

# Reducing Water Consumption for Residential Turfgrass with Adaptive Irrigation Controllers

by

Scott Ronald Fazackerley

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# Abstract

It has been estimated that 50-75% of residential water use is for irrigation [Deg07]. Current domestic systems are poor at adapting irrigation to meet demand, primarily due to incomplete information for system operators who rely either on visual inspection or periodic irrigation programs. This results in over-watering and fertilizer and soil leaching. This thesis describes a complete wireless sensor and irrigation control system that reduces water consumption for residential turfgrass irrigation. Presented is a proof-of-concept system that demonstrates potential benefits. The approach couples easy-to-deploy wireless soil moisture sensor nodes with an adaptive irrigation controller that waters to meet demand without user input. Watering events are dynamically scheduled in response to changes in soil water and adapt to unplanned additions and variable water flow. The adaptive irrigation controller was compared against a standard irrigation control program. Experimental results demonstrate significant water savings over using a preset watering program. Adaptive watering amounts are compared against actual crop water demand and found to meet the needs of the turfgrass without over-watering. The result is a system that requires less user intervention, lowers water consumption, and adapts to changing climatic conditions while maintaining a healthy turfgrass.

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# Dedication

*For Liam, my son.*

# Chapter 1

## Introduction

You may never know what results come of your action, but if you do nothing there will be no result.

---

Mahatma Gandhi (1869-1948)

Water is valuable for all life and its consumption increases as communities grow in size. According to Environment Canada's 2007 Municipal Water Use Report, the average residential water user in Canada consumed 329 litres of water per person per day in 2004. Residential British Columbia's consumed considerably more than the national average; for residential use, the average daily consumption was 429 litres. Environment Canada notes that while the 2004 daily average is the second lowest since 1991, Canada still is one of the largest water consumers among the Organization for Economic Co-operation and Development countries [Can07].

In semi-arid regions with large population's such as British Columbia's Okanagan Valley, over 75% of municipal water usage is attributed to residential turf grass irrigation [Deg07]. Despite the trend to xeriscape landscapes and low maintenance yards, there remains a considerable amount of turfgrass that requires irrigation. Large amounts of water are used for irrigating parks, recreational areas, and golf courses. The use of automatic and timed irrigation systems has made it easier to guarantee plants have adequate water but has also caused increased usage of water, often unnecessarily. Water is no longer a "free" resource that can be taken for granted. The price of water will increase as its availability is strained due to climate change, population growth, especially in arid areas, and overall increasing demand [Can07]. Society must be pro-active in the use and management of water resources, especially as it relates to irrigation.

Since the cost of water has been relatively low, there has been less effort in conservation and frugality. In British Columbia, only 29.8% of residences were charged using a water metering scheme, with the remainder paying a flat block rate regardless of consumption [Can07] which provides little

incentive to curb unnecessary water use. Consider a home owner with an automatic irrigation system who wants a green lawn. Common practice is to water every second day regardless of climate patterns. Some “sophisticated” systems have shut off systems based on recent rainfall (rainfall sensors) that have been shown to reduce water consumption significantly [CLD08]. Systems that employ soil moisture sensors as a bypass device reduce water consumption even more [CLDM08]. However, these systems are costly to install especially on an existing lawn when the soil moisture sensors must be connected by wires to the controller.

The basic question for the home owner is: When and by how much should I water the lawn to keep it green and use the least amount of water possible? Without proper data, this question is hard to answer. Home owners tend to favour over-watering in such conditions. Despite the demonstrated benefits of soil moisture sensors for residential irrigation, few users employ such techniques due to the cost and difficulty of installation.

With current technology, it is possible to build a data collection system that uses off the shelf soil moisture sensors and wireless sensor nodes to determine soil moisture content. Current technology is inadequate for several reasons. First, the cost of scientific sensors is prohibitive for many environments (especially residential use), and the products are not easily configurable or deployed. Many products rely on wires for transfer between sensors and logger, and existing wireless products are very costly. Recent work has shown that wireless networks can be used to measure soil moisture for large scale agriculture but fail to address how watering decisions are made using the sensing network [ZYWY09]. Other work has measured matric suction potentials in the soil matrix, but failed to introduce a closed loop strategy [MMG<sup>+</sup>08]. Regardless of how the data are collected, there is a requirement for an overall solution that handles the complete cycle of data collection, analysis, and automatic irrigation system control. This work has built an irrigation controller that dynamically schedules irrigation based on input from wireless soil moisture sensors. This system uses wireless sensor network nodes that are significantly lower in cost than commercial products.

This thesis presents a solution for closed loop control for turfgrass irrigation. The solution has the potential to realize significant water savings without the need for user input. The organization of this thesis is as follows. In Chapter 2, an overview of soil water interactions, current sensing technology, a typical residential irrigation system and the limitations of current technology is provided. In Chapter 3, the wireless soil moisture sensor nodes and the adaptive irrigation controller are described. In Chapter 4, a description of the experimental evaluation is provided and water usage data are

## *Chapter 1. Introduction*

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compared against current methods and actual water demands. The results demonstrate significant savings over recommended practices. In Chapter 5, the content of this thesis is summarized and conclusions are drawn from the experimental results. Appendix A and B continue a detailed discussion of different water content and matric sensing technologies.

## Chapter 2

# Background

The only source of knowledge is experience.

---

Albert Einstein (1879-1955)

Successful growth of a crop is determined by the tilth of a soil. This encompasses the classification of a soil by type and the nutrient level in addition to the energy status and amount of available water in the soil matrix and climate.

**Definition 1. *Tilth*** [Hil80b, p. 94] *Tilth is commonly used by agronomists to describe the suitability of a soil's physical conditions for cultivation in terms of the state of aggregation. A soil with good tilth allows free movement of air, water and nutrients making it suitable for plant growth.*

Air, water and nutrients are inter-related in terms of crop success and a deficit in any of the three is detrimental to the overall growth patterns. Anthropogenic effects have changed modern agriculture and placed significant stress on natural systems. Disregard for proper watering practices can lead to degradation of growing lands through nutrient depletion, salinization, and eutrophication of ground water sources. Civilizations have collapsed as a result of not understanding and managing water resources correctly [Hil80a, p. 98]. Responsible environmental stewardship calls for humanity to better understand and control unnecessary water consumption.

Key to measuring and managing this complex relationship is to have an understanding of how water moves in the soil matrix and how it can be measured. This section provides a background to soil water and its interaction with plants. It then continues to examine different methods of measuring soil water *in-situ* and how soil water can be managed with different irrigation practices. An examination of commercial and research irrigation controllers and a discussion of the current issues and limitations with existing systems is presented. This section concludes with an examination of the current research state for wireless sensor networks.

## 2.1 Soil Water

In the analysis of soils specifically for use in agricultural practices, two unique characteristics are observed and measured with respect to water. First, the total amount of water present in a soil, either by volume or mass is referred to as the water content or wetness of a soil and is expressed as  $\theta$ . Second, the energy status of water in the soil is referred to as the soil water potential and expressed as  $\psi$ . Understanding how plants interact with soil and the water contained within, requires a solid understanding of both measurements.

**Definition 2. Volumetric Water Content**  $\theta_v$  [BW04, p. 144] [FX94] is a dimensionless value that is defined as the volume of water associated with a given volume of dry soil often expressed as  $\text{m}^3 \text{H}_2\text{O}$  per  $\text{m}^3$  of soil and defines the amount of water contained within the soil's pore structure.

The value of  $\theta_v$  as  $\text{m}^3 \text{H}_2\text{O}$  per  $\text{m}^3$  of soil can also be expressed as a depth ratio by dividing the value by  $\text{m}^2$  water per  $\text{m}^2$  of soil which will give meters (depth) of  $\text{H}_2\text{O}$  per meter (depth) of soil. This value is commonly used to express the amount of water contributed from irrigation or rainfall in agricultural practice.

**Definition 3. Soil Water Potential**  $\psi$  [BW04, pp. 139-140] is the difference in the energy level of water between sites or conditions and determines the rate and direction of flow. Commonly, the difference in energy levels is expressed as the difference in energy between the soil water and pure water in a reference state.

The total soil water potential is contributed to by several forces such as the gravitational potential  $\psi_g$ , the matric potential  $\psi_m$ , and the osmotic potential  $\psi_o$ . Of these three, the one of most interest in this discussion is the matric potential, as it is the primary driving force behind unsaturated water flow [BW04, p. 149]. This movement is critical for plant roots as it is one of their main sources of soil water [BW04, p. 142]. The matric potential,  $\psi_m$ , results from a combination of adhesion, adsorption and capillarity which influence water movement and retention in a soil. As a result of a difference in  $\psi_m$ , water will flow from areas of high  $\psi_m$  to areas of low  $\psi_m$  if  $\psi_g$  are equal in both areas. The units used to express  $\psi_m$  in terms of pressure for a given soil are varied and can be expressed in terms of cm of water, mm of Hg, bar, torr, or pascal.

Plants exist as part of the Soil-Plant-Atmosphere Continuum (SPAC) which is a major component of the earth's hydrological cycle. Water is continuously cycled through different parts of the continuum. Plants extract

## 2.1. Soil Water

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water from the soil through their roots which continues through the plant. The water continues to the leaf surface and leaves the plant as water vapour which is called *transpiration* [Hil98, p. 547]. The direction of water movement in plants is seen in Figure 2.1 [Hil98, p. 547]. This loss is commonly combined with evaporative water losses from the soil surface. Together this loss is called *evapotranspiration (ET)* [BW02, p. 229]. For plants to be able to utilize water, an energy gradient must exist between different parts of the *SPAC* as in Figure 2.2 [BW02, p. 229]. The difference in  $\psi$  between the atmosphere and leaf, the leaf and stem, etc, down to the difference between the soil and roots allows for plants to uptake soil water. As the energy level of soil water increases, it becomes harder for plants to utilize it and they will transpire less [Hil98, p. 561].

Figure 2.1 has been removed due to copyright restrictions. It was a diagram of a plant showing the different water potentials the exist in the soil, roots, stem and leaves. Original source: Daniel Hillel (1998) *Environmental Soil Physics*. Academic Press, a division of Harcourt Brace & Company, 525 B Street, Suite 1900, San Diego, CA, 92101-4495, p. 547.

Figure 2.1: Water Potentials in a Plant.

Figure 2.2 has been removed due to copyright restrictions. It was a diagram showing the change is water potentials in the different parts of the soil-plant-atmosphere continuum at different soil water levels. Original source: Nyle C. Brady and Ray R. Weil (2002) *The Nature and Properties of Soils*. Thirteenth Edition, Pearson Education, Inc., Upper Saddle River, New Jersey, USA, F07458, p. 229.

Figure 2.2: Energy Levels in the Soil-Plant-Atmosphere Continuum.

In [LR97a], the authors note that water content in an unsaturated soil is a function of water matric potential, and this relationship can be expressed on a plot of volumetric wetness versus matric suction potential. For a specific soil, the bi-plot of  $\theta_v$  and  $\psi_m$  is termed a *soil water characteristic curve (swcc)*. The soil water characteristic curve is very important in irrigation applications as the relationship expresses how much water is available for plant use at a given energy level.



**Definition 4. Soil Water Characteristic Curve [FM77]** is a relationship between the volumetric water content  $\theta_v$  in an unsaturated soil and the corresponding matric suction  $\psi_m$  at  $\theta_v$ .

Figure 2.3 [FX94] is an example of a soil water characteristic curve for a silt loam soil. On the curve are highlighted the important values that define the curve. The values are

- $\theta_s$  : the saturated volumetric wetness
- $\theta_r$  : the residual volumetric water content

Fredlund and Xing [FX94] define the air-entry pressure to be the point at which air first enters the largest pores in the soil matrix. They define the residual volumetric water content as the point at which a large change in matric suction is required to change the water content. As this is an ambiguous definition, Fredlund and Xing suggest a tangent line method [FX94] to quantify  $\theta_r$ . For a given soil, a wetting (absorption) and drying (desorption) curve exist as soils typically exhibit hysteresis in terms of water content with respect to matric suction. For irrigation practices, only the desorption curve is considered.

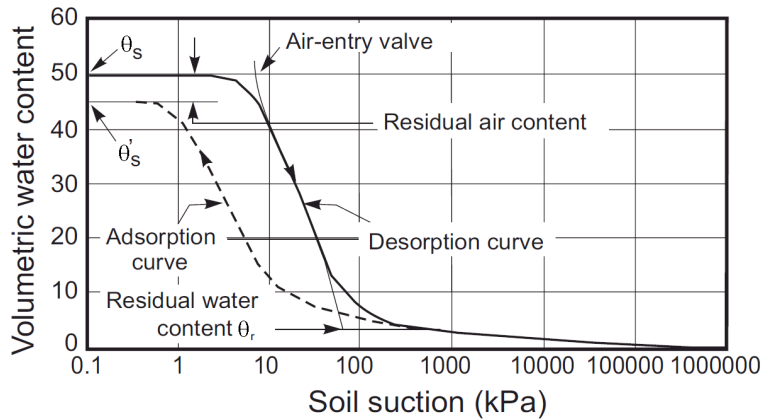


Figure 2.3: Important Features of the Soil Water Characteristic Curve. Reproduced from D.G. Fredlund and Anging Xing. Equations for the Soil-Water Characteristic Curve. *Canadian Geotechnical Journal*, 31(4):521:532, August 1994. ©2008 NRC or its licensors. Reproduced with permission.

Different soils have different soil water characteristic curves due to the different structure, make up, and pore size distribution. As a result, no

## 2.1. Soil Water

one curve can be used to describe all soils. Figure 2.4 [FX94] demonstrates typical differences in curves between soil types.

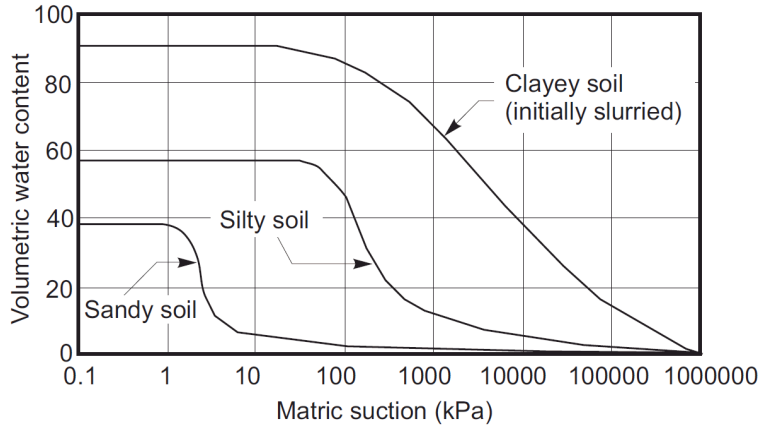


Figure 2.4: Soil Water Characteristic Curves for Sandy, Silty and Clayey Soils as a Function of Available Pore Space. Reproduced from D.G. Fredlund and Anqing Xing. Equations for the Soil-Water Characteristic Curve. *Canadian Geotechnical Journal*, 31(4):521:532, August 1994. ©2008 NRC or its licensors. Reproduced with permission.

In the relationship between  $\theta_v$  and  $\psi_m$  on the swcc, there are specific potential energy levels that are of interest. The two energy levels and associated water contents that are useful in irrigation practices are termed Field Capacity and Permanent Wilting Point.

**Definition 5. Field Capacity** [VH31] is the “amount of water held in soil after excess has drained away and the rate of downward movement (of water) has materially decreased, which usually takes place in 2-3 days after a rain or irrigation in pervious soils of uniform structure and texture”

Field capacity is used in irrigation practices as it represents a practical concept but has no solid definition in terms of soil physics. Field capacity is traditionally measured through a grab sample of known volume that is fully wetted and then allowed to sit under free drainage for 2 to 3 days until internal drainage has stopped [CG08, p. 919] [Hil80a, p. 67] [TRC01] but can vary depending on soil type. Methods also exist for determining field capacity *in-situ* [FL10a, GHWZ06].

The value of  $\theta_v$  at field capacity (FC) is commonly associated with matric suction levels ranging from -10 kPa to -33 kPa [MG99] on the swcc.

## 2.1. Soil Water

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This is the point where the flow of water due to gravity in small pores has significantly decreased, with larger pores being air filled. It represents the maximum amount of water in a soil that is useful to plants. Water applied to raise the energy level above this point, which is termed gravitational water, will rapidly move through a soil and be of no long term use to plants [BW04, p. 155].

The second important energy level is at  $\psi_m = -1500$  kPa and the associated  $\theta_v$ . At energy levels beyond this point, plants generally can not overcome the energy difference required to extract any remaining water from the soil matrix. This point is termed the Permanent Wilting Point (PWP).

**Definition 6. Permanent Wilting Point** [BW04, p. 156] *is the point at which soil water is only retained in the micropores, and water below this energy level is generally unavailable to plants.*

The soil water in the range between FC and PWP ( $-10$  kPa  $\geq \psi_m \geq -1500$  kPa) is termed Plant Available Water (PAW). This water is freely available for plant use [BW04, p. 156]. These points are seen on the swcc in Figure 2.5 [BW04, p. 209]. The points at which a soil is at FC or PWP is variable with the type of soil as shown in Figure 2.6 [BW04, p. 210]. A swcc for a specific soil can be used to determine how much water is available for a plant. The amount of plant available water is limited by the volumetric water contents at *FC* and at the *PWP*.

Figure 2.5 has been removed due to copyright restrictions. It was a diagram showing the soil water characteristic curve and the position of different terms used to describe the status of soil water. Original source: Nyle C. Brady and Ray R. Weil) *The Nature and Properties of Soils*. Thirteenth Edition, Pearson Education, Inc., Upper Saddle River, New Jersey, USA, 07458, p. 209.

Figure 2.5: Field Capacity and Permanent Wilting Point on a Soil Water Characteristic Curve.

Having strong methods and techniques to measure both  $\theta_v$  and  $\psi_m$  *in-situ* without unnecessarily disturbing the soil body leads to a solid understanding of how much water needs to be supplied to a soil. Correctly addressing the water needs of a soil allows for proper maintenance and promotion of good tilth. Introducing unnecessary water to the soil profile may contribute to root rot, deep drainage, can potentially wash nutrients out of the soil profile, influence water table levels, and may lead to soil salinization.

## 2.1. Soil Water

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Figure 2.6 has been removed due to copyright restrictions. It was a diagram showing plant available water for different textural classes of soils. Original source: Nyle C. Brady and Ray R. Weil) *The Nature and Properties of Soils*. Thirteenth Edition, Pearson Education, Inc., Upper Saddle River, New Jersey, USA, 07458, p. 210.

Figure 2.6: Plant Available Water for Different Soil Types.

Note that while plant physiology responds to  $\psi$ , using this value to predict the amount (volume) of water to be applied in irrigation practices is difficult without a calibrated soil water characteristic curve. For a given soil,  $\psi$  does not linearly relate to the volumetric water content or wetness of a soil. As a result, using  $\psi$  alone as a measurement cannot be transferred directly to a depth of water. On the other hand,  $\theta$  can be used to determine the amount of water to be applied without the need of a calibrated soil water characteristic curve. As expressed in Definition 4, volumetric water content is a dimensionless value that can express a depth of water per meter depth of soil. As a result, the amount of water available in a given area of soil is determined as

$$\text{depth of water} = \frac{\text{depth of soil} \times \theta_v\left(\frac{m^3 \text{water}}{m^3 \text{soil}}\right)}{\text{area}(m^2)}. \quad (2.1)$$

While  $\theta$  can be used independently for irrigation practices, knowing  $\theta(\psi)$  can help to precisely determine turn on and turn off points for irrigation. By knowing the water content levels at which a soil reaches field capacity (FC) and the permanent wilting point (PWP), a more informed decision can be made.

Under normal irrigation, water will enter the soil and a sharp boundary will form between the wet and dry soil. This boundary is called a *Wetting Front* [BW02, p. 202]. While water near the surface moves primarily in response to gravity, water at the wetting front is influenced by both gravity and matric suction potentials. Figure 2.7 shows the movement of a wetting front through a soil profile during and after an irrigation event. As time proceeds from  $t_1$  to  $t_4$ , the water content will increase in response to the movement of water in the soil profile as the wetting front passes. After irrigation ceases, the wetting front will continue to move down in the profile and the water content will stabilize at a water content determined by the matric suction. In Figure 2.7 (ii), the water content in the rooting zone will

## 2.2. Soil Moisture Sensing Technology

continue to decrease as the plants respire and extract water from the soil. Water content levels near the surface will also drop as water is lost due to evaporation and a drying front proceeds in a downward direction.

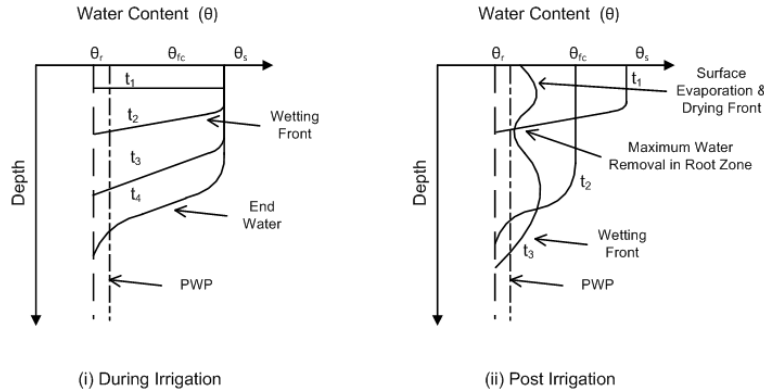


Figure 2.7: Wetting Front Movement During and After Irrigation.

