EC783
(Revised February 2016)

Principles and Operational Characteristics of Watermark Granular Matrix Sensor to Measure Soil Water Status and Its Practical Applications for Irrigation Management in Various Soil Textures

Suat Irmak, Soil and Water Resources and Irrigation Engineer, Professor
Jose O. Payero, Irrigation Specialist, Clemson University, South Carolina
Brandy VanDeWalle, Extension Educator, Fillmore County
Jenny Rees, Extension Educator, Clay County
Gary Zoubek, Extension Educator, York County
Derrel L. Martin, Irrigation Specialist, Professor
William L. Kranz, Irrigation Specialist, Professor
Dean E. Eisenhauer, Professor
Dan Leininger, Water Conservationist, Upper Big Blue Natural Resource District

Technology implementation in agricultural water management can significantly enhance crop water productivity and result in soil, water, and energy conservation. Over the years a number of newer and cost-effective technologies/tools have been developed to measure soil water status. Deciding which technique should be used depends on the purpose of the measurements, soil and crop conditions, desired accuracy, cost and durability of the sensor, ease of operation and interpretation of the data, and other factors.

This Extension Circular defines soil matric potential and describes principles and operational characteristics of one of the electrical resistance-type soil moisture sensors for irrigation management. It describes proper installation, maintenance, data downloading, interpretation, and use in irrigation management decisions. Examples show how soil matric potential can be used for irrigation management in various soil textures. The information, data, and recommendations made in this publication are based on long-term field research conducted by the first author at the UNL South Central Agricultural Laboratory, Clay Center, Neb., and other locations in Nebraska.

Water in the soil influences plant growth and yield along with many other variables and management operations, including performance of tillage operations, planting, nutrient uptake, soil temperature, and field hydrologic components (runoff, deep percolation, drainage). Measurement of soil water status (soil water content or soil water potential) is essential in agriculture for research and development and for routine on-farm monitoring of a current crop's status in terms of water stress so informed decisions about irrigation management can be made. Accurate determination of soil water status is a fundamental element of agricultural water management, and a fundamental component in studies related to soil water movement, crop water stress, evapotranspiration, hydrologic and crop modeling, and other agricultural practices. Irrigation management requires knowledge of when and how much water to apply to optimize crop production. Too much or frequent irrigations may cause anaerobic soil conditions and promote undesirable chemical and biological reactions in the soil, which can substantially reduce yield quantity and quality, and waste water resources. Conversely, too light or infrequent irrigation applications may cause drought conditions which also may reduce crop yield quantity and quality. Irrigation management requires the quantitative knowledge of when and how much water to apply to optimize crop production, which also requires utilizing technology for soil water status measurements.

Effective irrigation management requires that soil water status be accurately monitored over time in representative locations in the field. For optimum yield, soil water in the crop root zone must be maintained between desirable upper and lower limits of plant available water. Proper irrigation management will help prevent economic losses caused by over- or under-irrigation; leaching of nutrients, pesticides, and other chemicals into the groundwater and other water bodies; and wasting water and resources. This publication discusses one of the newer electrical resistance methods to quantify soil water status through measurement of soil matric potential, and its practical applications in irrigation management.

What Is Soil Matric Potential?

Soil water status can be expressed in two substantially different ways: (i) soil water content and (ii) soil water potential.

Soil water content is an indication of the amount of water present in the soil profile. Total soil water potential is the sum of gravitational, osmotic (due to soil salinity), and matric (or pressure) potential. However, in practice, gravitational and osmotic potentials are not taken into account and the term "soil water potential" is often used to represent matric potential in soils where salinity is not a major issue. As water is removed from the soil, the remaining water molecules are bonded to soil particles and other water molecules more strongly, and are not readily and easily removed from the soil by plants. Matric potential indicates the energy that must be spent by the plants to extract water from the soil. Once this energy is quantified, this information can be effectively used for irrigation management. When soil water is extracted by plants, the most readily available water is removed first. In most cases, the terms "soil water potential," "matric potential," "matric suction," "capillary potential," and "tension" (or soil-water suction) have been used interchangeably. The term "soil water potential" is used to refer to "matric potential" in this publication.

As water extraction from the soil continues, the plant will have to apply increasingly more energy to extract water from the soil. This is because water is first extracted from the large soil pores and is held more tightly in the smaller pores. Soil matric potential can be measured in a variety of units. It is usually given in units of pressure such as bars or atmospheres (1 bar = 1 atm = 14.7 psi), or in units of water head of an equivalent water column in centimeters (1 bar = 1022 cm H_2O at sea level) or equivalent mercury (Hg) column [1 bar = 76 cm (29.92 in) Hg at sea level]. Soil water potential also can be given in units of energy such as erg/g (1 bar = 1 x 10^6 erg/g), or in joule/kg (1 bar = 100 joule/kg). Commonly used subunits are megapascal (MPa), kilopascal (kPa), centibars (cb), or millibars (mb) (1 bar = 0.1 MPa = 100 kPa = 100 cb = 1000 mb). In many of the newer instruments, kPa is commonly used as an output of the soil matric potential measurements. Soil matric potential is negative to reflect the fact that energy must be exerted to extract water from soil. However, because it is implicit, sometimes the negative sign is omitted or the term "tension" is used. In this publication, the negative sign is omitted.

Soil-water Retention Curve

Soil water content and soil matric potential are related to each other. The relationship is different for each soil type and must be measured experimentally for each soil texture under consideration. Water is available to plants (no crop stress) over a narrow range of matric potentials. For example, in a typical Nebraska silt-loam soil, irrigations can be triggered at matric potentials between 90 to 110 kPa to avoid crop stress and yield reduction. Because of low water-holding capacity and limited available water in sandy soils, these soils are usually irrigated when matric potentials reach 30 to 50 kPa. Each soil texture has a unique relationship between soil water content and matric potential. This relationship describes the ability of a soil to hold water and the force (energy) with which water is held by the soil. An example of a typical soil-water retention curve for various soil types is presented in *Figure 1*.

In general, the greater the clay content, the greater the soil water content (retention) at any given matric potential. In a sandy soil, most of the pores are relatively large, and once the large pores are emptied, only a small amount of water remains. For a fine, sandy soil, a very small increase (drier soil) in matric potential causes a more drastic decrease in water content than in other soil types. Therefore, accurate determination of the soil water retention curve for a given soil texture is very important. The best way of obtaining the retention curve for a given soil type is to take soil samples and send samples to a soil physics laboratory to develop the curve. Retention curves also can be estimated with sufficient accuracy using soil physical properties models that use pedotransfer functions. Growers can contact UNL Extension educators, Natural Resources Conservation District (NRCS) office, or UNL irrigation faculty to check the availability of soil water retention curves for soils in their area.

