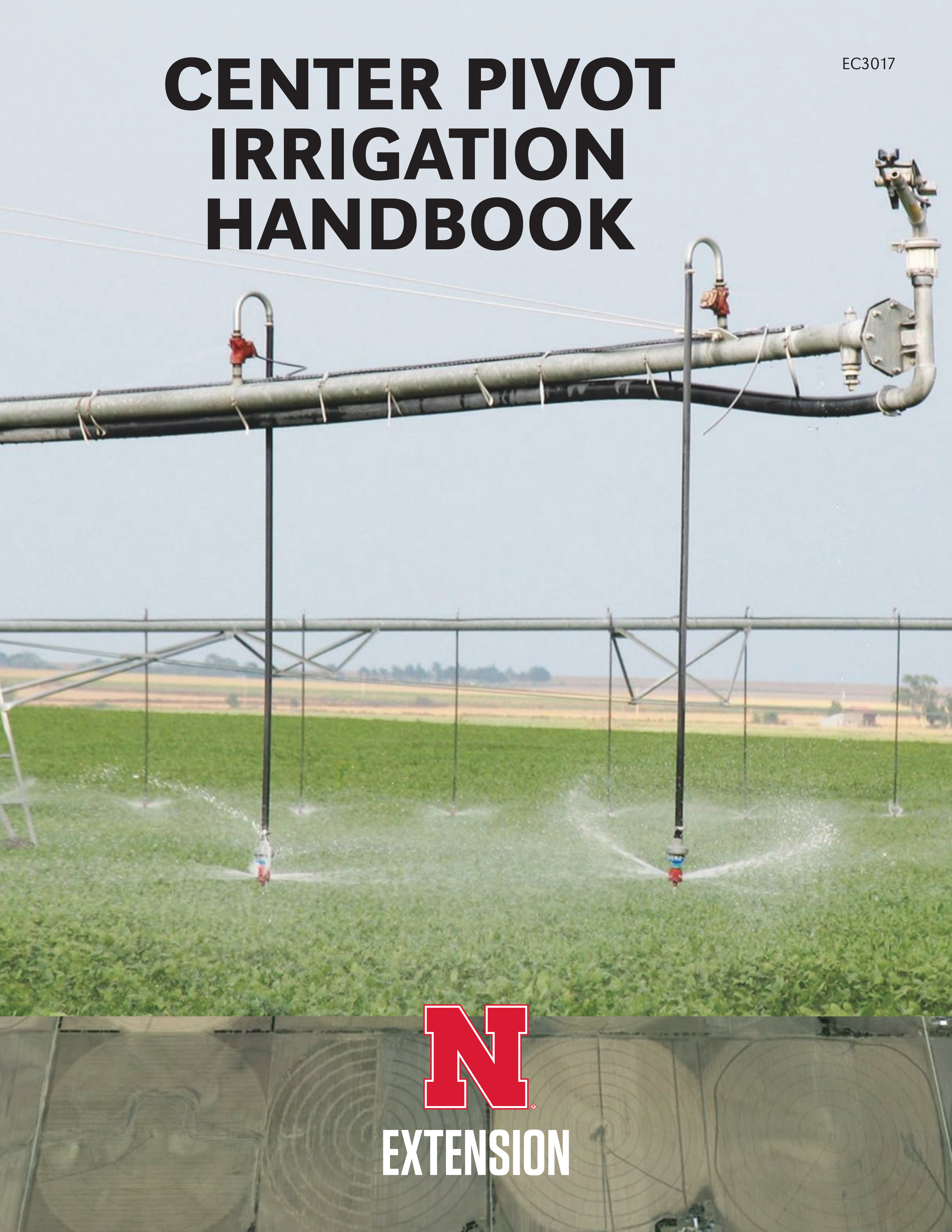
EC3017

CENTER PIVOT IRRIGATION HANDBOOK



EXTENSION

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Acknowledgement

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The Handbook was developed as supporting material for a series of daylong educational workshops focused on enhancing the performance of center pivots through improved understanding of the design and management characteristics of center pivots. We conducted workshops across the state at numerous locations over several years. The Handbook is organized to parallel a series of PowerPoint presentations for the workshops. A copy of the presentations is available upon request.

We appreciate contributions of personnel at the participating companies, state agencies and Extension staff who were instrumental in completing the project. Their ideas and assistance in designing and conducting this educational program were essential and we gratefully acknowledge their contributions. We are also thankful for the support from companies that allowed us to utilize some of their material in the Handbook or that provided product displays and consultation at the workshops. Finally, we also value irrigators, state and federal agency personnel and irrigation dealer and manufacturer staff that participated in the workshops.

Chapter 1. Introduction

Center pivot irrigation has been the most rapidly expanding form of irrigation in the Central Great Plains and across the United States. The amount of land irrigated with sprinkler, gravity and drip or trickle systems was determined for all states in the USA in the Farm and Ranch Irrigation Survey[1] by the USDA in 2012. Results of the survey for the Great Plains States shows that approximately 85% of the land in Nebraska is irrigated with center pivots and that very little land was irrigated with drip systems in 2012 (Figure 1). The percentage of land irrigated with sprinklers in neighboring states was similar to the percentage in Nebraska. Results for Colorado, New Mexico and Wyoming include irrigation from the western slopes of the Rocky Mountains where large surface water projects provide water to farms for gravity irrigation. The percentage of land irrigated with sprinklers is similar to that for Nebraska on the eastern plains of Colorado, New Mexico and Wyoming. Virtually all sprinkler-irrigated land in the Great Plains is by center pivots.

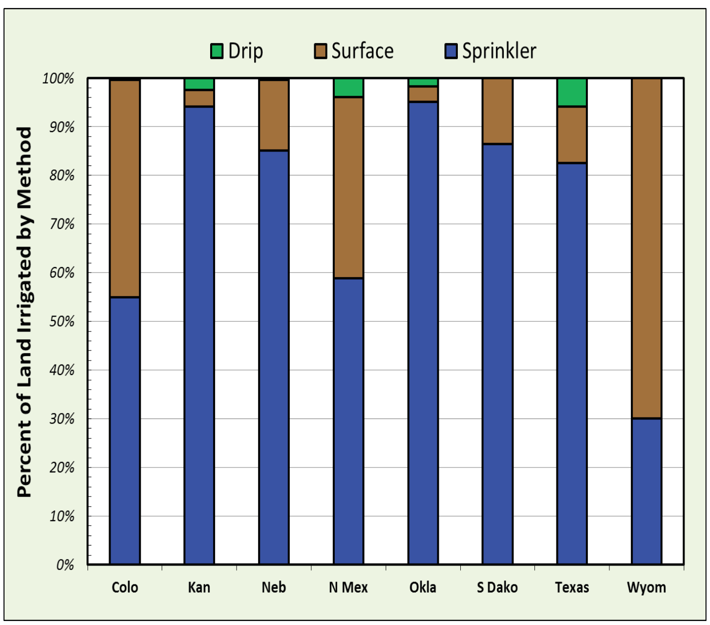


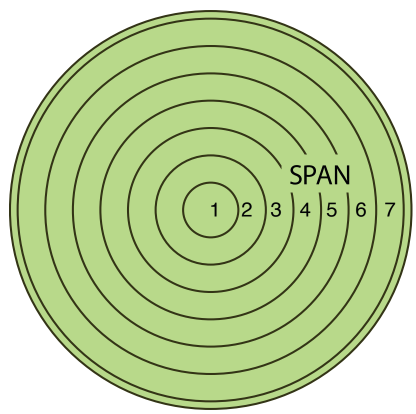
Figure 1. Percentage of land irrigated by sprinkler, gravity and drip/trickle systems in the Great Plains.

With widespread use of pivots, it is important to provide techniques to evaluate if pivots are operating as designed and to develop methods to identify issues in producer fields. In this document, we describe the design procedure for center pivots to illustrate how pivots should operate and discuss issues in center pivot performance that we are observing in producer fields. We also present procedures for selecting sprinkler packages and a checklist of things that can help ensure that the system is operating efficiently.

[1] At: https://www.agcensus.usda.gov/Publications/2012/Online_Resources/Farm_and_Ranch_Irrigation_Survey/

Chapter 2. Pivot Performance

The circular operation of the center pivot results in conditions illustrated in Figure 2. The system is a typical seven-span pivot with span widths of 180 feet and a 50-foot overhang at the end of the pivot lateral. The pivot in Figure 2 irrigates 124 acres when there is no end gun. Since the spans at the distal end of the system travel much farther per revolution of the pivot, the outer spans irrigate much more area than spans of the same length that are located at the center of the field. Because the outer spans irrigate more area, they also must discharge more water than inner spans. For the typical system shown in Figure 2 about 45% of the irrigated area is located under the 6th and 7th spans of the system, and correspondingly 45% of the total system flow is distributed from the 6th and 7th spans. In fact, 24% of the land area and 24% of the system discharge are associated with the last span. If sprinklers are spaced at the same distance along the lateral then sprinklers on the outer spans must discharge more water than sprinklers located nearer the pivot point.



Span	End of Span, ft	Acres Within Span	Discharge from Span, gpm
1	180	2.3	14
2	360	7.0	42
3	540	11.7	71
4	720	16.4	99
5	900	21.0	127
6	1080	25.7	156
7	1260	30.4	184
OH	1310	9.3	56
Total		124	750

Figure 2. Characteristics of a typical center pivot. Note, 45% of land is under outer two spans while 2% is under first span.

Proper operation of a pivot requires installation of the correct type of sprinklers and nozzles at the proper location along the pivot pipeline. We need to know what the capacity of the pivot system is to select the correct nozzles for the system. The secret to proper design and installation is to determine:

- Discharge needed for each sprinkler along the lateral.
- Pressure available at each sprinkler.
- Required size of nozzle needed in each successive sprinkler to meet the discharge requirement.

System Capacity

The diagrams in Figure 3 illustrate the system capacity. The system capacity (Cg) is the ratio of the flow into the pivot divided by the amount of land irrigated. Most producers know these values with reasonable accuracy.

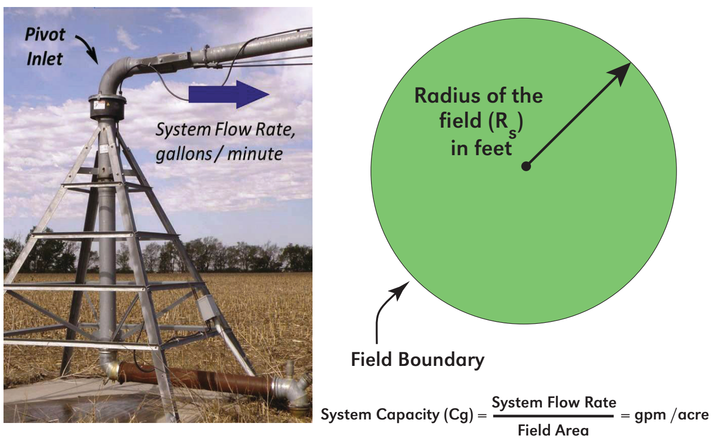


Figure 3. Definition of system capacity for a field.

System capacity relates to the ability of an irrigation system to meet crop water needs during periods with high water use rates. Large capacities provide flexibility to meet water use during hot-dry periods and to allow for periods when the irrigation system is shutoff for repair, maintenance and electrical load control. Large system capacities also contribute to higher water application rates and potentially runoff. Thus, the system capacity should be large enough to meet crop water use rates most of the time while not being so large that it contributes to runoff problems.

The recommended minimum system capacity depends on the location in the state (Figure 4) and the soil texture in the field (Table 1). Evapotranspiration (ET) is higher and rainfall is lower in the western portion of the state than the eastern region. This means that system capacity must be higher to meet crop water requirement in the west. For example, Table 1 shows that the minimum net capacity should be 4.62 gpm/acre if a system is located in the Nebraska panhandle on silt loam soil while only 3.85 gpm/acre is recommended for the eastern region.

Soil texture affects the amount of water that the soil can provide to crops during periods of high ET demand. The system capacity must be higher when less water is stored in the soil to buffer against water use during periods of high demand. Since sandy soil holds less water, a higher capacity is needed than for finer textured soil. For example, we recommend a minimum net capacity of 5.89 gpm/acre for sandy soil is western Nebraska compared to 4.62 gpm/acre for silt loam soil in western Nebraska.

The system capacity needed to match the peak ET is also listed in Table 1. Peak ET is the highest rate of water use that is expected by a crop. If a system has the capacity to meet the peak ET it will meet the crop water needs throughout the growing season without relying on the soil water supply. We have found that capacities equal to the peak ET rate may cause runoff problems.

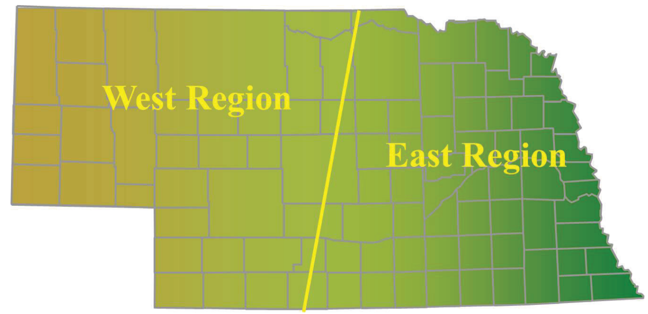


Figure 4. Regions for minimum system capacity.

Table 1. Minimum recommended net system capacity for soils and regions of Nebraska.

	Net Capacity* 9 of 10 years, gallons/minute/acre	
	East Region	West Region
Peak ET	5.65	6.60
Soil Texture		
Loam, Silt Loam, and Very Fine Sandy Loam with Silt Loam Subsoil	3.85	4.62
Sandy Clay Loam, Loam, Silt Loam, and Very Fine Sandy Loam with Silty Clay Subsoil	4.13	4.89
Silty Clay Loam, Clay Loam, and Fine Sandy Loam	4.24	5.07
Silty Clay	4.36	5.13
Clay and Sandy Loam	4.48	5.19
Loamy Sand	4.83	5.42
Fine Sands	4.95	5.89

*From von Bernuth, R.D., D.L. Martin, J.R. Gilley and D.G. Watts. 1984. Irrigation System Capacities for Corn Production in Nebraska. Trans. ASAE 27(2): 419-424, 428.

Table 2. Multiplier for system capacity based on application efficiency and downtime.

Application Efficiency, percent	Downtime, hours/week					
	8	12	16	24	36	48
80	1.31	1.35	1.38	1.46	1.59	1.75
85	1.24	1.27	1.30	1.37	1.50	1.65
90	1.17	1.20	1.23	1.30	1.41	1.56
95	1.11	1.13	1.16	1.23	1.34	1.47

The values in Table 1 represent the net system capacity which does not account for inefficiencies or downtime for a system. The multipliers listed in Table 2 adjust for the application efficiency and the number of hours that a system does not operate during the week. For example, the net system capacity for a center pivot located on silt loam soil in eastern Nebraska is 3.85 gallons/minute/acre. The gross or total system capacity for a system with 85% efficiency and 12 hours of downtime per week should be increased to $1.27 \times 3.85 = 4.9$ gpm/acre, equivalent to about 640 gpm for a traditional 130-acre field.

Sprinkler Discharge

The discharge required from a sprinkler depends on the system capacity, the distance of the sprinkler from the pivot inlet, and the spacing between sprinklers at that location along the lateral as illustrated in Figure 5. The following equation describes how to compute the required discharge from a sprinkler:

$$q_s = \frac{C_g \times R \times S}{6933}$$

where q_s is the discharge from the sprinkler (gpm), C_g is the system capacity (gpm/acre), R is the distance from the pivot point (feet), and S is the spacing between sprinklers (feet).

For example, if a sprinkler is located 1000 feet from the pivot, the local spacing of sprinklers along the lateral is nine feet and the system capacity is 6 gallons/minute/acre then the required sprinkler discharge is:

$$q_s = \frac{6 \text{ gpm/acre} \times 1000 \text{ ft} \times 9 \text{ ft}}{6933} = 7.8 \text{ gpm}$$

The required nozzle size can be determined after computing the sprinkler discharge. The pressure available to the sprinkler must be determined to select the nozzle size. If pressure regulators are used, the available pressure is usually the pressure rating of the regulator. If regulators are not used then the pressure in the sprinkler lateral at the designated location must be determined.

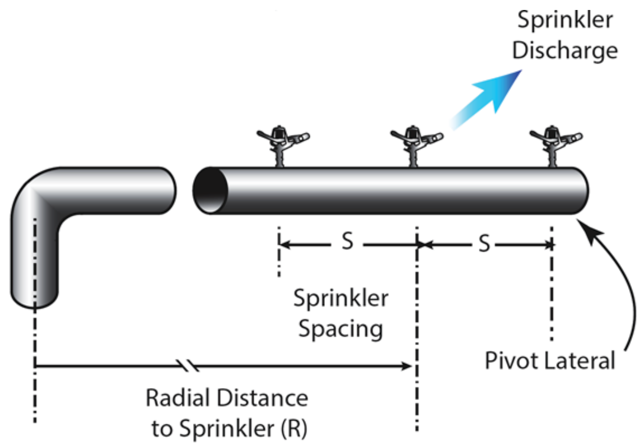


Figure 5. Information used to determine discharge required for a sprinkler along the center pivot lateral.

Sprinkler nozzles perform as illustrated in Figure 6. The nozzle diameter has a large influence on the discharge from the nozzle. In fact, the discharge depends on the square of the nozzle diameter. For example, the discharge for the ⅛-inch nozzle at a pressure of 40 psi is 2.8 gpm. The discharge from the ¼-inch nozzle is 11.2 gpm at a pressure of 40 psi. Therefore, when you double the nozzle diameter you get four times as much discharge. The effect of pressure is less significant than the nozzle diameter; in fact, the discharge varies as the square root of the pressure. The discharge from the ¼-inch nozzle at 20 psi is 7.96 gpm while at 40 psi the discharge is about 11.2 gpm. The ratio of the discharge is 1.4, so when you double the pressure you get a 40% increase in the discharge.

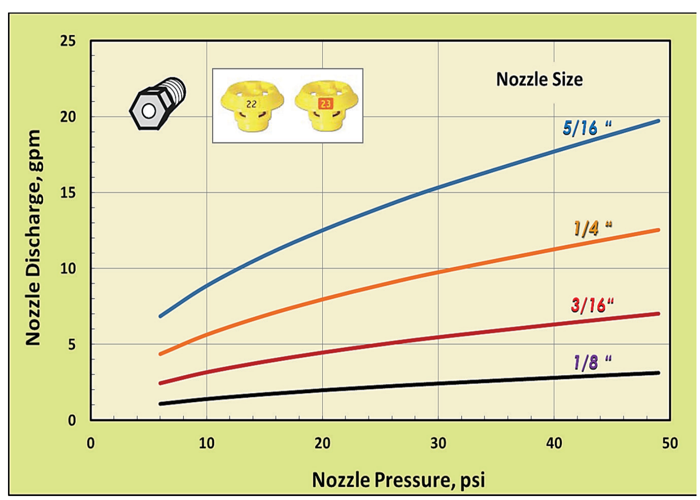


Figure 6. Nozzle performance for sprinkler devices.

The discharge required along the lateral increases linearly with the distance from the pivot inlet (Figure 7). The discharge is also directly related to the system capacity, so the larger the capacity the larger the required discharge. The right-hand side of the graph in Figure 7 includes the performance of the Nelson 3TN nozzles for a pressure of 20 psi. We previously determined that the discharge at 1000 feet should be 7.8 gpm when the sprinklers were nine feet apart. We see that a nozzle size of 32 is required when we go horizontally to the right-hand side of the figure. The Nelson Irrigation Corporation sizes their nozzles in terms of 128ths of an inch. So a size of 32 has an inside diameter of $32/128 = 1/4$ inch. We saw in the nozzle size example that the ¼-inch nozzle discharged 7.96 gpm at a pressure of 20 psi. This nozzle size provides the discharge that is closest to the target discharge of 7.8 gpm. You cannot be exact because nozzle sizes are discrete. The next smaller available nozzle size is a number 31, which produces 7.4 gpm at a pressure of 20 psi.

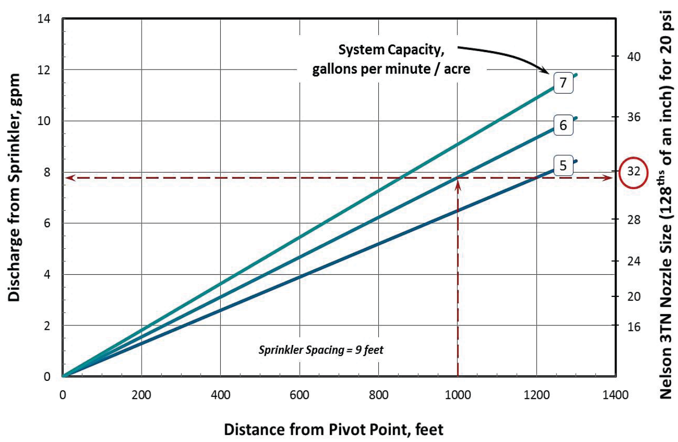


Figure 7. Discharge required for sprinklers located along the pivot lateral for three system capacities and the nozzle size needed for Nelson 3TN nozzles operated at 20 psi.

Sprinkler Pressure

The pressure available to a sprinkler along the lateral depends on the pressure at the pivot inlet, the change of elevation of the location versus the elevation of the pivot inlet and the loss of pressure along the pivot lateral due to friction (Figure 8). An elevation change of 23 feet is equivalent to 10 psi, so the pressure of the lateral at a location will be higher when the lateral is in the valley compared to when the lateral is on the hilltop. The pressure in the lateral is often the smallest at the distal end of the pivot when the outer end of the pivot is on the highest hill in the field.

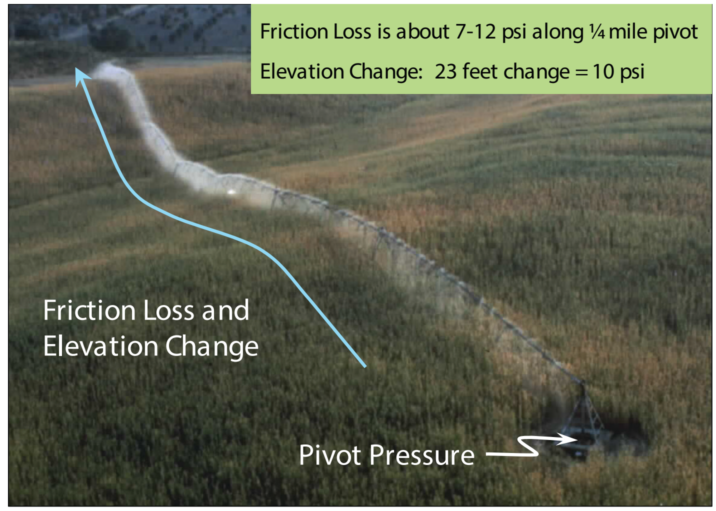


Figure 8. Pressure available to a sprinkler along pivot lateral depends on the pressure at pivot inlet, loss of pressure due to friction and change in elevation in the field.

The loss of pressure due to friction for the entire pivot lateral is illustrated in Figure 9 for varying flow rates and pipe sizes. The results in Figure 9 represent the decrease in pressure from the pivot inlet to the distal end of the pivot if the pivot was on flat land. For example, if the inflow into the pivot was 800 gpm and the lateral pipe size (actually outside diameter of the pipe) was 6 ⅝ inches then approximately 10.2 psi would be lost due to friction. As a general rule of thumb the pressure loss due to friction should be between about 7 and 12 psi. If the pressure loss is less than 7 psi then the investment cost could be reduced if a smaller pipe was used. If the pressure loss is more than 12 psi then the increased operating cost due to excessive friction loss amortized over the life of the pivot would probably pay for a larger pipe at the time of installation. Thus, the desired pressure loss range of 7 to 12 psi defines the practical range of flow rates for a given pipe size.

There are gaps in the practical flow rate range when only one size of pipe is used for the whole lateral. For example if the desired flow rate is 1000 gpm then the pressure loss for a single pipe size of 6 ⅝ inches yields a pressure loss much larger than 12 psi, while a single pipe size of 8 inches produces a loss of about 6 psi. Investment costs could be reduced by using the 8-inch pipe for the initial portion of the lateral and the 6 ⅝-inch pipe for the remainder of the pipeline. It is common to install larger pipe on the first couple of spans of the lateral and then smaller pipe for the rest of the lateral. An example is shown in Figure 9 for a lateral where the initial ⅓ of the lateral is 8-inch pipe and the distal ⅔ of the lateral is 6 ⅝-inch pipe. The results in Figure 9 show that the pressure loss of the combined pipe size yields a pressure loss of about 10 psi for an inflow of

1000 gpm which is within the practical range of pressure losses. The practical pressure range is only a guideline. The cost of pipe and energy will determine where the exact trade-off occurs and will usually be determined by the pivot manufacturer at the time of purchase.

The majority of the pressure loss along a pivot lateral occurs over the initial portion of the pipeline (Figure 10). Half of the total pressure loss along the pipeline occurs over the first 28% of the pipeline and 80% of the total loss occurs over the first half of the pipeline. The outer portion of the pivot will experience about the same pressure in the pipeline since most of the pressure loss has already occurred. Thus, if one measures the pressure in the outer portion of the pivot lateral the measurement is accurate for the outer spans.

The pressure in the lateral varies when a center pivot travels up and down hills in the field. The variation in pressure affects the discharge of water from sprinklers as the lateral revolves around the field. Thus, more water would be applied in valleys and less on hilltops.

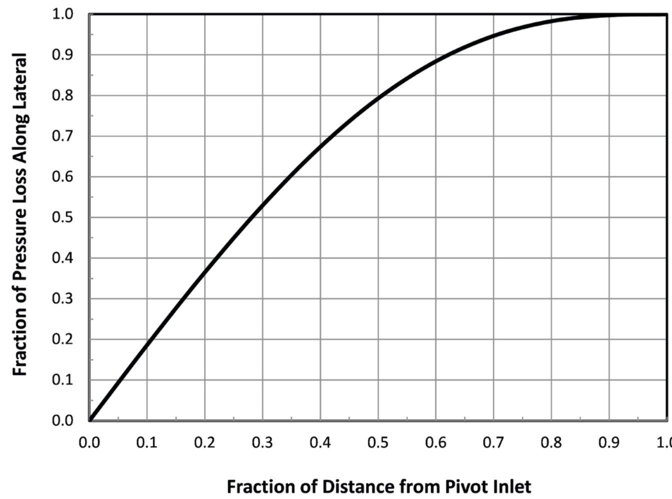


Figure 10 . Pressure loss distribution along pivot lateral.

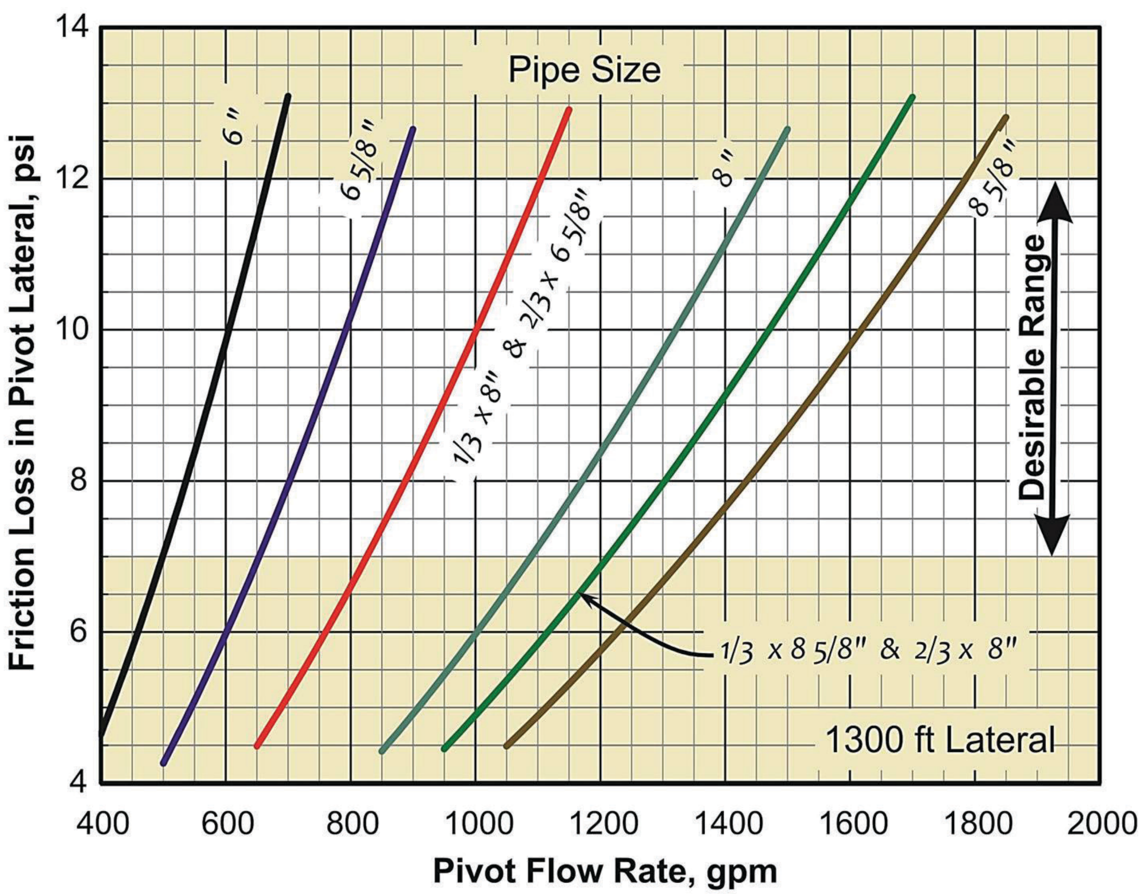


Figure 9. Pressure loss due to friction from water flow in pipe sizes often used for center pivot irrigation.

Pressure regulators are frequently used to minimize the variation in application for such situations. The operation of a pressure regulator is illustrated in Figure 11. The inlet pressure is the pressure available to the inlet of the regulator while the outlet pressure is the pressure at the outlet of the regulator –usually the inlet to the sprinkler. The performance chart for the Senninger Irrigation pressure regulator shows that the outlet pressure from the regulator is nearly constant over a wide inlet pressure range once the inlet pressure exceeds the rated pressure plus about 5 psi. So, the outlet pressure is about 20 psi for inlet pressures between 25 and 100 psi for a regulator rated at 20 psi. Regulators deplete about 5 psi of pressure; therefore, one must ensure that the pressure in the lateral is at least 5 psi above the rated pressure of the regulator. The design pressure at the pivot inlet should account for the rated pressure of the regulator, the 5 psi loss in the regulator, the friction loss in the pivot lateral, and the difference in elevation between the distal end of the pivot at its highest point and the elevation at the pivot inlet.

Pressure regulators are not required if the field is relatively flat. A general rule of thumb is that the discharge of a sprinkler should not vary by more that 10% as it traverses the field. Since the discharge from a sprinkler is related to the square root of the pressure and because 2.31 feet of elevation change equals 1 psi, we see that the 10% discharge variation rule requires that the change in elevation be less than 0.46 times the sprinkler pressure. If the elevation change in the field is less than this limit then regulators would not be required (Figure 12). For example, suppose that the design pressure is 30 psi. The elevation change allowed before regulators would be used would then be 0.46 x 30 = 13.9 feet (Figure 12). So, if the elevation changes by more than about 14 feet then regulators should be used for a design pressure of 30 psi. We note that the on-off operation of an end gun often induces pressure head variation along the lateral of about 10 to 15 feet. Thus, regulators may be required for design pressures less than about 30 psi if an end gun is added to the pivot.

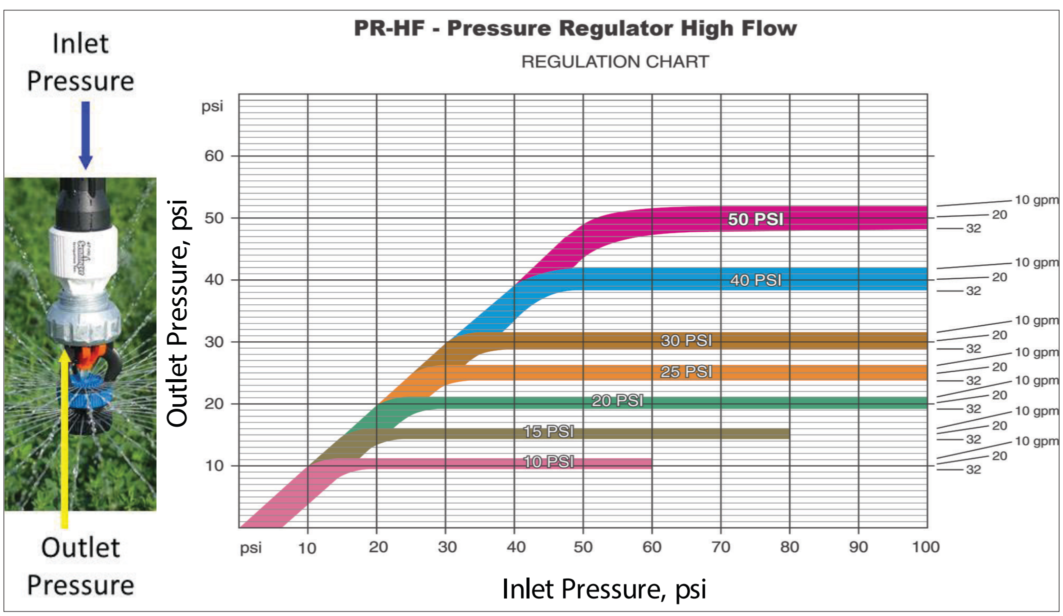


Figure 11. Performance of pressure regulators (courtesy of Senninger Irrigation, Inc.).

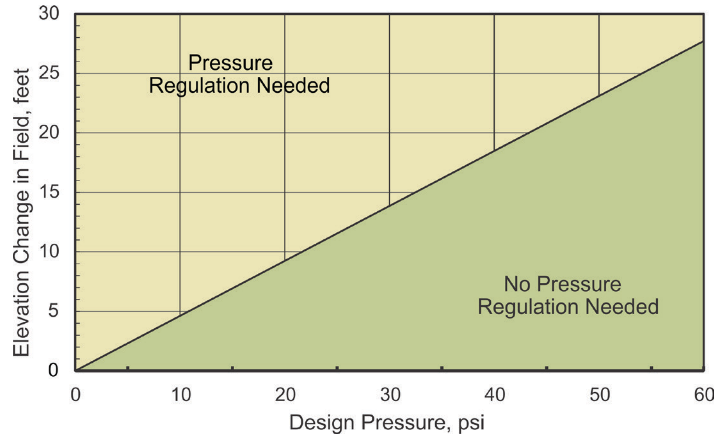


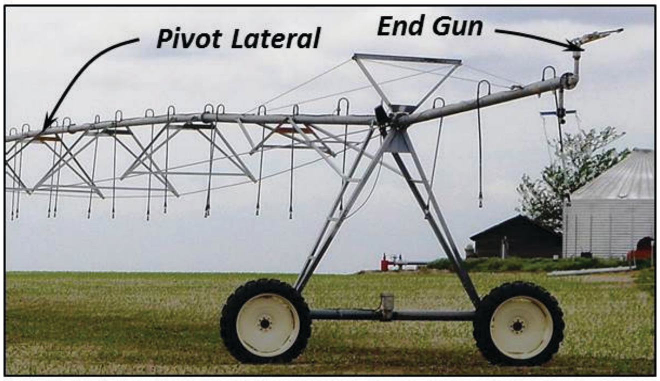
Figure 12. Recommendations for when to use pressure regulators based on elevation change in the field.

End Guns

Center pivots can be equipped with an end gun to increase the portion of a field that is irrigated (Figure 13). The end gun is a large sprinkler mounted on the end of the pivot lateral. The gun throws water a long distance thereby increasing the amount of land irrigated. A valve attached to the end gun opens when the pivot rotates to the corners of the field. When the pivot lateral reaches a preset angle of rotation, the valve opens and water flows to the end gun. In many cases, a booster pump attached to the valve increases the pressure for the end gun above that needed for the sprinkler package on the main lateral of the pivot. The discharge from the end gun depends on the radius of the end gun relative to the radius of the field.

For example, suppose that the radius of the field for the main system is 1300 feet and that the total discharge from the main system is 750 gpm. An irrigated radius of 1300 feet produces an irrigated area of about 122 acres (A_i, in acres = R_s^2 / 13866 where the radius is in feet). If the wetted radius of the end gun is 130 feet then from Figure 14, the ratio of the radii is 0.1, so the discharge from the end gun should be about 22% of the discharge from the main system, i.e., end gun discharge = 0.22 × 750 gpm = 165 gpm.

The amount of irrigated area from operating the end gun in all four corners can be determined from Figure 14. Since the ratio of the end gun throw to the main system radius is 0.1 then the end gun will contribute about 9.5% of the area under the main system. In this case, the gained irrigated area is (0.095 × 122 acres) or about 11.5 acres.



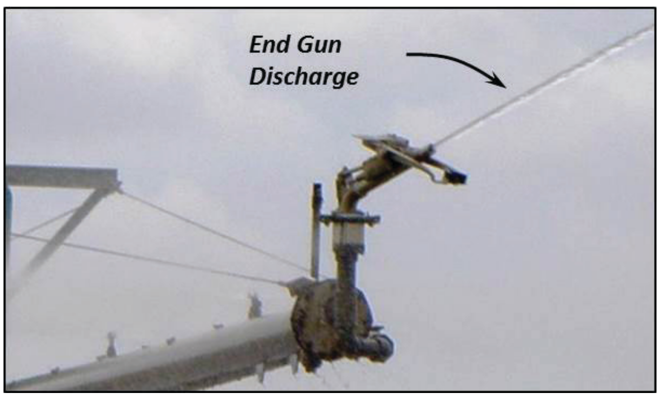
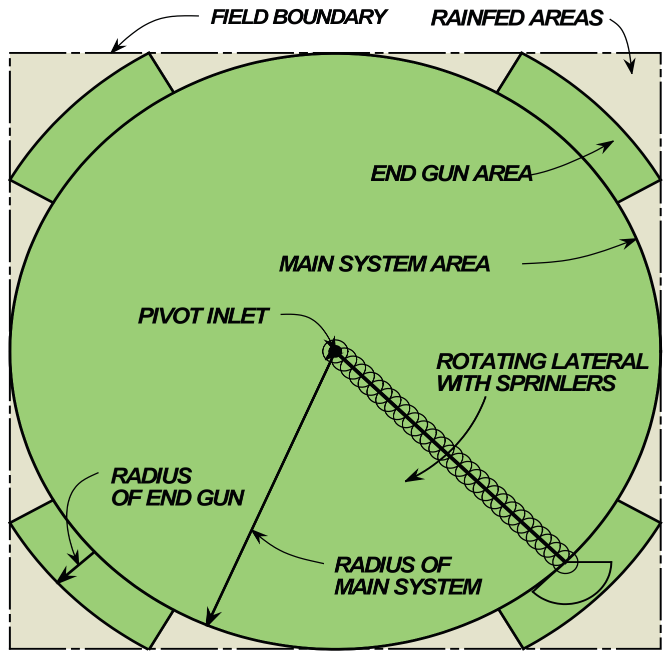


Figure 13. Pictures of end guns used to increase irrigated area in the corners of the field.



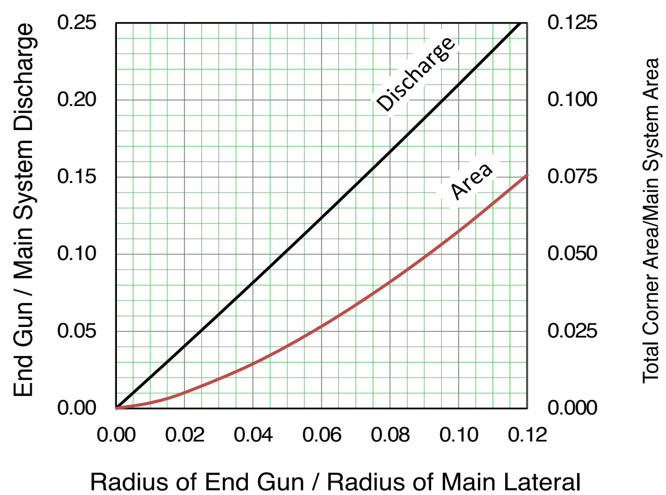


Figure 14. Illustration of areas irrigated by end guns, and the required discharge from the end gun as a function of the wetted radius of the end gun and the main systems.