Due to the non-linear nature of water movement through soil [LR97b], the rate at which water can move through a soil can vary over several orders of magnitude as the soil moisture levels change. As a result it may take many hours for the wetting front to move through the soil in reaction to the added water from irrigation. The rate at which water can enter a soil profile is affected by cracks and macro pores leading to preferential flow [BW02, p. 197]. Macro pores are a common feature in natural soils that are the result of worm movement, root channels or soil cracking. The macro pores allow water to enter a small area of soil faster than the regular pulse of water is moving into the soil body as a whole [BW02, p. 198]. It has been observed that matric suction and the corresponding volumetric water contents respond to preferential flow [BB91]. As time proceeds, water that has entered through the preferential flow channels will be drawn into the soil matrix as the energy levels at the channel boundaries equilibrate with the energy levels of the internal soil water. As a result, the volumetric water content will also change.

## 2.2 Soil Moisture Sensing Technology

A wide variety of measuring technologies are currently used to measure soil moisture and the method used depends on the type of measurement desired. Generally, measurements are divided into methods that measure

the amount of water (in %, weight or volume per volume or mass of soil) and measurements that determine the energy status of water in the soil matrix which does not depend on the volume of soil.

Water content measurements can be divided into two classes: direct and indirect measurements. In direct measurements,  $\theta_v$  is a direct measurement of the amount of water contained in the soil. Gravimetric analysis is an example of a direct measurement, as the technique measures the volume of water contained in the sample and expresses the water content as a percentage to the mass or volume of the sample. Indirect methods estimate  $\theta_v$  based on a characteristic of the soil that is influenced by changes in the amount of water in the sample. Soil type and physical properties influence how a measurement is made and the type of sensors required [MC04].

### 2.2.1 Water Content Sensors

Common *in-situ* volumetric methods can be divided into groups based on the principles of operation. Most available commercial sensors suitable for *in-situ* use fall into one of two groups; nuclear methods or dielectric methods. Nuclear methods include neutron absorption and gamma attenuation, both of which use the absorbed or attenuated radiation by the water present in the soil to determine water content. These methods are not suitable for non-specialist use. Details on nuclear methods can be found in Appendix A.1 and A.2. Dielectric methods include time domain reflectometry, capacitive sensing, frequency domain reflectometry, amplitude reflectometry, time domain transmission and phase transmission. These methods measure the dielectric constant or impedance for a soil and infer  $\theta_v$  based on a known relationship between  $\theta_v$  and the dielectric constant. These methods work based on the principle that the dielectric constant of dry minerals is approximately 3 to 4 and the dielectric of water is approximately 80, a 20 fold increase; thus, in wet soils the dielectric measured is predominately influenced by the presence of water in the soil. It should be noted that there are other methods that can be used in the laboratory to measure  $\theta_v$  but they are not suitable for *in-situ* measurements.

#### Time Domain Reflectometry

Time domain reflectometry (TDR) has been used over the last 30 years as a method to measure the dielectric constant of a soil. It was first applied by Davis and Chudobiak in 1975 [DC75] and has been used under a broad range of conditions and scales, becoming a standard method of water content

measurement. A detailed discussion on TDR can be found in Appendix A.3.

TDR is principally an electromagnetic method where a series of short rise time pulses or waves are initiated and propagated through a soil body guided by a transmission medium known as a wave guide. As the wave propagates through the soil, the velocity and amplitude of the wave is influenced by the soil surrounding the wave guides. The observed change in the wave is related to the amount of moisture in the soil in addition to the soil's electrical conductivity [ZX94].

In [MC04], the author summarizes the measurement characteristics for the TDR method as follows: the usable range of the TDR method is  $5\% \leq \theta_v \leq 50\%$  for uncalibrated soils. This range can be extended to  $5\% \leq \theta_v \leq \text{saturation}$ , when correctly calibrated to a specific soil. With soil specific calibration the accuracy of the device is  $\pm 1\%$ . The sensing volume of the device is about 3 cm in radius along the length of the waveguide.

Figure 2.8 [Nob01] shows the different components of a TDR. The sensor consists of a pair of parallel metal rods that form a balanced transmission pair and are coupled to a pulse generator and signal receiver. The length and spacing of the rods is dependent on the measurement application [CG08, p. 941]. Most devices now use three rod probe configuration [ZWJ89]. The rods are inserted into the soil where the rods act as waveguides for the electromagnetic pulse and the soil surrounding the rods forms the dielectric medium [Hil98, p. 140]. In addition to the receiver and parallel rods, the system includes a timing circuit, a pulse generator and recording device. Most commercial devices incorporate all components into a single unit [CG08, p. 941].

It is particularly useful for *in-situ* measurements [CG08, p. 940]. It can be coupled directly to a computer for automated data collection. Commercial application specific devices have also been developed and offer the ability to multiplex numerous probes in addition to offering automated analysis [CG08, p. 941]. While it is not a direct measurement technique, the moisture content of a soil can be related to the dielectric constant of a soil [Str00, p. 180] and does not require knowing additional soil parameters such as bulk density [CG08, p. 941]. Additional advantages and disadvantages are discussed in Appendix A.3.

### Other Dielectric Methods

Other designs of dielectric probes infer the volumetric water content in the soil by attempting to measure the dielectric constant for the soil of interest. Alternatively, a parameter influenced by the dielectric constant, such as the

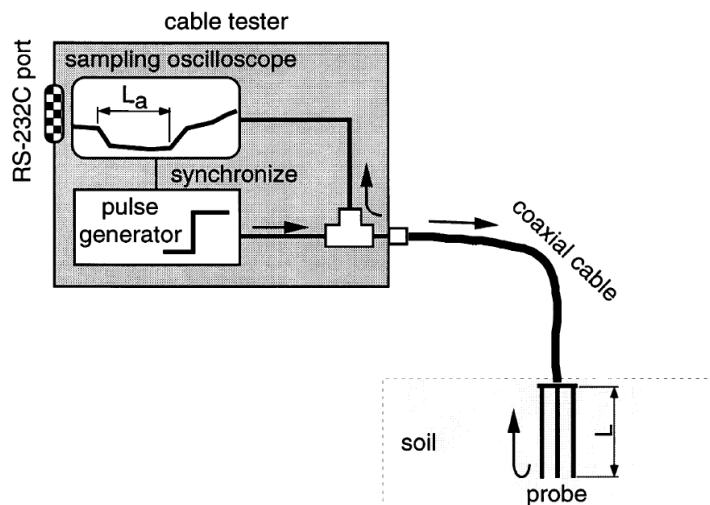


Figure 2.8: The Components of a Time Domain Reflectometer. Reprinted from *Computers and Electronics in Agriculture*, 31(3), K. Noborio, Measurement of Soil Water Content and Electrical Conductivity by Time Domain Reflectometry: a Review, 213-237, Copyright (2001), with permission from Elsevier

soil impedance, can also be measured. In this way, these methods attempt to measure the same electrical characteristics as TDR. In industrial literature, these probes are often grouped together and classified as capacitive type probes, such as the EC-5 probe sold by Decagon Devices from Pullman Washington [Dec08] or amplitude domain reflectometry (ADR), such as the Theta Probe sold by Delta-T Devices<sup>1</sup>. This category also includes probes that are based on phase transmission (PT) and time domain transmission (TDT). This grouping may lead to confusion, as the probes appear to work in a similar method and fashion to TDR as they all rely on the measurement of a dielectric, but unlike true TDR which is a full spectrum method, these methods typically rely on the use of a single frequency. A detailed discussion on ADR, PT, and TDT can be found in Appendix A.4.

Similar to TDR, the measurement is done using a high frequency energy pulse moving through a waveguide. The dielectric constant of the soil can then be related to the volumetric moisture content of the soil [ZX94]  $\theta_v$  as in Equation (A.4) for most mineral soils. The range of frequencies used

<sup>1</sup><http://www.delta-t.co.uk>



with the devices is obscured by the different manufactures and the exact methods are often not available. The cost of these devices are generally much lower than TDR and they are designed to be easily coupled to datalogging equipment, making them suitable for large scale deployment. One of the most significant advantages for the dielectric type probes is the responsive nature of the device. Sampling for a given site can be concluded in a very short time frame as the reading is almost instantaneous.

In [MC04], the author summarizes the measurement characteristics for non-TDR dielectric methods: the usable range of the capacitive, FDR, and ADR methods is from 0% to saturation with accuracies of the devices being  $\pm 1\%$  if used with soil specific calibration. For particular commercial capacitive and FDR devices, the measurement volume is a sphere approximately 4 cm in radius surrounding the device. For particular commercial ADR devices, the sensing volume of the device is a cylinder about 3 cm in radius around the length of the waveguide. For PT and TDT methods, the usable range is  $5\% \leq \theta_v \leq 50\%$ . With soil specific calibration, PT is accurate to  $\pm 1\%$  and TDT is accurate to  $\pm 5\%$ . The sensing volume for specific commercially available PT devices is a cylinder of 15 to 19 litres. The sensing volume of TDT is a cylinder of 0.75 to 6 litres around the waveguides with a radius of 5 cm.

Capacitive, FDR and ADR sensors can experience problems with regard to placement in the soil. If a sensor is placed in close proximity to air pockets or an air gap is produced around the probe, possibly due to movement or settling of the soil profile, the sensor may not produce reliable readings. Some devices report increased temperature sensitivity when the probe is placed near the surface due to the impact of temperature on the dielectric  $\epsilon$  [Cam]. Additionally, the sensing volume of the sensor is relatively small due to the design of the sensors; if a large volume of soil is to be measured, multiple probes may be required [MC04]. Additional advantages and disadvantages are discussed in Appendix A.4.

### 2.2.2 Water Potential Sensors

Common water potential methods to measure  $\psi_m$  are based on tensiometric techniques that estimate  $\psi_m$  through capillary and adsorption effects of the soil. They can also be divided into direct and indirect methods. All devices have a porous material that must contact the soil in such a fashion that water movement is not inhibited. Water migrates in and out of the porous material depending on the energy status of the soil; a dry soil will draw moisture out from the porous material and conversely, the porous material will draw water

in from a wet soil until an equilibrium condition exists between the porous material and the soil. The device measures the potential of the water in the porous material to determine  $\psi_m$ . This group includes the direct method of tensiometers and the indirect methods of resistance blocks, heat dissipation sensors and thermocouple psychrometers [MCYLO02].

### Thermocouple Psychrometer

Thermocouple psychrometry is one of the most widely accepted methods for measuring the matric potential  $\psi_m$  of water in soils due to its wide operational range and accuracy [SKM99, p. 92] but is mostly restricted to lab use. A detailed discussion on thermocouple psychrometry can be found in Appendix B.1.

A thermocouple psychrometer measures the relative humidity of the moisture in soil pores *in-situ*. The relative humidity is related to the potential energy of the equilibrium partial pressure of water vapour in the pore space. If the soil is in thermal equilibrium with the sensor, the potential of the vapour in the sensor is in equilibrium with the matric and osmotic potentials in the sample [Hil98, p. 164]. The relation between the partial pressure of water vapour in the pore space and the total potential energy of pure liquid water at the same temperature can be expressed as [Car93, p. 561]

$$\psi_m = \left( \frac{RT}{V_m} \right) \ln \left( \frac{e}{e_s} \right) \quad (2.2)$$

where  $R$  is the universal gas constant ( $\text{Jmol}^{-1}\text{K}^{-1}$ ),  $T$  is the temperature of the probe (in K),  $V_m$  is the volume of the sample space,  $e$  is the partial pressure of the water vapour in the sample, and  $e_s$  is the saturation partial pressure at temperature  $T$ . It is noted that the dimensionless relation of  $e/e_s$  is defined to be the measurement of relative humidity [CG08, p. 975].

If the thermocouple psychrometer is used alone to measure  $\psi_m$ , it will not provide complete coverage over the range of potentials monitored in agricultural soils due to its poor performance at energy levels where pores may be completely filled with water. The range of operation is generally accepted to be  $-50 \text{ kPa} \geq \psi \geq -3000 \text{ kPa}$ . The accuracy of the device if used with soil specific calibration is  $\pm 20 \text{ kPa}$  [MC04]. Figure 2.9 [MC04] shows the typical size and construction of a thermocouple psychrometer. The measuring volume of the device is a sphere surrounding the porous cup, 6.5 cm in radius. The device is often coupled with other energy measuring devices, such as a tensiometer which offers coverage from  $0 \text{ kPa} \geq \psi_m \geq -80 \text{ kPa}$  [CG08, p. 974].

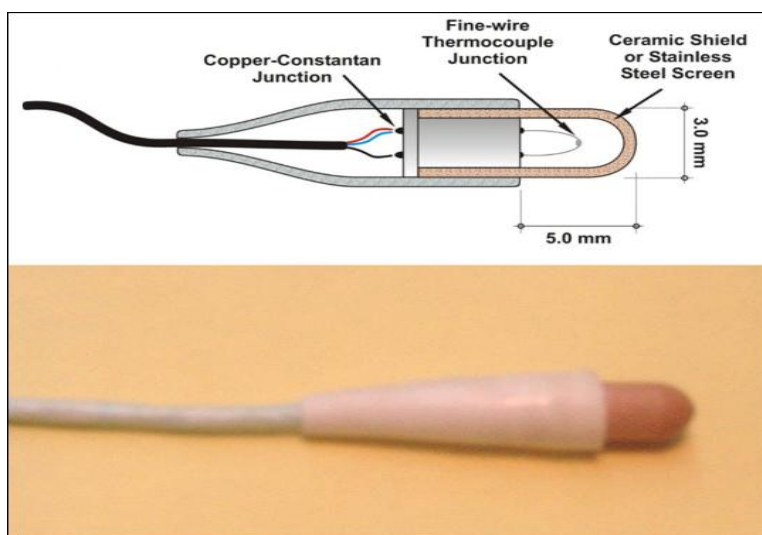


Figure 2.9: Thermocouple Psychrometer. Reprinted from R. Muoz-Carpena, Field Devices for Monitoring Soil Water Content (Bulletin 343). Gainesville: University of Florida Institute of Food and Agricultural Sciences. Copyright (2004). Retrieved January 2010, from <http://edis.ifas.ufl.edu/ae266>.

As with other technologies for measuring  $\psi_m$ , the thermocouple psychrometer is slow to react to changes in matric potential. This is due to the time required for the vapour pressure inside the sensing bulb to equilibrate with the vapour pressure of water in the soil. Additionally, the device has a relatively small sensing volume. The cost of the sensor also presents a barrier to entry as specialized equipment is required to drive the sensor which may limit its suitability for large scale deployment [MC04]. The most strict requirement with this device is the requirement for thermal equilibrium between the soil and all parts of the sensor. This requirement typically limits its use to the lab. Additional advantages and disadvantages are discussed in Appendix B.1.

### Electrical Resistance Blocks

The electrical resistance block is a resistive type sensor that is a commonly used method for *in-situ* estimation of the matric potential  $\psi_m$ . They are relatively inexpensive devices that can provide a continuous estimate, especially in dry soils where  $\psi_m \leq -50$  kPa. Blocks are typically manufactured from

a hydrophilic porous material such as gypsum, fiberglass, or nylon [CG08, p. 972] with a known soil water characteristic curve (Section 2.1). When the block is buried at depth in the soil of interest, water flow will take place in the block until  $\psi_m$  is the same between the block and the soil. With this method,  $\psi_m$  is inferred from the electrical resistance of the block and determined from a resistance versus matric potential calibration curve. Two distinct types are commonly used in commercial applications: the gypsum electrical resistance block and the granular matrix sensor (GMS). A detailed discussion on electrical resistance blocks and GMS devices can be found in Appendix B.2.

The usable range of the gypsum electrical resistance block is  $-30 \text{ kPa} \geq \psi_m \geq -2000 \text{ kPa}$ . With soil specific calibration the accuracy of the device is purported to be  $\pm 1 \text{ kPa}$ . The sensing volume of the device is a sphere greater than 10 cm in radius around the block. For the GMS, the usable range is  $-10 \text{ kPa} \geq \psi_m \geq -2000 \text{ kPa}$ . Similar accuracy to the gypsum electrical resistance block can be achieved with calibration. The sensing volume is a sphere approximately 2 cm in radius around the sensor [MC04].

Problems exist for the naive user with this device. In [SB92], the GMS sensor was shown to have a non-reproducible response for given soils. As a result, calibration is not repeatable and different between soil types. Devices also required individual calibration and have a large temperature dependence. In [MKW92], the authors note that the equilibration time is unreasonable at matric suctions levels below  $-60 \text{ kPa}$  as well as being plagued by hysteresis effects. In [SDM07], the authors note that for landscape and turfgrass applications, the ranges of matric suction that are of interest are outside the usable range for the GMS sensor. Additional advantages and disadvantages are discussed in Appendix B.2.

### **Tensiometer**

The tensiometer is a device that measures  $\psi_m$  directly for a given soil. It is a commonly used method in agriculture for measuring matric potential in soil science [Hil98, pp. 163-164] for the range of  $0 \geq \psi_m \geq -80 \text{ kPa}$ . The device allows for continuous *in-situ* measurement of the matric suction potential of a soil. The tensiometer is ideal for long term placement in soils because of its ability to track changes in the soil water energy status over time. As soil moisture is decreased through drainage and plant uptake or increased due to irrigation, rainfall or change in the water table, the tensiometer will respond accordingly [Hil98, p. 162]. A detailed discussion on tensiometer devices can be found in Appendix B.3.

## 2.2. Soil Moisture Sensing Technology

Figure 2.10 [MC04] shows a schematic of a tensiometer. The accuracy of the device depends on the quality of the gauge or pressure transducer coupled to the device. With proper equipment and device calibration, the accuracy of the device is  $\pm 1$  kPa. The sensing volume of the device is a sphere greater than 10 cm in radius around the porous cup [MC04].

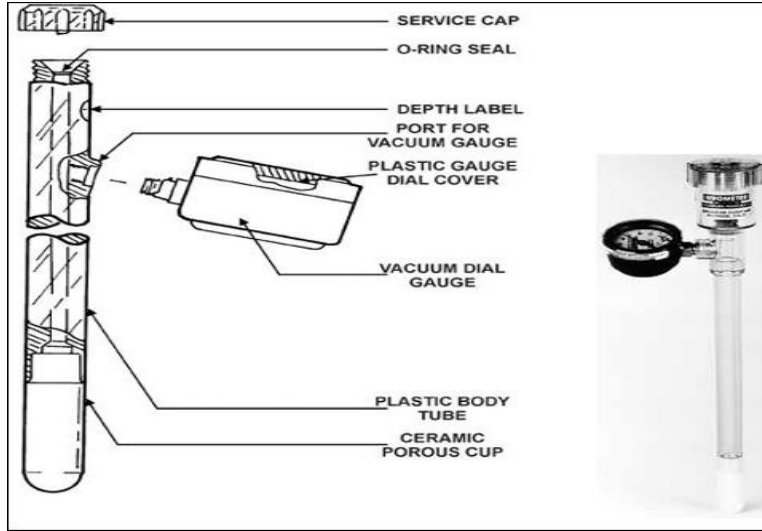


Figure 2.10: The Tensiometer. Reprinted from R. Muoz-Carpena, Field Devices for Monitoring Soil Water Content (Bulletin 343). Gainesville: University of Florida Institute of Food and Agricultural Sciences. Copyright (2004). Retrieved January 2010, from <http://edis.ifas.ufl.edu/ae266>.

The tensiometer has numerous advantages over other devices that measure matric potential. The devices are low in cost, complexity, and can be easily automated, making them ideally suited for sites requiring a large number of measurements [CG08, p. 968]. The device requires minimal maintenance which mostly consists of ensuring that the supply tube is completely filled with water.

The most prominent disadvantage is the operational range of the device being  $0 \text{ kPa} \geq \psi_m \geq -80 \text{ kPa}$ . This range represents only a small portion of the total soil water that may be available to plants [ZX94]. It is still suitable for applications where maintaining low matric potentials are favourable for plant growth [Hil98, p. 163]. In general, the lower limit for good growth for most crops is beyond this range. If a tensiometer is solely relied on to determine scheduling for irrigation, it may lead to over watering of the

soil [ZX94]. Problems can arise from improper installation and maintenance and entrained air can slow the response time of the device. Additional advantages and disadvantages are discussed in Appendix B.3.

### Heat Dissipation

The first designs of heat dissipation sensors measured the rate at which heat dissipates in a given soil were proposed in the 1930's by Shaw and Baver [Str00, p. 187]. The rate of heat dissipation is related to the thermal conductivity of the soil which in turn relates to  $\theta_v$ . A soil specific calibration is then used to derive  $\psi_m$ . The direct measurement relies upon a fixed and known swcc for the soil being measured. Second generation designs [PHR71][PRH71] utilize a ceramic block in hydraulic contact with the soil. The block has a known and fixed swcc. As a result,  $\theta_v$  in the block can be related to  $\psi_m$  in the block which will equilibrate to the  $\psi_m$  of the soil. A detailed discussion on the heat dissipation sensor can be found in Appendix B.4.

The sensor consists of the sensing device and set of specialized electronics to control the heating of the sensor and to make measurements. With first generation devices, the soil is directly heated. Second generation devices are now more commonly used, where a ceramic block is placed in contact with the soil and heated. Hillel notes that several investigations have found that the relationship between the rate of heat dissipation and  $\psi_m$  is linear [Hil98, p. 166]. Regardless of the advantages, the heat dissipation sensor is widely used due to problems during installation. The development and maintenance of good thermal contact between the soil of interest and the sensor is critical for proper operation [Str00, p. 187].

The usable range of the heat dissipation is at most  $-10 \text{ kPa} \geq \psi \geq -1000 \text{ kPa}$  for uncalibrated soils. Readings can be extended to  $-3000 \text{ kPa}$  with lower accuracy. Overall, with soil specific calibration the accuracy of the device is 7% of the absolute deviation [MC04].

