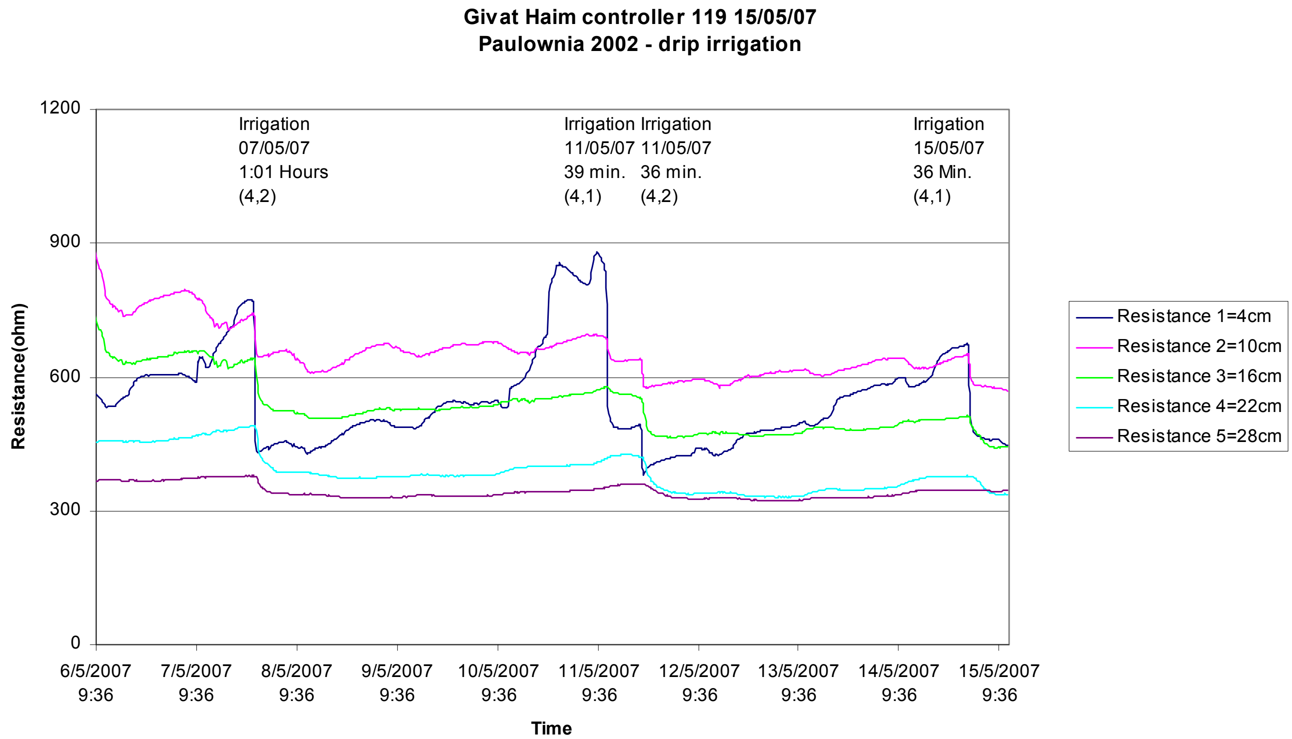


Fig. 7 – Time changes of the impedance by sensors along the probe.
Olive grove, drippers, irrigation control with feedback.



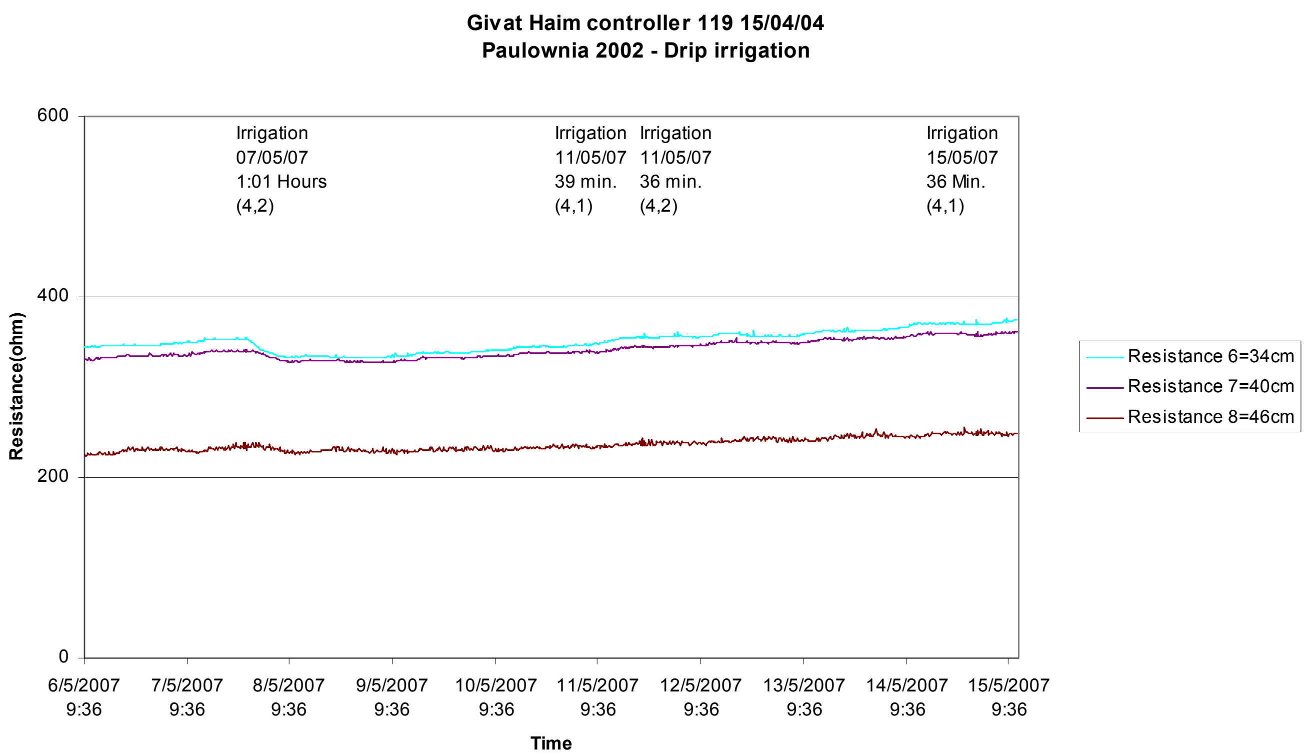


Fig. 8 – Time changes of the impedance by sensors along the probe.
Paulownia Tree Plantation, drippers, Irrigation control with feedback