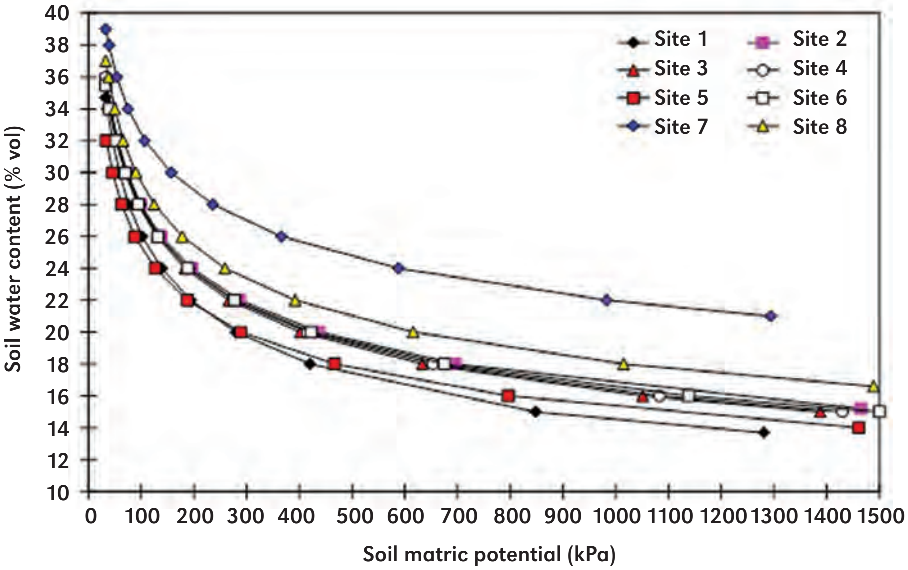

Figure 1. An example of soil-water retention curve developed to convert soil matric potential to soil water content for various soil textures.

How Do We Measure Soil Matric Potential?

Principles and Operational Characteristics of the Watermark® Sensor

One of the most robust electrical resistance-type sensors is the Watermark® Granular Matrix sensor marketed by Irrometer, Co., Riverside, Calif. (*www.irrometer.com*). The Watermark sensors (model 200SS) operate on the same principles as other electrical resistance sensors. Water conditions inside the Watermark sensor change with corresponding variations in water conditions in the surrounding soil. These changes within the sensor are reflected by differences in electrical resistance between two electrodes imbedded in the sensor. Resistance between the electrodes decreases with increasing soil water. In other electrical resistance sensors, plaster of paris, gypsum, glass fibers, ceramic, or nylon cloth has been used as the porous medium between the sensor and the surrounding soil, which is also known as the equilibrium medium. The Watermark is made of a porous ceramic external shell with an internal matrix structure containing two electrodes. In the newer design of the Watermark sensor, the matrix material is surrounded by a synthetic membrane for protection against deterioration and as a contact point with the soil. An internal cylindrical tablet buffers against soil salinity levels that occur in some irrigated soils. A synthetic porous membrane is surrounded by a stainless steel casing or sleeve with holes (*Figure 2*).

The Watermark sensor contains a transmission material of a consistency close to that of fine sand wrapped in a porous membrane. The new transmission material was designed to respond more quickly to soil wetting and drying cycles. The Watermark sensor does not dissolve in the soil over time, which generally occurs with older type sensors that used gypsum as a water transmission material. Hence, in gypsum blocks, the relationship between sensor resistance and soil matric potential varies not only from block to block, but also for each block over time. The range of matric potential that can be measured with the Watermark handheld meter is from 0 (near-saturated soil to 199 kPa (dry soil), which covers the range of soil water contents that are usually sufficient for irrigation management in most soils. In sandy soils, however, the measurement range is from 10 to 199 kPa. When using Watermark Monitor data logger, the measurement range is from 0 to 239 kPa.

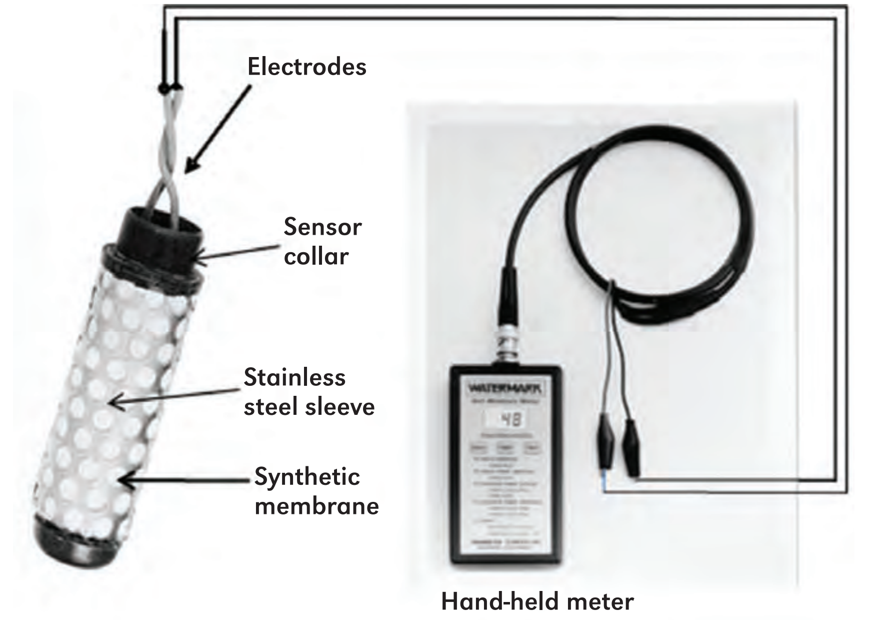

Figure 2. Model 200SS Watermark sensor with stainless steel sleeve and a handheld meter.

Installation and Measurement Procedures

Watermark sensors should be installed in locations with representative soil and crop conditions. They should be installed in the crop row, rather than between the rows, for most accurate representation of the crop water status. More than one station should be installed in each field depending on the magnitude of soil properties and other variability (slope, crop emergence, etc.) that exists in the field. In a center pivot-irrigated field, at least two stations can be selected. In the first station, sensors should be installed just ahead of the "start" point of the pivot because this location will be the driest location in the field when the irrigation is completed and will most likely be used to decide the next irrigation time. The other station can be at the end point where the pivot completes the irrigation to assess the amount of water applied and evaluate the effectiveness of the irrigation event in refilling the soil profile to a desired level. In most cases, the irrigations should be managed to replenish soil water to 90 percent of the field capacity, and not to 100 percent of the field capacity, to leave storage space for capturing any potential rainfall. In each station, at least three sensors should be installed every foot (four sensors are preferred) to determine the soil water status in the typical crop root zone, which is 4 ft for most row crops.

