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Design of an Automated Irrigation System

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Presentation

This paper was presented to the 2005 NABEC Student Paper Competition. It was initially submitted on April 18, 2005 as the final report for the undergraduate-level course ABEN 495 – Design II at McGill University. In this course, students are required to implement a project previously chosen and proposed (in ABEN 490) either physically or virtually, and to write a report that explains the design and criticizes the students' own work. This paper is the report of experimental work conducted by the author in the design of a residential-scale automated irrigation system.

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Abstract

The modern challenge for improving plant growth and reducing costs justifies the development of an automated irrigation system that will minimize the waste of water and reduce labour and monitoring overhead. Feedback-based approaches enable more efficient handling of resources than open-loop systems, at the expense of complexity and stability issues. Soil moistures are difficult to measure, and their target levels cannot be maintained very successfully. A design is proposed for a residential environment. It is made of reliable parts and has a relatively low cost. Its different sections have been simulated and tested, and their effectiveness in reducing water consumption and human intervention has been demonstrated. The design is also resource-efficient by itself by consuming low power. However, much more testing on the system as a whole must be conducted to measure the real water and labour savings.

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Introduction

Water is a resource that all living species need. It is therefore very precious and has to be used with moderation to be preserved for the generations to come. Agriculture is an industry that uses a lot of water. Most of the time, this resource is not used efficiently and substantial amounts of water are wasted. In the near future, these wastes will represent a large sum of money. The ones who manage this resource efficiently will be winning time and money.

In this project report, an automated irrigation system is suggested to minimize the water input and human intervention, while satisfying the plants' needs. First, the details of the problem are summarized. The objective and the scope of the project are described. Some general approaches to the design are reviewed. The results and conclusions of an experiment to determine the required amounts of water are discussed. Then, the suggested design is explained in detail with the purpose, requirements and constraints, simulation and test results for each of its parts. A brief cost analysis is performed to estimate the viability of such a project on the market. Finally, the design is criticized, and suggestions are made for future improvements.

1. Problem Statement

Irrigation of plants is usually a very time-consuming activity; to be done in a reasonable amount of time, it requires a large amount of human resources. Traditionally, all the steps were executed by humans. Nowadays, some systems use technology to reduce the number of workers or the time required to water the plants. With such systems, the control is very limited, and many resources are still wasted.

Water is one of these resources that are used excessively. Mass irrigation is one method used to water the plant. This method represents massive losses since the amount of water given is in excess of the plants' needs. The excess water is evacuated by the holes of the pots in greenhouses, or it percolates through the soil in the fields.

The contemporary perception of water is that of a free, renewable resource that can be used in abundance. However, this is not reality; in many parts of North America, water consumption is taxed. It is therefore reasonable to assume that it will soon become a very expensive resource everywhere.

In addition to the excess cost of water, labour is becoming more and more expensive. As a result, if no effort is invested in optimising these resources, there will be more money involved in the same process. Technology is probably a solution to reduce costs and prevent loss of resources.

2. Objective and Scope

The objective of this project was to design a small-scale automated irrigation system for indoors that would use water in a more efficient way, in order to prevent water loss and minimize the cost of labour.

The following aspects were considered in the choice of a design solution:

- Installation costs;
- Water savings;
- Human intervention;
- Reliability;
- Power consumption;
- Maintenance;
- Expandability.

A critical consideration is the installation costs, since costs generally determine the feasibility and viability of a project. The installation must be simple enough for a domestic user. The water savings was also an important aspect, since there is a demand to minimize water loss and to maximize the efficiency of water used. Since the objective is to minimize the cost of labour, minimal supervision and calibration must be needed. The system must operate with optimized consistency. The power consumption must also be monitored. For maintenance, the replacement parts must be readily available and easy to install in the case of failure. Finally, the possibility for implementing the system at a larger scale (e.g. in greenhouses) should be investigated.

3. Research

3.1 Sources of Information

The required information was found from a variety of sources. Information about the various principles and types of soil moisture probes was acquired from the Ontario Ministry of Agriculture, Food and Rural Affairs website [9] and several probe manufacturers and vendors. A promotional package containing technical datasheets, test results and a sample geotextile sheet were obtained from Soleno Textiles [10]. Different types of electric valves were researched on the Internet, and a solenoid valve was offered by the Mechanical Engineering Department at McGill University. The datasheets of the electronic parts were obtained directly from the manufacturers or from intermediate suppliers. During the design, a manual on digital system design [3] and a manual on electrical power [4] were consulted.

3.2 Required Input Data

Depending on the type of plants to be irrigated (e.g. cactus or geranium), the required soil moisture for growth and maintenance varies. It is also useful to determine the amount of water that the plants absorb during a certain period to choose the size of the reservoir and the refilling frequency. Plants were purchased and placed in a typical environment, and their water consumption was evaluated experimentally. This experiment is discussed in Section 4.

In the future, the user will not have to know how much water the plants consume, only their required soil moisture levels. The feedback will control the amount of water supplied automatically to the plants. A table of moisture levels for most common plant species may be attached to the retail package for convenience.

3.3 Design Approaches

To solve this problem, it is important to remember the two main objectives, which are to make a more efficient use of the water and to minimize the labour.
The constant open-loop approach is the simplest line of attack. Constant open loop means that the valve is always open and a constant rate of water flows through the pipes. Water saving already exists because the geotextile limits the evaporation. With this method, it is important to use a very small flow to prevent overflow of the geotextile and plant mildew.

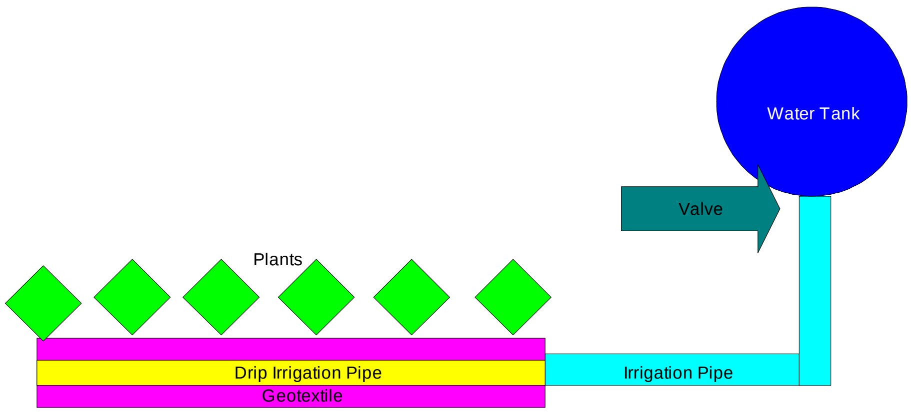

Figure 1: Constant open-loop control

With this system, the number of components is minimal (geotextile, pipes, valve and water reservoir), which means that the system is very simple to assemble and has a smaller chance of failure. The cost is also reduced because fewer pieces are involved. The disadvantage is that the system lacks a feedback path. The water input is not regulated to the actual water consumption, which may result in waste or overflow. This task will have to be performed by humans, who know the plants' needs beforehand.

Another approach is a simple open-loop on/off control. In such a system, the valve controlling the water input is in one of two states: on or off. Its state is controlled by a timer, which sends water only during a certain period of the day. The rest of the time, the valve is closed. This approach can be adapted to the evapotranspiration schedule; the timer may be programmed such that the water flows only at night. This system is superior to the constant open-loop flow in that the water input can be controlled by programming more or less irrigation hours per day. However, there is still no feedback. The timing must be decided in advance, depending on the plants' needs.

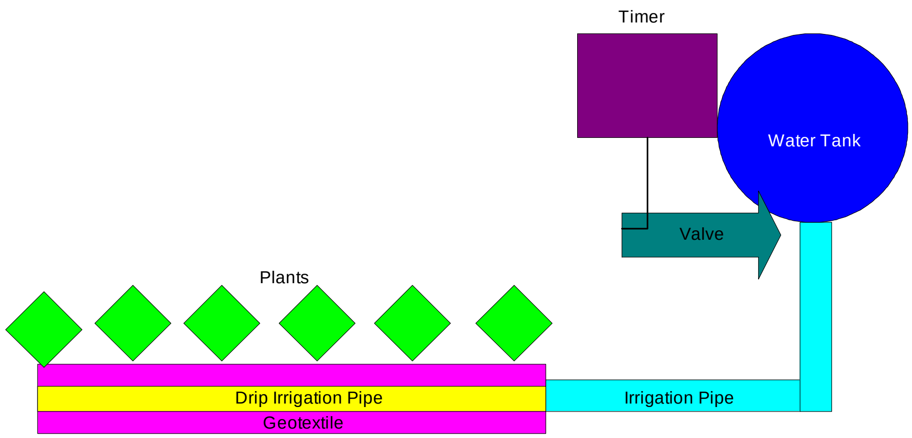

Figure 2: Open loop on/off

A more complex approach is the two-level feedback control. It requires an electric soil moisture probe and an electronic controller. The controller may be a custom electronic circuit or a programmable microcontroller. The probe reads the soil moisture periodically and the controller saves it into a register. This data is compared to a threshold level, and depending on the output of the comparator, the valve is either opened or closed. The feedback loop has two definite advantages over all open-loop approaches. First, the water flow is based on demand; this reduces the risk of waste or overflow. Second, there is virtually no human monitoring required. The trade off is complexity: it increases the costs and the risk of failure. More effort must be invested in testing the stability of such a system to avoid a situation in which water would flow indefinitely.

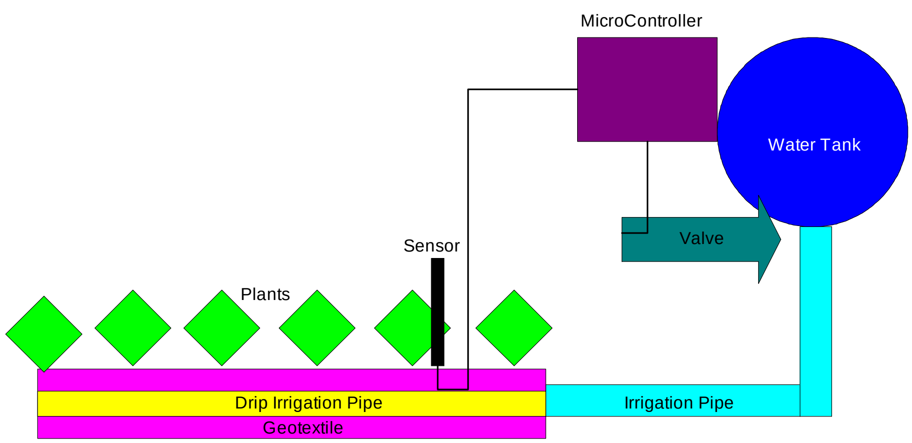

Figure 3: Two-level feedback control

3.4 Expected Results

The chosen approach is expected to yield the following results. All design candidates can be evaluated separately and compared with each other in terms of these elements.

- **Low installation cost.** A domestic user must be able to afford the system to irrigate his or her home plants. The installation must be simple enough not to require a technician. The assembly of the system must also be inexpensive.
- **Reduced labour.** Once the system is installed, the required labour will be limited to refilling the water supply periodically. This is the first aspect implied by full automation.
- **Reduced monitoring.** The control will necessitate only minimal human surveillance (e.g. once a day to verify the state of the system). This is the second aspect of full automation.
- **Decrease in water input.** If the water used depends only on the actual consumption of the plants and no water is wasted, one should observe a decrease in the water input. In the future, this can be translated into money savings.
- **Low maintenance.** A good system requires very small maintenance. Maintenance can be measured in terms of life cycle. No parts should fail in the first five years, and replacement parts should be cheap, easy to find and easy to replace.
- **Low power consumption.** The consumption of electrical energy can also be minimized to reduce the total costs associated with the system. This is especially relevant if it is implemented in a large scale. Each component can be optimized independently, but the objective relates to the total power consumption.

4. Experimentation

4.1 Objective and Method

The objective of the experiment was to determine the water input required to maintain a constant given soil moisture. It was conducted to evaluate the required water flow in order to estimate the size of the pipes and of the reservoir. It was performed by using a single common plant, the African violet. This plant was chosen because it requires average soil moisture.

The small-scale automated irrigation system is of dimensions acceptable for a house. The surface area dedicated to the plant is of about one square meter. The whole system has been tested in a house. Because the experiment was done during the winter season, the house needed to be heated to maintain a constant temperature of 20 to 22 ^{o}C; this also means that the relative humidity inside the house had to remain quite stable. The system was located close to a window since there was no artificial light supplied to the plants.

Everyday during in a six-week period, the soil moisture was measured using a moisture meter. Since the African violet requires a relative moisture level of 4/10, an effort was made to maintain this level by injecting measured volumes of tap water with a syringe. The water was absorbed from below to simulate the presence of a geotextile.

4.2 Results and Analysis

The results (Appendix B) are illustrated in Figure 4. From the graph, it is evident that maintaining constant humidity, even with daily monitoring, is easier said than done. The average moisture curve fluctuates between 1.7 and 5.0. Even though the response time between the watering and the soil moisture rise is usually very short, it is very variable. The rate of absorption of the plants depends on many factors such as sunlight, temperature, and air humidity. Sometimes, it took several days until the plants absorbed the excess water (e.g. plants 2 and 4 from Feb. 17 to Feb. 21). On other occasions, wetting the plants everyday had no effect on the soil moisture (e.g. Feb. 22 to Mar. 3). However, the general trend followed expectations: watering increases soil moisture, while periods without water input result in decreased soil moisture. On average, the mean humidity level was 3.1.

A total of 4240 mL of water was supplied to the six plants during the 40 days period. This corresponds to an average water consumption of 17.67 mL per day per plant. Considering that each plant was in a separate pot of approximately 250 mL, and that this consumption is the average of that of most home plants, it can be calculated that 70 mL of water per day is required for each litre of soil to be maintained at 3.1/10 humidity.

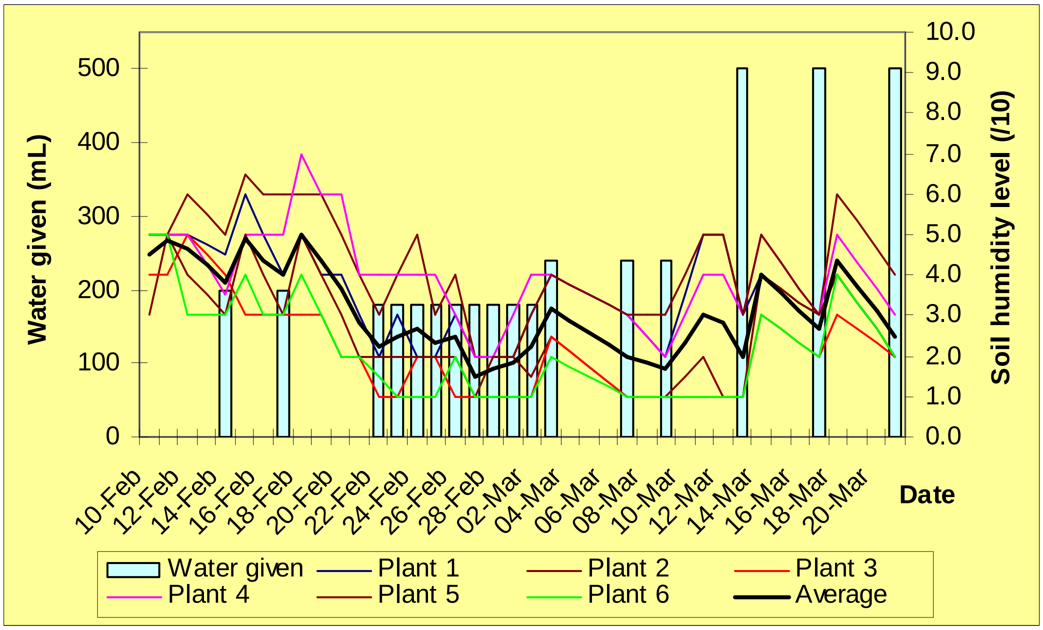

Figure 4: Experimental soil humidity levels and water quantities given vs. time

These estimates are very questionable, due to the unreliability of the results obtained. However, they certainly provide an order of magnitude for the size of the water tank and for the required flow rate. Assuming that the relationship between water input and soil moisture is linear, if the range of humidity levels for most home plants is between 1/10 and 8/10, the minimum and maximum extrapolated water inputs are 5.7 mL and 45.6 mL per day per plant. Furthermore, supposing that the system irrigates 10 plants of the size of the violets, that the water tank needs a 14-day supply for 8.0 soil moisture, and that the summer consumption is twice that of the experimental setup, and including a 1.25 safety factor, the tank size must be at least 16 L. The geotextile must be chosen to have a water retention capacity larger than the size of the tank in order to avoid any possibility of overflow. To provide such a small flow, a ¼-inch pipe is more than sufficient.

The experiment was inconclusive in terms of the accuracy of measurements and calculations. Nonetheless, the following conclusions can be drawn:

- Moisture levels are difficult to measure, and plant requirements even harder to assess.

- Large day-to-day variations make it nearly impossible to maintain constant soil moisture with only human monitoring.
- This justifies the use of automated feedback control, which may be performed at much higher sample rates than with humans, with insignificant cost increases.
- The water flow from the mains or a tank will be more than sufficient for the plants' needs. Since the flow will be actually much too large, the water input can only be limited by time.
- Pipe sizes will be dictated by other specifications such as the size of the drip irrigation pipe and the size of the valve outlet.

5. Final Design

5.1 Approach

The selected approach is an on/off timed feedback control. It requires an electric soil moisture probe, an electric valve, and an electronic circuit. The plants are placed on a geotextile, which retains water, and absorb water by capillarity. This design is suitable for most indoor plants, especially those that require watering from below.

In the prototype, there is only one probe, so for now all plants should be in the same pot. The probe reads the soil moisture at a specific time. The Comparator Circuit then compares this value to threshold levels. The Logic Circuit selects one of the comparator outputs based on the user's switch selection and opens or closes the valve for a pre-determined period. The Clock Circuit gives the Logic Circuit its timing pulse. A Level Display shows the last measured humidity level. The valve allows water flow from the water input (mains or tank) to the geotextile.

Figure 5 is a block diagram representation of the whole system. The boxes represent the sections of the system and the lines represent signal and resource flow. From this, it is possible to observe that the whole system operates as a closed loop.

