Irrigation Water Management Strategies for Precision Farming

Introduction

Under Precision Farming, agronomic practices are varied within a field to match locally varying conditions. This concept, when applied to irrigation water management, requires that we look at those conditions which could vary locally, and which could influence water management strategy.

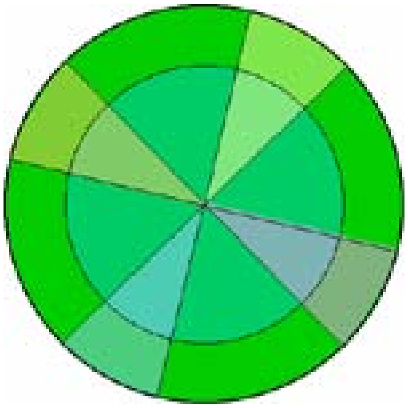
It should be noted that we are only concerned with variations that occur on a scale smaller than the smallest manageable block. For example, there may be tremendous variability over 320 acres. But if the fields and irrigation systems are divided so that individual 40-acre blocks can be managed separately (different irrigation timing and amount), only the variations within the 40-acre blocks may require special treatment.

Plant Conditions

Although we tend to think of commercial agriculture in terms of fields planted to a uniform crop (monoculture), there are times when certain crop factors may vary within a field.

1. Multiple crops may be grown within the same field. Although not common in California or the West, occurrences of this phenomenon precipitated some early instances of what might be called precision irrigation in today's terminology.

An example (see below) is the use of center pivot irrigation systems to irrigate large fields comprised of smaller sub-fields, each with its own crop. The sub-fields may be divided by radial lines, like a pie, with each sector containing a different crop. Or, the sub-fields may be divided by circumferential lines, like the rings on a target. Combinations may also be used. Applications engineers have devised special systems to provide the benefits of large scale center pivot irrigation to collections of smaller plots by arranging these plots in this fashion.

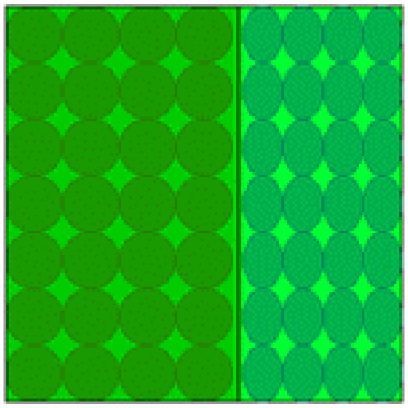


A center-pivot field comprised of smaller sub-fields.

In one project [1], the sprinklers on the center pivot were divided into an inner and outer set. The inner set ran along the inner 70% of the machine's length, and covered an inner circle of 50% the total irrigated area. The outer set ran along the outer 30% of the machine's length, and also covered 50% of the total irrigated area. The machine could operate with one or the other or both sprinkler sets spraying water. Further subdivisions were made radially, and the speed of the machine varied the watering time. This system provided the water managers with considerable flexibility and control. With judicious placement of crops according to system capabilities and requirements, proper water management could be achieved for multiple crops throughout the field.

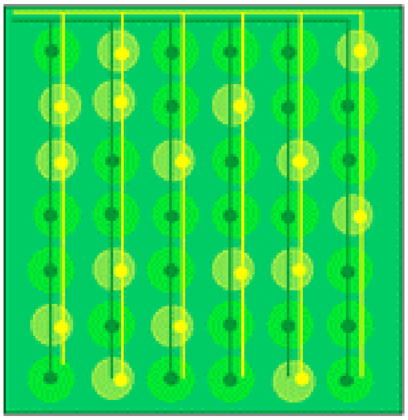
More recently [2], site-specific water applications have been accomplished by fitting up to three, independently valved, 30-foot long manifolds at each location along a center pivot. Each manifold was designed to apply 1, 2 or 4 times the minimum application rate. By operating various combinations of manifolds at each location, and adjusting the center pivot's rotation speed, variable irrigation depths can be applied to blocks through out the irrigated circle. The report of this work [2] includes a review of other recent work to modify center pivot or linear move irrigation machines to achieve similar aims.

2. Plant variety and/or spacing may change. In a vineyard, for example, a single field may contain blocks with different conditions. The variety, spacing, or trellis/pruning regime may vary from block to block (see below for an example). The irrigation system or operation may need to be adjusted to accommodate the block-to-block variations. If vine spacings vary between blocks, then furrow irrigation frequency or hours of operation may need to vary also to compensate. In the case of drip irrigation, changing drip emitter discharges may provide sufficient compensation. In this case, the field may be irrigated as a whole, and wouldn't require a separate system for each block.



A vineyard with two sub-blocks containing different vine spacings.

3. Plant size may vary. Particularly for permanent crops like trees and vines, the cumulative effect of past practices may have resulted in trees of varying size throughout the field. Or replacement of damaged may result in newer, and hence smaller, plants at some locations. A recent project [3] categorized citrus trees in a field as either large or small, and supplied water to large and small trees independently by using two independently valved irrigation lines down each tree row. One line supplied water to microsprinklers adjacent to the large trees, while the other one similarly supplied the small trees (see illustration below).



Independently valved irrigation lines allow separate irrigation regimes for large and small trees randomly located throughout the field.

A similar, but more complex system has been used to differentially irrigate a mix of indoor, ornamental potted plants [4]. A complicating factor was that the mix of plants was expected to change from time to time. Plants were identified as belonging to one of four categories based on type, size and water requirements. The irrigation system consisted of four independently valved sub-systems, each with supply lines running through our the area to be irrigated. A line from each sub-system was placed along each plant row, and each location was fitted with drip outlets from all four lines. The outlets could be manually opened or closed. Whenever a plant was placed or replaced at a particular location, the drip outlet to the appropriate line was opened. The irrigation time and frequency for each sub-system was varied to match the needs of plants in that category.

4. Plant size (cont'd) may also vary in a way that is not known a priori. This is particularly true for annual crops, where to identify and map undersized plants prior to the installation of the irrigation system may not be feasible. In this instance, a precision farming would require sensing the size of the plant, using sensors placed or brought to each location, and adjusting the agronomic practice based on the sensor readings. For precision irrigation, smaller water applications would be delivered to the smaller plants.

A location could be an individual plant or contiguous group of plants. If the agronomic practice were delivered by vehicle, then an optical (or other) sensor on the vehicle could provide the information needed to adjust the delivery rate. Moving irrigation systems, such as center pivot or linear move systems could use such an approach, with several sensors located along the length of the moving machine. Controllable areas might be on the order of hundreds of square feet: the 30 foot manifolds mentioned above, combined with a spay pattern width of 10 feet yields a control area of at least 300 square feet. So sensors need the ability to survey and integrate their readings over such areas.