The complexity of the control circuit places this sensor at a disadvantage. The heat dissipation sensor's control electronics are sophisticated compared to a standard datalogger or controller as the system needs to be able to control the heating and sampling of the sensor. The sensor cannot be directly interfaced to a standard controller without adding additional hardware and cost. Additional advantages and disadvantages are discussed in Appendix B.4.

### 2.2.3 Summary of *In-Situ* Sensing Technologies

The choice of the correct sensor to use for automated *in-situ* applications is not a straightforward process. Many facets must be considered such as soil type, texture, solar exposure, and what parameters and ranges are to be measured. Additionally, many are not suitable for a naive user. For a large scale deployment over many hectares, it would not be uncommon for a variety of soil textures to be present in the profile. Cost must also be considered, not only for the device but for the cost associated with the degree of accuracy required, maintenance schedules and difficulty of use. To help with decision making in regard to sensor selection, a summary of the different decision parameters for each sensor has been compiled with the volumetric sensor data in Table 2.1 [MC04, ZX94] and soil water potential sensor data in Table 2.2 [MC04, ZX94, MCYLO02].

Each sensor presents its own pros and cons for use with no one method clearly being better than the others. No one sensor can cover the complete range of  $\psi_m$  representing the zone of plant available water (Section 2.1) with reasonable accuracy. A combination of sensors will often be required if concessions in data quality do not want to be made. For  $\theta_v$  measurements, most sensing techniques will cover the desired range and a single type of sensor for a given soil may suffice. The decision will be driven by the cost and suitability of the sensor for a given soil. The correct choice depends on the level of accuracy required. While many of the in-situ sensors may not be suitable for detailed hydrological studies, many are suitable for the coarse grain measurements required in irrigation.

Table 2.1: Functional and Cost Parameters for Volumetric Measurement Techniques [MC04, ZX94]

	TDR	Capacitance and FDR	ADR	PT	TDT
Usable range	5% to 50% or 5% to saturation with calibration	0% to saturation	0% to saturation	5% to 50%	5% to 50%
Accuracy (calibrated)	$\pm 1\%$	$\pm 1\%$	$\pm 1\%$	$\pm 1\%$	$\pm 5\%$
Typical Measurement volume	cylinder 3 cm in radius around the length of waveguides	sphere 4 cm in radius	cylinder 3 cm in radius	15 to 19 litre cylinder	0.75 to 6 litre cylinder
Response time	instant to 30 s	instant	instant	instant	instant
Problematic soils	organic, dense, saline or high clay soils	saline	saline	saline	organic, dense, saline or high clay soils
Cost(USD)	\$400-\$23,000	\$100-\$3,500	\$500-\$700	\$200-\$400	\$400-\$1,300



Table 2.2: Functional and Cost Parameters for Soil Water Potential Measurement Techniques [MC04, ZX94, MCYLO02]

	Tensiometer	Electrical resistance block	GMS	Heat dissipation	Thermocouple psychrometry
Usable range	0 to -80 kPa	-30 to -2000 kPa	-10 to -3000 kPa	-10 to -1000 kPa	-50 to -3000 kPa
Accuracy (calibrated)	$\pm 1$ kPa	$\pm 1$ kPa	$\pm 1$ kPa	$\pm 7\%$	$\pm 20$ kPa
Measurement volume	sphere > 10 cm in radius	sphere > 10 cm in radius	sphere > 2 cm in radius	20 cm cylinder	sphere > 10 cm in radius
Response time <sup>a</sup>	instant if properly filled; 2 to 3 hrs if air bubbles have developed	2 to 3 hrs	2 to 3 hrs	hours to days	< 3 min.
Problematic soils	sandy or coarse soils	sandy or coarse soils; 2:1 clays	sandy or coarse soils; 2:1 clays	coarse	sandy or coarse soils; 2:1 clays
Salinity affects	no	>6 dS/m	>6 dS/m	no	yes (ceramic cup only)
Maintenance required	yes	yes: blocks dissolve gradually over a season changing the swcc and calibration	low (only if device dries out)	no	yes (high salt soils)
Cost <i>USD</i>	\$75-\$250	\$400-\$700	\$200-\$500	\$300-\$500	\$500-\$1,000

<sup>a</sup> All matric suction sensing devices see increased equilibration times at high matric suctions

## 2.3 Existing Systems

Extensive work has been conducted in the development of irrigation controllers and approaches. While there is a wide selection of commercial systems available utilizing a variety of different technologies, active research persists into improved control, measurement and practice. Previous research has seen numerous implementations of systems to collect and monitor data [MMG<sup>+</sup>08, CHY05, KEI08, PE08, ZYWY09]. These systems use a variety of methods but fail to offer closed loop control. While a large amount of hydrological information is collected, they fail to address the key issue of automation. As a result, a user is still required to interpret the data at a knowledge level above a typical home user.

Figure 2.11 shows a schematic representation of a typical residential irrigation system. A residential landscape is divided into different irrigation zones. A *zone* is an area that is watered at the same time. Zones are created based on different irrigation needs (lawn, shrubs, flower and garden beds). The number of sprinkler heads that can be run simultaneously is limited by the available water pressure and flow rate. Each zone has an associated *valve* that when opened supplies water to the zone. An *irrigation controller* is a device that allows the user to control when each zone is watered and the frequency of application.

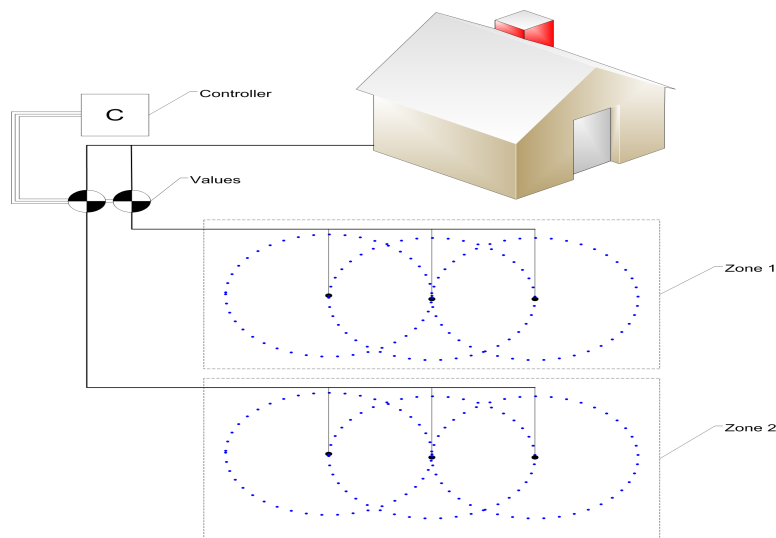


Figure 2.11: A Typical Irrigation System.

### 2.3.1 Commercial Systems

A range of controllers are available for both residential and commercial applications with the price extending from hundreds to thousands of dollars [OTRCG07]. Low-end controllers have simple scheduling mechanisms that allow a user to specify one or more watering *programs* which include a start time for the program and the amount of time for each zone that water should be applied. More costly controllers allow for more programs. The issue is that the user now must decide how much water to apply to each zone. Typically, users decide to water zones on a daily or two day interval often based on local regulations and recommendations. Users rarely adjust the programs unless the effects of insufficient watering are visually noticeable, even though the amount of water required varies significantly throughout the season based on temperature and precipitation [dGN01].

Previous work has shown that water use efficiency can be improved through the addition of add-on sensors (such as rainfall) to existing irrigation controllers or through the use of more sophisticated controllers [CLD08, CLDM08, SDM07, GVB<sup>+</sup>08, OD08]. The types of control systems that are used in common practice can be classified as rainfall shutoff sensors (*RS*), soil moisture sensors (*SMS*) and evapotranspiration controllers (*ET*) [OD08].

A rainfall sensor dramatically reduces the amount of water consumed in areas with high rainfall [CLD08]. The rainfall sensor will override an existing program if the sensor indicates that sufficient rainfall has occurred such that irrigation is not required. Figure 2.12 [CLD08] shows a typical rainfall sensor used as a bypass switch for commercial controllers. A similar approach has been used for soil moisture sensors that measure the amount of water content in the rooting zone. A single *SMS* is used with a standard controller. If the reading falls below a preset soil water content threshold, the controller will then execute the preset watering program [CLDM08, OTRCG07]. These systems still rely on a user defined program and will only bypass the program if the water content is sufficient. The weakness of these approaches is that they only block an existing program from occurring, they do not create their own irrigation programs based on the data collected. Additionally, these systems require an extensive cable network to connect zone sensors back to the controller.

Another weakness with the SMS approach is how it responds to water movement in the soil. If a soil moisture sensor is used as a bypass, due to the slow movement of water in soils by the time the wetting front has reached the sensor, too much water may have accumulated above the sensor. The water levels will continue to rise even after the watering has ceased and

Figure 2.12 has been removed due to copyright restrictions. It was a diagram of a Hunter Industries rain sensor showing the adjustment points. Original source: Bernard Cardenas-Lailhacar and Michael D. Dukes (2008), Expanding Disk Rain Sensor Performance and Potential Irrigation Water Savings, *Journal of Irrigation and Drainage Engineering*. 134(2):67-73

Figure 2.12: Hunter Industries Mini-click Rain Sensor. The trigger point is adjusted with (a) and the drying rate is adjusted with (b).

potentially continue to move to deep drainage and be wasted. Conversely, if the moisture sensor intersects a macro pore in the soil, the sensor may read a prematurely high water content. If preferential flow enters the area around the soil moisture sensor it will cause the system to turn off prematurely leading to an abnormally low level of water being applied.

On-demand controllers improve on the basic *SMS* controller approach. These systems are extremely expensive, typically use wired *SMS*, and are currently only available in large scale commercial systems. These controllers offer the best overall performance in terms of turf quality and efficiency [GVB<sup>+</sup>08]. With on-demand controllers, two set points are used for water content. The user defines a lower and upper water content set point. The controllers will water when the water content in the soil reaches the lower point and will terminate watering once the water content reaches the upper limit [OTRCG07]. As water moves through soil at a very slow, on-demand controllers use a soak time on the order of 10 minutes, interspersed through watering events as an attempt to allow the wetting front to reach the sensor. This method may not actually capture the wetting front correctly which can lead to under or over watering.

An alternate approach is used with *ET* controllers that attempt to estimate the plant water demand based on local weather patterns and schedule based on the water requirements. This information is provided as a service to users for specific locations and conditions. These controllers require a method of accessing daily evapotranspiration models [OTRCG07, OD08].

With *ET* systems, the accuracy of the watering calculations depends on the quality of the input data. If used in an area with a large variance in terms of local climate, the performance of the unit may lead to less than optimal results. As the daily *ET* is only an estimate, the actual crop *ET* will differ from the estimate due to daily environmental changes. Extensive

testing in North Carolina has shown that *ET* systems produced no savings in water due to overestimation of evapotranspiration demands [GVB<sup>+</sup>08].

#### 2.3.2 Research Systems

Attempts have been made to use wireless sensor technologies in irrigation and agricultural applications [KEI08, PE08, ZYWY09, MMG<sup>+</sup>08]. In [PE08], the authors present a complete wireless sensor network that is a series of dataloggers linked over a radio backbone. The data are recorded for analysis, but no real time control is implemented. The system encountered ongoing problems due to the very high power costs for transmission. In [ZYWY09], the authors present a theoretical treatment of wireless technologies for irrigation control systems. The work suggests using ZigBee technology (Section 2.5) strictly as a wire replacement. Each wireless station was used to control remote valves for watering or collecting information from weather stations. No closed loop control is used. In [KEI08], the authors use Bluetooth technologies as serial line replacements for commercial data logging solutions, which limits the size, range, and expandability of the network. The system monitors and gathers soil parameters useful for irrigation, but user intervention is required to make irrigation decisions.

In [MMG<sup>+</sup>08], the authors present a wireless sensor system for measuring the water energy status of soils. The system uses granular matric suction (GMS) sensors to determine the moisture status of soils. Systems based on this technology have a short field life due to degeneration of the sensor and require complicated calibrations. Additionally, the device only measures matric suction. Matric suction alone is not a directly usable value in irrigation practices as the depth of water to be applied cannot be determined without a soil water characteristic curve. The system fails to recognize the shortcomings of the sensor technology in terms of the practical suitability for agriculture.

Problems have been discussed with systems based on the GMS (Section 2.2.2) which lead to this type of system being impractical for the naive user [CG08, Phe98, SB92] and are expanded on in Appendix B.2. As a result, while [MMG<sup>+</sup>08] presents a feasible wireless architecture, the sensing technology makes it infeasible for practical implementation. Overall, previous work has only considered component replacement and data gathering methods, but has failed to consider closed loop irrigation control.

For systems based on matric suction to be practically useful in closed loop irrigation, this value must be related to  $\theta$ , the volumetric water content of the soil which can then be directly related to a watering depth. The

relationship between water content and matric suction is non-linear and differs strongly between soil types [LR97a]. Water content can be used to directly calculate irrigation needs whereas the matric suction cannot be used alone without extensive sampling and modelling of a soil. While this allows for the construction of a soil water characteristic curve, it is not practical for residential use due to the complicated nature of establishing the relationship [Hil56].

## 2.4 Irrigation Scheduling Strategies

Different strategies exist in agricultural practices for determining how much water is to be applied as well as when or how frequently to irrigate. Home owners may blindly irrigate a fixed amount of water regardless of the time of season which represents a far from optimal strategy. Crop water demand is not uniform during the growing season [dGN01] and can vary on a day to day basis as well as being impacted by geographic variation between sites; hence using a fixed depth and interval strategy leads to excess usage. As a result, any small, incremental improvement to irrigation strategies will make a positive difference to current watering practices.

Common strategies that exist are based on a running water budget, estimated evapotranspirative demand or a water deficit methodology. A running water budget uses a tally system where the user attempts to track the amount of available water in the soil matrix [Nyv04]. Starting at a known water content, which typically is a soil that has been saturated and allowed to drain to field capacity, a user estimates changes in water content by tallying additions of water from irrigation and precipitation and subtracting losses from run-off, drainage and daily ET. The ET must be estimated and depends on the type of crop and time of season. From the inputs to the model, the user estimates what the soil moisture will be on day  $i$  based on what happened on day  $i-1$ . Once the estimated soil moisture reaches a point that is typically 50% of  $PAW$ , a depth of water can be calculated that is required to be added back to the soil profile. The water budget method, while not very accurate and subject to cumulative errors, has proven to be a robust solution [Jon04]. A sample of a water budget table is seen in Figure 2.13 [Nyv04].

More sophisticated users will water directly in response to the daily estimated ET for the crop. The strategy attempts to estimate the plant water demand based on local weather patterns, historical ET and schedule based on the water requirements. This information is provided as a service to

## 2.4. Irrigation Scheduling Strategies

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Figure 2.13 has been removed due to copyright restrictions. It was a diagram showing a schematic representation and example of using a water budget to schedule irrigation. Original source: Janine Nyvall (2004) *Factsheet No. 577.100-3. Sprinkler Irrigation Scheduling Using a Water Budget Method*. Resource Management Branch, B.C. Ministry of Agriculture, Foods and Fisheries, p. 6.

Figure 2.13: Sample Water Budget Worksheet.

users for specific locations and conditions, and controllers require a method of accessing daily evapotranspiration models [OTRCG07, OD08]. The daily estimate ET is provided as a service in many areas<sup>2</sup>. It can be calculated using an evaporation pan (Figure 2.14) [Hil80b, p. 637] where the depth of water that is lost each day is tracked due to wind, humidity and temperature and then converted to a crop ET [Hil98, pp. 636-638]. ET can also be determined using a mathematical model based on meteorological data<sup>3</sup>. The ET is provided as a depth of water used by the crop. The user can respond to the daily demand by adding the same depth of water back into the soil profile. While ET strategies have shown promise in some applications with suitable water savings [MDM09, SDM07, HDM07] it has been shown to overestimate in some situations [HDM07] and underestimate in others due to variability in local meteorology. These variations lead to unsuitable turfgrass quality [MDM09]. Hillel notes that ET for crops generally respond differently than values from pan ET estimates [Hil98, p. 561]. Thus, the success of the strategy is based on the quality of the estimated ET. Daily and seasonal variation from estimates impact the amount of water delivered.

Figure 2.14 has been removed due to copyright restrictions. It was a diagram showing a schematic representation of person filling an evaporation pan. Original source: Daniel Hillel (1980) *Applications of Soil Physics*. Academic Press Inc, 111 Fifth Avenue, New York, New York, 10003, p. 637.

Figure 2.14: Evaporation Pan used to Calculate Daily ET

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<sup>2</sup>In British Columbia, <http://www.farmwest.com/> provides daily ET estimates.

<sup>3</sup>Farmwest uses a modified Penman Monteith equation based on temperature data only. <http://www.farmwest.com/index.cfm?method=pages.showPage&pageid=230>

## 2.4. Irrigation Scheduling Strategies

A regulated deficit irrigation (*RDI*) strategy attempts to maximize crop yield while minimizing the cost of the production including water [FS07, Eng90, GR09] and is gaining popularity in agricultural areas where water is scarce or costly. With RDI, less water is applied to the crop than is required. This causes the crop to remove water from the soil matrix to make up the difference between what has been applied and the calculated ET requirement. Managed correctly, this can actually lower ET demand through induced changes in plant physiology [FS07] but notes that the application of excess water will not increase the yield. The relationship in Figure 2.15 [GR09] is called the crop water production function and demonstrates the link between crop yield and total relative ET. Using the CWP for a specific crop the amount of water to be applied can be determined based on how much stress the crop can withstand while maximizing yield with minimum costs. This results in an overall reduction in the required amount of water. For turfgrass, it has been shown that if managed correctly, induced stress can improve the health and durability of the crop [QFU97, BLM<sup>+</sup>06].

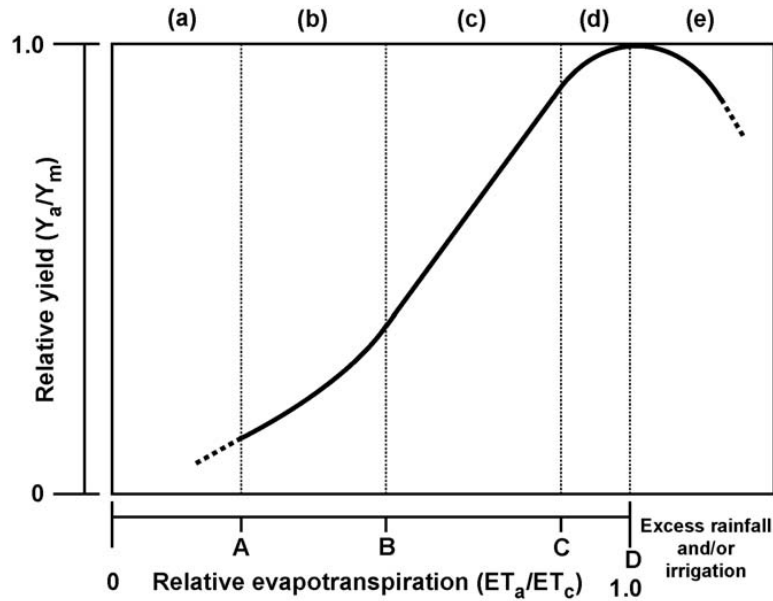


Figure 2.15: General Crop Water Production Curve. Reprinted from *Agricultural Water Management*, 96(9), Sam Geerts and Dirk Raes, Deficit Irrigation as an On-farm Strategy to Maximize Crop Water Productivity in dry Areas, 1275-1284., Copyright (2009), with permission from Elsevier.



## 2.5 Wireless Sensor Networks

Sensors networks have been an area of research interest finding application in military, environmental, agricultural and industrial applications [ASSC02, CES04, RM04]. Not to be confused with an ad-hoc network which offers high level functionality, wireless sensor networks typically have a greater device density, lower cost and complexity, and different communication paradigms [ASSC02]. Wireless sensor devices and the network formed by such, consist of an embedded processor (MCU), power management, sensing system, and a communications link [CES04, VCdSdM03] [Kri05, pp. 4-5]. Wireless sensor devices can utilize internal measurement systems or can utilize external sensors. Figure 2.16 [VCdSdM03] highlights the different components and how they interact. Communications between devices is accomplished using radio frequency *RF* modulation techniques [Kri05, p. 3] [BCDV09, VCdSdM03]. Each device, commonly known as a node, is tasked with processing information that it senses or measures, and communicates the observations back to a common collection point known as the sink [ASSC02, BCDV09, CES04]. This information is transferred by sending it over the communications link and may be accomplished via a single hop or as a series of relayed messages between nodes (multihop).

Figure 2.16 has been removed due to copyright restrictions. It was a diagram showing a schematic representation of the different parts of a wireless sensor. Original source: M.A.M. Vieira, C.N. Coelho Jr., D.C. da Silva Jr., and J.M. da Mata, (2003), Survey on Wireless Sensor Network Devices, In Proceedings of *Emerging Technologies and Factory Automation (ETFA '03)*, 2003. . volume 1, pp. 537-544.

Figure 2.16: Wireless Sensor Architecture.

In the design of wireless sensor networks, the energy characteristics and cost of the device present research challenges [VCdSdM03]. The MCU in a node is typically a small 8-bit device [VCdSdM03, ASSC02] with a small amount of local memory. Devices are chosen to be low in cost and energy efficient. The cost of a network is critical to its success as deployments of sensors may be dense and disposable such as in forest fire monitoring [ASSC02]. Adding to the cost is the labour in maintaining the source of power. A user faces increased labour costs for replacing batteries on a regular basis due to the large number of devices in a deployment. As a result, nodes must

be able to last for an extended period of time without battery replacement. To extend the life of a node, power control algorithms are critical to its success [VCdSdM03].