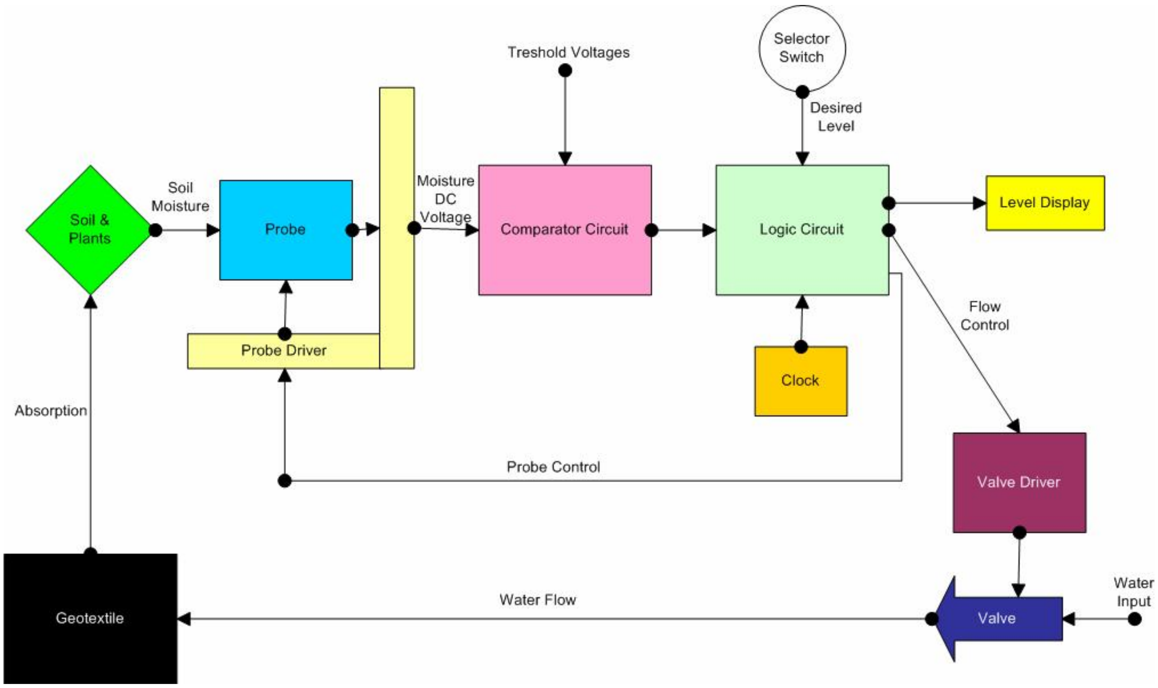

Figure 5: Full system block diagram

5.2 Geotextile

5.2.1 Purpose

The geotextile is used to reduce the water consumption by limiting the evaporation of excess water. This is done by a permeable layer that allows water to flow upward when pulled by the plants' roots, but not to evaporate. The geotextile acts as a permanent water table, which is replenished by a drip tape network when dry. Each plant pulls only the amount water it requires.

5.2.2 Requirements and Constraints

The geotextile has to fulfill the following requirements:

- It needs to contain at least the size of the tank in water to avoid overflow. If the mains are used as the water source, it must be able to hold at least the amount of water supplied in a full period of wetting.
- It must be resistant to roots, algae, weeds, and diseases that occur in a home environment. This is to prevent contamination between plants. Since the water

used is generally chlorinated, contamination is not likely to originate from outside the house.

- It needs to be durable. A life cycle of 5 years is a minimum.
- It has to be strong enough for humans to walk on it.

Additionally, the following constraints are imposed:

- The geotextile must be compatible with most pots commercially available.
- It must be large enough, approximately 2 m^2.
- Its cost must not be prohibitive.

5.2.3 Description

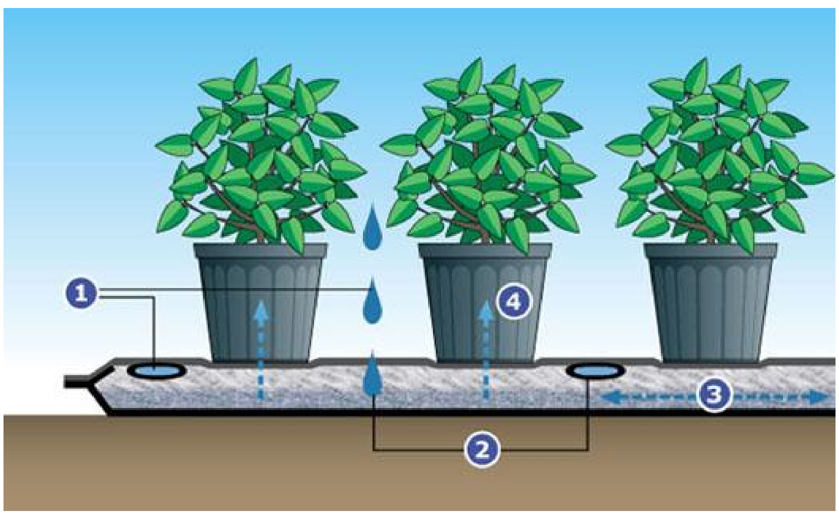

Figure 6: Plant setup on geotextile and watering process. (1) Irrigation. (2) Absorption. (3) Distribution. (4) Uptake. [10]

The selected geotextile is the Aquamat Water Conservation System, manufactured by Soleno Textiles. It is composed of an impermeable layer, an absorbent mat, and a permeable layer (Figure 7), all in synthetic materials. A drip tape distributes the water from the source pipe. The watering process illustrated in Figure 6 is described in detail in Appendix E.

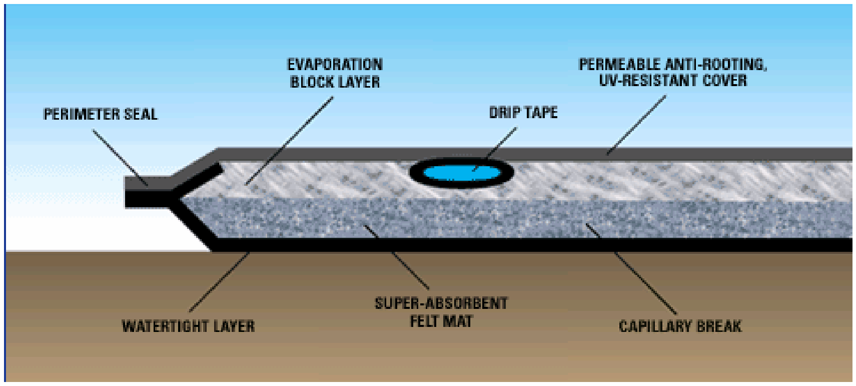

Figure 7: Cross-section of the Aquamat sheet [10]

This geotextile reduces the water consumption since the permeable layer minimizes evaporation. Overall, one square meter is able to retain 11.6 L of water. If 2 m^2 are used, the geotextile will be large enough for a 16 to 20 L tank. The geotextile costs approximately $11.20 per square meter.

5.2.4 Assembly and Testing

No testing was performed on the geotextile for the conception of the irrigation system. The choice of the Aquamat relied on previous testing done by the University of Florida (United States) and Université Laval (Canada). Two types of experiments were conducted. One, in 1995, compared different irrigation systems: a capillary mat system, overhead irrigation, micro-irrigation, pots in flat trays and similar containers on a woven black ground cover as a control. The second compared the capillary mat with overhead irrigation for different species at different nurseries.

Table 1: (Experiment 1) Production time and water used by different irrigation methods [10]

	Gallonnage of water		Weeks of production	
	Viburnun	Ligustrum	Viburnun	Ligustrum
Overhead	7733	5248	39	30
Aquamat	2720	2556	28	26
Trays	2216	1842	28	23
Microirrigation	4240	3357	39	31

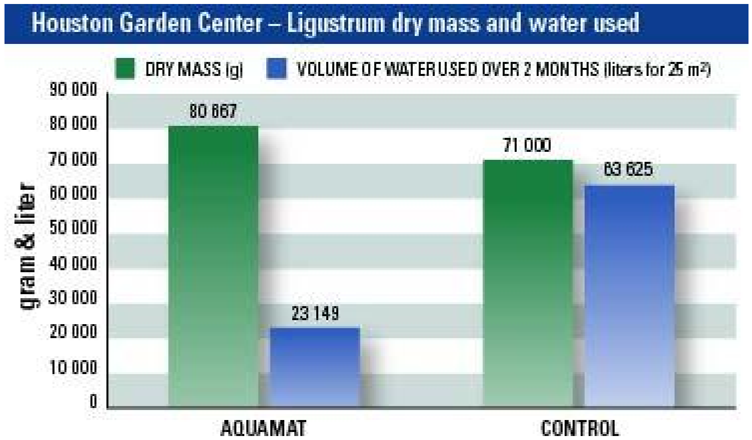

Figure 8: (Experiment 2) Gain in plant growth and water savings with Aquamat [10]

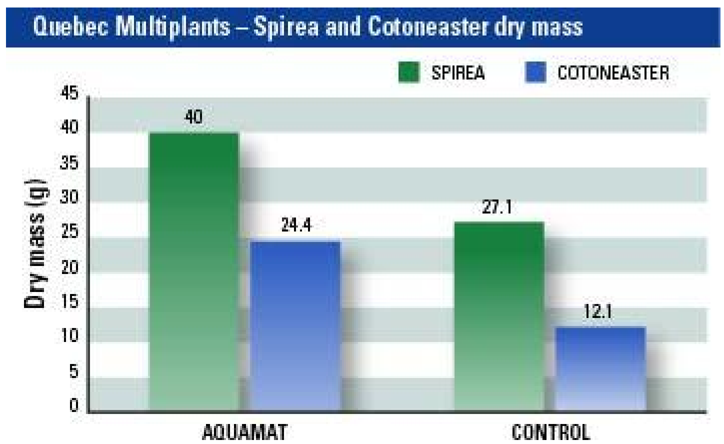

Figure 9: (Experiment 2) Growth of two plants using Aquamat [10]

The results of the experiments showed that plant growth was superior with the capillary mat and flat trays than with overhead irrigation. Furthermore, flat trays saved the greatest amount of water, followed by the capillary mat. The pots on the capillary mat maintained higher moisture than the control pots, and plants more easily extracted the water from the capillary mat. The pots on the capillary mat were also watered with greater uniformity than the pots under overhead irrigation, and the capillary mat could effectively redistribute water on land with a small slope (3%) [10].

The Aquamat requires partial assembly. Tables need to be levelled to a maximum slope of 3%. Different types of soil have been tested by the Aquilex Irrigation & Hydrology laboratories in Québec City. Soils containing more than 50% peat moss are best suited for capillary irrigation. A table containing the most suitable soils may be provided to the users. The geotextile must be unrolled and the drip tape needs to be inserted between the permeable layer and the absorbent mat. A small vinyl pipe of ¼-inch inside diameter connects the drip tape to a garden hose, which in turn is connected to the valve. Finally, the system should be submitted to a watering test to verify appropriate distribution of the water volume and adequate substrate water absorption.

5.3 Probe

5.3.1 Purpose

The probe is the feedback instrument of the automated irrigation system. It is used to measure the moisture content of the soil, in which it is placed permanently. When activated, it gives an electrical output to be read by the Comparator Circuit.

5.3.2 Requirements and Constraints

The probe requirements are as follows:

- The probe must have an electrical output variable that can be read by the Comparator Circuit.
- The relationship between soil moisture and signal output must be well known or parameterized. If this relationship varies with the type of soil, it should be known for the most common soils.
- The reading of the probe, when placed permanently in the soil, must be time-invariant.
- The probe has to be compatible with most soil types.
- It needs to be durable and resistant to humidity in the long term (5 years).

The constraints are:

- Reasonable cost;
- Small size;
- Lower power consumption;
- Large dynamic range;

- Medium resolution;
- Medium sensitivity;
- Good accuracy;
- Low flammability (UV resistance).

5.3.3 Description

The Irrometer Watermark, a solid-state, electrical resistance type sensor was selected. It consists of a fine aggregate mixed with gypsum crystals, held inside a permeable membrane and a perforated stainless steel sleeve [**Error! Reference source not found.**]. The measurement of soil moisture is based on the electrical resistivity of the medium, which decreases as the water content increases. This device is buried in intimate contact with soil and reaches equilibrium with the soil moisture. Stainless steel electrodes are embedded in the granular matrix. When the soil wets up, the sensor moisture gets higher and the electrical resistance is reduced. When the soil dries, the resistance is increased since the sensor moisture gets lower.

This sensor covers a soil moisture range of 10 kPa to 200 kPa, which corresponds to the entire range required in irrigated agriculture [7]. It is suitable for all soils. However, for very coarse or gravely soils, an oversized hole (1 to 1¼ inch diameter) may be needed to prevent abrasion damage. It is also resistant to freezing.

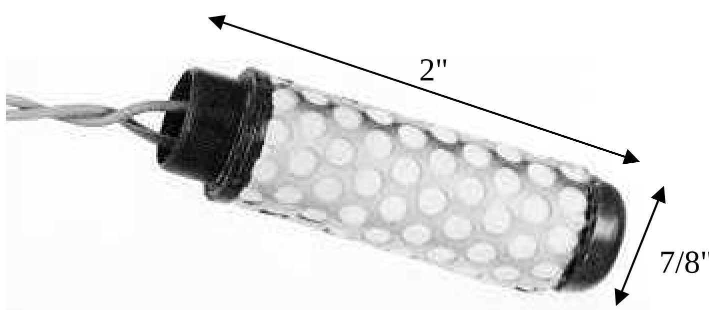

Figure 10: Irrometer Watermark [6]

When supplied an alternating voltage, the probe bears a resistance between 500 and 30,000 Ω depending on the soil moisture. The actual voltage across the probe must not exceed 5.0 V RMS to protect the inner components. Furthermore, for proper operation, the probe voltage must be above 4.5 V RMS.

The soil tension can be converted to percentage humidity using the graph in Figure 11, depending on the type of soil.

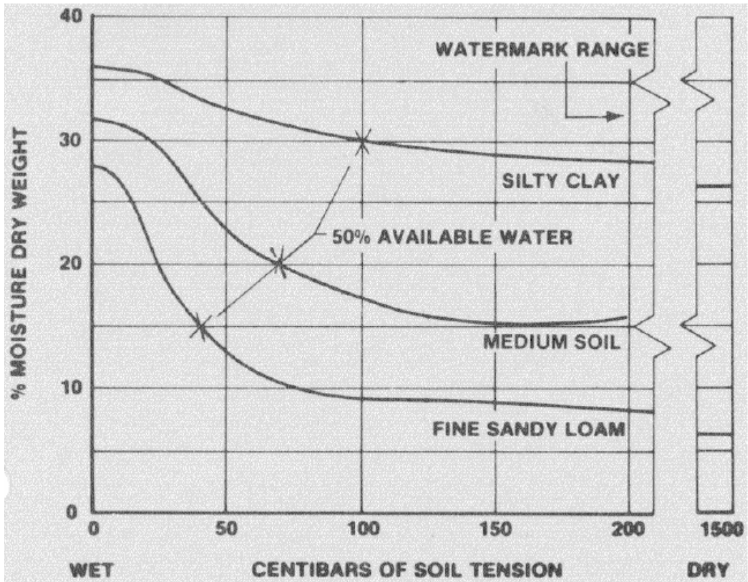

Figure 11: Relative moisture vs. soil tension for several types of soil [7]

A drawback of the Watermark is that it heats up under prolonged electrical currents. Therefore, it should be turned on for short periods only. Also to avoid heating, the probe must be shielded against direct currents.

5.3.4 Assembly and Testing

The Watermark requires no assembly. However, some directions must be followed for its installation. The probe must be soaked when inserted into the soil. For testing, it was wetted in irrigation water for 30 minutes in the morning, dried until evening, wetted for 30 minutes, dried overnight, wetted again for 30 minutes, dried again until evening, wetted overnight and installed wet. This procedure, which is described in more detail in the Installation and Operation Manual [8], is expected to improve the sensor response in the first few measurements. A 5 cm hole was dug into the plant soil and filled with water. After inserting the probe, the hole was refilled.

If longer wire lengths are required, additional waterproof wires may be spliced to the sensor's leads; the splice must be waterproof as well. However, long wires should be placed away from power cables to avoid electromagnetic interference.

No testing has been conducted on the Watermark probe during the design of the irrigation system. Instead, the results from the experiments of Dr. Richard G. Allen at the University of Idaho were used [2]. The purpose of the study was to compare continuous data logging systems for measuring soil water potential using Watermark sensors.

Dr. Allen found three equations to model the calibration table designed by Irrometer to convert electrical resistance to soil tension or water potential at given temperatures.

For R smaller than 1kΩ,

$$P = -20\left[R\left(1+0.018\left(T-24\right)\right)-0.55\right] \tag{1}$$

For R between 1kΩ and 8kΩ,

$$P = \frac{-3.213R-4.093}{1-0.009733R-0.01205T} \tag{2}$$

For R larger than 8kΩ,

$$P = -2.246-5.239R\left(1+0.018\left(T-24\right)\right)-0.06756R^2\left(1+0.018\left(T-24\right)\right)^2 \tag{3}$$

where P is soil water potential in kPa (centibars),

R is measured resistance in kΩ,

T is soil temperature in ^{o}C.

The standard error of estimate was determined to be 1.07 kPa. The equations best fit experimental data when used in tension ranges from -10 to -75 kPa. Uncertainties in readings at soil water potentials were found below -80 kPa.

In spite of Irrometer's warnings, Dr. Allen also found that direct currents can be used to read the sensors, as long as they are applied infrequently (a few times per day) and for very short periods of time (less than 0.5s). Nonetheless, to avoid any prolonged DC excitation, this design feeds the probe with AC only.

