Theta and Profiler Soil Moisture Probes – Accurate Impedance Measurement Devices - New Applications

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ABSTRACT

Volumetric soil water can be accurately measured by the Theta probe and the Profiler probe (the ML2 and PR1 from Delta T Devices, Ltd.). The Theta Probe uses a simplified standing wave ratio method to determine relative impedance or theta. The Profiler probe uses a similar technology as the Theta probe but gives volumetric water content at six distinct levels down to one meter and can be used with access tubes. Both probes may be connected to data loggers or used as portable devices. Theta probes typically do not require calibration for most applications, however Profile probes (PR1) should be calibrated, especially in soils with heavy clay or high saline content. Examples of easy calibration methods are discussed in this article, as well as irrigation automation devices.

Figure 1 - Theta Probe ML1 was introduced in 1995 by Delta-T Devices and jointly developed by the Macauley Land Use Research Institiue. The device is subject to USA, UK and Europe patents.

Introduction - Theta Probe

Theta Probe consists of a waterproof housing which contains the electronics, and, attached to it at one end, four sharpened stainless steel rods that are inserted into the soil.

The probe generates a 100 MHz sinusoidal signal, which is applied to a internal transmission line that extends into the soil by means of the array of four rods. The impedance of this array varies with the impedance of the soil, which has two components - the apparent dielectric constant and the ionic conductivity.

The 100 MHz signal frequency was chosen to minimize the effect of ionic conductivity, so that changes in the transmission line impedance are dependent almost solely on the soil's apparent dielectric constant. Water content determines the dielectric constant of soil because the dielectric of water (~81) is much higher than soil (typically 3 to 5) and air (1).

The impedance of the rod array affects the reflection of the 100 MHz signal, and these reflections combine with the applied signal to form a voltage standing wave along the transmission line. The output of the Theta Probe is an analogue voltage proportional to the difference in amplitude of this standing wave at two points, and this forms a sensitive and precise measure of soil water content.

Work published over many years by Whalley, White, Knight Zegelin and Topp and others, shows almost linear correlation between the square root of the dielectric constant, ($\sqrt{\varepsilon}$), and volumetric moisture content, (θ_v), and this has been documented for many soil types.

Each Theta Probe is adjusted during manufacturing to provide a consistent output when measuring media of known dielectric constant, making them readily interchangeable without system re-calibration. The output signal is 0 to1V DC for a range of soil dielectric constant, ε, between 1 and 32. This range of dielectric values corresponds to 0 to 0.5 $m^3.m^{-3}$ volumetric soil moisture content for mineral soils.

Most soil applications may take advantage of a linear calibration, however for research and irrigation, a non-linear calibration provides a wider range and improved accuracy.

Theta Probe Basics

The generalized calibrations have been optimized to cover a wide range of soil types, based on the following definitions:

Table 1 - Soil type chart	Optimized around organic content:	Use for organic contents:	Bulk density range ($g.cm^{-3}$):	Use for bulk densities
Mineral	~ 1 %C	< 7 %C	1.25 - 1.5 $g.cm^{-3}$	> 1.0 $g.cm^{-3}$
Organic	~ 40 %C	> 7 %C	0.2 - 0.7 $g.cm^{-3}$	< 1.0 $g.cm^{-3}$

The Theta Probe responds to soil dielectric as follows:

