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Spatial Variability Considerations in Interpreting Soil Moisture Measurements for Irrigation Scheduling

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Increasing production efficiency is becoming a necessity for sustained economic viability in today's increasingly competitive global market. In the case of irrigated agriculture, increased public concern about water conservation, water quality, threatened or endangered species, and environmental quality is pressuring producers to implement resource-efficient water management practices.

Irrigation scheduling and irrigation uniformity are two water management issues that need attention to maximize production efficiency. Irrigation scheduling involves determining the proper timing and amount of water applications throughout the growing season. The goal of sound irrigation scheduling practices is to supply crop water requirements without developing deficit or excess soil moisture. Irrigation uniformity describes how evenly the irrigation system distributes water over the agricultural field. More information on management practices to achieve and sustain high irrigation uniformity is available in University of Idaho Cooperative Extension System Bulletin 824, "Irrigation Uniformity."

The essence of irrigation scheduling involves repeated application of water to meet crop requirements while maintaining soil moisture between upper and lower bounds. The upper bound is governed by the water-holding capacity of soil in the crop root zone; the lower bound is insufficient soil moisture to the point that crop yield and quality are adversely affected. Theoretically, irrigation scheduling can be performed using a calculated daily water balance in conjunction with estimated daily crop water use values or repeated soil moisture monitoring. In practice, a combination of crop water use information and soil moisture monitoring is necessary to achieve acceptable results. A calculated water budget used by itself allows differences between actual and calculated crop water use to accumulate over the season, resulting in gross misapplication of water and/or crop water stress. Soil moisture monitoring alone does not allow crop water requirements to be estimated in advance. Most irrigation systems are incapable of "catching up" if allowed to fall behind, especially during the peak crop growth period. Thus, adjusting irrigation schedules to account for general changes in crop water use combined with soil moisture monitoring to correct for local conditions is necessary for effective irrigation scheduling. Details on using crop water use values for irrigation scheduling are available in University of Idaho Cooperative Extension System's CIS (Current Information Series) 1039 *"Irrigation Scheduling Using Water-Use Tables."*

The water-holding capacity of a soil has a large influence on irrigation system design and irrigation scheduling. An irrigation system must be designed with sufficient hardware and flow rate so water can be repeatedly applied before crop-water stress develops. Given that an irrigation system is sufficiently designed, routine irrigation scheduling ensures that crop-water requirements are met and soil moisture remains within an optimal range. The water-holding capacity of a soil and the numeric value of measures used to quantify soil moisture are highly dependent on soil texture. Unfortunately, soil texture commonly varies with depth and location. This spatial variability in soil texture is an important consideration in both irrigation system design and irrigation scheduling and can confound field soil moisture measurements taken for irrigation scheduling purposes. A good understanding of the effect soil texture has on soil water-holding capacity and soil moisture measurement is necessary for efficient irrigation management.

Soil Water Retention Characteristics

Soil is comprised of air spaces (voids) between solid mineral and organic particles. The soil profile has a finite capacity to store water in these voids for crop use. In general, for a mineral soil, 50% of soil volume is voids (water and air) and 50% is solids. When the voids are completely filled with water, (Figure 1a), the soil is said to be saturated. Most agricultural crops require a minimum amount of air in the soil profile for root respiration. The lack of adequate aeration in the root zone over a 24- to 48-hour period can adversely affect crop yield and quality. Fortunately, the largest voids in the soil profile freely drain by gravity under unrestricted conditions, providing adequate aeration in the crop root zone. The soil water content after free drainage from the largest voids has occurred for 12 to 48 hours is called field capacity, *(Figure 1b).* After this time period, drainage becomes very slow and negligible. Water remaining in the soil profile is available for removal by the plant root system to a lower limit. As soil water content decreases, the water occupies a smaller portion of the voids. Water is held in the smallest voids and as a film on the soil particles by molecular attraction, which has greater energy than what the plant can exert to remove it. The soil water content at which the plant can no longer remove water from the soil to survive is called the permanent wilting point (Figure 1c). Water