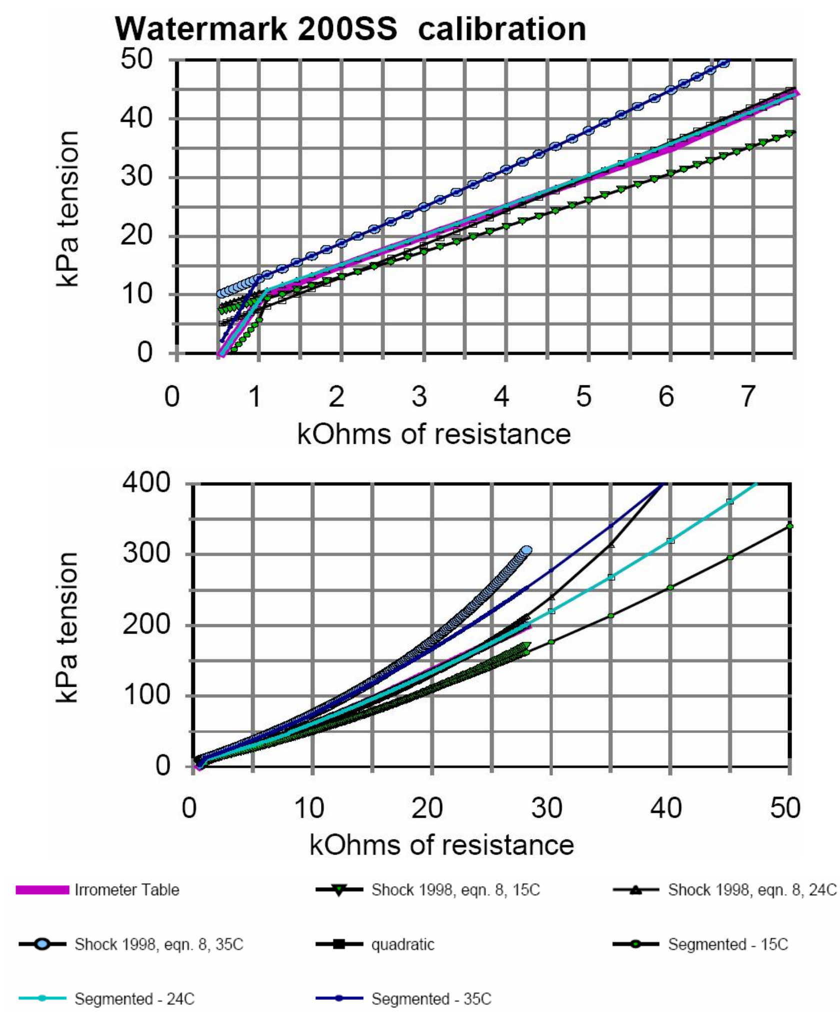

Figure 12: Model fitting for the Watermark calibration relationship, adapted from [1]

5.4 Probe Driver

5.4.1 Purpose

The Probe Driver electrically connects the probe to the rest of the system. It serves two purposes. The first is to activate the probe on the Probe Control signal from the Logic Circuit. The second is to convert the probe resistance output into a DC voltage to be read by the Comparator Circuit.

5.4.2 Requirements and Constraints

The Probe Driver must properly supply the probe when the probe control signal is high. The voltage supply must be 4.5 to 5.0 VAC for proper and safe operation. It should convert the probe resistance into a DC voltage that can be compared to the threshold levels set by the user or the manufacturer.

The probe, Logic Circuit and Comparator Circuit impose the following constraints:

- The Probe Control signal which is digital (DC) has to drive an AC signal. This suggests the use of a relay.
- The AC voltage at the probe terminals must be rectified to be compared to DC voltages with a small residual ripple.
- The transfer function of the Probe Driver must be calibrated to the moisture vs. resistance curve of the probe. The minimum and maximum probe resistances must both correspond to voltages within the dynamic range of the Comparator Circuit (0 V to 5 V).
- The probe must be isolated from direct currents.
- The AC current must not be allowed to flow back into the Logic Circuit or forward into the Comparator Circuit.
- As the probe is turned off, the output DC voltage must fall to zero slowly enough for the Comparator Circuit to fully process it, but fast enough so that steady state is reached before the next duty cycle.

5.4.3 Description

The input stage of the Probe Driver, which is connected to the output of the Logic Circuit, is driven by the 5.0 VDC supply. It drives an Omron G6C-1114P-US relay with a NPN transistor. The relay electrically isolates the Logic Circuit from the probe and output circuit, which is supplied by a 9.0 VAC wall transformer.

The resistance from the sensor varies from 500 to 30,000 Ω depending on the soil moisture. A 5 V level at the relay coil closes the contact and supplies the probe with an AC voltage. The probe resistance values must be converted to voltages so that they can be compared with the threshold values. Such conversion is performed by a voltage divider. Typically, the output of a voltage divider is given by

$$V_{out} = \sqrt{2}V_{AC} \frac{R_p \parallel R_{probe}}{R_p \parallel R_{probe} + R_s} = \frac{\sqrt{2}V_{AC} R_p R_{probe}}{\left(R_p + R_s\right) R_{probe} + R_p R_s} \tag{4}$$

where ‖ denotes the parallel operator, if the contact resistance of the relay is neglected (rated 100 mΩ). By inspection, the values of output can be seen to range from

$$V_{out} = 0 \text{ to } \frac{V_{AC} R_p}{R_p + R_s} \tag{5}$$

as the resistance of the probe varies from 0 to infinity. By calibrating R_p and R_s, the constructor ensures that the probe receives proper voltage in normal utilisation (4.5 V to 5.0 V RMS). Two AC blocking capacitors are inserted at each terminal of the probe.

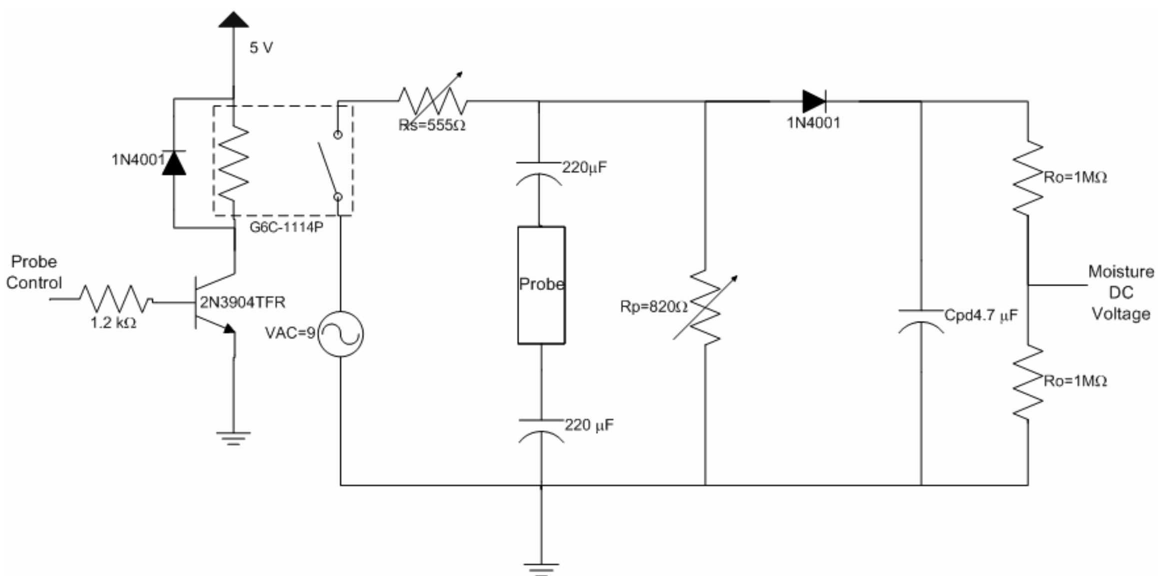

Figure 13: Probe Driver schematic

To perform the AC to DC rectification, a half-wave peak detector is used, made from a diode and a capacitor. Positive voltages charge the capacitor. The diode acts like valve, which ensures that the capacitor does not discharge back into the source. Therefore, the voltage across the capacitor follows the amplitude of the AC voltage across R_p. The capacitor is chosen such that its charging time is smaller than a quarter AC period:

$$5\left(R_s + R_p \parallel R_{probe}\right) C_{pd} \ll \frac{1}{4 \cdot 60Hz}. \tag{6}$$

On the other hand, the discharge time is fixed by the two 1 MΩ resistors:

$$T = 5(2R_o)C_{pd} = 47s \qquad (7)$$

It is more than enough for the comparators to stabilize.

5.4.4 Simulation

The input and output stages of the Probe Driver were modelled and simulated separately using SPICE. Fine adjustments were made to resistor values to account for nonlinearities of the diode. It was ensured that the probe never received excessive voltage. However, the relay contact was neglected from the output stage, and its coil was represented by a resistor.

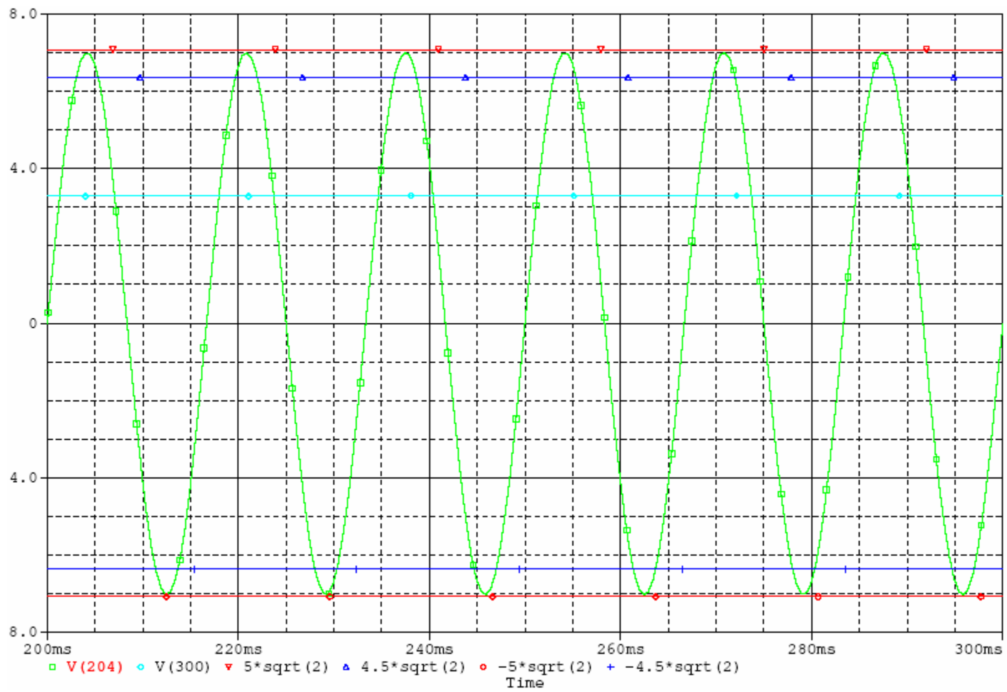

Figure 14: Probe Driver simulation results

Figure 14 shows the probe voltage (V(204) – red) and the output (V(300) – light blue) with infinite probe resistance (extremely low moisture). The dark blue lines represent the 4.5 V lower limits, and the red lines represent the 5.0 V upper limits. The simulation showed that:

- The probe was never at risk of heating;
- The output had a very small ripple;

- The minimum probe resistance to respect the 4.5 V condition was 2250 Ω, corresponding to a minimum -16.4 kPa soil tension.

5.4.5 Assembly and Testing

The Probe Driver prototype was assembled on breadboard for simplicity and adaptability. The probe was first replaced by equivalent resistors to ensure that the voltage was safe. Then the probe was connected, and sample voltages were recorded for varying soil moistures in a control pot containing only soil. The results helped adjust the calibration resistors R_p and R_s.

5.5 Comparator Circuit

5.5.1 Purpose

The Comparator Circuit is a mixed-signal system that converts the analog voltage from the Probe Driver into six binary voltages (approximately 0 V and 5 V). Each output is high when the humidity is higher than its corresponding threshold value and low when it is lower. These results are then forwarded to the Logic Circuit. Thresholds are based on common humidity levels required by home plants. They are associated with six fictitious values of 0, 20, 40, 60, 80, and 100% humidity.

5.5.2 Requirements and Constraints

The Comparator Circuit has the following requirements:

- The threshold voltages must be hardwired for stability.
- The circuit must assume a reliable 5.0 V DC supply.
- Six switches must be used to perform the six comparisons. The input switching region (linear regime) must be small.
- The accuracy is crucial.
- The circuit must present high input impedance to the Probe Driver in order to maximize the voltage transfer.

The only constraint is cost: the circuitry has to be simple. For instance, an analog to digital converter (ADC) is probably too expensive.

5.5.3 Description

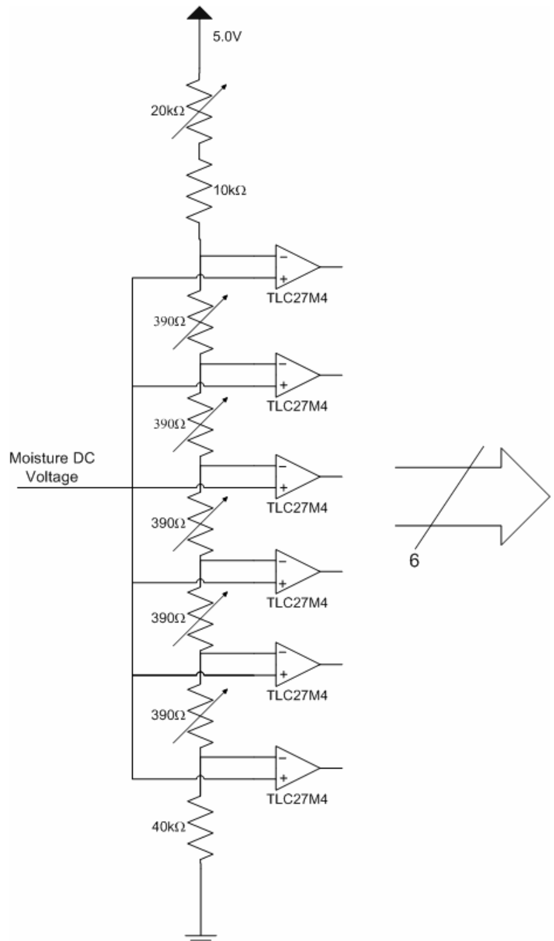

Figure 15: Comparator Circuit Schematic

In the chosen design, operational amplifiers are used as voltage level comparators. When their non-inverting input is larger than their inverting input by at least 0.03 mV (switching region), they output 5 V. When it is smaller, the op-amps return 0 V. A resistor chain is used to generate the threshold voltages to be compared to the actual soil moisture. Resistors were carefully chosen because the threshold levels are very sensitive to resistor tolerances (typically 5%). A 20kΩ trim potentiometer is inserted in the chain for calibration.

Texas Instruments TLC27M4 LinCMOS precision op-amps were selected because of their low cost ($1.17 for a quad chip), low power consumption (2.1 mW per chip at 25

°C), high input impedance (1 GΩ per input port), and low noise (32 nV/Hz^{½} equivalent input per channel).

5.5.4 Simulation

The circuit was simulated in SPICE using a DC sweep from 0 to 5 V at the input. Figure 16 is a zoom in of the output voltages around the threshold input voltages. The x-axis is the input voltage from the Probe Driver. Each of the rising curves (V(30) through V(35)) is the output of one op-amp and switches quickly to high within 10 mV of its associated threshold. The red lines represent the maximum low voltage and minimum high voltage recognised by the multiplexer used in the Logic Circuit. The simulated high voltages were all above 3.8 V, and the low voltages were all below 0.2 V.

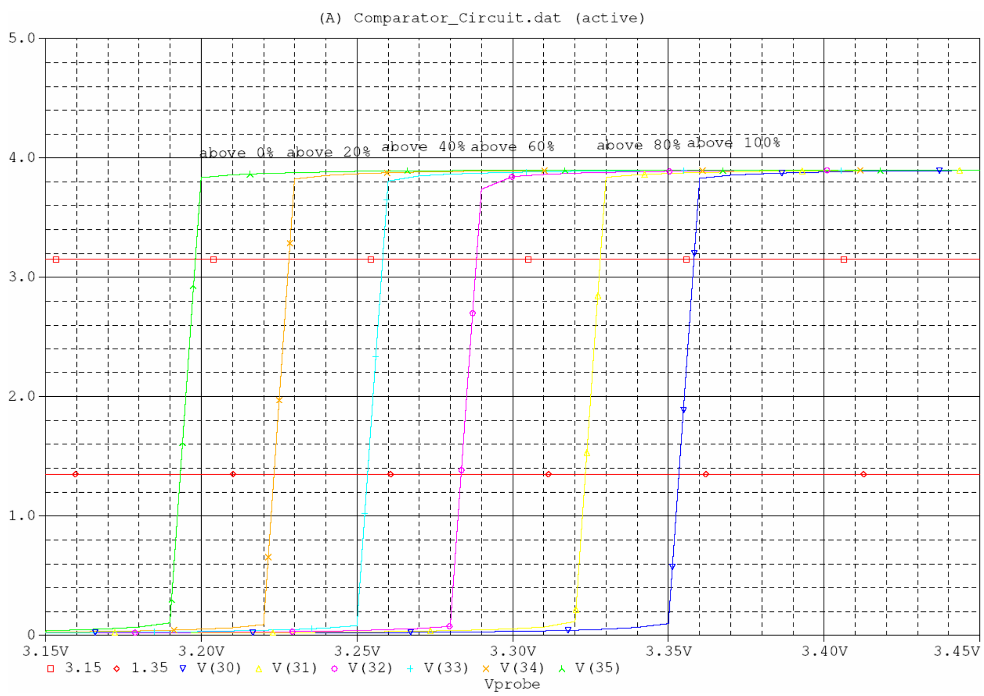

Figure 16: Comparator Circuit simulation results

5.5.5 Assembly and Testing

The circuit was assembled on breadboard for convenience. It was originally tested using a variable DC voltage source as input. To determine the threshold voltages, water was progressively added to the soil and the output voltage was recorded at chosen moisture levels indicated by a commercial moisture meter. The op-amp switched from low to high at the proper threshold levels. The op-amps were connected directly to the 5 V supply and ground to protect them from the current pulled by the Logic Circuit elements. A 220 μF capacitor was also placed between the power supply and ground for increased stability, a precaution recommended by Texas Instruments.

5.6 Clock Circuit

5.6.1 Purpose

A clock is required to generate a pulse of fixed frequency to drive the counter and memory elements of the Logic Circuit.

5.6.2 Requirements and Constraints

A clock cycle of $15/4$ seconds is required by the Logic Circuit. The timing must be precise with an error up to 2%, which represents 6.4 minutes for every 5:20-hour cycle. This suggests that a simple, inexpensive circuit can be used.

5.6.3 Description

In a RC circuit, the charge and discharge time of the capacitor are the same and are proportional to the time constant of the circuit:

$$T_c = RC \,. \tag{8}$$

Therefore, it is theoretically possible to measure time with high accuracy using a very simple RC network, provided that R and C are known precisely. A RC timer works on the principle that when the capacitor is sufficiently charged, it triggers an electronic switch that starts the discharge, and vice versa. RC timers are not as stable as crystals and are limited to low frequencies, but they are much less costly.