Nodes sample or measure the real world through an analogue to digital converter (ADC). A sensor converts a physical phenomena to an analogue electrical signal which is then interpreted by the ADC [VCdSdM03]. The ADC digitizes this signal so it can be manipulated by the MCU. A digitized signal is sent over the communications link to the sink. Numerous radio frequency methods are available with different transmission power, distance and deployment issues. Bluetooth, IEEE 802.11, UWB among other modulation techniques have been explored in research [BCDV09, VCdSdM03], but IEEE 802.15.4 [IEE07] is emerging as the dominant choice [BCDV09]. It is specifically designed for use with low power and low complexity devices that can tolerate low data rates [BCDV09, VCdSdM03] but natively only supports single hop messaging. Limited multihop routing and clustering has been added to IEEE 802.15.4 by the ZigBee Alliance<sup>4</sup> through the development of a proprietary standard. Unfortunately, IEEE 802.15.4 and ZigBee are used interchangeably with confusion. In practice they are two different standards with ZigBee building on the IEEE 802.15.4 standard. While IEEE 802.15.4 only defines the physical and MAC layers, ZigBee defines a network layer [BPC<sup>+</sup>07].

Extensive work has been done to produce low power sensor nodes resulting in the development of different research platforms with some becoming commercially available. The devices that have emerged as popular research platforms are the TelosB, Mica2, MicaZ, iMote<sup>5</sup> and BTNode<sup>6</sup> [DTV09, PSC05, VCdSdM03]. Table 2.3 [BPC<sup>+</sup>07] summarizes key attributes for popular platforms. Each platform has its own unique design features and performance attributes, but provide little more than a wireless gateway [PSC05] with local memory and limited on-board sensors. These platforms require the construction and addition of a peripheral interface card to support the additional functionality beyond the limited offering of temperature and light sensors.

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<sup>4</sup>[www.ZigBee.org](http://www.ZigBee.org)

<sup>5</sup> Available from Crossbow Technologies at [www.xbow.com](http://www.xbow.com).

<sup>6</sup><http://www.btnode.ethz.ch/>

Table 2.3: Various Sensor Architectures. Reprinted from *Computer Communications*, 30(7), Paolo Baronti, Prashant Pillai, Vince W.C. Chook, Stefano Chessa, Alberto Gotta and Y. Fun Hu, *Wireless Sensor Networks: A Survey on the State of the Art and the 802.15.4 and ZigBee Standards*, 1655-1695., Copyright (2007), with permission from Elsevier.

	Btnode 3	mica2	mica2dot	micaz	telos A	tmote sky	EYES
Manufacturer	Art of Technology	Crossbow	Crossbow	Crossbow	Imote iv	Imote iv	Univ. of Twente
Microcontroller	Atmel Atmega 128L	Atmel Atmega 128L	Atmel Atmega 128L	Atmel Atmega 128L	Texas Instruments MSP430	Texas Instruments MSP430	Texas Instruments MSP430
Clock	7.37 MHz	7.37 MHz	4 MHz	7.37 MHz	8 MHz	7.37 MHz	5 MHz
RAM (KB)	64 + 180	4	4	4	2	10	2
ROM (KB)	128	128	128	128	60	48	60
Storage (KB)	4	512	512	512	256	1024	4
Radio	Chipcon CC1000 315/433/868/916 MHz 38.4 Kbauds	Chipcon CC1000 315/433/868/916 MHz 38.4 Kbauds	Chipcon CC1000 315/433/868/916 MHz 38.4 Kbauds	Chipcon CC2420 2.4 GHz 250 Kbps IEEE 802.15.4	Chipcon CC2420 2.4 GHz 250 Kbps IEEE 802.15.4	Chipcon CC2420 2.4 GHz 250 Kbps IEEE 802.15.4	RFM TR1001868 MHz 57.6 Kbps
Max Range	150–300 m	150–300 m	150–300 m	75–100 m	75–100 m	75–100 m	75–100 m
Power	2 AA batteries	2 AA batteries	Coin cell	2 AA batteries	2 AA batteries	2 AA batteries	2 AA batteries
PC connector	PC-connected programming board	PC-connected programming board	PC-connected programming board	PC-connected programming board	USB	USB	Serial Port
OS	Nut/OS	TinyOS	TinyOS	TinyOS	TinyOS	TinyOS	PEEROS
Transducers	On acquisition board	On acquisition board	On acquisition board	On acquisition board	On board	On board	On acquisition board
Extras	+ Bluetooth						

The programming of these devices has not seen a convergence due to the need for application specific features. At a research level, TinyOS<sup>7</sup> has evolved as the most commonly used open source sensor operating system which is currently supported by the University of California, Berkeley. It is a single process operating system that supports multihop routing [DTV09, PSC05], but may not be suitable for all applications as programming of the operating system is complex and error prone [BPC<sup>+</sup>07]. There were more than 37 sensor operating system under development in 2009 each with unique strengths and weaknesses [DTV09]. As a result, the needs of a given specific application may not be met by current operating system offerings leading to the development of custom applications.

## 2.6 Summary

The goal of this work is to produce a low cost, easy to use residential irrigation system based on a wireless sensor network that is easy to use for a naive user. The system should operate in a self sufficient fashion monitoring the status of soil water and make appropriate watering decisions without the need for ongoing maintenance.

While numerous water content and matric suction sensors are presented, few are suitable for use. All of the matric suction sensors require routine maintenance or periodic calibration that make them unattractive choices for home users. For an irrigation controller to estimate the depth of water required by a given turfgrass using a matric suction sensor, a soil water characteristic curve must exist for the specific soil. Building a curve is beyond the scope of the average home owner.

Using a water content sensor presents the best strategy as water content can be linked to irrigation duration and volume. For water content sensors, both gamma ray and neutron scattering methods are infeasible for use due to cost, difficulty of use and health and safety restrictions. All the dielectric methods would be suitable for use except for the cost factor. As a result, a low cost dielectric sensor is the most suitable choice.

In the examination of different irrigation controllers, no one system examined could provide all the necessary functionality nor meet the desired price and performance point. Commercial controllers do not support highly customized numerical watering programs. Common wireless sensor nodes that have been used in research also fail to address the goals of this work. The wireless sensor nodes examined do have the ability to support different

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<sup>7</sup><http://www.tinyos.net/>

## 2.6. Summary

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programming but all require customization to support the different types of sensors, flow counters and solenoid valves required. To meet the performance and cost constraints of the application, a custom wireless sensor node was designed. The node is generalizable as it can be used for both sensing and control applications. It can easily interface with various sensors and intercommunicate over a wireless link.

With the customized platform, different irrigation strategies can be easily implemented with custom programming. Of the three different models presented a water budget model was selected. This model readily supports the introduction of sensor data without the need for complicated crop yield models or daily ET model updates. The water budget model coupled with a soil moisture sensor allows for a system to run independent from user input and without the need for ongoing maintenance. A minimum number of soil water parameters are needed as inputs to allow for the model to function. Section 3 presents a control strategy that couples a Decagon Devices EC-5 dielectric soil moisture sensor, with low cost wireless sensor nodes to addresses the design goals of this thesis.

## Chapter 3

# Adaptive Irrigation Controller

Science is what we understand well enough to explain to a computer. Art is everything else we do.

---

Donald Knuth (1928- )

The goal is to build an irrigation system that offers significant savings over current technologies without the need for excessive user input or maintenance. The approach uses soil moisture sensors to determine the water requirement for a soil and schedules events based on the water requirement. This results in a system that reduces water consumption by only watering when the soil conditions require it. Unlike other systems, this technology adapts to changes in flow, application efficiency, and crop water demands. It is simple to use as it requires no user intervention.

The system is schematically represented in Figure 3.1. A dielectric sensor was selected based on the size, cost and performance requirements. Unlike current *SMS* or on-demand controllers, the system just does not water until the water content reaches an upper threshold. Instead, the control method is based on a water budget [Jon04, Nyv04, ZX94] model using a penalty function based on a Deficit Irrigation [FS07] strategy to calculate the amount of water required per zone to re-establish water content levels without over watering. Based on the amount of water required by the soil, the system dynamically schedules the required event. The system offers advantages over current *ET*, *SMS* or traditional water budget systems.

### 3.1 Hardware

The system consists of three components: a controller node responsible for controlling and scheduling irrigation events, sensing nodes that are respon-

### 3.1. Hardware

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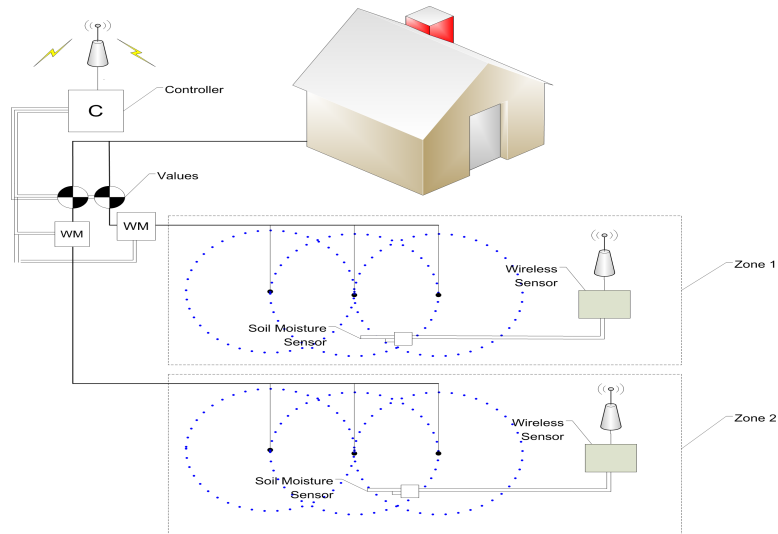


Figure 3.1: Adaptive Irrigation System Overview.

sible for measuring and reporting soil moisture readings, and a soil moisture sensor. In each zone of interest, a wireless soil moisture sensor is placed in the rooting zone of the plants. This soil moisture sensor collects readings at a regular interval and relays the readings back to the controller. The details of the sensing node are expanded upon in Section 3.1.1.

#### 3.1.1 Wireless Sensor Node

The goal was just not to build a better node with lower power consumption, but to design a system that was complete for use in environmental monitoring applications. The design is required to meet the criteria:

- be able to support a wide array of common environmental sensors without the need for additional hardware
- have low power consumption
- have low power non-volatile memory
- have a low construction price point.

Each sensor node is about 5 cm x 7.5 cm x 10 cm. The node is encased in water-resistant packaging and slightly buried under the soil. To evaluate these criteria, an iterative design process was followed. Table 3.1.1 outlines

### 3.1. Hardware

Table 3.1: Wireless Sensor Node Design Phases

Design Phases		
Phase	Date	Deliverables
Proof of Concept	May to September 2008	Initial evaluation of hardware and construction of prototype node
Design Review	September 2008 to December 2008	Reviewed design challenges from proof of concept model
Prototype Design	January 2009 to March 2009	Researched updated components and designed node hardware
Prototype Construction, Validation and Testing	March 2009 to April 2009	Constructed and tested node against specification
Firmware Review	April 2009 to June 2009	Reviewed and updated firmware to support new functionality
System Deployment	June 2009 to October 2009	Operational field testing

the major phases of the process followed. Cost and power consumption were principle factors in design choices. All designs were built from scratch on custom fabricated boards. The initial prototype was based on the Atmel Mega32 processor with 32K of EEPROM memory, two pulse counters and an eight port 10-bit analogue to digital converter. The initial prototype encountered problems with data storage space, interfacing with the watering solenoid valves and flow meters as well as with water penetration into the hardware enclosure.

During the review phase, failure modes of the prototype were isolated and analyzed. Using the feedback from the proof of concept phase, a prototype design was completed to address these failures. It was determined that a lower power processor was a requirement along with expanded data storage. A model of the prototype (Figures 3.2 and 3.3) was constructed to check for component placement and physical interferences. Figures 3.4 and 3.5 show the internal sensing board and completed node. The slightly buried nodes do not use the optional external antenna. The final prototype constructed contains an IEEE 802.15.4 wireless radio and an Atmel 644p microcontroller. The Atmel Mega644p processor was chosen because of its



### 3.1. Hardware

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low power consumption and suitable program space. Atmel Serial NOR flash was chosen for data storage due to the low power consumption and small size. The wireless radio is a Digi International XBee radio which is compliant with the 802.15.4 standard [IEE07].

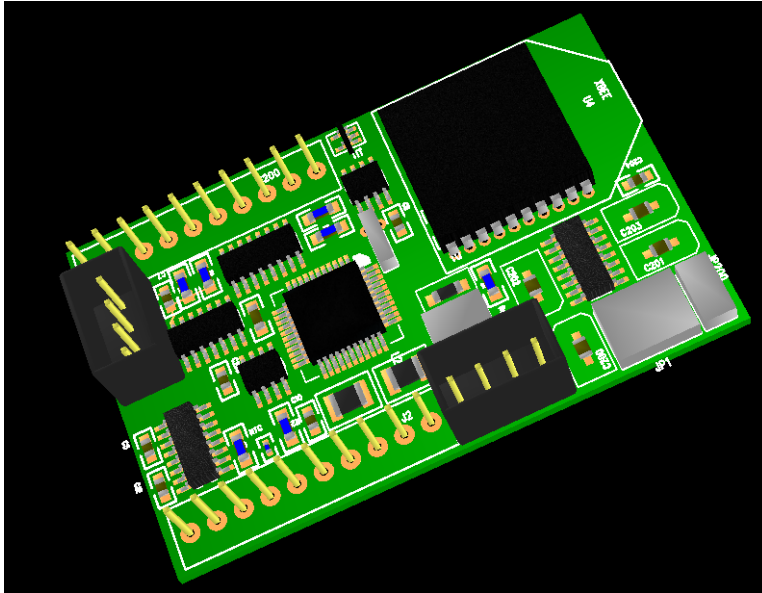


Figure 3.2: UBCO Mote Model: Front.

Each node also contains an eight port 12-bit analogue to digital converter, an eight port output driver, and three pulse counters. This allows for a sensor node to interact with the environment and conduct numerous functions. Each sensing node can connect up to eight analogue sensing devices. In this application, soil moisture sensors are used and report their status to the controller node eliminating the need for extensive wiring.

The soil moisture is monitored by an EC-5<sup>8</sup> low cost, soil moisture sensor (Decagon Devices) providing 0.1% resolution in water content [Dec08]. The EC-5 is a dielectric soil moisture sensor that is grouped with other non-TDR dielectric sensors (Section 2.2.1) and is purported to use capacitance/frequency domain technology. The EC-5 was selected as it met both the cost and performance requirements. The manufacturer claims that the device has an uncalibrated accuracy of  $\pm 3\%$ . The EC-5 was used uncalibrated. The node is powered by three AA batteries. Based on power models

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<sup>8</sup>Technical specifications available at <http://www.decagon.com/>.

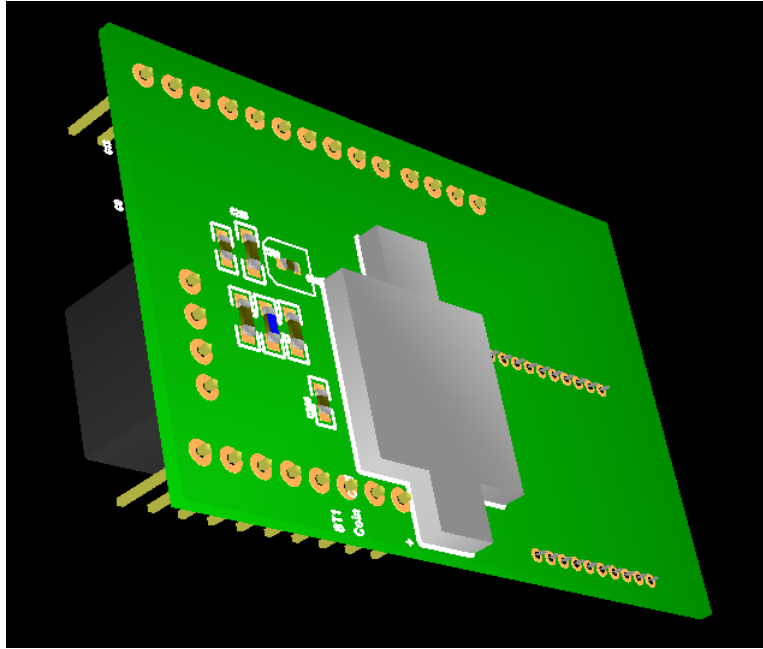


Figure 3.3: UBCO Mote Model: Back.

for the sensor node, nodes will last more than the length of a growing season on one set of batteries.

Many sensors require tightly regulated power. With the EC-5 sensor, if the input voltage drifts, the output signal will also be impacted. To address this issue, each sensing node includes a high accuracy low voltage dropout regulator that is dedicated to providing power to the sensing system. The sensing node has the ability to monitor its own power consumption and voltage levels during sampling. This allows for the device to recognize a low voltage condition during a sampling event that may compromise the quality of the data. This feature is not used for this application.

To improve the quality of the sensing system, the power system for the analogue sampling, radio and microprocessor are independent and isolated. The sensing node has the ability to turn off the radio to eliminate any spurious sources of interference when measuring analogue voltages. The sensing node also has the ability to conduct on board temperature measurements which are required for some sensors.

Each wireless sensing node performs monitoring on a fixed schedule. The node wakes from sleep at a minute interval, performs a reading from

### 3.1. Hardware

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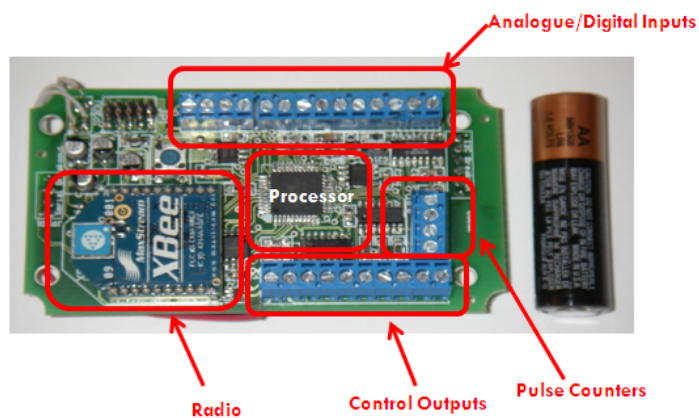


Figure 3.4: UBCO Mote: Internal Circuit Board.

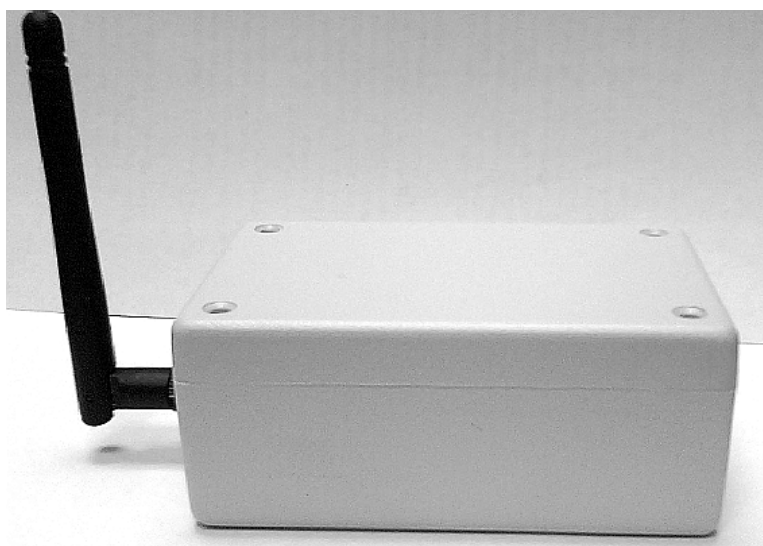


Figure 3.5: UBCO Mote: Complete Sensor Node in Enclosure.

the soil moisture sensor(s) and stores the results locally. The results are then wrapped in the valid IEEE 802.15.4 data packet and queued for transmission. The sensor node transmits results over the wireless link (radio layer) at a preset interval. For each sampling interval, the modelled power consumption is presented in Table 3.2 for nodes operating in a star topology where each node transmits directly to the sink. This includes the power budget for both

### 3.1. Hardware

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Table 3.2: Node Power Requirements for a One Minute Cycle Time

Phase	Current Draw (mA)	Est. Time (s)	Duty Cycle	Charge ( $mC$ )
Sleep	0.275	59.919	99.8%	16.477
Idle	10.7	0.01	0.0167%	0.107
Sample	20.7	0.02	0.0333%	0.414
Radio Idle	70.7	0.04969	0.0828%	3.513
Transmit	65.7	0.001398	0.00233%	0.091853

the wireless sensor node and the soil moisture sensor. For this application, the payload transmitted consists of 21 bytes. The values are represented as units of charge required per cycle.

Based on the estimated power figures, the total charge requirement is 20.603  $mC$  per cycle. With data being transmitted over the wireless link once every minute, the total power draw for one complete cycle is 0.343 mA. Assuming a 90% efficiency to account for internal losses, the node is capable of operating continuously for over 10 months when powered from three AA with a capacity of 2880 mAh. The large sleep current is due to the peripheral support.

#### 3.1.2 Controller Node

The controller uses the same sensor node hardware but has the additional task of controlling the irrigation. The pulse counters are used to measure flow during irrigation events. Figure 3.6 shows the controller node. A daughter board interfaces with the node to provide a suitable interface for the solenoid valves as well as a switching power supply to convert 24 VAC to suitable DC voltage levels. The controller node and the valve system is powered by 24 VAC.