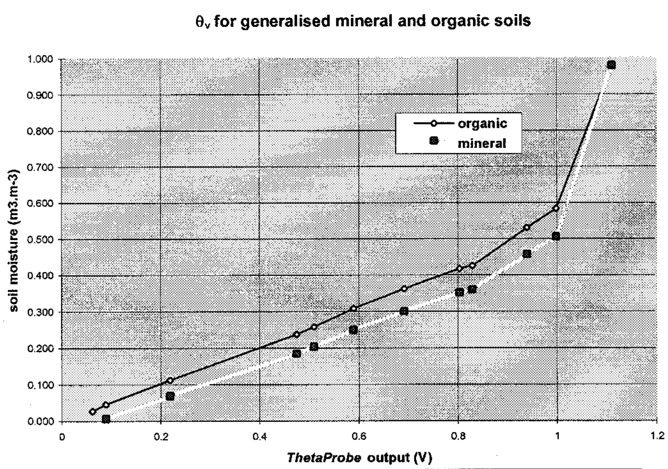

Figure 2 – Theta Probe signals versus moisture

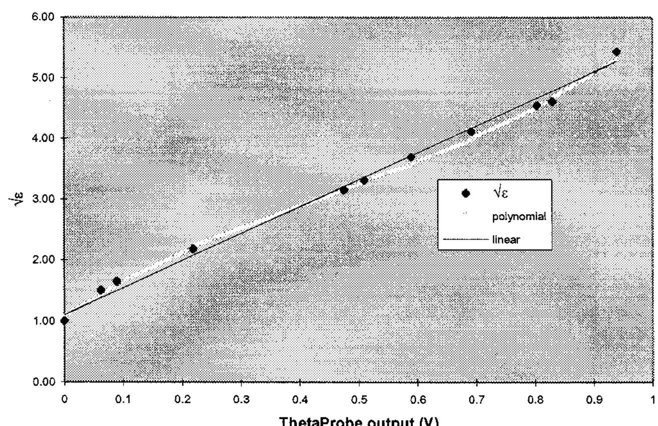

Figure 3 – Theta Probe response to dielectric properties

In the range 0 to 1 Volt, corresponding to a soil moisture range 0 to ~ 0.55 by volume, this dielectric relationship can be fitted very precisely by a 3rd order polynomial:

$$\sqrt{\varepsilon} = 1.07 + 6.4V - 6.4V^2 + 4.7V^3 \qquad (R^2 = 0.998)$$

Whalley, and White, Knight, Zeggelin and Topp showed that there is a simple linear relationship between the complex refractive index (which is equivalent to $\sqrt{\varepsilon}$), and volumetric water content, θ:

$$\sqrt{\varepsilon} = a_0 + a_1 \cdot \theta$$

Since the relationship beween *ThetaProbe* output and $\sqrt{\varepsilon}$ is already known, it is only necessary to determine the two coefficients, a_0 and a_1. For the general soil definitions in Table 1, the parameters in Table 2 are commonly accepted.

Table 2 Gen. Calibration	a_0	a_1
Mineral soils	**1.6**	**8.4**
Organic soils	**1.3**	**7.7**

Performance – Theta Probe

A combination of Theta Probe sensors and ceramic block water tension sensors were installed 45 cm deep in a phytoremediation study by Dynamax at the Cape Canaveral Air Station Landfill for Parsons Engineering. A customized weather station logged soil moisture data as well as sap flow and the important parameters related to water uptake and water status.

Figure 4 shows the response of the Watermark sensors over a 13-day period of irrigation and one day of significant rainfall. The sensor conversion to water potential included the standard resistance to water tension method as well as the temperature compensation recommended by the manufacturer.

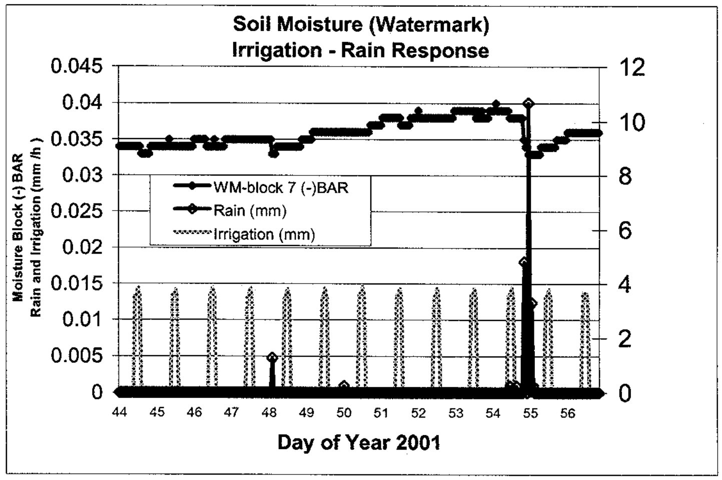

Figure 4 – Water tension compared to rainfall and irrigation

Figure 5 shows the Theta Probe response to the same type of irrigation and rainfall over a three-day period. In this example we noted that the Theta Probe responded quickly to a saturating rain as well as the daily irrigation. Note that the field capacity of the predominately sandy soil is about 18.5 % moisture by volume, the minimum reading after 24 hours of drainage. By comparison the water tension readings are registering little or no change and in a range of 0.01 Bar.