The Texas Instruments NE555 precision timer is a cheap circuit that can generate accurate oscillation. In its astable mode of operation, the frequency is controlled by external resistors and a single external capacitor. The clock cycle is then proportional to the sum of the time constants of the charge circuit and of the discharge circuit. The lengths of time when the clock is high and low are given by

$$T_H = \ln 2\left(R_A + R_B\right)C \,, \tag{9}$$

$$T_L = \ln 2\left(R_B\right)C \,, \tag{10}$$

respectively, where R_A, R_B and C are shown in Figure 17. The period of the clock cycle is then the sum of the two:

$$T_c = \ln 2\left(2R_A + R_B\right)C \ . \tag{11}$$

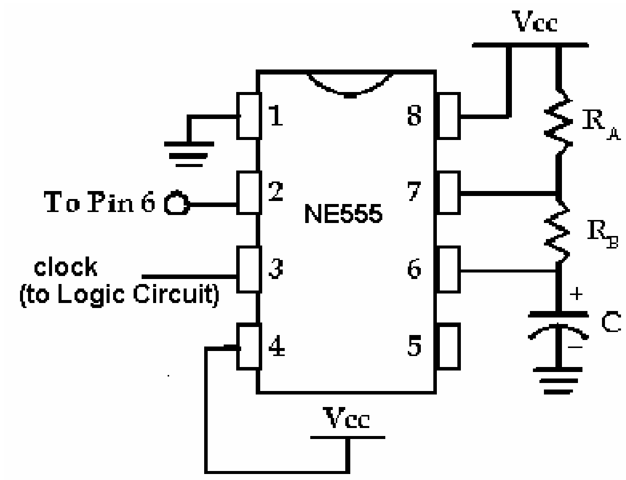

Figure 17: Clock Circuit schematic

Since the timer is supplied by a 5 V DC source, its output is approximately 5 V in amplitude.

5.6.4 Simulation

A simple Excel spreadsheet was used to determine the resistor and capacitor values required to achieve the target clock period of $15/4$ seconds.

5.6.5 Assembly and Testing

The Clock Circuit was assembled on breadboard. An external chronometer was used to calibrate the clock cycle. A 220 μF capacitor was initially placed and, using the values found in simulation as a starting point, the resistors were chosen by trial and error until the target cycle was achieved within acceptable tolerance. The selected resistances were $R_A = 18.9k\Omega$ and $R_B = 1186\Omega$. The measured error was approximately 0.5 second per minute (0.83%).

5.7 Logic Circuit

5.7.1 Purpose

The Logic Circuit is the controller unit of the irrigation system and comprises all digital elements of the controller. Decision-making is based on the user's selection of humidity level (among six) and outputs of the Comparator Circuit. The controller works in a fixed duty cycle of 5 hours 20 minutes. For the first 60 seconds (16 clock cycles), the Probe Driver relay is activated to measure the moisture level. Since the propagation delay between the probe and the comparator output is small, the controller has access to the relative humidity almost instantaneously. A multiplexer selected one of the six comparator outputs based on the position of a switch. During the same minute, if the selected input is low, the valve relay is closed and the water flows.

5.7.2 Requirements and Constraints

The Logic Circuit must provide a control signal for the activation of the probe and the valve. Considering its complexity, it should occupy a small surface on the circuit board and be as cheap as possible for its purpose. The electronic parts must be chosen for their size, price, and reliability.

5.7.3 Description

A custom electronic circuit was chosen instead of a programmable microcontroller because of the simplicity of the required tasks. There was no need to invest in a complex device. The drawback is that any future customizations must be done in hardware, whereas a microcontroller can be reprogrammed as many times as desired.

A 14-bit counter, triggered by the clock, maintains the time state. The chosen counter is a Texas Instruments CD4020B CMOS type. It features a common asynchronous reset line and a Schmitt trigger clock line. The reset line is used to restore the counter value to zero after 5 hours 20 minutes and the Schmitt trigger provides immunity to the noise produced by the clock. The duty cycle is hardwired into an AND gate for now, but it may be customizable in the future.

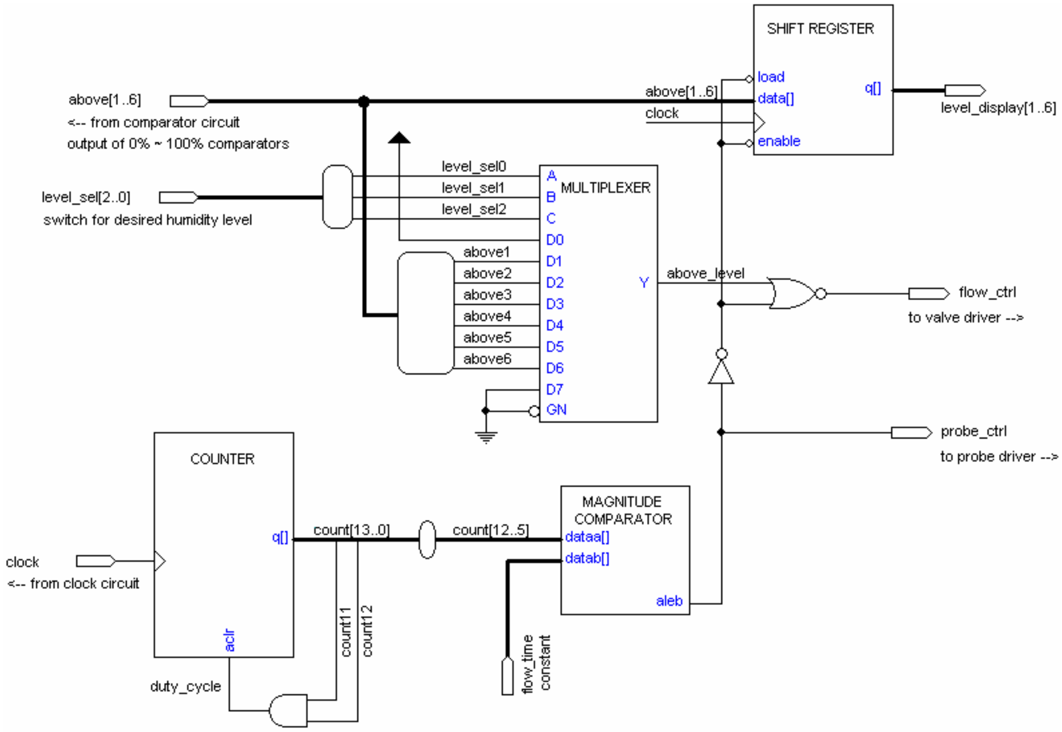

Figure 18: Logic Circuit functional diagram

The multiplexer is a Texas Instruments CD74HC151 CMOS chip. It accepts up to eight input channels and consumes low power. The 60-second flow and probe duration is tested by a Texas Instruments CD74HCT688E 8-bit magnitude comparator. A Fairchild Semiconductor 74F378 6-bit register is used to hold the value of the comparator outputs while the probe is off. This unit, sold for less than $0.40, does the job very well. A Panasonic SSA-LXB525YD 5-element LED array gives the user a visible indication of the last reading. All logic gates are included in a single Texas Instruments CD4572UBE CMOS hex gate. This chip is also inexpensive ($1.29) and power- and space-efficient.

5.7.4 Simulation

The Logic Circuit was modelled by equivalent generic elements and simulated using the Altera MAXplus+ software package. The correct behaviour of the circuit was verified. Propagation delays in the elements were much smaller than the clock cycle; they are neglected from now on.

5.7.5 Assembly and Testing

The arrangement of chips was assembled on breadboard. All chips were supplied by the same 5 V source. Due to the long periods of time involved, the Logic Circuit was tested using replacement clocks of 1 Hz, 10 Hz, and 100 Hz.

5.8 Valve and Pipes

5.8.1 Purpose

The valve and pipes are the medium used to bring the water from the tank or the mains to the geotextile. The valve is turned on by the Flow Control signal from the Logic Circuit.

5.8.2 Requirements and Constraints

For the valve and pipes, the following requirements are needed:

- The valve needs to be controlled by the Logic Circuit, which means that an electric valve is required.
- The valve must also work on the 9 VAC transformer used for the Probe Driver.
- It must not consume too much power, and this power must be mostly real (minimal reactive power consumed or supplied).
- The diameters of the pipes have to be compatible with the valve output and input, and with the geotextile drip tape.
- The pipes must be easy to install.

The constraint is primarily the cost of the electric valves. Some valves are prohibitively expensive (over $100).

5.8.3 Description

The Valve Driver is driven by the Logic Circuit. The valve is open for water to flow into the geotextile, and closed otherwise. The solenoid valve is an A24 type.

Solenoid valves are the cheapest type of electrical valve commercially available. They are based upon Ampere's law:

$$\oint_C \vec{H} \cdot d\vec{l} = \iint_S (\vec{J} + \frac{\partial \vec{D}}{\partial t}) \cdot d\vec{s} \tag{12}$$

where $\overrightarrow{H}$ is the magnetic field strength, $\vec{J}$ is the electric current density, and $\overrightarrow{D}$ is the electric flux density inside the surface S bounded by the contour C. The electric current through the solenoid windings creates a magnetic flux, which displaces the ferromagnetic aperture wall and allows the water to flow. A voltage supply causes the valve to open, and the valve is closed when there is no voltage.

Figure 19: A24 solenoid valve

The valve is rated 24 V AC/DC, but can be used for lower voltages; it then draws larger currents. The electrical characteristics of the valve can be assumed to vary significantly with its supplied voltage. Because of the number of the turns in the solenoid, the valve is generally an inductive load. Its exact impedance can only be determined under its actual operating conditions.

5.8.4 Assembly and Testing

The A24 valve has accepts water inputs of ½-inch copper or plastic, and its output is a ¾-inch garden hose. A ½-inch garden hose with a ¾-inch connector is connected to the valve output. It is scaled down to a ¼-inch vinyl tube, which is connected to the geotextile drip tape. In the prototype, the valve input was the water mains of a house. However, a tank (purchased separately) with a plastic pipe will probably work as well.

The valve and pipe system were not tested in this design project because of time constraints.

5.9 Valve Driver

5.9.1 Purpose

The Valve Driver is the circuit that activates the valve on the Flow Control signal from the Logic Circuit. It supplies the power to the valve to open it.

5.9.2 Requirements and Constraints

The Valve Driver must supply 9 VAC to the valve because it is connected to the same transformer that supplies the Probe Driver. The valve is an element that consumes a lot of power. Therefore, the Driver must sustain the large current that will be pulled by the valve. All elements connected in series with the valve may dissipate significant power by Joule's losses. This heat must be evacuated efficiently. Moreover, the current must not be allowed to flow back into the Logic Circuit. Finally, the power factor must be examined so that it remains close to one.

5.9.3 Description

The designed Valve Driver very much resembles the input stage of the Probe Driver. An Omron G6C-1114P-US relay is used to control the supply of 9 V AC to the valve's contact port. Driven by a NPN transistor, it also decouples the valve current from the Logic Circuit. A capacitor C_{pf} is added to the output stage to partially cancel the reactance of the valve and thus to ensure that the power factor is close to unity. Power factor compensation is described in Section 5.9.4.

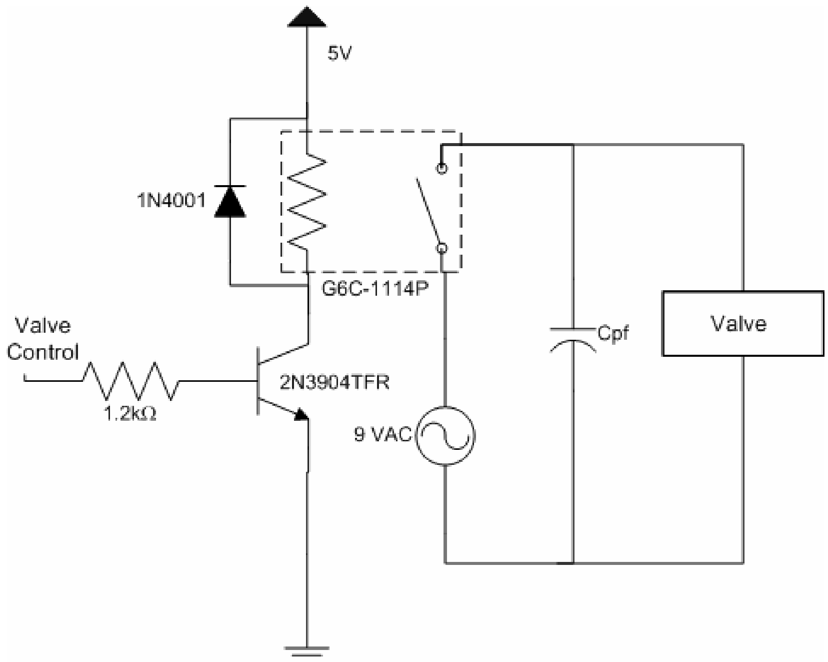

Figure 20: Valve Driver schematic

5.9.4 Assembly and Testing

To protect the electronics of the controller, the Valve Driver was initially tested by connecting a 5 V DC supply directly to the coil port of the relay. Once the circuit was considered safe, the relay could be connected to the Logic Circuit. The circuit was assembled on breadboard after the current pulled by the valve were measured to be safe.

The behaviour of the valve was unknown prior to the design. Moreover, its impedance was expected to vary with the voltage supply. An experiment was conducted to determine the electrical characteristics of the valve and to choose the proper capacitor C_{pf}.

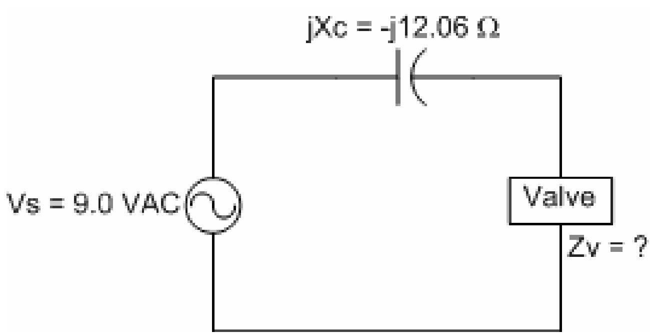

Figure 21: Setup for valve impedance measurement

The valve and a 220 μF capacitor were connected in series to the 9.0 VAC source (Figure 21) and the RMS voltages were measured across all elements. If $\bar{V}_t$, $\bar{V}_v$ and $\bar{V}_c$ are the voltage phasors across the transformer, valve and capacitor, respectively, it can be derived (Appendix C) that the valve impedance is

$$Z_v = \frac{|X_c|}{V_c^2}\sqrt{V_v^2 V_c^2 - \tfrac{1}{4}\left(V_t^2 - V_v^2 - V_c^2\right)^2} + j\frac{X_c}{2V_c^2}\left(V_t^2 - V_v^2 - V_c^2\right). \qquad (13)$$

and that its power factor is

$$pf = \sqrt{1 - \frac{\left(V_t^2 - V_v^2 - V_c^2\right)^2}{4V_v^2 V_c^2}} \;. \qquad (14)$$

These equations take into account the internal impedance of the transformer, but they do not imply knowledge of its value. The RMS voltages were measured to be $V_t = 8.5V, V_c = 3.2V, V_v = 11.2V$. Using the equations, the valve was found to have an impedance of $19.6 + j37.4\Omega$. This corresponds to a lagging power factor of 0.464. A 56 μF capacitor should suffice to raise the overall power factor to 1.000, if the internal reactance of the transformer is neglected. Under these conditions and assuming a 1.40 Ω real transformer Thévenin impedance, the current through the source would be 928 mA RMS. Therefore, the probe and Probe Driver would consume a total real power of 8.41 W with a power factor of 0.993.

6. Cost of Project

The project cost includes two distinct aspects: the cost associated with the design, prototyping, and development of the product; and the cost associated with commercializing the product.

6.1 Cost of Final Product

The total variable cost of the automated irrigation system is $152.02. This amount only includes the cost of the parts. The plumbing ($50.40) and electronics ($26.63) together account for half of the total. The other half comes from the soil moisture probe and the geotextile, which are expensive, specialized parts.

Table 2: Variable costs of final product

Part	Part number	Manufacturer	Qty	Price	Supplier	Total
Plumbing						
½" OD copper pipe 1/2" (1')			4	1.34	Plumbing Mart	5.36
24 V AC/DC solenoid valve			1	34.99	Botanix	34.99
¼" plastic pipe (250")			1	1.05	Rona	1.05
½" garden hose (25')			1	5.19	Rona	5.19
3/8" to 1/2" connectors			1	3.75	Rona	3.75
Teflon tape (5")			1	0.06	Rona	0.06
Special parts						
Soil moisture probe	IR200SS5-0	Irrometer	1	49.00	GENEQ	49.00
Geotextile (1 m2)	Aquamat S10	Soleno	2	11.20	Soleno	22.40
9 VAC wall transformer		Child Guidance	1	3.59	Addison	3.59
Electronics						
NPN transistor	2N3904TFR	Fairchild	2	0.06	Digi-Key	0.12
Rectifier diode	1N4001-T	Diodes Inc.	2	0.03	Addison	0.05
5 V relay	G6C-1114P-US	Omron	2	1.49	Digi-Key	2.98
220 uF electro. capacitor	M9715	Nichicon	3	0.25	Addison	0.75
4.7 uF electro. capacitor	ECE-A1VKS4R7	Nichicon	1	0.10	Digi-Key	0.10
56 uF electro. capacitor	UWX1E560MCL1GB	Nichicon	1	0.12	Digi-Key	0.12
1 kohm trim potentiometer	74W Series	Spectrol	1	0.99	Addison	0.99
10 kohm trim potentiometer	74W Series	Spectrol	1	0.99	Addison	0.99
Quad op-amp	TLC27M4	Texas Instruments	2	1.17	Digi-Key	2.34
Octal rotary switch	94HAB08WR	Grayhill	1	4.21	Digi-Key	4.21
Green switch button		Grayhill	1	0.34	Digi-Key	0.34
8-input multiplexer	CD74HC151	Texas Instruments	1	0.63	Digi-Key	0.63
14-stage binary counter	CD4020B	Texas Instruments	1	0.72	Digi-Key	0.72
8-bit magnitude comparator	CD74HCT688E	Texas Instruments	1	1.15	Digi-Key	1.15
6-bit parallel register	74F378	Fairchild	1	0.39	Digi-Key	0.39
Hex gate	CD4572UBE	Texas Instruments	1	1.29	Digi-Key	1.29
Timer	NE555D	Texas Instruments	1	0.59	Digi-Key	0.59
5-segment yellow LED array	SSA-LXB525YD	Lumex	1	1.99	Digi-Key	1.99
Green diffuse LED	LNG324GDG	Panasonic-SSG	3	0.29	Digi-Key	0.88
Printed circuit board			1	2.00	Digi-Key	2.00
Resistors, jumpers (est.)						2.00
Plastic casing (est.)						2.00

Total variable costs: $152.02

6.2 Research Costs

Research was relatively cheap because a laboratory, instrumentation and prototyping boards were provided free. The software used for design, simulation and reporting was also free. In a corporate environment, additional costs would be associated with the use of laboratory time and equipment, software and consultation.