The controller has a user interface for setting acceptable irrigation times and controlling the valves for each zone. A sample of the interface is seen in Figure 3.7. The controller analyzes the data provided by the sensor nodes and determines how much (long) to water and schedules an irrigation event using the adaptive watering model (Section 3.3). All data can be extracted to a PC for analysis. The main controller monitors water flow through a flow meter that is attached to a pulse counter input. The controller has a real-time clock that it uses to control watering start and end times. As each program event is determined, it is added to a watering queue. Since only one zone can be watered at a time, a program to be executed is placed on

### 3.1. Hardware

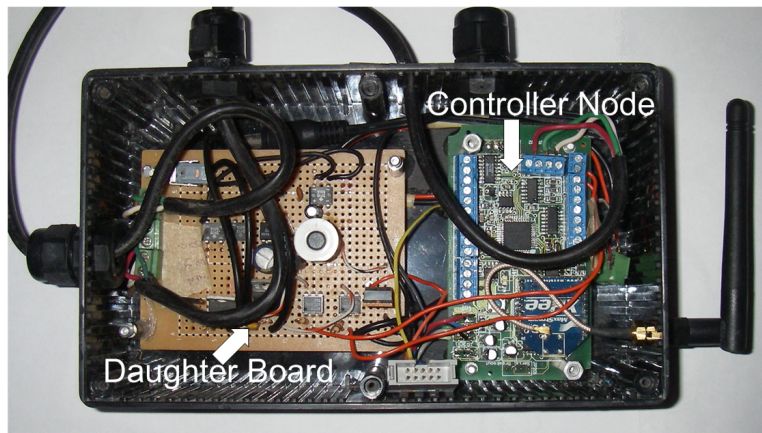


Figure 3.6: Controller Node with Solenoid Interface.

```
NW>status
CURRENT SYSTEM STATUS:
The system is currently not in debug mode.
The system is not currently running a watering program (status = 0).
The system is not currently watering in a zone.
Zone 1 is: 0 Zone 2 is 0

There are no programs for zone 1.

Zone: 2
1) start time 20:30:00 run time 00:15:00 interval 0 days until next event 0.

Current zones:
Zone 1 Flow counter: 672 Area: 90 Flow rate: 46 Blackout time: 0 Application Eff 412
Zone 2 Flow counter: 712 Area: 90 Flow rate: 78 Blackout time: 0 Application Eff 760

Current sensors:
Sensor 1 Field capacity: 300 wilting point: 200 sensor depth: 15 Zone id: 1
Sensor 2 Field capacity: 500 wilting point: 350 sensor depth: 15 Zone id: 2

Current queue:
Queue is empty

system black out time starts at: 08:00:00 and ends at: 20:00:00.

Data samples collected: 0
NW>getmem
No data to display.

NW>go
calculating next time.
calcTime 73800
The next event is from zone: 2 at position: 1 (starting at index 1) at time: 73800.
1) start time 20:30:00 run time 00:15:00 interval 0 days until next event 0.
```

Figure 3.7: Controller Interface.

the queue until it is available to be serviced.

The cost of each completed node including the controller is less than \$100 in small quantities excluding the cost of the soil moisture sensor. This is a significant reduction in cost as the lowest cost controller that is able to perform on-demand watering is approximately \$3000 [OTRCG07].

### 3.1.3 Node Communications

To abstract and facilitate communications with the radio layer from the application running on the sensor node, a transport API was constructed to interface with the XBee 802.15.4 radio hardware [Dig08]. The transport frame supports a 16-bit global source and 16-bit global destination address and a maximum 96 byte application payload. The frame structure is seen in Figure 3.8. The transport layer runs on a separate periodic thread from the main application in the sensor node. This allows the transport layer to run independently from the application allowing for easy re-purposing of the sensor node without having to rebuild the transport layer. A geographic routing protocol [AKK04] is implemented at the transport layer for use with the sensor nodes but was not required for this application. With this routing protocol, nodes try to route all packets toward the sink by selecting an outgoing link that minimizes the distance to the sink.

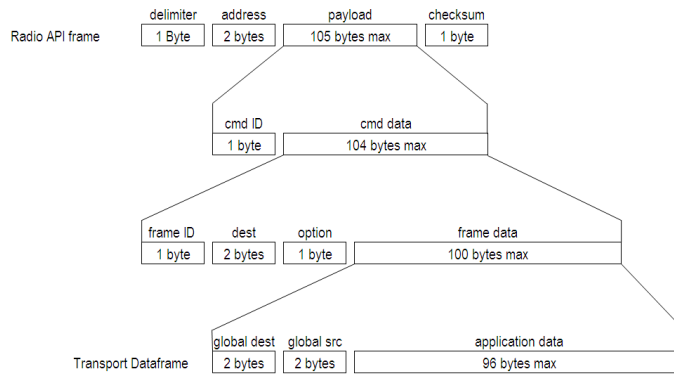


Figure 3.8: Transport Dataframe Interactions with XBee 802.15.4 Radio API.

The current network topology is a star topology with the controller at the centre of the network. The controller has continuous power whereas the sensor nodes are battery powered. The sensor nodes wake up at a set interval and transmit their readings to the controller (sink). The controller maintains a database of sensor readings used for its calculations. With the star topology, routing is trivial as every sensor node is within reach of the sink, but due to the implementation of the routing protocol in the transport layer, the sensor network can be easily extended for multi-hop routing.

#### 3.1.4 Engineering and Design Challenges

During the development cycle for the hardware platform, numerous challenges were encountered. During the first test season, as a prototyping system was used to develop the controller numerous problems were encountered with loose and intermittent connections. This was due to the environment that the development board was being used in. The unit was susceptible to corrosion as electrical traces were not protected. This issue was address through the use of improved enclosures and production quality circuit boards.

The initial prototype was designed using a microprocessor with 32k of program space. As the size and complexity of the program increased this became insufficient. To address this issue, a processor with larger code space was selected that maintained the same power efficiency profile. The initial prototype also suffered from memory corruption due to cross talk from other electrical systems. This also caused unexpected and unplanned watering events. This was addressed through better electrical shielding and an improved solenoid switching circuit. On the final design, efforts were taken to isolate data and control lines as well as shielding local sources of high frequency noise such as the radio and real time clock.

Challenges were also faced with memory corruption and lack of storage. In the initial prototype, a multi-chip memory solution was implemented were data had to be split across multiple devices. This solution provided limited memory storage and slow access times. In the final design, this memory was replaced with a single flash chip memory solution. This helped to reduce the amount of physical space required by the memory and eliminated problems with data splitting across multiple devices.

The single largest challenge in the development of the sensor network was the lack of a real time debugging environment. Unlike development of software on a desktop computer where debugging infrastructure is often available, when developing complex projects on an embedded system high level debugging is not available. As a result, strict software engineering design principles were applied to manage and understand the available resources of the device.

## 3.2 Irrigation Scheduler and Measurement Processing

The adaptive irrigation controller uses an event driven queue to schedule watering events and process measurements. Figure 3.9 provides an overview of the scheduling and measurement systems.

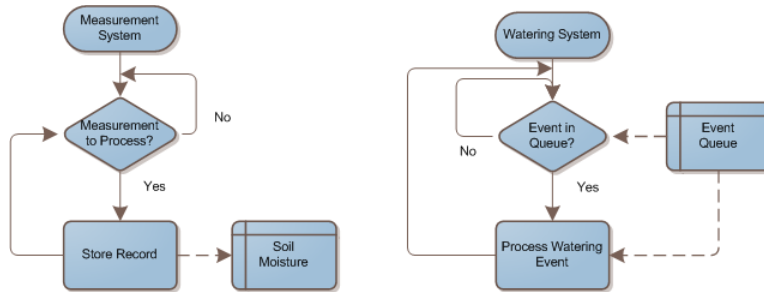


Figure 3.9: Scheduling and Measurement Algorithms.

The measurement processing system waits for measurements to be received from remote devices or the local hardware. When a measurement is available for processing, the system will store the data in local storage for use by the adaptive irrigation algorithm (Section 3.3).

The scheduling system dynamically schedules events as needed for watering. The system only services one event at a time. Events indicate the zone to water and the length of time required. For each event serviced the controller records the time at which the event started and how long it watered for. Total flow and calculated application efficiency (Section 3.3) are also recorded.

To facilitate comparison between the adaptive irrigation controller and a standard irrigation system, the controller used for the testing phase was designed to also concurrently runs a time based scheduler. When a watering event is required as determined by the time based program it is queued along with other adaptive events. This prevents events from clashing, allowing for both programming strategies to run side by side.

## 3.3 Adaptive Watering Model

The employed strategy is to build a robust system that can respond to changes in long term soil moisture. Figure 3.10 provides an overview of the adaptive irrigation algorithm.



### 3.3. Adaptive Watering Model

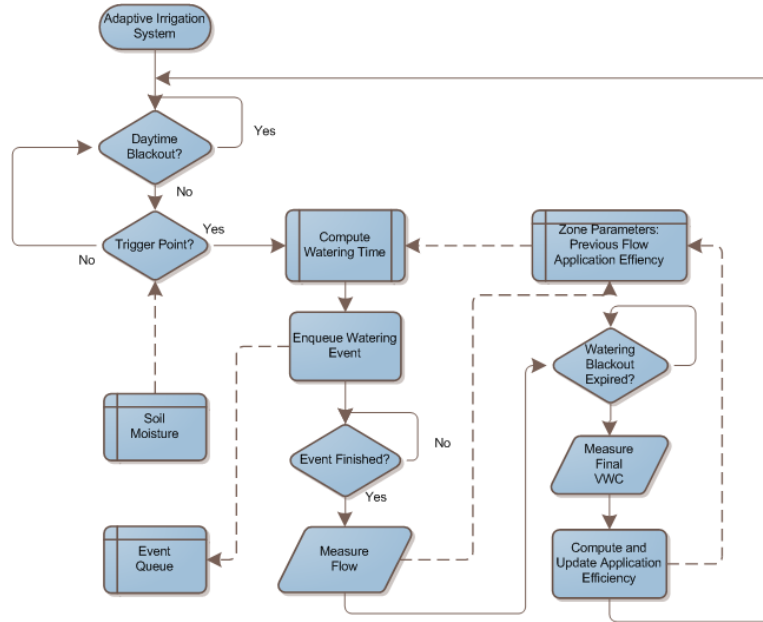


Figure 3.10: Adaptive Irrigation Algorithm.

In order to schedule an event, the controller must determine how much water is required and at what point it is required. The approach utilizes a water budget strategy to calculate watering amounts [Nyv04] with a penalty function based on a deficit irrigation philosophy [FS07]. Water is only applied according to the available water budget; the amount of water provided to the soil profile is less than or equal to the maximum amount the profile can hold before water starts to move to deep drainage. When water is applied at rates lower than what is required by the crop, water will be extracted from the soil matrix. The algorithm also blocks events from being enqueued if a given irrigation zone is in a daytime blackout period. A daytime blackout period prevents watering events during specific user selectable time periods. The controller also supports blackout periods where watering may not be allowed due to time of day or day watering restrictions.

Building on a water budget methodology which uses estimated ET demand, drainage losses and soil moisture levels, the model is simplified by only considering additions through irrigation and losses from root uptake but uses real time soil moisture measurements. Estimated demand from ET is not considered. Soil moisture is continually monitored through sensor nodes and updated for each zone in the controller. Unlike other on-demand

### 3.3. Adaptive Watering Model

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systems that use *SMS* to determine when to stop watering, the system uses sensors to determine how much water must be applied. To determine the amount applied, consider the following parameters for a specific soil:

- *Field Capacity* is the maximum amount of water expressed as  $\theta_{FC}$  that a soil can retain. Any excess water moves to deep drainage in a little as a few hours to 2 to 3 days. It is the upper bound on water levels for irrigation calculations.
- *Permanent Wilting Point* is the point at which roots can no longer extract water from the soil matrix and is expressed  $\theta_{PWP}$ . It is the lower bound of water levels for irrigation calculations.

Both of these parameters are soil dependent and are inputs to the controller. In the model, the turn on water content point  $\theta_{TO}$  is defined as

$$\theta_{TO} = \frac{\theta_{FC} + \theta_{PWP}}{2} \quad (3.1)$$

which sets the turn on point to be the point when half of available soil water storage has been consumed. This point was selected as the turn on point due to the shape of the soil water characteristic curve. As the volumetric water content drops below this point, the required amount of energy to influence a step change in water content increases.

In an irrigation system, the amount of water in the soil can be expressed as  $m^3$  water per  $m^3$  soil. This can be reduced to a water with Equation (2.1). This value can then be used to determine how much water is in the column of soil at our soil moisture sensor if we know the depth of the sensor. For example, if the sensor is placed at 0.1 m and the water content is at 0.26 m water per m of soil, the depth of water is

$$\text{depth of water} = z_{sensor} \times \theta_{current} \quad (3.2)$$

$$= 0.1 \text{ m soil} \times 0.26 \frac{\text{m water}}{\text{m soil}} \quad (3.3)$$

$$= 0.026 \text{ m} \quad (3.4)$$

where  $z_{sensor}$  is the depth of the sensor and  $\theta_{current}$  is the current water content measurement. Thus, the amount of water in the soil is 2.6 cm between the surface and the sensor. To calculate how much water is to be applied, the current depth of water is subtracted from the depth at field capacity as

$$\text{required depth of water} = z_{sensor} \times (\theta_{FC} - \theta_{current}). \quad (3.5)$$

### 3.3. Adaptive Watering Model

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The resulting value will be the maximum amount of water that can be stored in the column of soil above the sensor. By applying the difference, the soil water content will rise toward the field capacity value but not overshoot and lead to waste. For example if  $\theta_{FC} = 0.35$ , the required depth of water as from Equation (3.5) is:

$$\text{required depth of water} = z_{\text{sensor}} \times (\theta_{FC} - \theta_{\text{current}}) \quad (3.6)$$

$$= 0.1 \times (0.35 - 0.26) \text{ m} \quad (3.7)$$

$$= 0.009 \text{ m}. \quad (3.8)$$

Once the depth of water required has been determined by the controller through communications with the sensing nodes, the controller calculates how much water is required by the zone. In order to accomplish this the controller requires as an input the area of each zone. The controller then computes the volume of water required by analyzing past delivery performance from historical flow meter data from each zone. Knowing the flow rate for each zone, the area of the zone and the depth of water required, the system calculates the length of time required to deliver the correct amount of water and enters this event into the scheduler.

In irrigation, system losses must be considered. Sprinkler type, drop size, flow rate and pressure, and canopy cover affect delivery of water into the soil profile [dG09, Nyv04, Pho07]. The losses are grouped and termed as *Application efficiency* ( $A_e$ ) which relates percentage of irrigation water that is successfully delivered into the rooting zone relative to the amount of water applied. This must be considered when delivering water into the profile. In order to deliver the correct amount of water into the soil profile, more water must be applied than is needed to compensate for the losses. To determine the amount of applied water, the desired amount is divided by the application efficiency. Spray heads typically have an  $A_e$  of 76% [dG09] but this does not consider other loss sources. This value is used as a starting point and dynamically updated during the adaptive watering program. For example, if the required depth of water is 0.009 m then the actual amount required to be delivered is

$$\text{actual depth} = \frac{\text{required depth of water}}{A_e} \quad (3.9)$$

$$= \frac{0.009 \text{ m}}{0.76} \quad (3.10)$$

$$= 0.0118 \text{ m}. \quad (3.11)$$

In addition to losses due to  $A_e$ , applications can lose water due to evaporation and soil surface interactions [Nyv04]. As a result, all applications will

### 3.3. Adaptive Watering Model

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have this loss that is labelled as  $E_{irr}$ . A typical value for this loss is 0.005 m. A more sophisticated model could dynamically model the evaporative loss but for the purposes of this algorithm it is treated as a constant. The actual amount of applied water must include a 0.005 m depth to compensate for this loss. Continuing with the previous example, the actual amount of water required is now

$$\begin{aligned} \text{actual depth} &= \frac{\text{required depth of water}}{A_e} + E_{irr} \\ &= \frac{0.009 \text{ m}}{0.76} + 0.005 \text{ m} \end{aligned} \quad (3.12)$$

$$= 0.0168 \text{ m}. \quad (3.13)$$

If it is assumed that each zone contains 4 heads with a drop rate of 2 litres per minute, the entire zone consumes 8 litres per minute which is equivalent to  $0.008 \text{ m}^3$  per minute (based on flow meter measurements). For a zone that is  $9 \text{ m}^2$ , the system calculates the depth of water per minute as

$$\text{application rate} = \frac{\text{volume}}{\text{area}} \quad (3.14)$$

$$= \frac{0.008 \text{ m}^3/\text{min}}{9 \text{ m}^2} \quad (3.15)$$

$$= 0.00089 \text{ meters / minute}. \quad (3.16)$$

As the application rate is now known, the length of time that the watering event must run is determined by dividing the required depth of water by the application rate as

$$\text{watering time} = \frac{\text{required depth of water}}{\text{application rate}} \quad (3.17)$$

$$= \frac{0.0168 \text{ m}}{0.00089 \text{ m}/\text{min}} \quad (3.18)$$

$$= 18.88 \text{ minutes} \quad (3.19)$$

The complete model for calculating the required watering time is expressed as:

$$\text{time}(\text{min}) = [E_{irr} + \frac{(\theta_{FC} - \theta_{current}) \times z_{sensor}}{A_e}] \times \frac{A}{Q} \quad (3.20)$$

where  $\theta_{FC}$  is soil moisture level at field capacity,  $\theta$  is the current moisture status of the soil,  $z_{sensor}$  is the sensor depth,  $A$  is the area of the zone, and  $Q$  is the previous flow rate. Thus using Equation (3.20) the controller will generate a watering event for this zone for a period of 18.88 minutes. If an

### 3.3. Adaptive Watering Model

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event is generated during a blackout period it will be postponed and recalculated when the blackout time expires. During this event, the controller will monitor and update flow rates. Along with the requested event, a redistribution time is entered. This time prevents the system from creating a new watering event until the added water has been allowed to redistribute correctly through the soil profile. While redistribution time can range from tens of minutes to days, the adaptive irrigation algorithm uses a 6 hour post-irrigation blackout time. This is used to compensate for any water that may have entered through macro pores. During the post-irrigation blackout time, low energy water that may be in macro pores and collect around the sensor will be drawn into the soil matrix until it is in equilibrium with the soil water. This will compensate for anomalously high or low readings that may be encountered immediately after irrigation. Once the post-irrigation blackout has expired, the system will then re-enter the measurement phase and wait for the soil moisture level to drop below  $\theta_{TO}$  before scheduling the next event. Due to daytime blackout periods and changes in  $A_e$ , the amount of water required between events will change.

Once the redistribution blackout time expires, the controller determines how much water was delivered into the profile compared to the estimated amount. The controller uses the differences between the estimated and actual soil water content values to update  $A_e$  for each watering event to accurately characterize losses in the system. The new application efficiency is calculated as:

$$A_{e_{new}} = \frac{(\theta_{end} - \theta_{start}) \times z_{sensor}}{Actual\ Depth\ Water - E_{irr}} \quad (3.21)$$

With this method, the actual water content should never exceed field capacity under normal irrigation. This is due to evaporation of water during watering and interception of water by the turf canopy. As a result, by preventing the water content from rising above the field capacity point, excess waste water is minimized. This offers a significant advantage over the on-demand method as the system never has to react to water being applied as it uses a strictly prescriptive application method.

The adaptive irrigation algorithm and sensing method is more resistant to the presence of macro pores in the soil structure than current on-demand systems. Water can infiltrate into the soil through macro pores and collect around a sensor at a level higher than in the soil body. This artefact will cause current on-demand systems to read erroneously while the adaptive irrigation controller presents a more robust solution. This is due to the fact that the algorithm calculates the amount of water to be delivered, waters, and then waits for internal redistribution to occur before measuring the

updated water content. Any water that may have flowed into macro pores or collected around the sensor during the irrigation period will be drawn into the soil matrix during the redistribution time allowing for a more accurate reading of actual soil moisture after irrigation.

## 3.4 Penalty Function

The penalty function is a built in consequence of the application efficiency. It is imposed by limiting the amount of water delivered to the soil in response to an unscheduled addition of water that is co-incident with a watering event. This is accomplished through an adjustment in  $A_e$ . With unscheduled additions of water,  $\theta$  may rise above field capacity for periods of time. Unscheduled additions that are not co-incident with an irrigation event or blackout period are not considered for penalty. With unscheduled additions, both  $\psi$  and  $\theta$  will increase allowing for turfgrass to be exposed to longer periods of low energy water. Plants allowed to draw on low energy water for extended periods of time may be more susceptible to crop stress when water levels decrease [GR09].

To address this affect, the model introduces a slight stress into the water events after the unexpected addition of water, resulting in hardening of the crop. When an unexpected addition occurs coincident with irrigation, the system (Section 3.3) interprets the event as being overly efficient. In reaction to this ‘over-watering’, the algorithm will recalculate a new  $A_e$  via Equation (3.21) that may be higher than what is normally observed by the algorithm. The system will then apply less water during the next watering cycle as a result of the new  $A_e$ . This allows the turfgrass to be held in a slight deficit state which has been shown to increase crop health [JWV<sup>+</sup>03, BLM<sup>+</sup>06]. As subsequent watering events occur without the unexpected addition of water,  $A_e$  returns to the previous value.