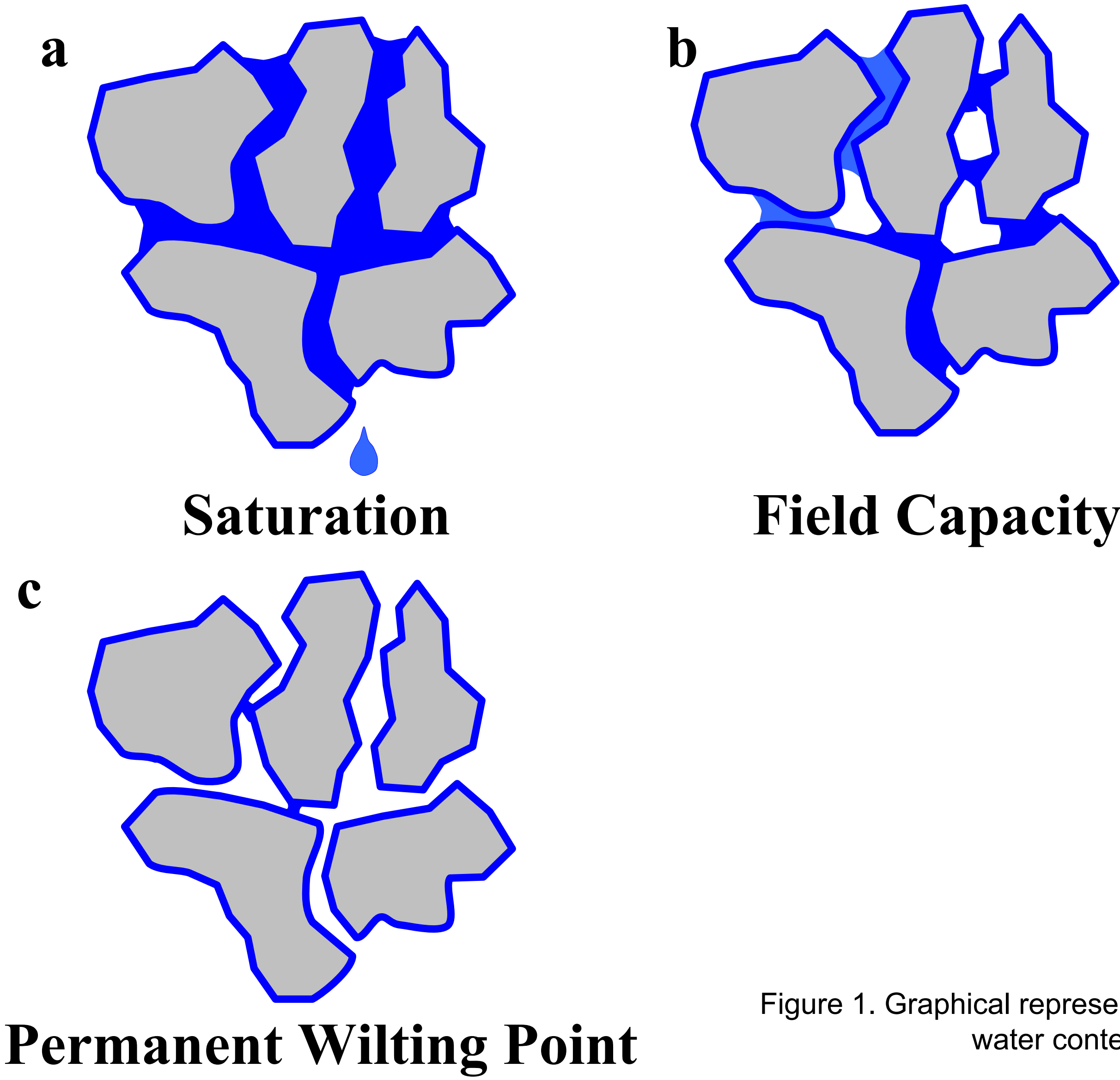

Figure 1. Graphical representation of critical soil water contents.

held in the soil between the soil water contents of field capacity and permanent wilting point is available to sustain plant life and is called available water. However, most plants begin to suffer water stress and reduced yield and/or quality well above permanent wilting point because of the increasing effort required to extract water from the soil as soil water content decreases. In general, most plants can extract 50% of the water held in the soil between field capacity and permanent wilting point without suffering adverse effects on yield and quality. However, there are some exceptions. Vegetable crops in general can withdraw a smaller percentage (15-35%) before suffering water stress and reduced yield and/or quality.

The water retention characteristics of soils are heavily dependent upon soil particle size distribution and organic matter content. Soil particle size distribution also is used to classify soil into textural groups. Soil particles sizes are classified based on physical dimension; sand (2.0-0.5 mm), silt (0.5-0.002 mm), and clay (<0.002 mm). Soil texture is classified according to distribution of these soil particle sizes. The size distribution of the voids in the soil is largely dependent upon the predominate particle size and particle size distribution. For example, a soil largely composed of sand-sized particles will have a high percentage of relatively large voids, which will freely drain. Soils having predominately sand-sized particles will hold the least amount of water, while soils having predominately clay-sized particles will hold the most water. Volumetric soil water contents for field capacity, permanent wilting point, and available water for common soil textural classes are shown in (Table 1). In general, soil water contents for field capacity and permanent wilting point increase with a decrease in predominate soil particle size. The difference between the two (available water) also increases with a decrease in predominate soil particle size. The range in volumetric soil water content values shown in Table 1 for a given soil texture corresponds to the allowed range in soil particle size fractions for the textural classification.

Soil water content on a volumetric basis can be used to directly compute the equivalent depth of water held in the soil profile. Equivalent depth expressed in inches of water per foot of soil depth represents the depth of water over a 1 square foot area if a soil volume one foot square by one foot deep were separated into water and soil particles. Conversion from percent soil water content by volume to equivalent depth in inches per foot of depth is done by multiplying by 0.12. For example, a soil water content of 15% corresponds to an equivalent depth of 1.8 in/ft (15 x 0.12 = 1.8). Similarly, soil moisture measurements showing volumetric soil water content for the

Table 1. Soil water contents for agricultural soils.

Texture	Particle Size Fraction (%)			Volumetric Soil Water Content (%)					
				Field Capacity		Permanent Wilting Point		Available Water	
Class	Sand	Silt	Clay	Average	Range	Average	Range	Average	Range
Sand	≥85	≤15	≤10	12	7-17	4	2-7	8	5-11
Loamy Sand	70-90	≤20	≤15	14	11-19	6	3-10	8	6-12
Sandy Loam	43-85	≤50	≤20	23	18-28	10	6-16	13	11-15
Loam	23-52	28-50	7-27	26	20-30	12	7-16	15	11-18
Silt Loam	≤50	≥50	≤27	30	22-36	15	9-21	15	11-19
Silt	≤20	≥80	≤12	32	29-35	15	12-18	17	12-20
Silty Clay Loam	≤20	40-73	27-40	34	30-37	19	17-24	15	12-18
Silty Clay	≤20	40-60	40-60	36	29-42	21	14-29	15	11-19
Clay	≤46	≤40	40-100	36	32-39	21	19-24	15	10-20

Source: Adapted from Jensen et al. 1990.

root zone 6% below field capacity means an irrigation application of 0.72 in/ft of root zone depth (6 x 0.12 = 0.72) is needed to replenish soil water to field capacity.

Spatial Variability

The natural forces of wind and water over geologic time are responsible for the soil deposits overlying basalt flows that constitute much of southern Idaho's fertile irrigated farmland. The action of wind and water also segregates many of the soil deposits according to particle size. The ability of both wind and water to move soil particles is velocity dependent. Thus, often the heavier sand-sized particles are left behind while the smaller particles are removed and deposited where velocities are decreased because of localized geographical obstructions. The result over geologic time is spatial variability in soil texture. The larger the area of concern, the greater the potential for spatial variability in soil texture. Spatial variability in soil texture results in spatial variability in water retention characteristics because of the close dependency on soil particle size distribution. Thus, soil texture spatial variability can create problems when interpreting soil moisture measurements from a large area for irrigation scheduling decisions.

For example, the spatial distribution of percent sand and clay in a 25-acre center pivot irrigated field near Firth, Idaho, is shown in Figures 2 and 3, respectively. The percent sand ranges from 75 to 96%, while the percent clay varies from 1 to 7% in a somewhat inverse relationship. While the soil textural classification is either sand or sandy loam for the field, the resulting water retention characteristics vary greatly. The resulting spatial distribution in field capacity and permanent wilting point for the field area are shown in Figures 4 and 5, respectively. Soil water contents representing field capacity range from 11 to 25% while those representing permanent wilting point range from 5 to 10%. This wide variation in soil water content values highlights the difficulty with indiscriminately using soil water content measurements to make irrigation scheduling decisions. For example, direct comparison of soil water content values taken within the field potentially could show a difference of 14% (24-11). This difference could lead to the conclusion that the northwest field area is in dire need of irrigation – which likely would be incorrect. This potential difference in soil water content is largely a reflection of spatial variability and not soil water deficit. This fact is highlighted in Figure 6 which shows the soil water contents across the field for a uniform 0.5 inch soil water deficit (i.e. 4.2% below field capacity). Any effective soil water monitoring plan must take into