Uniformity of Application

The wetted diameter of the sprinkler package is very important to the selection of sprinklers and management of a center pivot. The wetted diameter is the distance that sprinklers throw water perpendicular to the lateral (Figure 15). The wetted diameter depends on the design of the sprinkler device, nozzle size and pressure at the nozzle. The wetted diameter also depends on the height of the sprinkler above the surface of application when the droplets maintain a horizontal velocity. We conducted experiments when the Spinner device was 42 inches above the soil which caused the device to drop into the corn canopy. The wetted diameter decreased to about 12.5 feet when the device was in the canopy. Smaller wetted diameters reduce the uniformity of application and increase the potential for runoff.

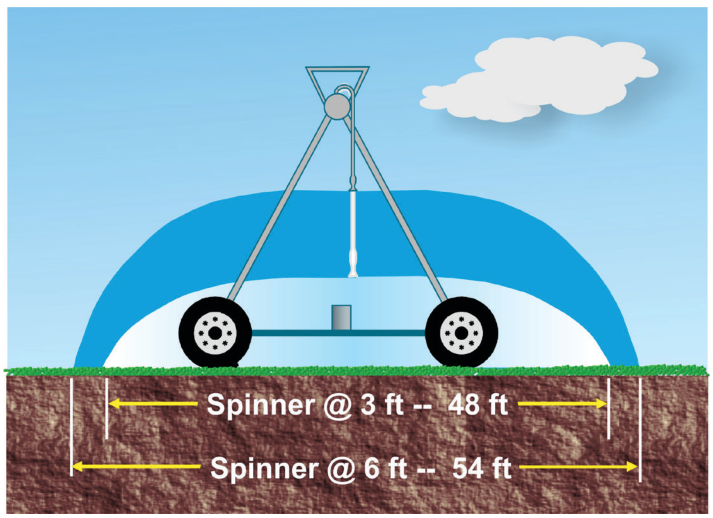


Figure 15. Examples of the wetted diameter for Spinner devices from the Nelson Irrigation Corp.

The efficiency of center pivots relies on uniform application. The uniformity depends on the spacing of the sprinkler devices along the lateral relative to the wetted diameter of the device. When one tries to reduce investment costs by placing sprinklers too far apart the uniformity declines and often the yield drops. The example in Figure 16 illustrates what can happen if the spacing is too large. In this case, the sprinkler spacing was 17.5 feet that was equal to the width of seven crop rows. The sprinkler was 3.5 feet above the soil surface which placed it in the canopy. The yield for rows close to the sprinkler devices was about 220 bushels of corn per acre while the yield halfway between sprinklers was about 180 bushels/acre. The yield reduction for the field averaged about 15 bushels/acre which equals about 2000 bushels for a traditional 130-acre pivot. The yield sacrificed due to poor uniformity would certainly exceed the cost of an appropriate sprinkler spacing.

The optimal sprinkler spacing provides equal opportunity to water for all crop rows. When there is adequate overlap and high uniformity all plants would receive about the same amount of water. Devices placed into the canopy may require a sprinkler spacing equal to twice the row spacing to ensure adequate water availability. Other research has shown that the spacing of devices in corn should not exceed about 7 feet or about three row widths.

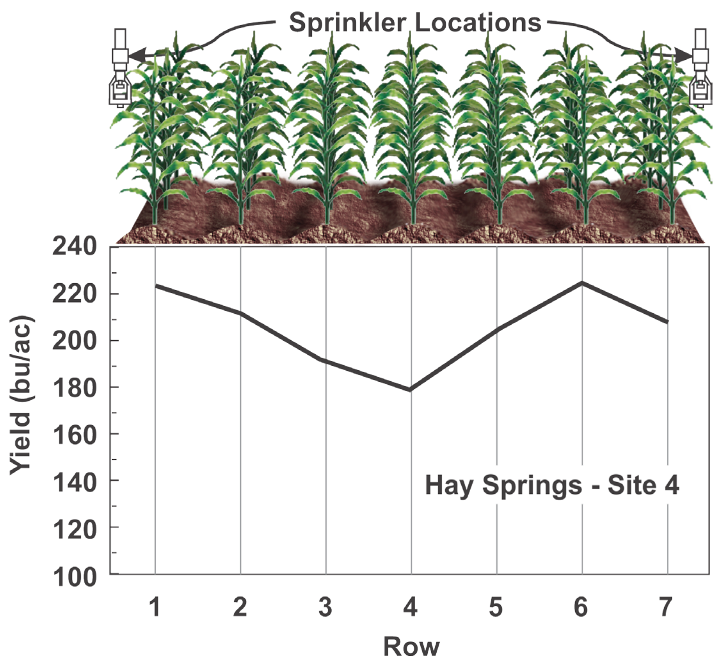


Figure 16. Variation of yield for wide spacing of sprinklers perpendicular to rows of corn.

Evaporative Losses

The efficiency of sprinkler irrigation decreases when water evaporates from the soil, the canopy or in the air before reaching the soil or crop. Producers often overestimate the amount of water that evaporates in the air. We conducted studies with the USDA-ARS at Bushland, Texas just outside of Amarillo. The USDA-ARS have some of the best lysimeters in the world to measure water use. Lysimeters are large boxes filled with soil. The lysimeter is weighed frequently with very accurate scales. The change in weight represents the amount of evaporation or transpiration from the system over the period. Adjustments must be made when the soil is irrigated and/or precipitation occurs. We used the lysimeters under a lateral-move irrigation system to measure the water use when a lysimeter was not irrigated and for two lysimeters irrigated with impact sprinklers placed on top of the lateral and with a stationary serrated spray-plate sprinkler. We also measured the rate of evaporation from the soil and the amount of water transpired through a group of corn plants using sapflow sensors. The results for a hot-dry day at Bushland (Figure 17) show that the water use for non-irrigated conditions was about 0.35 inches/day and that transpiration comprised the majority of the water use (i.e. evaporation was about 0.1 inches/day and transpiration was about 0.25 inches/day). There was no droplet or canopy evaporation for the non-irrigated plot.

The total water use was about 0.45 inches/day when irrigating the plots with impact sprinklers. Transpiration decreased to about 0.2 inches/day for plots irrigated with impact sprinklers, while evaporation from the soil increased to about 0.15 inches/day. Little water in droplets evaporated while they flew through the air. Direction evaporation from the canopy accounted for about 0.1 inches/day for impact sprinkler irrigated plots. The total water use increased about 0.1 inches/day. Note that the amount of water evaporated from the canopy compensates for transpiration. The reduction of transpiration represents about half of the increased canopy evaporation; therefore, not all of the canopy evaporation is a net loss.

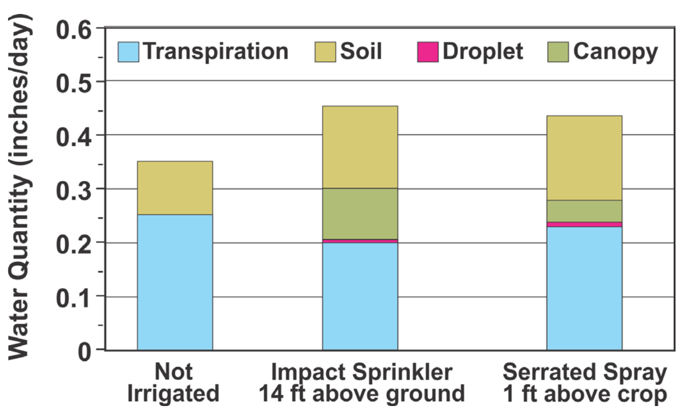


Figure 17. ET components for dryland plots and plots irrigated with impact sprinklers or stationary spray pad devices.

The total water use for plots irrigated with serrated-plate spray devices resulted in total water use of about 0.42 inches/day. Again, evaporation of water droplets in the air was very small while the canopy evaporation was about 0.04 inches/day. Transpiration was about 0.23 inches for the day. The amount of canopy evaporation is about twice the reduction in transpiration as with the impact sprinkler.

These and other results illustrate that evaporative loss of water while the droplets are in the air is very small and that evaporation from the canopy offsets about half of the reduction in transpiration. Our results show that canopy evaporation continues for about one hour after the sprinkler pattern passes a point. We made these measurements during the early afternoon when the evaporative demand is highest. The overall water use is for the entire day but the droplet and canopy evaporation would be highest during this time. Portions of the field irrigated at night would experience less canopy evaporation than during the middle of the day; however, transpiration is very low at night and there will be less transpiration compensation at night.

Our research indicates that evaporation of droplets in the air depends strongly on the diameter of the droplet (Figure 18). Evaporation loss for these climatic conditions could exceed 20% if the drops are very small, while very little evaporation occurs when the droplet diameter exceeds 0.040 inches, even for the harsh conditions for Figure 18.

The sprinkler industry has made great progress in developing sprinkler devices with controlled drop sizes. The results in Figure 19 show that drop sizes are smaller than 0.040 inches for a large percentage of the drops from for smooth pads while deep grooved stationary pads provide the majority of the droplets larger than 0.040 inches. Irrigators now have a wide range of choices in droplet diameter by selecting the appropriate pad.

We recommend selection of devices that have medium to large diameter droplets to minimize evaporation and drift losses. The only concern for large drops is when irrigating soils with little or no residue cover or crop canopy to protect the soil. Large drops strike the soil with significant amounts of energy that can lead to the breakdown of the structure of soils, especially for silt loam and fine sandy loam soils. The loss of structure results in a seal that forms on the soil surface that reduces the infiltration rate. Irrigation of unprotected soil is rare in the eastern two-thirds of the state where irrigation does not commence until there is substantial crop canopy development. Reduced-till systems that maintain residue cover also protects the soil surface.

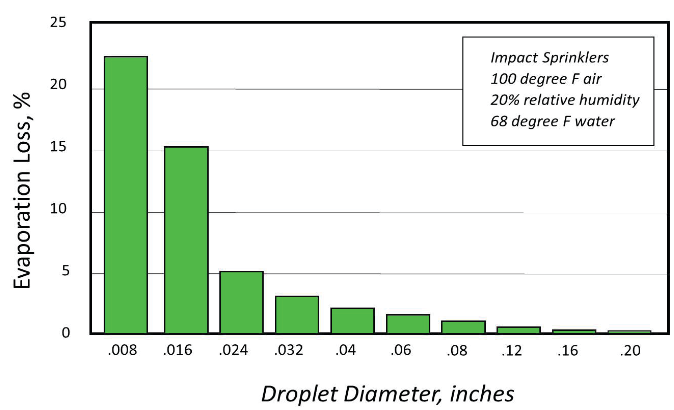


Figure 18. Evaporation rates for various sizes of droplets.

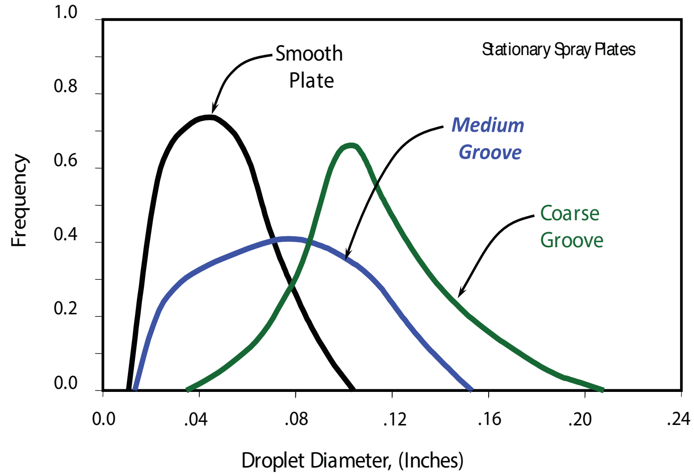


Figure 19. Drop size distributions for three types of stationary spray pad devices.

Runoff Problems

Runoff of irrigation water occurs when the center pivot applies water at a rate that exceeds the ability of the soil to infiltrate the water. Water applied at rates that exceed the infiltration rate will initially accumulate in depressions on the soil surface. The amount of water that can be stored on the soil surface is called the surface storage. If the water applied exceeds what the soil can infiltrate or store on the surface then water will begin to flow across the field as illustrated in Figure 20. The sketch on the left of Figure 20 shows that less storage is possible for steep slopes.

Potential runoff occurs when the surface storage is less than the excess application as illustrated in Figure 21. Water begins to pond on the soil surface when the application rate exceeds the infiltration rate. Runoff begins once the surface storage is full. The total potential runoff reaches a maximum when the application equals the infiltration rate near the end of the irrigation event.

The peak application rate shown in Figure 22 is determined by the sprinkler package design. The duration of the irrigation is directly related to the depth of water applied. Application of 2.4 inches of water leads to large runoff potential. Reducing the depth of application does not affect the peak application rate but shortens the irrigation duration. The potential for runoff drops to nearly zero when the depth of application drops to 0.8 inches.

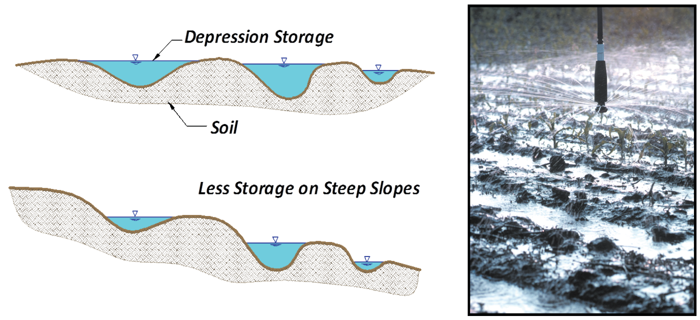


Figure 20. Illustration of surface storage that provides detention of water to extend time for infiltration.

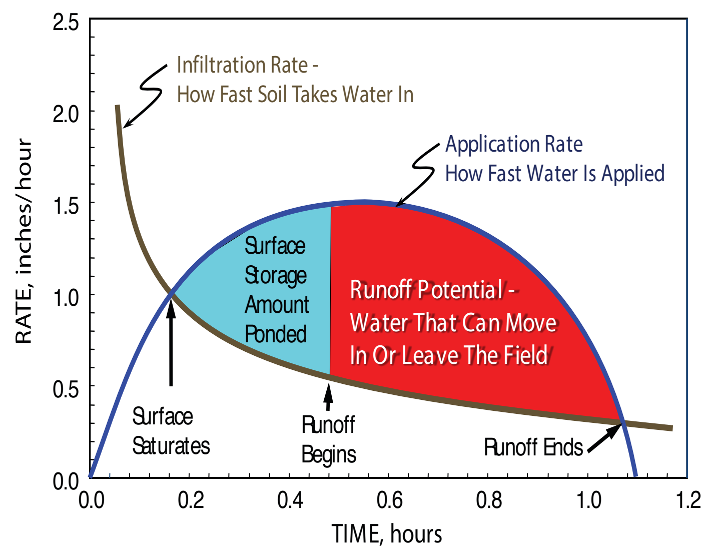


Figure 21. Illustration of processes affecting runoff potential from a center pivot.

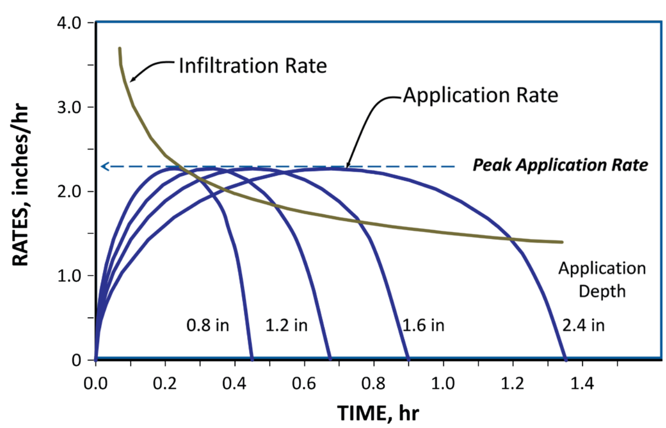


Figure 22. Effect of water application depth per irrigation on runoff potential.

Reducing the depth of application is about the only option available to irrigators during the irrigation season to reduce runoff if it is a problem. Producers should inspect the water application at the outer end of the pivot on the steepest portion of the field to determine if runoff is an issue in the field. If runoff occurs, the irrigator should consider speeding up the pivot to apply less water and reduce runoff. Long-term solutions include increasing the surface storage through tillage changes and increased amounts of residue. Reduced tillage has proven to improve infiltration over the long-term, which is usually advantageous for center-pivot irrigation.

Summary

Center pivots have the potential to be uniform and efficient, but they must be properly designed, installed and maintained to achieve that potential. The basic requirements for center pivot design were presented in this chapter. Additional details for center pivot management are presented in the remaining chapters of the handbook.

Chapter 3. Soil Water Management

Effective management of an irrigation system requires the understanding and use of the basic concepts of soil water. Without an adequate understanding of these concepts, the irrigator will not know how much water to apply or when to irrigate. The goal of irrigation management is to maintain the amount of water in the soil between wet and dry extremes to satisfy the plant's water requirements. The wet soil extreme occurs when plants suffer because of decreased aeration, and the dry soil extreme occurs when plants have difficulty obtaining the water they need. Thus, it is necessary to determine the amount of water available in the soil for plant use and the proper amount of irrigation water to apply when irrigating.

Two measures of soil water are important for managing irrigation systems. The first is the amount of water in the soil, which is the soil water content. The second property is the soil water potential, which is a measure of how available the water in the soil is to plants, in other words, how hard do plants have to work to remove water from the soil.

Water Content

As Figure 23 illustrates, soil is composed of three major components: soil particles, air, and water. The fractions of water and air are contained in the voids between soil particles. The ratio of the volume of pores (voids) to the total (bulk) volume of a soil is the porosity.

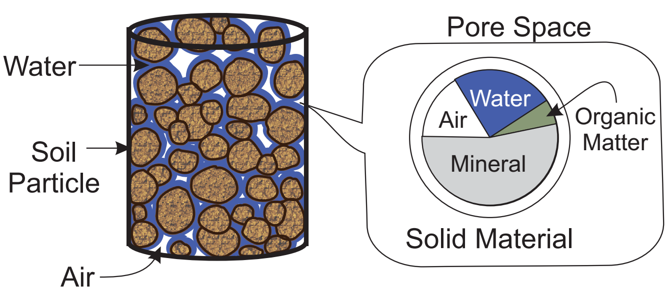
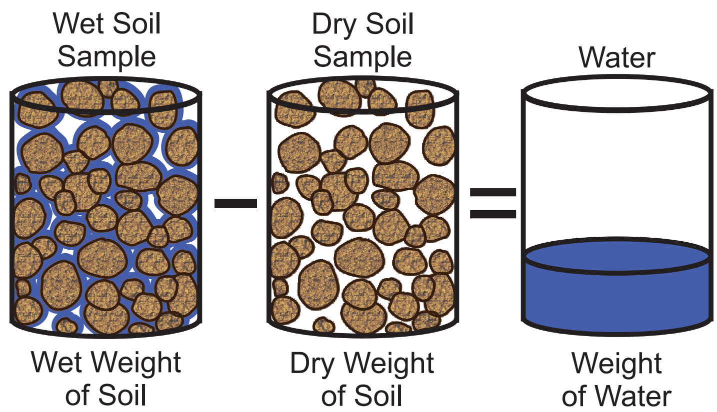


Figure 23. Composition of an unsaturated soil sample.

The amount of water in a soil can be expressed in many ways, including percent moisture on a dry soil basis (mass water content), percent moisture on a volumetric basis (volumetric water content), percent of the available water remaining and percent of the available water depleted. Confusion can occur with these terms.

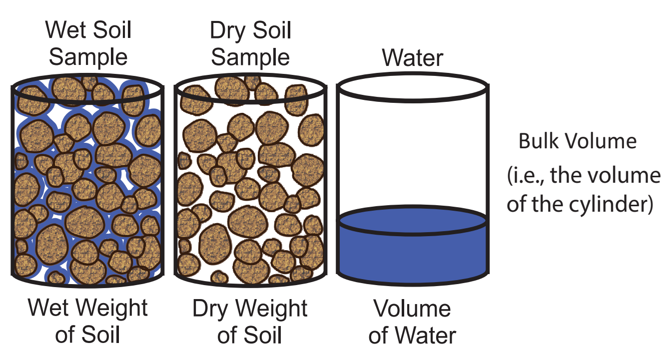
The mass water content (θ_m) is the ratio of the mass of water in a sample to the dry soil mass, expressed either as a decimal fraction or a percentage (Figure 24). Mass water content is determined by weighing a field soil sample, drying the sample for at least 24 hours at 220 °F, and then weighing the dry soil. The decrease in mass of the sample due to drying represents the mass of water in the soil sample. The weight of the sample after drying represents the mass of dry soil.



$$\theta_m = \frac{\text{Mass of Water}}{\text{Mass of Dry Soil}} = \frac{\text{Weight of Water}}{\text{Weight of Dry Soil}}$$

Figure 24. Concept of mass water content.

The volumetric water content represents the volume of water contained in a volume of soil. Figure 25 illustrates the components needed to calculate the volumetric water content. When comparing water amounts per unit of land area, it is frequently more convenient to speak in equivalent depths of water rather than water content. The relationship between volumetric water content and the equivalent depth of water in a soil layer is given by $d = \theta_v \times L$ where d is the equivalent depth of water in a soil layer, θ_v = the volumetric water content and L = depth increment of the soil layer.



$$\theta_v = \frac{\text{Volume of Water}}{\text{Bulk Volume}}$$

Figure 25. Concept of volumetric water content.

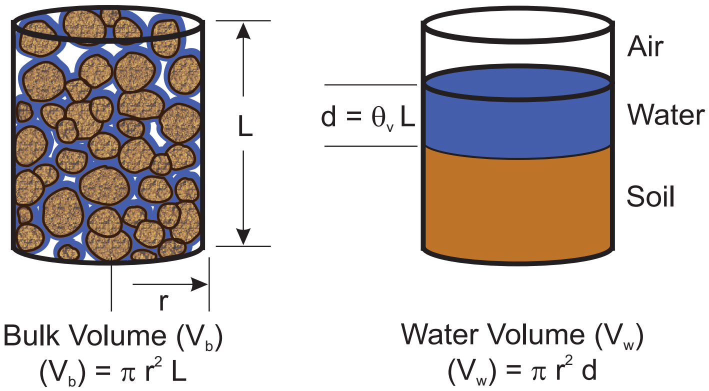


Figure 26. Illustration of depth of water per unit depth of soil.

Soil Water Potential

The amount of water in the soil is not the only concern in irrigation management. Plants must be able to extract water from the soil. Soil water potential is an indicator or measure of the energy status of soil water relative to that of water at a standard reference[2] and is often expressed as energy per unit of volume (in units of bars or centibars) or energy per unit of weight (in units of feet or centimeters of head). The three major components of total soil water potential are gravitational potential (ψ_z), matric potential (ψ_m), and solute potential (ψ_s). The total potential (ψ_t) is given by $\psi_t = \psi_m + \psi_s + \psi_z$. The gravitational potential is due to the force of gravity pulling downward on the water in the soil. Matric potential describes the force the soil matrix places on the water by adhesion and capillarity, and is known as the soil water tension. Dissolved solids (salts) in the soil water cause solute potential. The solute potential affects the availability and movement of water in soils when a semi-permeable membrane (like plant roots) is present.

During evaporation, water moves across the soil-air interface but salts stay behind in the soil. Over time this can lead to a build up of salts unless the salt is leached by rain or irrigation water. The concentration of salts in the soil is generally low where rainfall is significant, so the solute potential is small. The solute potential does not influence the flow of water through the soil profile; however, it does have an effect on water uptake by plants and on evaporation. The solute potential influences water uptake through plant roots. The higher the salt concentration in the soil solution the more work a plant has to do to extract water from the soil. Thus, where soil salinity is appreciable, solute potential must be considered for evaluating plant water uptake.

The component that dominates the release of water from soil to plants when salts are not present is the matric potential. Several forces are involved in the retention of water by the soil matrix. The most strongly held water is adsorbed around soil particles by adhesive forces. This water is held too tightly for plants to extract. Water is also held in the pores between soil particles by a combination of attractive (surface tension) and adhesive forces.

The strength of the attractive force depends on the sizes of the soil pores. Large pores have little attraction for water and freely give up pore water to plants or drainage due to gravitational forces. There is a corresponding matric water potential for a given amount of water in a particular soil. We express the magnitude of the matric potential as soil water tension. The curve representing the relationship between the tension of the soil and its volumetric water content is the soil water release curve. The curve in Figure 27 shows that water is released (volumetric water content decreases) by the soil as the tension increases.

Soil-water release curves are often used to define the amount of water available to plants. Two terms are used to define the upper and lower limits of plant water availability. The upper limit, field capacity (FC), is defined as the soil water content where the drainage rate, caused by gravity, becomes negligible. Thus, the soil is holding all of the water it can without any significant loss due to drainage. The wilting point (WP), the lower limit, is the water content below which plants can no longer extract water from the soil and will not recover if the water stress is relieved. Both limits are not exact. The WP usually corresponds to the water content corresponding to 15 bars (i.e., 1500 centibars) of soil water tension. This is a reasonable working definition because the water content varies slightly over a wide range of soil water tension near 1500 centibars. Therefore, if the plants permanently wilt at 2000 centibars of tension, the water content is not much different than at 1500 centibars and the errors in estimates of water available to plants are small. The volumetric water content at WP is given in Figure 27 for several typical soil types.

Field capacity is often defined as the water content at a soil water potential of minus one-third bar or a tension of 33 centibars. This is NOT a good definition for all soils. This tension for FC is good for some fine-textured soils but is too large for medium- and coarse-textured soils. The values for the field capacity shown in Figure 27 are more representative than a strict one-third bar (33 cbars) definition.

[2]Hillel, D. 1980. Fundamentals of Soil Physics. Academic Press, New York, NY.

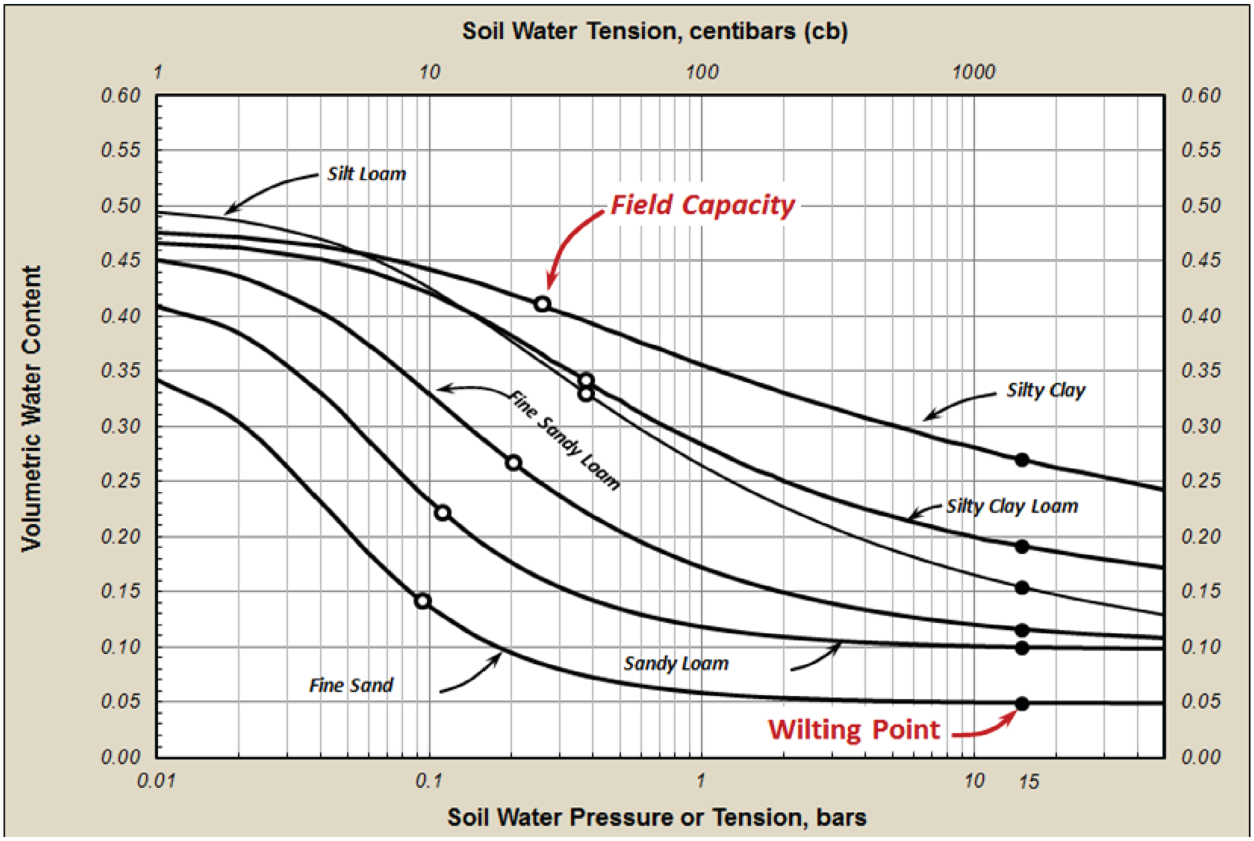


Figure 27. Soil water release curves for typical soil types.

Available Water

The water held between field capacity and the permanent wilting point is called the available water or the available water capacity (AWC), i.e., available for plant use. For the sandy loam soil shown in Figure 27, the volumetric water content at field capacity is 0.22, and the volumetric water content at WP is about 0.10. Thus, the available water capacity for that soil is 0.12 (0.22 - 0.10). The AWC of the soil is often expressed in units of depth of available water per unit depth of soil, i.e., inches of water per foot of soil. In the example above, the AWC is 0.12 in/in or 1.44 inches of water per foot of soil.

Field soils are generally at water contents between the FC and WP. Commonly terms in irrigation management are soil water depletion or soil water deficit (SWD). Soil water depletion refers to the amount of available water that has been removed. Moisture remaining is how much of the available water that is still in the root zone. It is very useful in irrigation management to know the depth of water required to fill a layer of soil to field capacity. This depth is equal to the SWD.

Data for soil properties are available from various sources. County Soil Survey Reports and the Web Soil Survey from the USDA-NRCS normally list these data. Ranges of values for available water holding capacity for typical soil texture classes are listed in Table 3. Organic matter often decreases with depth in the soil profile which reduces the soil water retention which is reflected by smaller water holding capacities for the subsoil and lower horizon compared to the topsoil in Table 3.

A table was developed by University of Nebraska-Lincoln Extension to relate soil matric potential to soil water depletion. Table 4 gives typical depletions for a range of matric potentials by soil type. The table also gives typical available water capacities and irrigation trigger points for each soil type. Irrigation trigger points are a suggested matric potential range for initiating irrigation for the soil types. The points are based on allowing the soil to reach a SWD of 35% of AWC.

Table 3. Available water holding capacity of representative soil texture classes (inches of water/foot of soil)[3].

	Soil Layer and Depth Interval		
	Topsoil	Subsoil	Lower Horizon
Soil Texture Class	0-12 inches	12-36 inches	36-60 inches
Coarse sand and gravel	0.48 - 0.72	0.36 - 0.60	0.25 - 0.50
Sands	0.84 - 1.08	0.72 - 0.96	0.60 - 0.84
Loamy sands	1.20 - 1.44	1.08 - 1.32	0.96 - 1.20
Sandy loams	1.56 - 1.80	1.44 - 1.68	1.32 - 1.56
Fine sandy loams	1.92 - 2.16	1.80 - 2.04	1.44 - 1.92
Very fine sandy loam	2.04 - 2.28	1.92 - 2.16	1.92 - 2.16
Loam	2.40 - 2.64	2.04 - 2.28	2.04 - 2.28
Silt loams	2.40 - 2.76	2.16 - 2.40	2.16 - 2.40
Silty clay loams (<35% clay)	2.52 - 2.76	2.16 - 2.40	2.16 - 2.40
Silty clay loams (>35% clay)	2.04 - 2.40	1.92 - 2.16	1.92 - 2.16
Sandy clay loams	2.16 - 2.40	1.92 - 2.16	1.80 - 2.04
Clay loams (<35% clay)	2.28 - 2.64	2.04 - 2.28	1.92 - 2.16
Clay loams (>35% clay)	1.92 - 2.28	1.80 - 2.04	1.68 - 1.92
Silty clays (<50% clay)	1.56 - 2.04	1.32 - 1.92	1.20 - 1.56
Silty clays (>50% clay)	1.20 -1.68	1.20 - 1.44	0.96 - 1.44
Clays (<50% clay)	1.44 - 1.92	1.20 - 1.80	1.20 - 1.44
Clays (>50% clay)	1.20 - 1.68	0.96 - 1.44	0.96 - 1.44

[3]From the USDA-NRCS at http://efotg.sc.egov.usda.gov//references/public/NE/NE_Irrig_Guide_Index.pdf.

Table 4. Soil water depletions (inches/foot) for a range of soil matric potentials for typical soil types. The water holding capacity and suggested range of soil matric potentials to use to initiate irrigation are also included.

Soil water matric Potential, centibars	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	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.20	0.30	0.30	0.30
33	0.20	0.14	0.00	0.00	0.55	0.50	0.45	0.55
50	0.45	0.36	0.32	0.30	0.80	0.70	0.60	0.70
60	0.50	0.40	0.47	0.44	1.00	0.80	0.70	0.70
70	0.60	0.50	0.59	0.50	1.10	0.80	0.80	0.80
80	0.65	0.55	0.70	0.60	1.20	1.00	0.93	1.00
90	0.70	0.60	0.78	0.70	1.40	1.20	1.04	N/A
100	0.80	0.68	0.85	0.80	1.60	1.40	1.10	N/A
110	0.82	0.72	0.89	0.88	1.60	N/A	N/A	N/A
120	0.85	0.77	0.91	0.94	N/A	N/A	N/A	N/A
130	0.86	0.82	0.94	1.00	N/A	N/A	N/A	N/A
140	0.88	0.85	0.97	1.10	N/A	N/A	N/A	N/A
150	0.90	0.86	1.08	1.20	N/A	N/A	N/A	N/A
200	1.00	0.95	1.20	1.30	N/A	N/A	N/A	N/A
Water holding capacity (in/ft)	1.8-2.0	1.8-2.0	2.20	2.00	1.80	1.40	1.10	1.00
Suggested range of irrigation trigger points (cb)	75-80	80-90	90-100	75-80	45-55	30-33	25-30	20-25

(*) The trigger points were calculated based on 35% depletion of the total soil water holding capacity per foot of soil layer. The sensor readings and the trigger points should be verified/checked against the crop appearance in the field during the season. Trigger point should be the average of the first 2 feet prior to crop reproductive stages and 3 feet once crop reaches the reproductive stage. For sandy soils, the average of the top 2 sensors should be used as a trigger at all times. (N/A) Not applicable.

Infiltration

Soil water is replenished from precipitation and irrigation by the process called infiltration, the entry of water into the soil. Infiltration is very important in irrigation since the goal is to supply water to the root zone to meet plant needs. In most cases, the goal is that all of the applied irrigation and rain enters the soil; thereby minimizing the amount of water that runs off the soil surface.

Two processes determine the rate of water infiltration, capillarity and gravity. Capillarity is the attraction of the soil for water and is determined by the size of pores in the soil matrix and the moisture content of the soil. Gravitational effects prevail when the soil is very wet, near saturation. During the initial stages of a water application, the capillary forces dominate water movement into the soil. Capillary forces work equally in all directions. Thus, the capillary forces pulling water into the soil are the same in the horizontal and vertical directions. As time progresses, the capillary forces diminish and gravity becomes the dominant force. This change in the dominant force is illustrated in Figure 28a where a wetted pattern under an irrigated furrow is almost semi-circular early in the irrigation but, as shown in Figure 28b, as infiltration progresses the wetted pattern elongates in the vertical direction. The elongation is due to the dominance of the gravitational force over capillary force with time.

Infiltration can be described in terms of the rate water enters the soil (i.e., the depth that infiltrates per unit of time) or the cumulative amount of infiltration over time. Cumulative infiltration is the total depth that has infiltrated after a specific time has elapsed. The curve shown in Figure 29 illustrates rates of infiltration with time for several soil types.

The curves show that initially the infiltration rate is very high and as time progresses, or more correctly, as the amount of water that has infiltrated increases, the rate of infiltration decreases. Therefore, a decay curve results with a decreasing rate of infiltration. As time continues, the infiltration rate will approach a nearly steady rate, sometimes called the steady-state rate or basic infiltration rate. The x-axis of Figure 29 is labeled as the elapsed time of application or the opportunity time.

The cumulative infiltration or depth of water infiltrated over time is shown in Figure 30. The cumulative depth increases with time but it is not a straight line. Infiltration accumulates at a fast rate early and then slows later in the irrigation or rainfall event. The slope of the curve approaches the steady-state infiltration rate shown in Figure 29.

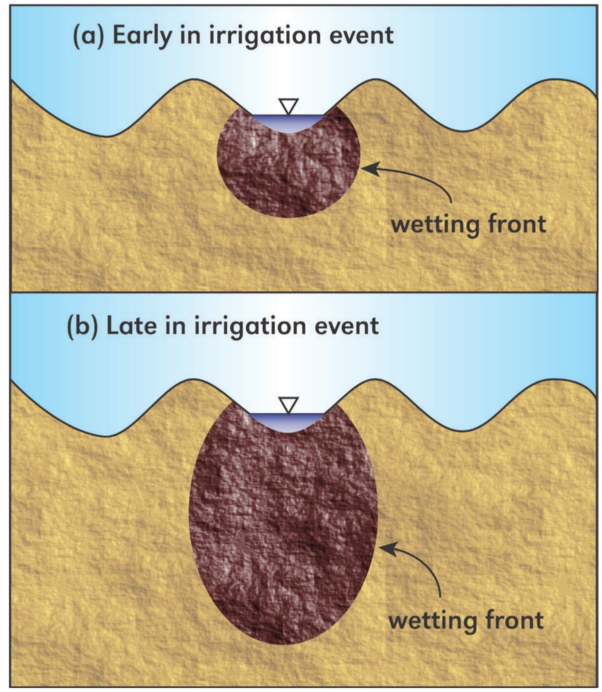


Figure 28. Wetting patterns early and late in furrow irrigation water application.

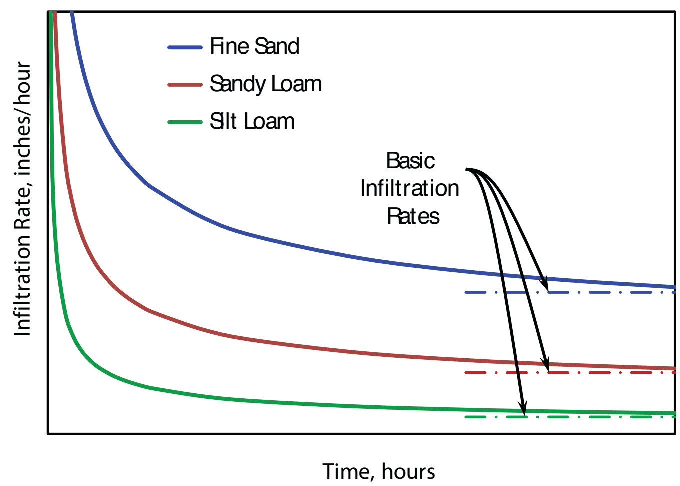


Figure 29. Infiltration rate vs. opportunity time.