To better understand the penalty function, consider the following example modelled on a Guelph Loam soil. Figure 3.11 shows the changes in matric suction and water content during a series of watering events. The matric suction values are shown to demonstrate what is happening in the soil matrix in terms of water energy status. In phase (a), normal watering is occurring. Watering starts at the turn on point of 23% VWC and raises the water content of the soil profile to 28% with the matric suction changing from -100 kPa to -30 kPa. In phase (b), an unexpected addition of water occurs raising the water content to 35% with a corresponding drop in matric suction to -10 kPa. As a result, the adaptive irrigation controller

### 3.4. Penalty Function

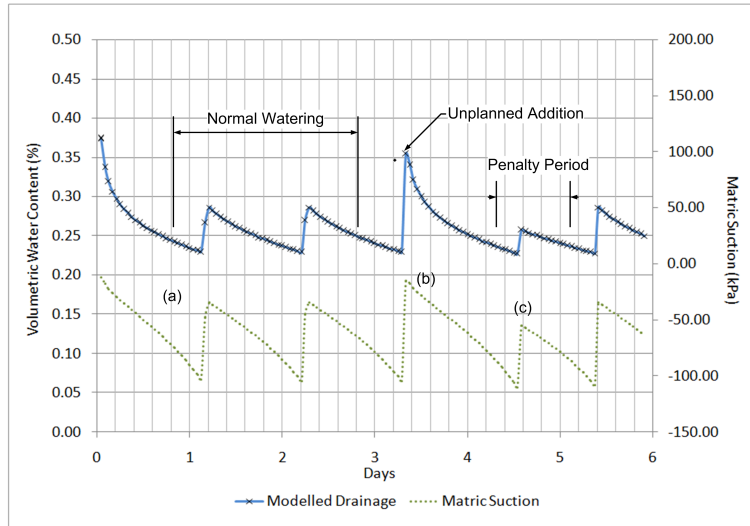


Figure 3.11: Water Contents and Matric Suctions for a Guelph Loam Soil.

will impose a penalty during the next watering event by changing  $A_e$ . The next watering event only delivers enough water to raise the water content to 25.5% during phase (c). This results in the matric suction being held below -60 kPa for an extended period of time which introduces slight stress in the turfgrass to compensate for the low energy water in phase (b).

The calculation of the new application efficiency is accomplished with Equation (3.21). Continuing with this example, if  $\theta_{TO} = 23\%$  and  $\theta_{FC} = 28\%$  this system would request a watering event of 13 minutes assuming the same flow and area parameters as in Section 3.3. After irrigation is complete, if  $\theta = 35\%$  the new  $A_e$  is calculated as

$$A_{e_{new}} = \frac{(0.35 - 0.23) \times 0.1}{0.0116 - 0.005} \quad (3.22)$$

$$= \frac{0.012}{0.0066} \quad (3.23)$$

$$= 118\% \quad (3.24)$$

assuming that the initial  $A_e = 76\%$ . Due to the expected addition of water, the system calculates the watering event to be 118% efficient. During the next watering event, the system will deliver less water to the turfgrass. The new application efficiency will impact the next watering event when the

### 3.4. Penalty Function

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system calculates the time as in Equation (3.20). The length of watering is

$$time(s) = \left[0.005 + \frac{(0.28 - 0.23) \times 0.1}{1.18}\right] \times \frac{9}{0.008} \quad (3.25)$$

$$= \left[0.005 + \frac{0.005}{1.18}\right] \times 1,125 \quad (3.26)$$

$$= 10.39 \text{ minutes.} \quad (3.27)$$

Assuming that the initial watering time was 13 minutes, this results in a reduction in applied water of 21.9%.

The algorithm presented therefore includes automatic adaptation to coincident rainfall without the need for separate rain sensing hardware or separate calculations. The penalty stress induced is specific for turfgrass and may not be suitable for other crop types.



## Chapter 4

# Experimental Program and Results

Nobody climbs mountains for scientific reasons. Science is used to raise money for the expeditions, but you really climb for the hell of it.

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Edmund Hillary (1919-2008)

The experimental setup of the test irrigation plot and methods used for evaluation of the adaptive irrigation controller are presented in this section. Results are then presented from the season of testing. The hypothesis was that the system would only deliver the required amount of water without impacting the health and quality of the turfgrass, and significantly improve watering efficiency compared to conventional industrial and research irrigation systems and approaches.

### 4.1 Experimental Setup

This section outlines the location, climatic variables and controller configuration for the test site.

#### 4.1.1 Site Description

An irrigation test site was constructed in the Belgo area of East Kelowna. The experimental area is a semi-arid environment. Climate data and calculated ET were available during the test period from a nearby agricultural weather station<sup>9</sup>. Figure 4.1 shows the maximum and minimum daily temperatures during the test period. The average maximum daily temperature was 33.14°C. Figure 4.2 shows the calculated daily and cumulative ET values

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<sup>9</sup>Farmwest Belgo recording station

#### 4.1. Experimental Setup

during the test period. Long periods of little or no precipitation were experienced presenting extended periods of high water demand. The site also experienced record setting single rainfall events during the month of August. During the two month period, only 6 days of rain were recorded with only 3 days producing more than 5 mm of precipitation. This translates to only 0.0029 m of effective precipitation over the test period.

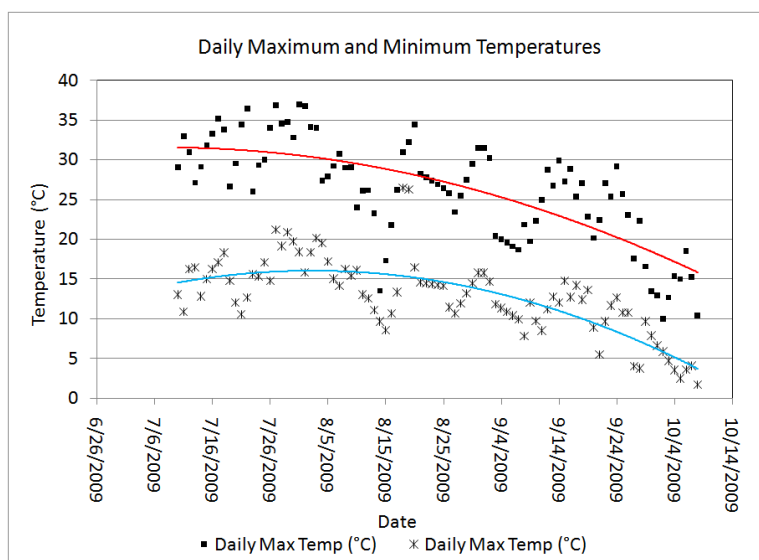


Figure 4.1: Daily Maximum and Minimum Temperatures from the Farmwest Belgo Reporting Station.

Figure 4.3 shows the experimental setup. The test area consisted of two 3 meter x 3 meter plots of turfgrass. One plot is a control plot which was watered using a fixed daily application of water. One plot is controlled by the adaptive irrigation model. The controller was placed above the ground in close proximity to the valve control box. Each zone was monitored by a flow meter to determine water consumption (Figure 4.4). The test system used spray heads which typically have an  $A_e$  of 76% [dG09]. This typical value does not consider losses from other sources. Each zone used a single uncalibrated EC-5 sensor placed at a depth of 10 cm.

#### 4.1. Experimental Setup

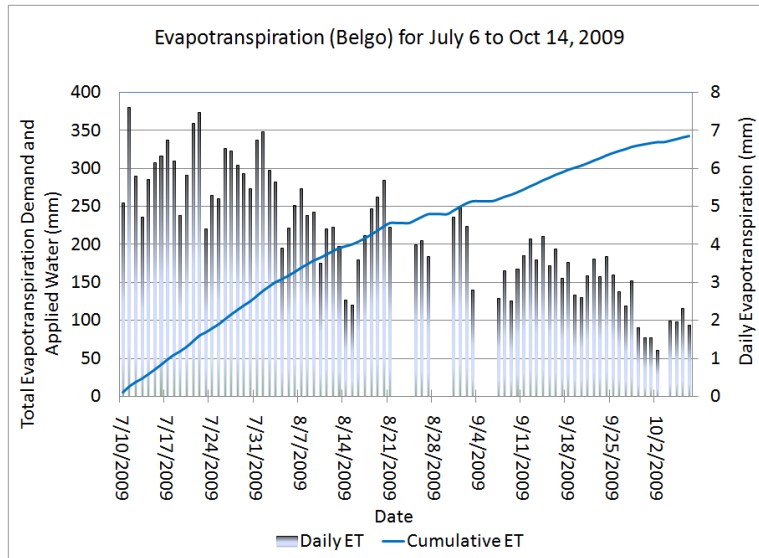


Figure 4.2: Daily and Cumulative ET Values from the Farmwest Belgo Reporting Station.



Figure 4.3: Overview of Test Site.

#### 4.1. Experimental Setup

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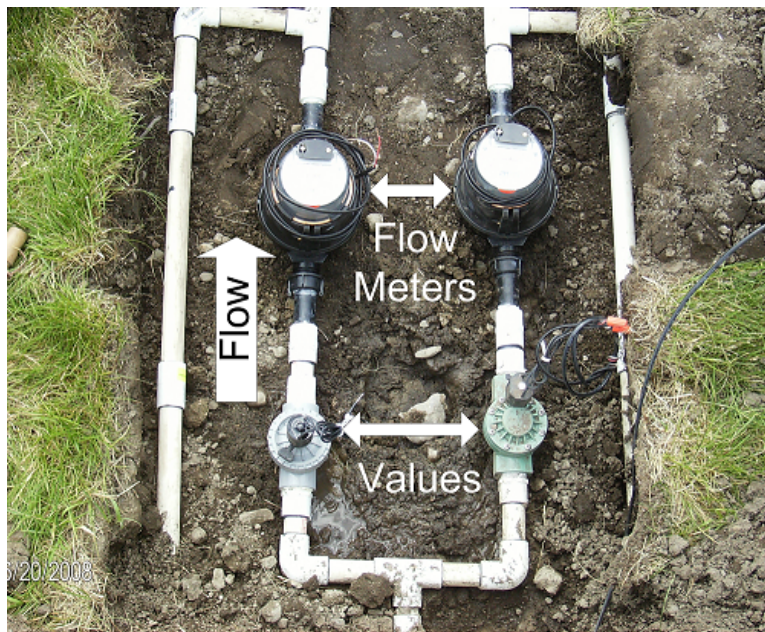


Figure 4.4: Control Values and Flow Meters.

### 4.1.2 Methods

The adaptive irrigation controller was compared against a recommended irrigation program and the actual water depth demand as estimated by ET. The adaptive irrigation controller also maintained a standard timing program for normal watering which was used to water the control zone. No daily watering restrictions were in place from the local watering authority; thus a daily watering program was used. The amount of water applied to the control zone was based on recommended watering patterns from [dG09]. The recommendations are based on the estimated demand using historical data. The depth of water applied to the control zone took into consideration its actual efficiency. The adaptive irrigation algorithm parameters of  $\theta_{FC}$  and  $\theta_{PWP}$  were determined as recommended by the British Columbia Ministry of Agriculture, Food and Fisheries<sup>10</sup>. The system recorded watering information, soil moisture, and flow data for each zone. Results for water usage and soil moisture were stored in the controller using the on board memory. Growing data was collected from July 10, 2009 to September 1, 2009 during the hottest summer months. Data was collected, comparing the water consumption of a conventional zone using a recommended watering program versus water consumption from the adaptive watering program. Total applied water for each zone was tracked. During the shoulder season, which extended from the end of the trial period to October 15, the system continued to operate. During the test period, the depth of water applied as determined by the adaptive program was compared to the actual measured ET demand at the agricultural weather reporting station.

The quality of the turf was graded using the subjective National Turfgrass Evaluation Procedure [NTE98] which considers both functional and aesthetic qualities and rates the turfgrass on a scale of 1 (worst) to 9 (best) with a rating of 5 being considered suitable quality [HDM07].

## 4.2 Results

The adaptive watering program delivered 54% less water with no noticeable effect on visual appearance within and between the test plots during the test period. The adaptive system delivered a total depth of 0.324 m of water whereas the control zone delivered a total depth of 0.719 m of water. The cumulative depths of applied water for the adaptive and control programs are in Figure 4.5. The adaptive irrigation controller watered a total of 13

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<sup>10</sup><http://www.agf.gov.bc.ca/resmgmt/publist/600Series/619000-1.pdf>

## 4.2. Results

days during the two month period. The estimated evaporative loss was calculated by multiplying the number of watering events by a fixed loss of 0.005 m per irrigation event. The results are summarized in Table 4.1.

Table 4.1: Adaptive Watering Program Results.

	Adaptive	Control
Total Volume (litres)	2915.4	6471.6
Total depth (meters)	0.324	0.719
Est. Evap. loss (meters)	0.065	0.265
Eff. Daily Avg. (meters)	0.00498	0.00873

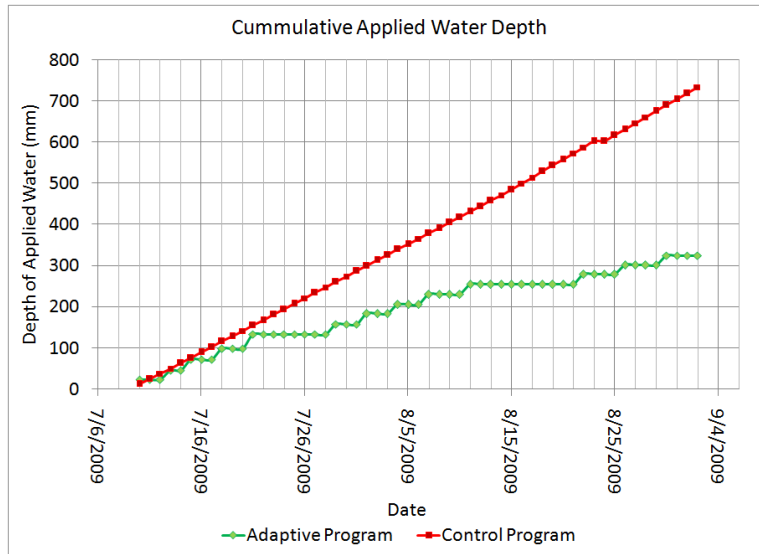


Figure 4.5: Cumulative Water Depths for Adaptive and Control Programs.

During the summer test period, the actual ET demand was 0.254 m of water<sup>11</sup>. The adaptive watering program delivered an effective depth of 0.2589 m of water; a difference of only 2% which can be considered to be statistically insignificant due to micro-climate variations between the test site and the weather reporting station. During the shoulder season, the daily average ET decreased to 2.7 mm per day from an average of 4.7 mm per day during the growing period. Figure 4.6 shows how the adaptive

<sup>11</sup>Actual ET demand at the Farmwest Belgo recording station

### 4.3. Discussion

irrigation controller automatically adjusted its watering patterns (frequency of events) to address the change in ET. No discernible difference in turfgrass quality was noticed between the control and test plots, with both being of high quality (7 to 8) based on the National Turfgrass Evaluation Procedure.

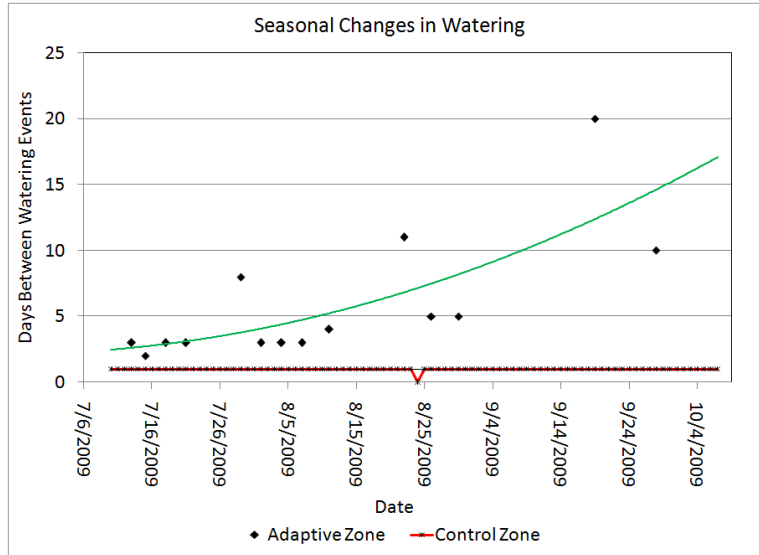


Figure 4.6: Number of Days Between Watering Events for the Control and Adaptive Irrigation Zones.

### 4.3 Discussion

The adaptive irrigation controller contributed to water savings by only watering a total of 13 days during the two month period (growing season). This schedule effectively reduced losses through evaporation. As growing conditions changed at the end of the season, Figure 4.7 shows how ET demand also decreases. Also shown is the total ET for the season in addition to the running total for water applied by the adaptive irrigation program. On average for the entire test period, the total depth of water applied follows the general trend of cumulative ET until the end of the growing season (start of September).

In response to decreased water demand from the crop due to changes in ET, the adaptive irrigation controller responded by watering less frequently.

#### 4.4. Conclusion of Experimental Program

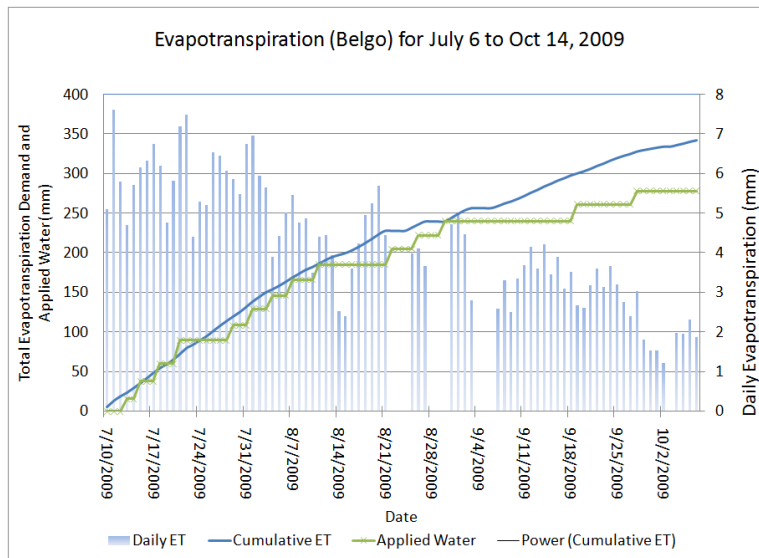


Figure 4.7: Recorded Evapotranspiration During Growing Season.

Figure 4.6 shows the trend in days between watering events for both the control and adaptive irrigation zones. The control zone continues to water every day regardless of the decrease in ET. The adaptive zone responded to changes in ET by watering less frequently.

Of particular note is how the adaptive program responded to rainfall events. Figure 4.8 shows how the soil moisture and watering events are affected by unscheduled additions of water through rainfall. It can be seen that after a rainfall event, watering events did not take place for several days as the turfgrass was able to extract existing water from the soil.

#### 4.4 Conclusion of Experimental Program

Figure 4.9 shows the changes in soil moisture levels for both zones during the course of the experiment. The adaptive irrigation program operated in an efficient fashion. With no unexpected additions of water from precipitation, the system routinely delivered the required amount of water to bring the soil to the target water content.

During the shoulder season, the adaptive irrigation program demonstrated improvements over conventional controllers. It responded to changes in ET while the control program over-watered. This re-enforces the need



#### 4.4. Conclusion of Experimental Program

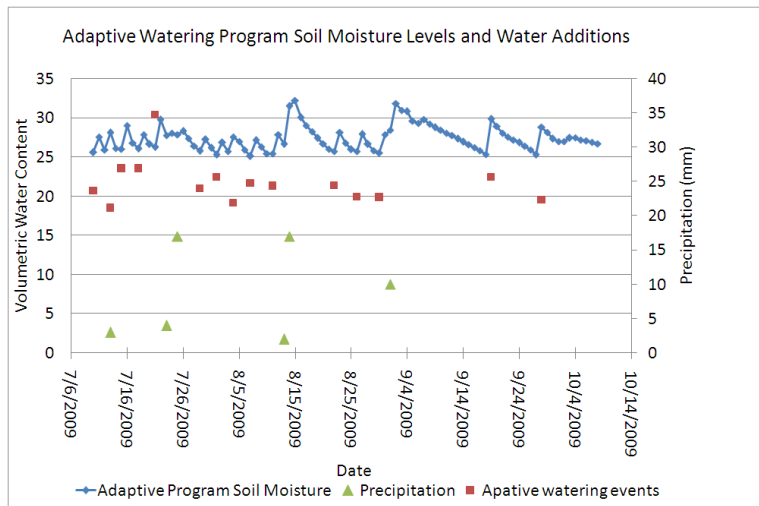


Figure 4.8: Water Additions for Adaptive Watering Program.

for users to be aware of changes in growing conditions in an effort to reduce water consumption. If a user was to continue with an unmodified daily watering program as used as a comparison in the experiment, the system would deliver an additional 0.546 meters of water into the soil profile. The adaptive controller only delivered 0.047 meters of water during the same time period. This amount is less than the total ET demand during the same period. As a result of the decreased ET demand, the changes in soil moisture over time in the adaptive control zone decreases. The crop requires less water from soil storage. As zone 1 continues to water unchanged, the water levels remains above field capacity leading to waste water moving to deep drainage.

The hypothesis is supported by the fact that the system delivered less water than the control program over the test period. Moreover, in comparison to ET modelling, it delivered the correct amount of water required by the turfgrass without the need for the ET infrastructure.

