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EC06-783 Watermark Granular Matrix Sensor to Measure Soil Matric Potential for Irrigation Management

Suat Irmak
University of Nebraska - Lincoln, suat.irmak@unl.edu

Jose O. Payero
Univesity of Nebraska-Lincoln, jpayero@clemson.edu

Dean E. Eisenhauer
University of Nebraska - Lincoln, deisenhauer1@unl.edu

William L. Kranz
University of Nebraska-Lincoln, wkranz1@unl.edu

Derrel Martin
University of Nebraska-Lincoln, derrel.martin@unl.edu

See next page for additional authors

Irmak, Suat; Payero, Jose O.; Eisenhauer, Dean E.; Kranz, William L.; Martin, Derrel; Zoubek, Gary L.; Rees, Jennifer M.; VanDeWalle, Brandy; Christiansen, Andrew P.; and Leininger, Dan, "EC06-783 Watermark Granular Matrix Sensor to Measure Soil Matric Potential for Irrigation Management" (2006). *Historical Materials from University of Nebraska-Lincoln Extension*. 3322.
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Authors

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Watermark Granular Matrix Sensor to Measure Soil Matric Potential for Irrigation Management

Suat Irmak, Irrigation and Water Resources Engineer; Jose O. Payero, Irrigation Engineer; Dean E. Eisenhauer, Hydrologic and Irrigation Engineering; William L. Kranz, Irrigation Specialist; Derrel L. Martin, Irrigation and Water Resources Engineer; Gary L. Zoubek, Extension Educator; Jennifer M. Rees, Extension Educator; Brandy VanDeWalle, Extension Educator; Andrew P. Christiansen, Extension Educator; Dan Leininger, Water Conservationist, Upper Big Blue NRD

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. Examples show how soil matric potential can be used for irrigation management.

Water in the soil not only influences plant growth and yield but also performance of tillage, planting and nutrient uptake. Measurement of soil water is required in many areas of agriculture for research and development, and for routine on-farm monitoring. Accurate determination of soil water status (soil water content or soil water potential) is fundamental to agricultural water management.

Irrigation scheduling requires the knowledge of "when" and "how much" water to apply to optimize crop production. 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 (yield quantity and quality) caused by over or underirrigation; movement of nutrients, pesticides and other chemicals into the groundwater and other water bodies; and wasting water resources and energy consumption.

Determination of soil water status for irrigation management using hand-feel method is practiced in the absence of accurate and low cost soil moisture sensors. The hand-feel method does not provide quantitative soil water status; rather it provides a qualitative indication of soil water status and is subject to the person's ability to feel the soil.

To improve irrigation management, quantitative knowledge of soil water status deep in the soil profile (e.g., 12, 24, 36 and possibly 48 inches) is necessary, but not possible with the hand-feel method. Any error in the hand-feel method will cause significant errors in determination of irrigation water requirement.

Over the years, a number of newer and cost-effective technologies/tools have been developed to measure soil water status. Decision making about which technique should be used depends on the purpose of the measurements, soil and crop conditions, desired accuracy, cost and other factors. This publication discusses one of the newer electrical-resistance methods to quantify soil water status through measurement of soil matric potential.

What is soil matric potential?

Soil water status can be expressed in two 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. Soil water potential determines availability of water to plants and is a direct indication of the energy required for plants to obtain water from the soil. 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 an issue.

As water is removed from the soil, the remaining water molecules are bonded to soil particles and to other water molecules, and are not readily and easily removed from the soil by plants. Matric potential indicates the energy that must be available in the plants to extract water from the soil.

In most cases, the term 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 the "matric potential" in this publication. When soil water is extracted by plants, the most readily available water is removed first.

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 height (head) of an equivalent water column in centimeters (1 bar = 1022 cm H_2O at sea level) or equivalent mercury column in centimeters (1 bar = 76 cm H_g at sea level). Soil water potential can also be given in units of erg-g^{-1} (1 bar = 1 x 106 erg-g^{-1}), or in joule-kg^{-1} (1 bar = 100 joule-kg^{-1}).

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 instruments using newer technology, 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.

What is a 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 for each soil under consideration. Water is readily available to plants (no crop stress) over a narrow range of matric potentials. For example, in a typical silt-loam soil in Nebraska, irrigations can be triggered at matric potentials between 100 to 120 kPa to avoid crop stress. 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 with which water is held by the soil.