For irrigation and research purposes, the response and accuracy of the Theta Probe appears to have a significant advantage in response as well as resolution. The water infiltration time from heavy rain or irrigation is seen easily in Figure 5. In one hour the wetting front moves to the sensor depth.

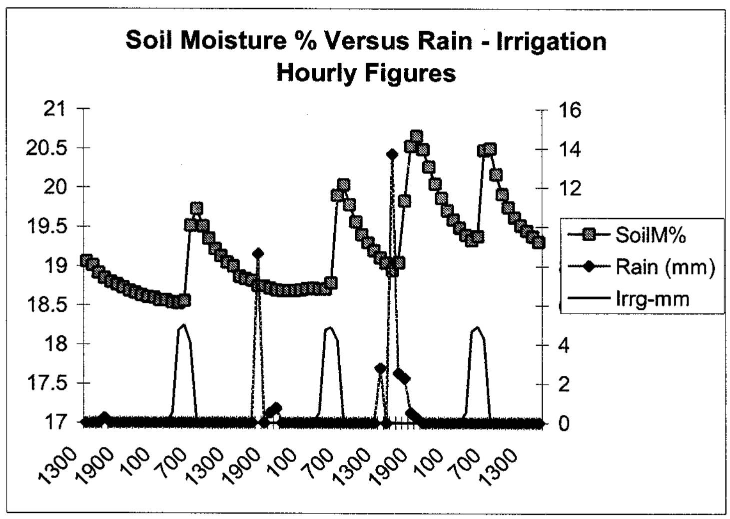

Figure 5 – Theta probe response to rainfall and irrigation.

Theta Probe Soil Moisture Calibration

Landfill soil moisture monitoring is a requirement for compliance in certain circumstances, particularly when the regulators need to establish that a soil cover does not allow significant leaching. In a November 2001 installation at the Riverside County, California Mead Valley landfill the surrounding soil was placed over the landfill instead of clay cover typically recommended by regulators. Theta Probe was selected to monitor the soil so that the soil water movement is logged continuously.

Prior to installation at a variety of borehole depths, Dynamax prepared the sensors as shown in Figure 6. PVC extension tubes are cut to the specified length and hold the sensor in a threaded fitting. On top of the tube, a sealed cap allows the sensor cable to extend upward and out to a logger.

Figure 6 – Theta Probe prepared for installation.

At the Riverside California Mead Valley Landfill soil moisture readings were taken by simultaneously reading seven sensors in a soil sample. The soil was taken from tailings left by making the probe bore holes in a sandy-clay mineral soil. Rocks were removed, and the soil was homogenized by stirring. After the soil was packed to its original density, the soil moisture probe readings were obtained by a custom Dynamax Dynamet logger (See Figure 7). The logger was programmed with the mineral soil calibration polynomial provided by the *Theta Probe Soil Moisture Sensor User Manual, 1999, Delta-T Device Ltd.* Each of the readings was recorded before the sensors were installed. Two locations were sampled, one at the top of the landfill shown in Figure 7 where the soil appeared to be very dry and rocky. At the lower SE side water was added to the sample and then homogenized to test the probe performance at the high end of the soil moisture range.