But for stationary irrigation systems, one, or even a several, sensors and information relay devices can't cover the entire field. Instead, one sensor and information relay is needed for each location. This is not presently feasible for the large plant populations associated with most annual crops.

Summary. So the precision farming strategies for variable plant conditions are two:

(i) group the plants into contiguous blocks of plants with similar characteristics (see numbers 1 and 2 above), or

(ii) identify the locations of plants with similar characteristics, essentially forming non-contiguous "nets" of plants with similar characteristics (number 3 above).

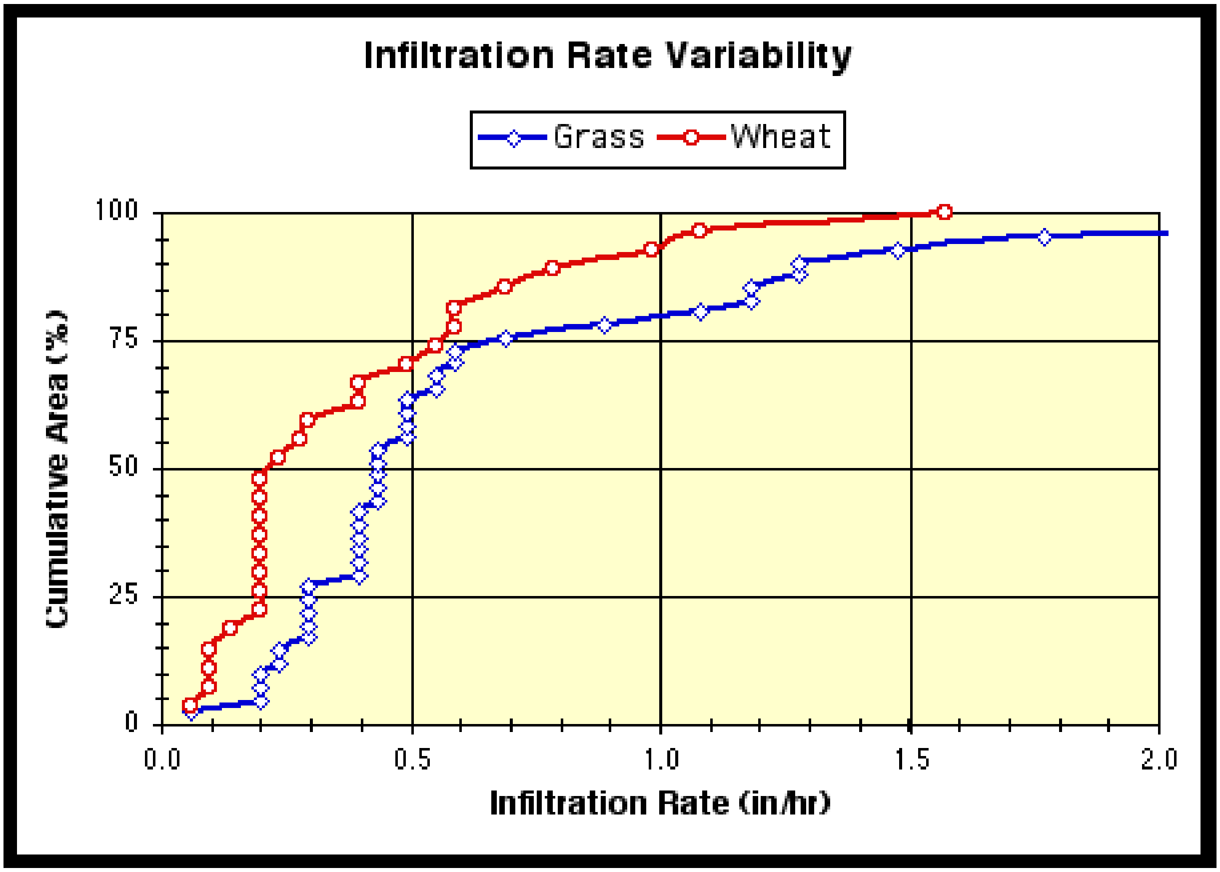
In either case, one must develop an irrigation system comprised of hardware and/or operational sub-groups appropriate to the plant characteristics in each block or net.

Soil Properties

It is well known that soil properties may vary on a geographic scale much smaller than the commercial agricultural field scale. Two important soil properties that influence irrigation and water management are infiltration rate and available water holding capacity (AWHC). These can be particularly important for surface irrigation methods, wherein the soil plays a key role both in transporting the water through out the field, and in controlling its infiltration into the plant root zone.

1. Infiltration Rate Variability. Infiltration rates may vary with location in either a systematic or random fashion. The most common cause of systematic variation is differences in soil compaction. Wheel rows tend to be more compacted than non-wheel rows, and consequently have lower infiltration rates.

Random variability in infiltration rate is the result of natural differences in soil properties throughout a field. The chart below illustrates the variation in infiltration rates at one site in Oklahoma [5]. The soils are generally loam and silt loam soils. The samples for both the wheat and grass data were taken from 4 sub-plot each of about 4 acres in size. The sub plots were adjacent, but separated by about 30 feet. Thus the variability shown for each crop is experienced over an area of less than 20 acres.



Variability in soil infiltration rate as measured by double-ring infiltrometers.