In general, the greater the clay content, the greater the 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 (dryer 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 field is very important. The best way of obtaining the retention curve for a given soil type is to take soil samples and send the samples to a soil physics laboratory to develop the curve. Retention curves can also be estimated with sufficient accuracy using soil physical properties models. Growers can contact an Extension irrigation specialist to check the availability of soil water retention curves for soils in their area.

How do we measure soil matric potential?

Principles and operational characteristics of the Watermark® sensor

One of the electrical resistance type sensors is the Watermark® Granular Matrix sensor (Irrometer, Co., Riverside California, www.irrometer.com). The Watermark operates on the same principles as other electrical resistance sensors. Water conditions inside the Watermark sensor change with corresponding variations in water conditions in the 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 have been used as the porous body. 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 (model 200SS) sensor, the matrix material is surrounded by a synthetic membrane for protection against deterioration. An internal cylindrical gypsum 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 1*).

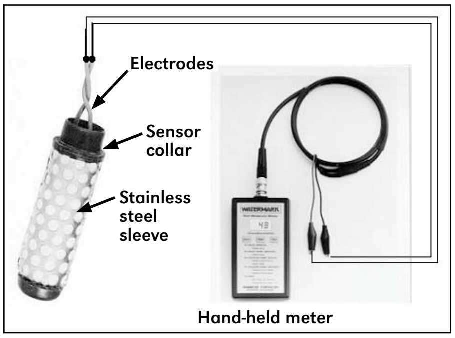

Figure 1. Model 200SS Watermark sensor with stainless steel sleeve and a hand-held meter.

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 a gypsum block. 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 hand-held meter is from 0 to 200 kPa, 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 200 kPa.

Installation and measurement procedures

Watermark sensors should be installed in locations with representative soil and crop conditions. More than one station should be installed in each field depending on the magnitude in soil and other variability that exists in the field. Monitoring soil water status over time to assess the trend of soil water is probably more important than monitoring soil water at several

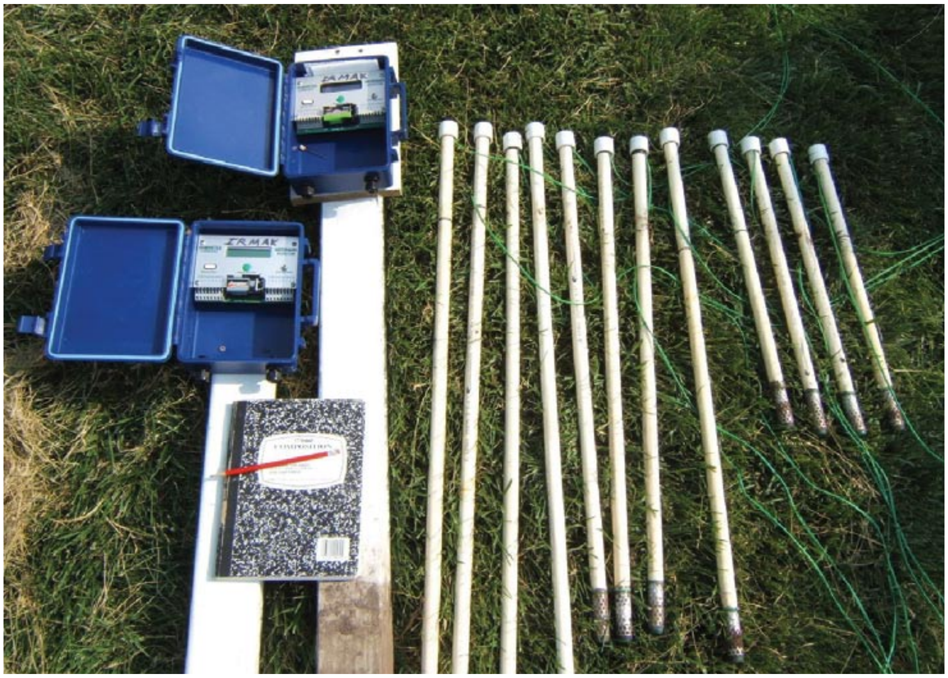

Figure 2. Watermark sensors attached to PVC pipes to be installed at different depths.

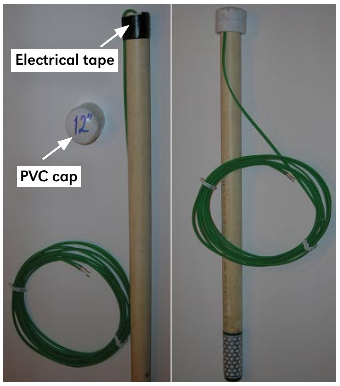

Figure 3. Attachment of the cap to prevent rain or irrigation water from entering the pipe.