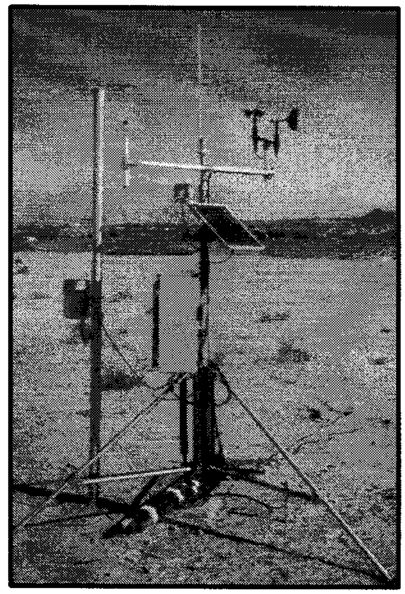

Figure 7 – Dynamax custom Dynamet weather station and soil moisture logger.

Soil Moisture Calibration Results

The Riverside County Waste Management Department took samples in sealed bags to an independent laboratory, Geologic Associates. The Laboratory provided moisture volume computed from the difference between the sample weight before and after oven drying. Table 3 shows the readings provided by the test. Since the difference in the independent test and the average soil reading was less than 0.5 % on the dry sample and about 2% on the wetted sample, there was no need to recalibrate the sensor. The Riverside County California Waste Management Department accepted the standard mineral soil calibration as the standard for routine future data analysis. These results are typical of other applications reported to the authors.

Table 3 - Soil Moisture Probe Calibration				
Mead Valley Landfill, Riverside County, California				
Station	Station 1, Topdeck		Station 2 SE Slope	
Probe	ML2 Reading	Laboratory	ML2 Reading	Laboratory
	(Moisture % Vol.)	(Moisture % Vol.)	(Moisture % Vol.)	(Moisture % Vol.)
0.5 ft Probe	No Data		37.1	35.6
1.0 ft.	12.8	12.8	36.3	35.6
1.5 ft.	12	12.8	38.3	35.6
2.0 ft.	13.5	12.8	37.9	35.6
2.5 ft	12.2	12.8	37.6	35.6
3.5 ft.	11.8	12.8	38.3	35.6
4.5 ft	12.4	12.8	38.9	35.6
Average	12.5	Error - 0.3 %	37.8	Error +2.2%
Std. Dev.	0.6		0.9	

Profile Probe

The "Profiler" is based on the Theta Probe technology and comes in two different models. The PR1/4 Profiler has readouts for 10, 20, 30 and 40 cm depths. The PR1/6 model has readouts at 10, 20, 30 and 40 cm depths, as well as 60 and 100 cm depths. The output is 0-2 volts, which is read with the HH2 Hand Held Readout device. Individual sensor channels can be read with most data loggers.

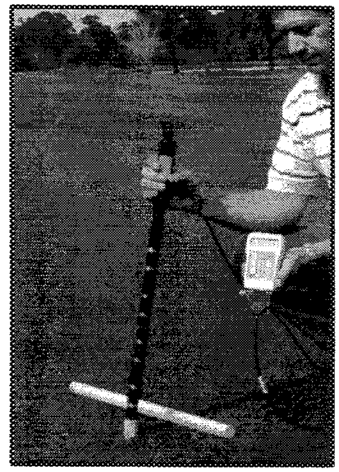

Figure 8 – Profile Probe, PR1, installs into fiberglass access tubes.

Access tubes in the soil allow the probe to be inserted, a reading taken, and then the profiler probe is moved to another access tube elsewhere in the field. The accuracy of the calibrated probe is +/- 3% in an access tube. If the application requires continuous logger readings, the profile probe should be buried with an access tube, due to the water barrier it provides and a standard factory calibration included.

The HH2 hand held display reader incorporates two standard algorithms: one a typical mineral soil type, the other for typical organic soil types. It is also possible to program a soil specific calibration curve into the HH2 for any unusual applications. The HH2 has memory for up to 1100 readings, including date, location number/plot ID, and has an RS232 communication cable included for PC data collection.

Performance – PR1 Profile Probe

The profile probe employs many of the same principles of the Theta Probe, ML2, however the probe does not have direct contact with the soil. The PR1 measures the soil dielectric value through an air gap between the sensor and the access tube. The tuned oscillator circuit responds slightly differently than the ML2 due to the shape of the sensor rings as well as the length of the leads from the rings to the circuit housed in the probe handle. Thus a general calibration for mineral and organic soils was produced and crosschecked in material with known dielectric constants.