Table 3: Research costs

	Consultation fees
Junior engineer	$40/hour
Special consultants	$150/hour
Travelling	$0.40/km

Consulting activities	Expected workload
Research and design	55 hours
Construction	10 hours
Testing	25 hours
Verification	10 hours
Reporting	15 hours

Testing supplies	Cost
Plants	$23.94
Geotextile	$0 (sponsored)
Electronics	$49.01
Plumbing	$12.08
Valve	$16.86
Sensor	$60.99

Total research costs: $5,335

6.3 Break-even Analysis

If one supposes that the selling unit price is $200, the breakeven point is at

$$BE = \frac{\$5335}{\$200 - \$152.02} = 112\,units \tag{15}$$

This estimate assumes that the fixed costs are only attributable to research (no building, machinery, fixed labour, etc.) and that there is no variable cost for assembly. In addition, the numbers in Table 2 are taken from official retail prices. Variable costs should go down due to scale saving when the system is marketed.

7. Discussion

7.1 Critical Analysis

In this design, not all benchmark elements have been fully studied and tested. This was mostly due to time constraints. However, the following observations were made:

- The installation of the automated irrigation system is very simple. The layout of the geotextile is the most cumbersome step. No technician is required. An installation manual should be provided to the user as well as a chart of the water needs of common houseplants and a list of compatible soil types. The pipe network should also be easy to set up. A tank and a compatible pipe may be included or recommended by the manufacturer. More elaborate work may be required to connect the valve to the water mains.

- Water savings have not been studied for the system as a whole. Nevertheless, the performance of the geotextile and of the moisture probe has been demonstrated by previous experiments in real agricultural contexts.

- An experiment showed that it is difficult to maintain a constant soil moisture level with only human feedback. In the short periods over which this system has been tested, virtually no human intervention was required. The user must only verify that the system is operational and that the water tank, if used, is not empty. On the other hand, there is no way to inform the user of emergencies such as overflow, empty tank, component failure, etc.

- Further testing should be done in a real home or greenhouse environment to assess the reliability and durability of the system. These tests should also be prolonged to determine the significance of the savings in water and labour. Furthermore, all measurements and tests were done on a very limited collection of plants of a single species. Different plants have different water requirements and are unequally resistant to deficiencies in the water supply.

- All the components were selected to achieve some degree of power efficiency. All the electronic components consume less than 400 mW on a constant basis. The probe consumes a maximum of 41 mW, but only for one minute per 5:20-hour duty cycle; in average, it should require less than a milliwatt. The valve is the element that uses the most power (8.41 W maximum, 26 mW average). On average, the whole system should require less than 450 mW of electricity with peak consumption of less than 8.9 W.

- Regular maintenance of the irrigation system is not required, except to refill the water tank (if used), to clean the geotextile, pipes and valve, and to replace parts when broken. Most replacement components can be found in an electronic shop or a hardware store. The maximum cost for an electronic part is 1.99 (LED array). A solenoid valve is sold for approximately $35.00 in specialized garden stores. The Aquamat geotextile is available from Soleno at $11.20 per square meter. The Watermark moisture probe is the most expensive part; GENEQ sells it for $49.00.

- A market analysis was not performed to evaluate the demand for such a product and to determine the viability of the irrigation system at large.

7.2 Possible Future Improvements

A few improvements can be suggested to the next version of the automated irrigation system:

- The timing can be defined by the user (e.g. with switch or a keypad and 7-segment display) instead of being hardwired in the Logic Circuit electronics.
- The threshold humidity levels may be adjustable using several multi-turn potentiometers.
- More options may be customizable, such as the size of the geotextile.
- The use of several moisture probes may be allowed with the addition of a multiplexing circuit or some kind of mathematical operation (e.g. average).
- Data logging and/or exporting (e.g. through a RS232 serial port) may be offered.

- All electronic components may be incorporated on a printed circuit board. They may also be integrated onto a single chip (so-called System On Chip).
- A single power supply is desirable to replace the dual (AC/DC) supply of the prototype. A full-wave rectifier and a voltage regulator should be incorporated on the PCB to ensure the stability of the 5 V source.
- Mass production of the controller will reduce the cost of components and assembly. In addition, scale saving on the probe and valve is likely to be achieved in mass commercialization.
- The system may be further extended for outdoor utilisation.

Conclusion

- An automated irrigation was successfully designed and assembled. It serves to reduce the consumption of water used, the human monitoring time and the labour associated with standard methods.
- This design uses a timed feedback control to measure the soil moisture and turn on the valve on demand, in regular intervals.
- Such a system can be manufactured at a relatively low cost using simple electronic parts. The soil moisture probe is the most expensive component.
- It can be installed easily in a home environment and requires little resources.
- The design is still in a prototype stage. More tests need to be conducted before the efficiency, durability, and reliability can be demonstrated. Additionally, many improvements can be made to make the system more versatile, customisable, and user-friendly.

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Appendix A: Time Frame

Time Constraints

The project began in the month of December 2004 and was completed by the month of April 2005. Since the whole experiment was done inside, there was no constraint in season, but the schedule had to allow a decent period of testing time to get sufficient data.

Approach Breakdown

1. Selection of the plants and determination of water intake.
   - For this testing, use as many plants as to be used on the geotextile;
   - Record their water needs;
   - This experiment was performed for a period of 6 weeks.
2. Initial design of the irrigation system.
   - System-level design of the prototype;
   - Decide either to design the controller or to program a microcontroller.
3. Selection of the components.
   - Moisture probe;
   - Controller components;
   - Pipes and valve.
4. Design of the controller.
   - Functional / schematic description of the controller;
   - Simulate the logic circuit;
   - Test the controller.
5. Assembly of the irrigation system.
   - Put all the pieces together;
   - Test the circuit parts;
   - Do some adjustments.
6. Final report.
   - Recommend the final product;
   - Suggest additional improvements.

Appendix B: Plant Experiment Results

For 40 days, the soil moisture of 6 different plants in separate pots was measured using a Moisture Meter MM328.

Date	Moisture Level							Water given (mL)	Weather	Comments
	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Average			
10-Feb	5.0	3.0	4.0	5.0	5.0	5.0	4.5	0	covered	
11-Feb	5.0	5.0	4.0	5.0	5.0	5.0	4.8	0	sunny	
12-Feb	5.0	6.0	5.0	5.0	4.0	3.0	4.7	0	sunny	
13-Feb								0		no record
14-Feb	4.5	5.0	4.0	3.5	3.0	3.0	3.8	200	cloudy	
15-Feb	6.0	6.5	3.0	5.0	5.0	4.0	4.9	0	rainy	
16-Feb	5.0	6.0	3.0	5.0	4.0	3.0	4.3	0	rainy	
17-Feb	4.0	6.0	3.0	5.0	3.0	3.0	4.0	200	sunny	
18-Feb	5.0	6.0	3.0	7.0	5.0	4.0	5.0	0	sunny	
19-Feb	4.0	6.0	3.0	6.0	4.0	3.0	4.3	0	sunny	
20-Feb	4.0	5.0	2.0	6.0	3.0	2.0	3.7	0	sunny	
21-Feb	3.0	4.0	2.0	4.0	2.0	2.0	2.8	0	cloudy	
22-Feb	2.0	3.0	1.0	4.0	2.0	1.5	2.3	180	sunny	
23-Feb	3.0	4.0	1.0	4.0	2.0	1.0	2.5	180	sunny	
24-Feb	2.0	5.0	2.0	4.0	2.0	1.0	2.7	180	sunny	
25-Feb	2.0	3.0	2.0	4.0	2.0	1.0	2.3	180	sunny	
26-Feb	3.0	4.0	1.0	3.0	2.0	2.0	2.5	180	sunny	
27-Feb	2.0	2.0	1.0	2.0	1.0	1.0	1.5	180	sunny	
28-Feb	2.0	2.0	1.0	2.0	2.0	1.0	1.7	180	cloudy	
01-Mar	2.0	2.0	1.0	3.0	2.0	1.0	1.8	180	cloudy	
02-Mar	3.0	1.5	1.0	4.0	3.0	1.0	2.3	180	sunny	
03-Mar	4.0	2.5	2.5	4.0	4.0	2.0	3.2	240	sunny	
04-Mar								0		no record
05-Mar								0		no record
06-Mar								0		no record
07-Mar	3.0	1.0	1.0	3.0	3.0	1.0	2.0	240	cloudy	
08-Mar								0		no record
09-Mar	2.0	1.0	1.0	2.0	3.0	1.0	1.7	240	sunny	
10-Mar								0		no record
11-Mar	5.0	2.0	1.0	4.0	5.0	1.0	3.0	0	sunny	
12-Mar	5.0	1.0	1.0	4.0	5.0	1.0	2.8	0	sunny	
13-Mar	3.0	1.0	1.0	3.0	3.0	1.0	2.0	500	sunny	
14-Mar	4.0	4.0	3.0	5.0	5.0	3.0	4.0	0	mixed	
15-Mar								0		no record
16-Mar								0		no record
17-Mar	3.0	3.0	2.0	3.0	3.0	2.0	2.7	500	sunny	
18-Mar	4.0	6.0	3.0	5.0	4.0	4.0	4.3	0	sunny	
19-Mar								0	sunny	no record
20-Mar								0	sunny	no record
21-Mar	2.0	4.0	2.0	3.0	2.0	2.0	2.5	500	sunny	

Appendix C: Valve Impedance Calculations

In the valve impedance measurement circuit, given the valve impedance $Z_v = R_v + jX_v$ and the capacitor impedance jX_c, with $\mathrm{R_v}, X_v, X_c \in \Re$, the voltage phasors across the transformer ($\overline{V_t}$), capacitor ($\overline{V_c}$) and valve ($\overline{V_v}$) are related to the current $\overline{I}$ according to:

$$\overline{V_t} = \overline{I}\left(Z_v + jX_c\right) \Rightarrow V_t = I\sqrt{\left|Z_v\right|^2 + 2X_v X_c + X_c^2} \tag{16}$$

$$\overline{V_c} = \overline{I}jX_c \Rightarrow V_c = I\left|X_c\right| \tag{17}$$

$$\overline{V_v} = \overline{I}Z_v \Rightarrow V_v = I\left|Z_v\right| \tag{18}$$

The absolute value of the impedance is thus:

$$(18)\&(17) \Rightarrow \left|Z_v\right| = \frac{\left|X_c\right|V_v}{V_c} \tag{19}$$

Its imaginary part (reactance) can be found:

$$(18)\&(16) \Rightarrow V_t = \frac{V_v}{\left|Z_v\right|}\sqrt{\left|Z_v\right|^2 + 2X_v X_c + X_c^2}$$

$$X_v = \frac{1}{2X_c}\left(\frac{\left|Z_v\right|^2 V_t^2}{V_v^2} - \left|Z_v\right|^2 - X_c^2\right) \tag{20}$$

$$(20)\&(19) \Rightarrow X_v = \frac{1}{2X_c}\left(\frac{\left(\frac{\left|X_c\right|V_v}{V_c}\right)^2 V_t^2}{V_v^2} - \left(\frac{\left|X_c\right|V_v}{V_c}\right)^2 - X_c^2\right) \tag{21}$$

$$X_v = \frac{X_c}{2}\left(\frac{V_t^2}{V_c^2} - \frac{V_v^2}{V_c^2} - 1\right) \tag{22}$$

$$X_v = \frac{X_c}{2V_c^2}\left(V_t^2 - V_v^2 - V_c^2\right) \tag{23}$$

Therefore, the real part (resistance) is :

$$(19)\&(23) \Rightarrow R_v = \sqrt{\left|Z_v\right|^2 - X_v^2} = \sqrt{\left(\frac{\left|X_c\right|V_v}{V_c}\right)^2 - \left(\frac{X_c}{2V_c^2}\left(V_t^2 - V_v^2 - V_c^2\right)\right)^2} \tag{24}$$

$$R_v = \frac{|X_c|}{V_c^2}\sqrt{V_v^2 V_c^2 - ¼\left(V_t^2 - V_v^2 - V_c^2\right)^2} \tag{25}$$

And the power factor of the valve is :

$$(25)\&(19) \Rightarrow \; pf = \frac{R_v}{|Z_v|} = \sqrt{1 - \frac{\left(V_t^2 - V_v^2 - V_c^2\right)^2}{4V_v^2 V_c^2}} \tag{26}$$

Appendix D: SPICE Simulation Decks

```
PROBE_DRIVER

* SPICE deck for output stage of soil moisture probe driver.
* Converts probe resistances to DC voltages.
* designed for ABEN 490/495: Design Project 1 & 2
* (c) Marie France Leroux w/ Eric Thibault
* Macdonald Campus, McGill University
*
* input:
* - Rprobe: resistance of probe (500 to 30000 ohms)
*           function of soil moisture content
*
* output:
* - V300: soil moisture level DC voltage (must be < 5.0V)

* AC power supply
Vac    200 0 SIN 0.0V 12.16V 60Hz

* relay contact
Rrelay 200 201 100mohm

* voltage division resistors
Rs     201 202 555ohm
Rp     202 0   820ohm

* DC-blocking capacitors for probe protection
Cblk   202 204 110uF

* probe resistance
* requires 4.5V to 5.0V RMS for proper operation
* ==> 2250ohm minimum, no maximum
Rprobe 204 0   30000000ohm

* peak detector
Dpd    202 205 D1N4001
Cpd    205 0   4.7uF

* votlage halfer (for V300 < 5.0V)
Rhf1   205 300 1040kohm
Rhf2   300 0   1040kohm

* next stage: Comparator_Circuit
RL     300 0   100000Megohm

* analysis request: transient from 0ms to 300ms
.TRAN  0  300ms  0.5ms  0.5ms

.PROBE

*********************
* 1N4001 diode model
* by Fairchild Semiconductor
.MODEL D1N4001 D (IS=29.5E-9 RS=73.5E-3 N=1.96 CJO=34.6P VJ=0.627
```

```
+M=0.461 BV=60 IBV=10U)

.END



RELAY_COIL_CIRCUIT

* SPICE deck for input stage of Probe Driver & Valve Driver
* designed for ABEN 490/495: Design Project 1 & 2
* (c) Marie France Leroux w/ Eric Thibault
* Macdonald Campus, McGill University

Vcc 100 0 DC 5.0V

Vb 20 0 DC 5.0V

Rentr 20 30 1.2kohm

Dprot 1 100 D1N4001
Rrelay 1 100 401ohm
Q1 1 30 0 Q2N3904

.DC Vb 0.0V 5.0V 0.01V

.PROBE

*********************
* 1N4001 diode model
* by Fairchild Semiconductor
.MODEL D1N4001 D (IS=29.5E-9 RS=73.5E-3 N=1.96 CJO=34.6P VJ=0.627
+M=0.461 BV=60 IBV=10U)

*********************
* 2N3904 NPN transistor model
* by Fairchild Semiconductor
.MODEL Q2N3904 NPN (Is=6.734f Xti=3 Eg=1.11 Vaf=74.03 Bf=416.4
+Ne=1.259 Ise=6.734 Ikf=66.78m Xtb=1.5 Br=.7371 Nc=2 Isc=0
+Ikr=0 Rc=1 Cjc=3.638p Mjc=.3085 Vjc=.75 Fc=.5 Cje=4.493p
+Mje=.2593 Vje=.75 Tr=239.5n Tf=301.2p Itf=.4 Vtf=4 Xtf=2 Rb=10)

.END



COMPARATOR_CIRCUIT

* SPICE deck for comparator section of soil humidity controller
* designed for ABEN 490/495: Design Project 1 & 2
* (c) Marie France Leroux and Eric Thibault
* McGill University
*
* inputs:
* - V300: output voltage of moisture probe circuit
*
* outputs:
* - V30: above 100% moisture
```

```
* - V31: above  80% moisture
* - V32: above  60% moisture
* - V33: above  40% moisture
* - V34: above  20% moisture
* - V35: above   0% moisture

*power supply
Vcc 100 0 DC 5.0V

*output (V300) of Probe_Circuit
Vprobe 300  0 DC 3.35V

*humidity level generators
* note: minimum safe resolution allowed by op amps is 0.2mV
Rpot  100 10 9.95kohm
Rser   10 11 10kohm
R80    11 12 390ohm
R60    12 13 390ohm
R40    13 14 390ohm
R20    14 15 390ohm
R00    15 16 390ohm
Rend   16  0 38.7kohm

*humidity comparators
*    +   -  vcc vee vout
Xc1x 300 11 100 0   30   TLC27M4
Xc80 300 12 100 0   31   TLC27M4
Xc60 300 13 100 0   32   TLC27M4
Xc40 300 14 100 0   33   TLC27M4
Xc20 300 15 100 0   34   TLC27M4
Xc00 300 16 100 0   35   TLC27M4

* analysis request: 0V - 5V DC sweep
.DC Vprobe 0.0V 5.0V 10mV

.PROBE

********************
* TLC27M4 op-amp macromodel subcircuit
* created using Parts Release 4.03 on 07/11/90 at 10:35
* Rev (N/A)      supply voltage: 5V
* Level 2 Model 2
* by Texas Instruments
* Connections:   Non-inverting input
*                | Inverting input
*                | | Positive power supply
*                | | | Negative power supply
*                | | | | Output
*                | | | | |
.SUBCKT TLC27M4  1 2 3 4 5
  C1   11 12 6.938E-12
  C2    6  7 15.00E-12
  CPSR 85 86 79.6E-9
  DCM+ 81 82 DX
  DCM- 83 81 DX
  DC    5 53 DX
  DE   54  5 DX
```

```
  DLP  90 91 DX
  DLN  92 90 DX
  DP    4  3 DX
  ECMR 84 99 (2,99)  1
  EGND 99  0 POLY(2) (3,0) (4,0) 0 .5 .5
  EPSR 85 0 POLY(1) (3,4) -90E-6  18.0E-6
  ENSE 89 2 POLY(1) (88,0) 185E-6  1
  FB 7 99 POLY(6) VB VC VE VLP VLN VPSR 0 25.22E6 -40E6 40E6 40E6 -40E6
25E6
  GA    6  0 11 12 39.87E-6
  GCM 0  6 10 99 2.248E-9
  GPSR 85 86 (85,86) 100E-6
  GRD1 60 11 (60,11) 3.987E-5
  GRD2 60 12 (60,12) 3.987E-5
  HLIM 90  0 VLIM 1K
  HCMR 80 1 POLY(2) VCM+ VCM- 0 1E2 1E2
  IRP 3 4 99E-6
  ISS   3 10 DC 6.000E-6
  IIO 2 0 .1E-12
  I1 88 0 1E-21
  J1   11  89 10 JX
  J2   12  80 10 JX
  R2    6  9 100.0E3
  RCM 84 81 1K
  RN1 88 0 40E3
  RO1   8  5 85
  RO2   7 99 85
  RSS  10 99 33.33E6
  VAD  60 4 -.5
  VCM+ 82 99 1.20
  VCM- 83 99 -2.3
  VB    9  0 DC 0
  VC 3 53 DC 1.68
  VE   54  4 DC .6
  VLIM  7  8 DC 0
  VLP  91  0 DC 20
  VLN   0 92 DC 20
  VPSR 0 86 DC 0
.MODEL DX D(IS=800.0E-18)
.MODEL JX PJF(IS=300.0E-15 BETA=529.8E-6 VTO=-.017 KF=8.2E-17)
.ENDS

.END
```

Appendix E: Part Datasheets

- Soleno Textiles, Aquamat: “How does it work?” [10]
- Soleno Textiles, Aquamat: “Components” [10]
- Soleno Textiles, Aquamat: “Benefits” [10]
- Irrometer, Watermark Sales Brochure [7]
- Irrometer, Watermark Installation and Operation Manual [8]

How does it work?