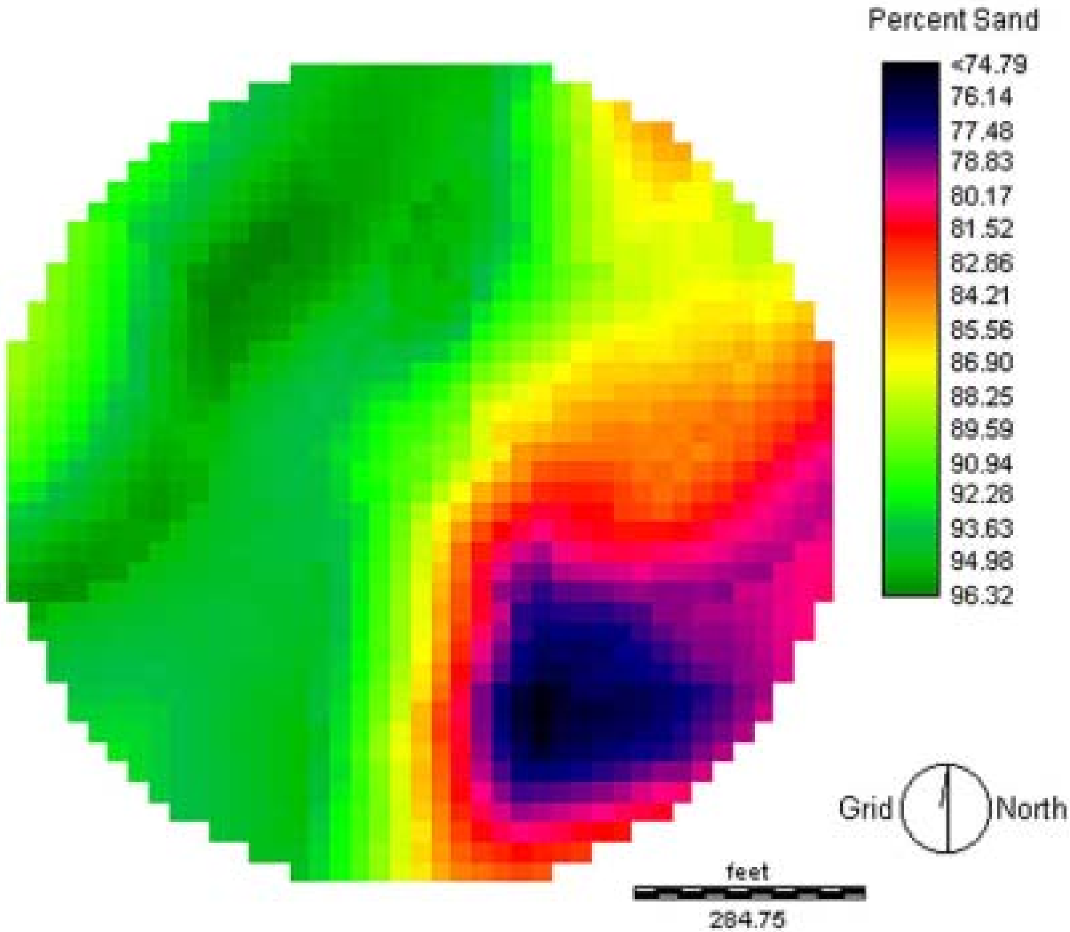

Figure 2. Spatial variability of sand fraction in 25 acre field.

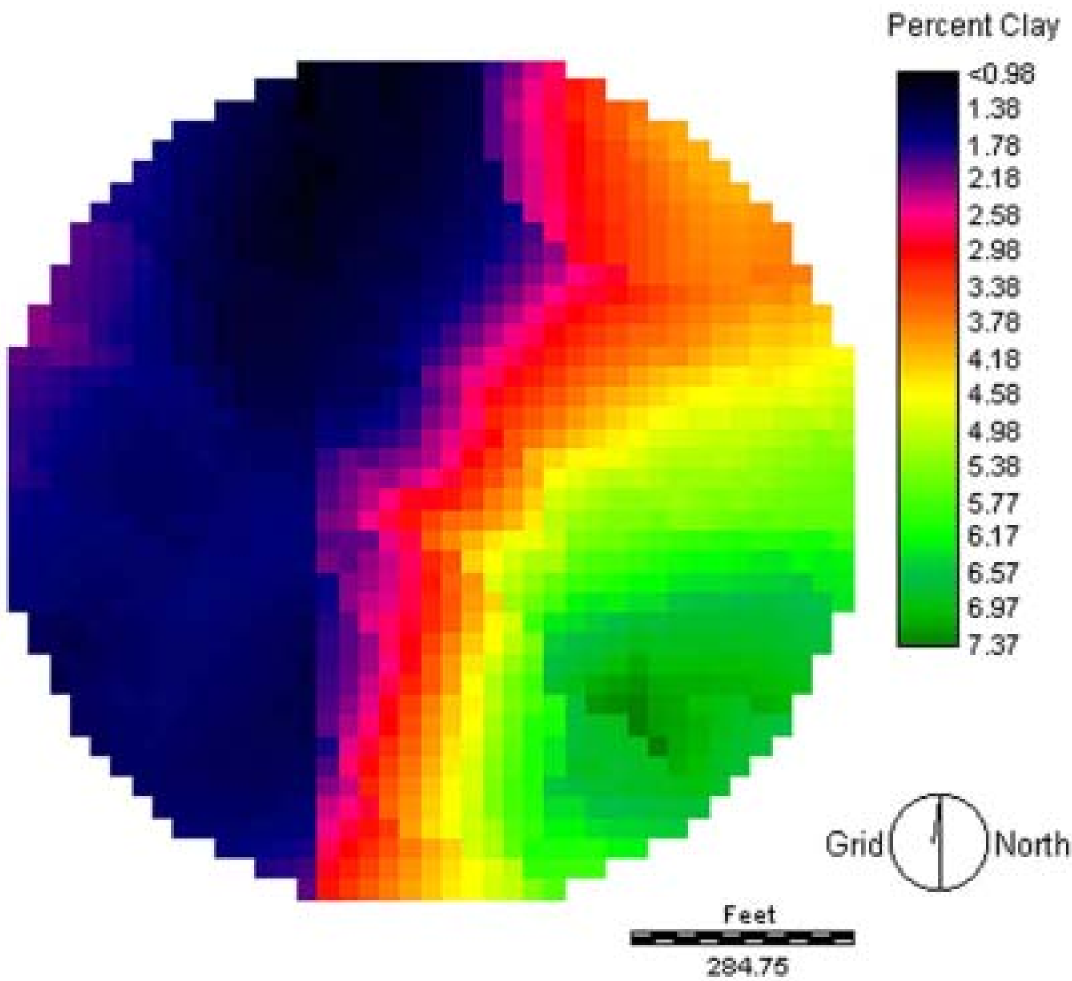

Figure 3. Spatial variability in clay fraction of 25 acre field.