Using soil moisture monitoring in gravity (furrow)-irrigated fields is more challenging than a center pivot-irrigated field. In a furrow-irrigated field, two stations can be selected, one about 100 ft down the run (furrow length) and the second one about 2/3 the way down the run, just ahead of the tail-water or backup water. These areas are most likely to have the least percolation along the furrow if the end of the furrow is blocked. If the end is not blocked, the least percolation usually occurs at the downstream end. For gravity irrigators who install two sets of sensors in their fields, sensors can be installed at about 1/3 to 1/2 way down the row of first irrigation set, and then the other sensors 1/3 to 1/2 way down the row of last irrigation set, so producers can determine the next irrigation timing. At each location, at least three sensors should be installed every foot. One can choose to select more than two stations in the field, depending on how much variability is present in the soil structure, slope, etc. In gravity-irrigated fields, the sensors installed at 1 ft depth may not get enough irrigation water to be representative if they are installed on the crop row between the two plants on top of the ridge. Especially after hilling is done, the irrigation water may not reach the 1 ft sensor that is installed on the hill. In this case, installing the sensor half way between the center of the furrow and the ridge top will help reduce the challenge of sensors not getting wet during an irrigation event. Installing the 1 ft sensor with about 40^{o}-45^{o} angle towards the furrow on the ridge will also help for the sensor to receive irrigation water to provide representative soil moisture status during and after an irrigation event.

In a subsurface- or surface drip-irrigated crop field, the sensors should still be installed in the crop row between two healthy plants regardless whether the drip lines are installed every row or every other row. The soil water status between the crop rows will be greater than those in the crop row because crop water uptake is greater in the crop row due to larger presence of crop root density. If the sensors are installed between the rows, then the sensors will indicate late or delayed irrigation trigger date than the actual soil water conditions in the crop row and this can cause under-irrigation and crop water stress, especially for crops that have more vertical rooting structures than horizontal such as soybean. Even through corn has much larger horizontal root development than soybean, most of the effective root zone for corn is still located in the crop row rather than between the two rows. Thus, crops will extract more water from within the crop row soil profile than the profile between the two crop rows.

For ease of use, the Watermark sensor can be attached to 1/2 in, Class 315 psi, thin wall PVC pipe, which will provide a snug fit. PVC glue (PVC/ABS cement) can be used over the sensor collar to attach the sensor to the PVC pipe. This permits pushing the sensors into the access hole during the installation. *Figure 3* shows Watermark sensors attached to different lengths of PVC pipes and ready for installation at different depths. A PVC cap can be used to close the top of the pipe to prevent rain or irrigation water from entering the pipe. Another option is to attach a PVC elbow or a 90° angle pvc, which will make it easier to remove the sensors at the end of the season, which is shown in *Figures 4 and 5*. Typical installation of Watermark soil moisture sensors in different corn fields are presented in *Figure* 5.

During installation, it is very important not to damage crops and roots that are close to the sensors. Damaged crops will have altered/different water uptake rates than healthy crops. This will affect readings by the Watermark sensors and may not provide accurate representation of field conditions. To avoid crop damage, installation should occur when plants are small, early in the season. This also allows time for the sensor to acclimate to the surrounding soil. Sensors should be installed in representative areas of

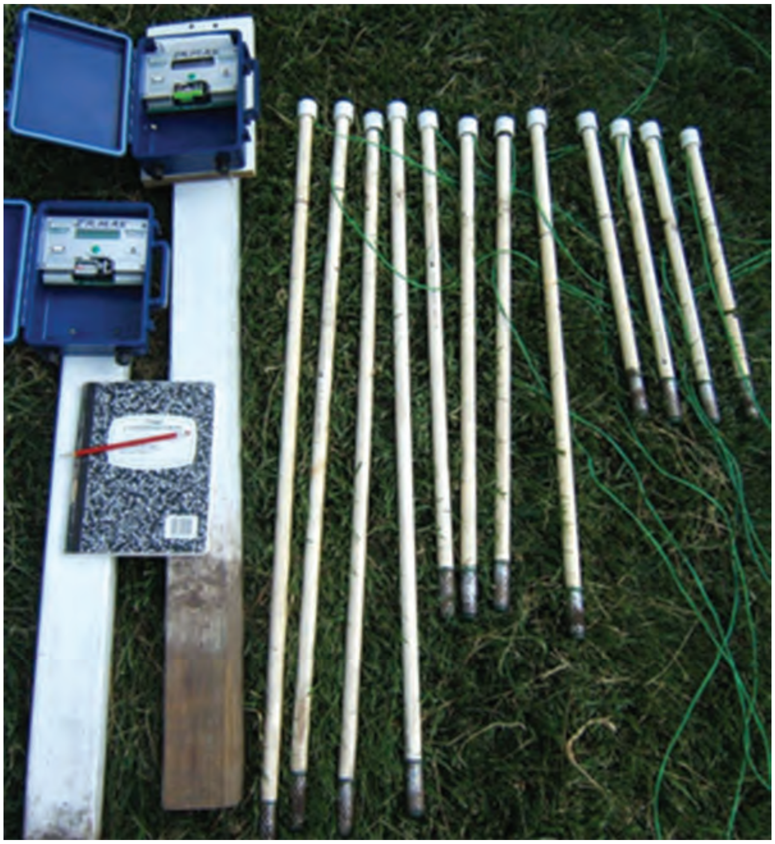

Figure 3. Watermark sensors attached to PVC pipes to be installed at different depths.

Figure 4. Attaching the 1/2 in PVC cap, 90, or an elbow to the top end of the PVC pipe prevents rain or irrigation water from entering the PVC pipe.

the field. They should not be installed in low spots or areas with excessively steep slopes. A spot where the plant population is representative of the field should be selected. It is also important to look for uniform plant spacing and uniform emergence. Placing sensors in areas with doubles or skips can provide unrepresentative sensor readings.

After installation, the depth of the sensors should be labeled on the top of the PVC pipe. Also, the edge of the field should be marked for easy location of the sensors. *Figure 5* shows proper installation of sensors between corn plants. Before installation, check sensor readings to ensure they read 199 kPa (dry sensor). Then soak sensors for 10-15 minutes. Wet sensor readings should be between 0-10 kPa. If they are not, the sensor may need to be replaced. Only wet sensors should be installed since wetting improves the response time of sensors by removing air within them. A 7/8-in diameter soil probe (or a rod) is the best to make a sensor access hole to the depths desired. Three sensors installed at 12, 24, and 36 in (and preferably 48 in) will provide a good indication of soil water status within the crop root zone for most agronomic crops. It is critical not to make the access hole diameter much larger than the sensor so that good contact between soil and sensor will be achieved. It is also critical not to make the access hole much smaller than the sensor diameter as this might damage the sensor membrane (abrasion) when pushing the sensor down the hole. After pushing the sensor into place, the access hole should be backfilled and tamped to eliminate air pockets. It is important to ensure no soil cracks surround the PVC pipe to prevent rain and irrigation water from running down the pipe and affecting sensor readings.

Pouring slurry in the hole before placing the sensors is not recommended. As the slurry dries out, cracks will likely result, creating space between the sensor and the soil, which will result

Figure 5. Typical installation of Watermark soil moisture sensors in various corn fields.