Be careful not to confuse the cumulative infiltration or depth of infiltration with the depth to which water has penetrated in the soil. View it as water in a rain gauge. The depth of infiltration is analogous to the depth of water in the rain gauge. It is the volume of water infiltrated per unit of land area.

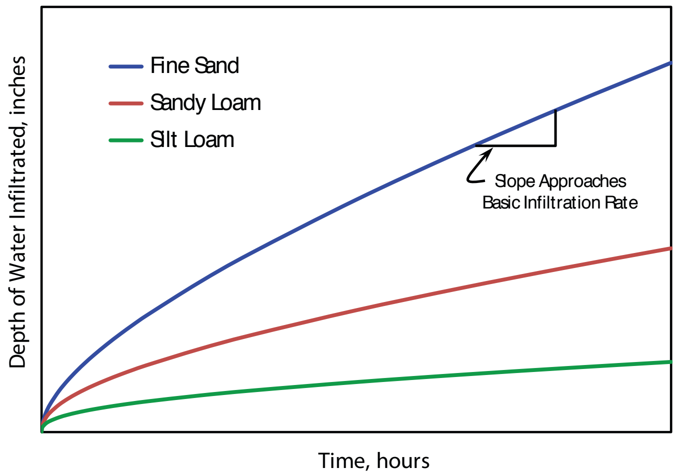


Figure 30. Examples of cumulative infiltration curves.

Several factors influence the infiltration rate of the soil. Often, the first thing that comes to mind is the soil texture. We generally think of coarser-textured (sandy) soils having higher infiltration rates than fine- (clay) and medium-textured (loam) soils. In theory, if the soils were uniform with depth, and if surface sealing did not occur, the steady-state infiltration rate would be equal to the permeability or saturated hydraulic conductivity of the soil. Permeability is a measure of a soil's ability to transmit water while saturated. The ranges of permeability of soils are often listed in soil survey reports. Usually, ideal conditions do not exist in the field and, hence, other factors influence the steady-state infiltration rate along with permeability.

Surface sealing is another factor influencing the infiltration rate. Surface sealing occurs when the shearing effect of flowing water or impact energy of large drops cause the aggregates on the soil surface to decompose into smaller aggregates and individual particles that tend to form a thin layer with low permeability on the soil surface. It is common to find large differences between infiltration during the first irrigation event and infiltration during later irrigation events due to surface sealing.

Another factor that has a large influence on infiltration is soil cracking. Soils that contain fine soil particles (clays) may shrink when drying and swell during wetting. Cracks formed during drying have a strong effect on the initial infiltration rate of a soil as water flows freely into the cracks. The cracks swell shut as the soil wets which causes the infiltration rate to decline. Once filled with water the cracks also provide more surface area for infiltration.

Tillage has a large impact on the infiltration rate and is often performed to enhance infiltration. Conservation tillage practices that leave crop residues on the soil surface enhance infiltration. Crop residue on the surface protects the soil from the impact of water drops from rain and sprinkler irrigation, thus reducing the formation of a surface seal. Likewise, deep tillage (chiseling) is sometimes used to enhance infiltration.

Soil water content is another factor that influences infiltration. The wetter the soil, the lower the infiltration rate. The initial infiltration rate of a moist soil is, in general, lower than the initial infiltration rate of an identical dry soil. As time progresses, the infiltration rate of these two conditions converge to the same steady-state value.

Water temperature is also known to influence infiltration rates. Temperature changes the viscosity of water. As temperature increases, the viscosity decreases, hence, the infiltration rate increases[4]. As water warms, the infiltration rate can go up. An excess amount of sodium can decrease infiltration. A sodic soil, one with excess sodium, is extremely difficult to irrigate because infiltration rates are so low.

Intake family

The USDA-NRCS rated soils for their ability to infiltrate water. Soils are assigned to representative classes related to infiltration rates in the units of inches/hour called the intake family. Soils classified in the intake families of 0.1, 0.3, 0.5, and 1.0 are generally those that are suited for center pivot irrigation but that have potential for runoff. Some sandy soils are classified into higher intake families such as intake family 1.5; however, these soils rarely have runoff problems. Table 5 categorizes the soils of Nebraska into intake families.

The intake family system is a general classification system for soils. Actual infiltration rates can vary considerably due to tillage, residue, and other cultural practices. Specific designs should involve measurement of actual soil conditions. However, the soil intake family system is useful for selecting sprinkler packages for center pivot systems.

4Duke, H.R. 1992. Water Temperature Fluctuations and Effect on Irrigation Infiltration. Trans. of the ASAE, 35(1):193-199.

Table 5. Soil series by NRCS intake family (http://efotg.sc.egov.usda.gov/references/public/NE/NE_Irrig_Guide_Index.pdf).

Soil Name	Intake Family	Soil Name	Intake Family	Soil Name	Intake Family
Ackmore Silt Loam	1.0	Bayard Loamy Fine Sand	2.0	Bolent Loamy Sand	3.0
Aksarben Silt Clay Loam	0.3	Bayard Sandy Loam	1.5	Boyd Silty Clay	0.1
Albaton Clay	0.1	Bayard Very Fine Sandy Loam	1.5	Bridget Loam	1.0
Albaton Silt Clay Loam	0.1	Bazile Fine Sandy Loam	1.5	Bridget Silt Loam	1.0
Albaton Silt Loam	0.3	Bazile Loam	1.5	Bridget Very Fine Sandy Loam	1.0
Albaton Silty Clay	0.1	Bazile Loamy Fine Sand	2.0	Bristow Silty Clay	0.1
Albaton Variant Clay	0.1	Bazile Silt Clay Loam	0.3	Brocksburg Fine Sandy Loam	1.5
Alcester Silt Clay Loam	0.3	Bazile Silt Loam	1.0	Brocksburg Loam	1.0
Alcester Silt Loam	1.0	Belfore Silt Clay Loam	0.3	Brunswick Fine Sandy Loam	1.5
Alda Fine Sandy Loam	1.5	Belfore Silt Loam	0.5	Brunswick Loamy Sand	3.0
Alda Loam	1.0	Benfield Silt Clay Loam	0.1	Buffington Silt Clay Loam	0.3
Alda Sandy Loam	1.5	Benkelman Very Fine Sandy Loam	1.0	Buffington Silty Clay	0.1
Alda Very Fine Sandy Loam	1.0	Betts Clay Loam	0.3	Bufton Clay Loam	0.3
Alice Fine Sandy Loam	1.5	Betts Loam	0.5	Bufton Silt Clay Loam	0.3
Alice Loamy Fine Sand	2.0	Bigbend Loam	1.0	Burchard Clay Loam	0.3
Alice Sandy Loam	1.5	Blackwood Loam	1.0	Burchard Loam	0.5
Alice Very Fine Sandy Loam	1.5	Blackwood Silt Loam	1.0	Burchard Silt Loam	0.5
Alliance Loam	0.5	Blake Silt Clay Loam	0.3	Busher Fine Sandy Loam	1.5
Alliance Silt Loam	0.5	Blanche Fine Sandy Loam	1.5	Busher Loamy Very Fine Sand	2.0
Altvan Fine Sandy Loam	1.5	Blanche Loamy Fine Sand	3.0	Busher Very Fine Sandy Loam	1.5
Altvan Loam	1.0	Blanche Loamy Sand	3.0	Bushman Very Fine Sandy Loam	1.0
Altvan Sandy Loam	1.5	Blanche Sandy Loam	1.5	Butler Silt Clay Loam	0.1
Angora Very Fine Sandy Loam	1.0	Blanche Very Fine Sandy Loam	1.5	Butler Silt Loam	0.3
Anselmo Fine Sandy Loam	1.5	Blencoe Silt Clay Loam	0.1	Calamus Loamy Fine Sand	3.0
Anselmo Loam	1.5	Blencoe Silty Clay	0.1	Calamus Loamy Sand	3.0
Anselmo Loamy Fine Sand	2.0	Blendon Fine Sandy Loam	1.5	Calamus Sandy Loam	1.5
Anselmo Sandy Loam	1.5	Blendon Loam	1.5	Calco Sandy Loam	0.5
Anselmo Very Fine Sandy Loam	1.5	Blendon Sandy Loam	1.5	Calco Silt Clay Loam	0.5
Aowa Silt Loam	1.0	Blyburg Silt Clay Loam	0.3	Calco Silt Loam	0.5
Ashollow Fine Sandy Loam	3.0	Blyburg Silt Loam	1.0	Campus Loam	1.0
Ashollow Loamy Very Fine Sand	3.0	Blyburg Silty Clay	0.1	Carr Fine Sandy Loam	1.5
Ashollow Very Fine Sandy Loam	1.5	Boel Fine Sandy Loam	3.0	Carr Silt Loam	1.5
Bahl Clay	0.1	Boel Loam	1.5	Caruso Loam	0.5
Baltic Silt Clay Loam	0.1	Boel Loamy Fine Sand	3.0	Caruso Variant Loam	0.5
Baltic Silty Clay	0.1	Boel Loamy Sand	3.0	Cass Fine Sandy Loam	1.5
Bankard Fine Sand	3.0	Boel Silt Clay Loam	0.3	Cass Loam	1.5
Bankard Loamy Course Sand	3.0	Boelus Fine Sand	2.0	Cass Silt Loam	1.5
Bankard Loamy Fine Sand	3.0	Boelus Loamy Fine Sand	2.0	Cass Variant Fine Sandy Loam	1.5
Bankard Loamy Sand	3.0	Boelus Loamy Sand	2.0	Cass Very Fine Sandy Loam	1.5
Bankard Sand	3.0	Bolent Fine Sand	2.0	Chappell Fine Sandy Loam	1.5
Bankard Very Fine Sandy Loam	3.0	Bolent Fine Sandy Loam	3.0	Chappell Sandy Loam	1.5
Bayard Fine Sandy Loam	1.5	Bolent Loam	1.5	Chase Silt Clay Loam	0.1
Bayard Loam	1.5	Bolent Loamy Fine Sand	3.0	Cheyenne Loam	1.0

Soil Name	Intake Family	Soil Name	Intake Family	Soil Name	Intake Family
Clamo Silty Clay	0.1	Dunn Loamy Fine Sand	2.0	Gibbon Loamy Sand	2.0
Clarno Loam	0.5	Dunn Loamy Sand	2.0	Gibbon Silt Clay Loam	0.3
Colby Loam	1.0	Duroc Loam	1.0	Gibbon Silt Loam	1.0
Colby Silt Loam	1.0	Duroc Silt Loam	1.0	Gibbon Variant Silt Clay Loam	0.3
Coleridge Silt Clay Loam	0.3	Duroc Very Fine Sandy Loam	1.0	Glenberg Fine Sandy Loam	1.5
Coleridge Silt Loam	0.5	Dwyer Fine Sand	3.0	Glenberg Loam	1.5
Colfer Sand	3.0	Dwyer Loamy Fine Sand	3.0	Glenberg Loamy Fine Sand	2.0
Colo Silt Clay Loam	0.3	Dwyer Loamy Sand	3.0	Glenberg Loamy Very Fine Sand	2.0
Colo Silt Loam	0.5	Edalgo Silt Clay Loam	0.1	Glenberg Very Fine Sandy Loam	1.5
Coly Silt Loam	1.0	Els Fine Sand	3.0	Goshen Loam	0.5
Cooper Silt Clay Loam	0.1	Els Loamy Fine Sand	3.0	Goshen Silt Loam	0.5
Cortland Loam	0.3	Els Loamy Sand	3.0	Gosper Loam	1.0
Cozad Loam	1.0	Els, Calcareous Fine Sand	3.0	Grable Silt Loam	1.0
Cozad Silt Clay Loam	0.3	Elsmere Fine Sand	3.0	Grable Variant Silt Loam	1.0
Cozad Silt Loam	1.0	Elsmere Fine Sandy Loam	3.0	Grable Very Fine Sandy Loam	1.0
Cozad Variant Loam	1.0	Elsmere Loamy Fine Sand	3.0	Graybert Very Fine Sandy Loam	1.0
Cozad Variant Silt Loam	1.0	Eltree Silt Loam	1.0	Grigston Silt Loam	1.0
Craft Loam	1.0	Eudora Loam	1.0	Gymer Silt Clay Loam	0.3
Craft Loamy Very Fine Sand	2.0	Eudora Silt Loam	1.0	Hadar Loamy Fine Sand	2.0
Craft Sandy Loam	2.0	Filbert Silt Loam	0.3	Haigler Fine Sandy Loam	2.0
Craft Very Fine Sandy Loam	1.0	Filley Fine Sandy Loam	1.5	Haigler Loam	2.0
Creighton Very Fine Sandy Loam	1.0	Fillmore Silt Clay Loam	0.1	Haigler Very Fine Sandy Loam	2.0
Crete Silt Clay Loam	0.1	Fillmore Silt Loam	0.3	Hall Silt Clay Loam	0.3
Crete Silt Loam	0.3	Fillmore Variant Silt Loam	0.3	Hall Silt Loam	0.5
Crete Variant Silt Clay Loam	0.1	Fonner Loam	1.0	Harney Silt Loam	0.5
Crofton Silt Loam	1.0	Fonner Sandy Loam	1.5	Hastings Silt Clay Loam	0.3
Dailey Loamy Fine Sand	3.0	Fonner Variant Loamy Sand	1.5	Hastings Silt Loam	0.5
Dailey Loamy Sand	3.0	Forney Silt Loam	0.3	Hastings Variant Silt Clay Loam	0.3
Dankworth Loamy Sand	3.0	Forney Silty Clay	0.1	Hastings Variant Silt Loam	0.5
Darr Fine Sandy Loam	1.5	Gates Fine Sandy Loam	1.5	Haverson Loam	1.0
Darr Sandy Loam	1.5	Gates Loamy Fine Sand	2.0	Haverson Silt Clay Loam	0.3
Darr Silt Loam	1.0	Gates Silt Loam	1.0	Haverson Silt Loam	1.0
Deroin Silt Clay Loam	0.3	Gates Very Fine Sandy Loam	1.0	Haxtun Loamy Fine Sand	2.0
Detroit Silt Loam	0.3	Gayville Loam	0.3	Haynie Silt Loam	1.0
Dickinson Fine Sandy Loam	1.5	Gayville Silt Clay Loam	0.3	Haynie Silty Clay	0.1
Doger Fine Sand	3.0	Gayville Silt Loam	0.3	Haynie Variant Silt Loam	1.0
Doger Loamy Fine Sand	3.0	Gayville Variant Silt Clay Loam	0.3	Haynie Very Fine Sandy Loam	1.0
Doughboy Loamy Fine Sand	2.0	Gayville Variant Silt Loam	0.3	Hemingford Loam	0.5
Dow Silt Loam	1.5	Geary Silt Clay Loam	0.3	Hennings Loamy Fine Sand	2.0
Draknab Loamy Fine Sand	3.0	Geary Silt Loam	0.5	Hersh Fine Sandy Loam	1.5
Dunday Fine Sandy Loam	1.5	Geary Variant Silt Clay Loam	0.3	Hersh Loamy Fine Sand	2.0
Dunday Loamy Fine Sand	3.0	Gering Loam	1.0	Hisle Loam	0.1
Dunday Loamy Sand	3.0	Gibbon Loam	1.0	Hisle Silt Loam	0.1

Soil Name	Intake Family	Soil Name	Intake Family	Soil Name	Intake Family
Hobbs Sandy Loam	1.0	Janude Fine Sandy Loam	1.5	Lawet Variant Loam	0.5
Hobbs Silt Loam	1.0	Janude Loam	1.0	Leisy Loam	0.5
Holder Loam	0.5	Janude Sandy Loam	1.5	Lemoyne Sand	3.0
Holder Silt Clay Loam	0.3	Jayem Fine Sandy Loam	1.5	Leshara Silt Loam	1.0
Holder Silt Loam	0.5	Jayem Loamy Fine Sand	2.0	Lex Clay Loam	1.0
Holder Variant Silt Clay Loam	0.3	Jayem Loamy Sand	2.0	Lex Loam	1.0
Holdrege Silt Clay Loam	0.3	Jayem Loamy Very Fine Sand	1.5	Lex Silt Loam	1.0
Holdrege Silt Loam	0.5	Johnstown Loam	0.5	Lex Variant Loam	1.0
Holdrege Variant Silt Clay Loam	0.3	Josburg Loam	0.3	Lexsworth Loam	1.0
Holly Springs Silt Clay Loam	0.1	Josburg Loamy Fine Sand	2.0	Libory Fine Sand	2.0
Holt Fine Sandy Loam	1.5	Judson Silt Clay Loam	0.3	Libory Loamy Fine Sand	2.0
Holt Variant Fine Sandy Loam	1.5	Judson Silt Loam	0.5	Lockton Loam	1.0
Holt Variant Loamy Fine Sand	2.0	Kadoka Silt Loam	0.5	Lockton Silt Loam	1.0
Hord Silt Clay Loam	0.3	Kanorado Silt Clay Loam	0.3	Lohmiller Silt Clay Loam	0.3
Hord Silt Loam	1.0	Keith Loam	0.5	Lohmiller Silty Clay	0.1
Hord Very Fine Sandy Loam	1.0	Keith Silt Loam	0.5	Longford Loam	0.3
Humbarger Loam	0.5	Kenesaw Silt Loam	1.0	Longford Loamy Fine Sand	2.0
Humbarger Variant Silt Loam	0.5	Kennebec Silt Clay Loam	0.3	Longford Silt Clay Loam	0.1
Ida Silt Loam	1.0	Kennebec Silt Loam	1.0	Loretto Loam	0.5
Inavale Fine Sand	3.0	Kenridge Silt Clay Loam	0.3	Luton Silt Clay Loam	0.1
Inavale Fine Sandy Loam	3.0	Keota Silt Loam	1.0	Luton Silt Loam	0.3
Inavale Loam	1.5	Keya Loam	0.5	Luton Silty Clay	0.1
Inavale Loamy Fine Sand	3.0	Kezan Silt Loam	1.0	Lynch Silty Clay	0.1
Inavale Loamy Sand	3.0	Kuma Loam	0.5	Mace Silt Loam	0.5
Inavale Very Fine Sandy Loam	3.0	Kuma Silt Loam	0.5	Malcolm Silt Loam	1.0
Inglewood Fine Sand	3.0	Kyle Silty Clay	0.1	Malmo Clay	0.1
Inglewood Loamy Fine Sand	3.0	Labu Silty Clay	0.1	Malmo Clay Loam	0.1
Interior Silty Clay	0.3	Laird Fine Sandy Loam	1.0	Malmo Silt Clay Loam	0.1
Ipage Fine Sand	3.0	Lamo Clay Loam	0.3	Manter Fine Sandy Loam	1.5
Ipage Loamy Fine Sand	3.0	Lamo Loam	0.5	Manter Loamy Fine Sand	2.0
Ipage Loamy Sand	3.0	Lamo Silt Clay Loam	0.3	Manvel Silt Clay Loam	0.3
Ipage Sand	3.0	Lamo Silt Loam	0.5	Marshall Silt Clay Loam	0.3
Janise Loam	0.5	Lamo Variant Loam	0.5	Marshall Silt Loam	0.5
Janise Loamy Fine Sand	2.0	Lancaster Loam	1.0	Maskell Loam	0.5
Janise Silt Loam	0.5	Las Animas Fine Sandy Loam	1.5	Mayberry Clay Loam	0.1
Jansen Fine Sandy Loam	1.5	Las Animas Loam	1.5	Mayberry Loam	0.3
Jansen Loam	1.0	Las Animas Loamy Fine Sand	2.0	Mayberry Silt Clay Loam	0.1
Jansen Loamy Fine Sand	2.0	Las Animas Very Fine Sandy Loam	1.5	Mccash Loamy Very Fine Sand	2.0
Jansen Loamy Sand	1.0	Las Loam	0.3	Mccash Very Fine Sandy Loam	1.0
Jansen Sandy Clay Loam	1.0	Laurel Loam	0.3	Mcconaughy Loam	1.0
Jansen Sandy Loam	1.0	Lawet Loam	0.5	Mccook Loam	1.0
Jansen Silt Loam	1.0	Lawet Silt Clay Loam	0.3	Mccook Sand	2.0
Jansen Variant Loamy Fine Sand	2.0	Lawet Silt Loam	0.5	Mccook Silt Clay Loam	0.3

Soil Name	Intake Family	Soil Name	Intake Family	Soil Name	Intake Family
Mccook Silt Loam	1.0	Norrest Clay Loam	0.3	Otero Very Fine Sandy Loam	1.5
Mccook Variant Loam	1.0	Norrest Loam	1.0	Otoe Silt Clay Loam	0.1
Mcgrew Fine Sandy Loam	1.5	Norrest Silt Clay Loam	0.3	Overlake Sand	2.0
Mcgrew Loam	1.0	Norwest Loam	1.0	Ovina Fine Sandy Loam	1.5
Mckelvie Fine Sand	3.0	Novina Fine Sandy Loam	1.5	Ovina Loam	1.5
Mckelvie Loamy Fine Sand	3.0	Novina Sandy Loam	1.5	Ovina Loamy Fine Sand	2.0
Mcpaul Silt Loam	1.0	Nuckolls Silt Loam	0.5	Owego Silty Clay	0.1
Merrick Loam	1.0	Nuckolls Variant Silt Clay Loam	0.3	Padonia Silt Clay Loam	0.1
Merrick Sandy Clay Loam	0.3	Nuckolls Variant Silt Loam	0.5	Pahuk Loamy Fine Sand	3.0
Merrick Variant Loam	1.0	Nunn Silt Loam	0.5	Paka Loam	0.5
Minatare Loam	0.1	Oglala Loam	1.0	Paka Sandy Clay Loam	0.3
Minnequa Silt Clay Loam	0.3	Oglala Very Fine Sandy Loam	1.0	Pathfinder Loamy Fine Sand	3.0
Mitchell Silt Loam	1.0	Olbut Silt Clay Loam	0.3	Pawnee Clay	0.1
Mitchell Variant Silt Loam	1.0	Olbut Silt Loam	0.3	Pawnee Clay Loam	0.1
Mitchell Very Fine Sandy Loam	1.0	Olmitz Loam	1.0	Pawnee Loam	0.3
Modale Silt Loam	1.0	Olney Loam	1.0	Pawnee Variant Clay	0.1
Modale Very Fine Sandy Loam	1.0	Omadi Silt Loam	1.0	Pawnee Variant Clay Loam	0.1
Monona Silt Loam	1.0	Onawa Clay	0.1	Percival Silty Clay	0.1
Moody Loam	0.5	Onawa Silt Clay Loam	0.1	Phiferson Loamy Very Fine Sand	2.0
Moody Silt Clay Loam	0.3	Onawa Silt Loam	0.3	Pierre Clay	0.1
Moody Silt Loam	0.5	Onawa Silty Clay	0.1	Pierre Silty Clay	0.1
Morrill Clay Loam	0.3	O'Neill Fine Sandy Loam	1.5	Pivot Fine Sandy Loam	3.0
Morrill Loam	1.0	O'Neill Loam	1.0	Pivot Loam	3.0
Moville Silt Loam	1.0	O'Neill Sandy Loam	1.5	Pivot Sandy Loam	3.0
Muir Silt Clay Loam	0.3	Onita Silt Clay Loam	0.3	Pohocco Silt Clay Loam	0.3
Muir Silt Loam	1.0	Onita Silt Loam	0.5	Pohocco Silt Loam	1.0
Munjor Fine Sandy Loam	1.5	Ord Fine Sandy Loam	1.5	Ponca Silt Clay Loam	0.3
Munjor Loam	1.0	Ord Loam	1.5	Ponca Silt Loam	1.0
Munjor Loamy Fine Sand	2.0	Ord Variant Fine Sandy Loam	1.5	Ponderosa Loamy Very Fine Sand	2.0
Munjor Variant Fine Sandy Loam	1.5	Ord Variant Loam	1.5	Ponderosa Very Fine Sandy Loam	1.5
Muscotah Silt Clay Loam	0.1	Ord Variant Silt Loam	0.5	Promise Silty Clay	0.1
Napa Silt Loam	0.1	Ord Variant Very Fine Sandy Loam	1.5	Ralton Loam	1.0
Napier Silt Loam	1.0	Ord Very Fine Sandy Loam	1.5	Redstoe Silt Loam	1.0
Nenzel Loamy Fine Sand	3.0	Orpha Loamy Fine Sand	3.0	Ree Loam	0.5
Nimbro Silt Loam	1.0	Ortello Fine Sandy Loam	1.5	Ree Silt Loam	0.5
Nishna Silty Clay	0.1	Ortello Loam	1.5	Reliance Silt Clay Loam	0.3
Nodaway Silt Clay Loam	0.3	Ortello Loamy Fine Sand	2.0	Reliance Silt Loam	0.5
Nodaway Silt Loam	1.0	Ortello Sandy Loam	1.5	Richfield Loam	0.5
Nodaway Variant Silt Loam	1.0	Ortello Very Fine Sandy Loam	1.5	Richfield Silt Loam	0.5
Nora Silt Clay Loam	0.3	Otero Fine Sandy Loam	1.5	Ronson Fine Sandy Loam	1.5
Nora Silt Loam	1.0	Otero Loam	1.5	Ronson Loamy Fine Sand	2.0
Nora Variant Silt Clay Loam	0.3	Otero Loamy Very Fine Sand	2.0	Rosebud Fine Sandy Loam	1.5
Nora Variant Silt Loam	1.0	Otero Variant Very Fine Sandy Loam	1.5	Rosebud Loam	1.0

Soil Name	Intake Family	Soil Name	Intake Family	Soil Name	Intake Family
Rosebud Sandy Loam	1.0	Shell Variant Silt Clay Loam	0.3	Vetal Loam	1.5
Rosebud Silt Loam	1.0	Sidney Loam	1.0	Vetal Loamy Fine Sand	2.0
Roxbury Silt Clay Loam	0.3	Silver Creek Silt Clay Loam	0.1	Vetal Loamy Very Fine Sand	2.0
Roxbury Silt Loam	1.0	Silver Creek Silt Loam	0.3	Vetal Very Fine Sandy Loam	1.5
Rusco Silt Clay Loam	0.3	Skilak Silt Clay Loam	0.3	Wabash Silt Clay Loam	0.1
Rusco Silt Loam	0.5	Solomon Silty Clay	0.1	Wabash Silt Loam	0.3
Rusco Variant Silt Clay Loam	0.3	Steinauer Clay Loam	0.3	Wabash Silty Clay	0.1
Rushcreek Loam	1.0	Steinauer Loam	0.3	Wakeen Silt Clay Loam	0.1
Salix Silt Clay Loam	0.3	Sulco Loam	1.0	Wakeen Silt Loam	1.0
Salix Silt Loam	0.5	Sulco Silt Loam	1.0	Wakeen Variant Silt Clay Loam	0.1
Salmo Silt Clay Loam	0.3	Sulco Very Fine Sandy Loam	1.0	Wann Fine Sandy Loam	1.5
Salmo Silt Loam	0.5	Sully Loam	1.0	Wann Loam	1.5
Saltine Loam	1.0	Sully Silt Loam	1.0	Wann Sandy Loam	1.5
Saltine Silt Clay Loam	0.3	Thirtynine Loam	0.5	Wann Silt Loam	1.5
Saltine Silt Loam	1.0	Thirtynine Silt Loam	0.5	Wann Variant Fine Sandy Loam	1.5
Sanborn Loam	1.5	Thurman Fine Sand	3.0	Wann Variant Loam	1.5
Sandose Loamy Fine Sand	2.0	Thurman Fine Sandy Loam	3.0	Wathena Fine Sandy Loam	1.5
Sansarc Clay Loam	0.1	Thurman Loamy Fine Sand	3.0	Waubonsie Very Fine Sandy Loam	1.5
Sansarc Silty Clay	0.1	Thurman Loamy Sand	3.0	Wewela Fine Sandy Loam	1.5
Sarben Fine Sandy Loam	1.5	Thurman Sand	3.0	Wewela Loam	1.0
Sarben Loamy Fine Sand	2.0	Tomek Silt Loam	0.5	Wewela Loamy Fine Sand	2.0
Sarben Loamy Sand	2.0	Trent Silt Clay Loam	0.3	Whitelake Loamy Fine Sand	2.0
Sarben Loamy Very Fine Sand	2.0	Trent Silt Loam	1.0	Wildhorse Fine Sand	3.0
Sarben Very Fine Sandy Loam	1.5	Tripp Loam	1.0	Wildhorse Loamy Fine Sand	3.0
Sardak Loamy Fine Sand	3.0	Tripp Loamy Very Fine Sand	2.0	Wildhorse Sand	3.0
Sarpy Fine Sand	3.0	Tripp Very Fine Sandy Loam	1.0	Wood River Fine Sandy Loam	0.3
Sarpy Fine Sandy Loam	3.0	Tuthill Loamy Fine Sand	2.0	Wood River Silt Loam	0.3
Sarpy Loamy Fine Sand	3.0	Uly Silt Loam	1.0	Woodbury Silty Clay	0.1
Sarpy Loamy Sand	3.0	Uly Variant Silt Clay Loam	0.3	Woodly Loamy Fine Sand	2.0
Sarpy Silty Clay	0.1	Ulysses Loam	1.0	Wymore Silt Clay Loam	0.1
Satanta Loam	0.5	Ulysses Silt Loam	1.0	Wymore Silty Clay	0.1
Satanta Very Fine Sandy Loam	0.5	Valent Fine Sand	3.0	Yockey Fine Sandy Loam	1.0
Savo Silt Clay Loam	0.3	Valent Loamy Fine Sand	3.0	Yockey Loam	1.0
Scott, Drained Silt Clay Loam	0.3	Valent Loamy Sand	3.0	Yockey Silt Loam	1.0
Scoville Fine Sand	2.0	Valent Sand	3.0	Yockey Very Fine Sandy Loam	1.0
Scoville Loamy Fine Sand	2.0	Valentine Fine Sand	3.0	Yutan Silt Clay Loam	0.3
Scoville Loamy Sand	2.0	Valentine Loamy Fine Sand	3.0	Zoe Silt Clay Loam	0.1
Selia Fine Sand	3.0	Valentine Loamy Sand	3.0	Zook Silt Clay Loam	0.1
Selia Loamy Fine Sand	3.0	Valentine Sand	3.0	Zook Silt Loam	0.3
Sharpsburg Variant Silt Clay Loam	0.3	Verdel Silt Clay Loam	0.1	Zook Silty Clay	0.1
Shelby Clay Loam	0.3	Verdel Silty Clay	0.1		
Shell Silt Clay Loam	0.3	Verdigre Loam	0.3		
Shell Silt Loam	1.0	Vetal Fine Sandy Loam	1.5		

Generalized Intake Families

The name of soils may change as soil surveys are updated or revised. Therefore, a specific soil may not be listed in Table 5. The USDA-NRCS lists generic descriptions of soils classified to each intake family. The generic descriptions for intake families for Nebraska are listed in Table 6. Other states have unique classifications for soils. The generic descriptions may work for other states or the local NRCS office may provide a list of soils and the associated intake families.

Table 6. Generic description of soils included in intake families by the USDA-NRCS (adapted from http://efotg.sc.egov.usda.gov/references/public/NE/NE_Irrig_Guide_Index.pdf).

Intake Family	Generic Description Including Several Subgroups.
0.1	• Deep soils on bottomland with clay, silty clay, or silty clay loam surface layers and slowly or very slowly permeable subsoils, underlain by clayey to sandy alluvium. • Deep soils on uplands and stream terraces with clay, silty clay, clay loam, or silty clay loam surface layers and slowly permeable subsoils. • Moderately deep soils with clay, silty clay, clay loam or silty clay loam surface layers and slowly permeable subsoils.
0.3	• Deep soils with silt loam, loam, or fine sandy loam surface layers and slowly permeable subsoils. • Deep soils with clay loam, silty clay loam, or sandy clay loam surface layers and subsoils with moderate to moderately slow permeability.
0.5	• Deep soils with silt loam or loam surface layers and subsoils with moderate to moderately slow permeability.
1.0	• Deep soils with a fine sandy loam or sandy loam surface layer and moderate or moderately slow permeability in the subsoil. • Deep soils with a silt loam, loam, or very fine sandy loam surface layer and moderately permeable, medium-textured subsoils. • Moderately deep soils with a silt loam, loam, or very fine sandy surface layer and moderate or moderately rapid permeability in the subsoil; underlain by bedrock or mixed sand and gravel.
1.5	• Deep soils with fine sandy loam to loam surface layers and moderately rapid to rapidly permeable subsoils. • Moderately deep soils underlain by bedrock or moderately deep soils over sand and gravel with a fine sandy loam or sandy loam surface layer and moderately rapid or moderate permeability in the subsoil.
2.0	• Deep soils with a sand, fine sand, loamy sand, loamy fine sand, or loamy very fine sand surface layer and moderately rapid permeability in the subsoil. Included are a few soils with a loamy subsoil and underlying material. • Deep soils with a loamy sand, loamy fine sand, or fine sandy loam surface layer and rapidly permeable subsoil.
3.0	• Deep soils with a fine sand or loamy coarse sand surface layer and subsoil. Permeability is rapid.

Measuring Water Content and Matric Potential

To manage soil water we must measure it. Measuring soil water content and/or matric potential is important to verify that soil water is within the allowable bounds, when the next water application should occur, and how much water the soil can hold without deep percolation. Many methods are available for measuring soil water conditions. Methods of obtaining accurate and timely soil moisture information vary in cost, labor requirements, and convenience. We discuss the more proven and practical methods—other authors have described a wider array of techniques[5]. Modern technologies have been developed to reduce the labor involved in taking periodic soil samples and improve the accuracy of determining soil moisture content.

Gravimetric

The gravimetric method is the standard for measuring soil water content. However, it is seldom used for irrigation management because it requires significant labor and has a delay of at least two days from sampling until measurements are complete. The procedure begins with taking a soil sample using a soil probe, soil auger, or shovel. Sample size should be about one-third of a cup (¼ lb). The soil is then sealed in an airtight container (frequently a plastic bag) so that moisture is not lost before weighing. Next, the wet sample is weighed with a balance or scale that can be read with an accuracy of 0.02 ounces. The sample is then dried at 220°F for 24 hours in a forced air oven. Following drying, the sample is reweighed. Mass water content is determined by dividing the weight of the water by the weight of the dry soil. The volume of the sample must also be determined to measure the volumetric water content. An advantage of the gravimetric approach is that soil samples can be taken at multiple locations within the field or irrigated area.

Feel and Appearance

The feel method uses a soil probe to take samples (Figure 31). The method requires the collection of soil samples at the desired depths. The soil sample is crumbled into small pieces and squeezed by hand to form a ball. The cohesiveness of the ball is an indication of the soil's wetness. Also, whether it leaves an imprint in the palm of the hand after squeezing should be noted. The soil is then ribboned out between the thumb and the forefinger. The soil water content is estimated based on the appearance and strength of the soil ball (Table 7). The USDA-NRCS developed a guide for the characteristics different soils exhibit at different moisture contents [6].

The feel method requires experience and self-calibration to be accurate. It requires a great deal of judgment and experience for good estimates of soil water content. Nevertheless, it is widely used. Experienced users probably achieve an accuracy of soil water depletion of plus or minus 10-15%. Thus, if the estimated depletion was 55%, the true value probably ranges from 45% to 65%. This method allows rapid moisture measurements at multiple locations. The feel method is inexpensive but continuous monitoring of field conditions requires significant labor at a time when producers are very busy. The method is good for irrigation management when spatial variability is significant.

Figure 31. Sampling and evaluation techniques for the feel method of soil water monitoring.

[5]For more information refer to Gardner, W.H. 1986. Water Content. In: A. Klute (ed). Methods of Soil Analysis, Part I, Physical and Mineralogical Methods, Second Edition. Agronomy Number 9, American Society of Agronomy, Madison, WI. pp. 493-544; and Ley, T.W. 1994. An In-Depth Look at Soil Water Monitoring and Measurement Tools. Irrigation Journal, 44(8):8-20.

[6]http://www.mt.nrcs.usda.gov/technical/ecs/agronomy/soilmoisture/index.html.

Table 7. Feel and appearance for judging how much water is available for crops.

Soil Texture	Fine Sand and Loamy Fine Sand	Sandy Loam and Loamy Fine Sand	Sandy Clay Loam, Loam and Silt Loam	Clay, Clay Loam, or Silty Clay Loam
Available Soil Water Percent	Available Water Capacity 0.6 to 1.2in/ft	Available Water Capacity 1.3 to 1.7in/ft	Available Water Capacity 1.5 to 2.1in/ft	Available Water Capacity 1.6 to 2.4in/ft
0 to 25	Dry, loose, will hold together if not disturbed, loose sand grains on fingers with applied pressure.	Dry, forms a very weak ball, aggregated soil grains break away easily from ball.	Dry. Soil clods break away easily. no Water staining on fingers, clods crumble with applied pressure.	Dry, soil clods easily separate, clods are hard to crumble with applied pressure.
25 to 50	Slightly moist, forms a very weak ball with well-defined finger marks, light coating of loose and aggregated sand grains remain on fingers.	Slightly moist, forms a weak ball with defined finger marks, darkened color, no water staining on fingers, grains break away.	Slightly moist, forms a weak ball with rough surfaces, no water staining on fingers, few aggregated soil grains break away.	Slightly moist, forms a weak ball, very few soil clods break away, no water stains, clods flatten with applied pressure.
50 to 75	Moist, forms a weak ball with loose and aggregated sand grains on fingers, darkened color, moderate water staining on fingers, will not ribbon.	Moist, forms a ball with defined finger marks. Very light soil/water staining on fingers. Darkened color, will not slick.	Moist, forms a ball, very light water staining on fingers, darkened color, pliable, and forms a weak ribbon between thumb and forefinger.	Moist. forms a smooth ball with defined finger marks, light soil/water staining on fingers, ribbons between thumb and forefinger.
75 to 100	Wet, forms a weak ball, loose and aggregated sand grains remain on fingers, darkened color, heavy water staining on fingers, will not ribbon.	Wet, forms a ball with wet outline left on hand, light to medium water staining on fingers, makes a weak ribbon between thumb and forefinger.	Wet, forms a ball with well-defined finger marks, light to heavy soil/water coating on fingers, ribbons between, thumb and forefinger.	Wet, forms a ball, uneven medium to heavy soil/water coating on fingers, ribbons easily between thumb and forefinger.
Field Capacity (100%)	Wet, forms a weak ball, moderate to heavy soil/water coating on fingers, wet outline of soft ball remains on hand.	Wet, forms a soft ball, free water appears briefly on soil surface after squeezing or shaking, medium to heavy soil/water coating on fingers.	Wet, forms a soft ball, free water appears briefly on soil surface after squeezing or shaking, medium to heavy soil/water coating on fingers.	Wet, forms a soft ball, free water appears on soil surface after squeezing or shaking, thick soil/water coating on fingers, slick and sticky.

NOTE: Ball is formed by squeezing a handful of soil very firmly.

Sensing Matric Potential

Soil water conditions can also be determined by measuring the soil matric potential. Two methods are usually used for measuring soil matric potential (Figure 32).

Tensiometers directly measure the matric potential. Tensiometers consist of a water-filled tube with a porous ceramic cup at one end and a reservoir and vacuum gauge at the other end (Figure 33). It is installed with the ceramic cup at the desired depth below the soil surface. The cup must be in close contact with the surrounding soil so that the water in the cup is hydraulically connected to the water in the soil. As the water content of the soil around the cup decreases, water flows through the porous cup. Since the other end of the tube is sealed, the water withdrawal creates a vacuum in the tube. Flow continues until there is equilibrium between the water in the tensiometer and the

Electrical Resistance Blocks *Tensiometers*

Figure 32. Methods used to measure soil water potential.

soil water. The vacuum gauge is a direct indicator of soil water tension. Usually the vacuum is registered in centibars and the scale reads from 0-100 centibars. As the tension or vacuum approaches 100 centibars, dissolved air in the water is released. The air accumulates in the top of the tube. When this happens the readings are no longer reliable; thus, the practical operating range for this instrument is 5-75 centibars.