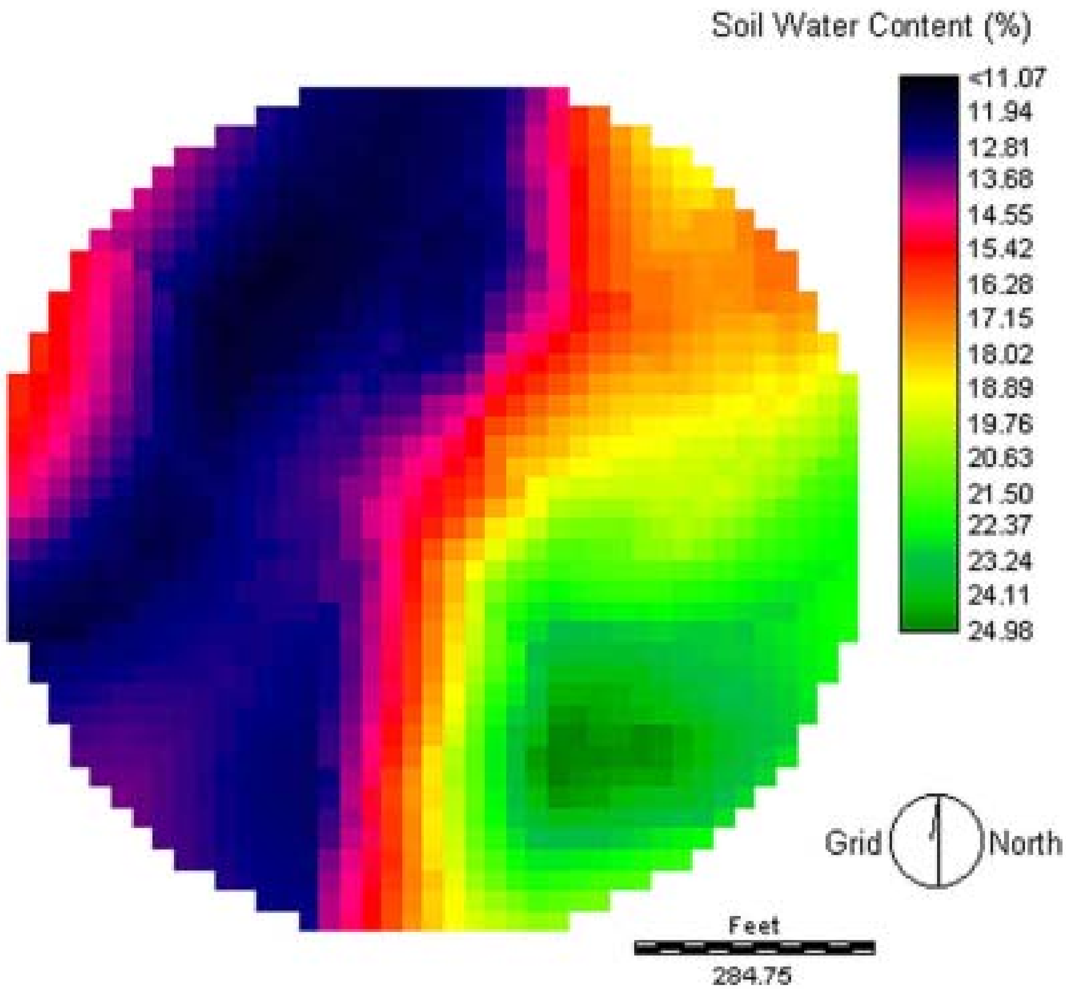

Figure 4. Spatial variability in field capacity of 25 acre field.

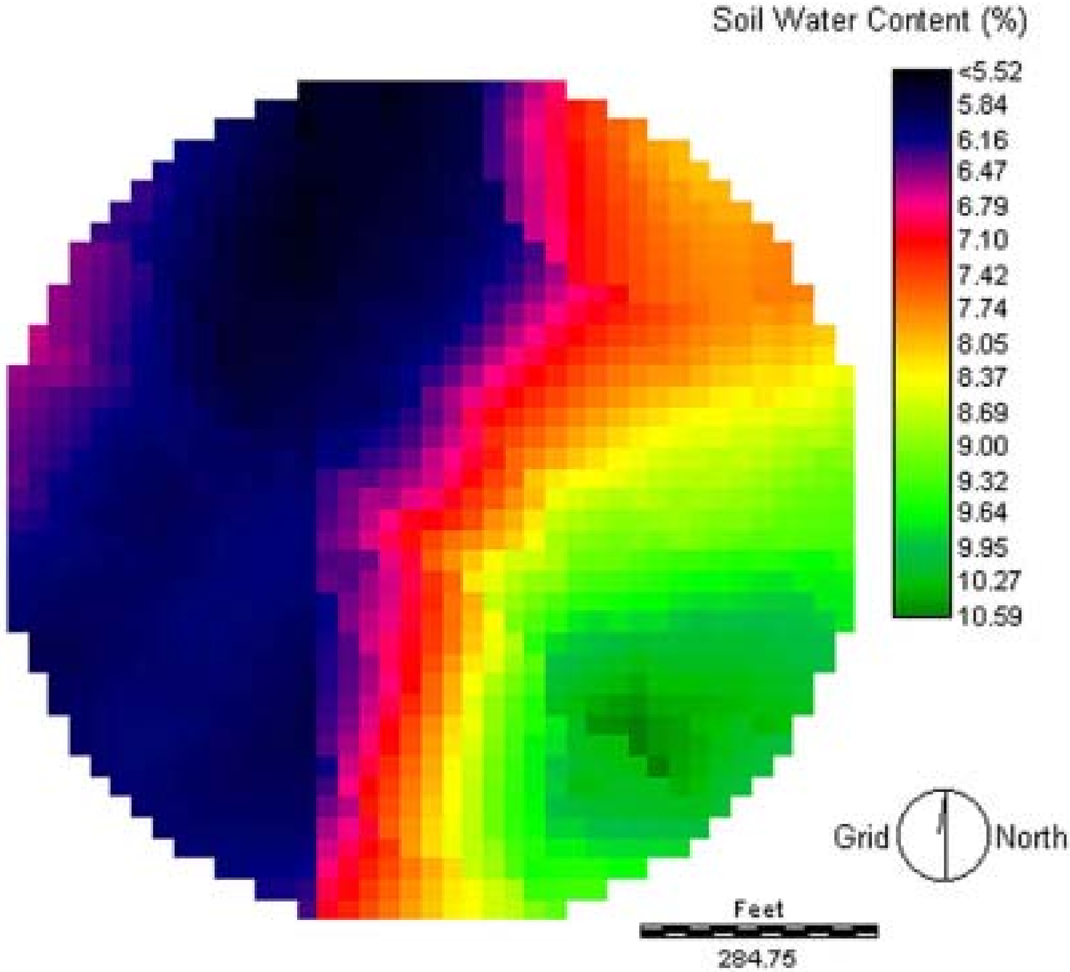

Figure 5. Spatial variability of permanent wilting point for 25 acre field.