#### 4.4. Conclusion of Experimental Program

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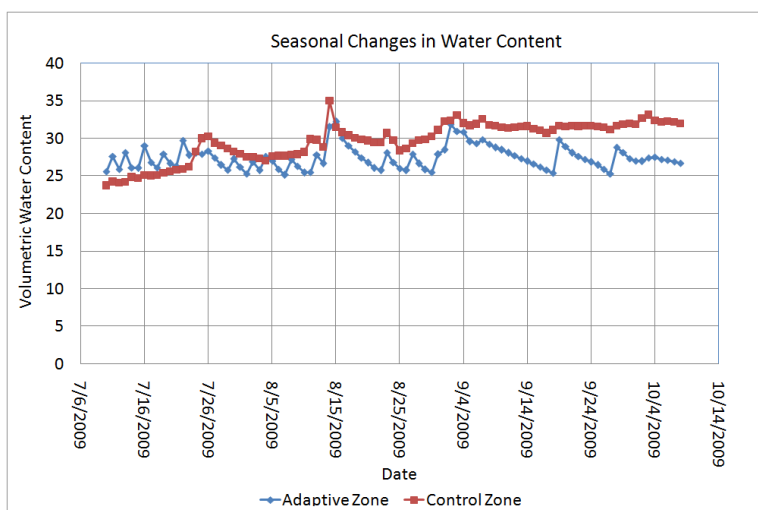


Figure 4.9: Seasonal Changes in Soil Moisture.

## Chapter 5

# Discussion and Conclusion

The scientist is not a person who gives the right answers, he is one who asks the right questions.

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Claude Lévi-Strauss (1908-2009)

This thesis began by providing a general background on soil water (Section 2.1) and the two unique characteristics used to describe the state of water in the soil matrix. Soil water can be expressed by volume as water content or by energy level as matric suction. The relationship between water content and matric suction is described using a soil water characteristic curve. Each soil has a unique soil water characteristic curve on which values for field capacity and permanent wilting point can be expressed. Understanding the field capacity and permanent wilting point for a soil are valuable for determining irrigation requirements and can be used to determine the amount of water that is available in the soil matrix for plants. Although they can be easily measured with commercial sensing technology (Section 2.2), current watering systems do not consider these parameters when watering and fail to offer users low cost and easy to use solution.

Section 2.3 presents an overview of existing commercial and research irrigation controllers. Many controllers are available but generally offer no dynamic control. More costly controllers may offer by-pass functionality using soils moisture sensors or rain sensors but generally rely on preset irrigation schedules. Other systems utilize subscription data to estimate water demand. Research systems present the use of wireless sensor technologies to monitor soil moisture in terms of  $\theta$  and  $\psi$  but offer no closed loop irrigation strategies where watering decisions are dynamically based on sensor readings. Irrigation decisions must still be made by the user. Three irrigation strategies commonly used in agriculture are presented (Section 2.4). Manual water budgeting, ET demand, and deficit irrigation all present the opportunity for increased water savings, but are complex in nature and require ongoing user intervention rendering them impractical for the naive user. They also require access to environmental and crop information that

may not be practically available. The technology presented in this thesis addresses both of these concerns. This work presents a system that significantly reduces potential water waste through closed loop control without the need for user interaction.

As current platforms and software offerings were not suitable, the adaptive irrigation controller and algorithms (Section 3) were built using custom designed wireless sensor nodes, flow meters and dielectric soil moisture sensors. The custom built node, specifically for use in environmental applications, monitors soil moisture and communicates the results to a central controller using the IEEE 802.15.4 protocol. The novel use of wireless sensors in this system significantly reduces the difficulty and cost of installation. The cost of the constructed system is significantly less than commercial controllers that contain less functionality. The controller uses an adaptive irrigation algorithm to track moisture levels in the soil and determines when and how long to water. Application efficiency and flow are tracked and used to adjust watering patterns without user intervention. The system also utilizes a penalty function to handle unscheduled additions of water.

Empirical results (Section 4) show that the adaptive irrigation strategy can lead to improved watering habits over a preset periodic function which is typically used by most residential users. This comparison assumes a worst case user that does not adjust their program to address seasonal or daily changes. For a more accurate comparison, the total depth of water applied by the adaptive irrigation controller was compared to the actual ET demand. It was found that the adaptive irrigation controller performed well, delivering only the amount of water required by the crop without user intervention. The system also successfully responded to daily changes in weather and never over watered. The system offered significant improvements over current systems during the shoulder season when ET levels decreased. Without continual user intervention, a typical system would deliver excess water. At the end of the season, the turfgrass was evaluated and found to be of good quality based on an industry standard evaluation.

Efficient residential water use is a key part of a responsible water management strategy. Water consumption can be significantly reduced in turfgrass irrigation by using soil moisture sensing technology. This work presents a novel approach to controlling turfgrass irrigation that can improve water consumption without the need for continual user input. It has been shown that a viable system can be constructed at a low cost that offers significant savings as the system delivers water amounts that correlate with actual plant ET. The ease of use due to the lack of programming, as well as the considerably lower cost compared to comparable products, makes this sys-

tem attractive for acceptance by residential users. The results of this work have been accepted for presentation and publication at IEEE Sensors Application Symposium (SAS2010) in Limerick, Ireland [FL10b]. Future work will examine the use of multiple sensors to manage large scale irrigation zones as well as examining the suitability of this system to measure other parameters in agricultural settings. Investigation will also be conducted on the use of multiple devices across heterogeneous soils. In conclusion, by using an adaptive irrigation strategy, significant water savings can be realized for the typical residential user.

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# Appendix A

## Water Content Sensors

The following section provides a more detailed explanation on the operation, usage, advantages and disadvantages for soil moisture sensors that are suitable for *in-situ* use.

### A.1 Neutron Probe Sensor Overview

Since the 1950s, neutron scattering has been widely used as a method of estimating volumetric water content. It gained wide acceptance as a technique that produces reliable results, is efficient [Hil98, ZX94] and is generally the best method for the measurement of water content [Str00]. Even though the use of neutron scattering produces good results, its practical use has decayed in industry due to health and regulatory issues [DGS08]. The method has many advantages over other methods. After initial installation, the device produces rapid and repeatable measurements without destruction of the sample.

Figure A.1 [MC04] shows a photo of a neutron probe installation. The neutron probe operates by emitting fast neutrons from a radioactive source that has been installed in the soil via a permanently installed access tube to the required depth. The device access tube can be installed so that the probe can be lowered to allow sampling near the surface to a depth of many meters [Str00]. The fast neutrons are slowed down or thermalized to slow neutrons by collisions with hydrogen atoms in the soil that are associated with water molecules. The water content of a given soil is proportional to the number of neutrons that are thermalized [ZX94] and can be calculated as

$$N_w/N_s = y\theta \tag{A.1}$$

where  $N_w$  is the slow neutron count rate from the sample soil,  $N_s$  is the count rate in water or a standard absorber, which is calibrated to include the absorption due to the mechanical components of the probe, and  $y$  is a constant of proportionality [Hil98, pp. 135-136]. This method presents numerous advantages as it can measure a large amount of soil volume as well





Figure A.1: Neutron Probe Placed in Soil. Reprinted from R. Muoz-Carpena, *Field Devices for Monitoring Soil Water Content*(Bulletin 343). Gainesville: University of Florida Institute of Food and Agricultural Sciences. Copyright (2004). Retrieved January 2010, from <http://edis.ifas.ufl.edu/ae266>.

as being able to scan and build a soil moisture profile from measurements over several depths.

The neutron probe consists of two separate units. The first component is the source of fast neutrons, commonly a radioactive source of americium-beryllium coupled with a detector for slow neutrons. The second component is a scaler or rate meter that records the rate at which the neutrons are scattered and attenuated [Str00, p. 168] [Hil98, p. 134]. In addition to the sensing unit, a bore hole must be drilled to accept the probe. Access tubes are required to be installed in the sampling bore hole to prevent the collapse of the bore hole, through which the probe is lowered.

The usable range of the neutron scattering device is  $0\% \geq \theta_v \geq 60\%$ . With soil specific calibration the accuracy of the device is  $\pm 0.5\%$ . The sensing volume of the device is a sphere surrounding the radioactive source of 15 to 40 cm [MC04] and varies with water content.

### A.1.1 Advantages

The neutron probe sensor can measure water in any phase. Unlike some other sensing technology, the measurement is directly related to the volumetric content of the water in the soil and is not significantly impacted by changes in temperature, pressure, and salinity. Additionally, as with most *in-situ* measurement techniques, the technique is non destructive and has a relatively fast responsive time between 1 to 2 minutes for coarse measurements. The time period can be extended in order to achieve better results. The technique is also suitable for automation and due to the method of installation, lends itself to profile measurement [Str00, p. 168] [ZX94] but is not practical for unattended monitoring due to the radioactive nature of the device.

### A.1.2 Disadvantages

While the neutron probe can produce good repeatable results, the cost and health risks associated with this method makes it impractical for most users [ZX94]. Transporting and procurement of the radioactive materials present significant safety issues due to radiation hazards [Str00, p. 174]. As with most sensing technologies, the probe must be calibrated to produce accurate results. Theoretical calibration can be done for a probe based on a detailed chemical analysis of the soil, specifically for elements in addition to hydrogen that may scatter neutrons; namely cadmium, boron and chlorine. For most applications this is impractical as the cost of such analysis is prohibitive and needs to be completed for each individual test hole. Laboratory calibration can be completed for the device using a soil sample from the target site. For this to be effective, an undisturbed soil core from the test site must be extracted. This core can weigh several tonnes as the test core is required to be at least 1.5 meters in diameter and 1.5 meters in depth. In practice, this is only useful with sand, gravels and silts [Str00, p. 171].

With this sensing technology, the volume of soil sampled around the probe depends on the design of the sampling apparatus. With the neutron probe, the sphere over which the device samples is dependent on the radioactive source, but typically presents a 15 cm sphere in wet soils and 30 cm in dry soils; this not only limits the resolution at which samples can be taken due to overlap in spheres, but limits how close a sample can be taken to the surface of the sample soil. Sampling within 20 cm of the surface can allow the neutron sampling sphere to extend into the atmosphere. This prevents the device from being used for requirements of sampling close to the surface,

such as would be required for shallow rooting crops. Additionally, sampling close to the surface presents a health risk due to potential human exposure to the neutron radiation [Str00, pp. 172-173].

## A.2 Gamma Ray Sensor

Gamma attenuation is a nuclear method that measures the adsorption of gamma rays by the water molecules present in a soil body. The method has been used in the field since the late 50's with commercial equipment, specifically a double-probe gamma ray device.

The device measures the water content of a soil between a radioactive source and detection unit over a fixed distance. As radiation passes through the soil body, the radiation will interact with the soil particles and form secondary radiation that is not related to the water content. The rays that pass directly through the soil are called primary rays and are the only rays of interest; secondary rays present unwanted noise to the system [Hil98, p. 138].

The intensity of radiation absorbed depends on the bulk density of the soil ( $D_b$ ) and the water content. Generally, it is assumed that the dry bulk density is fixed; thus, the intensity level only changes with water content. The water content as mass of water per unit volume of soil can be expressed as [Hil98, pp. 137-138]

$$\theta_m = -\frac{\ln\left(\frac{N_w}{N_d}\right)}{\mu_w x} \quad (\text{A.2})$$

where  $N_w/N_d$  is the count ratio comparing wet and dry soils that is measured by the detection system,  $\mu_w$  is the mass attenuation coefficient for water and  $x$  is the path length. The value of  $\theta_v$  can then be calculated from Equation (A.2).

The double-probe gamma attenuation sensor consists of two units; one being the source of gamma rays and the second being the detector. The two units are installed through parallel access ports drilled into the soil body of interest. The area that is measured is the volume between the two access ports. The source of gamma rays is typically Cesium-137. The detection unit contains a scintillation crystal, that illuminates when hit with gamma rays. The scintillation crystal is coupled to a photo multiplier tube and a pre-amplifier which converts the number of light pulses to electrical pulses. The signal is amplified to a level that can be measured with a scalar or other recording device. Additionally, coupled to the detection unit is a pulse height

analyzer which is used to discriminate the interactions between primary and secondary rays, thus removing unwanted noise [Hil98, p. 138].

In general, gamma attenuation offers improved spatial resolution over other methods and is suitable for *in-situ* testing as it is a non-destructive method but faces significant challenges when used for the determination of water content [Hil98, p.138].

### A.2.1 Advantages

Due to the geometry of the sensor, it has significantly improved resolution over neutron scattering. Spatial resolutions less than 2.5 cm in thickness is possible with response times of under 1 minute [ZX94]. This technology also has the ability to detect differences in water flow between different layers in the soil profile [Hil98, p. 138]. Due to the good spatial resolution, the device can also measure accurately near the surface. The device can be automated to record soil  $\theta_v$  as a function of depth, as well as having the ability to be left in the field for long term recording

### A.2.2 Disadvantages

Cost may make the sensor impractical for use. As gamma rays are also absorbed by the soil, changes in the soil bulk density in the soil profile can cause errors in measurement. This is partially due to the nature of the calculation of Equation (A.2) which requires a known count for dry soil. This value changes as  $D_b$  changes and this error source is amplified in highly stratified soils [ZX94]. Thus, soil and site specific calibration is required.

Improper installation of the device can present problems with accurate readings. Access tubes must be parallel to produce accurate readings as the distance between access tubes ( $x$ ) in Equation (A.2) is required to determine  $\theta_v$ . The actual distance between the access will change over the profile leading to errors in calculations if access tubes are not parallel. The device is also sensitive to changes in temperature, but this can be mitigated with proper field calibration [Hil98, p. 138].

As the device is a nuclear method, significant health risks are present due to the transportation and use of a radioactive substance and risk of human exposure. Special permits may be required to use and transport the device which further contributes to the cost associated with the device [SKM99, p. 94] and make it impractical for unattended operation.

### A.3 Time Domain Reflectometry Sensors

The TDR sensor consists of a pair of parallel metal rods that form a balanced transmission pair and are coupled to a signal receiver. The length and spacing of the rods is dependent on the measurement application [CG08, p. 941]. The rods are inserted into the soil where the rods act as waveguides for the electromagnetic pulse and the soil surrounding the rods forms the dielectric medium [Hil98, p. 140]. In addition to the receiver and parallel rods, the system includes a timing circuit, a pulse generator and recording device. Most commercial devices incorporate all components into a single unit [CG08, p. 941]. Alternate sensor designs are being presented in industry with three or more waveguides which may work to eliminate the need for a balanced transmission line [Str00, pp. 180-181].

To take a sample reading, a signal is generated with the signal generator and guided along the parallel rods, where the signal reflects off the end of the rods and returns to the signal receiver. The timing circuit measures the time interval between the transmission and reception of the signal. As shown by Topp and Davis [DD85], by knowing the length of the transmission rods and the time for the pulse return, the relative dielectric constant of the soil can be computed as:

$$\epsilon_r = (ct/2L)^2 \quad (\text{A.3})$$

where  $c$  is the speed of light,  $L$  is the length of the transmission rods, and  $t$  is the two way travel time of the pulse within the exposed waveguides. Topp *et al* [aJDA80] further related the volumetric water content of a soils to its dielectric constant as:

$$\theta_v = -5.3 \times 10^{-2} + 2.9 \times 10^{-2}\epsilon_r - 5.5 \times 10^{-4}\epsilon_r^2 + 4.3 \times 10^{-6}\epsilon_r^3 \quad (\text{A.4})$$

Within typical agricultural soils,  $\theta_v$  is only weakly dependent on soil type, bulk density, temperature and electrical conductivity of pore water [Hil98, p. 141]. The TDR method will fail at high soil water salinity levels (eg.  $> 8 \text{ dS/m}$ ) leading to incorrect readings.

From a technology perspective, the hardware to measure soil moisture with this technique is not specific to soil science. The most commonly used device is a Tektronix Model 1502 B or C portable cable tester which is readily available with a large existing knowledge base.

The pulse rise time transmitted through the waveguides is typically 200 picoseconds and during one sampling event, an average of 1000 readings is required to build up a moisture reading.

### A.3.1 Advantages

One of the principle advantages to TDR is that the measurement of water content is relatively independent of soil texture and temperature [ZX94], thus making the TDR probe a desirable technology for measurement in various soil bodies.

For most environmental and soil applications, TDR can provide suitably accurate results without the need for calibration. For uncalibrated soils, accuracy can be within  $\pm 2$  %; with calibration for specific soils, accuracy can be further improved. The design and placement of probes can be modified by the user without impacting the results allowing for any site specific requirements [CG08, p. 940].

### A.3.2 Disadvantages

The largest disadvantage to TDR is the cost of the equipment [ZX94] as a single unit can cost thousands of dollars, this technology may not be practical for budget conscious projects that are dealing with large scale deployment. Additionally, while the TDR is suitable for automated data collection, leaving equipment in the field for extended unattended periods is undesirable due to the potential loss in capital equipment due to theft or environmental degradation.

As the soil moisture reading is affected by the volume of soil between the waveguides, a potential source of error can arise from air gaps in the zone of influence. Air gaps may occur as soil shrinks upon drying during the period of installation, leading to inconsistent measurements [Hil98, p. 141]. Another disadvantage of TDR is the sample measurement time. The measurement time for some TDR devices has been purported to be in the order of 28 seconds [ZX94]. If measurements in response to rapid changes in soil moisture are required, the device will not be able to sample at the correct speed leading to a loss of data. Finally, the TDR method is not recommended for use in organic soils, high salt content soils, or soils high in clay [MC04] as the signal quality becomes increasingly uninterpretable.

## A.4 Other Dielectric Sensors

Regardless of the method of measurement, the general dielectric probe consists of two or more electrodes surrounded by soil and support electronics. This soil cell forms part of an electric circuit, in which the content of water in the soils affects the dielectric constant for the cell. Depending on the

method of measurement, the function of the soil cell is different and will be discussed in subsequent sections. Regardless of the design, all groups generally suffer from the same issues in implementation.

Depending on the manufacturer of specific probes, devices may include a display device to allow the operator to read and record the soil moisture. Others may not include a read out device, but can be interfaced to a data logging device.

### Capacitive Probes

For a strictly capacitive probe, the soil cell formed with the probes is coupled to an inductor ( $L$ ), forming a tuned circuit. The circuit has a characteristic ringing frequency that is dependent on the choice of  $L$ , the value of inductance, and  $C$ , the capacitive value of the soil [CG08, p. 953]. The capacitance of the soil is dependent on the configuration of the probe as well as  $\epsilon$ , which is determined in part by the amount of water in the soil sample. The capacitance of a cell is expressed as

$$C = g_2 \epsilon_{ra} \tag{A.5}$$

where  $\epsilon_{ra}$  is the dielectric constant for the given soil and  $g_2$  is a calculated geometrical constant for the cell [SP02]. In the construction of the probe, as the dielectric ranges are known for soils over a given water content, the value of the inductor is chosen such that the ringing frequency will be between 100 and 150 Mhz. Over this range the effects from dissolved ions in the soil is minimized. The resonant frequency can be expressed as a function of water content as [CG08, p. 953]

$$f(\theta_v) = \frac{1}{2\pi\sqrt{LC}} \tag{A.6}$$

By combining Equation (A.5) and Equation (A.6), a direct relationship between the dielectric constant of the soil under question and the frequency can be developed as [RGE<sup>+</sup>98]

$$f(\theta_v) = \frac{1}{2\pi\sqrt{Lg_2\sqrt{\epsilon_{ra}}}} = \frac{g_3}{\sqrt{\epsilon_{ra}}} \tag{A.7}$$

where  $g_3$  combines all design factors [CG08, p. 953]. In order to relate the frequency to water content, the sensor must be calibrated for a given soil type. A linear relation can be derived from Equation (A.7) making it relatively straight forward to evaluate [CG08, p. 953].

### Frequency Domain Reflectometer

The construction and theory of operation of the FDR is very similar to the capacitive probe. The primary difference between the two designs, is that unlike the capacitive device that is allowed to stabilize to its natural resonant frequency, the FDR uses an oscillator to sweep over a given frequency range. The supporting electronics look for the frequency with the greatest amplitude which is the resonant frequency for the soil. This frequency is then related to water content as done previously [MC04].

### Amplitude Domain Reflectometer

The amplitude domain reflectometer (ADR) is very similar in design to FDR and TDR methods. The probe has a similar design consisting of parallel rods that act as waveguides that are inserted into the soil of interest. The device transmits a sinusoidal electromagnetic wave along the waveguide. When the electromagnetic wave encounters a change in impedance, which is in part caused by a change in  $\epsilon$  due to the presence of water in soil, part of the wave is reflected back along the waveguide. The reflected wave and transmitted wave interact forming a standing wave of which the amplitude is measured [MC04]. The amplitude of the standing wave can be directly related to the impedance of the soil [MISN98, GM96]. The measured impedance,  $Z$ , is inversely related to  $\epsilon$ , the dielectric of the soil, as [GM96]

$$Z = \frac{60}{\sqrt{\epsilon}} \ln \left( \frac{r_2}{r_1} \right) \quad (\text{A.8})$$

where  $r_1, r_2$  are geometrical parameters for the probe. A photo of an ADR probe is seen in Figure A.2 [MC04].

### Phase Transmission

The phase transmission (PT) sensor consists of two waveguide electrodes formed into two concentric circles, such that each end of the electrodes can be interfaced to the sensor electronics. The sensor transmits a fixed frequency sinusoidal electromagnetic wave along the waveguides. As the wave traverses the sensor, the velocity of propagation of the wave may be slowed due to moisture in the soil surrounding the waveguides. This change in velocity causes a phase shift in the wave which can be measured at the end of the waveguides and compared to the original wave injected into the system. The degree of phase shift can be directly related to  $\theta_v$  [MC04]. A photo of a PT probe is seen in Figure A.3 [MC04].