The Aquamat™ system!

This unique patented system is based on a high-performance multi-layer textile mat incorporating the very latest technological advances. One of the layers acts as a reservoir from which water is displaced constantly and evenly throughout the entire area. The Aquamat system is a new growth solution specifically designed for outdoor and indoor potted plant growers.

The complete Aquamat system is a four-layer product whose top layer is a durable coated woven, micro-perforated fabric.

The second layer consists of a special fluffy textile sheet, which lifts and separates the top layer from the lower absorbent pad to prevent surface evaporation. When pots are placed on the mat, the second layer collapses, allowing contact with the pad and capillary uptake.

The third textile layer is a super absorbent pad with high capillary properties allowing even distribution of water from pot to pot. Water flows in, with conventional overhead sprinklers or supplied drip-tape system watering the selected area. Many growers find a combination of both is useful.

The bottom layer is a highly puncture-resistant polyethylene film that forms a fully contained watertight reservoir. A isolating “capillary break” is placed every 10' in the length of the mat.

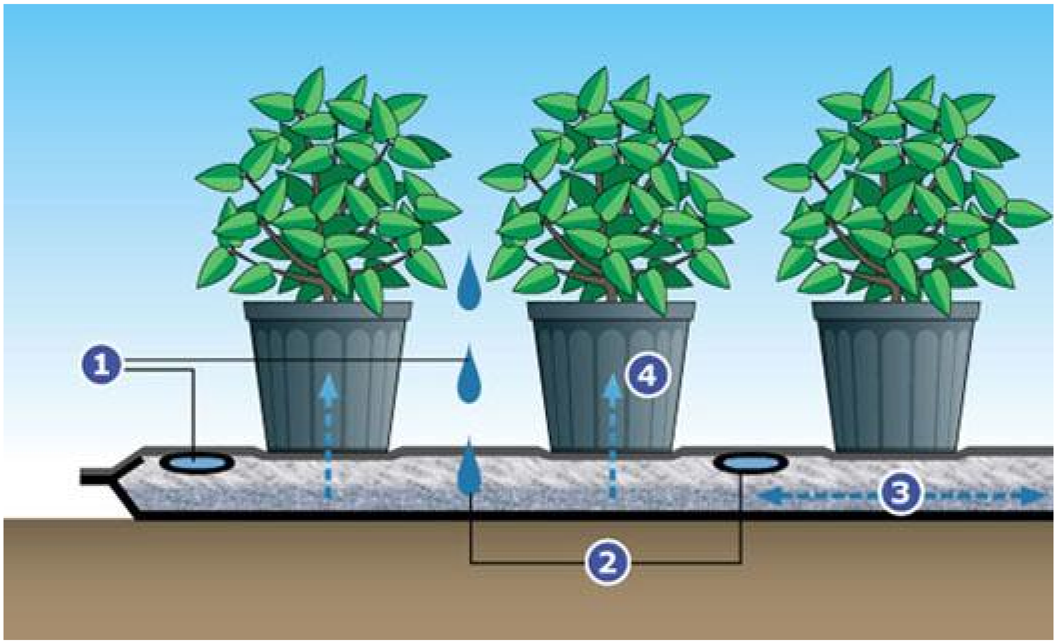
Each of these layers plays a specific role in creating the most efficient, flexible and ingenious irrigation system known.

Improve crop growth while saving water and money!

Specifically designed for nurseries and potted plant growers, this revolutionary multi-layer water conservation system is now used by growers intent on saving water and money while getting their crops to market faster:

- Uses less than 50% of the water required by conventional overhead irrigation systems.
- Accelerates plant growth by up to 35% over standard irrigation systems, making it possible to get more crops to market more quickly.
- Ensures total containment of runoff water and fertilizers.
- Dramatically reduces fertilizer requirements through more efficient use.
- Easy to install using in-house equipment.
- Measurably reduces electrical energy from pumping for lower labor costs and shorter production time.

The watering process:



1. Irrigation

- Water flows in, with conventional overhead sprinklers or supplied drip-tape system watering the selected area. The volume of irrigation water required is calculated and adjusted based on substrate properties, crop type and seasonal rainfall recorded for the area.

2. Absorption

- Unlike conventional overhead systems, all water (rainfall and irrigation) that doesn't end up in the pots is recovered and absorbed by the capillary mat. You get total containment and no water loss!
- The water will easily penetrate the first 2 layers of micro-perforated cover and evaporation block layers, ending up in the mat's "reservoir". To facilitate the absorption process, particularly when the cover is new, it is recommended that the top layer be sprayed with a wetting agent immediately following installation.

3. Distribution

- The high-performance textile layer acts as a reservoir.
- Thanks to its capillary and transmission properties, the Aquamat irrigation system allows the unfettered, uniform circulation of water in all directions while preventing loss through evaporation or leaks. The water used by the plants is automatically replaced by that held in the surrounding mat, ensuring a constant, uninterrupted supply.
- Due to its significant 5-inch (12.5 cm) capillary rise, the Aquamat can distribute water successfully on slopes of up to 3%. The absorbent felt is broken into separate sections and an isolating "capillary break" is formed every 10' in the length of the mat. This dramatically reduces the possibility of puddling.
- The super high transmission or wicking properties of the absorbent pad result in the uninterrupted flow of water throughout the mat.
- The high quality and special blend of polyester fibers used in the Aquamat yield a reservoir with a 2.5 gal./square yard (11.6 liters/square meter) water-retention capacity, i.e., the highest watering-mat capacity on the market.

4. Water uptake

- Water is easily and constantly drawn up into holes on the bottom of the pot and evenly distributed through potting substrates by capillary uptake. Capillary rise is strong and uniform, preventing the occurrence of dry spots. Water is supplied to the plant constantly, even on gentle slopes as a result of the separate water pads and capillary breaks. Every plant is watered equally regardless of pot size. Plants can receive water from both the internally irrigated capillary mat and the overhead irrigation system. This gives the grower the flexibility needed to avoid water stress. The overhead system is often combined with the internal source for young plants or under extreme climatic conditions.
- For maximum water uptake, all substrates, which are an important component of the watering process, must have the appropriate hydraulic or wicking properties to ensure maximum performance of the Aquamat.

In order to stay abreast of changing water-restriction requirements, growers must adopt a proactive stance. To this end, Soleno Textiles strives to forge the type of close working relationship that leads to the development of the most suitable and effective solutions.

Indeed, studies and university researchers have confirmed that, for growers intent on saving water, the Aquamat system emerges as a truly innovative technological solution.

Better yet, the Aquamat system provides the peace of mind that comes from knowing that plants are watered accurately and efficiently.

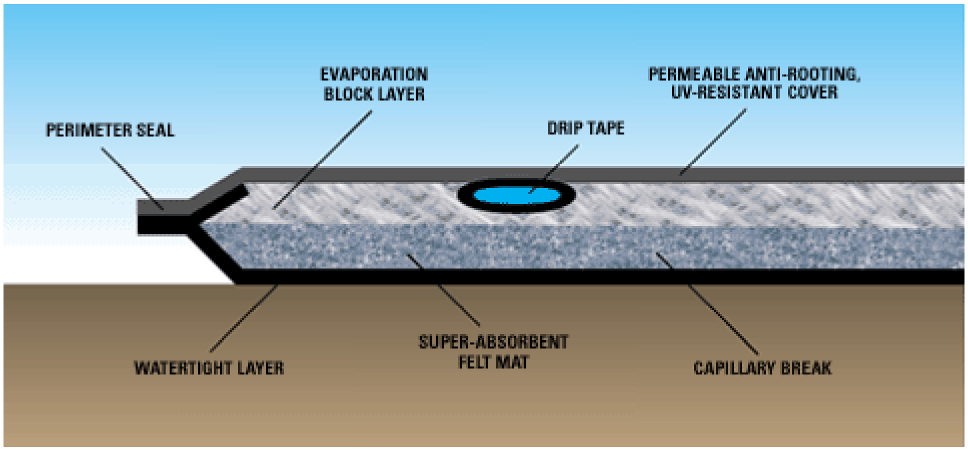
These and other factors make the Aquamat growing system the most technologically advanced and cost-effective way of growing currently available.

Components

The Aquamat system, the result of 10 years of laboratory research, field tests and ongoing optimization, is based on a high-performance multi-layer textile mat incorporating the very latest technological advances. The Aquamat system provides a new growth solution specifically designed for outdoor and indoor potted plant growers.

The complete Aquamat system consists of an internal drip-tape system plus four patented and patent-pending engineered layers, each of which plays a specific role. Together, they form the most efficient irrigation system currently available. One of the layers acts as a reservoir from which water is displaced constantly and evenly throughout the entire area. Another layer is a special fluffy textile sheet, which prevents surface evaporation while drawing water into the pot through capillary uptake.

Description of components:



1. Permeable anti-rooting, UV-resistant cover

- Available only from Soleno Textiles, the top layer, called MicroFab™, consists of a strong, highly UV-resistant woven textile sheet that is custom coated with a black plastic layer providing a smooth clean surface. This is then micro-perforated using our special process to create a water-permeable product that roots cannot invade. It also features blue lines printed at 6-inch (15 cm) intervals for easy plant spacing.
- Made of a tightly woven polyethylene fiber with a black coating, it will stop light transmission into the mat, and eliminate the growth of algae. This tear-resistant material will withstand small truck and tractor traffic.

2. Evaporation block layer

- The patented evaporation lock, today's most technologically advanced textile, acts like a valve. This fluffy textile layer prevents the top layer from touching the absorbent mat, thus precluding surface evaporation. The weight of the pot collapses this layer, allowing water to enter through capillary uptake. It lets in free water (rainfall and irrigation) but will only release it under pressure from the nursery pots.
- This resilient 100% polyester high-quality fiber structure is restored to its original thickness once pots are removed. Thanks to its insulating properties, the ground cloth will remain clean and dry, preventing the growth of algae and weed germination.

3. Super-absorbent felt mat

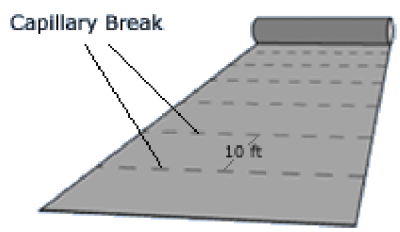
- The third layer is an enhanced water distribution media whose high capillary properties allow the uniform and unfettered circulation of water in all directions. This high-performance textile layer is distinguished by its high water-retention capacity and its ability to distribute water evenly throughout the matting, constituting an effective water distribution network. The water used by the plants is automatically replaced by that held in the mat, ensuring a constant, uninterrupted supply.
- With a water-retention capacity of 2.5 gal./square yard (11.6 liters/square meter) and a capillary rise of 5 inches (12.5 cm), the reservoir layer will easily distribute water on slopes up to 3% and uneven benching. The 100% polyester virgin fibers are non-phyto toxic and can be disinfected with most active ingredients specified for this purpose.
- At the core of the Aquamat system, layers 2 and 3 are bound together. The result is a mat unlike any other on the market.

4. Watertight layer

- Beneath the water reservoir and the distribution system lies an impervious highly puncture-resistant, black, 6-mil polyethylene film, which covers the ground and prevents water from seeping into the soil.

5. Capillary break

- The polyethylene film has a 1/2 inch (1.2 cm) high fold every 10 feet (3.05 meters) that forms separate cells. This engineered part reduces the possibility of disease transfer and contributes to watering uniformity, even on very uneven terrain.



6. Drip Tape

- Drip tubes are placed in the mat, just below the top layer. They are at 2-foot intervals (61 cm) and can be easily moved right to left to adjust for slope of bench and pot placement. Drip tapes have an output of 1 - 1/2 gallons of water per minute per every 100 feet (30.5 meters) in length. The tape requires a constant water pressure of 7 to 11 psi to rapidly and evenly fill the mat to its capacity of 2.5 gallons per square yard (11.6 liters/square meter).

7. Perimeter seal

- The top and bottom layers are welded, forming a fully sealed envelope ensuring total containment of your valuable water and nutrients in field or bench applications.

Specifically designed for nurseries and potted plant growers, this revolutionary multi-layer system comes in standard widths and almost any length, and is very easy to install. Used with sprinklers or supplied drip tapes, the Aquamat system requires no change to standard cultivation practices: no land leveling, same containers, same potting soils if deemed adequate further to a site evaluation. You just end up using far less water. Furthermore, the Aquamat system has an average lifespan of 5 to 10 years, providing an outstanding return on investment for growers intent on saving water and money while getting their crops to market faster.

Contact your local Aquamat dealer to experience the performance of this vestal irrigation system and start saving time, labor and resources.

TECHNICAL CHART

AQUAMAT S-10			
Properties	**Test method**	**Value**	
Capillary rise	SAGEOS GX 009-02	5 inches (125 mm)	
Water holding capacity	SAGEOS GX 010-02	2.5 gal/yd^2 (11.6 l/m^2)	
Tickness	ASTM D5199	6.3 mm	
Transmissivity	SAGEOS GX 009-02	4.14 in/min (10.5 cm/min)	
	Roll Width & Weight	**Drip tape lines***	**Fill time**
Standard offering	11 feet (3.35 m) 169 lbs (77 kg) 7 feet (2.13 m) 108 lbs (49 kg) 6 feet (1.83 m) 93 lbs (42 kg) 5 feet (1.52 m) 77 lbs (35 kg) 4 feet (1.22 m) 62 lbs (28 kg)	6 4 3 3 2	max 34 min** 32 min 37 min 31 min 37 min
Standard Roll length	100 feet (30.5 m)		
Custom lengths available at no extra charges.			
Fiber: Polyester			
Fabrication: Needlepunched Nonwoven			

* **Drip tape & driplock (supplied)**: 8 mil thickness, 1 inch wide flat, 5/8 inch diameter, flow rate 1.5 gpm/100 lin feet; spaced every 2 feet starting at 6-12 inches from edges. If required, spacing and quantity of drip tape lines can be changed to avoid placement under containers. Use “T” connector or supplied driplock (Chapin 250 or equivalent) to connect drip tape lines. Use a 0.14 inch punch to plug driplock into manifold pipe.

Water supply equipment (not supplied): Use a 7-10 psi pressure regulator (Chapin AG-10 or equivalent) with appropriate flow rate (gpm) to accommodate the length of drip tape lines to be connected to a manifold with a minimum diameter of 3/4 inch. Use a 180-200 mesh filter. Refer to drip tape recommendation specs sheet for more details.

** **Pulsing cycles** are commonly used instead of one cycle depending on crop, weather or on a new mat. For example: 2 cycles of 16 min. instead of 1 cycle of 32 min. to fill Aquamat.

Soleno Textiles, April 2004

Benefits

A vision of growth rooted in efficiency

PRINT THIS PAGE

In a world increasingly ruled by the dual challenges of rationalization and optimization, growers seeking improved production efficiency must look beyond the “tried and true” to new technologies — technologies like the Aquamat system! The Aquamat is a high-performance multi-layer textile mat specifically designed for nurseries, greenhouses and garden centers to optimize every phase of their irrigation process.

It’s not only the plant-watering process that must be upgraded, but the cost-effectiveness of the watering process as a whole. In response to this fundamental requirement, the technology built into the Aquamat system delivers solutions! In fact, you get the most efficient use of water, labor, electricity and production time from a system that fosters larger average growth and faster harvesting, along with an exceptionally short payback period.

Better yet, the Aquamat system provides the peace of mind that comes from knowing plants are watered both accurately and efficiently. These and other factors make the Aquamat system’s growth technology the most cost-effective and environmentally sound growing method currently available.

Advantages of the Aquamat System:

Reduces water requirements – water savings of more than 50%

- Increasing concern over decreasing water supplies are addressed by the Aquamat system:
  - Since the end of the 1990s, significant droughts have plagued several parts of the United States and Canada.
  - We are witnessing the introduction of stringent water restrictions in some areas. Total containment is also becoming a real issue.
  - Others must pay by the gallon when using more than 100,000 gallons of water per day (350,000 liters/day).
  - Some growers are facing the occasional imposition of alternate-day irrigation.
  - Growers must be aware of the best management practices (BMP) with regards to watering.
  - The Aquamat system allows the expansion of nurseries located in water restricted areas with quotas per acreage.
  - In areas where water costs are rising, the Aquamat system can dramatically improve production profitability.
- Studies and university research have confirmed that the Aquamat system uses less than 60% of the water required by conventional overhead irrigation systems, and reduces runoff.
- Acting as a reservoir (no water waste - total containment), the capillary mat supplies water to the plants easily, constantly and evenly. Each plant is watered equally resulting in more uniform growth.
- The possibility of using the integrated drip tape in combination with your existing overhead system is a true advantage of the Aquamat system, as it will allow you to better control your irrigation water requirements.

Accelerates plant growth by up to 35%

- Studies and field tests have confirmed that the Aquamat system fosters optimal plant nourishment for faster growth.
- Between irrigations, water rises from the Aquamat to the soil by capillarity keeping it well moistened and aerated. This dramatically reduces plant water stress, resulting in accelerated growth. The capillary mat helps build a strong root system.
- As a result, growers can get their crops to market up to twice as fast or produce the same number of crops of larger plants every year, significantly enhancing the system's cost effectiveness.