Figure 4. Watermark sensors installed at 12, 24 and 36-in. depths in center-pivot irrigated corn field.

locations in the field.

In a center pivot-irrigated field, 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 spot 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. In each station, at least three sensors should be installed every foot to determine the soil water content in the crop root zone.

In a furrow-irrigated field, two stations can be selected, one about 100 ft down the run and the second one about 2/3 the way down the run, just ahead of the tailwater 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. 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.

For ease of use, the sensor can be attached to 1/2 inch, 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 and makes it easier to remove the sensors at the end of the season.

Figure 2 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. The sensor cable that comes out of the pipe can be taped to the pipe at the top and the PVC cap can go on top of the pipe with the cable running between the cap and the pipe (*Figure 3*).

During installation, it is very important not to damage the crops that are close to the sensors. Damaged crops will have different water uptake rates than healthy crops. This will affect the 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 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.

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 4* shows proper installation of sensors between corn plants. Before installation, sensors should be soaked in water for 2 hours followed by 24 hours drying. This procedure should be repeated twice before installation. Only wet sensors should be installed. Wetting improves the response of sensors because it removes air from them.

A 7/8 or 1-inch in diameter soil probe (or a rod) can be used to make a sensor access hole to the depths desired. Three sensors installed at 12, 24 and 36 inches 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 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 cause damage to 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. Pouring slurry in the hole before placing the sensors is not recommended. When the slurry dries it will crack and move away from the soil, creating space between the sensor and the soil. This also may be true without using slurry, but slurry will increase the chance of poor contact between the soil and the sensors. Installing the sensors early in the growing season before the root system has developed is important. 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.

Readings can be taken using a hand-held meter (*Figure 1*) twice a week to determine the soil moisture level and to assess when the next irrigation should occur and how much water should be applied. A datalogger is also available to monitor soil water content continuously (*Figures 5A and B*). Eight Watermark sensors can be attached to each datalogger and the readings can be recorded for hourly, or longer, periods. The measurement range of the Watermark monitor is 0 to 239 kPa. If a temperature sensor is attached to the first channel of the datalogger, readings from remaining sensors will be automatically adjusted for soil temperature. The temperature sensor should be installed at a depth of 18 inches. This depth will provide a good representation of the soil temperature in the crop root-zone. The Watermark Monitor datalogger is marketed with eight Watermark sensors and a temperature sensor.

Figure 5A and B. Watermark Monitor datalogger. Up to eight Watermark sensors can be connected to the datalogger to monitor matric potential continuously.

Soil temperature effects on soil matric potential

Variations in soil temperature can affect sensor performance slightly. The Watermark sensor has been calibrated for a soil temperature of 70°F. This is because in an irrigation season, in many cases soil temperature does not fluctuate significantly within the primary crop root zone (top 3 feet) from 70°F. Thus, the effect of soil temperature on soil matric potential is negligible. However, if the user has measurements of soil temperature at the depth the soil matric potential is being measured, 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:

$SMP_{adj} = SMP + (Ts - 70^\circ F) \times 0.01 \times SMP$; where SMP_{adj} = adjusted soil matric potential, SMP = soil matric potential reading from the Watermark sensor, Ts = soil temperature (°F).

The base temperature of 70°F that is used in the Watermark datalogger and the hand-held meter is a good average soil temperature value that represents the soil temperature range during the growing season. *Figure 6* shows measured soil temperature in a corn field in a silt-loam soil at the South Central Agricultural Laboratory near Clay Center, Neb., during the 2004 growing season. The soil temperature was measured at the 18-inch soil depth. The soil temperature did not fluctuate more than ±5°F throughout the growing season. Soil temperature increased from early June through late June before the crop canopy closed the rows. This was caused by increased solar radiation reaching the soil surface due to incomplete crop cover.