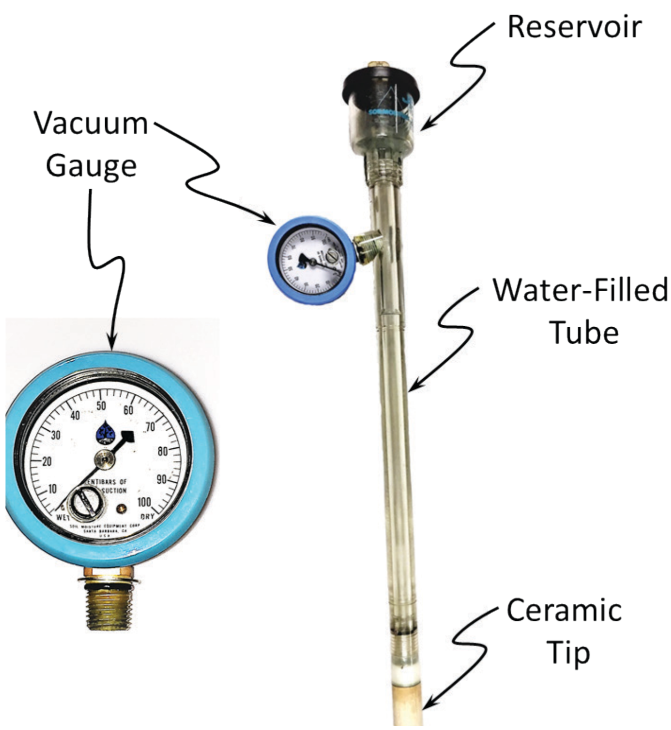


Figure 33. Components of a tensiometer.

Tensiometers are accurate but require frequent in-field service and are difficult to automate. A zero vacuum reading corresponds to a saturated soil while, as shown in Figure 27, a reading of 10 centibars corresponds to field capacity for fine sand soils and a reading of about 38 centibars is field capacity for silt loam soils. Results in Figure 27 show that more than 75% of the available water capacity has been depleted at 75 centibars (the upper limit of the instrument) for fine sand, but only about 50% of the available soil water has been depleted for silt loam at 75 centibars. A common criteria for irrigation is to allow up to 50% depletion of the available soil water before irrigation. This criteria indicates why tensiometers have limitations for irrigation management on finer textured soils, especially soils with a high clay content.

Electrical resistance blocks indirectly measure the soil matric potential. Electrical resistance blocks consist of a porous material, usually gypsum, with two embedded electrodes. The blocks are buried in the soil to the desired depth. As with tensiometers, good contact with the surrounding soil is essential. When the soil water equilibrates with the water in the block, an ohmmeter with an AC current source can be used to measure electrical resistance between the electrodes. There is a relationship between the resistance and the water content of the gypsum and therefore, the soil water potential and the resistance are related. You might ask, why not just embed the electrodes directly into the soil and bypass the use of the gypsum? The problem with this approach is the effect of electrolytes in the soil on the resistance. Thus, electrical resistance in the soil is dependent on both soil water and soil salinity. The gypsum somewhat buffers the effect of the salts in the soil on observed resistance. In saline soils, the effect of salts on the measured resistance cause inaccurate readings of matric potential. These sensors are inexpensive and easy to read. They work well in clayey soils but are not very sensitive in sandy soils. Gypsum dissolves in soil over time so the useful life depends on soil conditions and is very short in acidic soils. One limitation of resistance blocks is that the gypsum matrix is fine material. Thus, the usable range is in the higher soil water tensions, usually greater than 50 centibars. To overcome the limitation of gypsum blocks in the wet range, blocks composed of a coarser media, such as sand, have been developed. These coarser blocks have a usable range of 5-200 centibars.

Another widely used version of a moisture block is the Watermark Granular Matrix Sensor. These sensors measure soil water potential indirectly through electrical resistance between two electrodes, similar to gypsum blocks. However, Watermark Sensors use a matrix similar to fine sand with an external shell, surrounded with a synthetic membrane to protect against deterioration. This means that the matrix will not dissolve as rapidly over time as gypsum blocks. The Watermark Sensors can be read by a handheld meter, or connected to a data logger for continuous measurement and remote sensing. Publications have been developed to provide more information about Watermark Sensors.[7]

Thermal dissipation blocks are another approach that uses porous blocks. Thermal dissipation blocks have heaters and temperature sensors embedded within the block. Blocks are heated by passing current through the heaters. The rate of heat dissipation is then measured. The rate that heat dissipates is related to the soil matric potential. Heat dissipation blocks are sensitive to soil water over a wide range. Unfortunately, the heat dissipation blocks must be individually calibrated and are considerably more expensive than electrical resistance blocks.

[7]Refer to http://irrometer.com/sensors.html#wm and http://www.ianrpubs.unl.edu/live/ec783/build/ec783.pdf

Dielectric Constant Methods

Two soil water measurement techniques take advantage of the fact that the soil's dielectric constant is dependent on soil water; time domain reflectometry (TDR) and frequency domain reflectometry (FDR).

Time-domain reflectometers require the placement of parallel rods (wave guides) into the soil. An electromagnetic wave is pulsed along the wave guides. The reflected signal from the wave guide is monitored in the instrument, which also measures the travel time of the wave. The travel time is related to soil water content. TDR systems are usually accurate and measure soil moisture over the length of the rod instead of at a point. The zone of soil sampled is dependent on the length of the rods and the spacing between rods. The distance sampled is about 1.5 times the spacing between rods. An example of a TDR system from Campbell Scientific Inc, is shown in Figure 35. TDR is relatively expensive so its primary use has been limited to research applications.

Figure 34. Watermark soil water monitoring system including sensors, hand-held readout and data logger.

Figure 35. Example of TDR system (courtesy of Campbell Scientific Inc.).

Frequency domain reflectometry (FDR) uses the soil as a dielectric and measures the capacitance of the soil, an indirect indicator of soil water. Electrodes must be inserted in the soil. The capacitance circuit is pulsed with high-frequency radio waves. A resonant frequency is established which depends on the capacitance. There are two forms of FDR probes. One requires an access tube like neutron scattering. A cylinder of soil is sampled. The other FDR probe is a portable hand device that is pushed into the soil to the desired depth, usually less than 3 feet. The portable hand probe has a nondimensional relative scale that goes from 0-100. Low readings indicate low soil water content and high readings suggest high soil moisture.

Capacitance probes also use the dielectric properties of the soil to determine the soil water content. The sensors pass a current between two electrodes through the soil. As the soil water content increases, so does the ability of the soil to transmit electrical current. Figure 36 shows examples of capacitance probes. Capacitance probes can be easily interfaced to a datalogger for continuous soil moisture monitoring and transfer to internet or wireless sites to allow producers to upload data when away from the field.

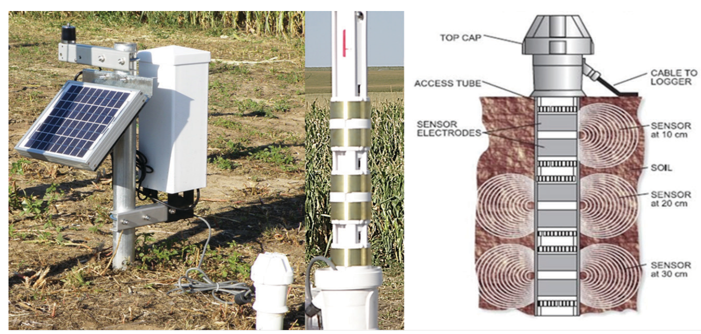


Figure 36. Example of capacitance probe for monitoring soil water.

Dataloggers and wireless communication

Many electronic soil moisture sensors have the capability to be connected to a datalogger (Figure 37) that takes period readings and records them for later use. The data can be downloaded to a computer and displayed in a chart (Figure 38). Companies also make wireless soil moisture systems that can be accessed remotely. These systems have a datalogger positioned on the edge of the field to which multiple wireless transmitters, each capable of reading several Watermark sensors, communicate with a web site. This system can be accessed through the internet. Soil moisture can also be monitored in real-time from a computer or smart phone.

secured from shallow sampling usually are inadequate to describe what is really happening within the plant's root system.

Figure 37. Hansen AM400 and Watermark datalogger for Watermark sensors.

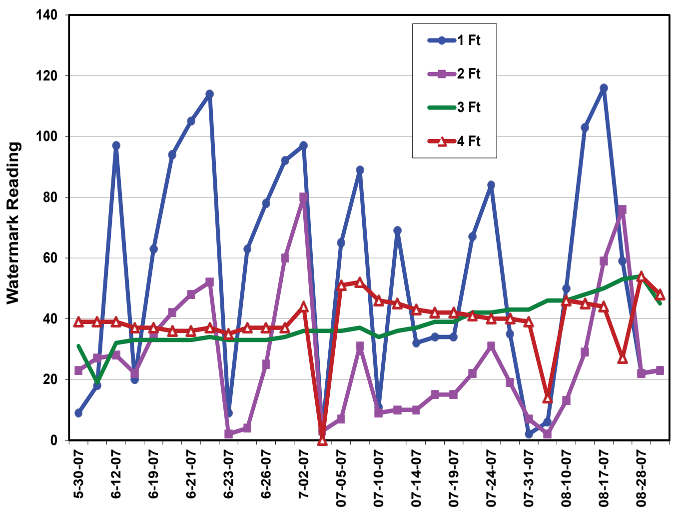


Figure 38. Watermark record of one growing season.

Sensor placement

It is important to locate soil moisture monitoring equipment in locations that will give accurate and timely readings. The sensors should be placed under different spans of the pivot and in dominate soil textures. Figure 39 illustrates the concept of measuring the water content of the soil in the area of the field that has gone the longest since irrigation (start positions) and the area that was most recently irrigated (stop positions). Soil moisture monitoring equipment costs need to be balanced with having accurate information.

All methods of soil water measurement require that representative sites be selected for sampling. This means that sampling must consider the variability in soils, the variability of water application, and the variability of plant populations within the irrigated area. The microclimate around the area to be measured should also be considered.

Soil water measurements must be taken at depths that represent the plant root zone. Estimates of soil water content secured from shallow sampling usually are inadequate to describe what is really happening within the plant's root system.

One of the frustrations of measuring soil water is the large number of samples required before you feel comfortable with how well the measurements represent the soil water conditions in the irrigated area. Because of natural variability of soil properties and the variability in depth of rainfall and irrigation applications within the irrigated area, considerable variability in measured soil water can be expected. Another problem is the number of samples that must be taken to truly represent the plant root zone. A minimum of two depths, and often three or four, are required to properly represent root zone moisture conditions. Selection of the monitoring sites requires information about the distribution of soils in the field.

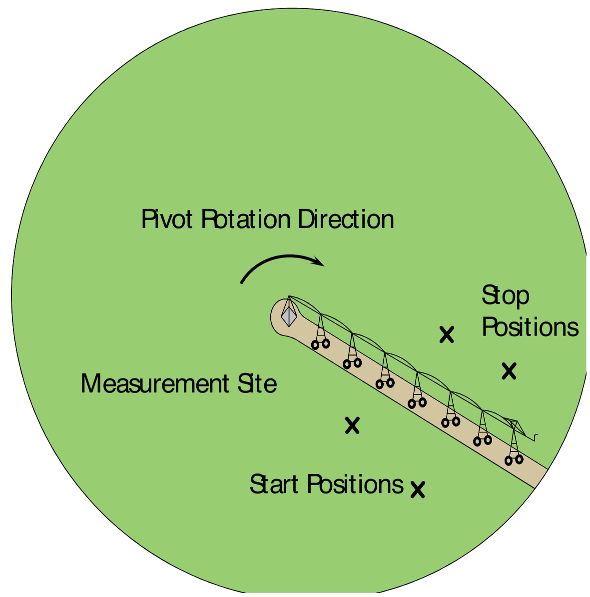


Figure 39. Sensor placement at starting and stopping positions.

Web Soil Survey

A useful tool for obtaining soil information is the Web Soil Survey (WSS) from the Natural Resource Conservation Service (NRCS) [8]. This on-line soil survey includes a tutorial that is helpful for learning to navigate the WSS and retrieve the information needed. An example is presented here.

Once WSS is launched, there are many options to locate the area to be studied including the address, the county, latitude and longitude, and the public land survey system (section, township, range). Once the area of interest (AOI) is selected the soil data is retrieved and available for viewing. The soils of a field located at the Agricultural Research and

[8]See http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm.

Development Center near Mead, NE is illustrated in Figure 40. First zoom into the field and select the area as your Area of Interest (AOI), (Figure 41). Next, a soil map will be displayed when the Soil Map tab is clicked. Figure 42 shows the soil map along with the map unit names and the areas of each map unit. Over half of this field is a Yutan silty clay loam. Another important soil is the Filbert silt loam, making up over 50 acres of this field. From the soil descriptions we can determine that the greatest slope will likely be 6%.

Figure 40. Example of the initial screens of the Web Soil Survey system from the NRCS.

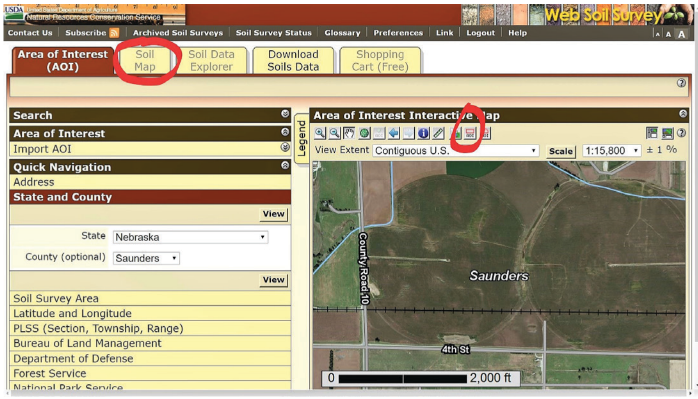


Figure 41. Screen to select the field as the Area of Interest (AOI). and then to select icon to generate soil map.

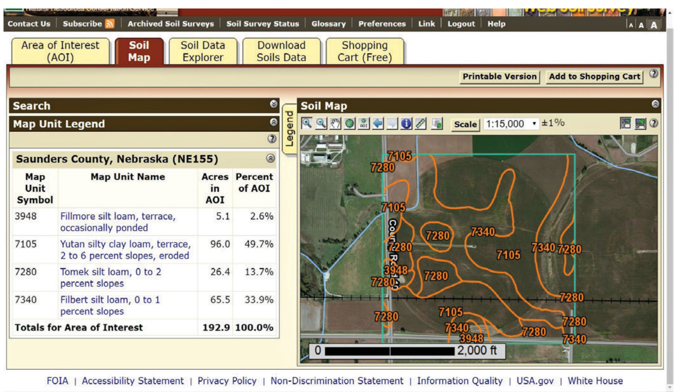


Figure 42. Soil map generated for the field.

Clicking on the map unit name on the left displays a description of the soil (Figure 43). For each map unit, the landform setting, parent material, slope, and texture can be found in these map unit descriptions. Tables are also available in the system to estimate the water holding capacity of the soil and the soil texture. This provides much of the information needed to design and manage center pivot systems.

Summary

When designing and managing an irrigation system, it is important to know and understand the properties of the soil that influence the application efficiency of a system. Properties such as texture, slope, water holding capacity, and intake family impact sprinkler selection as well as application depth and frequency. The Web Soil Survey from the NRCS is a very useful tool to help locate the different soils of a field as well as properties of those soils. When managing an irrigation system it is important to monitor soil moisture to ensure adequate water for the crop as well as to avoid over-application. There a many methods to monitor soil moisture from the traditional hand feel method to moisture blocks and tensiometers and also capacitance and TDR probes. Modern technology makes it easy to monitor, access, and record soil moisture information.

Saunders County, Nebraska

7105—Yutan silty clay loam, terrace, 2 to 6 percent slopes, eroded
Map Unit Setting
National map unit symbol: 2scyh — Elevation: 980 to 1,660 feet
Mean annual precipitation: 28 to 39 inches
Mean annual air temperature: 50 to 55 degrees F
Frost-free period: 158 to 203 days
Farmland classification: All areas are prime farmland
Map Unit Composition
Yutan, eroded, and similar soils: 92 percent — Minor components: 8 percent
Estimates are based on observations, descriptions, and transects of the mapunit.
Description of Yutan, Eroded
Setting
Landform: Terraces — Landform position (three-dimensional): Tread
Down-slope shape: Linear — Across-slope shape: Linear
Parent material: Loess
Typical profile
Ap - 0 to 6 inches: silty clay loam — Bt1 - 6 to 13 inches: silty clay loam
Bt2 - 13 to 28 inches: silty clay loam — BC - 28 to 43 inches: silt loam
C - 43 to 79 inches: silt loam
Properties and qualities
Slope: 2 to 6 percent
Depth to restrictive feature: More than 80 inches
Natural drainage class: Well drained — Runoff class: Medium
Capacity of the most limiting layer to transmit water (Ksat): Moderately low to moderately high (0.06 to 0.20 in/hr)
Depth to water table: More than 80 inches
Frequency of flooding: None — Frequency of ponding: None
Calcium carbonate, maximum in profile: 2 percent
Salinity, maximum in profile: Nonsaline to very slightly saline (0.0 to 2.0 mmhos/cm)
Available water storage in profile: High (about 10.9 inches)
Interpretive groups
Land capability classification (irrigated): 3e
Land capability classification (nonirrigated): 2e
Hydrologic Soil Group: C
Ecological site: Loamy Upland (R106XY075NE)
Other vegetative classification: Loam (G106XY100NE)
Hydric soil rating: No
Minor Components
Tomek
Percent of map unit: 8 percent — Landform: Terraces
Landform position (three-dimensional): Tread
Down-slope shape: Linear — Across-slope shape: Linear
Ecological site: Loamy Upland (R106XY075NE)
Other vegetative classification: Loam (G106XY100NE)

Figure 43. Map unit description for Yutan silty clay loam.

Soil Water Example

Watermark sensors are installed at 6, 18, and 30 inches in a field of corn in the dough stage. The soil is a Holdrege silt loam and the current sensor readings are:

Depth (inches)	Watermark reading (cb)
6	90
18	100
30	110

If you assume that each sensor represents 1 foot of soil:

a) How much water is available to the crop?

b) Do we need to begin irrigation?

c) If we wanted to leave room to store 1 inch of rainfall in the profile, how much irrigation could we apply?

<u>Answers:</u>

a) Average Watermark reading = $\frac{90 + 100 + 110}{3} = 100$ cb

Soil water depletion for each depth from Table 4 = 0.85 in/ft

Water holding capacity from Table 4 = 2.20 in/ft

2.20 in/ft AWC – 0.85 in/ft SWD = 1.35 in/ft AW x 3 ft profile = 4.05 inches of available water remains

b) Irrigation trigger point from Table 4:

Suggested trigger point range: 90-100 kPa (note: 1 kPa = 1 cb)

Average sensor reading over the 3-foot soil profile is 100 cb.

This is within the irrigation trigger range so irrigation should begin soon.

c) Total soil water depletion is 0.78" + 0.85" + 0.89" = 2.52 inches

2.52" depletion – 1" rainfall storage = 1.52 inch irrigation application

We could apply just over 1.5 inches of irrigation water and still capture 1 inch of rainfall in the root zone.

Chapter 4. Sprinkler Packages

Selecting the proper sprinkler package is vital to the efficiency of an irrigation system. The sprinklers must be able to apply the water in a uniform manner while reducing runoff, evaporation, and drift. Sprinklers must be spaced correctly and at the proper height to maximize uniform application. Also, operating the system at the designed pressure will eliminate many problems observed with application uniformity.

When beginning to consider the appropriate sprinkler package for a center pivot system it is important to obtain information about the soils within the field. Relevant soils information includes texture, infiltration rate, water holding capacity, and slope. All of these are discussed further in the Soil Water Management chapter.

In the Center Pivot Management chapter, application efficiency is described as a measure of the percentage of water applied that is available for the crop to use for transpiration. The types of losses that reduce application efficiency that can be affected by the sprinkler package were listed as overspray and drift, droplet evaporation, canopy evaporation, and runoff.

Wetted Diameter

Runoff can occur when water is applied at a rate higher than the infiltration rate of the soil and after the surface storage has been filled. The type of sprinkler used on a system affects the potential runoff by changing the duration of water application and therefore the peak application rate. The total time that water is applied to a point in the field as the pivot moves over it is directly related to the wetted diameter. A sprinkler package that has a larger throw diameter will spread water over a larger area, thus increasing the total time that water is being applied at a point in the field. If water is applied to an area longer, the rate of application decreases compared to a sprinkler with a smaller wetted diameter.

Figure 45 shows the typical wetted diameter of common sprinkler designs. Impact sprinklers have the largest wetted diameter while devices on drops usually have smaller wetted diameters. Stationary spray-pad devices often have the smallest wetted diameter.

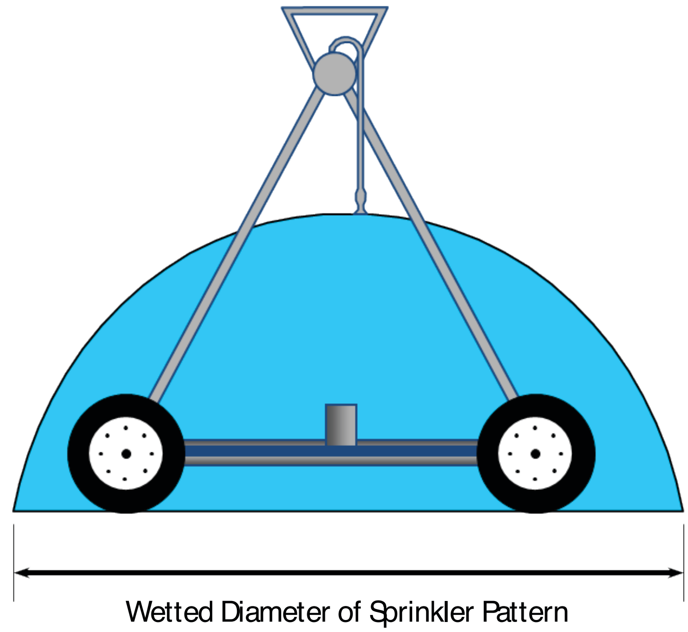


Figure 44. Illustration of wetted diameter of a sprinkler package.

Required Wetted Diameter

Runoff occurs when the water application rate from the center pivot is too high. The peak application rate decreases as the wetted diameter increases—i.e., it is inversely related to the wetted diameter—as illustrated in Figure 46. These results illustrate that the sprinkler package has a strong impact on the peak application rate and therefore the runoff potential for a given soil. One method to minimize runoff is to select sprinkler packages that have large wetted diameters that provides smaller peak rates and longer application times. The minimum wetted diameter needed to avoid runoff can be determined based on the soil intake family and the amount of water that can be stored on the soil surface (i.e., surface storage).

We use the information from the USDA-NRCS to estimate the amount of surface storage that is available in a field. Their method depends on the general slope and the amount of residue cover in the field. The USDA-NRCS presents typical values as listed in Table 8. You can estimate the amount of residue in the field using the method described by Shelton and Jasa. As an example, Table 8 shows that soils with a slope of 2% produces surface storage of 0.30 inches when there is no crop residue and up to 0.65 inches when residue cover is about 70%.

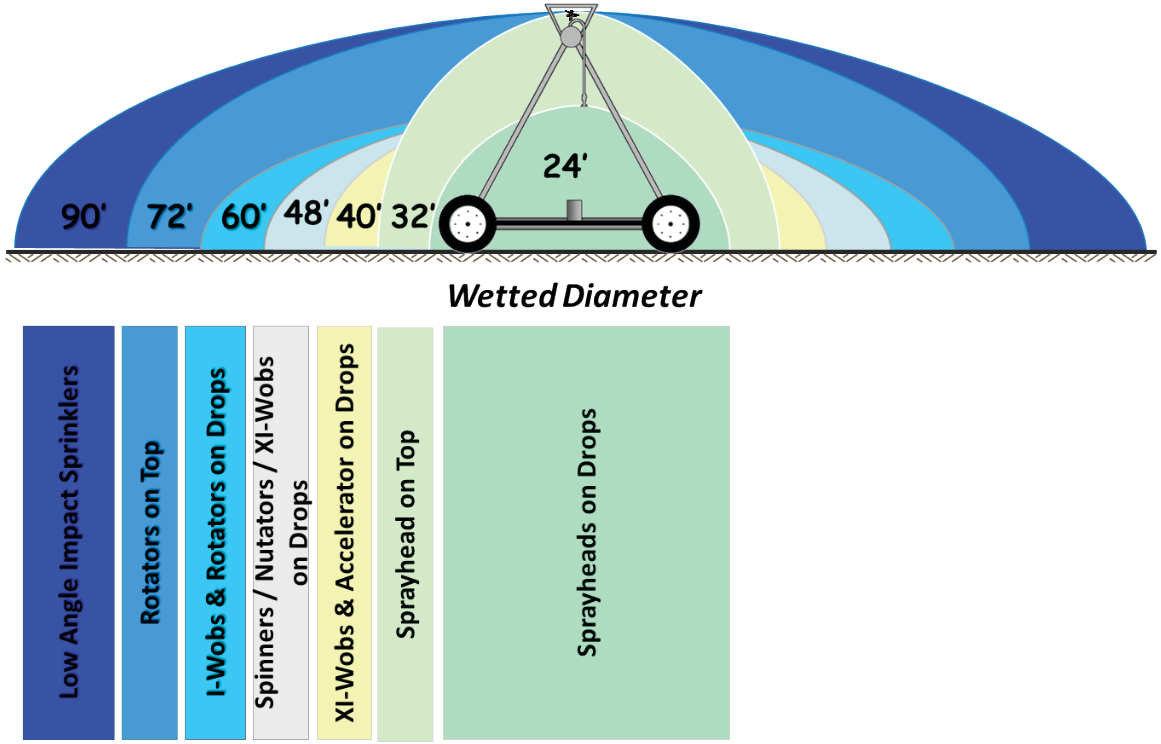


Figure 45. Approximate wetted diameter of various sprinkler products.

Table 8. Surface storage (inches) available due to residue and slope.

Percent Residue Cover	Storage Due to Residue, inches	Field Slope, %								
		0.5	1	1.5	2	2.5	3	3.5	4	5
0	0.00	0.50	0.44	0.38	0.30	0.26	0.20	0.16	0.1	0.00
10	0.01	0.51	0.45	0.39	0.31	0.27	0.21	0.17	0.11	0.01
20	0.03	0.53	0.47	0.41	0.33	0.29	0.23	0.19	0.13	0.03
30	0.07	0.57	0.51	0.45	0.37	0.33	0.27	0.23	0.17	0.07
40	0.12	0.62	0.56	0.5	0.42	0.38	0.32	0.28	0.22	0.12
50	0.18	0.68	0.62	0.56	0.48	0.44	0.38	0.34	0.28	0.18
60	0.24	0.74	0.68	0.62	0.54	0.5	0.44	0.4	0.34	0.24
70	0.35	0.85	0.79	0.73	0.65	0.61	0.55	0.51	0.45	0.35

Values greater than 0.6 inches should be used sparingly.

Adapted from NRCS at https://efotg.sc.egov.usda.gov/references/public/NE/NIG_Amend_1_surface_storage_pg6-90.pdf.

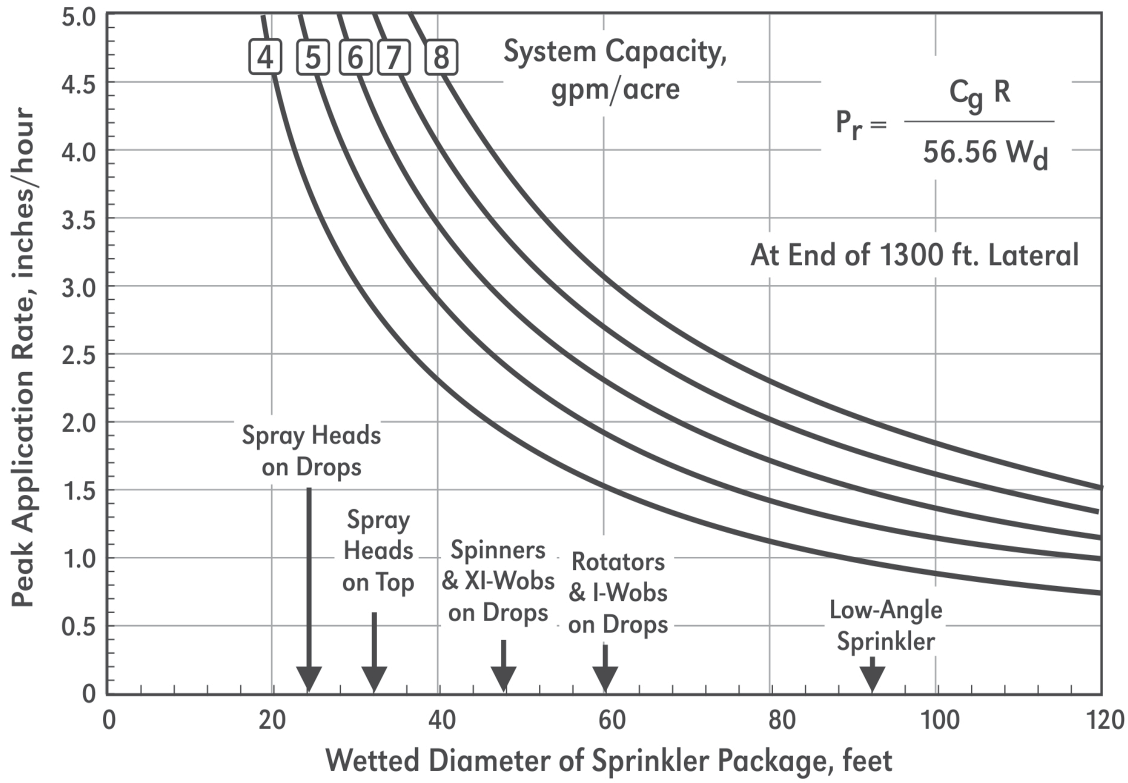


Figure 46. Wetted diameter of sprinkler package versus peak water application rate at end of a 1300-ft pivot lateral.

The USDA-NRCS uses a computer program that we developed called CPNozzle to develop sprinkler package guidelines based on designation of soils into intake families. We developed a graphical procedure (Figures 47 - 51) to estimate the minimum required wetted diameter of a sprinkler package based on the application depth, available surface storage and system capacity. This procedure produces essentially the same results as the computer program. Using the procedure requires determination of the intake family that best represents the soil for the most runoff prone areas in the field. Those soils should include enough area to be significant and should be located at the outer end of the pivot lateral where the water application rate is the highest. The next step is to select the typical application depth per irrigation and the available surface storage for your field. The system capacity of your system in gpm/acre is also needed.

The procedure is illustrated in Figure 48 for sprinkler devices located near the end of a traditional center pivot with a lateral that is 1300 feet long. The example is for determining the required wetted diameter based on a 0.3 intake family soil with an available surface storage of 0.3 inches and a system capacity of 6 gpm/ acre. If an application depth of 1 inch is expected (blue line), move horizontally to the available surface storage found in Table 8. Then move straight down until you intersect your system capacity, then over to the right to find the minimum required wetted diameter. In this case, the required wetted diameter would be almost 70 feet. If the maximum depth of application is reduced to 0.75 inches (green line), the required wetted diameter is reduced to just over 40 feet. By reducing the amount of application, the required wetted diameter to prevent runoff is decreased.

The example shown in Figure 48 illustrates that low-angle impact sprinklers or devices such as Rotators from the Nelson Irrigation Company would be suitable for application of one inch per application for the 0.3 Intake Family soil. If three-quarters of an inch is applied each irrigation, there are many sprinkler devices that will provide adequate throw (Figure 45).

Graphs in Figures 47-51 can also be used in an inverse fashion to determine the maximum application depth that should be applied for a selected sprinkler package used on a specific soil with a defined amount of surface storage.

Examples in Figures 47-51 show how to find the minimum required wetted diameter for systems with varying system capacities and amounts of surface storage. A range of conditions can be evaluated. The included examples were based on a unique capacity and surface storage for some soils. The capacity was 5 gpm/acre for the 0.1 intake family soils and 6 gpm/acre capacity for the remainder of the intake families. We used a surface storage of 0.4 inches for the 0.1 intake family, 0.3 inches of surface storage for the 0.3 and 0.5 intake family soils and 0.2 inches of storage for the 1.0 and 1.5 intake family soils. An application depth of 0.75 inches was used for the 0.1 intake family while a maximum application depth of 1 inch was used for the rest of the intake families. The results for the conditions designated in Figures 47-51 show that the minimum wetted diameter is 60 feet for the conditions for the 0.1 intake family, 70 feet for the 0.3 intake family, 45 feet for the 0.5 intake family, 30 feet for the 1.0 intake family and 22 feet for the 1.5 intake family. These results are for those specific conditions. Other sprinkler options would be acceptable if smaller depths or more residue were present. Those conditions can be assessed using Figures 47 through 51. It is essential to ensure you are using the correct chart for a specific soil intake family.

The runoff nomographs in Figures 47-51 represent the results at the distal end of a traditional 1300-ft center pivot. Pivots with longer laterals require larger wetted diameters to avoid runoff than traditionally sized pivots. The required minimum wetted diameter should be varied in a linear fashion for pivots with laterals longer or shorter than a traditionally sized pivot. The minimum required wetted diameter is given by:

$$WD_{Rs} = WD_{1300} \times \left(\frac{R_s}{1300} \right)$$

where R_s is the length of the pivot lateral, WD_{Rs} is the required minimum wetted diameter for the pivot lateral and WD_{1300} is the wetted diameter required from Figures 47-51 for pivots that are 1300 feet long. From Figure 48 the minimum required wetted diameter for the one-inch application was 80 feet. Suppose that the real pivot is 1480 feet long. For the longer pivot the minimum wetted diameter would be:

$$WD_{Rs} = 80 \times \left(\frac{1480}{1300} \right) = 91 \text{ feet}$$

So the minimum wetted diameter for the longer pivot would be approximately 90 feet, which may require impact sprinklers to avoid runoff at the end of the lateral.

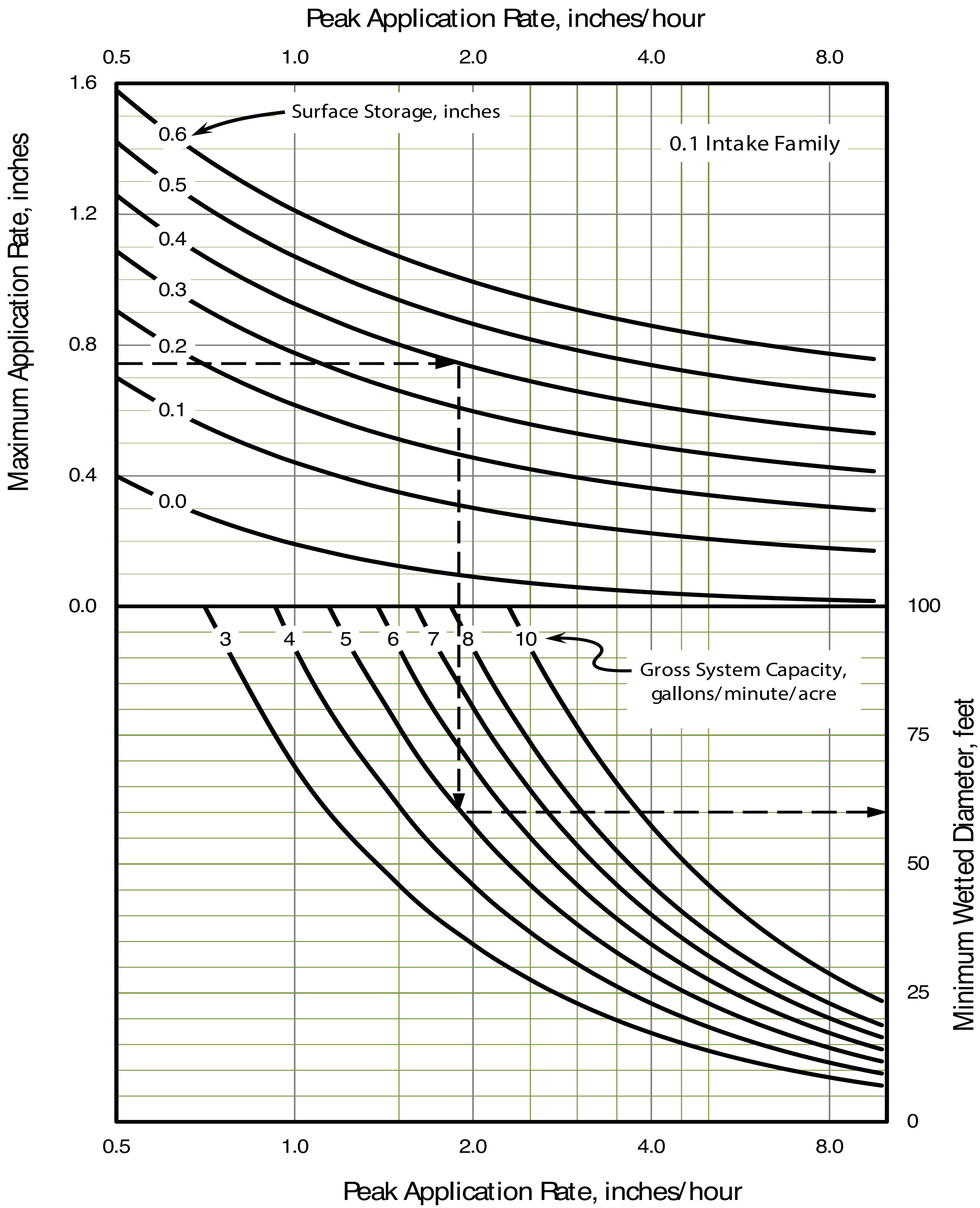


Figure 47. Minimum required wetted diameter for 0.1 intake family soils for a center pivot that is 1300 feet long.

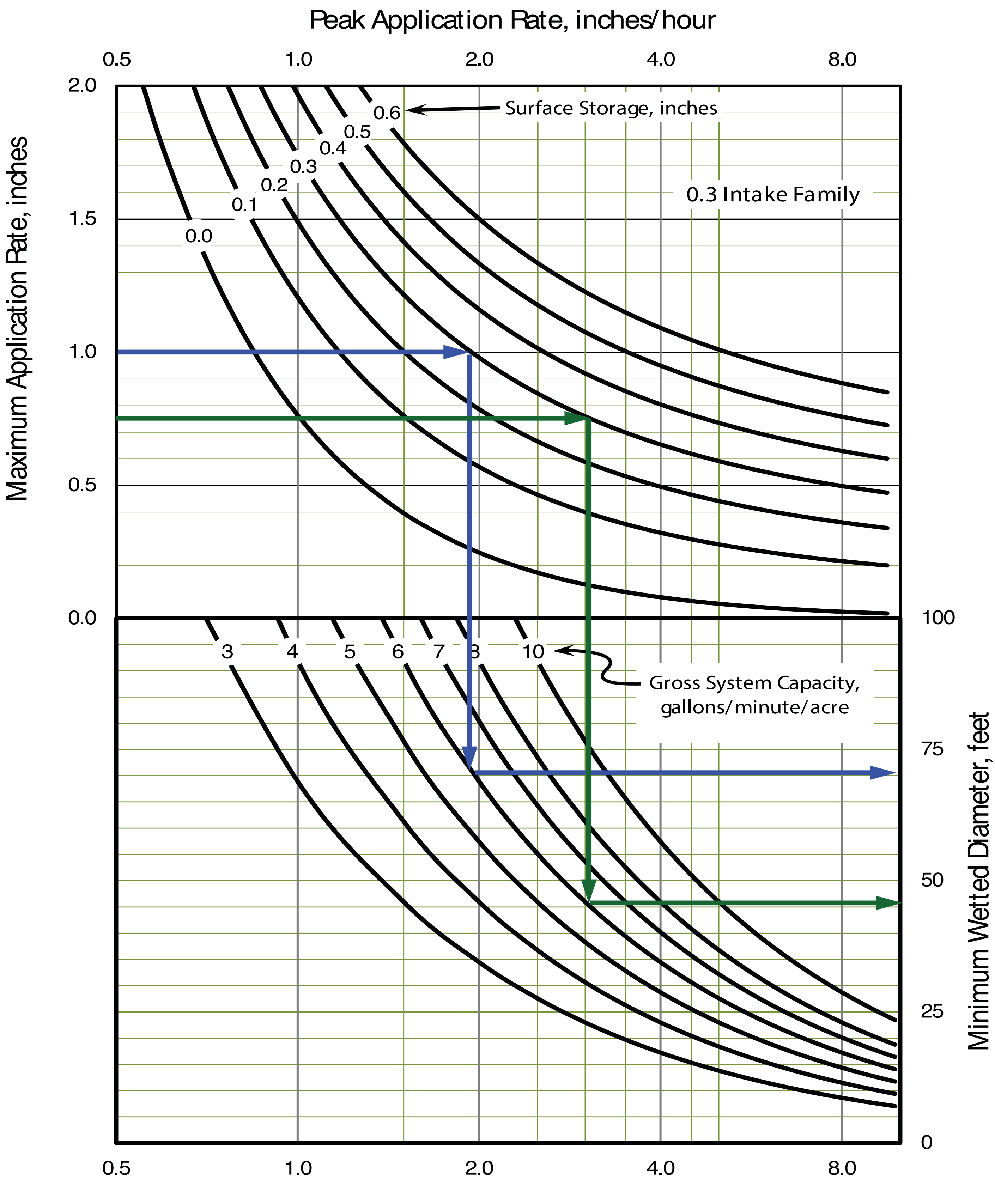


Figure 48. Minimum required wetted diameter for 0.3 intake family soils for a center pivot that is 1300 feet long.