Figure 6. Watermark Monitor data logger. Up to eight Watermark sensors can be connected to the data logger to monitor matric potential continuously.

in faulty/non-representative readings. This will be the case even without using slurry, but slurry will increase the chance of poor contact between the soil and the sensors. Also, when slurry is being made, some of the soil physical properties such as pore size distribution, bulk density, and texture are destroyed. Thus, the sensor will measure the matric potential of the slurry that has different textural properties than the surrounding soil. Installing the sensors early in the growing season before the root system has developed is important because the soil moisture and the sensor moisture will have enough time to reach equilibrium before sensor readings are used for irrigation decisions. Making the access hole to install the sensors after the root system is developed will damage the roots near the area where the sensor is installed. These roots may or may not re-grow and may cause non-representative readings. When the sensors are soaked in water, some amount of water will rise up in the PVC pipe due to capillary action. It is critical that the water inside the PVC pipe is emptied before sensor installation; otherwise, the water in the PVC pipe will slowly and continuously wet the Watermark sensor causing the sensor to read wet soil moisture (approximately up to two to three weeks).

Readings can be taken using a handheld meter (*Figure 1*) twice a week (or more) to determine the soil moisture level and to assess when the next irrigation should occur and how much water should be applied (this procedure will be discussed in detail for different soil textures in the next sections). A Watermark Monitor data logger is also available to monitor soil matric potential continuously (*Figure 6*). Eight Watermark sensors can be attached to each data logger and readings can be recorded every 1, 5, 10, 15, 30 minutes or every 1, 2, 4, 8, 12, or 24 hours. If the data logger is programmed to read and record data every minute, the data logger memory will be full in two days when reading eight sensors. For hourly measurements, the memory will record data for 170 days when using eight sensors. The measurement range of the Watermark monitor is from 0 to 239 kPa. If a temperature sensor is attached to the first channel of the data logger, readings from remaining sensors will be automatically adjusted for soil temperature. The temperature sensor should be installed at a depth of 10 to 18 in. This depth will provide a good representation of the soil temperature in the crop root zone.

Soil Temperature Effects on Soil Matric Potential

Variations in soil temperature can slightly affect sensor performance, depending on the season when measurements are being made. The Watermark sensor has been calibrated for a default soil temperature of 70°F. This is because in an irrigation season, soil temperature does not fluctuate significantly from 70°F within the primary crop root zone. Thus, the effect of soil temperature on soil matric potential during the growing season is negligible. However, if the user has measurements of soil temperature, the Watermark readings can be adjusted for temperature fluctuations. This will increase the accuracy of matric potential readings slightly. To correct for temperature, the soil matric potential reading can be decreased by 1 percent for each degree greater than 70°F. Likewise, the soil matric potential reading can be increased by 1 percent for every degree less than 70°F. The following equation can be used to make adjustments when the soil temperature is different than 70°F:

$$\text{SMPadj} = \text{SMP} - (\text{Ts} - 70^{\circ}\text{F}) \times 0.01 \times \text{SMP}$$

Where:

SMPadj = adjusted soil matric potential

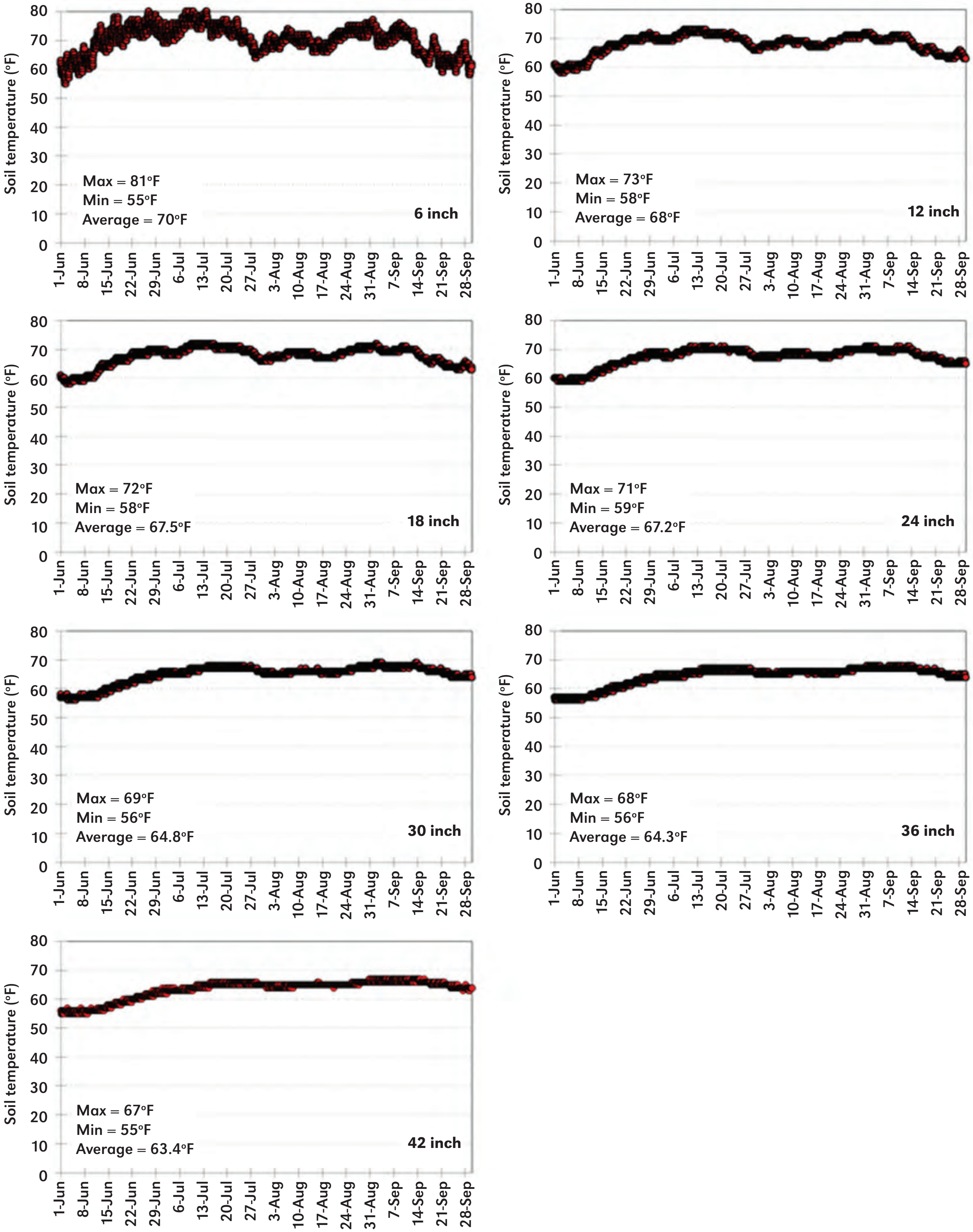

Figure 7. Soil temperature measured on an hourly basis at 6, 12, 18, 24, 30, 36, and 42 in soil layers on Hastings silt loam soil at the South Central Agricultural Laboratory, Clay Center, Neb.