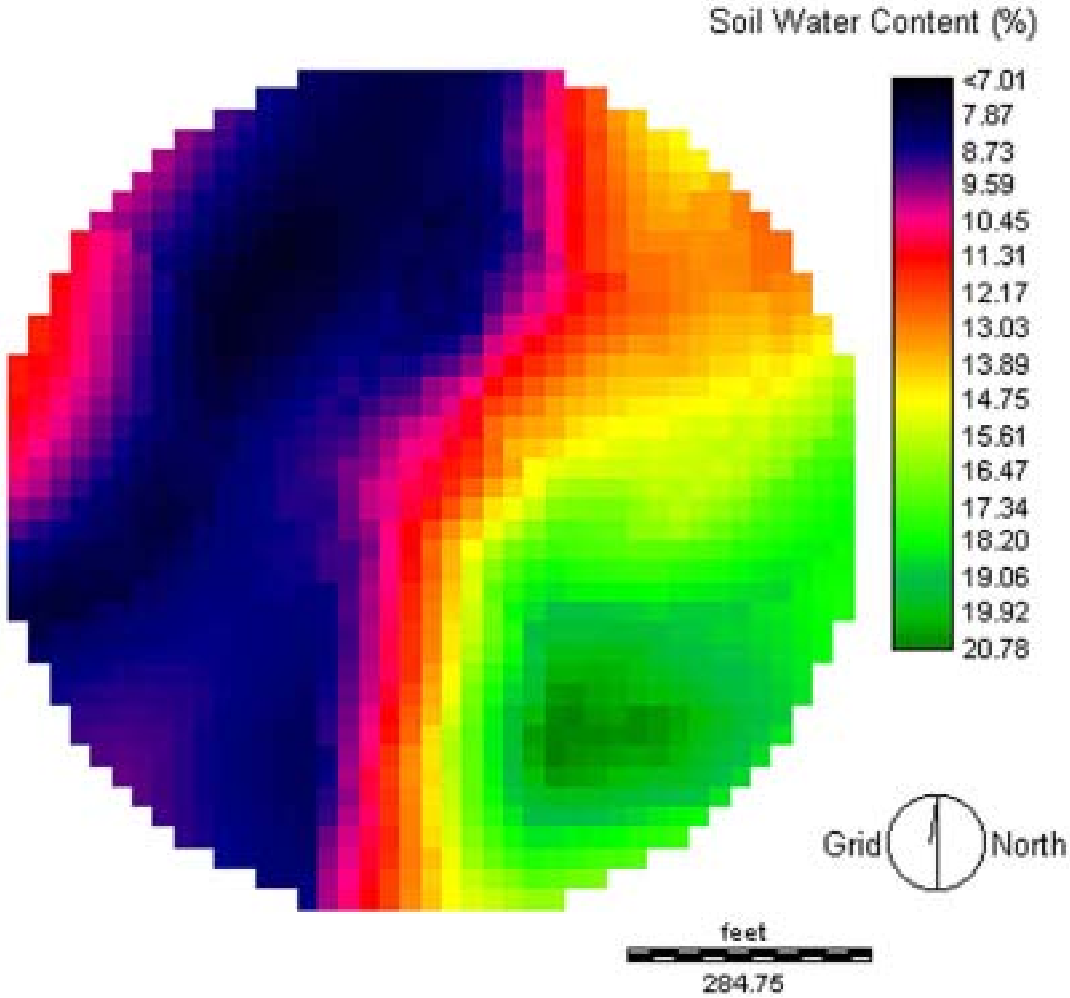

Figure 6. Spatial variability of soil water content value representing a 0.5 inch soil water deficit for a 25 acre field.

account the influence of soil texture spatial variability in order to obtain useful information for scheduling irrigation.

Spatial variability of water holding capacity for the example field is shown in Figure 7. Water holding capacity varies by a factor of 2.6 (5.8-15.1%) across the field, due entirely to spatial variability in soil texture. The area of the field with the lowest water holding capacity is the most critical in terms of irrigation system design requirements and irrigation scheduling to avoid crop water stress and leaching of nitrogen below the crop root zone.

Spatial variability in soil texture usually becomes apparent during normal field tillage operations. Significant variations in soil texture show up as differences in draft as tillage operations traverse the field. Spatial differences in surface soil structure and soil color also are good indicators of soil texture spatial variability. The areal extent of soil textural classes often can be determined from USDA-NRCS soil survey maps and/or aerial photography of bare soil conditions. Dividing the field into water management zones based on soil textural classification provides a basis for locating soil water monitoring equipment. Each water management zone can then receive separate irrigation scheduling if the irrigation system provides such capability, which often is not the case. Theoretically, scheduling irrigations for the area of the field with the lowest water holding capacity should satisfy the irrigation needs of the remaining field area. However, in practice this may lead to areas of the field becoming wetter than optimum. In general, scheduling irrigations for the predominate soil texture may become the best solution. Some areas of the field may develop soil water contents through the seasons that are above and below the optimum range for the crop.

Accommodating Spatial Variability

The influence of soil texture spatial variability on soil water content can be effectively removed by using a site-specific calibration of the soil water monitoring equipment. For irrigation scheduling purposes, the absolute value of soil water content is not important; the relative value with respect to that corresponding to field capacity is of consequence, however. This applies to both stationary and portable soil water-monitoring systems. The important feature of a soil water monitoring system for irrigation scheduling is repeatability and reliability. The key to using any soil water monitoring system is to remove measurement bias that could result from sensor error or soil texture spatial variability by developing a site-specific calibration(s) for the monitoring location(s). This is accomplished by interpreting a specified reading for soil water