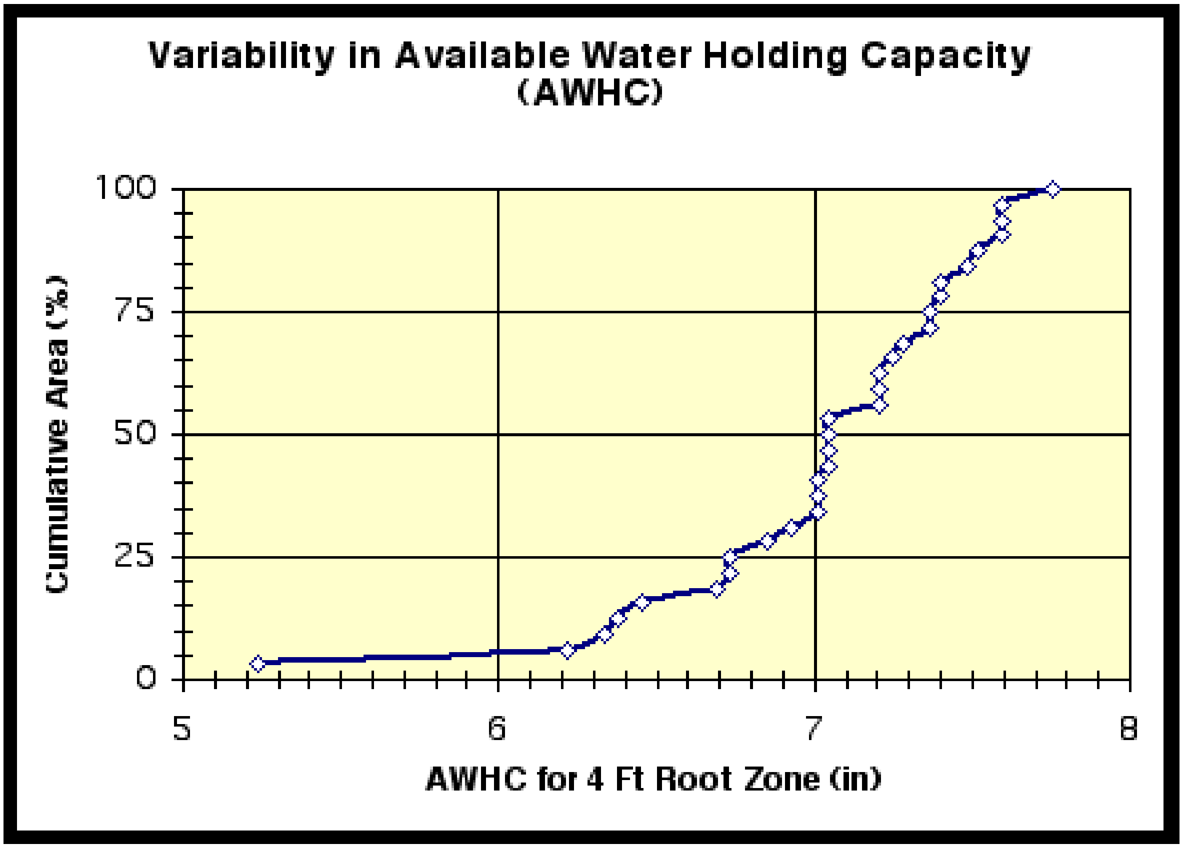
The median infiltration rate for the wheat area was about 0.2 in/hr. But about 15% of the area had infiltration rates of half that rate or less, and about a third of the area had infiltration rates of twice that rate or more. The median infiltration rate for the grass area was about 0.4 in/hr. But about 10% of the area had infiltration rates of half that rate or less, and about 25% of the area had infiltration rates of twice that rate or more.

2. AWHC Variability. The amount of water that is held by the soil and is available to the plants is dependent on soil type. Typical values [8] for a range of soil types are tabulated here:

Soil Type	Available Water Holding Capacity (AWHC, in/ft)
Fine Sand	0.86
Sandy Loam	1.07
Clay Loam	1.68
Loam	1.78
Clay	1.87
Silt Loam	2.08

The silt loam holds more than two and a half times more water that the fine sand. This is an important consideration when trying to determine irrigation frequency and duration.

The following chart illustrates the variation in available water holding capacity at one site in Arizona [6]. The data are from neutron probe measurements made at 32 sites equally spaced through out an area of just over 3 acres. Measurements were made at 8 inch increments and integrated over a 4-foot root zone.



Variability in soil available water holding capacity.

The median AWHC was just over 7 inches for a 4-foot root zone. About 15% of the area had AWHC values of 6.5 inches or less, and about 15% of the area had AWHC values of 7.5 inches or more.

3. Strategies for Variable Infiltration Rates. Possible responses to variable infiltration rates depend on irrigation system type.

With surface irrigation methods, the depth of water applied at any one location is controlled by infiltration rate, opportunity time (the length of time water is ponded on the soil surface) and wetted area. Opportunity time depends on the advance of the water across the field, which in turn is controlled by land grading (slope), surface roughness, and by water inflow rates. For furrow systems, furrow size and shape may affect both advance and wetted area.

Systematic differences in infiltration rate due to wheel row compaction may be minimized by using "torpedoes," or weights drawn through non-wheel row furrows to increase compaction and reduce infiltration rates. An alternate approach is to irrigate the wheel rows and non-wheel rows on different irrigation schedules.

With the possible exception of furrow shape and size, surface irrigation factors affecting infiltrated amount cannot generally be varied on a local scale. And even local variations in furrow size may affect conditions far beyond the local area of the change. For example, narrowing the furrow width to reduce wetted area could compensate for the high infiltration rate in sandy areas. However, narrowing the furrow width would affect water advance, and hence opportunity time at all locations down-slope from the location of the change.

So surface irrigation strategies for minimizing the influence of variable infiltration rates is probably limited to reducing the size of managed irrigation blocks, perhaps by reducing the lengths of furrows or border strips. Depending on the length scale over which the infiltration rate changes occur, this may or may not reduce the amount of infiltration rate variability in any one block,. But it will tend to minimize other variations affecting water applications, particularly opportunity time differences.

With sprinkler irrigation, systems are usually designed so that the application rate is less than the infiltration rate. This means that the system's application rate controls water entry into the root zone, not the soil infiltration rate. So soil infiltration rate variability should not require any adjustment in sprinkler system equipment or operation.

High application rate sections of moving systems, such as center pivot and linear move sprinkler systems, may apply water faster than the soil's infiltration rate. But these systems depend on surface storage of temporarily ponded water to prevent runoff until the applied water can be absorbed. Surface storage may be increased by implementing no-till or low-till practices, or by using special tillage equipment to form many small basins to impound ponded water. This latter approach is especially appropriate if the center pivot or linear move systems are fitted with LEPA (Low Energy Precision Application) water emission devices.

With microirrigation systems, the application rate of the emission device controls the amount of water that enters the root zone. While very tight soils can sometimes experience localized runoff problems, even with microirrigation, these are usually controlled by reduced emission rates (accompanied by longer or more frequent irrigations), or localized physical control of the water (small basins).

Summary. So the precision farming strategies for variable soil infiltration rates are these:

(i) for surface irrigation systems

(a) control compaction-based variability in infiltration rates with "torpedoes" or by irrigating wheel rows and non-wheel rows on different irrigation schedules.

(b) reduce the size of managed irrigation blocks, perhaps by reducing the lengths of furrows or border strips.

(c) switch to some form of pressurized irrigation system (sprinkler or microirrigation).

(ii) for pressurized irrigation systems

(a) use application rates below the infiltration rates

(b) if sprinkler application rates must exceed the soil's infiltration rate, use tillage practices to create and maintain surface storage.

(c) if microirrigation on a very tight soil experiences a localized runoff problem, consider reduced emission rates (accompanied by longer or more frequent irrigations), or localized physical control of the water (small basins).