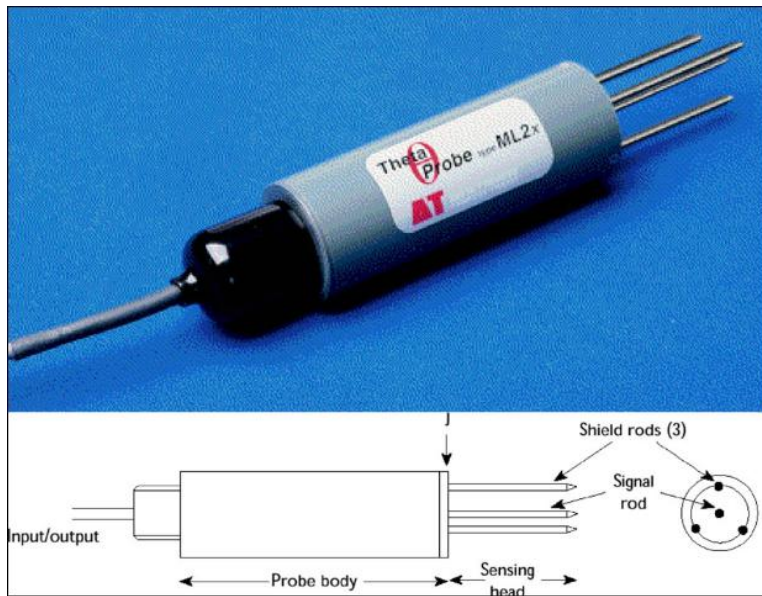


Figure A.2: ADR Probe. Reprinted from R. Muoz-Carpena, Field Devices for Monitoring Soil Water Content(Bulletin 343). Gainesville: University of Florida Institute of Food and Agricultural Sciences. Copyright (2004). Retrieved January 2010, from <http://edis.ifas.ufl.edu/ae266>.

### Time Domain Transmission

Of all dielectric methods, the time domain transmission (TDT) sensor is the most similar to TDR. As with TDR, the transmission waveguides form an open circuit in the soil; with TDT, the waveguides are electrically connected at both ends, similar in fashion to the electrode design of a PT sensor. The sensor measures the time for a one way electromagnetic pulse to travel along the length of the waveguide [MC04]. The determination of  $\theta_v$  with respect to  $\epsilon$  are as given in Equations (A.3) and (A.4). TDT also has the same soil restrictions encountered with TDR, in terms of use. A photo of a TDT is seen in Figure A.4 [MC04].

#### A.4.1 Advantages

Dielectric sensors relatively easy to calibrate and calibration may not be required if soil bulk electrical conductivity is  $< 0.02$  S/m [CG08, p. 955]. Devices will generally be accurate to  $\pm 1\%$ . For applications where only a relative change of soil moisture is required, these devices are suitable as the



Figure A.3: Phase Transmission Probe. Reprinted from R. Muoz-Carpena, Field Devices for Monitoring Soil Water Content(Bulletin 343). Gainesville: University of Florida Institute of Food and Agricultural Sciences. Copyright (2004). Retrieved January 2010, from <http://edis.ifas.ufl.edu/ae266>.

output of the sensor can be linearized from Equation (A.7); thus a relative change in  $\theta_v$  will correspond to a linear change in the output voltage of the sensor. Accuracy for ADR without calibration is noted to be  $\pm 5\%$ , in addition to being less sensitive to temperature variation when compared to the other dielectric methods. It is also noted as being the least invasive sensor in terms of soil disturbance due to the waveguide design [MC04].

Of the dielectric sensors, the capacitive, FDR and ADR sensors may work in highly saline soils where other techniques such as TDR will not [MC04]. One of the unique attributes of PT and TDT compared to the other sensors, is that some commercial probes can measure a significant volume of soil due to the configuration of the waveguides.

#### A.4.2 Disadvantages

For the dielectric methods of PT and TDT that are strongly related to TDR, the author [MC04] notes the following problems with TDT and PT. When attempting to measure soil moisture levels in soils with high saline levels,

#### A.4. Other Dielectric Sensors

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Figure A.4: Time Domain Transmission Probe. Reprinted from R. Muoz-Carpena, Field Devices for Monitoring Soil Water Content(Bulletin 343). Gainesville: University of Florida Institute of Food and Agricultural Sciences. Copyright (2004). Retrieved January 2010, from <http://edis.ifas.ufl.edu/ae266>.

PT will be sensitive to saline levels above 3 dS/m. Additional problems are also noted with PT and TDT over the other dielectric methods in regards to *in-situ* installation. As the size of the sensing volume is significantly larger than with other methods, soils may be heavily disturbed during installation leading to the need for the devices to be permanently installed at a given location. Additionally, both PT and TDT experience decreased precision due to deformation of the pulse as it travels the length of the waveguide. TDT also has restrictions similar to TDR with respect to the types of soils in which it can be used.

## Appendix B

# Water Potential Sensors

The following section provides a more detailed explanation on the operation, usage, advantages and disadvantages for water potential sensors that are suitable for *in-situ* use.

### B.1 Thermocouple Psychrometer Sensor

The thermocouple psychrometer sensor consists of a small porous cup, typically 1 cm in length and width. The cup is commonly manufactured out of brass, stainless steel or ceramic such that it will allow for water vapour to pass through its surface. This will allow the vapour pressure of the water inside the cup to be in equilibrium with the vapour pressure of water outside the cup. The cup typically is closed with a Teflon plug. The sensor wires pass through the plug. The actual sensing surface is comprised of a thermocouple junction of two fine dissimilar metal wires such as chromel and constantan, in combination with a reference junction that is typically made of copper [CG08, p. 974].

The materials used to form the thermocouple junction demonstrate two unique properties that enable this sensor to work. First, if a temperature gradient is applied across the junction, a voltage potential is created across the junction. Secondly, if a voltage gradient is applied across the junction, a temperature gradient is produced across the junction; the direction of current flow through the junction dictates the direction of heating. This will cause one side of the junction to heat, while the other side will cool. This is called the Peltier Effect, with the junction being referred to as a Peltier junction. Exploiting this effect allows for the measurement of the energy potential of the water vapour [Hil98, p. 165]. Using this principle, two different styles of thermocouple psychrometers are commonly used to measure  $\psi_m$ .

### Peltier Psychrometers

Using the configuration described previously, a single measurement can be taken by placing a voltage across the Peltier junction such that the temperature of the sensor starts to decrease. The rate of cooling of the junction is monitored, looking for the dew point of the air in the sensor. As the temperature passes through the dew point, water will condense on the junction surface which changes the rate of cooling due to the thermal capacity of the water on the junction surface. The temperature decrease can be read as a voltage across the junction and is typically  $0.5 \mu\text{V MPa}^{-1}$  [Car93, p. 564]. By comparing the dew point temperature to the temperature of the reference junction, which measures the temperature of the surrounding soil and porous cup, the relative humidity can be calculated. Using Equation (2.2), the energy status of the soil with respect to water can be calculated [SKM99, p. 92]. A similar technique can be employed without use of the reference junction, where the junction is cooled to the dew point. With this method, the Peltier junction's output is placed through an amplifier such that the potential across the junction can be measured. By measuring the temperature change across the junction with respect to time, the rate of evaporation can be determined which directly correlates to the vapour pressure of water in the soil air. The measured evaporation rate is then compared against a calibration curve of vapour pressures and known water potentials [Boy95, pp. 59-60].

### Dew Point Hygrometers

Many thermocouple psychrometers have the ability to provide a continuous water potential status by operating in a fashion referred to as a dew point hygrometer [NT72]. With this method, the Peltier junction is cooled to the dew point of the air such that water condenses on the junction. As water condenses on the junction, the thermal mass increases and the rate of cooling changes. The system responds by increasing the drive to the Peltier junction through a series of pulses to keep the junction at the dew point. The measured dew point is then compared against a calibration curve to determine  $\psi_m$  [Boy95, p. 59]. In this mode of operation, the device typically has a larger output signal sensitivity of  $0.75 \mu\text{V MPa}^{-1}$ , which represents a 50% increase in signal sensitivity.

### B.1.1 Advantages

Thermocouple psychrometers have numerous advantages that complement the other technologies for measuring  $\psi_m$ . Both methods have good sensitivity, typically in the range of 50 kPa, which is useful for soils with high matric potentials where the tensiometer will not function [Hil98, p. 166]. The readings are also considered to be scientifically rigorous and have a very wide operating range of 50 kPa to -10,000 kPa [BW04, p. 145]. It should be noted that this method performs best at levels below -200 kPa. This makes the sensor ideal for measuring potential in dry soils. Additionally, the sensor is suitable for automation [MC04].

### B.1.2 Disadvantages

From an implementation and use perspective, the thermocouple psychrometer presents some significant issues for a user that is unaware of the challenges associated with this technique. The sensor itself is exceptionally sensitive to temperature gradients, both in the sensor cup and the wire leads from the sensor itself. Wires must be protected from thermal gradients as this can lead to skewed readings. Further, the sensor itself can not be used reliably in the upper 15 to 30 cm of a soil profile due to large thermal gradients that may exist in this area. This problem arises from thermal gradients being present between the reference and sensing junction; a difference of 0.001 °C translates to an error of 10 kPa. Newer designs utilizing materials with high thermal conductivities have reduced measurement errors due to thermal gradients [CG08, p. 975]. Carter [CG08, p. 975] argues that devices operating in the dew point mode of operation may be less susceptible to ambient temperatures changes whereas Boyer [Boy95, p. 59] argues that the device calibration is still susceptible to changes in ambient temperatures. Regardless of this, while thermal gradients may present a problem with sampling, standard practices are well documented for placement of *in-situ* devices to minimize the effects of thermal gradients [CG08, p. 976].

Carter [CG08, p. 976] notes that of all devices used to measure water potential, the thermocouple psychrometer is the device most susceptible to failure and damage due to lack of proper maintenance in addition to improper use and has identified the following issues. The sensing junction and porous cup are very sensitive to effects from corrosion, contamination with salts, and infiltration of fungi. Contamination of the porous cup can lead to slowing of the response time due to a delay in the equilibrium condition. Further, this effect may invalidate the calibration of the device due to exis-

tence of non-uniform vapour concentrations. Contamination on the sensing junction may further lead to inconsistent evaporation of liquids, contributing to errors in the dew point calculation. The junction is also susceptible to corrosion by dissolved salts, especially in saline and sodic soils. This issue should not deter use of the sensor as they can be properly managed with regular routine maintenance, but may present problems for long term *in-situ* use [CG08, p. 976].

These issues can be managed by implementing routine maintenance procedures that focus on cleaning the porous cup surrounding the sensor in addition to removing any accumulated salts and debris that may have built up on the thermocouple junction. Unfortunately, the maintenance procedure for the device can take many hours and can not be reasonably completed in the field. The cleaning procedure involves soaking the sensor for many hours in water or using multiple washes with various solvents to remove any contaminants, followed by an extensive drying cycle. In an effort to deal with some of the contamination issues, manufacturers offer sensors made from different materials ranging from brass to stainless steel. While the stainless steel sensor cup has a higher cost, it presents significantly reduced maintenance needs due to the ability of stainless steel to resist corrosion. While significantly lower in cost, sensor cups made from brass present considerably higher maintenance requirements [CG08, p. 976]. Use of this sensor and choice of components should involve a cost-benefit analysis if being considered for large scale deployment.

## B.2 Electrical Resistance Block Sensors

Two different types of electrical resistance block sensors are commonly used for *in-situ* use; the Gypsum Electrical Resistance Block and the Granular Matrix sensor.

### Gypsum Resistance Blocks

The sensor consists of two components; the sensing block containing two electrodes embedded within the block and a device to excite the electrodes and read the potential. The water in the block saturates with respect to gypsum and has a constant conductivity. The bulk electrical conductivity of the block is determined by placing an alternating current across the electrodes. Knowing that the water conductivity is constant, the bulk conductivity can be related to the water content in the block. A calibration curve is produced for the resistance of each block with respect to  $\psi_m$  for

## B.2. Electrical Resistance Block Sensors

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each soil under investigation [ZX94]. The trend for electrical resistance blocks is that the conductance is normally zero when dry and increases as the block wets [CG08, p. 972]. A photo of a gypsum resistance block is seen in Figure B.1 [MC04].

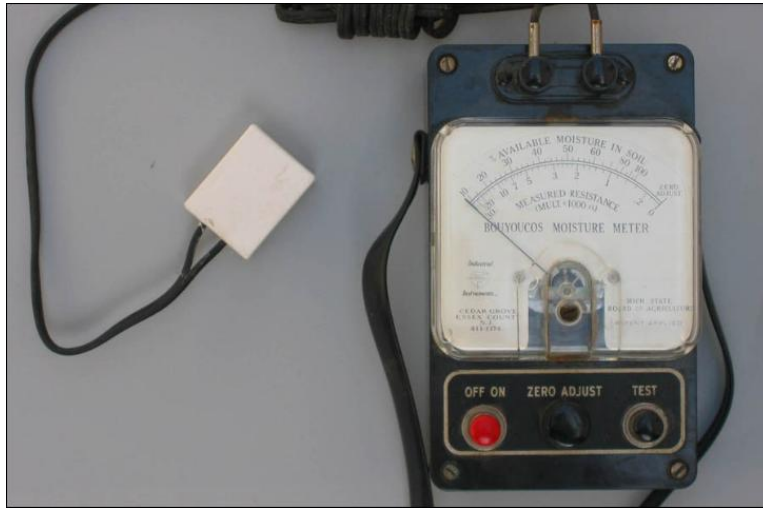


Figure B.1: Gypsum Resistance Block. Reprinted from R. Muoz-Carpena, *Field Devices for Monitoring Soil Water Content*(Bulletin 343). Gainesville: University of Florida Institute of Food and Agricultural Sciences. Copyright (2004). Retrieved January 2010, from <http://edis.ifas.ufl.edu/ae266>.

### Granular Matrix Sensor

The sensor is very similar in operation to the gypsum resistance block but offers some field life improvements. The principles of operation are the same as with the basic sensor but measurements are made through electrodes embedded in a granular quartz matrix which is surrounded by a synthetic membrane encased inside a stainless steel sleeve. A small amount of gypsum is also included inside the sensor to help buffer against saliently effects and maintain constant soil water conductivity [MC04]. A photo of a granular matrix sensor is seen in Figure B.2 [MC04].

#### B.2.1 Advantages

The major advantage to the electrical resistance block is the cost of the sensor itself [ZX94]. As it is a very low cost sensor, it is possible to place



## B.2. Electrical Resistance Block Sensors



Figure B.2: Watermark Granular Matrix Sensor. Reprinted from R. Muoz-Carpena, Field Devices for Monitoring Soil Water Content (Bulletin 343). Gainesville: University of Florida Institute of Food and Agricultural Sciences. Copyright (2004). Retrieved January 2010, from <http://edis.ifas.ufl.edu/ae266>.

numerous devices throughout an area of interest, allowing for a cost effective, large scale deployment that does not require maintenance on a regular basis. Various materials are readily available from a large selection of suppliers and are easily attached to data loggers for automated recording. Devices can be programmed to read out direct water potential readings [CG08, p. 973]. Additionally, devices also can operate in saline soils up to 6 dS/m.

Gypsum resistance blocks are able to read over a wide range of available soil water and are generally used from  $-100 \text{ kPa} \geq \psi_m \geq -1500 \text{ kPa}$  [BW04, p. 145]. The GMS sensor offers a slightly improved range from  $-30 \text{ kPa} \geq \psi_m \geq -2000 \text{ kPa}$  which may make it suitable for regulated-deficit irrigation in addition to having an improved in-situ lifespan over the gypsum resistance block [MC04].

### B.2.2 Disadvantages

Unfortunately, the disadvantages for the electrical resistance methods largely outweigh the advantages to the device. Both devices generally have poor resolution, making them impractical for use in research applications [MC04]. *In-situ* use may be hampered due to degeneration of blocks made from gypsum leading to frequent replacement. Calibration is a challenge with this type of device as well; each individual block requires a unique profile to be developed for each specific soil being measured [CG08, p. 973] [SB92]. Due to the degradation of the blocks with time, standard practice dictates that the devices should be re-calibrated every three months in addition to limiting the lifespan of the device [CG08, p. 973] [Phe98]. Degradation is due to clay deposition and gypsum dissolution within the sensor. The lifespan is strongly influenced by soil type and water infiltration rates for the given application. Gypsum electrical resistance sensors are generally not well suited for sandy or coarse soils, and soils containing 2:1 clays. The GMS offers some improvement against this problem over the gypsum resistance block through an improved resistance against clay deposition and gypsum dissolution [MC04].

From a measurement perspective, the devices experience significant hysteresis, in addition to having a non-linear response to changes in  $\psi_m$  with respect to time [MKW92]. This possibly increases the difficulty of use in the field for quick measurements as a device transfer curve is required to convert the voltage measured to  $\psi_m$ . Additional challenges are introduced with the device when replacement is required in the field. A new device cannot just simply be installed, but must be first primed; that is the electrical resistance block must be pre-soaked in a slurry made from the target soil for 24 hours [CG08, p. 973]. The device has a very slow response time of up to 2 to 3 hours before a reading stabilizes or reflects the change of water energy state in the soil surrounding the sensor for a single measurement [ZX94]. The device also has a degree of temperature sensitivity that contributes to a decrease in accuracy [SDM07]; this can be compensated for by measuring the temperature of the sensing device during sampling [MC04]. The GMS type compared to the gypsum electrical resistance sensor, exhibits additional in-situ problems. Unlike the gypsum resistance block sensor, if the GMS is allowed to dry it will not recover as the soil re-wets. In order for the device to recover, it must be removed and re-saturated in a slurry made from the target soil before being reinstalled [MC04].

## B.3 Tensiometer Sensor Overview

The design of a tensiometer is straightforward, consisting of a porous cup which is typically made from ceramic or porous metal attached to a hollow tube filled with de-aired water. Also attached to the tube is a manometer, suction gauge, or pressure transducer which records the suction potential [CG08, p. 969]. In normal operation, the porous cup is saturated with water and placed in contact with the soil that is to be measured. De-aired water is placed in the device which is at atmospheric pressure. When the cup comes into hydraulic contact with the soil, water will migrate through the porous cup such that the suction potential will equilibrate as it draws out water from the device, creating a negative pressure potential. This pressure potential can then be read on the manometer or via the pressure transducer.

The porous cup is permeable to both water and solutes such that the solutes in the soil freely diffuse into the cup so that the water in the device and the soil water have the same concentration of solutes. This allows the device to be insensitive to osmotic pressure  $\psi_\pi$  [Hil98, pp. 162-163] [CG08, p. 969].

### B.3.1 Advantages

The tensiometer works well in the saturated range of soils over the range of  $0 \text{ kPa} \geq \psi_m \geq -80 \text{ kPa}$ . It is well suited for automation as the transducer can be coupled to a data logger and can operate over a long period of time with proper maintenance. The tensiometer can also work with fluids other than water, such as ethylene glycol, making them useful for measurements in frozen soils [ZX94].

### B.3.2 Disadvantages

The response time of tensiometers can be quite slow compared to other technologies. As the vacuum increases in the device, air bubbles are drawn out of the fluid in the tube or from the porous cup [Str00, p. 190]. This can lead to slowing of the tensiometer response due to the increased compressibility of the fluid. The response time of the device to changes in  $\psi_m$  can be in the order of 2 to 3 hours. The device is also sensitive to placement and installation; if the device is forced into a soil or against rocks, the porous cup can be damaged rendering the device useless. Additionally, if the soil around the measurement point on the surface is disturbed, it may present an infiltration pathway around the tube to the porous cup allowing water to

infiltrate down to the sensing surface during irrigation or rain fall events. If this is the case, the device will read erroneously [ZX94]. Erroneous reading can also be caused by lack of maintenance of the sensing device; progressive vaporization will eventually empty the device of water leading to the eventual failure of the device [CG08, pp. 969-970]. Another source of erroneous readings can be attributed to temperature gradients developing in the device between various parts. This effect can be nullified if the device is properly shaded from direct sunlight [Hil98, p. 163].

## B.4 Heat Dissipation Sensor Overview

The sensing device consists of a heating device and a thermal sensor embedded in a porous ceramic block which is placed in direct contact with the soil of interest. To determine  $\psi_m$  for a given soil, the temperature of the block in the soil is taken and then a heating pulse is applied to the block. The temperature is then measured at some fixed time interval. The measured change in temperature of the block is proportional to  $\theta_v$ . A calibration of  $\theta_v$  and  $\psi_m$  for a given device allows  $\psi_m$  to be measured as a function of thermal conductivity [Hil98, p. 166]. The sensing device must be placed in direct contact with the soil and allowed to come into thermal equilibrium with the soil before taking any measurement [MC04].

### B.4.1 Advantages

The device is also well suited to work in all soil types as it is not affected by ionic concentrations due to its principle of operation; thermal conductivity of a soil is not related to the salinity. With specialized electronics included with the sensor or coupled to a datalogger that can control the sensor, it is well suited for *in-situ* application as no maintenance is required for the device. The device can also be used to collect data in a continuous fashion.

### B.4.2 Disadvantages

The heat dissipation sensor may not function correctly in soils with large hydraulic conductivities such as sand or coarse soils. This is due to the slow reaction time of the sensor coming into thermal equilibrium with the surrounding soil; for some soils, water may drain faster than the equilibrium conditions with the sensor can be reestablished. This will cause erroneous readings [MC04] as the value of  $\psi_m$  being measured is not correct. From an operations perspective, the heat dissipation sensor will only be useful with

#### *B.4. Heat Dissipation Sensor Overview*

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careful calibration and may suffer from hysteresis [Hil98, p. 166]. Additionally, unlike other devices that have an absolute error, the heat dissipation sensor's error is a percentage of the total reading; larger readings will have larger errors, thus making the device unfavorable for values of  $\psi_m \leq -1000$  kPa.