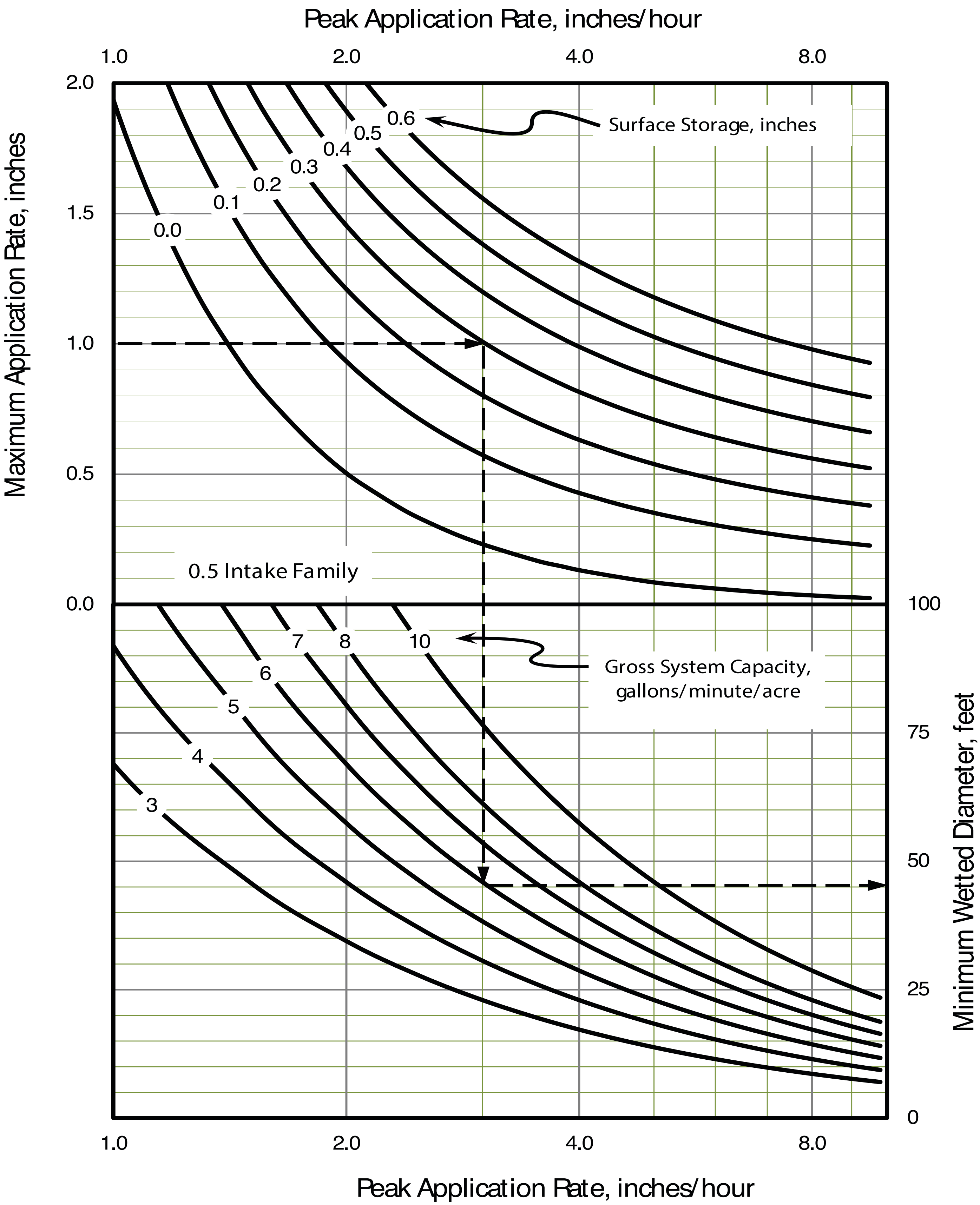


Figure 49. Minimum required wetted diameter for 0.5 intake family soils for a center pivot that is 1300 feet long.

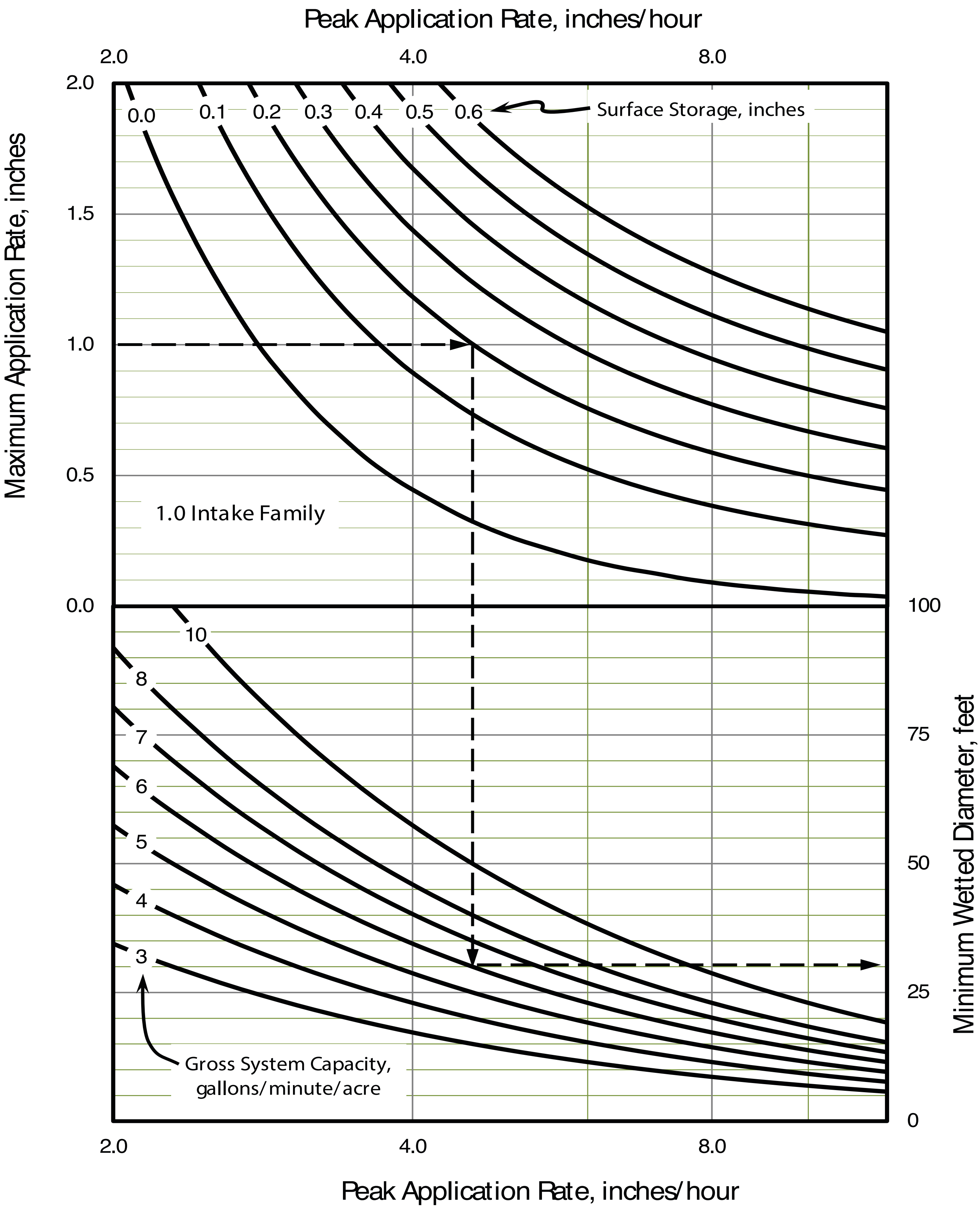


Figure 50. Minimum required wetted diameter for 1.0 intake family soils for a center pivot that is 1300 feet long

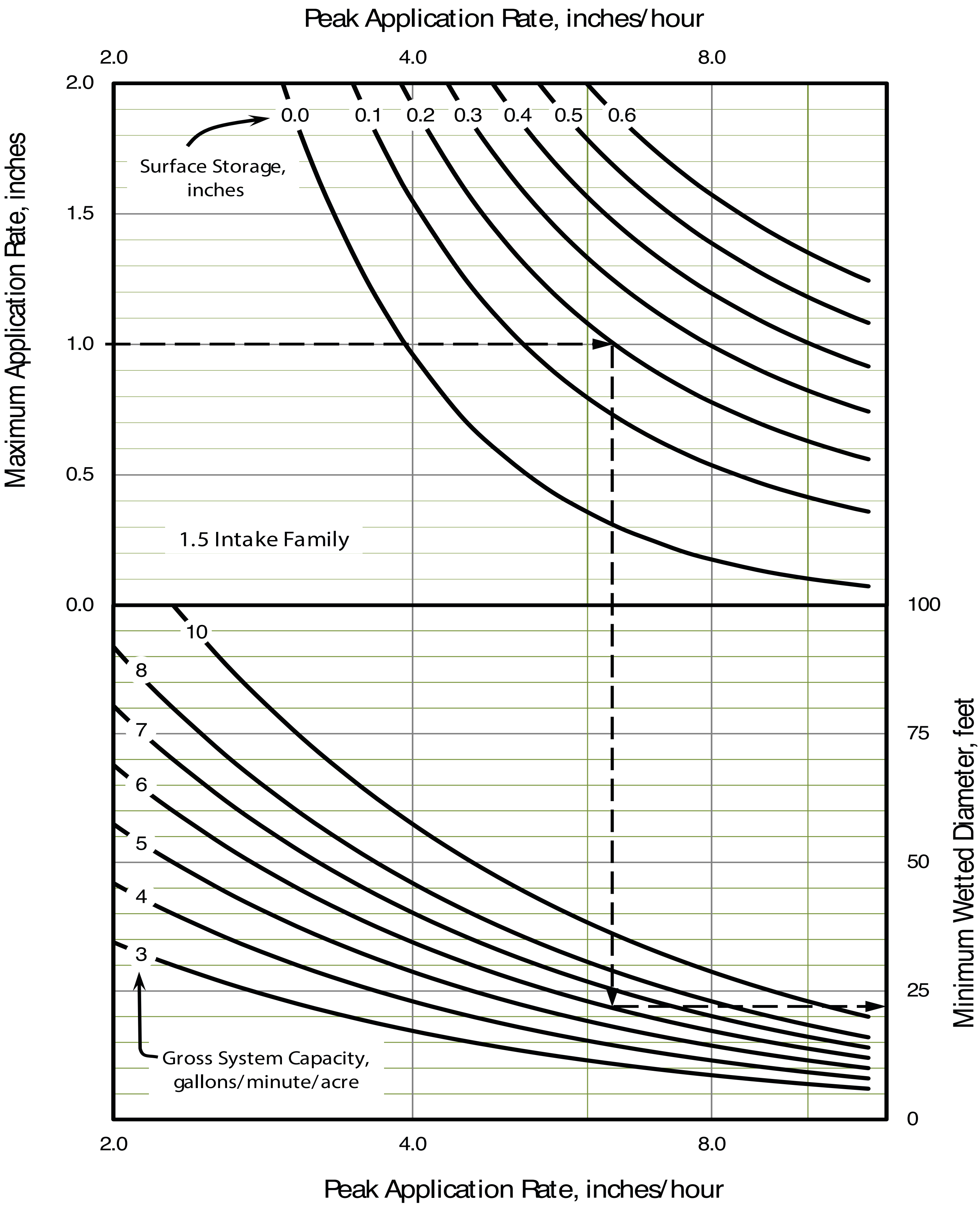


Figure 51. Minimum required wetted diameter for 1.5 intake family soils for a center pivot that is 1300 feet long.

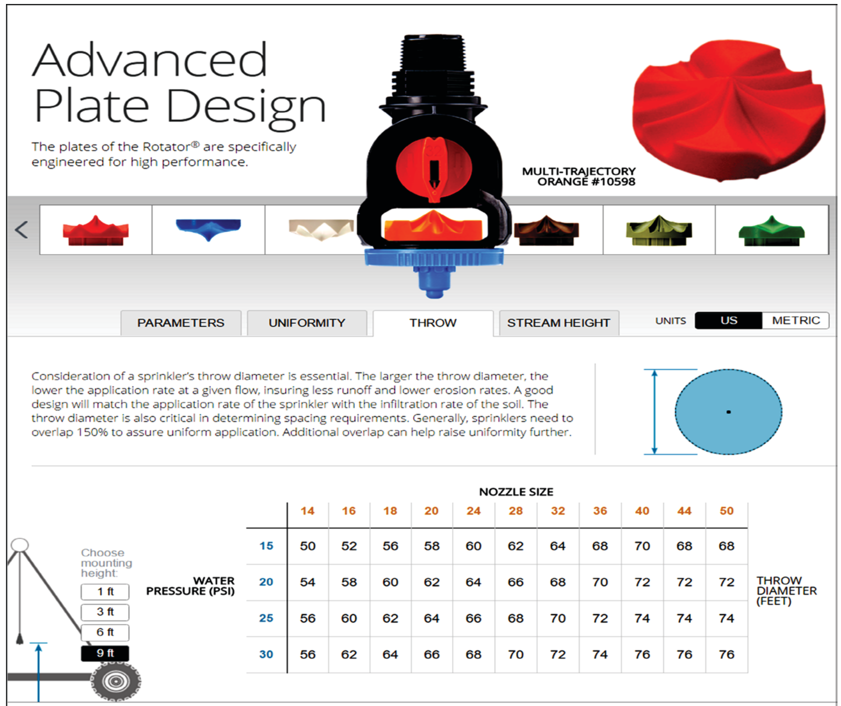
Wetted Diameter of a Sprinkler

Sprinkler manufacturers' literature give the expected throw diameter for their sprinkler types and nozzle sizes. Figure 52 displays an example of such literature. The Nelson Irrigation Corp. literature shows a range of throw diameters that depend on the operating pressure and height of installation. For example, the R3000 sprinkler mounted nine feet above the surface and with a #20 nozzle would produce a throw diameter of 58 feet when operated at 15 psi, and up to 64 feet when the nozzle size is increased to a #32 nozzle. The Senninger Irrigation Inc. literature also gives varying throw diameters that depend on the mounting height, exit angle and operating pressure. For example, a blue deflector in an Xi-WOB sprinkler device would produce a maximum wetted diameter of 48.6 feet when mounted nine feet above the ground. It is necessary to consult product dealers, literature and/or internet sites to obtain sprinkler performance data.

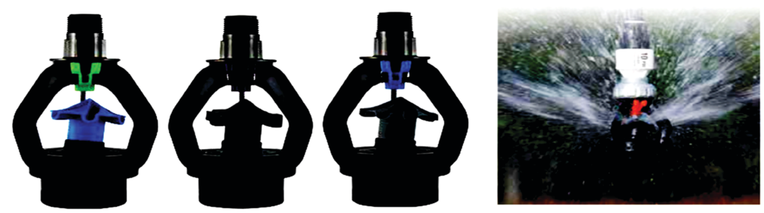
Sprinkler Height and Spacing

The height that sprinklers are mounted has an impact on the throw diameter. Figure 53, shows the change in wetted diameter for a rotating pad sprinkler device for four combinations of nozzle size and pressure. These data show that the wetted diameter increases with the pressure and the nozzle size.

If sprinklers are mounted at a height that places them into the crop canopy during the growing season the wetted diameter will be smaller than if the devices were installed above the canopy. Figure 54 shows the effect that placing sprinklers in the crop canopy can have on application uniformity. Crops interfere with the throw of the sprinklers and cause more water to fall near the sprinkler and less reaches the crop rows between the sprinklers. Figure 55 shows this effect for crops near McCook in 2002. The crops near the sprinklers are visibly taller than the crops in the rows between the sprinklers. It is important to keep the sprinklers above the canopy when possible. If sprinklers are placed into the canopy, the spacing must be reduced and more sprinklers are needed to ensure adequate uniformity.



WATER PRESSURE (PSI)	14	16	18	20	24	28	32	36	40	44	50
15	50	52	56	58	60	62	64	68	70	68	68
20	54	58	60	62	64	66	68	70	72	72	72
25	56	60	62	64	66	68	70	72	74	74	74
30	56	62	64	66	68	70	72	74	76	76	76



Xi-Wob System Design Criteria	Model 610 (Blue) 6-Groove 10° Trajectory Medium Droplets	Model 615 (Black) 6-Groove 15° Trajectory Large Droplets	Model 910 (Grey) 9-Groove 10° Trajectory Smaller Droplets
Nozzle sizes			
Minimum	#7 7/64" (2.78 mm)	#10 5/32" (3.97 mm)	#10 5/32" (3.97 mm)
Maximum*	#24 3/8" (9.53 mm)	#24 3/8" (9.53 mm)	#24 3/8" (9.53 mm)
Flows			
Minimum	1.09 gpm (248 L/hr)	2.24 gpm (509 L/hr)	2.24 gpm (509 L/hr)
Maximum	15.78 gpm (3584 L/hr)	15.78 gpm (3584 L/hr)	15.78 gpm (3584 L/hr)
Diameters			
Minimum at 3 ft (0.91 m)	29.5 ft (9.0 m)	38.0 ft (11.6 m)	33.0 ft (10.1 m)
Maximum at 3 ft (0.91 m)	40.0 ft (12.2 m)	43.2 ft (13.2 m)	36.4 ft (11.1 m)
Minimum at 6 ft (1.83 m)	34.5 ft (10.5 m)	43.0 ft (13.1 m)	38.0 ft (11.6 m)
Maximum at 6 ft (1.83 m)	44.6 ft (13.6 m)	50.0 ft (15.2 m)	42.8 ft (13.0 m)
Minimum at 9 ft (2.74 m)	37.0 ft (11.3 m)	45.6 ft (13.9 m)	43.0 ft (13.1 m)
Maximum at 9 ft (2.74 m)	48.6 ft (14.8 m)	55.4 ft (16.9 m)	49.6 ft (15.1 m)
Maximum Spacing			
at 6 ft (1.8 m) ground clearance	18 ft (5.5 m)	20 ft (6.1 m)	18 ft (5.5 m)
Pressure at the Nozzle			
Minimum	10 psi (0.69 bar)	10 psi (0.69 bar)	10 psi (0.69 bar)
Maximum	15 psi (1.03 bar)	15 psi (1.03 bar)	15 psi (1.03 bar)

Figure 52. Sprinkler manufacturer's literature showing throw diameter (courtesy of Nelson Irrigation Corp and Senninger Irrigation Inc.).

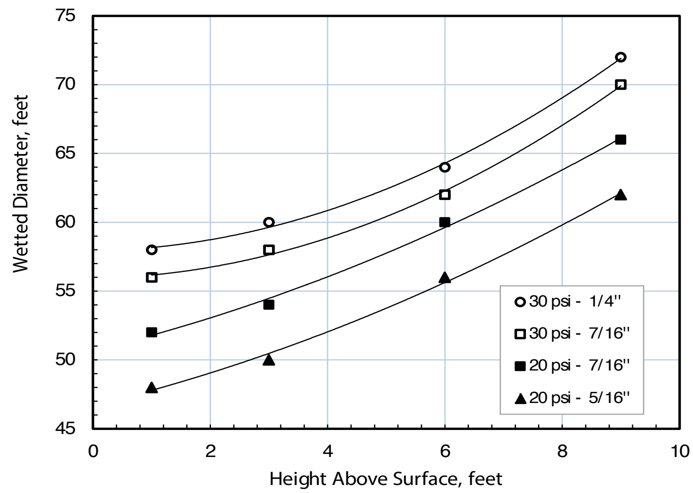


Figure 53. Effect of height of sprinkler above surface on throw diameter for four combinations of discharge pressure and nozzle size.

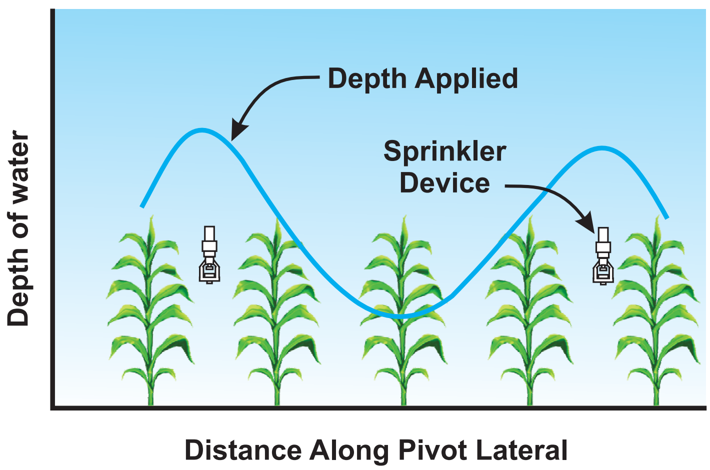


Figure 54. Reduction of application uniformity when sprinklers are mounted low enough to be in the canopy during the season.

Figure 55. Effect of sprinklers that are mounted below the top of the canopy and spaced too far apart to provide uniformity.

We suggest the following recommendations regarding sprinkler spacing:

1. Follow manufacturer recommendations on spacing. They conduct extensive testing and know how products perform for a range of conditions and applications.

2. Keep sprinklers out of canopy to the extent possible. Our research shows that placing devices into the canopy reduces uniformity and can increase runoff on steep slopes.

3. Results show that the spacing must be reduced (to as little as twice the row spacing) when sprinkler devices are placed deep into the canopy.

4. Narrow spacing for expensive sprinklers may not be advisable. The larger diameter from expensive devices may be unneeded when placing sprinklers close together.

5. Go into the field and see how good the coverage is when the crops are tall. You can often observe how well the sprinklers apply water when you observe them in operation. Water from about four sprinklers should apply water to a location when the sprinklers are at or above the top of the canopy. If the sprinkler spacing is narrow, i.e. twice the row width, then only one or two sprinkler may overlap.

6. Check on runoff when the lateral aligns with row direction and on the steepest slope. If the wetted diameter is too small, runoff may occur. The runoff often accumulates when the pivot lateral aligns with crop rows. Runoff is more severe on steep slopes as well.

Wheel Tracks

As the center pivot moves through the field, the wheels can create ruts in the wet soil. These ruts can make the field rough and cause damage to equipment during field operations. The irrigation system may also become stuck in the saturated soil with higher application depths. A method to reduce these problems is to use boom backs. These are designed to extend the sprinklers behind the wheels and most use part-circle sprinklers. With this design, the wheel tracks are kept dry until the pivot passes. The irrigation system in Figure 56 does not make a full circle so it is equipped with boom backs extending to both sides of the lateral. A valve controls which side is turned on depending on the direction the pivot travels.

Figure 56. Center pivot equipped with boom backs.

Operating Pressure

Once a sprinkler package is designed and installed, operating the system at the designed pressure is vital to the application uniformity of a sprinkler package. Figure 57 shows the droplet distribution of an impact sprinkler when operating at the correct pressure. Smaller drops have a higher drag to momentum ratio. This drag will slow the smaller drops faster causing them to fall closer to the sprinkler. Larger drops have more momentum and travel further from the sprinkler.

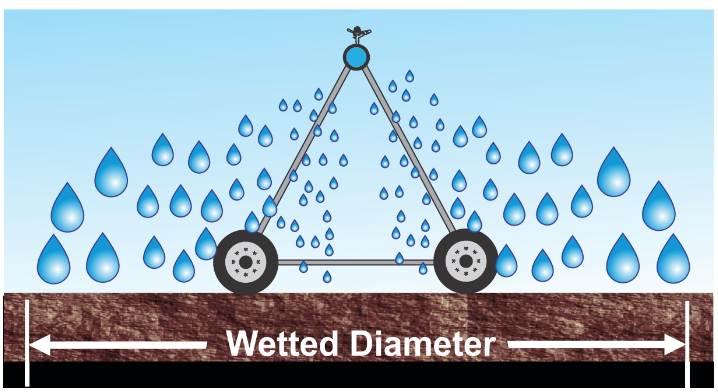


Figure 57. Proper droplet distribution with correct operating pressure.

Figure 58 shows the pattern of water application around a sprinkler when the system is operated at a pressures greater than recommended for the sprinkler. The increased pressure causes larger drops to break into many small drops. These small drops decelerate and fall near the sprinkler. The wetted diameter is reduced and the application rate is increased near the sprinkler, increasing the potential for local runoff.

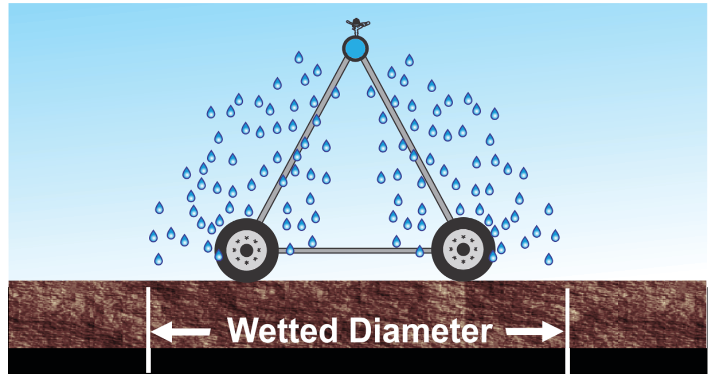


Figure 58. Droplet distribution with high operating pressure.

When a system is operated below the designed pressure, the distribution pattern observed in Figure 59 results. In this scenario, the large drops do not break up enough and most of the water is applied in an annular ring located near the radius of throw. Also, reducing the pressure decreases the velocity of water as it exits the nozzle, causing a reduction of the wetted diameter. This pattern is often referred to as a doughnut-shaped pattern.

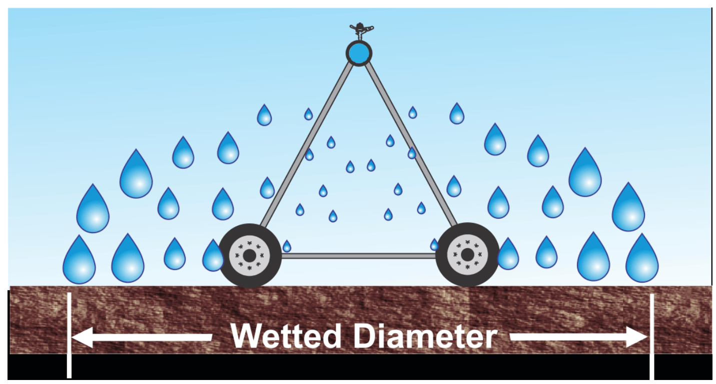


Figure 59. Droplet distribution with low operating pressure.

Figure 60 compares the distribution pattern of sprinklers operated at pressures that are too high, within the recommended operating range and at pressures less than recommended. In summary, when the pressure is too high the water is applied near the sprinkler and when the pressure is too low the water is applied in a doughnut shape away from the sprinkler with both scenarios having reduced wetted diameters.

Summary

Knowing your soil's intake family, slope, and the expected residue cover is crucial to selecting the proper sprinkler with a wetted diameter large enough to eliminate runoff. To minimize application uniformity problems, keep the sprinklers above the crop canopy when possible. Select sprinklers that produce large droplets to reduce evaporation and drift. Operating the system at the designed pressure will ensure proper distribution from the sprinklers.

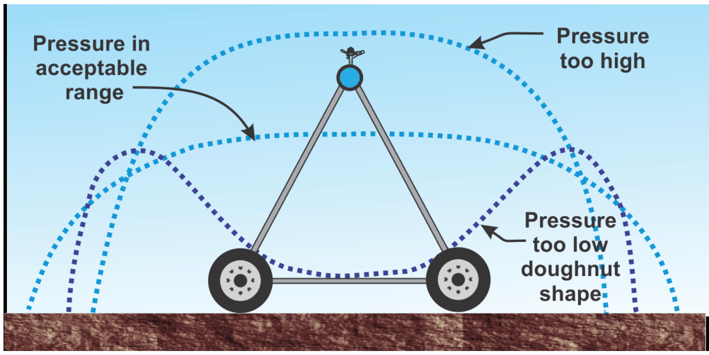
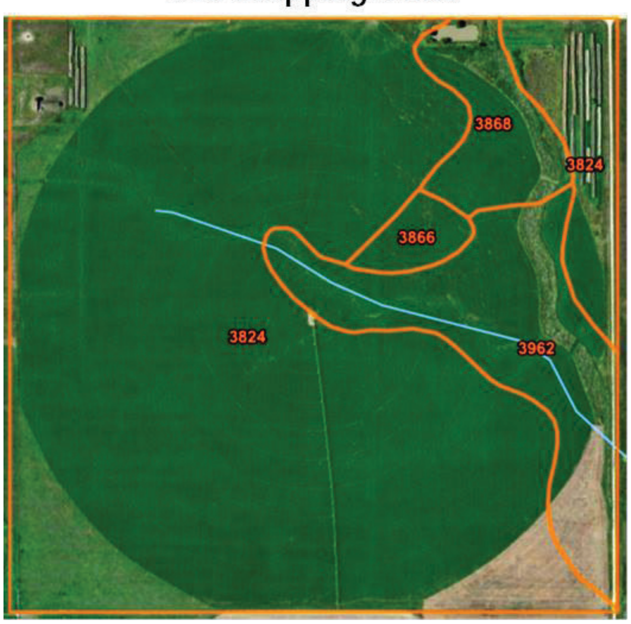


Figure 60. Application distribution for three operating pressure scenarios.

Example 2. Minimum wetted diameter.

A center pivot is being installed to water 130 acres of a quarter section. The soil map of the field is shown in the figure below. No-till is practiced on this farm leaving 50% residue cover when irrigation is performed. The slope is approximately 5% on the steepest portion of the field. The well pumps water at a rate of 650 gallons per minute and the anticipated application depth is 1 inch.

Soil Mapping Units



Map Unit Symbol	Map Unit Name	Acres in AOI	Percent of AOI
3824	Crete silt loam 0 to 1 percent slopes	129.9	81.1%
3866	Hastings silt loam, 1 to 3 percent slopes	2.7	1.7%
3869	Hastings silt loam, 3 to 7 percent slopes	8.1	5.1%
3952	Hastings silty clay loam, 7 to 11 percent slopes, eroded	19.4	12.1%
4100	Crete silt loam, thick solum, 0 to 1 percent slopes	0.0	0.0%
Totals for Area of Interest		160.2	100.0%

Determine:

a) soil most likely to have runoff problems
b) intake family for that soil
c) expected surface storage
d) system capacity
e) minimum wetted diameter needed to avoid runoff

Answers:

a) The area of the field most likely to have runoff issues is the Hastings silty clay loam, highlighted in red in the figure below. It is the portion of the field with the highest slope. It is also the soil with the most clay.

b) From Table 5, Hastings silty clay loam is in the 0.3 intake family.

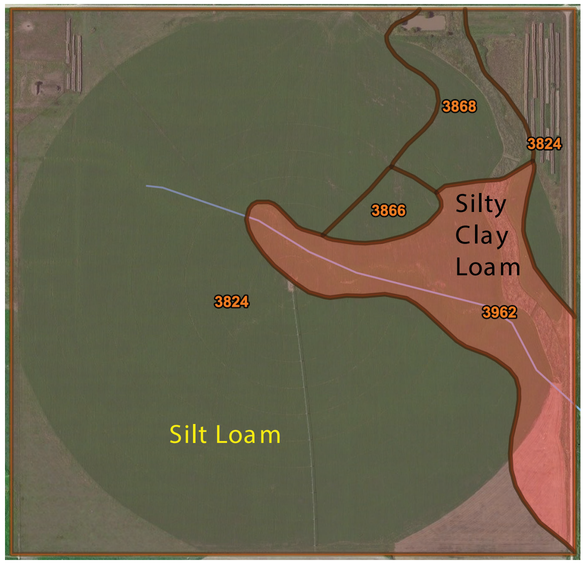
c) Using Table 8, the available surface storage for soil with a 5% slope and 50% residue coverage is 0.18 inches.

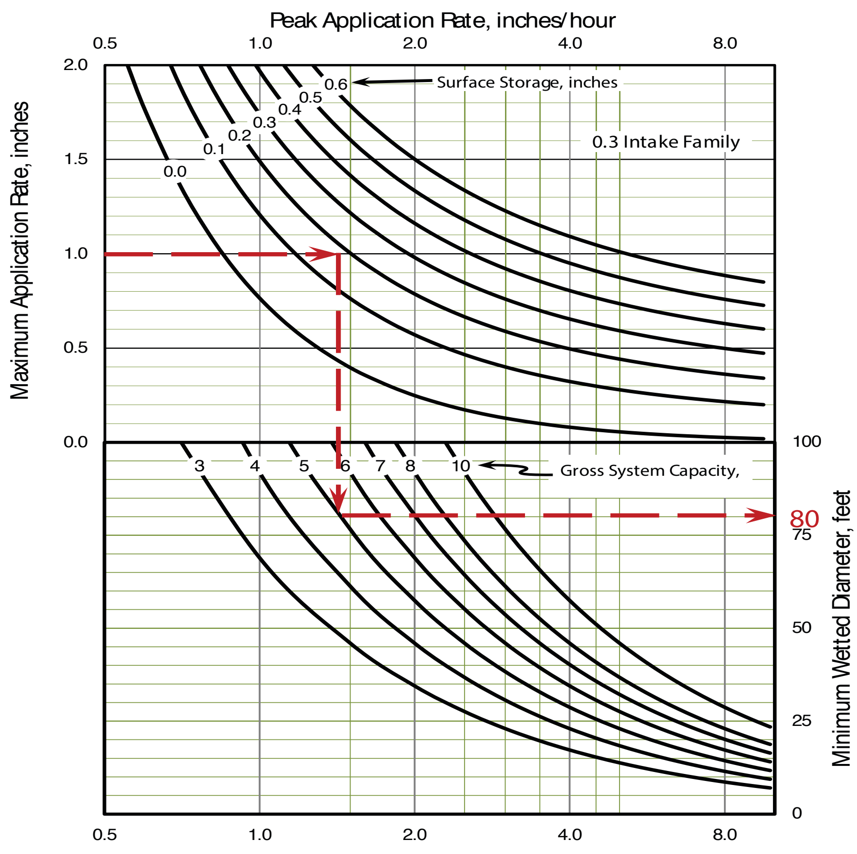
d) The system capacity is determined using the equation in Figure 3 (Chapter 2):

$$\frac{650 \text{ gpm}}{130 \text{ acres}} = 5 \text{ gpm / acre}$$

e) The minimum wetted diameter can be determined using the previous answers. The intake family that we would use is the chart in Figure 48. First, we begin with our application depth of 1 inch. We follow that to the right where we estimate the surface storage of 0.18 inches to be located. From that point, we move down until we intersect our system capacity at 5 gpm/acre. Then, we move to the right to find our minimum wetted diameter of 80 feet.

Surface Texture





For this system, we would need sprinklers that have a wetted diameter of at least 80 feet. If we wanted to use sprinklers with a smaller wetted diameter, we would need to reduce the application depth or increase surface storage to avoid runoff.

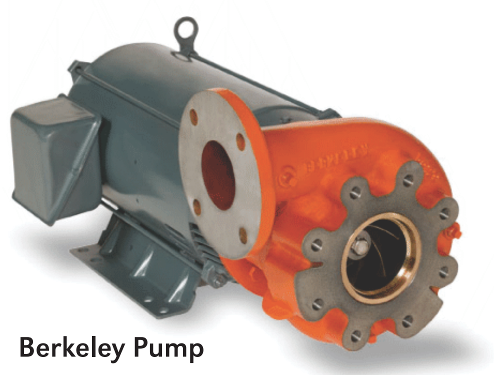
Chapter 5. Pumping Plants

Pumps

Most irrigation systems require a pump to lift water from its source and develop the pressure required to distribute water through a center pivot. Pumps are used in irrigation to convert mechanical energy from the power source into hydraulic energy. The types of pumps used to convey water for irrigation include horizontal centrifugal pumps and vertical turbine or submersible pumps.

Centrifugal Pumps

Horizontal centrifugal pumps are commonly used for pumping water from an open source or adding pressure to a pipeline. As seen in Figures 61, these pumps have a horizontal shaft and can be coupled with an electric motor or driven by an engine. A typical installation is shown in Figure 62 where water is pumped from a pond or stream.



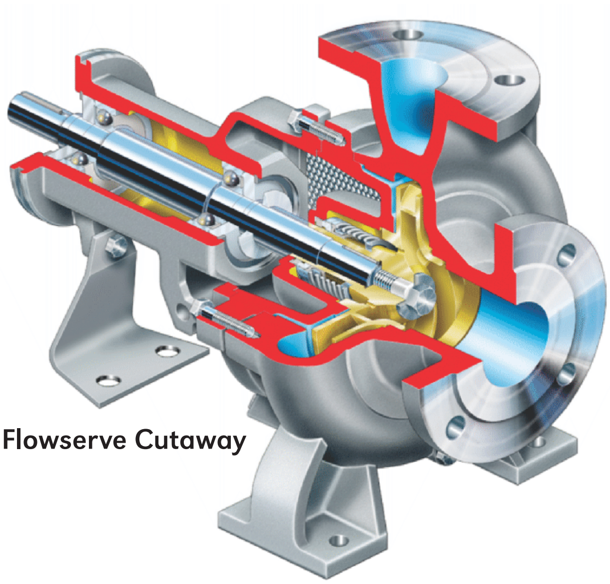


Figure 61. Example of horizontal centrifugal pumps (courtesy of Flowserve Corp. and Pentair Ltd.).

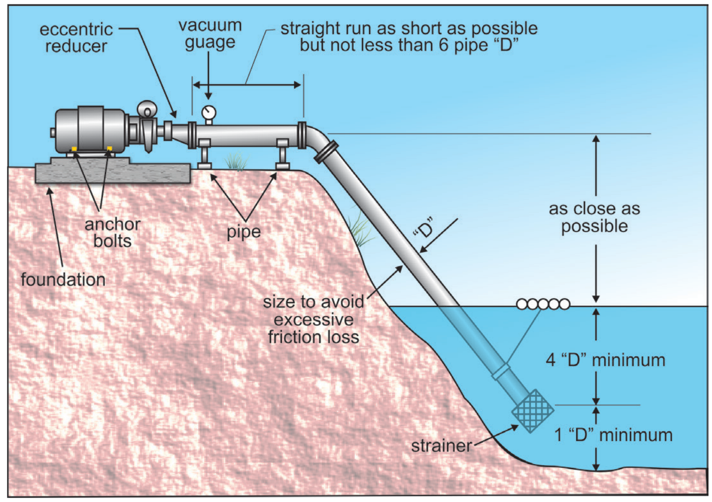


Figure 62. Horizontal centrifugal pumps lifting water from a pond.