SMP = soil matric potential reading from the Watermark sensor

Ts = soil temperature (°F)

The base temperature of 70°F, used as a default in Nebraska Watermark data loggers and handheld meters, is a representative average soil temperature typically observed during the growing season. *Figure 7* presents measured hourly soil temperature in an irrigated corn field in a silt-loam soil at the South Central Agricultural Laboratory during the 2013 growing season. The soil temperature was measured at 6, 12, 18, 24, 30, 36, and 42 in soil depths under sod (rainfed grass) and croplands on an hourly basis since 2004 as a part of Nebraska Water and Energy Flux Measurement, Modeling, and Research Network (NEBFLUX) project. The topsoil (6 in) is subject to most fluctuations as it interacts most with the environmental variables (rainfall, temperature, wind speed, solar radiation, and humidity) than any other soil depths. The top soil temperature ranged from 55°F to 81°F with a seasonal average of 55°F. However, from June until early September, which covers the typical irrigation season, the temperature even in the topsoil was around 70°F. The soil temperature did not fluctuate more than ±4.8°F from 70°F throughout the growing season at a 6 in depth. The temperature fluctuated within ±3.4, 3.2, 3.1, 3.2, 3.2, and 3.3°F at 12, 18, 24, 30, 36, and 42 in depths, respectively. Soil temperature in the top 12 in increased from early June through late June before the crop canopy reached complete cover. This was caused by increased solar radiation reaching the soil surface due to incomplete crop cover, resulting in increased soil temperature. After the canopy was fully developed, the soil temperature stayed close to 70°F, yet showed a moderate decline toward the end of September. Starting in mid-September, the soil temperature started a more rapid decline as a result of cooler fall temperatures and loss of plant leaves, which resulted in heat transfer from warmer soil to cooler air. The average soil temperature for the growing season for the 12, 18, and 36 in layers was also close to 70˚F. The maximum and average soil temperature decreased with depth. The minimum temperature for the 6, 12, 18, 24, 36, and 42 in layers was 55, 58, 58, 59, 56, 56, and 55, respectively. The maximum and average soil temperatures at the 42 in layer were 14 and 6.6°F lower than the top soil temperature. The minimum temperature was highest at the 24 in depth as 59°F. If the Watermark sensors are used to monitor soil water status during the growing season, using soil temperature sensors to adjust soil matric potential is not critical. However, in spring, fall or winter, soil temperature should be measured to adjust Watermark readings. Overall, measured soil profile temperature data presented in *Figure 7* support the use of 70°F as a base temperature with the Watermark data logger and the handheld meter.

Maintenance and Troubleshooting

Watermark sensors require minimal maintenance. When sensors are removed from the field at the end of the growing season they should not be cleaned with rough materials. They should be washed with water so that the sensor's membrane is not damaged. Before sensors are reused, they should be checked for proper operation. This can be done by placing sensors in water for 10 to 15 minutes and taking a reading. The sensors should read zero kPa or close to zero in water. If the reading is more than 10 kPa in water, the sensor should be replaced. With a completely dry sensor (a sensor left in the sun for three to four days), the reading should be 199 kPa or "DRY." If the handheld meter or Watermark data logger gives a message of "DRY" also, it could mean either there is disconnected or damaged wire, the sensor is out of range (i.e., the soil moisture is drier than 199 kPa, or no sensor is connected to the data logger. To check if the sensor is off scale or not, a moist sensor can be placed in the topsoil and connected to the data logger or handheld meter to check the reading. If properly handled and maintained, the same sensors can be used for at least four to five years without replacement.

Cable Length and Telemetry Data Transfer Option

The Watermark sensors are available from the manufacturer with long wire leads. In many cases, the best location to install the sensors might be somewhere in the middle of the field, making it inconvenient to read the sensors, especially in large fields and when the crops are tall. One economical solution might be to extend the cable to the edge of the field to read the sensors more easily. The cable leads could be connected to a data logger or labeled in some manner to be read with a handheld meter. For distances to 1,000 ft, use 18 AWG wire; for distances to 2,000 ft, use AWG 16 wire; and for distances to 3,000 ft, use AWG 14 wire. "UF" wire is recommended because it is rated for direct burial in the soil. This is a typical type of wire used for irrigation valves, such as AWG 18/2 "UF," which is a two-conductor 18-gauge wire with each conductor enclosed in an outside jacket. It is available in multiple conductor bundles, such as the AWG 18/8 wire, which has eight individual wires that could be used to connect four sensors. Another option is a wireless data logger package to read the sensors. The manufacturer of the Watermark sensor also provides a wireless cellular gateway for long distance data collection that can transfer data to an online platform for real time data access. Using the wireless option will eliminate the time it takes to read the sensors manually and will help prevent rodent damage

Table 1. Depletion (in per foot) in available soil water holding capacity versus soil matric potential; available water holding capacity; and suggested irrigation trigger points for different soil textures (N/A: not applicable)

	Soil type, depletion in inches per foot associated with a given soil matric potential value measured by the Watermark sensors, and available water holding capacity for different soil types							
Soil matric potential (kPa)	**Silty clay loam topsoil, Silty clay subsoil (Sharpsburg)**	**Silt-loam topsoil (Keith)**	**Upland silt loam topsoil, Silty clay loam subsoil (Hastings, Crete, Holdrege)**	**Bottom land silt-loam (Wabash, Hall)**	**Fine sandy loam**	**Sandy loam**	**Loamy sand (O'Neill)**	**Fine sand (Valentine)**
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.20	0.30	0.30	0.30
33	0.20	0.14	0.00	0.00	0.55	0.50	0.45	0.55
50	0.45	0.36	0.32	0.30	0.80	0.70	0.60	0.70
60	0.50	0.40	0.47	0.44	1.00	0.80	0.70	0.70
70	0.60	0.50	0.59	0.50	1.10	0.80	0.80	0.80
80	0.65	0.55	0.70	0.60	1.20	1.00	0.93	1.00
90	0.70	0.60	0.78	0.70	1.40	1.20	1.04	N/A
100	0.80	0.68	0.85	0.80	1.60	1.40	1.10	N/A
110	0.82	0.72	0.89	0.88	N/A	N/A	N/A	N/A
120	0.85	0.77	0.91	0.94	N/A	N/A	N/A	N/A
130	0.86	0.82	0.94	1.00	N/A	N/A	N/A	N/A
140	0.88	0.85	0.97	1.10	N/A	N/A	N/A	N/A
150	0.90	0.86	1.08	1.20	N/A	N/A	N/A	N/A
200	1.00	0.95	1.20	1.30	N/A	N/A	N/A	N/A
Water holding capacity (in/ft)	**1.8-2.0**	**1.8-2.0**	**2.20**	**2.00**	**1.80**	**1.40**	**1.10**	**1.00**
***Suggested range of irrigation trigger point (kPa)**	**75-80**	**80-90**	**90-110**	**75-80**	**45-55**	**30-33**	**25-30**	**20-25**

(*)The trigger points were calculated with the assumption of no sensor malfunction. The trigger points were calculated based on the 35 percent depletion of the total soil water holding capacity per foot of soil layer. The sensor readings and the suggested trigger points should be verified/checked against the crop appearance in the actual field conditions during the season. Trigger point should be the average of first 2 ft of sensors prior to crop reproductive stages and 3 ft once crop reaches the reproductive stage (i.e., average of top 2 ft sensors before tassel and average of top 3 sensors after tassel for corn). However, for sandy soils, the average of top 2 sensors should be used as a trigger point throughout the growing season. The suggested trigger points are for normal operation conditions and these values should be adjusted (lowered) based on well and irrigation system capacity to be able to keep up with the crop water requirement with lower well capacities.

to cables. Another option for reading the Watermark sensor wirelessly is the Profiler from Servi-Tech, wireless data loggers from Spectrum Technologies, and various others companies.