Easy to install

- Light and easy to move, this practical 4-layer system comes in standard rolls of 4, 5, 6, 7, and 11 ft x 100 feet (1.22, 1.52, 1.83, 2.13 and 3.35 m. x 30.5 meters). Custom lengths and even some widths are available.
- Thanks to its flexibility, the Aquamat system conforms to the lay of the land, leaving no dry zone.
- Technical assistance from your certified dealer is provided for proper installation and use.

To see and feel the product for yourself; **click here** and order our InfoPack! Or call us at 866.765.3661 in Montreal Canada or 650.593.6700 for the US representative.

Resistance to undesirable growth

- Algae and weed growth are virtually eliminated with the Aquamat, since its unique evaporation block layer keeps the engineered top surface dry and prevents light from entering the mat.
  - The top layer consists of a strong, highly UV-resistant, coated woven polyethylene fabric first subjected to a micro-perforating system. These perforations are specifically adjusted to admit water while keeping out roots and light.
  - The coating creates a smooth surface with no areas for algae or weed growth to start. The only water that would allow weed seed germination and algae growth is located at the point where the edge of a container compacts the top layer causing capillary uptake from the bottom layer. A regular hose provides sufficient pressure to remove spilled soil or debris during annual cleaning, a feature that growers appreciate in that it helps cut the incidence of disease and reduces labor.
- A capillary break at every 10 feet (3.05 meters) creates a closed environment, preventing the transmission of disease from one section of a panel to another. Each panel also constitutes a totally separate system.
- Reduced overhead irrigation cycles help control foliar disease in plants irrigated by sprinklers. When the Aquamat's integrated drip-tape system is used alone, the risk of foliar disease is virtually nil.

Economical use

- With proper installation and maintenance, this system has an average lifespan of 5 to 10 years, providing an outstanding return on investment.
- Electrical energy for pumping is measurably reduced as are labor costs and production time.
- If water is billed according to consumption, savings provided by the Aquamat system will have a major economic impact.

No change in standard cultivation practices

- No land or bench levelling needed, except in excessively concave areas where significant amounts of water can accumulate. Slopes of up to 3% are acceptable and have been successfully tested with overhead irrigation. Slopes of 0-1% are recommended for drip-tape system.
- Suitable for most potting soils with peat content.
- No need to change containers provided they have perforated bottoms.
- Highly effective in use with regular 1 to 3-gallon containers.
- Can be used with sprinklers or the supplied, internal drip-tape system or both, depending on crop development and environmental demands.

Ecologically sound

- In addition to saving water, the system will reduce most of the runoff and comply with future containment legislation in this regard.
- Helps control foliage disease and limit fungicide applications in sensitive plants by reducing irrigation frequency.

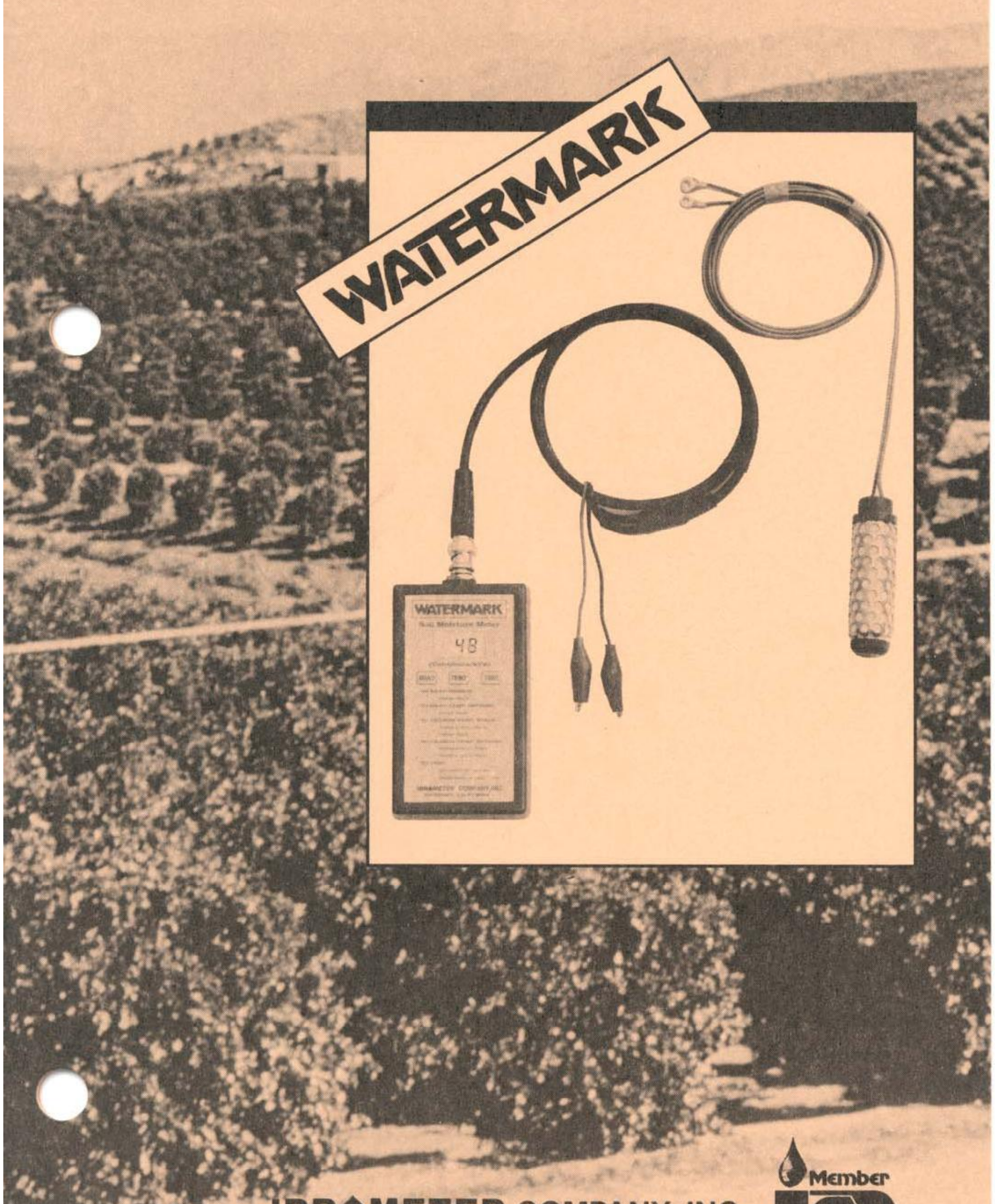
Aquamat: the most cost-effective irrigation system

Money saved on water consumption, electrical energy, labor costs and production time, plus money earned from harvesting faster add up to an extremely short payback period. In fact, the initial investment can sometimes be recovered on the first two crops. Designed for maximum yields, this cost-effective irrigation system improves the overall performance of your business operations. In short, it is a most attractive investment!

In order for you to actually experience the performance that translates into tangible profits, **contact your local Aquamat dealer!**

Water and Aquamat:
Two essentials for growth and profitability!

Soil Moisture Sensor



IRROMETER COMPANY, INC.
Riverside, California

WATERMARK SOIL MOISTURE SENSORS

For over sixty years, plant scientists have verified the value of actual soil moisture measurement as the most effective method for precise irrigation scheduling. These in-field measurements allow an irrigation manager to know exactly how fast the soil is being depleted of moisture, and **WHEN** to initiate an irrigation cycle to replenish soil moisture for maximum plant growth. By obtaining soil moisture readings in different areas of the field, and at different depths in the root zone, the manager can also establish **HOW MUCH** water to apply, from experience and good record keeping. This "Irrigation to Need" can result in:

- ☑-Lower Water Cost
- ☑-Lower Energy Bills
- ☑-Prevent Excessive Leaching of Fertilizers
- ☑-Better Crop Quality
- ☑-Better Crop Yields

WHY WATERMARK

The **Watermark** is a solid state, electrical resistance type sensor, in use since 1978. Unlike other electrical resistance sensors, the patented **Watermark** provides accurate readings from 10 centibars to 200 centibars, which covers the entire soil moisture range required in irrigated agriculture, even in the heavier clay soils. They require no water, or vacuum gauge, which makes them maintenance free. The **Watermark** does not dissolve in the soil which generally occurs with a gypsum block in a short period of time. However, this sensor includes internally installed gypsum which provides some buffering for the effect of salinity levels normally found in irrigated agricultural crops and landscapes. Because they are unaffected by freezing temperatures, they do not require removal during winter in cold climates. And, they can be used with sophisticated data loggers to automatically record and chart the readings. In automatic irrigation systems, the **Watermark** can be used to control or interrupt irrigation cycles which are not needed. See Page 7.

WHAT DO THE READINGS MEAN?

The **Watermark** readings reflect soil water tension or suction. The meter internally converts the electrical resistance reading of the sensors to this tension or suction value. This major physical force of soil water is a direct indicator of how hard the plant root system has to work to extract water from the soil. The drier the soil, the higher the reading. As a general guideline the interpretation of these readings is listed below and has been found practical for use under field conditions.

Soil Suction	Interpretation
0-10 centibars	Saturated soil. Occurs for a day or two after irrigation.
10-20 centibars	Field capacity. Soil is still wet in all but coarse sands where water is beginning to become depleted. This range is usually maintained in drip irrigation 12"-18" from the emitter.
30-60 centibars	Usual range for irrigation in most soils. Irrigate at the lower end of this range in hot dry climates and with the lighter soils. Irrigate at the upper end of this range in cool humid climates and with the higher water holding capacity soils. Observe crop response closely.
70-100 centibars	In heavy clay soils and crops requiring a greater dry down between irrigations, irrigation can be delayed until this range. Exercise caution in the 90-100 range.
100-200 centibars	Dry conditions. Proceed with caution and knowledge.

By reading your sensors 2-3-times between irrigations you will notice the rate at which the soil is drying out. The "rate of change" is as important as the actual reading in determining when to irrigate to avoid moisture stress. See Figure 2 on page 5. Readings are best taken in the morning. The **Watermark** meter has a soil temperature compensation feature. This allows for greater accuracy as electrical resistance readings vary 1% per degree of Fahrenheit encountered in the soil. On a day to day basis, this will not have a major effect, but on a seasonal basis (spring vs. summer) it needs to be taken into account.

DETERMINING WHEN TO IRRIGATE

Figure 1 shows how variations in soil affect the ability of the soil to store water (water holding capacity). Heavier clay soils store much more water than sandy soils. But even more important, the plant cannot readily extract all of this stored moisture, only the "available" portion. The general rule of thumb is that irrigation should commence before you reach 50% of the "available" portion being depleted. From Figure 1 you can see what the soil moisture tension is at the 50% level of available moisture.

Assuming your soil was in the middle, this 50% level would occur at about 60-70 centibars. While determination of the proper irrigation point is largely dependent on soil type, you must also consider the crop and your irrigation method. Sensitive crops may require irrigation sooner, less sensitive crops may not need water until later. Surface irrigation may allow you to apply water much more rapidly than a drip system, thus you need to consider how quickly your system can react in order to avoid moisture stress. See Figure 2.

DETERMINING HOW MUCH TO IRRIGATE

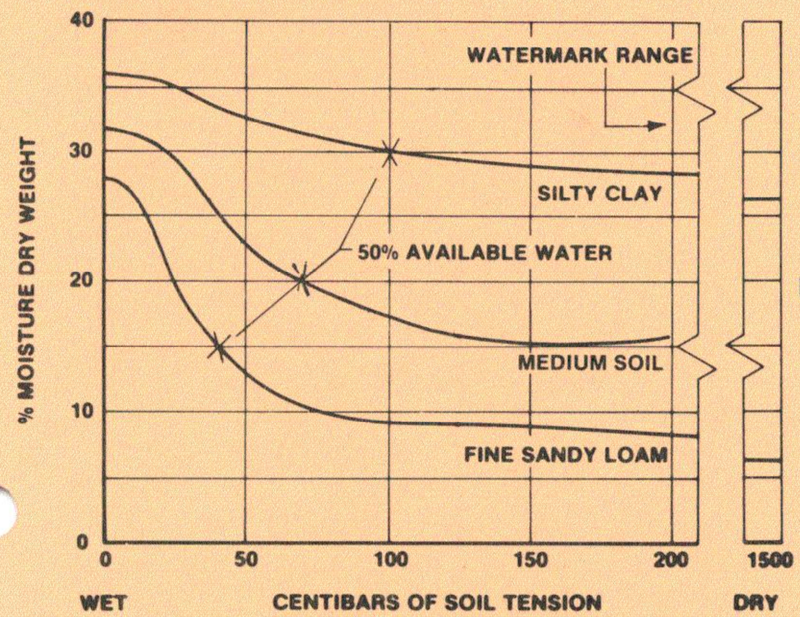
Your own record keeping system, and experience with your crop, soils and irrigation method are essential with any good management system. With **Watermark** Sensors properly placed in both the top (eg. 12") and bottom (eg. 24") of the crop root system, your readings will tell you whether it is the shallow or deep moisture which is depleted. If your shallow reading is 60 and your deep reading is 10, you know you only need to apply enough water to rewet the top 12". If the readings are reversed, with 40 for the shallow and 60 for the deep, you may need to apply twice as much water. The local farm advisor or SCS can be of great help to you in determining your individual soils and how much water they store. This will lead to your use of the **Watermark** Sensor readings to effectively control your irrigation scheduling and to prevent excessive leaching of plant nutrients. See Figure 2.

SENSOR INSTALLATION

The basic procedure is to make a hole with a 7/8" diameter rod to the desired sensor depth. With coarse or gravelly soils, it is sometimes difficult to get a snug fit between the sensor and the soil. With this situation, making an oversized hole (1" - 1 1/4") may be necessary. Then prepare a "grout" of the soil and water and pour it down into the bottom of the hole. Push the sensor down to the bottom of the hole (a piece of 1/2" class 315 PVC pipe is handy) to ensure it bottoms out and snugly fits into the soil. If desired, the 1/2" class 315 PVC can be solvent welded to the sensor collar to provide a permanent stake. If the PVC is not left in place after sensor installation, carefully backfill the access hole and tamp the soil down sufficiently to prevent water channeling down the hole to the sensor. Specific instructions are included with each shipment.

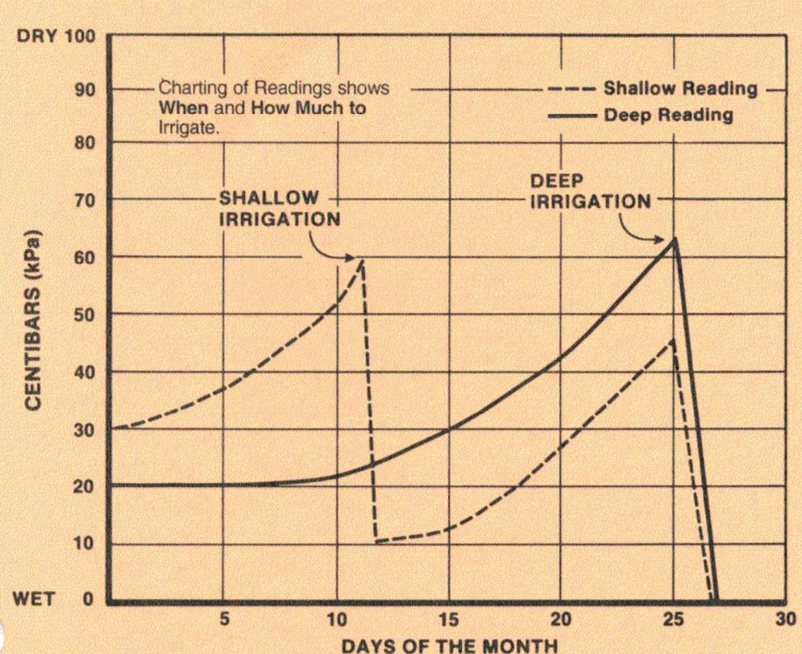
SENSOR MAINTENANCE

Once the sensors are installed, there is no further need for maintenance. With permanent crops such as trees and vines, the sensors may be left in place all winter, providing your cultural operations would not disturb them. With annual crops, where field operations are required, removal of the sensors prior to harvest is a standard practice. If the sensors are removed, simply clean them off and store them in a dry area until spring.



40
30
20
10
0
% MOISTURE DRY WEIGHT
WATERMARK RANGE
SILTY CLAY
50% AVAILABLE WATER
MEDIUM SOIL
FINE SANDY LOAM
0
50
100
150
200
1500
WET
CENTIBARS OF SOIL TENSION
DRY

Fig. 1



DRY 100
90
80
70
60
50
40
30
20
10
WET 0
CENTIBARS (kPa)
Charting of Readings shows When and How Much to Irrigate.
Shallow Reading
Deep Reading
SHALLOW IRRIGATION
DEEP IRRIGATION
5
10
15
20
25
30
DAYS OF THE MONTH

Fig. 2

HOW THE WATERMARK WORKS

The patented **Watermark** Sensor consists of two concentric electrodes buried in a special reference matrix material that is held in place by a stainless steel case. The matrix material has been selected to reflect the maximum change of electrical resistance over the growth range of production crops. In operation, soil moisture is constantly being absorbed or released from the sensor. As the soil dries out, the sensor moisture is reduced and the electrical resistance between the electrodes is increased. This resistance is read by the **Watermark** Meter. The sensor is manufactured from non-corrosive parts and lasts for years. It is 7/8" in diameter by two-inches long.

If the sensor is being used with a data logging device, sensor excitation current is 5 VAC, 100 — 120 H_z (square wave) and sensor output is 500-30,000 ohms of electrical resistance which equates to 0-200 centibars of soil water suction (non-linear).

The **Watermark** Meter Model 30KTCD-NL gives a digital readout in centibars (kPa) of soil water suction (calibrated). Using an AC bridge circuit powered by a nine-volt battery, the meter converts the electrical resistance reading of the sensor to the centibar (kPa) value. It also has the capability of inputting the soil temperature (°F or °C), which helps compensate for the effect which soil temperature has on the reading ("fine-tunes the data").

In operation, follow the instructions which are on the face of the meter, and in the pamphlet included with the meter. Pushing the "READ" button "wakes up" the meter - you will see "--". It stays "awake" for 5 seconds - or for 60 seconds if you immediately push "READ" a second time. While the meter is "awake," you can take readings and check or change the temperature setting. The reading is held for 60 seconds, which allows time to record it.