Centrifugal pumps are also used to add pressure to water in a pipeline. A common use of centrifugal pumps for center pivots is to boost the pressure of water supplied to an endgun as illustrated in Figure 63.

Figure 63. Example of a centrifugal pump used to boost pressure for the end gun of a pivot.

Vertical Turbine Pumps

Vertical turbine and submersible pumps are used when pumping water from a well (Figure 64). For turbine pumps, water enters the eye of the impeller and, through centrifugal force, water is pushed outward and upward by the vanes of the impeller. This process develops head needed for an irrigation system. Lifting water and delivering it at a desired pressure may require staging the impellers and bowls. This means that water will be pumped from one impeller into another until the desired head is achieved (Figure 65).

Turbine pumps can utilize either a closed or open impeller design shown in Figure 66.

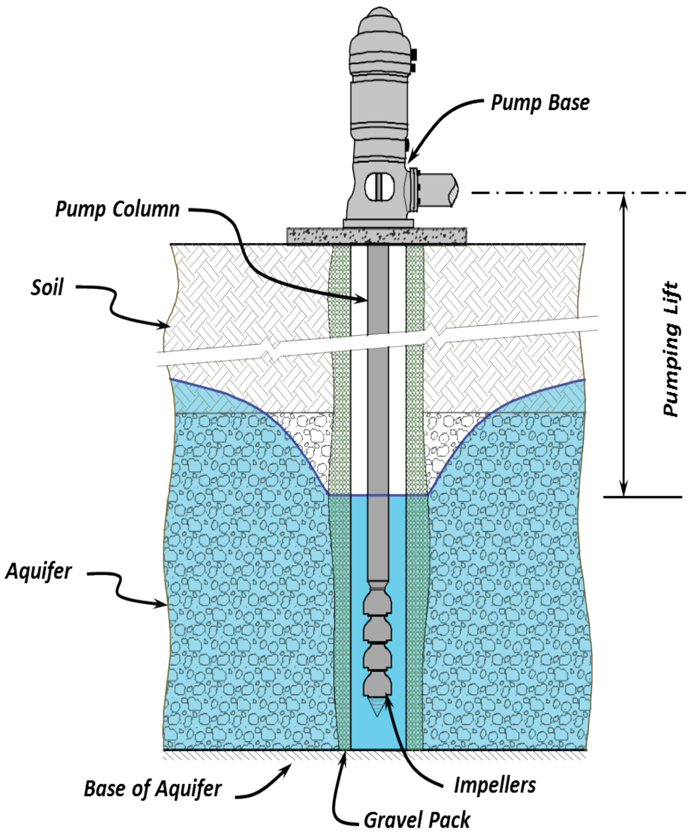


Figure 64. Vertical turbine pump system.

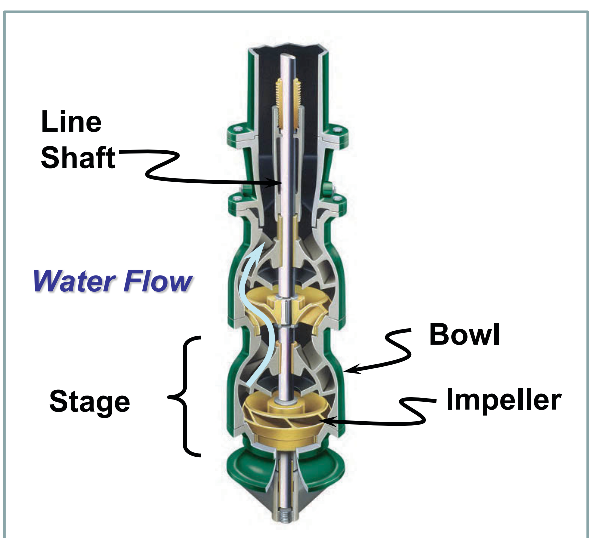


Figure 65. Water flow through vertical turbine pump (drawing courtesy of Pentair Fairbanks Nijhuis®).

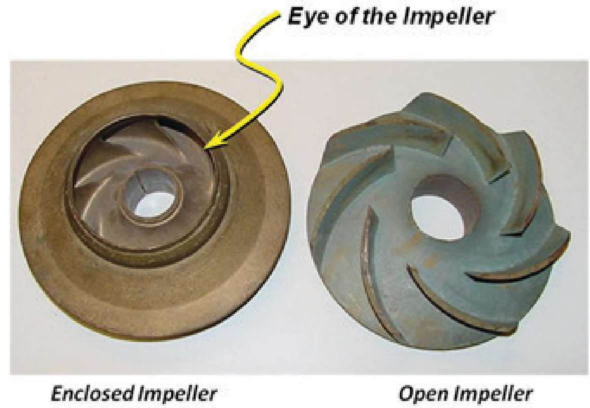


Figure 66. Types of impeller design.

Submersible Pumps

Submersible pumps are very similar to vertical turbine pumps except that they are driven by an electric motor directly below the pump (Figures 67). This design reduces inefficiencies seen in drive systems of a vertical turbine design. Submersible pumps are very good in deep wells and can be used in wells as small as 4 inches in diameter.

Figure 67. Examples of submersible pumps (courtesy of ITT Goulds Pumps).

Pump Information

Information about the well design and pump characteristics can be found from manufacturers and from the information included on the pump discharge head. The discharge head is the base on which the electric motor or right-angle gearhead sits. There should be a nameplate that gives information about the make, impeller size and number of stages. There may also be information about the well size and depth. Irrigation wells have to be registered in Nebraska. Information from the registration process can provide data about the specific well and pump. Registration information can be accessed at the website sponsored by the Nebraska Department of Natural Resources [9].

Pump Curves

Pump curves, also known as characteristic or performance curves, describe the operating characteristics of pumps (Figure 68). Manufacturers provide curves for their pumps. Curves, which are essential for design and analysis of pumping plants, provide information on flow capacity, total head developed, efficiency of the bowls, and the horsepower required to operate the pump. The pump curve in Figure 68 is for a single stage of a 12-inch pump operating at a 1760 rpm with an impeller diameter of 9.02 inches.

Pump capacity in gallons per minute (gpm) is given on the bottom scale (x-axis) while the total dynamic head in feet is given along the vertical scale (y-axis). A pump with a specific diameter of impeller operating at a selected speed produces a certain amount of head for a given flow. The thicker curve in Figure 68 is the head-capacity curve relating the flow to head. As the head increases, the flow decreases. Likewise, the smaller the head, the larger the flow.

A pump curve also gives the efficiency of the bowls and the brake horsepower (bhp) required to produce flow at the corresponding head. There are many formats for graphs used to describe pump performance. An example in Figure 68 shows the efficiency in the upper part of the graph and the bhp in the lower part. Pump manufacturers also provide information about the amount of head needed at the pump inlet to avoid cavitation in the pump. This process is described later.

The brake horsepower needed for the pump can be computed based on the flow, head and pump efficiency. The brake horsepower is equal to the water horsepower (whp) divided by the pump efficiency (expressed as a decimal fraction, i.e., 0.95 for 95% efficiency):

[9]http://dnrdata.dnr.ne.gov/wellscs/Menu.aspx.

$$whp = \frac{Flow(gpm) \times Head(feet)}{3960}$$

$$bhp = \frac{whp}{Eff_p} = \frac{Flow(gpm) \times Head(feet)}{3960 \times Eff_p}$$

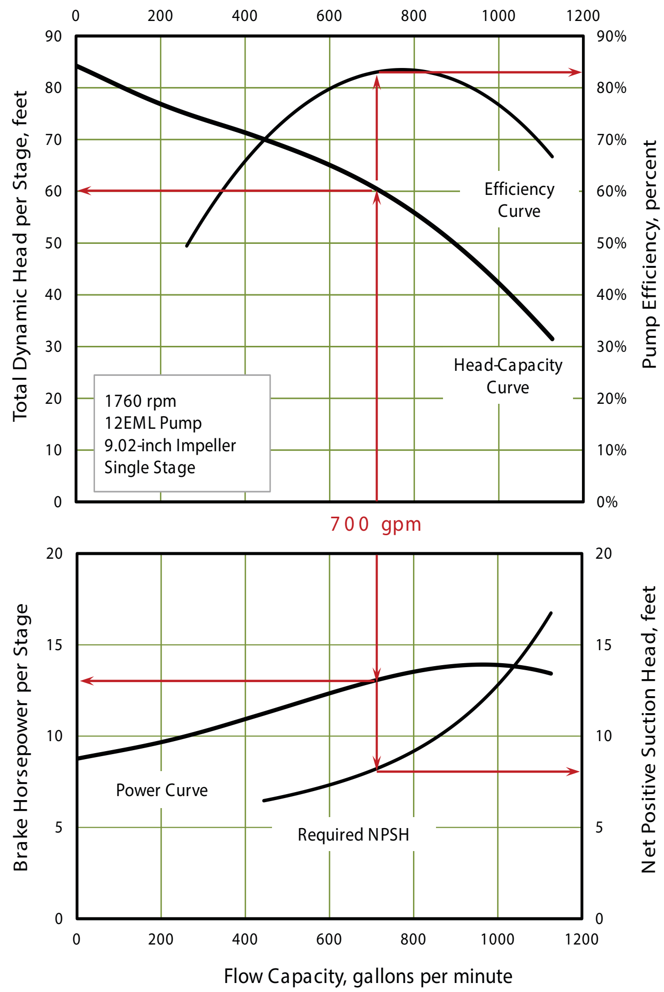


Figure 68. Example of a pump curve.

Reading a pump curve is straight forward. Suppose the total dynamic head, pump efficiency, and horsepower are needed when the pump in Figure 68 produces 700 gpm. Start at 700 gpm for the flow. Move vertically upward to the head-capacity curve. Move to the left to read the total dynamic head the pump will produce; which is about 60 feet for each stage. Moving upward and to the right shows that the efficiency will be about 84%. The brake horse power requirement for 700 gpm at 60 feet of head and an efficiency of 84% is about 13 horsepower per stage. The required net positive suction head for 700 gpm is about 8 feet.

One can also start out knowing the head requirement and determine the gpm output, efficiency, and bhp. For example, using the pump in Figure 68, suppose the head requirement is 50 feet, then the flow will be about 900 gpm, the efficiency will be about 84% and the brake horsepower requirement will be 14 feet per stage.

Impeller Speed and Trim

Vertical turbine and centrifugal pumps are based on centrifugal force which means operating characteristics of a pump vary when the speed of rotation or the impeller diameter changes. This allows pumps to be used over a range of conditions while maintaining good efficiency. Instead of making a single pump performance chart for each size of impeller or speed, manufacturers often place several pump curves in a single graph. This gives better view of how pumps perform for different speeds or impeller sizes (also known as trim sizes).

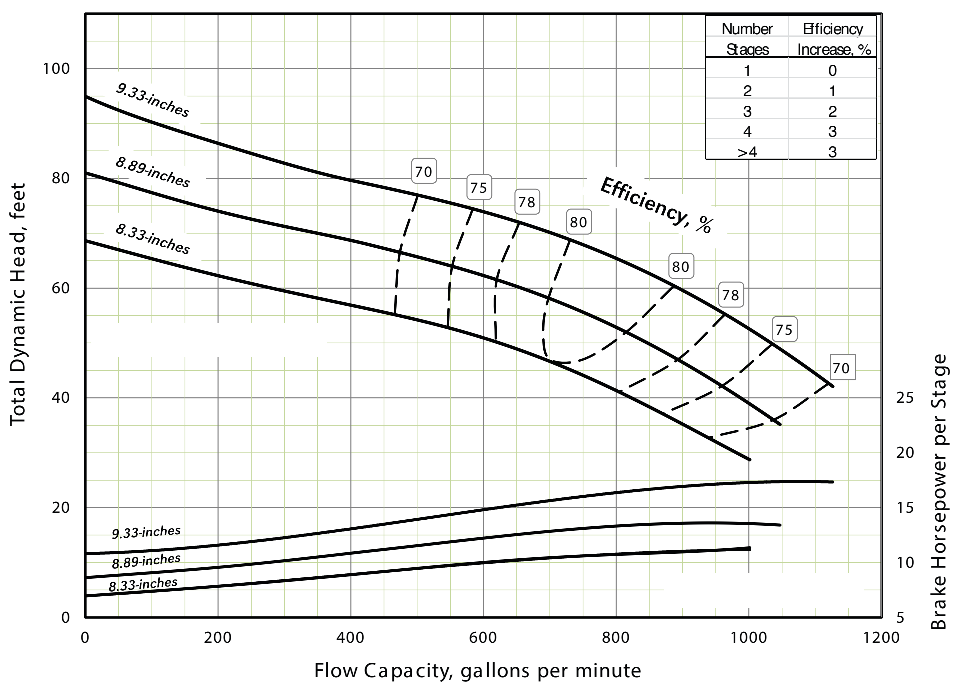


Figure 69. Pump curves for varying impeller diameters.

The performance of the pump in Figure 68 is shown in Figure 69 for three diameters of impellers. The head-discharge and the brake horsepower curves are similar to Figure 68.

The efficiency is often shown as a series of lines superimposed over the head-discharge curve. The hatched curves show lines of equal bowl efficiency. The number of stages of impellers and bowls affects the efficiency as well. The insert in Figure 69 shows that the efficiency can be increased when multiple stages are used. For example, if the 8.89-inch impeller was used and the discharge was 700 gpm, then the efficiency for a single stage is about 80%. If four stages of the pump were needed the efficiency would increase to 83%.

The performance curve of the same pump with an impeller diameter of 8.89 inches but operated at three pump speeds is shown in Figure 70.

Pump Staging

A single stage pump often does not produce enough head for the water lift and/or discharge pressure required for an irrigation system. Vertical turbine pumps can be installed with stages (i.e., bowl and impeller) in series to increase the head for a specific flow. This is known as staging. Water passes through each stage where pressure is added to the water for each stage. Thus, the head-capacity and horsepower curves for a single stage can be added to give the performance for a series of stages as shown in Figure 71. For example, a single stage produces about 60 feet of head when the flow is 650 gpm for a single stage. If two stages were installed in series the head would be approximately 120 feet at 650 gpm for two stages. Three stages would triple the head to 180 feet and the horsepower would also triple. Four stages would quadruple the head to 240 feet and so on for more stages. In this manner pump companies can use one pump model, and add stages to fit a range of pumping applications. The insert in Figure 69 illustrates that the efficiency usually improves when multiple stages are used compared to a single stage.

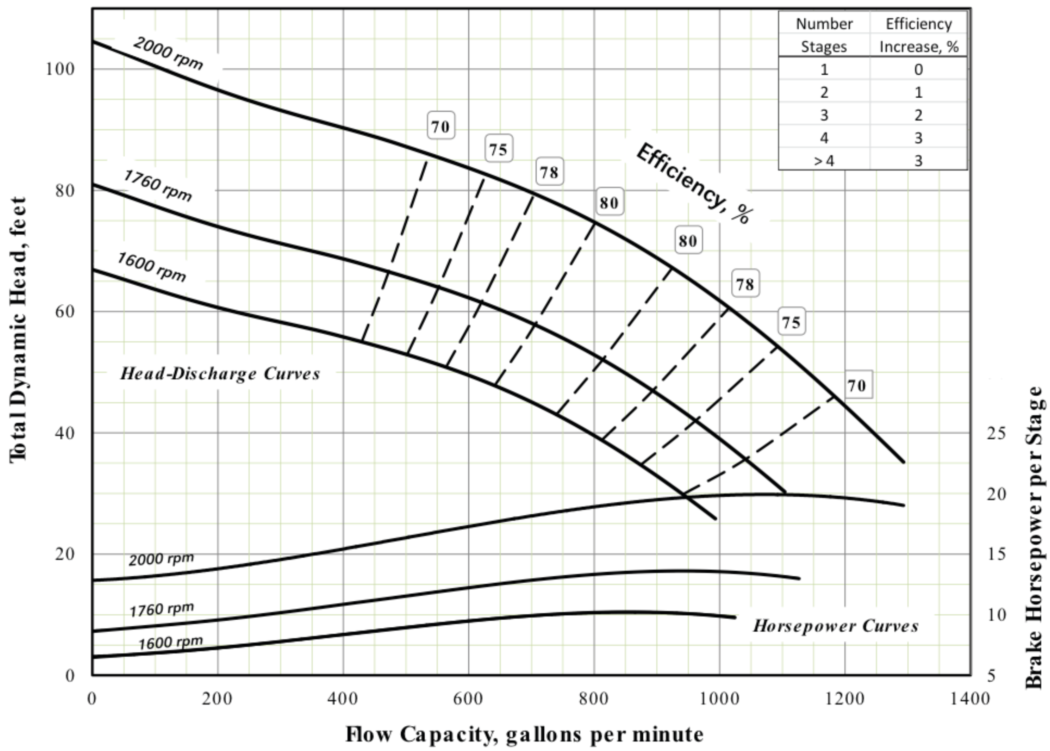


Figure 70. Pump curves for multiple pump speeds.

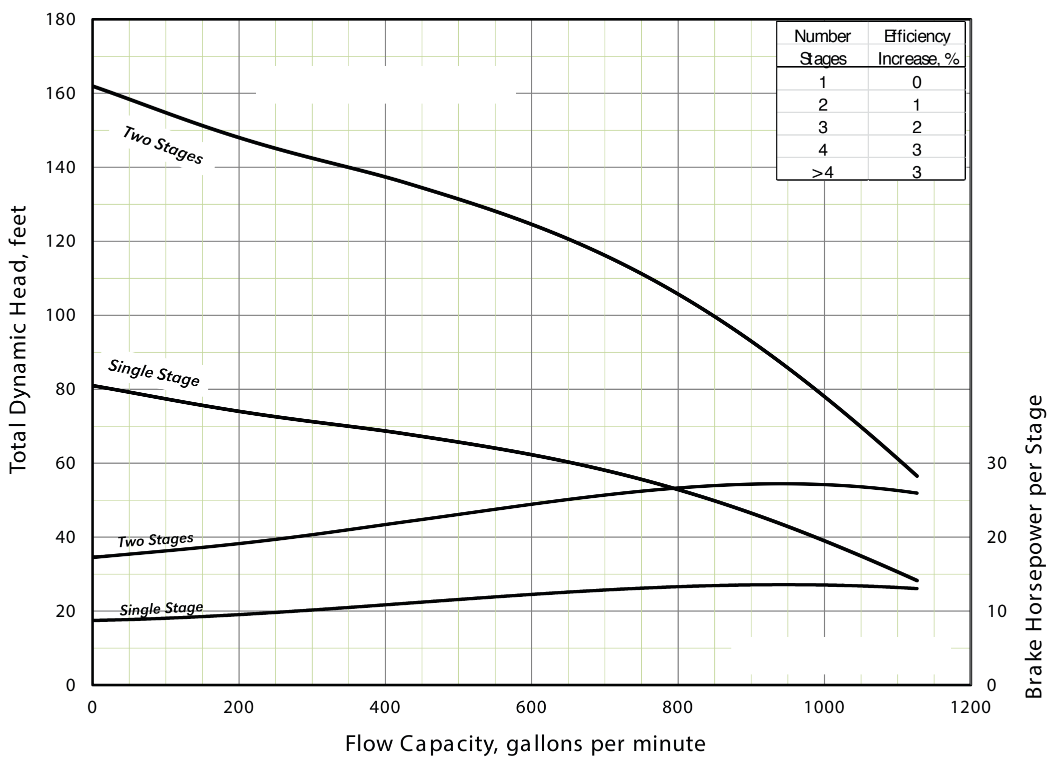


Figure 71. Pump curves for a single stage and two stages in series.

Affinity Laws

Pump manufacturers often publish head-capacity curves for a full diameter impeller operating at the 4-pole electric motor speed of 1760 or 1770 rpm. They usually publish head-capacity curves for other speeds or trim sizes. Pumping conditions may require an impeller diameter or speed that is not included on published pump curves. For example, if an engine is used to power the pump the speed may vary from speeds that occur with electric motors. There are laws, known as the Affinity Laws, which allow us to derive head-capacity and horsepower curves for speeds and diameters different from published curves. Many companies now offer software tools to create performance curves for selected pumping conditions. Those tools are preferable to the affinity laws presented here for detailed analysis. However, affinity laws can be used to understand how pumps perform and to develop quick solutions for changes in rotation speed or trim diameter.

One application of the Affinity Laws involves the rotational speed of a pump. The ratio of the flow for the new speed to the flow for the initial speed equals the ratio of the final and initial rotational speed :

$$gpm_2 = gpm_1 \times \left(\frac{rpm_2}{rpm_1}\right)$$

The ratio of the final head to the initial head is proportional to the square of the ratio of the final and initial rotational speed:

$$Head_2 = Head_1 \times \left(\frac{rpm_2}{rpm_1}\right)^2$$

The ratio of the final brake horsepower to the initial brake horsepower is proportional to the cube of the ratio of the final to the initial rotational speed:

$$bhp_2 = bhp_1 \times \left(\frac{rpm_2}{rpm_1}\right)^3$$

The Affinity Laws holds true for most types of pumps used in irrigation including centrifugal, angle flow, mixed flow and propeller pumps. As a general rule the laws should not be applied for very large changes in speed.

To illustrate the approach consider Figure 72. This is the curve for a pump operated at 1760 rpm which is the published speed. We desire a curve for a speed of 1900 rpm. Since all three values are based on the ratio of the final speed to the initial speed, the first step is to find this ratio, 1900 rpm/1760 rpm = 1.08.

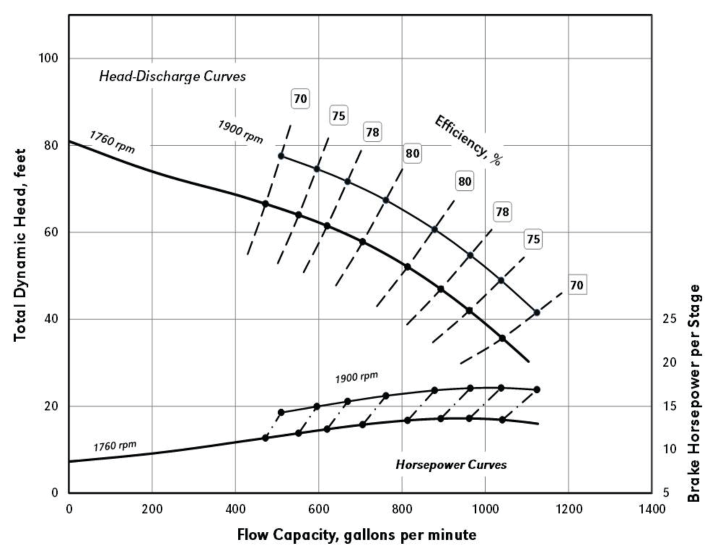


Figure 72. Pump curve derived from affinity laws for pump speed.

Select points along the original curve for analysis. It is usually good to pick points at the intersection of the efficiency lines. Eight points on the 1760 rpm curve were selected in Figure 72. The first point is at a flow of 472 gpm and a head of 66.6 feet. This point translates to a flow of about 510 gpm (i.e., 1.08 x 472 gpm) and a head of 77.6 feet (i.e., 66.6 ft x 1.08^2) for 1900 rpm. The remaining seven points are translated in a similar fashion to produce the new curve for a speed of 1900 rpm. The efficiency for the points on the 1760 rpm curve translate to the 1900 rpm curve as well. Thus, the efficiency of each point on the 1760 will have the same efficiency on the 1900 rpm curve as it had on the 1760 rpm curve. A similar process is used to develop the new brake horsepower curve for 1900 rpm. Notice that the new head-capacity curve is parallel to the original curve but the new bhp curve is not parallel to the original. It is therefore necessary to plot several points to derive a new bhp curve.

The second form of the Affinity Law has to do with the diameter of the impeller. This version of the Affinity Law is used to determine the change in performance when the diameter of the impeller is changed from the published size. The diameter of a full sized impeller can be machined down to a smaller diameter to provide the desired head-capacity curve when specific applications require such accuracy.

The effect of the diameter is similar to the effect of pump speed. The discharge for a new impeller diameter is linearly related to the ratio of the final and initial impeller diameters: The head is proportional to the diameter ratio squared and the brake horsepower is proportional to the cube of the diameter ration. The relationships for the effect of diameter are expressed as:

$$gpm_2 = gpm_1 \times \left(\frac{D_2}{D_1}\right)$$

$$Head_2 = Head_1 \times \left(\frac{D_2}{D_1}\right)^2$$

$$bhp_2 = bhp_1 \times \left(\frac{D_2}{D_1}\right)^3$$

The second version of the Affinity Law is applied similar to the speed based version.

For example if a full impeller as shown in Figure 69 is 9.33 inches and if the impeller was machined down to a diameter of 8.4 inches, then the diameter ratio would be 0.9. For this case the flow would be reduced to 0.9 times the original flow, the head would be 0.81 times the original head and the brake horsepower would be 0.73 times the original horsepower. The efficiency would be the same as the original point. New curves can be developed for the custom made impeller similar to the process for the impact of changing impeller speed.

Strictly speaking the diameter-based version of the Affinity Law only applies to centrifugal pumps. However, it does give a close approximation for mixed flow pumps like the vertical turbine pumps used in irrigation. When a discrepancy exists between the calculated and actual curves the calculated or derived curve will always be above the actual curve. Impellers with a steeper angle of inclination from horizontal will have more discrepancy than impellers with flatter angles of inclination; thus, diameter-based version of the Affinity Law works best for centrifugal pumps with radial flow.

The diameter-based Affinity Law should not be used for trims larger than 20%. Changes in the nature of the impeller are usually too significant for such large reductions of diameter. As always, it is strongly advised to coordinate pump changes with a pump supplier to ensure that proposed changes are advisable.

Matching Pumps and Systems

Pump curves describe the amount of head that the pump will develop at specific flow rates. The previous sections describe the performance of a pumping system that has multiple stages operated at varying speeds and with specified diameters of impellers. The output from the pump has to match the head requirements for the irrigation system. The head required for varying flows within the irrigation system is referred to as the system curve.

Consider the system illustrated in Figure 73. The pump must develop enough head to lift water from the pumping level in the well to the pump base, lift water from the pump base to the elevation of the center pivot lateral, and overcome pressure loss due to friction of water flow in pipes and fittings along the pipeline. The pump must also develop the pressure required to operate the sprinklers on the pivot lateral and to overcome the pressure loss in the pivot lateral and lift water to the highest elevation at the end of the pivot lateral. Some factors such as the elevation from the pump to the pivot inlet, or the depth of water below the pump base to the static water level are constant. Those values do not change with the amount of flow through the system. Other factors such as the friction loss and the pressure required to operate the pivot depend on the rate of flow through the system.

The head-capacity curves for pumps with 3, 4 and 5 stages are shown in Figure 74. The head required for specific flows is referred to the system curve and is illustrated for an example system in Figure 74.

The actual operating point for the system occurs where the output head from the pump matchs the head required for the system. The points where the heads are equal are often referred to as match points as shown in Figure 74. The operating point for the combined pump, pipe and pivot system depends on the number of stages of impellers installed with the pump. If only three stages were included then the flow would be about 655 gpm with a total dynamic head of 180 feet of head. If four stages were used, the flow and head increase to about 780 gpm and 215 feet. Five stages provides about 860 gpm and 245 feet of head. The most desirable operating point is the one closest to the design flow rate for the center pivot. The pump efficiency for the selected match point should also be near the peak efficiency so that operation is economical. In this case all three match points have efficiencies above 80% which is near the maximum value. The brake horsepower for the match point with four stages is about 51 horsepower.

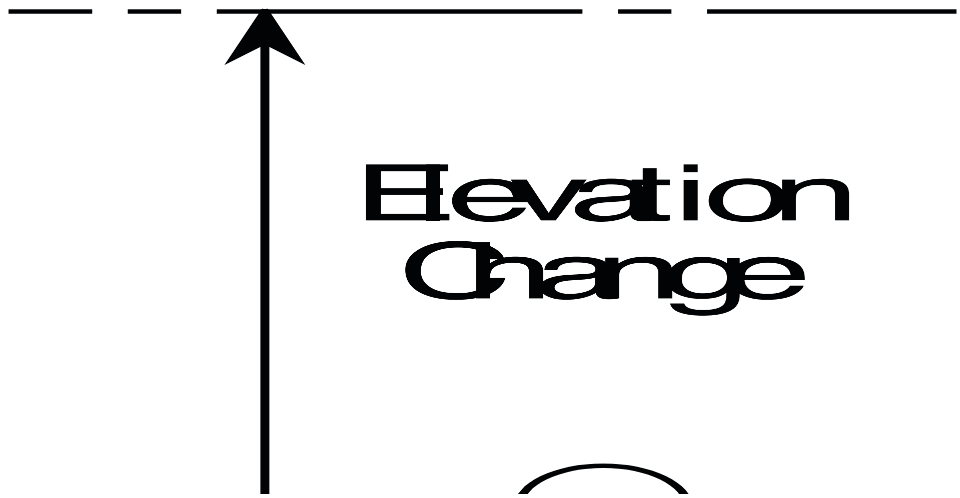


Figure 73. System layout for a typical center pivot field.

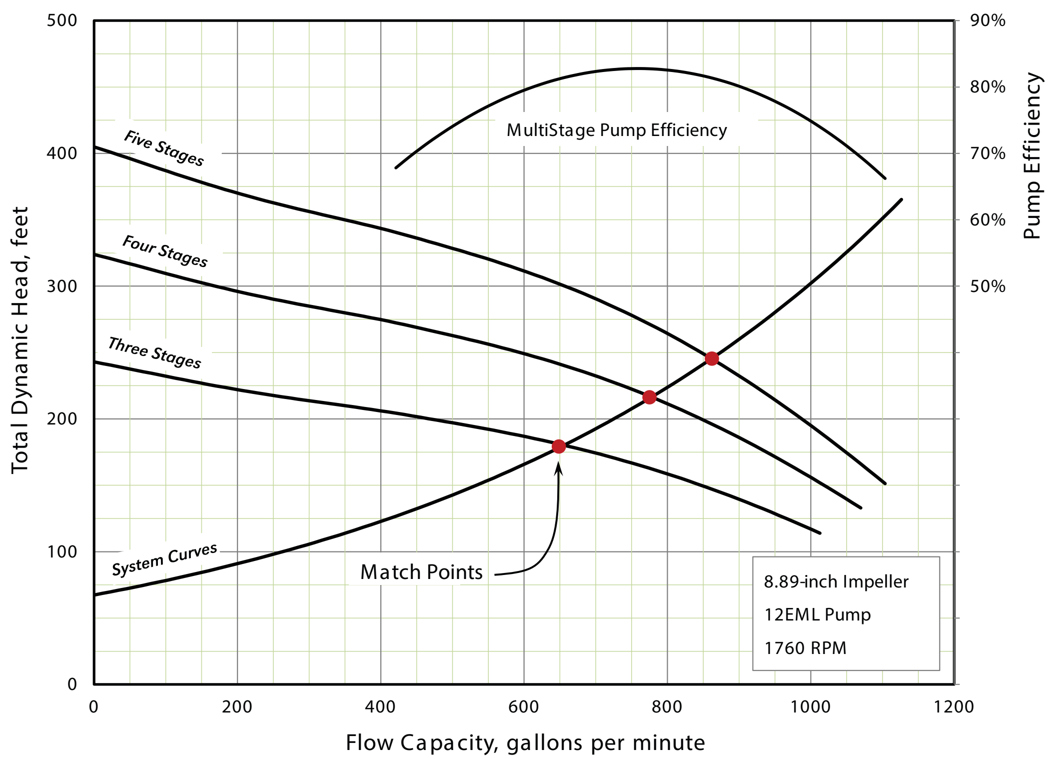


Figure 74. Characteristic curves used to determine the flow and head where the pump and the system match.

Irrigation systems only work efficiently when motors or engines, drive systems, pumps, and water distribution systems are properly matched. Any change in the system usually requires a change in some or all of the units. For example, switching from surface to sprinkler irrigation often requires modification of the pump and/or drive system and may require an engine changes. As a rule, changes in one component requires evaluation of other components in the system to be sure they still match. Mismatchs can materially increase pumping costs.

The bowls, line shaft, column, and base of a pumping plant must all be matched for efficient operation. The bowls should have the correct head characteristics or develop the needed pressure for the desired flow. The column and pump head must not offer too much resistance to flow and the line shaft should be the right size so impellers will operate properly.

Figure 75. Examples of direct drives for motors and engines (drawing is courtesy of ITT Gould Pumps).

PUMP DRIVES

There are three general methods of supplying power to a pump: direct drive, v-belt drive and right angle gearheads connected to an engine.

Direct drives are mostly used with electric motors but occasionally with engines. Examples of direct drive systems for electric motors and an engine are shown in Figure 75. Direct drives fix the speed of the pump to that of the power unit, so the speed ratio is 1:1. Since electric motors often operate at speeds of 1760 or 1770 rpm, or at higher speeds of 3400 rpm, pump manufacturers often publish pump curves for these pump speeds. This allows direct application of pump curve information. The brake power requirement from the curves provides the power output needed from an electric motor. Power requirements of engines is more involved as explained in a following section.

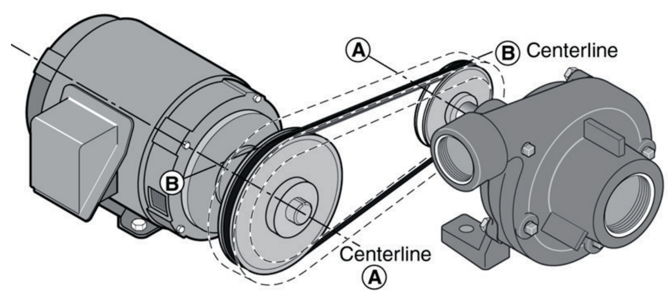


Figure 76. Diagram of pulley driven centrifugal pump (adapted from Berkeley Pumps - Pentair Ltd.).

V-belt drives or right angle gearheads (see Figures 76 and 77 for examples) allow for variable pump speeds relative to the engine or motor speed. These drives are usually categorized by the drive ratio which is the speed of the power unit relative to the speed of the pump. A ratio of 11:10 means that the power unit operates at a higher speed than the pump. The ratio depends on the diameter of the drive gear or pulley to the diameter of the driven gear or pulley.

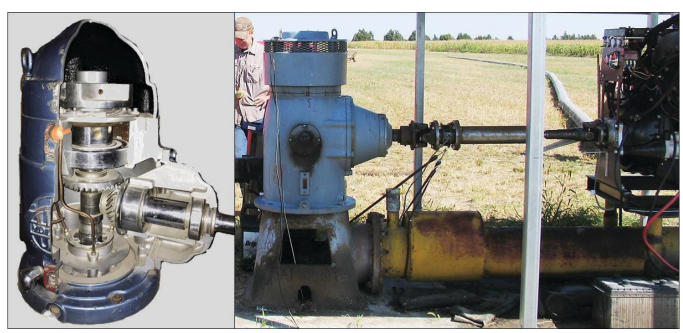


Figure 77. Example of a right angle gearhead used with engines to power vertical turbine pumps.

Pulley size ratios for a V-belt drive are given in the same manner. Motor speed is given as the first number in the ratio. However, with V-belt drives, the ratio refers to the pitch diameter (effective diameter of a loaded pulley). Attention to gear ratios and the drive shaft alignment are important in setting up a gear drive. The careful selection of the gear ratio will give the engine speed desired to get the recommended pump speed. Also, the shaft should be carefully aligned so angularity in either the horizontal or vertical direction does not exceed five degrees. Then the power loss through the drive will not exceed five percent.

Gearheads and v-belt drives lose some mechanical energy in transferring power from the motor or engine to the pump. The loss of energy is represented with a drive efficiency (Eff_d). The drive efficiency is the percent of the brake horsepower provided to the pump relative to the power output of the motor or engine. Conversely, the power output from a motor or engine (ehp) must satisfy the brake horsepower requirement and the loss of energy in the drive system:

$$ehp = \frac{bhp}{Eff_d}$$

The drive efficiency for direct drives is usually taken as 100% while the drive efficiency of right-angle gearhead drives is usually 95%. The drive efficiency should be used as a decimal fractional above (i.e., 0.95 for 95%). The drive efficiency of v-belt systems is more variable depending on the configuration of pulleys and idlers. The efficiency for good systems should be above 90% for well maintained v-belt applications.

POWER UNITS

Electric Motors

The nameplate power output of an electric motor should be closely matched to power requirement of the pump when a direct connect drive is used. If other pump drives are used, then the drive loss should be considered. There is no advantage to oversizing an electric motor as the original investment is higher and no operating savings occur, also, standby charges may be greater.

Engines

The power unit on an irrigation pumping plant must supply power to lift water, build pressure, overcome power losses in pumps and drives while operating under the temperature and elevation conditions at the field location.

Engine manufacturers usually publish horsepower curves when engines need to supply full power intermittently or when subjected to a constant load (Figure 78). Since irrigation is a continuous load, the curve that is of interest to the pumping plant designer is the continuous horsepower curve.

If only the intermittent horsepower curve is available for the engine, the continuous horsepower can be estimated by multiplying the intermittent horsepower by 0.85.

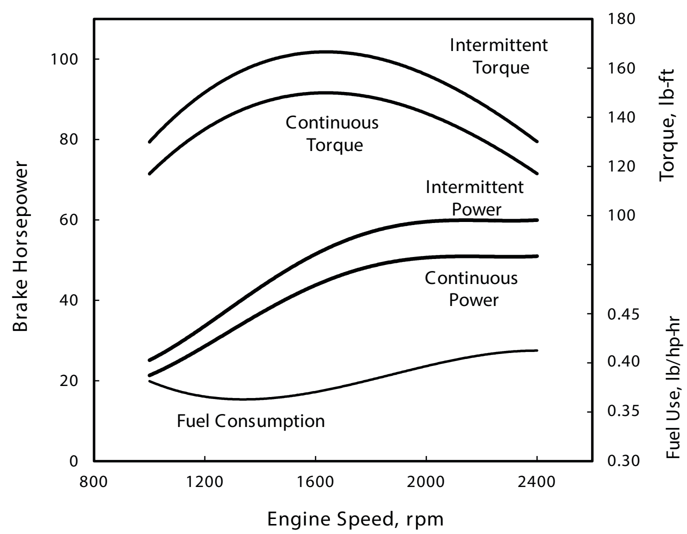


Figure 78. Engine performance curves.

Performance curves also provide the torque for intermittent and continuous loading. The specific fuel consumption rate is also provided on the performance curves. The consumption is the mass of fuel consumed per horsepower per hour of operation. Smaller values for the specific fuel consumption result in more economical engine operation.

The engine performance curve is needed to ensure that the engine will produce enough power to meet the pump and drive system needs at the specific engine and pump speed. If more power is needed, the gear ratio can be changed to operate the engine at a higher speed to gain more power while operating the pump at the designed speed. Matching the pump and the power source is an essential step in developing an efficient pumping plant.

An internal combustion engine may have some accessories, such as fans and water cooling coils, that consume some of the power produced by the engine. Thus, less power is available to pump water than the continuous brake horsepower rating of an engine without accessories. Therefore, take care in reading engine curves and specifications. Know what accessories were on the engine at the time the engine was tested and what effect other accessories not included at the time of the test will have on usable power. Engine manufacturers may not use the same accessories during engine tests; therefore, it is necessary to determine what accessories were used during the test of a specific engine. The elevation and temperature for the test and at the installation location may also be important. Some engines need to be derated for high elevations or hot operating environments. Other engines may not require any adjustment of test results for a wide range of environments.