Using Watermark Sensors for Irrigation Management in Different Soil Textures

The soil water in the crop root zone between field capacity and permanent wilting point is available for plant uptake. Although it varies as a function of many factors, as a rule of thumb, half of this water is readily available to experience water stress, and this can cause yield reduction. The yield reduction due to water stress varies depending on the crop stage. While crops (e.g., corn) are sensitive to water stress to different magnitudes in different growth stages, water stress (depending on the stress levels that crops are exposed to) at any growth stage until physiological maturity can result in yield reduction. The available water capacities per foot of soil depth for different soil textures are given in *Table 1*. The total available water in the active crop root zone is determined by multiplying the crop root-zone depth by the available water capacity per foot.

Information about various Watermark matric potential readings and associated available or depleted amount of water for eight major soil types in Nebraska are also presented in *Table 1*. Suggested trigger matric potential values for each soil type is also included in the table based on 35 percent depletion.

In *Table 1*, available soil water for different soil textures is given as a function of soil matric potential. This information can be used to determine how much water is available or depleted in the soil profile for given soil matric potential values measured by the Watermark sensors. Values for allowable soil water depletion, as a function of crop rooting depth, without causing crop water stress are given in *Table 2* for corn, dry beans, sorghum, soybean, small grains, and sugar beets. These are average values for various crops and can change with management practices and other factors. As mentioned earlier, in general, recommended matric potential values as measured using Watermark sensors to trigger irrigation for a silt loam soil are

Table 2. Average (typical) allowable soil water depletion (inches) values for dry beans, corn, sorghum, soybean, small grains and sugarbeets in different soil types.

	Soil type							
Crop root-zone depth (ft)	Silty clay loam topsoil, Silty clay subsoil (Sharpsburg)	Silt-loam topsoil (Keith)	Upland silt loam topsoil, Silty clay loam subsoil (Hastings, Crete, Holdrege)	Bottom land silt-loam (Wabash, Hall)	Fine sandy loam	Sandy loam	Loamy sand (O'Neill)	Fine sand (Valentine)
1.5	1.5	1.5	1.6	1.8	1.3	1.1	0.7	0.7
2.0	1.9	1.7	2.1	2.6	1.9	1.3	1.0	1.0
2.5	2.1	2.3	2.4	3.0	2.1	1.7	1.3	1.1
3.0	2.8	2.8	3.1	3.1	3.9	2.8	1.5	1.4
Average	**2.1**	**2.1**	**2.3**	**2.8**	**2.0**	**1.5**	**1.1**	**1.1**

between 90 and 110 kPa. Considering the time it takes for irrigation preparation and to irrigate the entire field, irrigations should be started immediately when the matric potential reaches that range to avoid crop stress.

It is important to note that this suggested range (i.e., 9-110 kPa for silt loam soil) changes with soil texture. For example, a matric potential value of 50 kPa is associated with 0.45 in depletion in available water in a silty clay loam soil, whereas it is associated with 0.80 in depletion in a fine sandy loam soil (*Table 1*). During an irrigation season, the soil matric potential will fluctuate from approximately zero to 30 kPa after irrigation or considerable rainfall to near 100-110 kPa (or greater) just before the next irrigation. A typical pattern of fluctuation in matric potential in a growing season for corn grown in a silt loam soil is shown in *Figure 8*. The matric potential values in *Figure 8* were measured in three depths (12, 24, and 36 in) and averaged. Arrows on *Figure 8* indicate irrigation (IR) or rainfall (R) events. The matric potential increases gradually as the soil water is depleted by the crop and/or evaporated from the soil. It decreases abruptly after irrigation or rainfall. In this particular field, irrigations were applied when the average of first and second ft sensors matric

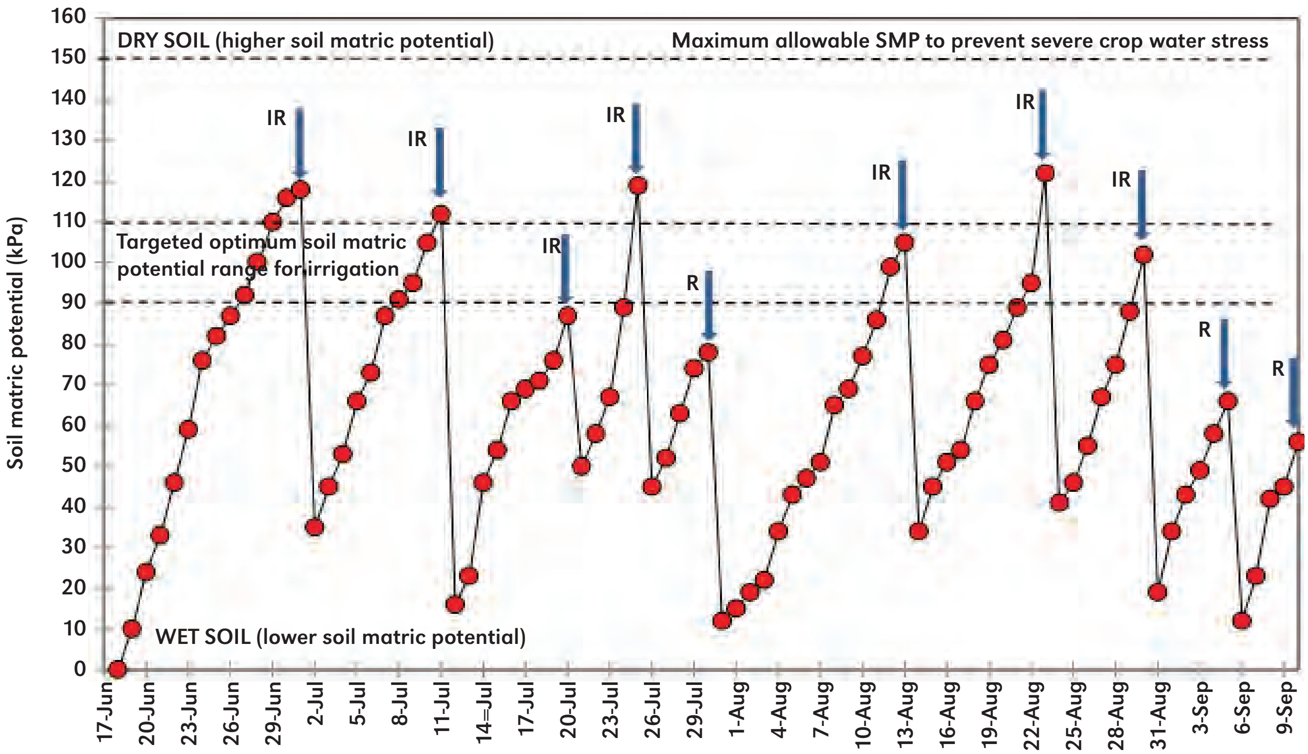

Figure 8. Typical pattern of average soil matric potential fluctuations during an irrigation season as measured using Watermark sensors installed at 12, 24, and 36 in soil depth in a center pivot-irrigated corn field at the South Central Agricultural Laboratory near Clay Center, Neb, in a Hastings silt-loam soil. Arrows indicate either irrigation (IR) or rainfall (R) events. Note that irrigation and/or rainfall water causes matric potential to decrease.