4. Strategies for Variable AWHC. Available Water Holding Capacity (AWHC) is the total amount of water in the plant root zone that is available to plants. The strategic response to variable AWHC depends on the irrigation management objectives.

For many crops, the irrigation objective may be summarized as "full irrigation." Each irrigation is designed to refill the root zone - the net application amount should equal the amount of water used by the crop since the last irrigation. The irrigation frequency is chosen to ensure that the soil never gets "too dry" between irrigations. This means that irrigation should be performed before the soil moisture tension reaches a level that would be detrimental to crop growth and yield. As we shall see shortly, the irrigation strategy for locally variable AWHC doesn't necessarily involve locally variable irrigation applications.

For some crops, an irrigation objective other than full irrigation is desirable. These crops need to be stressed at some point in their growth cycle to achieve certain agronomic objectives. An example important to California is the production of wine grapes. Vineyard managers may wish to stress the vines to control vigor and lateral growth of the vines, to maintain berry size, or to affect the chemistry within the fruit (sugar content, etc.). The vines are stressed by maintaining elevated levels of soil moisture tension. Higher soil moisture tensions can be achieved if the net application amount at each irrigation is less than the amount of water used by the crop since the last irrigation. For these reasons, irrigation regimes associated with desirable stress may be called "deficit irrigation." With these irrigation objectives, locally variable irrigation amounts may be the appropriate strategic response to locally variable AWHC.

4.a. With Full Irrigation. Available Water Holding Capacity (AWHC) is the total amount of water in the plant root zone that is available to plants. For a given rate of plant water use (crop evapotranspiration, ETc), field locations with lower AWHC will need more frequent irrigation, and when irrigated will require smaller water amounts when irrigated.

But the situation for high AWHC locations isn't exactly the opposite. Field locations with higher AWHC, could tolerate an extended irrigation interval, but don't require one. Field locations with higher AWHC, would require larger water amounts when irrigated only if an extended irrigation interval were used.

In general, the time between irrigations is determined by how much water can be used by the crop before undesirable stress sets in (related to AWHC) and by how fast the crop is using water (ETc). However, the amount of water to add back to the soil at each irrigation is determined by how long it has been since the last irrigation, and how much water the crop has used since then. This means that even in variable AWHC fields, we can manage the irrigations effectively be selecting the irrigation interval appropriate to the those locations with low AWHC, and by setting the irrigation amount appropriate to this interval and the crop water use rate. Those areas with higher AWHC will receive water a little more frequently, and in somewhat smaller amounts than if the irrigations were being managed for them, but no harm is done. They will also remain above the critical stress-generating water level.

Therefore the strategy for locally variable AWHC doesn't necessarily involve locally variable irrigation applications. Knowledge of the variability in AWHC will be used, but only to set the irrigation interval for the field as a whole. When the irrigation is actually done, a uniform amount can be used for the entire field.

Example. A numerical example will illustrate this concept. Consider a crop with a 4 foot root zone using 0.25 inches per day. A full irrigation regime is planned, with the irrigation frequency chosen so that the soil moisture tension never exceeds 125 centibars (125 cb). The crop is grown in a field containing both Sandy Loam and Silt Loam soils. Relevant data for the two soils are as follows [8]:

Soil Type	Silt Loam	Sandy Loam
Field Capacity (FC)	3.49 in/ft	2.64 in/ft
Permanent Wilting Point (PWP)	1.80 in/ft	1.57 in/ft
Available Water Holding Capacity (AWHC = FC - PWP)	1.69 in/ft	1.07 in/ft
Moisture Content at 125 cb Tension	2.77 in/ft	2.20 in/ft

The amount of water per foot that can be used before the soil reaches the maximum allowed tension is:

FC - Moisture Content at 125 cb

For a 4 foot root zone, the total amount of water that can be used before the soil reaches the maximum allowed tension is:

4 x (FC - Moisture Content at 125 cb)

The maximum irrigation interval will be the this amount of water divided by the rate of crop water use, 0.25 in/day in this example:

[4 x (FC - Moisture Content at 125 cb)]/[0.25 in/day]

The results of these calculations may be summarized as follows:

Soil Type	Silt Loam	Sandy Loam
Field Capacity (FC)	3.50 in/ft	2.64 in/ft
Moisture Content at 125 cb Tension	2.54 in/ft	2.20 in/ft
Allowable Water Use, Per Foot	0.96 in/ft	0.44 in/ft
Allowable Water Use, Total	3.83 inches	1.75 inches
Rate of Crop Water Use	0.25 in/day	0.25 in/day
Maximum Irrigation Interval	15.3 days	7 days

Irrigating at any interval longer than 7 days will cause the soil moisture tension to exceed the allowable 125 cb in the Sandy Loam portion of the field. But if the entire field is irrigated with an interval of 7 days, the soil moisture tension will remain below 125 cb for both soils.

For both soils, the amount of water used during 7 days will be:

7 days x 0.25 in/day = 1.75 inches

For the 4 foot root zone, this corresponds to:

[1.75 inches]/[4 foot root zone] = 0.44 in/ft

The moisture content just prior to each irrigation will be:

FC - Water Used During 7 days

For the Sandy Loam soil, the moisture content will be

2.64 in/ft - 0.44 in/ft = 2.20 in/ft

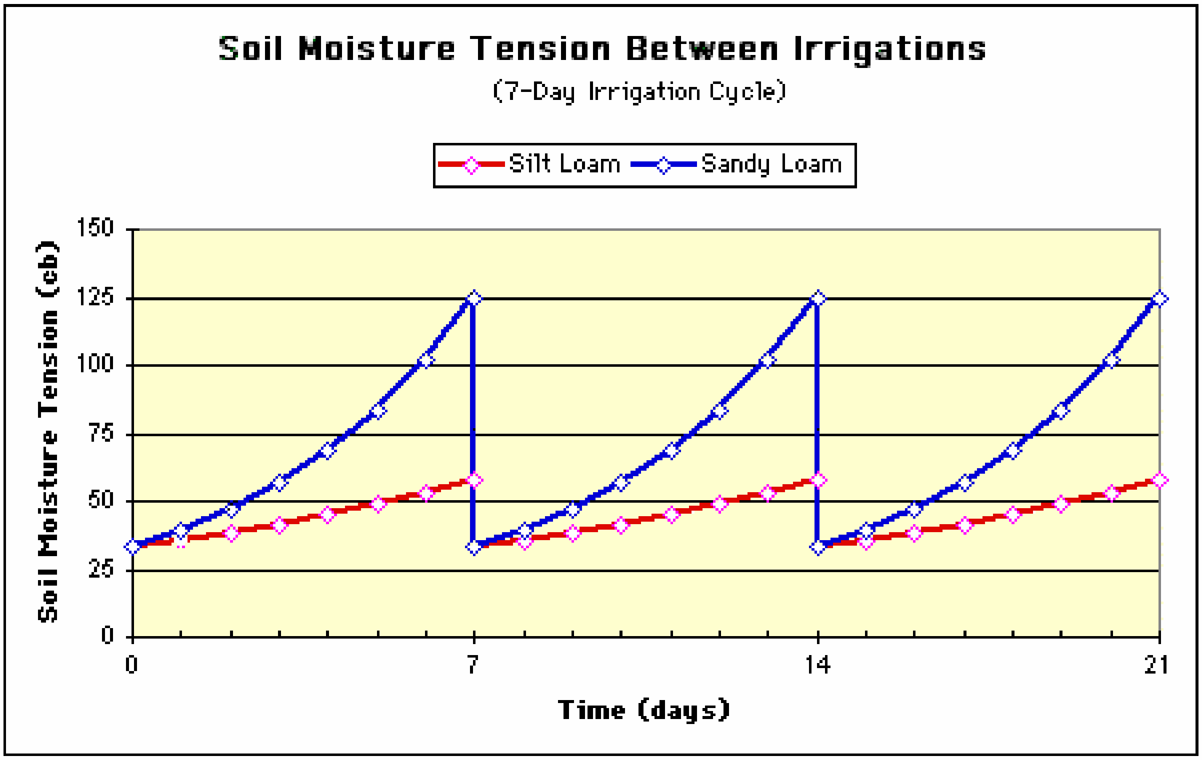
which we know corresponds to 125 cb soil moisture tension.

For the Silt Loam soil, the moisture content will be

3.49 in/ft - 0.44 in/ft = 3.05 in/ft

It turns out that for the Silt Loam soil, this corresponds to only 58 cb soil moisture tension, which is still within allowable limits (below 125 cb).

Thus, selecting the irrigation frequency based on the soil with the lowest AWHC, the sandy loam soil in this case, will provide an irrigation regime acceptable for both soils. The change in soil moisture tension between irrigations, assuming a 7-day irrigation cycle, is shown below for both soils. The tension in the Sandy Loam soil increases most rapidly, and reaches 125 cb seven days after an irrigation. The tension in the Silt Loam soil increases more slowly, reaching only 58 cb by the end of the seven day irrigation cycle.



The Influence of Rainfall. In areas where significant rainfall occurs during the irrigation season, this strategy may need to be adjusted. The timing and amount of rainfall is uncontrollable. The amount of water stored in the soil from any rainfall event will vary location to location, depending on AWHC. Thus the amount of "effective" precipitation will vary with AWHC. Since irrigation needs only to supply the difference between crop water needs and effective precipitation, this implied locally variable water amounts may be desired. In most areas of California, this shouldn't be a major factor. In the eastern part of the country, though, this may be a significant consideration.

One study looking at the rainfall/AWHC interaction was done in Georgia on soybeans [7]. The field (about 30 acres) was divided into 5 management zones based on soil properties, with the largest zone being about 12 acres. The study used a soybean growth model to estimate the economics effects of different irrigation regimes. An optimal irrigation strategy was developed for each zone, and computer-tested against 25 years of historical weather data. As the previous discussion suggested, the optimal strategy for each zone was a little different. Irrigating each zone independently, according to its own optimal strategy, produced the highest gross margin. The extra cost to implement independent zone irrigation was not included, however. The strategy of irrigating the field uniformly according to the optimal schedule for the largest management zone produced the second highest gross margins, less than 2% below independent zone irrigation.

Summary. So the precision farming strategies for fields containing soils with varying AWHCs and crops requiring full irrigation are these:

(i) unless rainfall during the irrigation season is significant, irrigate the field uniformly, according to the frequency appropriate to the lower AWHC values for the field.

(ii) if rainfall during the irrigation season is a significant factor, irrigate the field uniformly according to the schedule appropriate to the largest management zone within the field.

4.b. With Deficit Irrigation. When the irrigation objective is to create or maintain a given level of stress throughout a field with varying soil types, it may not be possible to successfully achieve this goal unless different soil zones are irrigated differently.

Reaching the Desired Stress Level. One consideration involves drying down a field after a period of full irrigation to some desired level of stress (soil moisture tension). Coarse textured soils (with lower AWHCs) hold relatively little water, and will "dry down" to a given stress level relatively quickly. Fine textured soils (with higher AWHCs) hold relatively more water, and will "dry down" to a given stress level relatively slowly. It is not hard to find examples (see below) where the coarser textured soils in a field will substantially exceed the desired stress level before the finer textured soils in the same field have reached the desired goal.

The problem is even more difficult when different levels of stress are desired at different times during the crop's growth cycle. For instance, one vineyard manager offered the following comments regarding desired stress levels during the year:

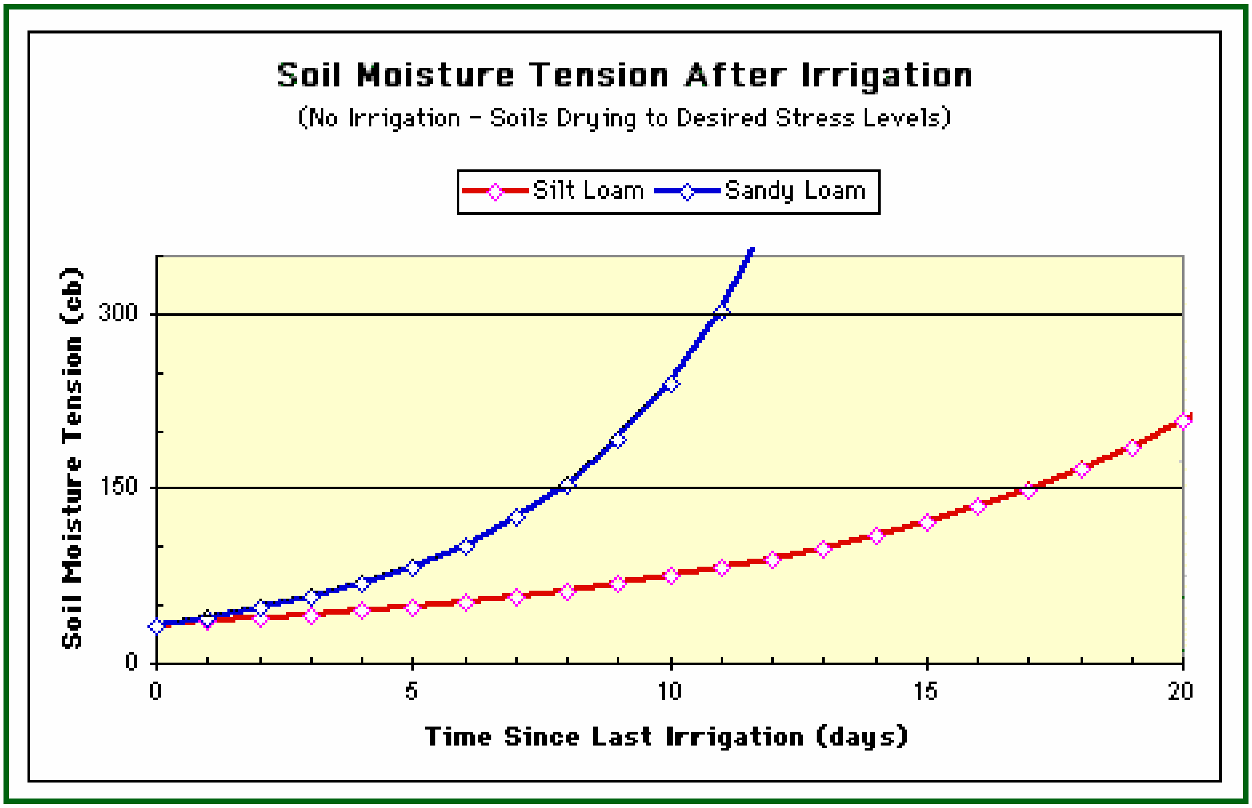
Stage of Growth	Rationale for Stress
Bud Break to Flowering	Some Stress - To Reduce Vigor
Flowering to Fruit Set	Some Stress - To Reduce Lateral Growth
Fruit Set to Veraision	Increased Stress - To Maintain Berry Size
Veraision to Harvest	Slight Stress - For Flavor Compounds
Harvest to Leaf Fall	No Stress

So to effectively manage a crop where desired stress levels vary throughout the season it may be necessary to use differential irrigation on the different soil zones of the field.

Example. A numerical example will illustrate this concept. Consider a crop with a 4 foot root zone using 0.25 inches per day. After a period of full irrigation, the crop is to be brought to a desired stress level of between 150 and 300 centibars (150-300 cb) moisture tension. The crop is grown in a field containing both Sandy Loam and Silt Loam soils. Relevant data for the two soils are as follows [8]:

Soil Type	Silt Loam	Sandy Loam
Field Capacity (FC)	3.49 in/ft	2.64 in/ft
Permanent Wilting Point (PWP)	1.80 in/ft	1.57 in/ft
Available Water Holding Capacity (AWHC = FC - PWP)	1.69 in/ft	1.07 in/ft
Moisture Content at 150 cb Tension	2.43 in/ft	2.15 in/ft
Moisture Content at 300 cb Tension	2.06 in/ft	1.95 in/ft

As time passes after the last full irrigation, water extracted for crop evapotranspiration will "dry down" the soil, and increase soil moisture tension. The drying curves for these two soils are illustrated below:



The Sandy Loam soil will reach 50 cb after about 8 days. But at that time, the Silt Loam soil will not be providing sufficient stress for the crop (still only about 60 cb). The Silt Loam soil won't achieve the 150 cb tension level until after about 17 days. But at this time, the Sandy Loam soil will have long since exceeded the maximum tension level of 300 cb (it exceeds 300 cb after about 11 days). Even with the relatively broad band of allowable tensions, irrigation of the coarser textured soil will be required before the finer textured soil has dried down to required tension level.

It is clear that irrigation on the Sandy Loam soil will have to resume no later than 11 days after the dry down period started, but irrigation on the Silt Loam soil will have to wait until 17 or more days have passed. The two soil zones will need to be irrigated differently.

You might think that things would be easier if the drying period for the Silt Loam soil was started before the drying of the Sandy Loam soil - but this also would require differential irrigations of the two soil zones.

Maintaining the Desired Stress Level. A second consideration involves selecting an irrigation interval and net application amount that will maintain some desired level of stress (soil moisture tension) once that stress level has been reached. This problem is actually similar to the case of full irrigation. Once a desired stress level has been achieved, irrigating the entire field on the frequency appropriate to the soil with the lowest AWHC will suffice to keep all soils within the desired range of stress.

Example. A numerical example will illustrate this concept. We continue with the circumstances illustrated in previous examples. The a crop has a 4 foot root zone and crop evapotranspiration is 0.25 inches per day. The irrigation regime is to be chosen so that the crop is maintained at stress levels between 150 and 300 centibars (150-300 cb) moisture tension. The crop is grown in a field containing both Sandy Loam and Silt Loam soils. Relevant data for the two soils are as follows [8]:

Soil Type	Silt Loam	Sandy Loam
Field Capacity (FC)	3.49 in/ft	2.64 in/ft
Permanent Wilting Point (PWP)	1.80 in/ft	1.57 in/ft
Available Water Holding Capacity (AWHC = FC - PWP)	1.69 in/ft	1.07 in/ft
Moisture Content at 150 cb Tension	2.43 in/ft	2.15 in/ft
Moisture Content at 300 cb Tension	2.06 in/ft	1.95 in/ft

The amount of water per foot that can be used while the soil is within the allowed tension range is:

Moisture Content at 150 cb - Moisture Content at 300 cb

For a 4 foot root zone, the total amount of water that can be used before the soil reaches the maximum allowed tension is:

4 x (Moisture Content at 150 cb - Moisture Content at 300 cb)

The maximum irrigation interval will be the this amount of water divided by the rate of crop water use, 0.25 in/day in this example:

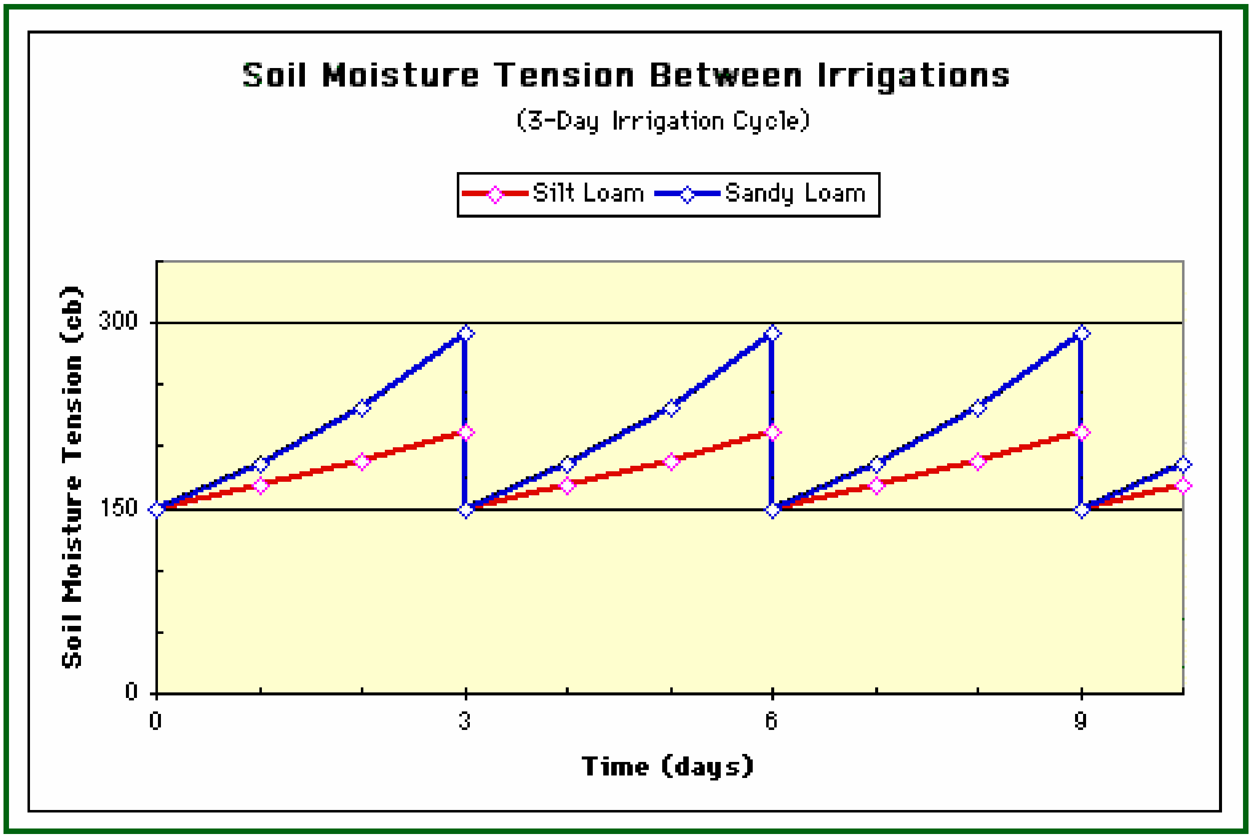
$$\frac{[4 \text{ x } (\text{Moisture Content at 150 cb - Moisture Content at 300 cb})]}{[0.25 \text{ in/day}]}$$

The results of these calculations may be summarized as follows:

Soil Type	Silt Loam	Sandy Loam
Moisture Content at 150 cb Tension	2.43 in/ft	2.15 in/ft
Moisture Content at 300 cb Tension	2.06 in/ft	1.95 in/ft
Allowable Water Use, Per Foot	0.37 in/ft	0.19 in/ft
Allowable Water Use, Total	1.49 inches	0.77 inches
Rate of Crop Water Use	0.25 in/day	0.25 in/day
Maximum Irrigation Interval	6 days	3.1 days

Assuming the desired soil tension level of 150 cb has been achieved, irrigating at any interval longer than 3 days will cause the soil moisture tension to exceed the maximum allowable 300 cb in the Sandy Loam portion of the field. But if the entire field is irrigated with an interval of 3 days, the soil moisture tension will remain above 150 cb, but below 300 cb for both soils.

Thus, selecting the irrigation frequency based on the soil with the lowest AWHC, the sandy loam soil in this case, will provide an irrigation regime adequate to maintain the desired stress level for both soils. The change in soil moisture tension between irrigations, assuming
(i) The desired tension level of 150 cb has already been reached, and
(ii) a 3-day irrigation cycle is used
is shown below for both soils. The tension in the Sandy Loam soil ranges between 150 cb and 300 cb, while the tension in the Silt Loam soil ranges between 150 cb and 209 cb during the three day irrigation cycle.



Summary. So the precision farming strategies for fields containing soils with varying AWHCs, and crops requiring varying degrees of stress during the growing season are these:

(i) to reach a level of stress, zones within the field having differing soils may need to be irrigated differently. Coarser textured soils (with lower AWHC values) will reach a given stress level more quickly, and irrigation should resume earlier than for finer textured soils (with higher AWHC values). Soils with higher AWHC values will dry down to a given stress level more slowly, so irrigation should resume later on these soils. Starting the dry down period for the finer textured soils earlier may facilitate management, but this also requires differential irrigation regimes for differing soil types.

(ii) once a given level of stress has been achieved, the stress may be maintained within allowable levels if the field is irrigated uniformly, according to the frequency appropriate to the lower AWHC values for the field.

(iii) achieving irrigation management objectives is even more difficult when different levels of stress are desired at different times during the crop's growth cycle.

Implementing Precision Irrigation

To implement precision irrigation, two basic tasks must be accomplished:

(1) Zones in the field that are to be irrigated with differing amounts and frequencies must me identified; and

(2) The irrigation system must be designed and installed so that it is capable of sending water to each of these zones on different schedules.

Following are some comments in each of these areas, based on practices employed on some commercial-scale operations in Northern California.

Determining Soil Types by Gridding. A soil sampling grid is established, and the soil is evaluated at a site within each grid cell. At each site, the soil should be evaluated to a depth equal to the rooting depth of the crop. The cost of identifying soil zones by this method can be quite high, depending on the grid interval chosen. The table below tabulates the number of sites to be evaluated in a 80 acre field for various grid intervals.

Grid Size (ft x ft)	Grid Size (acres)	Grid Sites per 80 Acres
660 x 660	10	8
600 x 600	8.3	10
500 x 500	5.7	14
400 x 400	3.7	22
300 x 300	2.1	39
208 x 208	1	80
100 x 100	0.23	348

The more intervals per acre that a farmer can afford the more accurate the resulting soil profile. However, the cost of creating a soil map by gridding can be quite high for accurate results. So, many farmers choose to use alternate solutions, such as aerial imagery or soil moisture conductivity tests to determine where to do the soil evaluations, thus minimizing the amount of soil samples.

Alternate Strategies for Determining Soil Sampling Sites. One option for determining where to dig soil pits in a field is Aerial Infrared Imagery (IR). IR quantifies the reflectance of the soil surface; therefore IR can distinguish between fine sand, loam and clay soils. Once the farmer knows where the surface soils change, soil evaluation costs can be reduced by selecting only one site per IR-identified soil zone. A word of warning is that just because the surface soils are similar does not mean that the sub soils are the same.