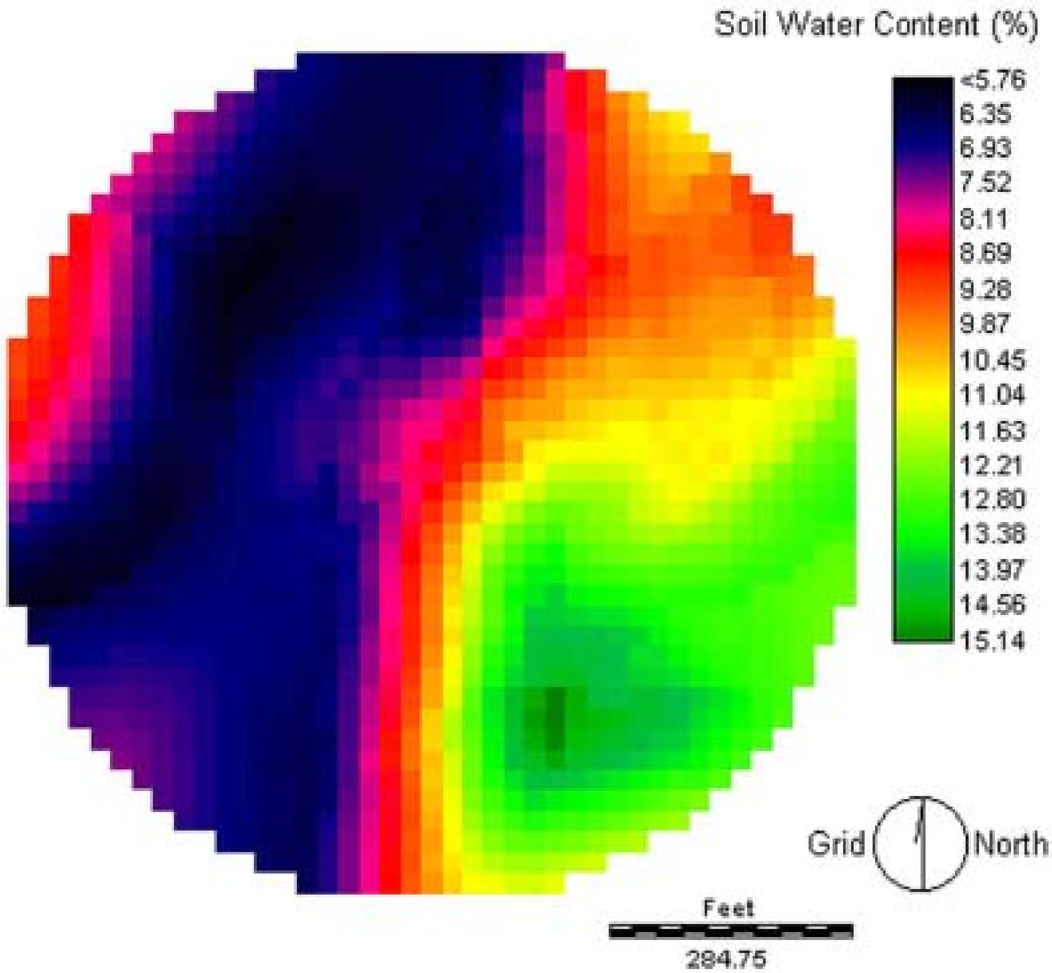

Figure 7. Spatial variability of water holding capacity (% volume) for 25 acre field.

content relative to the reading for soil water content at field capacity. It is imperative that the sensor reading corresponding to field capacity be determined from actual field measurements and not taken from a textbook or laboratory analysis. The reading for field capacity at a given location can be estimated as that obtained in the spring 12 to 24 hours after a full irrigation. This procedure assumes that drainage is not restricted and that the irrigation is sufficient to replace the soil water deficit at the sensor location in the soil profile. For a soil water monitoring system that uses a sensor that is reasonably accurate (i.e. ±3%) and insensitive to soil texture (i.e. one calibration curve) to determine volumetric soil water content, the difference between the field capacity reading and any other reading can be used directly to determine soil water deficit or available soil water.

For example, assume the soil water content readings taken for field capacity in the spring at locations A and B were 15 and 31%, respectively. Further, assume that current soil water content readings for sensors located in the 0-12 inch depth are 10.5 and 25% for locations A and B, respectively. Then the soil water deficit at location A is 4.5% (15-10.5=4.5) or 0.5 inch (4.5x.12=0.54) and at location B is 6% or 0.7 inch. The corresponding percent available soil water can be estimated using the soil texture based values of available water given in Table 1. For example, at location A the soil water content readings are representative of those for a sand that could be confirmed from visual inspection. From Table 1, the available water for a sand is 8% on average. Percent available soil water is calculated as:

$$\left[\frac{\text{Available Water} - \text{Soil Water Deficit}}{\text{Available Water}}\right] \text{x}\,100 \qquad \text{Equ. 1}$$

Thus, the percent available soil water in the 0-12 inch depth for location A is approximately 44% [((8-4.5)/8)x100=43.8]. Similarly, for location B, the soil water content readings are indicative of a silt loam soil with an average available water of 15%. Thus, the estimated percent available soil water in the 0-12 inch depth is 60% [((15-6)/15)x100=60] at location B. The rather large difference in percent available soil water between the two locations is because a silt loam soil has nearly twice the water holding capacity of a sand.

The preceding example was based on a soil moisture sensor that is insensitive to soil texture. In the past ten years, more electronic-based sensors for measuring soil water content have appeared on the market than in the previous 50 years. Nearly all of these new sensors are based on one of two principles for measuring the bulk electrical properties of soil to infer soil water content. These two principles are Time Domain Reflectometry (TDR) and Capacitance or Frequency Domain Reflectrometry (FDR). Both techniques are based on the fact that the bulk dielectric constant of a dry mineral soil is approximately 4 and that of water is approximately 80. Thus, the mass (volume) of water in the soil greatly influences the bulk dielectric constant of soil. Both techniques measure the bulk soil dielectric constant which is correlated to soil water content and thus used as an indirect measure of soil water content. In the case of TDR, two parallel electrical conductors are buried in the soil and a high frequency voltage pulse is applied at one end. The voltage pulse travels down the parallel conductors and is reflected back when it reaches the end of the parallel conductors. The time it takes for the voltage pulse to return to the source end of the parallel conductors is directly related to the bulk soil dielectric constant and hence can be calibrated to indicate soil water content. Since the travel time of the voltage pulse is the measured parameter, the technique is called Time Domain Reflectometry.

In the case of FDR, two poles from which electromagnetic radiation is generated using a high frequency oscillator are established in the soil profile with soil separating the poles. The capacitance of the soil separating the two poles causes a frequency shift in the oscillator relative to its natural frequency. The capacitance is a function of the geometry of the system and the bulk soil dielectric constant and hence soil water content. Unfortunately, the frequency shift of the oscillator also depends upon bulk soil electrical conductivity which is a function of soil texture, clay mineralogy, bulk density, and soil salinity. The influence of soil electrical conductivity decreases with increasing oscillator frequency to a limit. Some FDR-based sensors simultaneously measure soil electrical conductivity and use the measurement to compensate for the effect on frequency shift, allowing the development of a single calibration curve. The potential effect of soil texture on the response of an FDR-based sensor is shown in Figure 8 which depicts manufacturer supplied calibration curves for a particular sensor. The net effect is that soil water content, as well as sensor output, are influenced by soil texture. Soil-texture dependent FDR sensor response, coupled with spatial variability in soil texture, makes site-specific calibration a necessity for their effective use in irrigation scheduling.