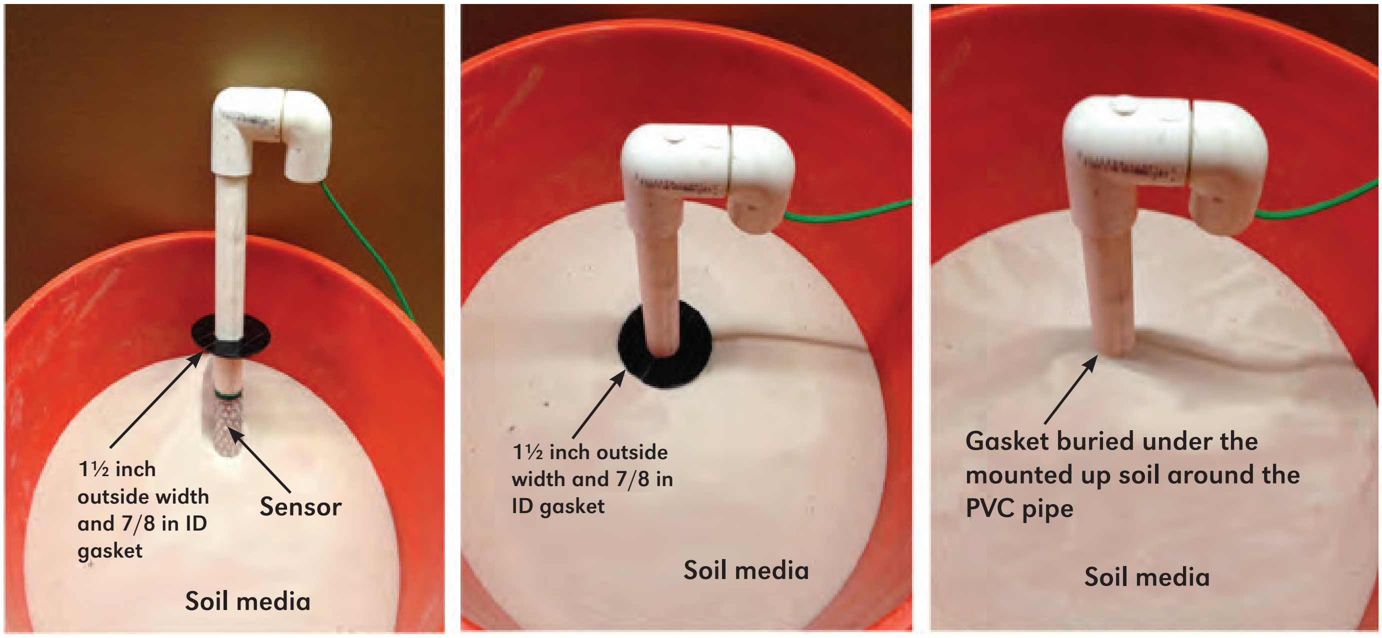

Figure 9. Place a gasket around the PVC pipe during the sensor installation to prevent irrigation and/or rainfall water from penetrating between the PVC pipe and the soil.

potential was around 100 kPa before tassel and by taking the average of first, second, and third ft sensors after tassel for corn crop. After any irrigation and/or rainfall event, the soil matric potential may not always decrease to or close to zero. If the sensors are properly installed, the irrigation and/or rainfall water will be held in the top layers before reaching the sensors at the deeper layers. Thus, the lower limit of the matric potential value after irrigation and/or rainfall event will not be the same (unless there is a heavy rainfall event — i.e., 1½ in — in which case the soil profile will be wet enough for the soil matric potential value to drop to or close to zero).

The decrease in matric potential after an irrigation rainfall event is a strong function of the initial soil moisture condition of the soil layers before the irrigation and/or rainfall event. For example, if a sensor that is installed at 24 in depth is reading 85 kPa before the rainfall and if the rainfall amount is 0.30 in, then the sensor reading in the 24 in depth may not change after the rainfall because all of the rainfall will be captured in the top soil layer and will not reach to the sensor at 24 in depth. Since crop water uptake will continue after rainfall, the sensor in the 2 ft may actually increase right after the rain. Depending on the irrigation water application amount, this scenario will also apply to irrigation water. If the irrigation amount applied can be held in the 1 and 2 ft soil layers (depending on the initial soil moisture conditions just before irrigation), the sensor installed in the 3 ft layer may not respond to the irrigation application if the soil moisture deficit in the 1 and 2 ft layer is large enough to store all of the irrigation water.

As mentioned earlier, if the Watermark sensors are installed properly, the magnitude of decrease in soil matric potential after irrigation and/or rainfall event(s) is determined by the initial soil moisture status of the soil layers. In almost all cases, unless there is a very heavy rainfall event, the soil matric potential value of the sensors in the deeper soil layers (i.e., third and fourth ft) should never decrease to or close to zero (near saturation) throughout the growing season. If they do, this is most likely due the fact that there is a gap between the PVC pipe and surrounding soil and water penetrates from this gap all the way down to the Watermark sensor that is installed in the third or fourth ft. To prevent this issue, a rubber gasket (O-ring) with a 1½ in inside diameter (ID) can be attached to the PVC pipe during the installation (*Figure 9*). After packing the topsoil around the PVC pipe after the pipe is inserted, the gasket can be place on the top soil to seal any potential gap between the PVC pipe and soil. After packing the soil around the PVC pipe, a small amount of soil can be mounted up or build up around the PVC pipe on the gasket. Placing the gasket around the PVC pipe during the installation will significantly reduce or eliminate any water penetrating between the PVC pipe and the soil.