An engine dealer should be consulted regarding specific information for available engine models that match your requirements (i.e. needed bhp at desired rpm). Look at the engine curves and determine which models have the best fuel economy at the needed horsepower. These engines will be well suited to your pump. When a fuel curve is not available with the engine's performance curve, then determine which model produces the highest torque at the desired rpm.

Matching Engines to Pumps

An example will illustrate the process of matching engine output to pumping needs. Consider the following conditions:

Static Water Level	28 ft
Pumping Rate	950 gpm
Pumping Water Level	39.5 ft

From the farm field make-up and cropping system, and water supply, the decision was made to use a low pressure, electric drive center pivot irrigation system which requires 40 psi pressure at the pump.

The needed information to select a pump impeller and bowl assembly include:

a) Pumping rate as given	950 gpm
b) Pumping water level to surface	39.5 ft
c) Converting psi to feet of head	92.4 ft (40 psi x 2.31)
d) Total head in feet =	132 ft

1) From the manufacturer's curves, an impeller is selected that will deliver 950 gpm, at 66 ft of head, and at 1760 rpm with the highest possible efficiency. The selected pump model delivers 950 gpm at a respectable 81% efficiency and produces 66 ft of head per stage.

2) To calculate the number of stages needed simply take total head (132 feet) and divide by the head produced by each stage (66 ft/stage). In this case, the pump will require 2 bowls or stages.

3) Water horsepower is calculated as follows:

$$\frac{950\,\text{gpm} \times 132\ \text{ft of head}}{3960} = 32\ \text{WH}$$

4) Determining the size of power plant needed:

Because of the location relative to electric lines, the decision was made to use an internal combustion engine. In this example, a turbocharged diesel engine with a cooling fan, charging alternator, and power generator will be used.

The elevation and temperature at the well site are:

Elevation above sea level*	1000 ft
Temperature, max. intake*	100°F.

Elevation and temperature affect naturally aspirated engines, but the performance of turbocharged engines are not affected by elevation and temperature until the elevation is greater than 7,000 feet. Some engines can be used without adjustment up to 10,000 feet.

Adjustments are needed for the accessories installed on the engine:

Accessories, cooling fan 5%;	100% - 5% = .95
Charging alternator 1%;	100% - 5% = .99

The engine also needs to be large enough to overcome the friction loss of the gearhead and the losses due to the pump efficiency:

Drive efficiency, for the gearhead is(95%):	0.95
Pump efficiency, (81%)	0.81

The engine must also drive a 10 kVa 3-phase alternator to supply power to the drive motors on the center pivot. Alternators are generally 85% efficient, therefore:

$$\frac{10\ \text{kVa}}{0.85} \times \frac{\text{hp}}{0.746\ \text{kVa}} = 15.8\ \text{hp for alternato}$$

A 15% reserve is usually added to provide for changes in an engine's performance due to wear or manufacturing tolerances.

The continuous horsepower requirement is:

$$bhp = \frac{32\ whp}{0.95 \times 0.99 \times 0.95 \times 0.81 \times 0.85} + 15.8 = 52 + 15.8 = 68\ hp$$

Since the engine needs to run at 1760 rpm to produce 68 horsepower and the pump also needs to run at 1760 rpm, a gearhead with a 1:1 ratio is needed.

6) To ensure maximum pumping plant efficiency, the pump and engine both must operate at 1760 rpm. But the pivot alternator has to run at 2000 rpm to produce the necessary 480 volts. (Remember to operate the system at the proper rpm for the pump and engine, not by the volt meter on the alternator).

In order for the alternator to operate properly, calculate the ratio between the engine speed and required alternator speed:

$$\frac{1760\ rpm}{2000\ rpm} = \frac{0.88}{1}$$

If the pulley on the engine is 8 inches in diameter, multiply 8 inches by .88 for the size of the alternator pulley. In this case the alternator pulley should be 7" in diameter.

The matched components of the pumping plant are now complete. A 12" pump with 2 bowls will supply 950 gpm of water to an electric drive center pivot sprinkler system at 40 psi. The system will be powered continuously by a 68 horsepower turbocharged diesel engine operating at 1760 rpm. A gearhead with a 1:1 gear ratio will run the pump at 1760 rpm. The pulleys to drive the alternator are 8" on the engine and 7" on the alternator.

Matching an Electric Motor to an Irrigation Pump

The amount of water and total head and other conditions for the pump and drive are the same as for the diesel engine example. This includes steps 1-6. In step 6 we found 32 whp for 950 gpm and head of 132 feet. Because of a location near an electric transmission line, a 3-phase power line to the pump site is economical. Therefore, an electric motor is decided on as the power unit (Figure 79).

Figure 79. Electric motor for pumping irrigation water.

To determine the correct size of the electric motor, information about the whp, operating temperature, drive efficiency, and pump efficiency are needed.

whp output from the pump	32
Temperature of the well site, maximum	
110° F. is acceptable for an electric motor	
Drive efficiency, direct drive	
no loss for the drive-direct coupled	1.00
Pump efficiency	0.81

$$Motor\ Size = \frac{32\ WHp}{1.0 \times 0.81} = 39.5\ hp$$

Most electric motors have a service factor rating printed on the nameplate. The service factor for large three-phase electric motors is often about 1.15. This allows an overload of 15% above nameplate horsepower provided the motor is used in an environment conducive to adequate cooling (e.g. not dusty or enclosed in a non-ventilated well house.) For the example given, the next motor size smaller than a 39.5 hp is 30 hp. To see if a 30 hp motor could be used multiply by the service factor 30 x 1.15 = 34.5 hp. 39.5 hp is greater than the allowable overload so the next larger motor size would be required. This would be a 40 hp motor. As a word of caution, some motor enclosures have smaller service factors so one must be cautious about overloading motors.

Cavitation

Cavitation results due to the formation of vapor cavities in a liquid –i.e. small vapor bubbles– often because water is subjected to rapid changes of pressure. Subjecting vapor bubbles to higher pressure at a downstream location causes the voids to implode which can generate an intense shock wave. Within a centrifugal pump, the flow area at the eye of the impeller is usually smaller than either the flow area of the pump suction piping or the flow area through the impeller vanes. The velocity of water entering the impeller increases because of the smaller flow area which then results in a consequent pressure decrease. The greater the pump flow rate, the greater the pressure drop between the pump suction and the eye of the impeller. If the pressure drop is large enough, or if the temperature is high enough, the pressure drop may cause the water to flash to vapor when the local pressure falls below the saturation vapor pressure of water. Vapor bubbles formed by the pressure drop at the eye of the impellers are swept along the impeller vanes by the flow of the fluid. When the bubbles enter a region where the local pressure is greater than the saturation vapor pressure, the vapor bubbles abruptly collapse. This process of the formation and subsequent collapse of vapor bubbles in a pump is called cavitation.

Cavitation in a centrifugal pump has a significant effect on pump performance. Cavitation degrades the performance of a pump, resulting in a fluctuating flow rate and discharge pressure. Cavitation can also be destructive to pump components. The shock resulting from implosion of the vapor bubbles can create small pits on the leading edge of the impeller vane. Individual pits may be microscopic in size, but the cumulative effect over a period of hours or days can damage a pump impeller. Cavitation can also cause excessive pump vibration, which could damage pump bearings, wearing rings, and seals.

Cavitation can be avoided by maintaining adequate absolute pressure on the suction side of the pump. Water at the surface of a pit or channel is at the atmospheric pressure. Since the pump in Figure 80 is above the water level in the pond the water in the suction pipe and the suction side of the pump is below atmospheric pressure (i.e., there is a vacuum on the suction side of the pump). The severity of the vacuum depends on the friction loss in the pipe components on the suction side of the pump and the distance that water is lifted from the pond or channel. If the absolute pressure (i.e., the atmospheric pressure minus the vacuum) drops below the pressure where water vapor forms (i.e., the saturation vapor pressure) then cavitation may occur.

Net Positive Suction Head

Pump manufacturers test pumps and provide information on the amount of absolute pressure required to avoid cavitation within their pumps. The pressure head needed to avoid cavitation is called the required net positive suction head (NPSHR). The required NPSH increases with the pump discharge (capacity) see Figure 81. The Berkeley pump shown in Figure 81 requires a NPSH of 10 feet at a flow rate of 1000 gallons per minute to avoid cavitation.

To avoid cavitation the absolute pressure available at the pump inlet should exceed the NPSH required for the pump. The amount of pressure available is often referred to as the net positive suction head available at the pump inlet (NPSHA); thus, to avoid cavitation the NPSHA should be greater than the NPSHR. The NPSHA is determined by the:

- Atmospheric pressure at the elevation of pump (P)
- Saturation vapor pressure at water temperature (e_s)
- Friction loss in plumbing on suction side of pump (F_L)
- Distance water must be lifted above the water level in the pond or canal (L), and
- A safety factor (S_F) of two feet is often used to account for uncertainty.

The NPSHA is computed as:

$$NPSH_A = P - e_S - S_F - F_L - L$$

Frequently the challenge is to compute the maximum distance that water can be lifted above the open water source without the risk of cavitation. In this case, the required NPSH is substituted for the NPSHA and the above equation is solved for the maximum lift as:

$$L_{max} = P - e_s - S_F - F_L - NPSH_R = L_{pot} - F_L - NPSH_R$$

$$\text{where } L_{pot} = P - e_s - S_F$$

The potential theoretical lift (L_{pot}) depends on the altitude at the pumping site and the temperature of the water. Results in Table 9 lists the potential theoretical lift for a range of elevations above sea level and water temperatures. The values in Table 9 include a safety factor of 2 feet. If the pump shown in Figure 81 were installed at a location 2000 feet above sea level and the water temperature was 70 degrees then the potential theoretical list would be 30.7 feet. If the pump discharge is 1000 gpm then the maximum lift and the friction loss on the suction loss of the pump must be less than 20.7 feet since NPSHR is 10 feet.

Friction loss in the pipe and fittings on the suction side of the pump must be determined using the friction loss procedure described in the pipeline section of the handbook.

Table 9. Potential theoretical lift as a function of elevation and water temperature.

Elevation Above Sea Level, feet	Potential theoretical lift, feet							
	Water Temperature, F							
	45	50	55	60	65	70	75	80
0	33.6	33.5	33.4	33.3	33.2	33.1	32.9	32.7
500	33.0	32.9	32.8	32.7	32.6	32.5	32.3	32.1
1000	32.4	32.3	32.2	32.1	32.0	31.9	31.7	31.5
1500	31.8	31.7	31.6	31.5	31.4	31.3	31.1	31.0
2000	31.2	31.1	31.1	31.0	30.8	30.7	30.6	30.4
2500	30.6	30.6	30.5	30.4	30.3	30.1	30.0	29.8
3000	30.1	30.0	29.9	29.8	29.7	29.6	29.4	29.3
3500	29.5	29.5	29.4	29.3	29.2	29.0	28.9	28.7
4000	29.0	28.9	28.8	28.8	28.6	28.5	28.3	28.2
4500	28.5	28.4	28.3	28.2	28.1	28.0	27.8	27.6
5000	27.9	27.9	27.8	27.7	27.6	27.4	27.3	27.1
5500	27.4	27.4	27.3	27.2	27.1	26.9	26.8	26.6
6000	26.9	26.8	26.8	26.7	26.6	26.4	26.3	26.1
6500	26.4	26.3	26.3	26.2	26.1	25.9	25.8	25.6

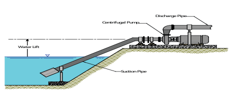


Figure 80. Typical centrifugal pumping plant that lifts water from a canal or reservoir.

Pump Size: 4 x 5 x 13 BH

Model: B4J_BH

Curve No. 9013

Type	CCMD	FM CPLG	FM BELT	SAE	Hydraulic	AC Engine
Model	B4JPBH	B4JRMBH	B4JRMBH	B4JQBH		

Nominal RPM: **1750**
Based on Fresh Water @ 68°F (20°C)
Maximum Working Pressure:266 PSI (18 BAR)

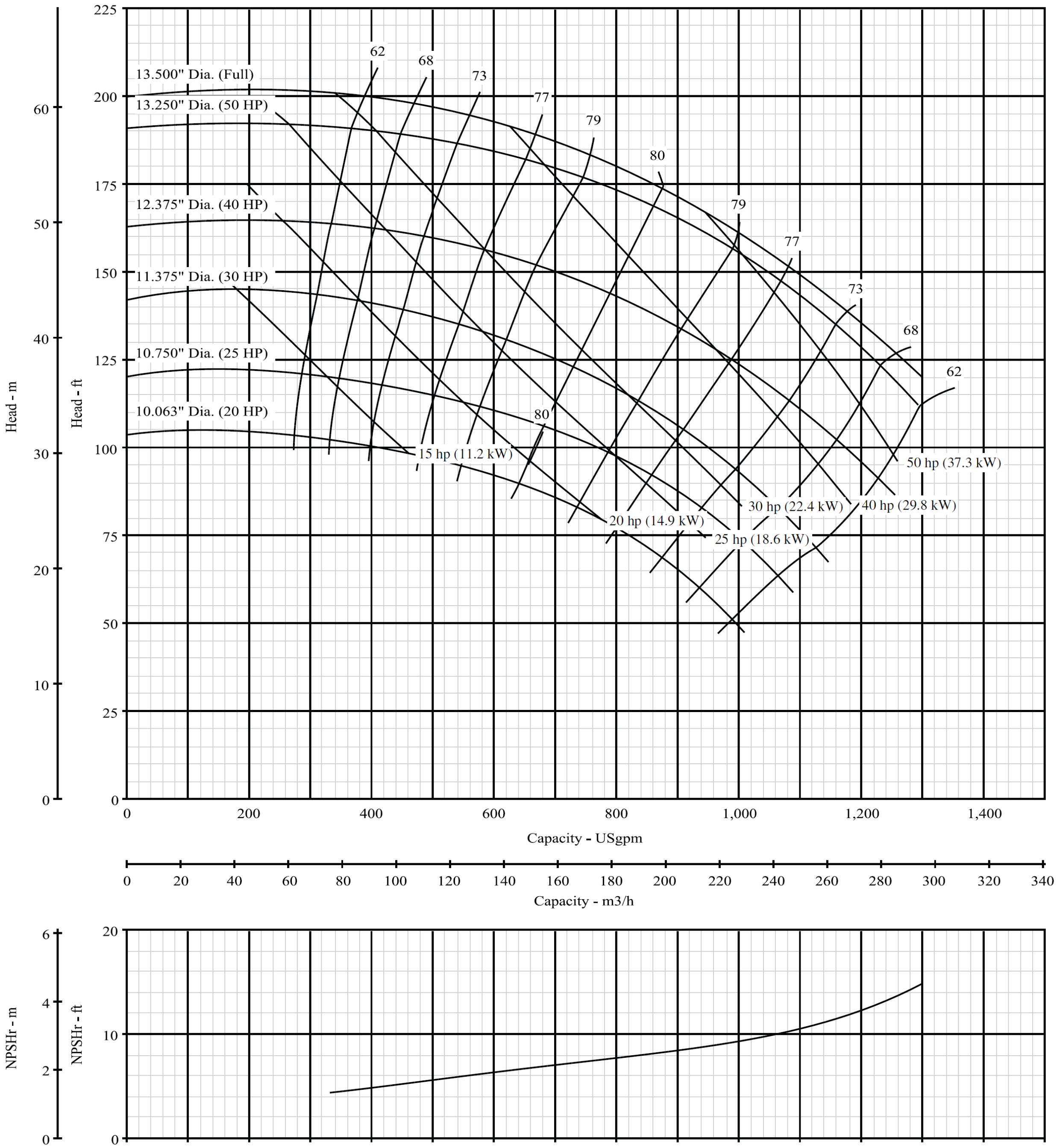


Figure 81. Example pump curve for a centrifugal pump showing net positive suction head (courtesy of Bekeley/Pentair Ltd.).

Chapter 6. Pipeline Systems

Various types of pipes are common for center pivot systems. Steel pipe is typical for pivot laterals, pivot risers, and other above ground components. Other types of pipes are also available depending on the corrosivity of the irrigation water. Steel, polyvinyl chloride plastic (PVC), polyethylene plastic (PE) or aluminum pipe are usually used for the mainline. Drop tubes for conveying water from the pivot lateral to individual sprinklers are frequently steel, PVC or PE pipe.

Many considerations enter into designing and managing pipelines that economically convey water from the pump to the center pivot inlet while protecting against pipe damage. This handbook focuses on assessing the pressure loss in the pipeline system to ensure proper conditions for efficient operation of the center pivot. Pipe performance depends on the characteristics of the pipe. Standard dimensions are used in manufacturing pipes to allow for interconnections and to provide adequate strength to avoid bursting during pressure surges when operating the irrigation system. The type of pipe affects the required thickness of the wall of the pipe for an upper limit of operating pressure. Pipes are often characterized by their outside diameter and the thickness of the wall of the pipe. This leads to the inside diameter of the pipe (Figure 82). Pipes that connect by inserting fittings into the pipe require a controlled inside diameter. In those cases, the outside diameter varies depending on the required wall thickness. The standard dimension ratio (SDR) is also used to characterize pipes. The SDR is the ratio of the outside diameter of the pipe relative to the thickness of the wall. Smaller SDR values represent thicker pipes that can withstand higher operating pressures.

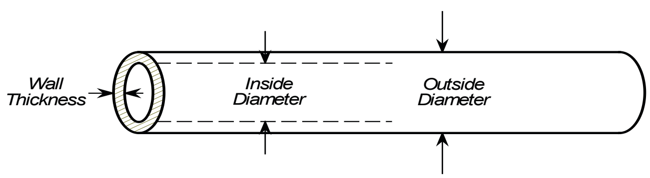


Figure 82. Pipe cross section.

PVC pipe is frequently used for mainlines. Two standards are used for PVC pipe, iron pipe sizes (IPS) and plastic irrigation pipe (PIP); thus pipes are labeled as PVC-IPS or PVC-PIP. The pipe diameter and the wall thickness determine the maximum operating pressure for the pipe. Therefore, pressure classes are used to further categorize PVC pipes. A pipe might be designated as Class 100 PVC-PIP which means that the pipe dimensions are represented by the plastic pipe criteria to withstand a maximum operating pressure of 100 psi. Pipes in a pressure class will have the same SDR. Standard dimensions, referred to as pipe schedules, have also been used for steel or plastic pipe. A common type of plastic and/or steel pipe has been Schedule 40 pipe that is sized according to iron pipe sizes.

Friction Loss

The viscosity of water and the drag of water along the walls of the pipe cause a loss of pressure as water flows through pipes. These factors act together to create a variation of water velocity in the pipe. Water near the wall of the pipe flows very slowly and the maximum velocity occurs in the center of the pipe. The pressure loss due to friction depends on the flow rate of water in the pipe, the inside diameter of the pipe and the roughness of the pipe. Higher flow rates result in higher water velocities in the pipe and increased friction loss. The viscosity of water depends on the temperature of the water, thus the friction loss also depends on the water temperature. However, temperature effects are smaller than the influence of flow rate, pipe diameter or pipe roughness; thus, friction loss charts are developed based on a standard temperature. Friction losses in the following charts are based on a standard temperature of 73.4 °F. Head loss decreases (increases) approximately 1% for every 3 degrees Fahrenheit above (below) the reference temperature (73.4°F). Values at the reference temperature are satisfactory for most applications.

Several approaches have been developed to compute the friction loss in pipelines. The irrigation industry often uses the Hazen-Williams equation to compute friction loss. The Hazen-Williams equation is given by:

$$P_f = 1054 \times \left(\frac{Q}{C}\right)^{1.852} \frac{1}{D^{4.866}}$$

where P_f is friction loss in pounds per square inch (psi) per 100 feet of pipe, Q is the flow of water in the pipe in gallons per minute (gpm), C is the roughness coefficient for the pipe, and D is the inside diameter of the pipe in inches.

The roughness coefficient (C) represents the roughness of the pipe. Smooth pipes, such as PVC, have high values for C, typically 150. Steel pipe is rougher and has smaller values roughness coefficients. The C value for 12-gauge galvanized steel pipe used for center pivot lateral varies from about 135 to 140. Typical values for the roughness coefficient for pipe materials used with center pivots are included in Table 10. The multiplier value listed in Table 10 can be used to compare the friction loss of the specific pipe to the loss for PVC pipe, which has a roughness coefficient (C) value of 150. For example, if the pipe dimensions were the same then the friction loss for aluminum pipe with couplers would be approximately 50% more than for PVC.

Table 10. Roughness coefficient (C) values for Hazen-Williams method.

Pipe Material	C Value	Multiplier
Aluminum pipe with couplers – 30 ft. pipes	120	1.51
Cement Asbestos pipe	140	1.14
Galvanized 12-gauge Steel Pivot Pipe	135	1.22
Galvanized Steel Pipe	100	2.12
Polyethylene Plastic Pipe	150	1.00
PVC Plastic Pipe	150	1.00
Steel – 15 years OLD	100	2.12
Steel – NEW	130	1.30
Cast Iron Pipe	100	2.12

The friction loss is sensitive to the flow in the pipe. Doubling the flow increases the friction loss by a factor of 3.6. The friction loss is very sensitive to the diameter of the pipe. The friction loss for the same flow for a pipe with an inside diameter of 4 inches is about 30 times the loss for an 8-inch pipe.

We also need to consider the velocity of water flow in the pipe. The average velocity of water can be computed as:

$$V = \frac{0.408 \times Q}{D^2}$$

where v is the velocity in feet per second, Q is the flow in gpm and D is the inside diameter in inches. The velocity of flow in the pipeline is important because pressure surges can occur in the pipeline when valves close quickly, the system is started or due to other changes that cause the water velocity to change rapidly. The surge pressure depends on the flow velocity. For example when a valve is quickly closed, a pressure surge occurs because water upstream of the valve continues to flow when the valve is first closed. The rapid change of water velocity in the pipe creates the pressure surge. The pipe walls initially absorb the pressure surge. If the pressure surge is too large, the pipe may burst. This is especially significant for plastic pipes. To avoid high-pressure surges the velocity of flow should be less than 5 feet per second for enclosed pipelines such as mainlines. The velocity should be less than 7 feet per second when the pipe is used for a sprinkler lateral where the pressure surge could be partially released through increased flow from nozzles.

A general estimate of the friction loss for plastic pipe with a Hazen-Williams roughness coefficient (C=150) can be made using Figure 83. For example, if the flow rate is 800 gallons per minute and the inside diameter of the pipe is 8 inches then the friction loss will be about 0.95 feet of pressure head per 100 feet of pipe. If the pipe were 1000 feet long then the friction loss would be 9.5 feet. The list of unit conversions in Appendix II shows that 1 foot of pressure head is equal to approximately 0.43 psi. Thus, the friction loss in pounds per square inch (psi) is about 0.41 psi per 100 feet (see values on the right side of Figure 83. Therefore, the pressure loss would be about 4.1 psi in the 1000-ft pipeline.

Figure 83 also includes lines that represent flow velocities of 5 feet per second, which is the practical upper limit for enclosed pipelines such as mainlines. The line for a velocity of 7 feet per second is also included in the figure. The velocity for 800 gallons per minute in a pipe with an inside diameter of 8 inches is about 5 feet per which is close to the velocity limit. Eight-inch pipe is just acceptable for a mainline if the flow is 800 gpm. Larger diameter pipelines should be used for flows larger than 800 gpm.

The friction loss for other types of pipe material can be estimated using the multipliers listed in Table 10. So for example, if aluminum pipe was used for the mainline to supply a pivot with an inflow of 800 gpm then the friction loss will be about 1.51 times that for PVC pipe shown in Figure 83. Thus, the friction loss would be about 14.3 feet for the 1000-ft pipeline or about 6.2 psi.

Results in Figure 83 are useful for general estimates. Analysis that is more detailed requires precise dimensions for a given pipe. Computation of the friction loss for the range of pipe materials available for conveyance requires a large number of figures and tables. Many sources have been developed for each type of pipe. One example is from the Irrigation Association at https://www.irrigation.org/uploadedFiles/PDF_Documents/IA_Friction_Loss_Charts.pdf. While these charts are very useful, a large number of charts are necessary to determine the pressure loss for all types of pipes used with center-pivot irrigation systems. To reduce the number of charts in this handbook we have referred the friction loss for specific PVC and polyethylene plastic pipe to the pressure loss for Schedule 40 PVC-IPS plastic pipe. The friction loss for the Schedule 40 PVC-IPS plastic pipe is shown in Table 11. Results in Table 11 show that conditions from the above example, i.e. 800 gpm flowing in an eight-inch diameter Schedule 40 PVC-IPS plastic pipe, would result in a friction loss is 0.423 psi per 100 feet of pipe and that the velocity just exceeds 5 feet per second. The variation from Figure 83 occurs because the inside diameter of Schedule 40 pipe is 7.942 inches which increases the velocity and friction loss compared to a diameter of 8 inches.

Table 12 includes data for other types of plastic pipe used for irrigation. The multipliers included in the table represent the friction loss for specific types of pipe because of the variation of the inside diameter for different pressure ratings. For example, the friction loss for 8-inch 100-psi PVC plastic irrigation pipe (PVC-PIP) is about 1.118 times the friction loss for schedule 40 PVC pipe. Therefore, the friction loss for 8-inch PVC-PIP pipe carrying 800 gpm would be about 0.47 psi per 100 feet of pipe (i.e. 0.423 × 1.118). The pressure loss for 1000 feet of pipe would be 4.7 psi versus 4.2 psi for the Schedule 40 PVC.

We have also included tables for the friction loss in Schedule 40 Steel pipe (Table 13), galvanized 12-gauge steel tubing (Table 14) and aluminum irrigation pipe with couplers (Table 15).

The values in Table 14 represent the friction loss for typical center pivot pipelines or laterals. So for example, the pressure loss for a flow of 800 gpm in a typical center pivot with a nominal pipe size of 6 ⅝ inches would be approximately 1.463 psi per 100 feet of pipe. Values in Table 14 should be multiplied by the appropriate multiplier for a center pivot lateral as noted in the last row in the table. Thus, the loss would be 0.54 × 1.463 = 0.79 psi per 100 feet if the end gun is not operating. If the pivot were 1300 feet long then the loss in the total lateral would be about 10. 3 psi (i.e. 0.79 per 100 feet × 1300 or just 0.79 ×13).

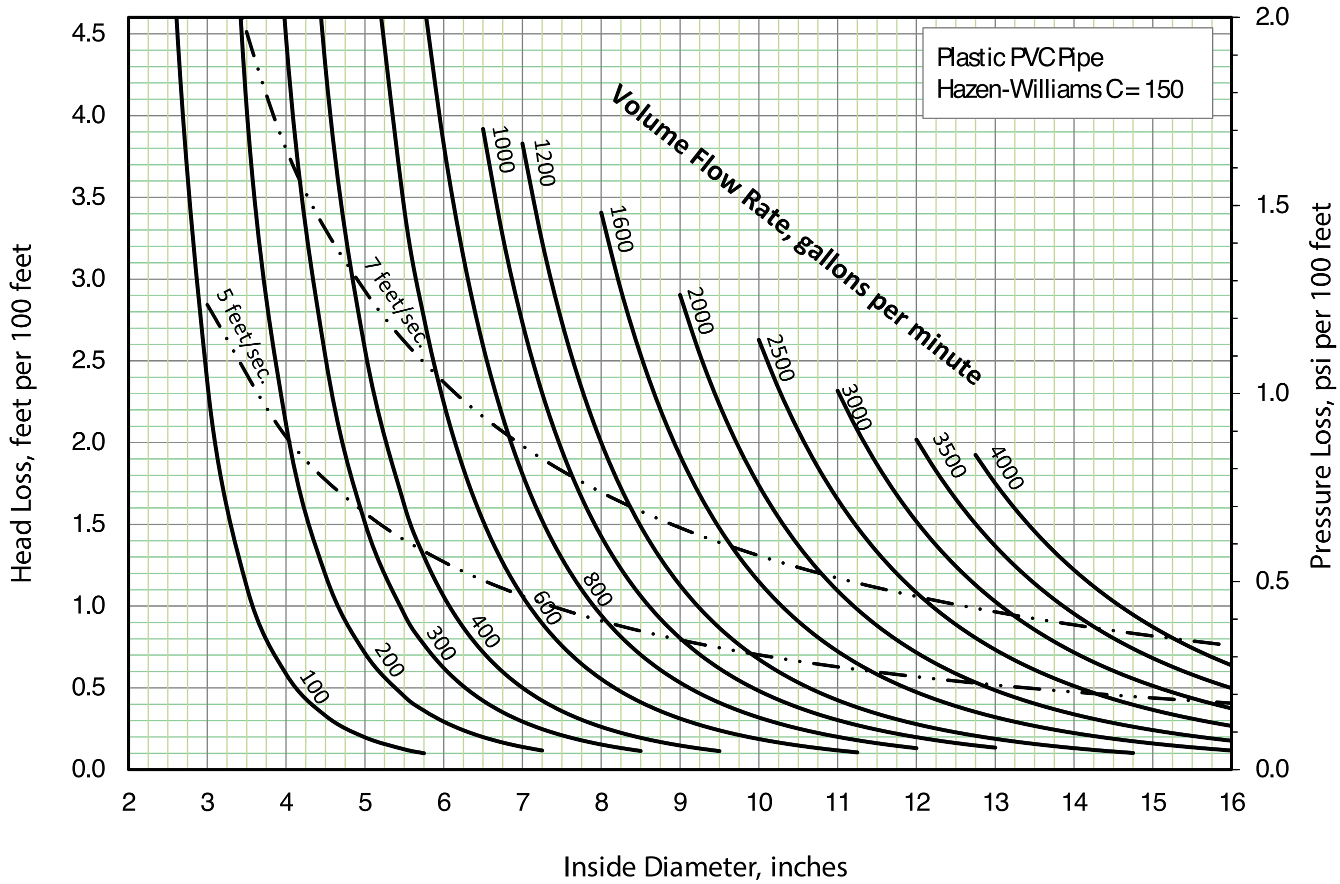


Figure 83. Friction loss for Schedule 40 PVC-IPS plastic pipe using the Hazen-Williams method.

Table 11. Friction loss for Schedule 40 PVC-IPS pipe (psi/100 feet of pipe) using C=150.

	Nominal Pipe Size, inches									
	3/4	1	1 1/4	1 1/2	2	2 1/2	3	3 1/2	4	5
Flow,	Inside Diameter, inches									
gpm	0.804	1.029	1.360	1.590	2.047	2.445	3.042	3.521	3.998	5.016
1	0.123	0.037								
2	0.444	0.134	0.034							
3	0.941	0.283	0.073	0.034						
4	1.604	0.483	0.124	0.058						
5	2.424	0.730	0.188	0.088	0.026					
6	3.398	1.023	0.263	0.123	0.036					
7	4.521	1.361	0.350	0.164	0.048	0.020				
8	5.789	1.742	0.449	0.210	0.061	0.026				
9	7.200	2.167	0.558	0.261	0.076	0.032				
10	8.751	2.634	0.678	0.317	0.093	0.039				
11	10.441	3.143	0.809	0.378	0.111	0.047				
12		3.692	0.950	0.444	0.130	0.055				
13		4.282	1.102	0.515	0.151	0.063	0.022			
14		4.912	1.264	0.591	0.173	0.073	0.025			
15		5.582	1.437	0.672	0.196	0.083	0.029			
16		6.290	1.619	0.757	0.221	0.093	0.032			
17		7.038	1.812	0.847	0.248	0.104	0.036			
18		7.824	2.014	0.942	0.275	0.116	0.040			
19			2.226	1.041	0.304	0.128	0.044	0.022		
20			2.448	1.144	0.335	0.141	0.049	0.024		
22			2.920	1.365	0.399	0.168	0.058	0.029		
24			3.431	1.604	0.469	0.198	0.068	0.034		
26			3.979	1.860	0.544	0.229	0.079	0.039	0.021	
28			4.564	2.134	0.624	0.263	0.091	0.045	0.024	
30			5.187	2.425	0.709	0.299	0.103	0.051	0.027	
32				2.733	0.799	0.337	0.116	0.057	0.031	
34				3.057	0.894	0.377	0.130	0.064	0.034	
36				3.399	0.994	0.419	0.145	0.071	0.038	
38				3.757	1.099	0.463	0.160	0.078	0.042	
40				4.131	1.208	0.509	0.176	0.086	0.047	
42				4.522	1.323	0.557	0.192	0.094	0.051	
44					1.442	0.607	0.210	0.103	0.055	
46					1.565	0.659	0.228	0.112	0.060	
48					1.694	0.713	0.246	0.121	0.065	0.022
50					1.827	0.769	0.266	0.130	0.070	0.023
55					2.179	0.918	0.317	0.156	0.084	0.028
60					2.560	1.079	0.373	0.183	0.099	0.033
65					2.969	1.251	0.432	0.212	0.114	0.038
70					3.406	1.435	0.496	0.243	0.131	0.043
80						1.837	0.635	0.312	0.168	0.056
90						2.285	0.789	0.387	0.209	0.069
100						2.778	0.959	0.471	0.254	0.084
110							1.145	0.562	0.303	0.100
120							1.345	0.660	0.356	0.118
130							1.560	0.766	0.413	0.137
140							1.789	0.878	0.473	0.157
150							2.033	0.998	0.538	0.178
175								1.328	0.715	0.237
200								1.700	0.916	0.304
225									1.140	0.378
250									1.385	0.459
300										0.644
350										0.857
400										1.097
450										

Shaded areas represent flow velocities between 5 and 7 feet per second. Flows for mainlines should be less than 5 feet/second or smaller than flows in the shaded areas.

Table 11 continued.

Flow, gpm	Nominal Pipe Size, inches									
	6	8	10	12	14	15†	16	18	20	24
	Inside Diameter, inches									
	6.031	7.942	9.976	11.889	13.073	14.082	14.940	16.809	18.743	22.544
100	0.034									
125	0.052									
150	0.073									
175	0.097	0.025								
200	0.124	0.032								
225	0.154	0.040								
250	0.187	0.049								
275	0.224	0.059								
300	0.263	0.069	0.023							
325	0.305	0.080	0.026							
350	0.349	0.092	0.030							
375	0.397	0.104	0.034							
400	0.447	0.117	0.039							
425	0.501	0.131	0.043							
450	0.556	0.146	0.048	0.020						
475	0.615	0.161	0.053	0.023						
500	0.676	0.177	0.058	0.025						
525	0.740	0.194	0.064	0.027						
550	0.807	0.211	0.070	0.030						
575	0.876	0.230	0.076	0.032	0.020					
600	0.948	0.248	0.082	0.035	0.022					
625		0.268	0.088	0.038	0.024					
650		0.288	0.095	0.040	0.025					
675		0.309	0.102	0.043	0.027					
700		0.330	0.109	0.046	0.029	0.020				
725		0.353	0.116	0.050	0.031	0.022				
750		0.376	0.124	0.053	0.033	0.023				
775		0.399	0.132	0.056	0.035	0.025				
800		0.423	0.140	0.059	0.037	0.026				
850		0.473	0.156	0.066	0.042	0.029	0.022			
900		0.526	0.174	0.074	0.047	0.032	0.024			
950		0.582	0.192	0.082	0.051	0.036	0.027			
1000		0.640	0.211	0.090	0.057	0.039	0.030			
1050		0.700	0.231	0.098	0.062	0.043	0.032			
1100			0.252	0.107	0.068	0.047	0.035			
1200			0.296	0.126	0.079	0.055	0.041	0.023		
1300			0.343	0.146	0.092	0.064	0.048	0.027		
1400			0.393	0.168	0.106	0.074	0.055	0.031		
1500			0.447	0.190	0.120	0.084	0.063	0.035	0.021	
1600			0.504	0.215	0.135	0.094	0.071	0.040	0.023	
1800				0.267	0.168	0.117	0.088	0.049	0.029	
2000				0.324	0.204	0.142	0.107	0.060	0.035	
2250				0.403	0.254	0.177	0.133	0.075	0.044	
2500					0.309	0.215	0.161	0.091	0.054	0.022
2750					0.368	0.257	0.192	0.108	0.064	0.026
3000						0.302	0.226	0.127	0.075	0.031
3250						0.350	0.262	0.148	0.087	0.035
3500							0.301	0.170	0.100	0.041
3750							0.342	0.193	0.113	0.046
4000								0.217	0.128	0.052
5000									0.193	0.079
6000									0.271	0.110
7000										0.147
8000										0.188
9000										

Shaded areas represent flow velocities between 5 and 7 feet per second. Flows for mainlines should be less than 5 feet/second or smaller than flows in the shaded areas.

†. 15-inch pipes is not typical for Schedule 40 PVC but is included for computing losses for other types of pipes.

Table 12. Multiplication factor to determine pressure loss for other types of plastic pipe.

	Type of Plastic Pipe										
	PVC-IPS						PVC-PIP				Polyethylene Inside Diameter Controlled
		63-psi	100-psi	125-psi	160-psi	200-psi	50-psi	80-psi	100-psi	125-psi	
		Standard Dimension Ratio					Standard Dimension Ratio				
Nominal Pipe Size, inches	Schedule 40	64	41	32.5	26	21	81	51	41	32.5	
3/4	1.000				0.547	0.547					0.887
1	1.000				0.524	0.538					0.911
1-1/4	1.000				0.597	0.658					0.931
1-1/2	1.000				0.656	0.722					0.941
2	1.000				0.748	0.826					0.954
2-1/2	1.000				0.695	0.768					0.954
3	1.000				0.770	0.849					0.959
4	1.000	0.671			0.850	0.944					0.967
6	1.000	0.751	0.821	0.879	0.958	1.064	1.035	1.115	1.170	1.272	
8	1.000	0.791	0.867	0.929	1.013	1.123	0.990	1.065	1.118	1.215	
10	1.000	0.819	0.900	0.966	1.051	1.166	1.014	1.090	1.145	1.249	
12	1.000	0.838	0.922	0.988	1.077	1.194	0.980	1.055	1.108	1.183	
14	1.000		0.930	0.994	1.083	1.202	0.735				
15	1.000						0.754	0.811	0.853	0.928	
16	1.000		0.930	0.995	1.083	1.203	0.808				
18	1.000		0.930	0.995	1.084	1.608	0.677	0.723	0.759	0.827	

Table 13. Friction loss for Schedule 40 steel pipe (psi/100 feet of pipe) (C=100).

	Nominal Pipe Size, inches							
	3/4	1	1 1/4	1 1/2	2	2 1/2	3	4
Flow,	Inside Diameter, inches							
gpm	0.824	1.049	1.38	1.61	2.067	2.469	3.068	4.026
1	0.231	0.071						
2	0.835	0.258	0.068	0.032				
3	1.770	0.547	0.144	0.068	0.020			
4		0.931	0.245	0.116	0.034			
5		1.408	0.371	0.175	0.052	0.022		
6		1.973	0.520	0.245	0.073	0.031		
7		2.625	0.691	0.327	0.097	0.041		
8			0.885	0.418	0.124	0.052		
9			1.101	0.520	0.154	0.065	0.023	
10			1.338	0.632	0.187	0.079	0.027	
11			1.597	0.754	0.224	0.094	0.033	
12			1.876	0.886	0.263	0.111	0.038	
13			2.175	1.028	0.305	0.128	0.045	
14			2.495	1.179	0.349	0.147	0.051	
15				1.339	0.397	0.167	0.058	
16				1.509	0.447	0.188	0.065	
17				1.689	0.501	0.211	0.073	
18				1.877	0.557	0.234	0.081	0.022
19				2.075	0.615	0.259	0.090	0.024
20				2.282	0.676	0.285	0.099	0.026
22				2.722	0.807	0.340	0.118	0.031
24					0.948	0.399	0.139	0.037
26					1.100	0.463	0.161	0.043
28					1.261	0.531	0.185	0.049
30					1.433	0.604	0.210	0.056
32					1.615	0.680	0.236	0.063
34					1.807	0.761	0.265	0.070
36					2.009	0.846	0.294	0.078
38					2.221	0.935	0.325	0.087
40					2.442	1.028	0.357	0.095
42					2.673	1.126	0.391	0.104
44						1.227	0.426	0.114
46						1.332	0.463	0.123
48						1.442	0.501	0.134
50						1.555	0.540	0.144
55						1.855	0.645	0.172
60						2.179	0.757	0.202
65						2.527	0.878	0.234
70							1.008	0.269
75							1.145	0.305
80							1.290	0.344
90							1.605	0.428
100							1.950	0.520
110							2.327	0.620
120							2.734	0.729
130								0.845
140								0.969
150								1.101
160								1.241
170								1.389
180								1.544
190								1.707
200								1.877
220								2.239
240								2.630

Table 14. Friction loss for galvanized 12-gauge steel pipe (psi/100 feet of pipe) (C=135).