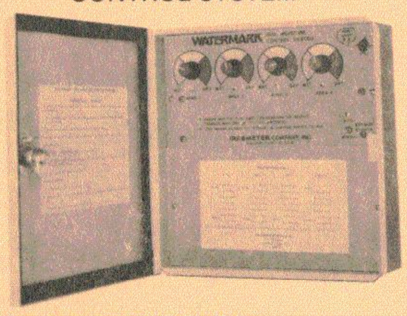
YOU — THE MANAGER

The concept of soil moisture measurement in managing irrigation schedules to meet crop "need" has been demonstrated for many decades. It's not just simply a matter of conserving water and energy, although this has become a most critical factor. When you irrigate precisely, you can indeed achieve these savings, but the real bonus from good management comes in the area of better production and healthier, longer living, ornamental plants and turf. These results however, are not achieved by guesswork; the key ingredient is You — The Manager! Tools such as the **Watermark** give you the extra advantage needed to be successful. Why not ask your irrigation advisor to help you add soil moisture measurement to your management program?

AUTOMATIC IRRIGATION SYSTEM CONTROL

For standard 24 volt automatic irrigation systems, the **Watermark** Soil Moisture Control System (controls the entire time clock) or the **Watermark** Electronic Module (controls individual valves) can be used to control or interrupt pre-programmed irrigation cycles. These switching devices rely on the **Watermark** sensors to measure soil moisture continuously and to operate as "thermostats" for your irrigation system. Complete specifications, installation details and operating instructions are available from your irrigation supplier on request.

SOIL MOISTURE
CONTROL SYSTEM



FEATURES:

- 4 MOISTURE ZONES
- ALL FOUR ZONES ADJUSTABLE
- OVERRIDE SWITCH
- COMPATIBLE WITH ALL 24 VOLT CONTROL SYSTEMS
- EASY TO INSTALL—NEW OR RETROFITS
- EASY TO USE
- LED's ON PANEL FOR CHECKING OPERATION

WATERMARK
ELECTRONIC MODULE

FEATURES:

★ INDIVIDUAL VALVE CONTROL BASED ON SOIL MOISTURE READING

★ FULLY SOLID STATE

★ EASILY BYPASSED

★ ELECTRONIC MODULE POTTED FOR LONG LIFE

★ FULLY ADJUSTABLE OVER ENTIRE MOISTURE RANGE

BENEFITS

★ NON MAINTENANCE SENSORS

★ SAVE WATER! ENERGY! FERTILIZER!

★ EASY TO USE

★ CONTROL IRRIGATION COSTS

★ HEALTHIER TURF/PLANTS

IRROMETER®
COMPANY, INC.

P.O. Box 2424 • Riverside, CA 92516
Phone: 909/689-1701 • Telefax: 909/689-3706
URL: http://www.irrometer.com

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SAVE MONEY!

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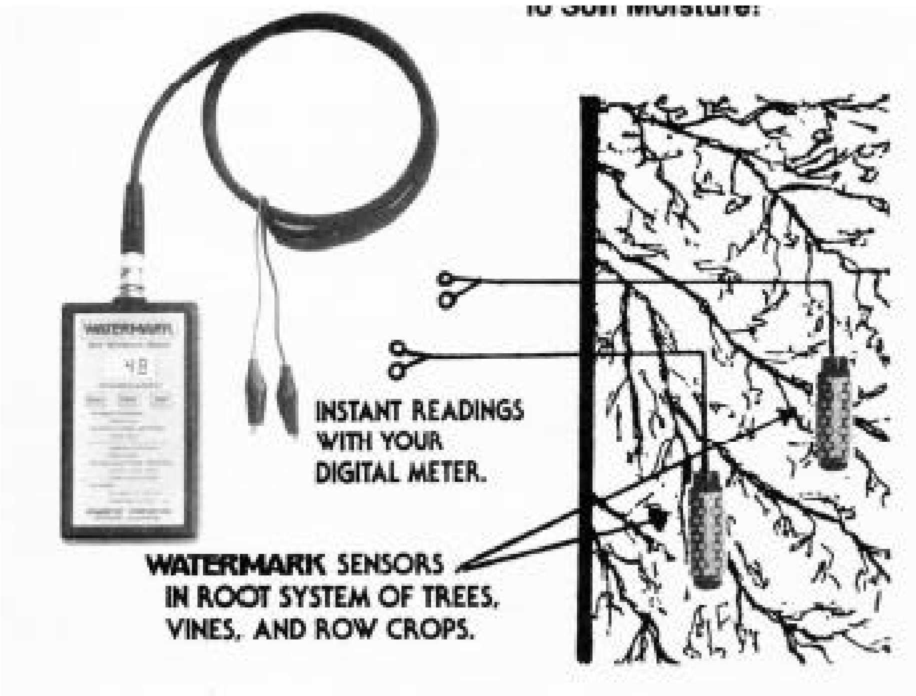
WATERMARK



The soil acts as a reservoir to store water between irrigations, or rainfall events, so that it is available to the crop or plants as needed for healthy growth. The purpose of using sensors to measure soil water is to give you a better understanding of how fast it is being depleted in the different areas of your field, so you can better schedule your irrigations and correctly evaluate the effectiveness of any rainfall. By reading the sensors 2 – 3 times between irrigations, you will gain an accurate picture of this process over time, and develop an irrigation scheduling pattern that meets your crop's "need" for water. This eliminates the guesswork, and can result in water savings, lower pumping costs and the elimination of excess leaching of nitrogen due to over irrigation.

SENSOR SITE SELECTION

Often more than one sensor should be placed at a given location, at varying depths. For instance, one sensor in the upper portion of the plant's effective root zone and other sensors located deeper into the root zone profile. We refer to this as a "sensing station", and it can give a better representation of the plant's uptake of water.

PLACEMENT

Furrow or Flood Irrigation: Locate sensing station about 2/3 the way down the run, just ahead of the tail or backup water. This is the area where water penetration is usually the poorest. With tree crops, locate sensors on the southwest side of the tree (in the Northern Hemisphere) as this side gets the hot afternoon sun.

Sprinkler Irrigation: Even though the distribution is typically more uniform with sprinkler irrigation, there can be great differences in penetration and holding capacity due to soil variations, interfaces and contour. These variation sites make good locations for sensor stations. With tree crops, locate sensors at the drip line of the canopy being sure that they are not obstructed from the sprinkler's distribution. With row crops, locate sensors right in the plant row.

Center Pivot Irrigation: Place sensors at 4 – 5 locations down the length of the pivot (between towers) just ahead of the "start" point. Additional locations at "hot spots" or good production areas of the field, can help give a better overall view of the field. Be sure to use enough "sensing stations," every 10 – 15 acres is a good rule of thumb.

Drip or Micro Irrigation: Sensors must be located in the wetted area. With Drip emitters, this is usually 12" – 18" from the emitter. With micro-sprinklers, usually 24" – 36" is best. Monitor often enough to get a good overall picture of the field, or irrigation "block", and consider the soil variations which exist. Keep in mind that light soils dry very quickly and heavy soils more slowly.

DEPTH

This depends on the rooting depth of your crop, but can also be affected by soil depth and texture. With shallow rooted vegetable crops, one depth may be adequate (root system less than 12"). With deeper rooted row crops (small grains, vines and trees) you need to measure soil moisture in at least two depths. With deep well-drained soils, crops will generally root deeper – if moisture is available. With coarse, shallow or layered soils, root systems may be limited in depth. In general, sensors must be located in the effective root system of the crop. Guidelines on proper depths for specific crops and conditions can be obtained from us as well as your local farm advisor.

NOTE

Our recommendation for anyone using sensors for the first time is to use an adequate number of "stations" over a smaller area to begin with to get an accurate picture. Then read them regularly over the season to learn the patterns which normally develop.

INSTALLATION

Soak the sensors overnight in irrigation water. Always “plant” a wet sensor. If time permits, wet the sensor for 30 minutes in the morning and let dry until evening, wet for 30 minutes, let dry overnight, wet again for 30 minutes the next morning and let dry again until evening. Soak over the next night and install WET. This will improve the sensor response in the first few irrigations.

Make a sensor access hole to the desired depth with an Irrometer installing tool or a 7/8” O.D. rod. Fill the hole with water and push the sensor down into the hole so it “bottoms out”. A length of ½” Class 315 PVC pipe will fit snugly over the sensor’s collar and can be used to push in the sensor. A good snug fit in the soil is important. This PVC can be solvent welded to the sensor collar with a PVC/ABS cement (IPS Weld-On #795 or equal).

If the PVC pipe is not left on the sensor, then backfill the hole so the sensor is buried (see Fig. 1). The sensor’s wires can easily be staked up for easy access. If PVC is left on, then compact the soil around the surface to seal off the hole (see Fig. 2). The PVC acts as a conduit for the sensor’s wires. Be sure to cap off or tape the top of the pipe, so surface water will not infiltrate to the sensor and give a false reading.

For very coarse or gravelly soils, an oversized hole (1” – 1-1/4”) may be needed to prevent abrasion damage to the sensor membrane. In this case, auger a hole to the desired depth and make a thick slurry with the soil and some water. Fill the hole with this slurry and then install the sensor. This will “grout in” the sensor to ensure a snug fit.

Another method of installing sensors in difficult gravelly soils, or at deeper settings is to use a “stepped” installing tool (see Fig. 3). This makes an oversized hole for the upper portion and an exact size hole (sensor is 7/8” O.D.) for the lower portion where the sensor is located. The hole must be carefully backfilled and tamped down to prevent air pockets, which could allow water to channel down to the sensor.

If sensors are removed, clean and dry them. They can be stored indefinitely in a clean, dry location.

WIRING SENSORS

If additional wire length is needed, simply splice the additional wire to the sensors wire leads. This wire splice must be fully waterproof (3M Scotchpak, Duraseal heat shrink splice connector, or equal). This wire can be extended up to 1000’ with #18 gauge UF wire. Avoid long wire runs near power cables. The transient currents can affect the small current used by the Watermark meter. This can be checked by reading the sensors at both ends of the wire run.

WATERMARK METER – 30 KTCD-NL

(Green Case)

Hook the meter’s leads to the sensor’s wires with the alligator clips, being sure the separate leads are not touching each other.

Press “READ” to wake up the meter, you will see “- -“ in the display. The meter will stay awake for 5 seconds (to keep meter awake for 60 seconds, press “TEMP” before “- -“ goes away).

Press “READ” again while “- -“ is in the display. The soil moisture reading will immediately appear in the display and remain there for 60 seconds while you record it. The meter will then turn itself off.

When taking readings, the soil temperature adjustment should be set for early morning ambient temperature. This setting compensates for seasonal variations in soil temperature, which can go from the sixties in the spring to the eighties in the summer. This variation in soil temperature can affect the readings by 1% per degree Fahrenheit, so the temperature compensation greatly improves the accuracy of your readings.

To check the temperature settings, press “TEMP”. The temperature setting and the scale (°F or °C) will alternate in the display.

To change the temperature scale, press and hold “READ”, then alternately press “TEMP” until the desired scale (°F or °C) appears in the display and then release READ button.

To change the temperature setting, press and hold “TEMP” then press “READ” to change the setting. The temperature setting will begin to increase until the desired setting appears in the display. The full scale of temperature setting is 41°F (5°C) to 105°F (40°C). Once the temperature scrolls up to 105°F, it will go to 41°F and begin scrolling upwards again. You can reverse the direction of scrolling at any time by releasing the “READ” button and depressing it again (while continuing to hold “TEMP” down).

The temperature settings you programmed in will remain until you change them. The meter comes with a default setting of 75°F.

The meter has a built in test function. To test the meter for accuracy, with the temperature setting at 75°F (24°C), press and hold “READ” and “TEST” simultaneously. A reading of between 95 and 105 should appear in the display. This reading indicates the meter is functioning properly. D**uring test, make sure cable leads are not touching or hooked to a sensor.**

This digital meter has a full range of 0 to 199 centibars built in.

The digital meter utilizes solid state electronics and is sensitive to extreme heat. Do not store the meter on the dashboard or any other very hot location. Replace with a good quality 9V alkaline battery at least once each year. The meter has a low battery indicator and the battery should be replaced whenever “LO” appears in the display.

DATA LOGGING DEVICES

If Watermark sensors are to be read by a data logging device, the electrical resistance range is from 500 to 30,000 ohms. The alternating current input to the sensor must be small (4.5 to 5 VAC) to prevent sensor heating, and should not be maintained for any length of time.

Sensor hookup should be through a multiplexer that uses a relay. With direct hookup to a data logger input port, AC blocking capacitors should be used on both legs of the sensor wire. This protects the sensors from any current leakage from the data logger.

Follow the data logger manufacturer’s instructions and make sure it is compatible with Watermark moisture sensors.

NOTE

Our old style 30 KTCD meters, with the tan colored case, are still fully usable. They operate a bit differently than the newer 30 KTCD-NL, with the green case, but we will still offer repair and upgrade services for a number of years.

TROUBLESHOOTING

Every now and then you may encounter a situation where the sensor doesn’t seem to be working properly. Please follow the steps below to determine if the equipment is functioning correctly or to determine if the field condition needs modification.

1. First check the meter.
   - A. Is the battery O.K.? It should be replaced at least once a year, more often with frequent use. Check to be sure the battery contacts are clean and tight on the battery terminals.
   - B. Follow the test procedure on the meter.
   - C. If there has been some wire damage to the meter’s leads, it could malfunction. To check this, clip the leads to each other and push the “READ” button. The number 0 should appear in the display. If it does, then the leads are O.K.
   - D. The LCD display on the meter has three digits. If you see only partial digits, the LCD may be suspect and should be returned for examination and or repair.
2. Then check the sensor.
   - A. With a sensor submerged in water, your meter reading should be from 0 to 5. If the sensor passes this test, go on to step B.
   - B. Let the sensor air dry for 30 to 48 hours. Depending on ambient temperature, humidity and air movement, you should see the reading go right up from zero to 150 or higher – even off scale (LCD will read 199 when it reaches 199 cb **or more**)
   - C. Put the sensor back in water with the meter leads attached. The reading should return to zero within 2 minutes. If the sensor passes these tests, it is O.K.
3. Next check the field conditions.
   - A. The sensor does not have a snug fit in the soil. This usually happens when an oversized access hole has been used and the backfilling of the area is not complete. Re-install the sensor nearby, carefully backfilling the access hole.
   - B. Sensor is not in an active portion of the root system, or the irrigation is not reaching the sensor area. This may happen if the sensor is sitting on top of a rock, or below a hardpan, which may impede water movement. Re-installing the sensor should solve the problem.
   - C. If the soil dries out to the point where you are seeing readings higher than 80 centibars, the contact between the sensor and the soil can be lost. The soil starts to shrink away from the sensor. If the irrigation only partially re-wets the soil (soil suction above 40 centibars), it will not fully re-wet the sensor and may result in continued high readings. Fully rewetting the soil and sensor usually restores the contact. This is most often seen on heavier soils during peak crop water demand periods when irrigation may not be sufficient. Plotting your readings on a chart provides the best indication of this type of behavior.

MANAGEMENT

The key element in proper soil moisture measurement is the operator. Taking the time to properly read your sensors will give you a vivid picture of what is happening with the soil moisture down in the root system of your crop. Usually 2 – 3 readings between irrigations is sufficient. Plotting these readings onto a chart for each sensing station creates soil moisture curves, which show you exactly how quickly (or slowly) your soil moisture is being depleted.

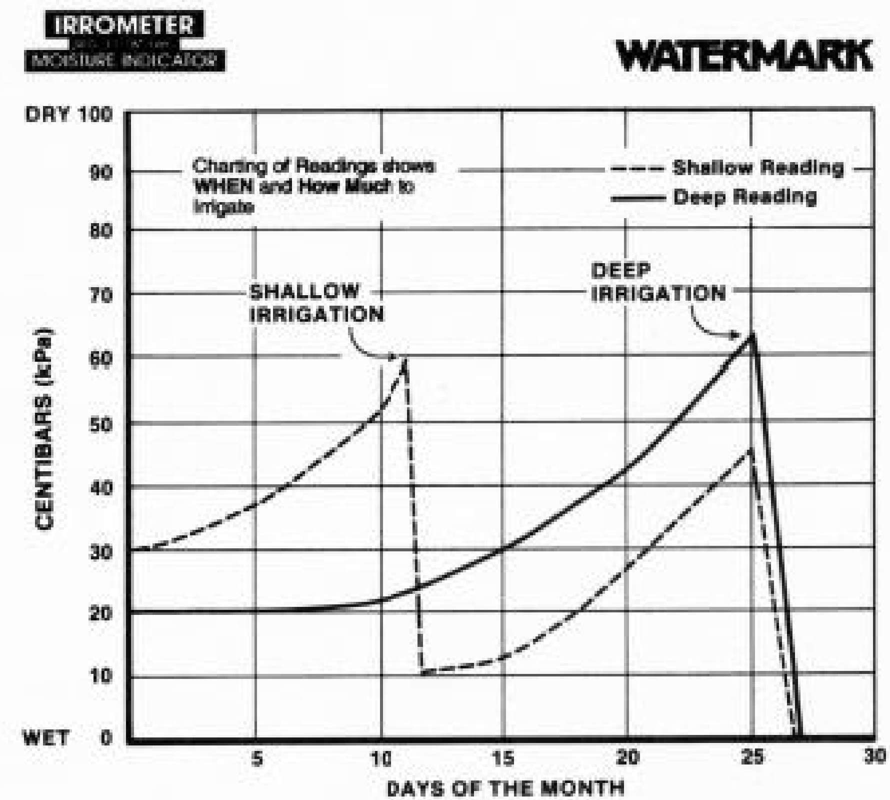
Use the following readings as a general guideline:

- 0 – 10 centibars = Saturated soil (field capacity)
- 10 – 20 centibars = Soil is adequately wet (except coarse sands, which are beginning to lose water)
- 30 – 60 centibars = Usual range for irrigation (except heavy clay soils)
- 60 – 100 centibars = Usual range for irrigation in heavy clay soils
- 100 – 200 centibars = Soil is becoming dangerously dry for maximum production. Proceed with caution!

Your own situation may be unique because of differences in crop, soils and climate. Perhaps the most important soil moisture reading is the difference between today's reading and that of 3 – 5 days ago. That is to say, how quickly is the reading going up. A slow increase means the soil is drying out slowly. But a big jump means the soil is losing water very rapidly. This tells you **WHEN** to irrigate (see chart on next page).

By using sensors at two or more depths in the root system, you soon learn **HOW MUCH** water to apply. If the shallow sensor shows a rapidly increasing reading, but the deep sensor shows adequate moisture, you can run a short irrigation cycle as you only need to replenish the shallow root profile. If the deep sensor also shows a dry condition, then a longer irrigation cycle is needed to fully re-wet the entire root zone. The readings you take after an irrigation or rainfall event will show you exactly how effective that water application really was.

Your own experience and management will soon point you in the proper direction. You will be practicing "irrigation to need" with the expected positive results that come from any good management program.



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