Application of FDR-based sensors for irrigation scheduling involves using the soil water monitoring system to maintain soil moisture within upper and lower bounds while basing irrigation timing and amounts on regional crop water use estimates. The soil water monitoring system provides the feedback as to how well the irrigation schedule is doing at meeting the crop

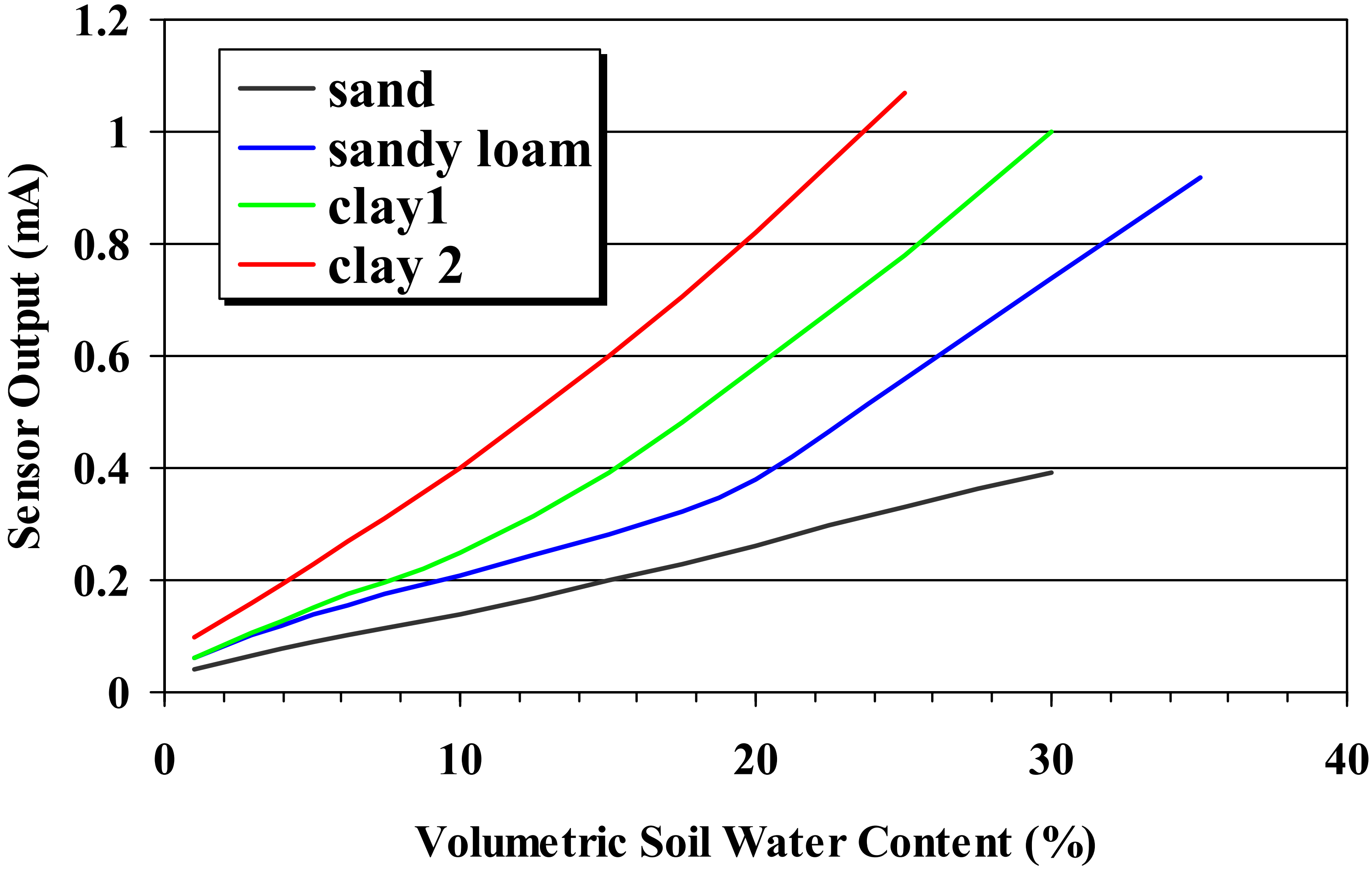

Figure 8. Soil texture dependent calibration curve for an example soil moisture sensor that uses the FDR technique to determine soil water content.

needs and guiding adjustment of regional crop water use estimates to the local field scale. Site-specific calibration involves establishing the upper and lower bounds for soil moisture in the output measure of the soil water monitoring system. These upper and lower bounds are best established early in the season when daily crop water use is low and can be adjusted if necessary during the season. The upper bound represents field capacity for the location in terms of the output measure of the monitoring system. The upper bound can be taken as the reading 12-24 hours following an irrigation. Excess water should drain from the soil profile and decrease to a negligible rate after this time period. This approach assumes that the irrigation is sufficient to remove any soil water deficit at the sensor depth and drainage is not restricted. If crop water use is minimal, the decrease in drainage from the root zone when field capacity is attained should show up as an inflection point in a graph of soil water content data collected by the soil water monitoring system (Figure 9). The "ideal" response depicted in Figure 9 (curve A) shows an inflection point at approximately 0.59 mA which then represents field capacity in terms of sensor output. This ideal response is representative of sensors within the top 12 inches of the crop root zone.

For sensors placed deeper in the root zone, water movement to and past the sensor may be slowed, requiring a longer time period after irrigation to select the upper bound and obscuring an identifiable inflection point. An example graph of this situation also is shown in Figure 9 as curve B. In the event that the irrigation is insufficient to increase soil moisture to field capacity, the output from the soil moisture monitoring system will increase but not decline rapidly following irrigation. This situation is depicted as curve C in Figure 9. Establishing the upper bound for soil moisture from output of the soil moisture monitoring system requires that crop water use be minimal so that the response following an irrigation is not obscured by water use of the crop. Establishing the upper bound is easier with sensors placed in the top 12 inches of the root zone because soil moisture is more dynamic than at greater depths, and by necessity field capacity must be reached in order to create drainage to replenish soil water deeper in the root zone when water is applied at the soil surface. For soil profiles that are reasonably homogeneous with depth, the upper bound established for sensors in the top 12 inches can be used to approximate the upper bound for sensors at greater depths.

The lower bound represents the soil water content below which crop yield and/or quality are adversely impacted as water stress develops. This lower bound is crop- and often time-