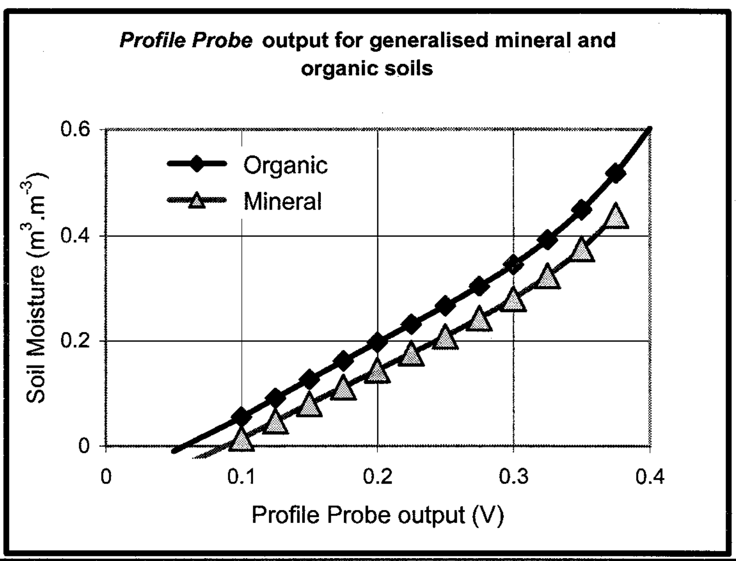

Figure 9 – Profile probe soil moisture versus output signal.

The Profile Probe's response to soil moisture is governed by these two equations where $\sqrt{\varepsilon}$ is the square root of the dielectric constant, V is the probe signal in Volts, and theta is the soil moisture content :

$$\sqrt{\varepsilon} = 0.88 + 4.24V + 65.6V^2 - 272.7V^3 + 402.9V^4 \quad [1]$$

and $$\sqrt{\varepsilon} = \boldsymbol{a}_0 + \boldsymbol{a}_1 \cdot \theta \quad [2]$$

Analyzing samples of known moisture content yields values for a_0 and a_1 in Table 4.

Table 4 - typical soil constants	Organic	Mineral
a_0	1.	1.
a_1	7.	8.
Field Capacity	0.3	0.3

Typical soil calibration constants are shown in Table 4.

Nevertheless, dissolved salts within the pore water contribute to the ionic conductivity of the soil, and this affects all dielectric probes. The effects are obviously not confined to clay soils, but clay soils are likely to exhibit some natural conductivity resulting from the slight solubility of the minerals of which they are composed. Generally the effects of ionic conductivity are greater at lower probe frequencies, and most recently designed dielectric probes operate at 30MHz or higher in order to minimize their sensitivity to ionic conductivity. The Theta Probe, operating at 100MHz, exhibits only slight sensitivity to ionic conductivity, and readings may be taken reliably at ionic conductivities up to 2000 $mS.m^{-1}$. The readings are significantly affected only when the probes are calibrated for a non-saline soil that is subsequently irrigated with saline water. The Profile Probe however was found to have a different reaction to clay soils either with high salinity or with moderate salinity and a high conductivity due to the presence of manganese and calcium. An example of this reaction is the following table of results taken from soil from the Stahman Farms in New Mexico (Table 5).

Table – 5 Stahman Farms Soil Results			
Soil Moisture	PR1 Before Calibration		
Gravimetric %	Average %	mV	n
51	96	519	9
30	41.5	335	5
30	39.8	327.3	5
0	8.1	118	6
0	7.25	112	4

The signal output from the PR1 profile probe was significantly higher than expected, and therefore the overestimate of the moisture content was computed by the HH2. A soil specific calibration can resolve the unusual soil type and provide accurate results.