A second method of determining a soil map is by measuring soil conductivity with machines such as a VERIS or and EM-38. These machines measure soil conductivity while being pulled through a field in a grid like pattern. These machines do not identify soil type directly, but they can identify zones within the field where EC values are similar. Presumably, this is related to other soil properties, so EC zones are assumed to indicate boundaries for soil zones. The EC values do not determine the soil hydraulic properties (infiltration rates or AWHC) for the soil zones - these are determined by evaluating soil samples taken from each zone identified.

For fields of existing trees or vines, evaluations of plant growth may be useful. Measurements such as trunk diameter or canopy size may provide indirect indicators of underlying soil properties. Zones of similar values of these indicators may used to identify soil zones, and thus suggest locations for soil sampling.

Vine Spacing. In addition to differential irrigation treatment, some vineyards have gone so far as to use different vine spacings with each identified soil zone. The goal is to create a uniform vigor throughout the field by varying vine spacing according to the soil type within each zone. The irrigation system is then designed to supply a different irrigation regime to each zone of soil type and vine spacing.

Irrigation System. Once the zones requiring differential irrigation treatment have been identified, a certified irrigation designer to create an irrigation system design that takes into account not only the topography of the land but the soil and plant spacing characteristics in the identified zones as well. Since the zone boundaries may not match natural subdivisions of field and row dimensions, the resulting design may have to accommodate different soils and vine spacings within the same vine row. This will normally require additional piping and valving, thus increasing irrigation system cost. Before proceeding with such a system, the owner must be convinced that the advantages outweigh the disadvantages.

The manager of one vineyard employing such an approach summarized these consideration as follows:

Disadvantages

* Installation requires a higher degree of management supervision

* Varying vine spacing within a row increased labor costs

\- Laborers were shifted from piece-rate to hourly pay

\- Multiple irrigation sets within one vine row means
that laborers must walk up and down rows several
times during flushing

* Increased materials costs for the irrigation system
(approximately $700/acre in this case)

Advantages

*Reduction in unwanted stress to the vines

* Increased management flexibility - the system enables not only differential irrigation, but differential fertigation practices as well

* Reduced water use and pumping costs due to the fact that irrigation is based on smaller and more uniform soil conditions

* Improved yields from this high value crop should more than off-set the increased installation and labor costs

Soil Moisture Sensors and Computer Automation. Equipment for monitoring the soil moisture status in the various zones may be a desirable addition to the installation. Discussing the zoning of the field and the irrigation block layout with the irrigation designer should help in determining the number and location of soil moisture sensors to be used. Some sensors may be connected (hard wire or radio linking is possible) to a computer or data logging system to provide real-time soil moisture monitoring. A fully automated system would link the soil moisture sensors through a computer program to the irrigation pump and block valves.

A fully automated system operates under the control of a computer program. Most computer programs allow the farmer to choose what triggers will start and stop irrigation cycles. These triggers could be soil moisture readings, evapotranspiration readings, and/or temperature readings. When one of the start triggers has been reached the computer program sends a signal to the irrigation block that is needing water and opens the block valve and starts the pump. When that irrigation block's stop trigger has been reached the computer program will send a signal to turn off the pump and shut off the block valve.

Most farmers who have installed automated irrigation systems recommend that the system should measure more than just one variable (i.e. soil, plant, or environment). Additionally, someone must monitor the fields frequently to verify what the computer screen coincides with what is actually what is happening in the field.

Irrigation Tutorial

The recommended irrigation strategies involve trying to apply water uniformly to fields, contiguous blocks or zones, or to non-contiguous nets. The problem of applying water uniformly is the subject of traditional irrigation system design and management. With this in mind, a brief irrigation tutorial is included with this information. The information in the tutorial is organized into 4 section, with sub-sections as outlined below.

Irrigation Systems

General

Terms and Units

Soil-Water-Plant Relationships

Plant Response to Water

- Irrigation Water Management Strategies for Precision Farming
  - Soil-Water-Plant-Facts
  - Soil Texture
  - Soil Moisture
  - Practice Irrigation Calculations
- Irrigation Efficiency & Distribution Uniformity
  - Efficiency
  - Water Destination Diagrams
  - Useful Formulae
  - Examples
- Irrigation Scheduling Basics
  - Car Analogy
  - Evapotranspiration (ET) Based Scheduling
  - Review of Soil/Plant/Water Factors
  - Choice of Management Allowed Depletion (MAD)
  - Portable Sprinkler Example
  - Microspray Example
  - Row Crop Drip Example

Notes

[1] Solomon, KH. 1972. Unpublished field notes.

[2] Camp, CR, EJ Sadler, DE Evans, LJ Usrey and M Omary. 1998. Modified Center Pivot System for Precision Management of Water and Nutrients. Applied Engineering in Agriculture 14(1):23-31.

[3] Torre-Neto, A, JK Schueller and DZ Haman. 2000. Networked Sensing and Valve actuation for Spatially-Variable Microsprinkler Irrigation. Presented at the July 2000 ASAE International Meeting, Milwaukee, WI, Paper No. 001158. ASAE, 2950 Niles Rd., St. Joseph, MI.

[4] Solomon, KH. 1977. Unpublished field notes.

[5] Figure 1 was adapted from data found in Vogel, JR, J Garbrecht and GO Brown. 2000. Spatial and Temporal Variability of Infiltration, Bulk Density, and Soil Composition in Dryland Winter Wheat and Native Warm Season Grass. Presented at the July 2000 ASAE International Meeting, Milwaukee, WI, Paper No. 002141. ASAE, 2950 Niles Rd., St. Joseph, MI.

[6] Figure 2 was adapted from data found in Colaizzi, PD, CY Choi, PM Waller, EM Barnes and TR Clarke. 2000. Determining Irrigation Management Zones in Precision Agriculture Using the Water Deficit Index at High Spatial Resolutions. Presented at the July 2000 ASAE International Meeting, Milwaukee, WI, Paper No. 001092. ASAE, 2950 Niles Rd., St. Joseph, MI.

[7] Nijbroek, N, G Hoogenboom, and JW Jones. 2000. Predicting Soybean Yield Variability Under an Irrigated Environment. Presented at the July 2000 ASAE International Meeting, Milwaukee, WI, Paper No. 003038. ASAE, 2950 Niles Rd., St. Joseph, MI.

[8] Saxton, KE, WJ Rawls, JS Romberger and RI Papendick. 1986. Estimating Generalized Soil-Water Characteristics from Texture. SSSA 50(4):1031-1038. The numerical examples presented earlier have used soils and soil moisture characteristics for typical soils as outlined in this reference.