Another new feature of the Watermark system is that a rain gauge can also be attached to the Watermark data logger to monitor rainfall (*Figure 10*). Thus, the same Watermark Monitor data logger can be used to measure soil temperature, soil moisture, and rainfall in the

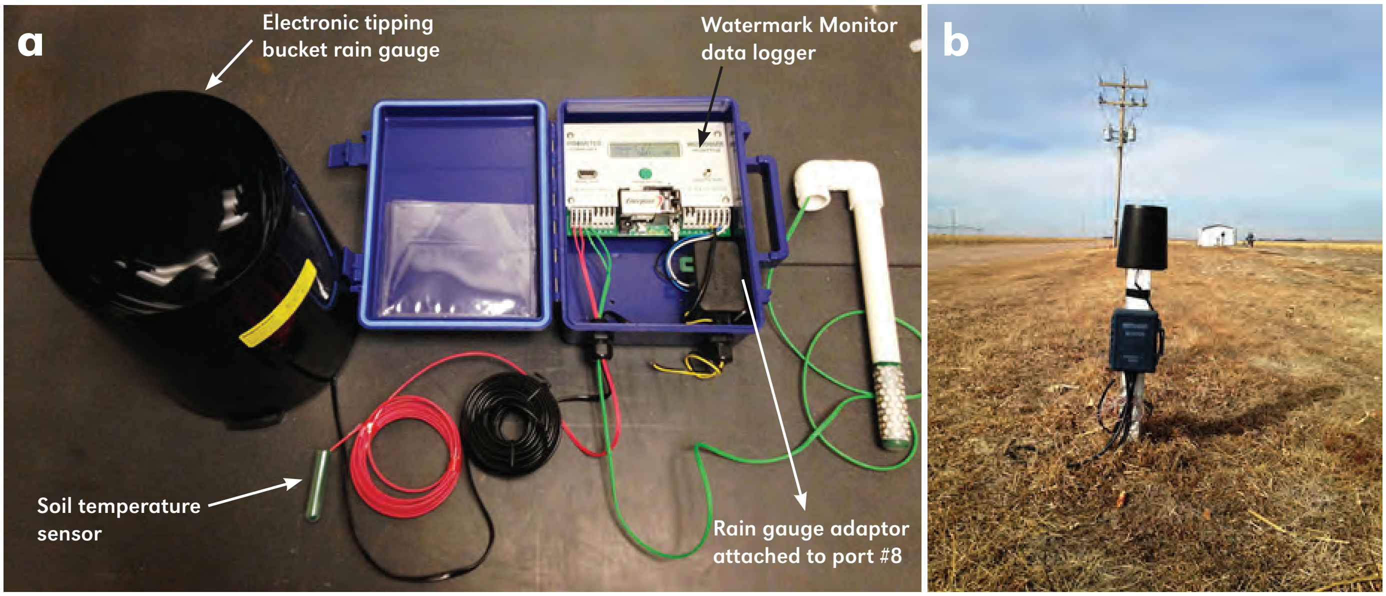

Figure 10. (a) An electronic tipping bucket rain gauge, soil temperature sensor, rain gauge adaptor, and a Watermark sensor attached to a Watermark Monitor data logger; and (b) a rain gauge connected to a Watermark data logger installed nearby a field.

same location at the same time. In a center pivot irrigated field, the rain gauge should be installed on the edge of the field, not in the field, to be able to separate the rainfall amount from the irrigation amount. The rain gauge also can be used to monitor the irrigation application rate by installing it in the field under the pivot, but the rain gauge should be kept above the canopy at all times to prevent canopy interference with the rain gauge adequately capturing the rain water. *Figure 10* presents a tipping bucket rain gauge with a magnetic reed switch (Davis Instruments, Hayward, Calif.), a soil temperature sensor, and a Watermark sensor attached to a Watermark Monitor data logger. The Watermark Monitor (Model 900M-RGA) that is already equipped with the rain gauge adaptor should be used to read the rain gauge output. The temperature sensor should always be attached to the first port. The program in the Watermark Monitor will automatically adjust all the matric potential readings for the measured soil temperature. The rain gauge should always be attached to the last port (#8). The rain gauge will measure the rainfall with a 0.01 in resolution (increment). The rain gauge also can be programmed to record the rainfall in millimeters. The Firmware Version 3.1 (or newer) should be used to program the rain gauge. The gauge is made of a UV-stabilized ABS plastic and has a diameter of 8.75 in, height of 9.5 in with a total rain collection area of 33.2 sq in. If the rain gauge is placed on the edge of a field, it should be away from large objects (trees, phone lines, electrical lines, etc.) so they do not block the rainfall into the gauge for accurate measurements. The gauge should be installed on a level surface. Use the bubble level or pour water into the T-shaped leveling trough on the collector base and observe the surface of the water to ensure the collector is leveled. Make sure there is an unobstructed path for water runoff from the drain screens. The rain gauge contains a magnet-operated switch which may not operate correctly if it is mounted on or near any object which attracts a magnet or magnetic field. To install the gauge on a sheet metal roof, the gauge must be insulated by making a platform out of wood. The base of the gauge can be mounted at least 2 in away from any steel or iron surface, and make sure the reed switch is at least 2 in away from any nails, metal parts, steel, or iron objects. Over time, dust, debris, etc., might accumulate inside the rain gauge. Clean the gauge periodically so debris does not block the rain entrance point (funnel).

Example of Using Watermark Readings for Irrigation Management

Example:

Consider the matric potential readings at three different depths given in the *Table 3* for center pivot irrigated corn on a Hastings silt loam soil (upland siltloam topsoil in *Table 1*) at the South Central Agricultural Laboratory. The available water capacity is 2.2 in/ft and crop water use is averaging 0.30 in/day. Assume the rooting depth is 3.0 ft. To prevent crop water stress, irrigation needs to occur before three days have elapsed.

Table 3. Watermark sensor depth, sensor readings, and amount of soil water depletion for Hastings silt loam soil

Sensor depth (inch)	Sensor reading (kPa)	Soil water depleted (inch)
12	90	0.78
24	60	0.47
36	50	0.32
Total water depleted		1.57

1. Total available soil-water holding capacity (from *Table 1*) = 2.20 in per ft x 3.0 ft = 6.60 in.
2. Remaining available water in 3 ft crop root zone = 6.60 - 1.57 = 5.03 in.
3. Allowable soil water deficit for 3.0 ft rooting depth (from *Table 2* for upland silt loam) = 3.1 in. When should the next irrigation be applied assuming no rainfall will occur? Water available before stress occurs = 3.1 - 1.57 = 1.53 in. Estimated days for the next irrigation before stress occurs = 1.53 in / 0.30 in ~5 days.

The exact schedule will depend on the irrigation system capacity, crop water use rate, and other factors.

References

Irmak, S. 2010. Nebraska Water and Energy Flux Measurement, Modeling, and Research Network (NEBFLUX). *Transactions of the ASABE* 53(4): 1097-1115.

Irmak, S. and D.Z. Haman. 2001. Performance of the Watermark granular matrix sensor in sandy soils. *Applied Engineering in Agriculture* 17(6): 787-795.

This publication has been peer reviewed.

Disclaimer

The mention of trade names or commercial products is solely for the information of the reader and does not constitute an endorsement or recommendation for use by the authors or the University of Nebraska–Lincoln and Clemson University.