Materials - Methods

First soil samples were obtained from the field from both sandy and sandy –clay soils. Samples were sealed to maintain the original moisture content. A profile probe calibration device was constructed to easily replicate the readings from a field sample. Standard four-inch PVC schedule 40 pipe was cut, and pipe caps were drilled with holes so that a normal access tube could fit into the end caps. As shown in Figure 9, the device is simple, and holds an adequate soil volume of about 1.5 liters. Once the pipe and end caps were filled with soil and compacted to the original field density, a hole down the center of the soil calibrator was drilled with the PR1 gouge auger. At the same time a soil sample was set aside for gravimetric water content analysis. The center hole was augured very carefully so that no air gaps are possible between the soil and access tube. Then a short length of access tube was installed down the middle, and all joints were sealed with a silicone sealing glue. Delta-T Device's previous studies reported that the zone of influence is primarily within four cm from the access tube and 90% of the zone of influence is within five cm of the probe centerline.

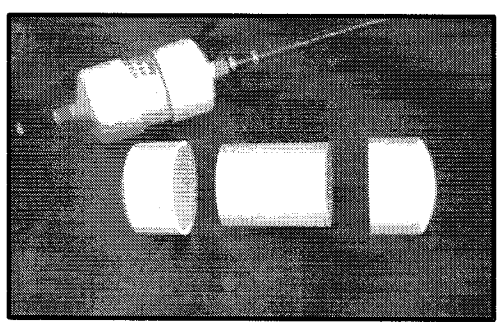

Figure 9 – Profile Probe soil calibration device parts and operation (background).

Calibration Procedure

A two-point calibration is recommended for its simplicity and fair application to high clay and highly conductive soils. Profile Probe readings from Table 2 and the corresponding gravimetric analysis was performed on both moist and dry soils. One sandy soil and one clay soil type was analyzed and calibrated. In this case the dry soil was completely oven dried for 24 hours. The basic steps were:

1) Make readings V_d, and V_w from the Profile Probe in the soil calibrator for both moist and dry samples.

2) Take soil samples from the same soil placed in the soil calibrator, at least 250 ml. Determine the water content (θ_d, θ_w) by gravimetric analysis.

3) Then a_0 can be calculated from: $a_0 = \sqrt{\varepsilon} - a_1 \cdot \theta$, and since θ_d=0, $a_0 = \sqrt{\varepsilon_d}$

4) Then a_1 can be calculated from: $a_1 = \left(\sqrt{\varepsilon_w} - \sqrt{\varepsilon_d}\right)/(\theta_w - \theta_d)$

Again for this case θ_d=0, thus $a_1 = \left(\sqrt{\varepsilon_w} - \sqrt{\varepsilon_d}\right)/(\theta_w)$

Results

After processing the values for a0 and a1, the following Table 3 was produced. The sandy soil type was found to have calibration constants similar to the typical mineral soil (Table 1) with slightly higher a_0 and a_1 values. The clay soil type was found to have considerably higher values for a_0 and a_1, caused by the increased apparent conductivity. Applying the new calibration constants yielded the results shown in Table 4. After calibration, the results appeared to be consistent and in agreement with the gravimetric method.

Table 6 - Stahman soil constants	Sandy	Clay
A0	1.	1.9
A1	8.	15.3
Field Capacity	0.3	0.5

Similar results can be expected for recalibration to soil having unusual properties.

Soil Moisture	Table 7 - PR1 After Calibration		
Gravimetric. %	Avg. %	mV	N
51	51	519	9
30	31	335	5
30	29	327.3	5
0	1	118	6
0	0	112	4

New Applications for Accurate Soil Moisture Sensors

Theta Probe - Moisture Level Control

Irrigation water management and water conservation can strike a balance by applying the newest technologies available. Irrigation with time based schedules have made significant advances over the last ten years with sophisticated programming schemes to allow landscape water management a great

Figure 10 – Theta Soil Moisture Controller (TMLC), Dynamax Inc.

deal of flexibility. New irrigation systems for high-end golf courses and high visibility sports turf stadiums can be adjusted by evapotranspiration (ET) models. However, soil moisture sensors available now make the regulation of water for irrigation an easy and automated task. Moisture sensors in the past were unreliable, slow to respond to actual soil conditions, and very inaccurate. New developments in electronic technology have advanced the state of soil moisture sensor accuracy, durability and easy installation.