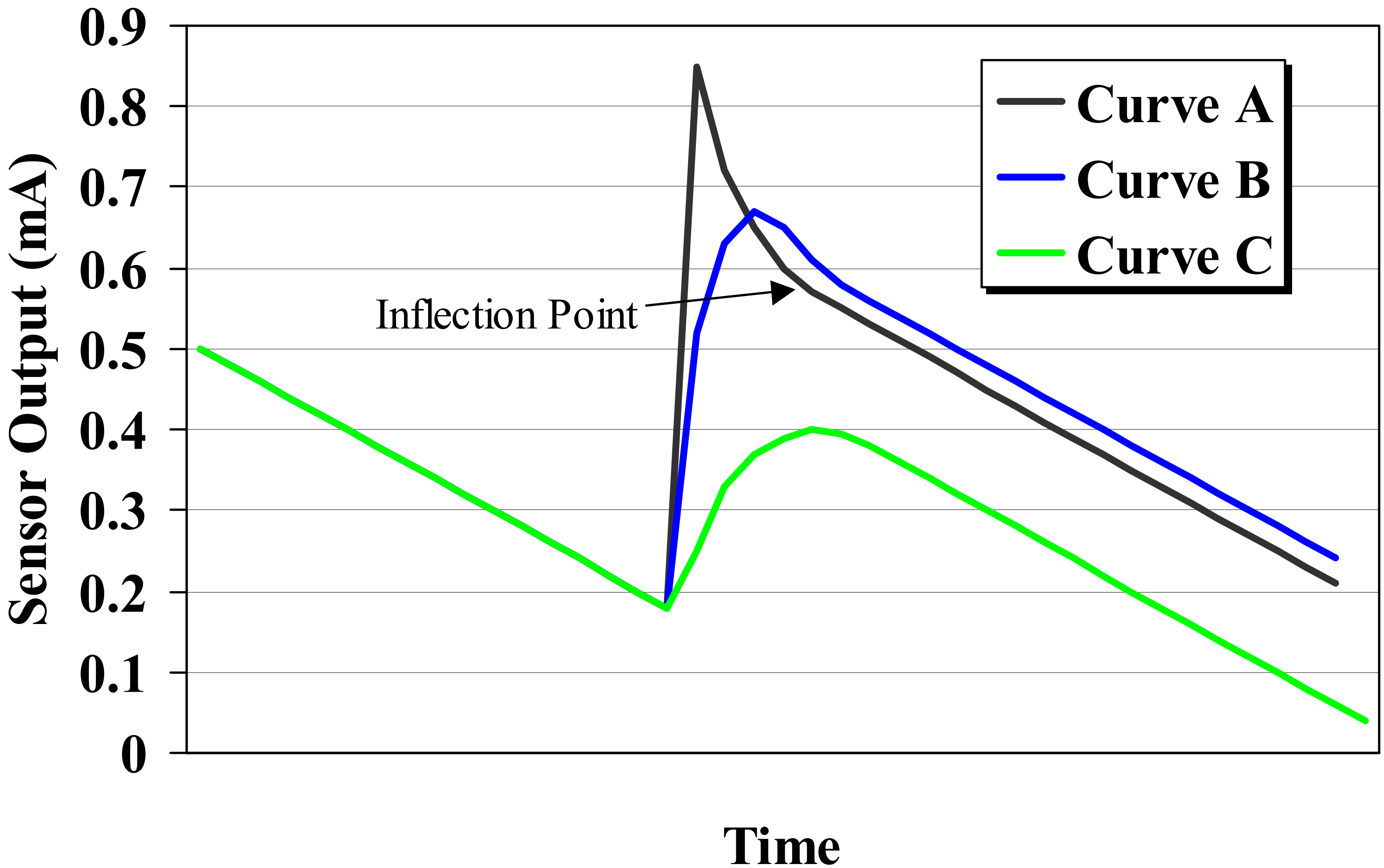

Figure 9. Graph of soil moisture monitoring system output used to estimate the upper bound on soil water content following irrigation

dependent. It is normally given as a percentage of available water remaining in the crop root zone. For example, percent available soil water in the root zone for potatoes should remain above 65%. Since plants typically withdraw more water from the upper root zone than the lower root zone, soil water contents will typically be lower in the upper root zone compared to deeper in the root zone when a given percentage of available water is remaining for the total root zone. Thus, the lower bound for soil water content usually can be less for the upper root zone compared to the lower root zone.

Conceptually, the lower bound can be established on the basis of the soil moisture contents for field capacity and permanent wilting point given in Table 1. Unfortunately, this is difficult to do when using a soil water monitoring system that does not provide absolute values of soil water content. However, one of two approaches can be used to estimate a suitable lower bound. A lower bound can be established on the basis of visual observations of crop and near-surface soil conditions coupled with experience. The lower bound established for sensors in the upper root zone can then be applied to those in the lower root zone. While this approach is highly qualitative, it provides a suitable reference for maintaining soil water content within the desirable range throughout the season.

The second approach involves using calibration curves from the manufacturer and visual evaluation of soil texture to establish a lower bound. For example, assume that the sensor calibration curves shown in Figure 8 are for the sensor being used and the soil is a sandy loam. From Table 1, the approximate soil water contents for field capacity, permanent wilting point, and available water are 23, 10, and 13%, respectively. Assume the desired lower bound represents 65% available water. The corresponding soil water content can be calculated as:

$$\text{Permanent Wilting Point} + [\text{Available Water}] * \left[\frac{65}{100}\right] \qquad \text{Equ. 2}$$

Thus, the soil water content corresponding to 65% available water is 18% [10+(13)(65/100)=18.4]. From Figure 8 and the calibration curve for a sandy loam soil, the corresponding lower bound for sensor output is 0.33 mA which represents 18% volumetric soil water content. This approach provides a good initial estimate for this lower bound of soil water content in terms of sensor output.

Site-specific calibration of sensor output based on a thorough understanding of soil water retention characteristics and experience are necessary for obtaining useful information for making irrigation scheduling decisions. The site-specific calibration procedures must be applied at each soil water monitoring location in order to mask the effect of soil texture spatial variability on soil water measurements. For the preceding example, the upper and lower bounds were established in terms of sensor output as 0.59 and 0.33 mA, respectively. Following establishment of these bounds, irrigation amounts and timing can occur according to a daily soil water budget or less desirably based on experience. Routine evaluation of soil water content(s) can then be compared to the established upper and lower bounds and the irrigation schedule adjusted accordingly. For example, if the soil water content just prior to irrigation is increasing over time, the irrigation amount and/or frequency needs to be reduced. Conversely, if the soil water content just prior to irrigation is decreasing over time, the irrigation amount and/or frequency needs to be increased. Site-specific calibration of sensor response provides the basis for making correct adjustments to the irrigation schedule and maintaining soil moisture within the optimum range for the maximum crop yield and quality.

Summary

Soil moisture monitoring is necessary for effective irrigation scheduling. It provides the information needed to ensure the irrigation schedule is supplying the water needs of the crop while maintaining optimum soil moisture for maximum crop yield and quality. Soil texture has a large impact on actual soil water content values and water holding capacity. The existence of spatial variability in soil texture can create problems when interpreting soil water measurements for irrigation scheduling decisions. A good understanding of the relationship between soil texture and soil water content is necessary in order to interpret soil water measurements.

Evaluating soil water measurements relative to that corresponding to field capacity for a specific field location is an effective way to filter out spatial variability effects. Many of the new sensors for measuring soil water content based on the bulk electrical properties of the soil also are influenced by soil texture. Practical application of these new soil water monitoring systems for irrigation scheduling requires that they be calibrated for a specific field location. This is accomplished by establishing an upper and lower bound for the output of the soil water monitoring system which represents the desired range for soil water content. The upper bound is established by inspection of output from the soil water monitoring system following an irrigation. The lower bound can be established on the basis of visual crop and soil conditions and experience or from the manufacturer's calibration curves and knowledge of appropriate soil water content values.

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