After the canopy was fully developed, the soil temperature stayed close to 70°F, yet showed a moderate decline toward the end

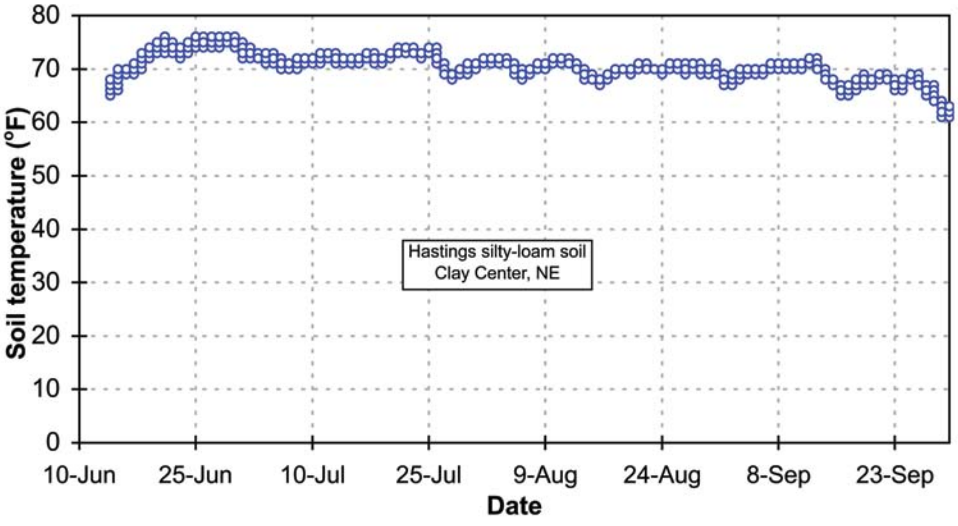

Figure 6. Soil temperature measured at 18 inches in Hastings silt-loam soil near Clay Center, NE.

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. The average soil temperature for the growing season was 70˚F. Data in *Figure 6* support the use of 70˚F as a base temperature with the Watermark datalogger and the hand-held 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 be cleaned, placed in a plastic bag and stored. The sensors should not be cleaned with rough materials. They should be washed with water so that the sensor's membrane is not damaged. A wetting and drying cycle (soaking in water) should be repeated at least twice every season just before installation.

Before re-using the sensors, they should be checked for proper operation. This can be done by placing the sensors in water for about 30 minutes and taking a reading. The sensors should read zero kPa in water. If the reading is more than 2-3 kPa in water, the sensor should be replaced. With a completely dry sensor (a sensor left in the sun for 2-3 days), the reading should be 199 or 200 kPa.

If the hand-held meter or Watermark datalogger gives a message of "DRY," it could mean either: (i) there is a disconnect or damaged cable, or (ii) the sensor is out of range or no sensor is connected to the datalogger. To check if the sensor is off scale or not, a moist sensor can be placed in the topsoil and connected to the dataloger or hand-held meter to check the reading. If properly handled and maintained, the same sensors can be used for at least four years without replacement.

Cable length issues and radio 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. This would make it inconvenient to read the sensors, especially in the large fields and when the crop gets tall. One economical solution might be to extend the cable to the edge of the field to read the sensors more easily. 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 datalogger package to read the sensors. The manufacturer of the Watermark sensor provides a wireless radio telemetry option that can transfer the data up to 14 miles. The range can be extended with addition of the Repeater Radio Module(s). Using the wireless option will eliminate the time it takes to read the sensors manually and will help prevent rodent damage to cables.

Relationship between soil matric potential and available soil water

The soil water in the crop root-zone between field capacity and permanent wilting point is available for plant uptake. The available water capacities per foot of soil depth for different soil textures are given in *Table I*. 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.

Soil matric potential (kPa)	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							
	Silty clay loam topsoil, Silty clay subsoil (Sharpsburg)	Silt-loam topsoil, Clay loam subsoil (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	0	0	0	0	0	0	0
20	0	0	0	0	0.20	0.30	0.30	0.30
33	0.20	0.14	0	0	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	1.0	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	-
100	0.80	0.68	0.85	0.80	1.60	1.40	1.10	-
150	0.90	0.86	1.08	1.20	-	-	-	-
200	1.00	0.95	1.20	1.20	-	-	-	-
Available water capacity (in/ft)	1.8-2.0	1.8-2.0	2.2	2.0	1.8	1.4	1.1	1.0

Table I. Depletion (in/ft) in available soil water versus soil matric potential for different soil textures.

Root depth (ft)	Soil type							
	Silty clay loam topsoil, Silty clay subsoil (Sharpsburg)	Silt-loam topsoil, Clay loam subsoil (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	1.4	1.4	1.5	1.9	1.4	1.0	0.8	0.8
2.0	1.8	1.8	2.0	2.5	1.8	1.4	1.1	1.0
2.5	2.2	2.2	2.5	3.1	2.2	1.8	1.4	1.2
3.0	2.7	2.7	3.0	3.8	2.7	2.1	1.6	1.5

Table II. Allowable soil moisture depletion (inches) values for dry beans, corn, sorghum, soybeans, small grains and sugarbeets in different soil types.