With a soil moisture sensor such as the Theta Probe, a simple voltage signal indicates the moisture percentage contained by the soil. This signal may be used to automate an irrigation system with a moisture level detector, or controller. Dynamax Inc. has produced an instrument for this application called the Theta Moisture Level Controller, or TMLC (See Figure 10).

Soil moisture controllers alone cannot take the place of an irrigation timer. The irrigation timer is responsible for a sequence of water application to a number of zones that requires full water pressure to operate sprinklers. One cannot turn on all emitters in an irrigation system the moment it gets dry, because the water pressure would drop. The irrigation timer is needed to apply water efficiently in the evenings and mornings when evaporation is minimal.

A soil moisture controller such as the Dynamax TMLC compares the desired set point to the actual water in the soil. When the moisture is below the target, irrigation starts on the next scheduled cycle. Irrigation continues for however many cycles are required for a wetting front to reach the sensor.

Specifications for TMLC

Sensors
ThetaProbe: Millivolt signal (0-1 V).
Volumetric soil moisture content 0-60 %
HH2 ThetaMeter: Displays millivolts, Soil moisture in % for mineral or organic soils.

Set Point Range
0-1V
0-60% Volumetric Soil Moisture
Hysterisis Lo - 1.5%, Hi - 3% - Jumper selected

Controls
10 control valve solenoids, 1.5 A ea., 15 A max inrush current at 24 VAC

Voltage Range
Voltage input: 24 V AC - 28 V AC
May be converted to 12 V DC operation

System Current
Relay open: 90mA - A.C.
Relay Closed: 100mA - A.C.

Relay Controls
Six Outputs:
Normally Open - Hot, Neutral
Normally Closed - Hot, Neutral
Common - Hot, Neutral

Relay - Electrical
Nom. Power 200mW
Relay DPDT 12 V. DC
Max Contact Cur. @ 28V AC - 15 A.

Enclosure
NEMA 1, 4, 4X, 12 protection, IP 66.
Fiberglass reinforced polycarbonate, non-corrosive

Dimensions
W x L x D: 3.5" x 5" x 3"

Central Irrigation Controls

Central controllers usually have status inputs or a rain switch where the TMLC can connect directly. Newer satellite and commercial timers have the same input options. The key to even application is to have multiple start times and short cycles for each zone monitored by TMLC.

Satellite and Standard Timer Scheduling

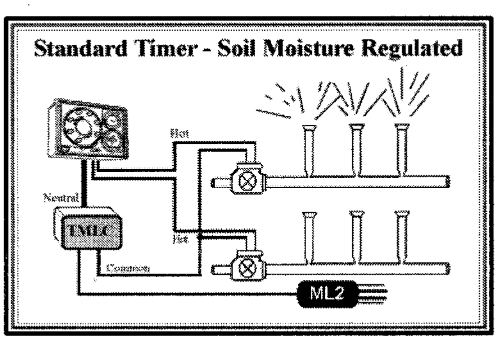

Figure 11- Typical moisture level controller regulating an irrigation control timer.

TMLC controls the neutral line for all valves grouped together. The ML2 is buried in the most critical zone. All valves are enabled when the moisture is below the irrigation start point.

The sensor is positioned at the depth of the root system. After sufficient irrigation cycles the root system then has enough water, the valves are automatically shut off, and there is no water wasted. The irrigation designer or manager can adjust to the right level of moisture for the plant and soil type, and leave the setting alone year round.

Accurate soil moisture sensors are not fully integrated into irrigation controllers yet. That is why the new technology is available only as a separately specified add-on. The main user for moisture level control is currently the university researcher and high-end landscape designer. It takes mass production methods to reduce the cost, and mass product demand to drive the production before this will become a reality for the average city landscape, farm or the typical commercial design.

Moisture control will become common when accurate sensors are demanded and designed into landscape and crop irrigation control. The pressure is on for water conservation and the combination of greenscape design needs and the scarcity or water will bring the advanced soil moisture instruments into common application.

Acknowledgements

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