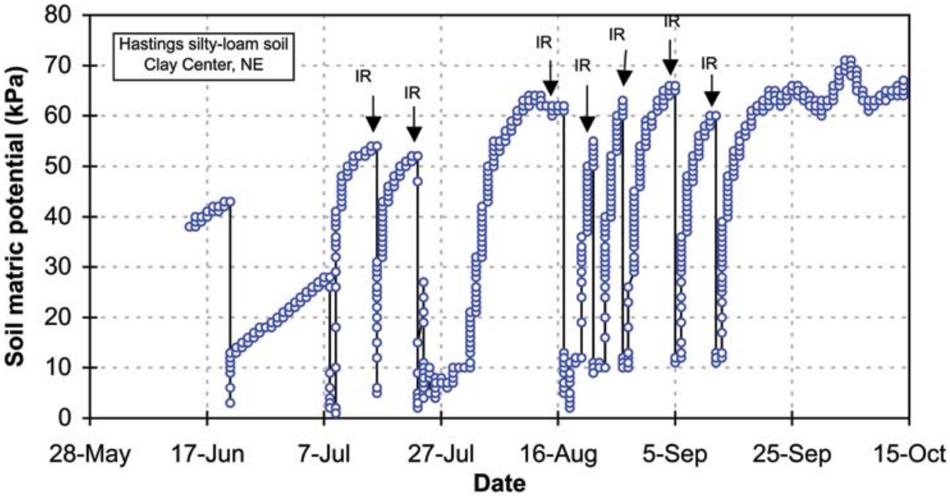

Figure 7. Typical pattern of soil matric potential fluctuations during an irrigation season as measured (hourly) using Watermark sensors installed at 24 inches in a corn field at the South Central Agricultural Laboratory near Clay Center, Neb. Soil is Hastings silt-loam. Arrows and IR indicate irrigation events. Note that irrigation causes matric potential to become close to zero with smaller negative values.

In *Table I*, available 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 significant crop stress are given in *Table II* for corn, dry beans, sorghum, soybeans, small grains and sugarbeets. In general, recommended matric potential values as measured using Watermark sensors to trigger irrigation for a silt-loam soil are between 100 to 120 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 remember that this suggested range changes with the 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 I*).

During an irrigation season, the soil matric potential will fluctuate from approximately 10 kPa after irrigation or considerable rainfall to near 100-120 kPa 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 7*. The matric potential values in *Figure 7* were measured hourly.

Arrows on *Figure 7* indicate irrigation (IR) events. The matric potential decreases (larger negative values) gradually as the soil water is depleted by the crop and/or evaporated from the soil surface. It increases (smaller negative values) abruptly after irrigation. In this particular field, irrigations were applied when the matric potential was around 60 kPa and not between 100 to 120 kPa as suggested earlier. This is related to the irrigation frequency used in this field. This field was irrigated twice a week using a subsurface drip irrigation system. Therefore, the soil profile was kept wetter, compared with surface or center pivot-irrigated fields where the matric potential will usually exceed 60 kPa before the next irrigation.

Using Watermark readings for irrigation management

Example:

Consider the matric potential readings at three different depths given in the following table for center pivot irrigated corn on a Hastings silt-loam soil (upland silt-loam topsoil in *Table I*) at the South Central Agricultural Laboratory near Clay Center, Neb. The available water capacity is 2.2 inches/feet and crop water use is averaging 0.30 inches/day. Assume the rooting depth is 2.5 feet.

To prevent crop water stress, irrigation needs to occur before three days have elapsed. The exact schedule will depend on the irrigation system capacity.

Sensor depth (in.)	Sensor reading (kPa)	Water depleted (in.)
12	90	0.78
24	60	0.47
36	50	0.32
Total water depleted		1.57

Table III.

1. **Total available water capacity (Table I) = 2.20 in/ft x 3 ft = 6.60 in.**
2. **Remaining available water in 3-ft zone = 6.60-1.57 = 5.03 in.**
3. **Allowable soil water deficit for 2.5-ft rooting depth (from Table II for upland silt-loam) = 2.5 in. When should the next irrigation be applied assuming no rainfall will occur? Water available before stress occurs = 2.5-1.57 = 0.93 in. Estimated days for the next irrigation before stress occurs = 0.93/0.30 ~ 3 days.**

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