	Nominal Pipe Size, inches						
	4"	5"	6"	6 5/8"	8"	8 5/8"	10"
Flow,	Inside Diameter, inches						
gpm	3.782	4.782	5.782	6.407	7.782	8.407	9.782
50	0.112	0.036					
60	0.157	0.050					
70	0.209	0.067	0.026				
80	0.267	0.085	0.034	0.021			
90	0.333	0.106	0.042	0.026			
100	0.404	0.129	0.051	0.031			
110	0.482	0.154	0.061	0.037			
120	0.567	0.181	0.072	0.044			
130	0.657	0.210	0.083	0.051			
140	0.754	0.241	0.096	0.058	0.023		
150	0.856	0.273	0.109	0.066	0.026		
160	0.965	0.308	0.122	0.074	0.029		
170	1.080	0.345	0.137	0.083	0.032	0.022	
180	1.201	0.383	0.152	0.092	0.036	0.025	
190	1.327	0.424	0.168	0.102	0.040	0.027	
200	1.459	0.466	0.185	0.112	0.044	0.030	
220	1.741	0.556	0.221	0.134	0.052	0.036	
240	2.045	0.653	0.259	0.157	0.061	0.042	0.020
260	2.372	0.757	0.301	0.182	0.071	0.049	0.023
280		0.869	0.345	0.209	0.081	0.056	0.027
300		0.987	0.392	0.238	0.092	0.063	0.030
320		1.113	0.442	0.268	0.104	0.071	0.034
340		1.245	0.494	0.300	0.116	0.080	0.038
360		1.384	0.549	0.333	0.129	0.089	0.043
380		1.530	0.607	0.368	0.143	0.098	0.047
400		1.682	0.668	0.405	0.157	0.108	0.052
420		1.841	0.731	0.443	0.172	0.118	0.057
440		2.007	0.797	0.483	0.188	0.129	0.062
460		2.179	0.865	0.525	0.204	0.140	0.067
480		2.358	0.936	0.568	0.220	0.151	0.072
500			1.009	0.613	0.238	0.163	0.078
550			1.204	0.731	0.284	0.195	0.093
600			1.415	0.859	0.333	0.229	0.110
650			1.641	0.996	0.387	0.265	0.127
700			1.882	1.142	0.443	0.305	0.146
750			2.139	1.298	0.504	0.346	0.166
800			2.410	1.463	0.568	0.390	0.187
850				1.636	0.635	0.436	0.209
900				1.819	0.706	0.485	0.232
950				2.011	0.781	0.536	0.257
1000				2.211	0.859	0.590	0.282
1100					1.024	0.703	0.337
1200					1.203	0.826	0.395
1300					1.396	0.958	0.459
1400					1.601	1.099	0.526
1500					1.819	1.249	0.598
1600					2.050	1.408	0.674
1800						1.751	0.838
2000						2.128	1.018
2200							1.215
2400							1.427
2600							1.655
2800							1.899
3000							2.158

Multiply values in this table by 0.54 for center pivot laterals when there is no end gun or the end gun is off. Multiply by 0.56 when water is flowing from the end gun.

Table 15. Friction loss for aluminum irrigation pipe with couplers 30 feet apart (psi/100 ft. of pipe) .

Flow, gpm	Nominal Pipe Size, inches						
	4	5	6	7	8	10	12
	Inside Diameter, inches						
	3.906	4.896	5.884	6.872	7.856	9.918	11.818
100	0.396	0.131	0.053	0.025			
110	0.474	0.157	0.064	0.030			
120	0.560	0.185	0.075	0.035			
130	0.652	0.215	0.088	0.041	0.021		
140	0.750	0.248	0.101	0.047	0.024		
150	0.855	0.283	0.115	0.054	0.028		
160	0.967	0.320	0.130	0.061	0.032		
170	1.085	0.359	0.146	0.068	0.035		
180	1.209	0.400	0.162	0.076	0.039		
190	1.340	0.443	0.180	0.084	0.044		
200	1.477	0.488	0.198	0.093	0.048		
210	1.621	0.536	0.218	0.102	0.053		
220	1.771	0.585	0.238	0.111	0.058		
230	1.927	0.637	0.259	0.121	0.063	0.020	
240	2.089	0.691	0.281	0.131	0.068	0.022	
250	2.258	0.746	0.303	0.142	0.074	0.023	
260	2.432	0.804	0.327	0.153	0.079	0.025	
270	2.613	0.864	0.351	0.164	0.085	0.027	
280	2.800	0.926	0.376	0.176	0.091	0.029	
290		0.989	0.402	0.188	0.098	0.031	
300		1.055	0.429	0.200	0.104	0.033	
350		1.414	0.575	0.269	0.139	0.044	
400		1.823	0.741	0.346	0.180	0.057	0.024
450		2.280	0.926	0.433	0.225	0.072	0.030
500		2.785	1.132	0.529	0.275	0.088	0.037
550			1.356	0.634	0.329	0.105	0.044
600			1.600	0.748	0.388	0.124	0.052
650			1.863	0.871	0.452	0.144	0.061
700			2.144	1.002	0.520	0.166	0.070
750			2.445	1.143	0.593	0.189	0.080
800			2.764	1.292	0.671	0.214	0.091
850				1.450	0.752	0.240	0.102
900				1.616	0.839	0.268	0.113
950				1.791	0.929	0.297	0.126
1000				1.974	1.025	0.327	0.139
1100				2.366	1.228	0.392	0.166
1200				2.791	1.449	0.462	0.196
1300					1.687	0.538	0.228
1400					1.942	0.620	0.263
1500					2.214	0.707	0.299
1600					2.503	0.799	0.338
1700						0.896	0.380
1800						0.999	0.423
1900						1.107	0.469
2000						1.220	0.517
2200						1.463	0.620
2400						1.726	0.731
2600						2.009	0.851
2800						2.313	0.980
3000						2.637	1.117
3200							1.263
3400							1.417
3600							1.580
3800							1.750
4000							1.930

Increase friction loss by 7% for lengths of pipe that are 20 feet long and decrease by 3% for pipe sections that are 40 feet long.

Minor Losses

Pressure is also lost when the direction of water flow changes such as through an elbow or tee or when fittings are included in the pipeline such as valves. To account for these losses we use a resistance (K) factor times the velocity head for flow in the pipeline:

$$H_m = K \times H_v$$

where H_m is the friction loss in the fitting in units of feet, K is the resistance coefficient and H_v is the velocity head in feet for the flow in the pipe line. Values for the velocity head for a range of flow rates and pipe diameters are given in Table 16, while resistance coefficients for pipe fittings are included in Table 17. For example, if the 8-inch pipeline had a flow of 800 gpm and included a 90° flanged elbow then the velocity head would be 0.40 (Table 16) and the resistance coefficient would be 0.26 (from Table 17). Therefore, the friction loss for the elbow would be $Hm = 0.26 \times 0.4 = 0.1$ feet. Remember that 2.31 feet of head is equal to 1 psi so the friction loss would be very small at 0.043 psi. If a swinging check valve were included for chemigation protection, then the resistance coefficient would be 2 and the minor head loss would be $2 \times 0.4 = 0.8$ feet or 0.35 psi. It is often more convenient to compute a total resistance coefficient for all the fittings of one size and then multiply by the velocity head. For example, if the pipeline included two 90° flanged elbows and the swinging check vale the total resistance coefficient would be $2 \times 0.26 + 2 = 2.52$. Therefore, the overall friction loss for all of the fittings would be $2.52 \times 0.4 = 1.08$ feet or 0.44 psi.

The friction loss for fittings is often not a large number and can often be ignored for hydraulic calculations for center-pivot irrigation systems. Resistance values for some fittings, such as globe valves and sudden enlargements, are much larger and should be carefully considered. Two places were friction loss for fittings is important is for drop tubes used to suspend sprinkler devices below the pivot lateral closer or into the crop. The other instance where minor losses are critical is in computing the maximum distance water can be lifted from a pond or canal using centrifugal pumps. In each case, care should be taken for minor losses.

Table 16. Velocity head in circular pipes flowing full, feet.

Flow Rate, gpm	Inside Diameter of Pipe, inches												
	3/4	1	1 1/4	1 1/2	2	3	4	5	6	8	10	12	16
1													
2	0.03	0.01											
3	0.07	0.02											
4	0.13	0.04	0.02										
5	0.20	0.06	0.03	0.01									
7.5	0.46	0.15	0.06	0.03									
10		0.26	0.11	0.05	0.02								
15		0.58	0.24	0.11	0.04								
20			0.42	0.20	0.06	0.01							
30				0.46	0.15	0.03							
40					0.26	0.05	0.02						
50					0.40	0.08	0.03	0.01					
60					0.58	0.11	0.04	0.01					
70						0.16	0.05	0.02					
80						0.20	0.06	0.03	0.01				
90						0.26	0.08	0.03	0.02				
100						0.32	0.10	0.04	0.02				
125						0.50	0.16	0.06	0.03				
150						0.72	0.23	0.09	0.04	0.01			
175							0.31	0.13	0.06	0.02			
200							0.40	0.17	0.08	0.03	0.01		
225							0.51	0.21	0.10	0.03	0.01		
250							0.63	0.26	0.12	0.04	0.02		
300								0.37	0.18	0.06	0.02	0.01	
350								0.51	0.24	0.08	0.03	0.02	
400								0.66	0.32	0.10	0.04	0.02	
450									0.40	0.13	0.05	0.03	
500									0.50	0.16	0.06	0.03	
550									0.60	0.19	0.08	0.04	0.01
600									0.72	0.23	0.09	0.04	0.01
650										0.27	0.11	0.05	0.02
700										0.31	0.13	0.06	0.02
750										0.35	0.15	0.07	0.02
800										0.40	0.17	0.08	0.03
850										0.46	0.19	0.09	0.03
900										0.51	0.21	0.10	0.03
950										0.57	0.23	0.11	0.04
1000										0.63	0.26	0.12	0.04
1100											0.31	0.15	0.05
1200											0.37	0.18	0.06
1300											0.44	0.21	0.07
1400											0.51	0.24	0.08
1500											0.58	0.28	0.09
1600											0.66	0.32	0.10

Values in the shaded cells are between 5 and 7 feet per second

Table 17. Resistance coefficients for fittings (adapted from ftp://ftp.wcc.nrcs.usda.gov/wntsc/waterMgt/irrigation/NEH15/ch11.pdf.

	Pipe Diameter, inches						
Fitting or valve	3	4	5	6	7	8	10
Elbows:							
Regular flanged 90°	0.34	0.31	0.30	0.28	0.27	0.26	0.25
Long radius flanged 90"	0.25	0.22	0.20	0.18	0.17	0.15	0.14
Long radius flanged 45"	0.19	0.18	0.18	0.17	0.17	0.17	0.16
Regular screwed 90	0.80	0.70					
Long radius screwed 90	0.30	0.23					
Regular screwed 45	0.30	0.28					
Bends:							
Return flanged	0.33	0.30	0.29	0.28	0.27	0.25	0.24
Return screwed	0.80	0.70					
Tees;							
Flanged line flow	0.16	0.14	0.13	0.12	0.11	0.10	0.09
Flanged branch flow	0.73	0.68	0.65	0.60	0.58	0.56	0.52
Screwed line flow	0.90	0.90					
Screwed branch flow	1.20	1.10					
Valves:							
Globe flanged	7.00	6.30	6.00	5,8	5.70	5.60	5.50
Gate flanged	6.00	5.70					
Gate screwed	0.21	0.16	0.13	0.11	0.09	0.08	0.06
Gate screwed	0.14	0.12					
Swing check flanged	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Swing check screwed	2.10	2.00					
Angle flanged	2.20	2.10	2.00	2.00	2.00	2.00	2.00
Angle screwed	1.30	1.00					
Foot	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Strainers-basket	1.25	1.05	0.95	0.85	0.80	0.75	0.67
Inlets or entrances:							
Inward projecting	0.78						
Sharp cornered	0.50						
Slightly rounded	0.23						
Bell-mouth	0.04						
Sudden Enlargements:	Downstream Diameter, inches						
Upstream Diameter, inches	3	4	5	6	7	8	10
3		0.60	3.16	9.00	19.75	37.35	102.23
4			0.32	1.56	4.25	9.00	27.56
5				0.19	0.92	2.43	9.00
6					0.13	0.60	3.16
7						0.09	1.08
8							0.32
Sudden Contraction:	Downstream Diameter, inches						
Upstream Diameter, inches	3	4	5	6	7	8	10
3							
4	0.13						
5	0.29	0.09					
6	0.39	0.22	0.07				
7	0.47	0.32	0.17	0.05			
8	0.52	0.39	0.26	0.13	0.04		

Pressure Calculation Example

A frequent application of friction loss calculations is for determining the difference in pressure from the pump discharge to the pivot inlet as shown in Figure 84. We may know the pressure at one location or the other and need to estimate the pressure at the other location. When computing the pressure difference one must take into account the friction losses and the difference in elevation between the two locations:

$$P_2 = P_1 - F_L - 0.433 \times (H_m + E_i + R_h)$$

where P_1 is the upstream pressure (i.e., at the pump discharge), P_2 is the pressure at the downstream location (i.e., the pivot inlet), F_L is the friction loss in the pipeline, H_m is the head loss in the fittings, E_i is the increase in elevation between the two locations (if the second point is below the first location then the elevation increase will be a negative number) and R_h is the height of the pivot riser.

Suppose that the pressure at the pump discharge for the system shown in Figure 84 is 70 psi and that the flow in the system is 800 gpm. The friction loss for the PVC-PIP pipe is determined from Table 11 and 12 (0.423 psi/100 feet × 1.215 × 1500 feet) to be $F_L = 7.7$ psi. We need to add the pressure loss in the two Z pipes that are about 30 feet long in total. The friction loss in the Z pipes is about 0.568 psi per 100 feet × 30 feet = 0.17 psi. The velocity head is 0.4 feet for 800 gallons per minute in an eight-inch pipeline. The total resistance coefficient equals 4 × 0.17 + 2 × 0.26 = 1.72 for four 45° elbows and two 90° elbows. Note that the swinging check valve is not included because it is upstream of the discharge pressure measurement. Finally, the pivot inlet is about 25 feet above the pump elevation and the pivot riser is 12 feet high. The pressure at the pivot inlet is then about:

$$P_2 = 70 - (7.7 + 0.17) - 0.433 \times (1.72 + 25 + 12) = 45 \text{ psi}$$

The friction loss in a 6 ⅝ inch center-pivot lateral for a flow of 800 gpm is determined from Table 14 as 0.54 × 1.463 psi per 100 feet × 1300 foot lateral = 10.3 psi. Thus the pressure at the distal end of the lateral will be about 35 psi when the pivot is oriented due north since the elevation at the end of the pivot would be about 1825 feet which is the same at the pivot point. The pressure at the distal end of the lateral would be higher when the pivot is oriented toward the northwest near the well. At that angle the elevation is about 1800 feet so the pressure would increase by 0.433 × 25 feet = 10.8 psi so the pressure in the lateral would be about 56 psi.

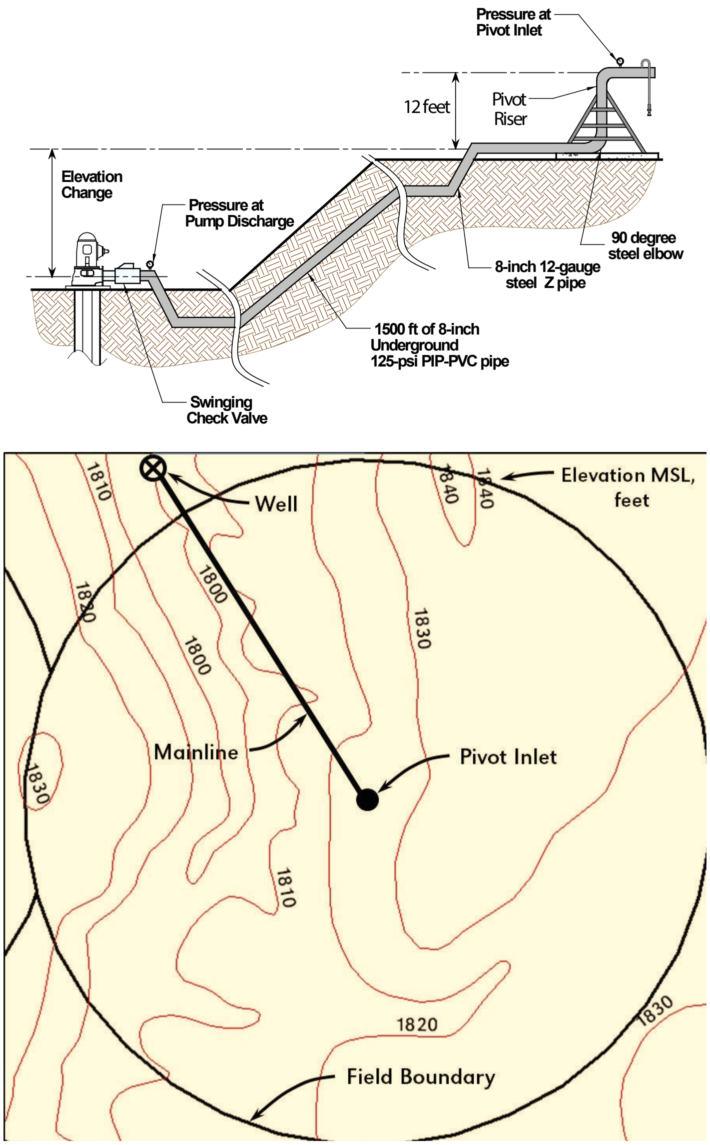


Figure 84. Example of piping system and topographic map for a center-pivot system in Central NE (topographic map from Web Soil Survey).

Chapter 7. Energy Use in Irrigation

Irrigation accounts for a large portion of the energy used in Nebraska agriculture. Analysis of data from the 2012 USDA Farm and Ranch Irrigation Survey shows that the average energy use for irrigating crops in Nebraska would be equivalent to about 350 million gallons of diesel fuel annually if all pumps were powered with diesel engines. While use varies depending on annual precipitation, average yearly energy consumption is equivalent to about 40 gallons of diesel fuel per acre irrigated. The cost for energy is significant for producers. Maintaining a well designed pumping plant and center pivot system, and periodic evaluations can help minimize pumping costs.

The cost to irrigate a field is determined by the amount of water pumped and the cost to apply a unit (acre-inch) of water (Figure 85). Factors that determine pumping costs include those that are fixed for a given location (in the ovals in Figure 85) and those that producers can influence. The factors that producers can influence include: irrigation scheduling, application efficiency, efficiency of the pumping plant, and the pumping pressure required for center pivot system. Pumping costs can be minimized by concentrating on these factors. Irrigators may also consider changing the type of energy used to power irrigation if they determine that one source provides a long-term advantage.

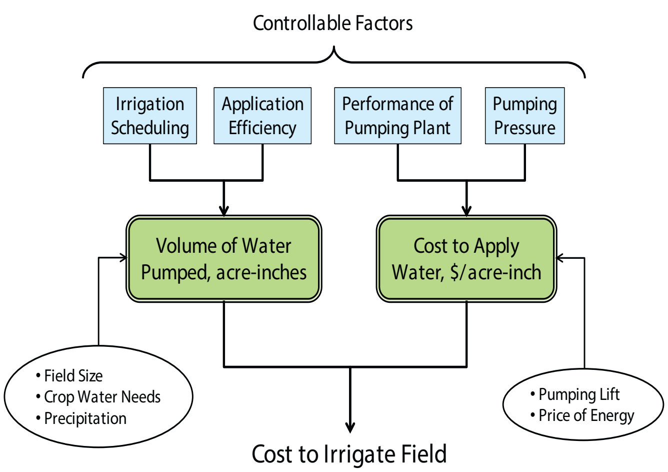


Figure 85. Diagram of factors affecting irrigation pumping costs.

Irrigation scheduling can minimize the total volume of water applied to the field. Demonstration projects over time have indicated that 1.5-2.0 inches of water can be saved by monitoring soil water and estimating crop water use rates. The goal is to maximize use of stored soil water and precipitation to minimize pumping.

Improving the efficiency of water application is a second way to conserve energy. Water application efficiency is a comparison between the depth of water pumped and the depth stored in the soil where it is available to the crop. Irrigation systems can lose water to evaporation in the air or directly off plant foliage. Water is also lost at the soil surface as evaporation or runoff. Excess irrigation and/or rainfall may also percolate through the crop root zone leading to deep percolation. For center pivots, water application efficiency is based largely on the sprinkler package. High pressure impact sprinklers direct water upward into the air and thus there is more opportunity for wind drift and in-air evaporation. In addition, high pressure impact sprinklers apply water to foliage for 20-40 minutes longer than low pressure spray heads mounted on drop tubes. The difference in application time results in less evaporation directly from the foliage for low pressure spray systems. Caution should be used so that surface runoff does not result with a sprinkler package. Good irrigation scheduling should minimize deep percolation.

Energy use can also be reduced by lowering the operating pressure of the irrigation system. One must keep in mind that lowering the operating pressure will reduce pumping cost per acre-inch, but reducing the pressure almost always results in an increased water application rate for a center pivot. The key is to ensure that the operating pressure is sufficient to eliminate the potential for surface runoff. Field soil characteristics, surface roughness, slope and tillage combine to control how fast water can be applied to the soil surface before runoff occurs. If water moves from the point of application, the savings in energy resulting from a reduction in operating pressure is counterbalanced by the need to pump more water to ensure that all portions of the field receive at least the desired amount of water.

Finally, energy can be conserved by ensuring that the pumping plant is operating as efficiently as possible. Efficient pumping plants require properly matched pumps, systems and power sources. By keeping good records of the amount of water pumped and the energy used, you can discover if extra money is being spent on pumping the water and how much you can afford to spend to fix components that are responsible for increased costs.

This document describes a method to estimate the cost of pumping water and to compare the amount of energy used to that for a well maintained and designed pumping plant. The results can help determine the feasibility of repairing the pumping plant. Methods to compare energy sources are also presented.

Energy Requirements

The cost to pump irrigation water depends on the type of energy used to power the pumping unit. Electricity and diesel fuel are used to power irrigation for about 85% of the land irrigated in Nebraska (Figure 86). Propane and natural gas are used on about 4 and 11% of the land respectively. Very little land is irrigated with gasoline powered engines.

The cost to pump an acre-inch of water depends on the:

- Work produced per unit of energy consumed,
- Distance water is lifted from the groundwater aquifer or surface water source,
- Discharge pressure at the pump,
- Performance rating of the pumping plant, and
- Cost of a unit of energy.

The amount of work produced per unit of energy depends on the source used to power the pump (Table 18). One gallon of diesel fuel will generate about 139,000 BTU of energy if completely burned. The energy content can also be expressed as the horsepower-hours of energy per gallon of fuel (i.e., 54.5 hp-hr/gallon). Not all of the energy contained in the fuel can be converted to productive work when the fuel is burned in an engine. The Nebraska Pumping Plant Performance Criteria was developed to provide an estimate of the amount of work that can be obtained from a unit of energy by a well designed and managed pumping plant (Table 18). Values were developed from testing engines and motors to determine how much work (expressed as horsepower-hours) could be expected from a unit of energy. An average efficiency for the pump and drive system for well designed and maintained pumping plants was used to provide the amount of work that could be expected from a “good” pumping plant. The overall performance of the engine/motor and pump system is expressed as water horsepower hours (whp-hr).

Research conducted to develop the Nebraska Pumping Plant Criteria showed that diesel engines produced about 16.7 hp-hr of work per gallons of diesel and that good pumping plants would produce about 12.5 whp-hr/gallon of diesel fuel. The performance of the engine and pumping plant systems can also be expressed as an efficiency, i.e., the ratio of the work done compared to the energy available in the fuel. Results show that a diesel engine that meets the Nebraska Pumping Plant Criteria is only about 30% efficient and that the overall efficiency is only about 23%. Diesel engines are more efficient than spark engines (Table 18).

The amount of energy required for a specific system depends on the location of the water source relative to the elevation of the pump discharge. For groundwater the pumping lift depends on the distance from the pump base to the water level when not pumping (static water level) plus the groundwater drawdown as shown in Figure 87. Note that the lift is not the depth of the well or the depth that the pump bowls are located in the well. The lift may increase over time if groundwater levels decline during the summer or over the years. It is best to measure the pumping lift directly but the value can be estimated from well registration information for initial estimates.

The discharge pressure depends on the pressure needed for the irrigation system, the elevation of the inlet to the irrigation system relative to the pump discharge, and the pressure loss due to friction in the piping between the pump and the irrigation system. It is best to measure the discharge pressure with a good gauge near the pump base.

Table 18. Energy content of fuels for powering irrigation engines‡

Energy Source	Average Energy Content		Nebraska Pump Plant Criteria		Engine or Motor Efficiency, %	Pumping Plant Conversion, %
	BTU	horsepower hour	Engine or Motor Performance, hp-hr/unit	Pumping Plant Performance, whp-hr/unit†		
1 gallon of diesel fuel	138,690	54.5	16.7	12.5	31	23
1 gallon of gasoline	125,000	49.1	11.5	8.66	23	18
1 gallon of liquefied petroleum gas (LPG)	95,475	37.5	9.20	6.89	25	18
1 thousand cubic foot of natural gas	1,020,000	401	82.2	61.7	21	15
1 therm of natural gas	100,000	39.3	8.06	6.05	21	15
1 gallon of ethanol #	84,400	33.2	7.80	5.85	X	X
1 gallon of gasohol (10% ethanol, 90% gasoline)	120,000	47.2	11.08	8.31	X	X
1 kilowatt-hour of electrical energy	3,412	1.34	1.18	0.885	88	66

‡ Conversions: 1 horsepower = 0.746 kilowatts, 1 kilowatt-hour = 3412 BTU, 1 horsepower-hour = 2,544 BTU

† Assumes an overall efficiency of 75% for the pump and drive.

Nebraska Pumping Plant Criteria for fuels containing ethanol were estimated based on the BTU content of ethanol and the performance of gasoline engines.

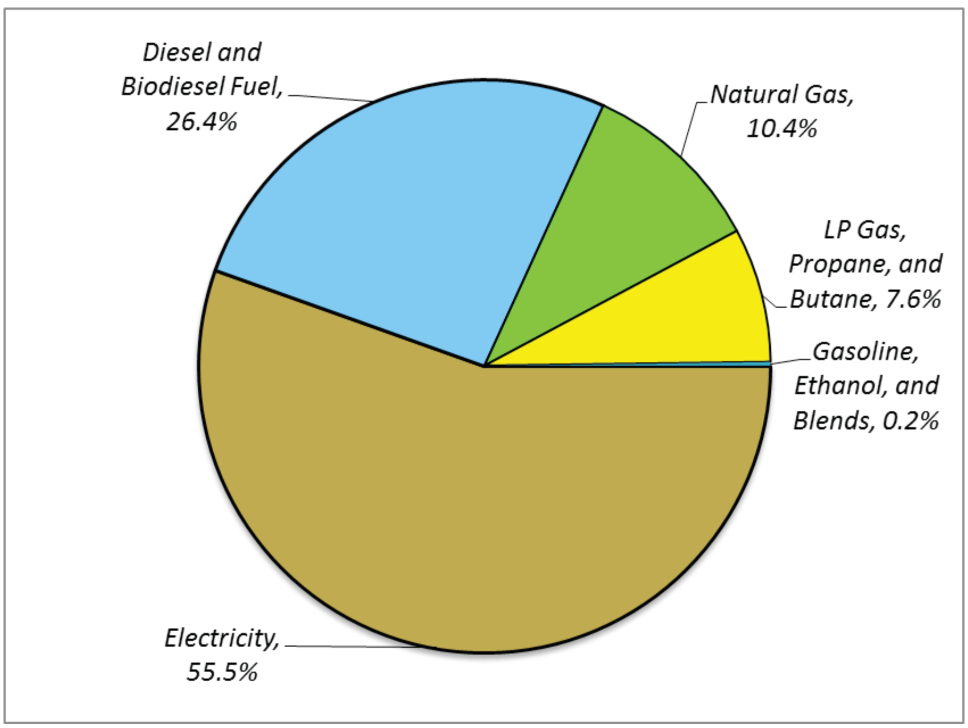


Figure 86. Percent of land irrigated in Nebraska by energy source (from USDA Farm and Ranch Irrigation Survey, 2013).

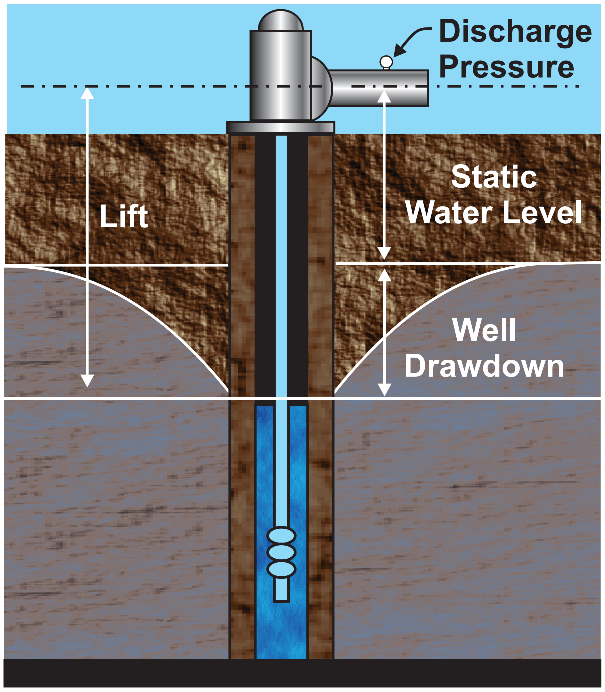


Figure 87. Factors required for evaluating pumping plant performance.

Pumping Plant Efficiency

The amount of energy required for a properly designed and maintained pumping plant to pump an acre-inch of water can be determined from Tables 20 and 21. For example, a producer who has a system with a pumping lift of 150 feet and operates at a pump discharge pressure of 60 pounds per square inch (psi) would require 2.63 gallons of diesel fuel to apply an acre-inch of water. If the producer uses electricity the value of 2.63 should be multiplied by the factor in Table 21 to convert energy units. So, for electricity (2.63 x 14.12) = 37 kilowatt-hours would be needed per acre inch of water.

The amount of energy required for an actual pump depends on the efficiency of the pump and power unit. If the pumping plant is not properly maintained and operated, or if conditions have changed since the system was installed, the pumping plant may not operate as efficiently as listed in Table 20. The energy needed for an actual system is accounted for in the performance rating of the pumping plant. Table 22 can be used to determine the impact of a performance rating less that 100%. For a performance rating of 80% the multiplier is 1.25, so the amount of energy used would be 25% more than for a system operating as shown in Table 20. The amount of diesel fuel for the previous example would be (2.63 x 1.25) = 3.29 gallons per acre-inch of water.

Producers can use Tables 20-22 and their energy records to estimate the performance rating for their pumping plant and the amount of energy that could be saved if the pumping plant was repaired or if operation was adjusted to better match characteristics of the pump and power unit.

Producers can also use hourly performance to estimate how well their pumping plant is working. For the hourly assessment an estimate of the pumping lift, discharge pressure, flow rate from the well and the hourly rate of energy consumption are required. The acre-inches of water pumped per hour can be determined from in Table 23.

The performance of the pumping plant (Pp) in terms of energy use per acre-inch of water is then the ratio of the hourly energy use divided by the volume of water pumped per hour:

$$P_p = \frac{\text{hourly fuel use rate (gallons / hour)}}{V \text{ (acre-inches / hour)}}$$

For example, suppose a pump supplies 800 gallons per minute and the diesel engine burns 5.5 gallons of diesel fuel per hour. A flow rate of 800 gpm is equivalent to 1.77 acre-inches per hour (Table 23). The pumping plant performance is computed as 5.5 gallons of diesel per hour divided by 1.77 acre-inches of water per hour. This gives 3.11 gallons of diesel per acre-inch.

Suppose that the pumping lift is 150 feet and the discharge pressure is 60 psi for this example. If the system operates at the Nebraska Pumping Plant Performance Criteria only 2.63 gallons of diesel per acre-inch would be required (Table 20). The pumping plant performance rating (R) would be:

$$R = \frac{100 \times \text{Value from Table 2}}{P_p} = \frac{100 \times 2.63}{3.11}$$

For this case the performance rating is 85 meaning that the system uses about 17% more diesel fuel than required for a system at the Nebraska Criteria. The multipliers in Table 22 can also be used with the hourly method for other energy sources.

Paying for Repairs

Energy savings from repairing the pumping plant should be compared to the ability to pay for the repairs. The money that can be paid for repairs is determined by the length of the repayment period and the annual interest rate. These values are used to compute the series present worth factor (Table 24). The breakeven investment is the value of the annual energy savings times the series present worth factor.

The series present worth factor represents the amount of money that could be repaid at the specified interest rate over the repayment period. For example, for an interest rate of 7% and a repayment period of 10 years each dollar of annual savings is equivalent to $7.02 today. Only $4.10 could be invested for each dollar of savings if the investment was to be repaid in 5 years rather than 10 years.

Table 19. Amount of work produced per unit of energy used for a well designed and maintained pumping plant.

Energy Source	Value	Work Per Unit of Energy Use
Diesel	12.5	whp-hours / gallon
Gasoline	8.66	whp-hours / gallon
Propane	6.89	whp-hours / gallon
Natural Gas	61.7	whp-hours / 1000 ft^3
Electricity	0.885	whp-hours / kilowatt hour
whp stands for water horsepower		

Table 20. Gallons of diesel fuel required to pump an acre-inch at a performance rating of 100%.

Lift feet	Pressure at Pump Discharge, psi						
	10	20	30	40	50	60	80
0	0.21	0.42	0.63	0.84	1.05	1.26	1.69
25	0.44	0.65	0.86	1.07	1.28	1.49	1.91
50	0.67	0.88	1.09	1.30	1.51	1.72	2.14
75	0.89	1.11	1.32	1.53	1.74	1.95	2.37
100	1.12	1.33	1.54	1.75	1.97	2.18	2.60
125	1.35	1.56	1.77	1.98	2.19	2.40	2.83
150	1.58	1.79	2.00	2.21	2.42	2.63	3.05
200	2.03	2.25	2.46	2.67	2.88	3.09	3.51
250	2.49	2.70	2.91	3.12	3.33	3.54	3.97
300	2.95	3.16	3.37	3.58	3.79	4.00	4.42
350	3.40	3.61	3.82	4.03	4.25	4.46	4.88
400	3.86	4.07	4.28	4.49	4.70	4.91	5.33

Table 21. Conversions for other energy sources.

Energy Source	Units	Multiplier
Diesel	gallons	1.00
Electricity	kilowatt-hours	14.12
Propane	gallons	1.814
Gasoline	gallons	1.443
Natural Gas	1000 cubic feet	0.2026

Table 22. Multiplier when pumping plant performance rating is less than 100%.

Rating, %	100	90	80	70	50	30
Multiplier	1.00	1.11	1.25	1.43	2.00	3.33

Table 23. Volume of water pumped per hour.

Pump Discharge, gpm	Water Pumped per Hour, acre-inch/hr	Pump Discharge, gpm	Water Pumped per Hour, acre-inch/hr
250	0.55	1250	2.76
300	0.66	1300	2.87
350	0.77	1350	2.98
400	0.88	1400	3.09
450	0.99	1500	3.31
500	1.10	1600	3.54
550	1.22	1700	3.76
600	1.33	1800	3.98
650	1.44	1900	4.20
700	1.55	2000	4.42
750	1.66	2100	4.64
800	1.77	2200	4.86
850	1.88	2400	5.30
900	1.99	2600	5.75
950	2.10	2800	6.19
1000	2.21	3000	6.63
1050	2.32	3200	7.07
1100	2.43	3400	7.51
1150	2.54	3600	7.96
1200	2.65	3800	8.40

Table 24. Series Present Worth Factor

Repayment Period, years	Annual Interest Rate					
	6%	7%	8%	9%	10%	12%
3	2.67	2.62	2.58	2.53	2.49	2.40
4	3.47	3.39	3.31	3.24	3.17	3.04
5	4.21	4.10	3.99	3.89	3.79	3.60
6	4.92	4.77	4.62	4.49	4.36	4.11
7	5.58	5.39	5.21	5.03	4.87	4.56
8	6.21	5.97	5.75	5.53	5.33	4.97
9	6.80	6.52	6.25	6.00	5.76	5.33
10	7.36	7.02	6.71	6.42	6.14	5.65
12	8.38	7.94	7.54	7.16	6.81	6.19
15	9.71	9.11	8.56	8.06	7.61	6.81
20	11.47	10.59	9.82	9.13	8.51	7.47
25	12.78	11.65	10.67	9.82	9.08	7.84

Examples

Example 1

Suppose a pivot was used on 130 acres to apply 13.5 inches of water. The pumping lift was about 125 feet and the discharge pressure was 50 psi. Energy use records for the past season show that 5500 gallons of diesel fuel were used. The average price of diesel fuel for the season was $3.00 per gallon.

The analysis of this example is illustrated in the worksheet in Figure 88. An efficient pumping plant would require about 3843 gallons of diesel fuel for the year (i.e., 2.19 gallons/acre-inches times 1755 acre-inches of water). If a producer's records show that 5500 gallons were used to pump the water, then the performance rating would be (3843 / 5500) x 100 = 70%. This shows that 1657 gallons of diesel fuel could be saved if the pumping plant performance was improved. The annual savings in pumping costs would be the product of the energy savings times the cost of diesel fuel; i.e., $3/gallon times 1657 gallons/year = $4971/year. If a 5-year repayment period and 9% interest were used, the series present worth factor would be 3.89. The breakeven repair cost would be $4971 × 3.89 = $19,337. If repair costs were less than $19,337 then repairs would be feasible. If costs were more than $19,337 the repairs may not be advisable at this time. Low performance ratings often indicates that system repairs will ultimately be necessary.

Example 2

Example 2 represents a center-pivot field irrigated with a pump powered by electricity. In this case the pumping lift is 175 feet which is not listed in Table 20. The lift of 175 feet is half way between 150 and 200 feet so the amount of diesel fuel per acre-inch of water is estimated as 2.44 gallons per acre-inch (i.e., halfway between 150 and 200 feet). Since electricity is used to power the pumping plant the multiplier of 14.12 is used in row M of Figure 88. The calculations for the second example are similar to the first example for the rest of the information in Figure 88. This pumping plant has a performance rating of 88% and given the cost of electricity only about $3,770 could be spent for repairs.

Example 3

This example illustrates the application of the hourly method for a propane powered pumping plant. This system has a performance rating of 88%, and about 13% of the annual energy cost could be saved if the pumping plant was brought up to the Nebraska Criteria.

	1. Known Information	Annual Diesel Example	Annual Electric Example	Hourly Propane Example		
A	Pumping lift, feet	125	175	250		
B	Pressure at pump discharge, psi	50	40	55		
C	Size of the irrigated field, acres	130	128	130		
D	Depth of irrigation applied, inches	13.5	13			
E	Amount of energy used to irrigate the field for the year	5500	65,000			
F	Type of energy source used to pump water	Diesel	Electric	Propane		
G	Cost of a unit of energy ($/gallon, $/kWh, etc)	$3.00	$0.07	$1.80		
H	Annual interest rate, %	9	7			
I	Repayment period, years	5	10			
2. Annual Performance						
J	Gallons of diesel fuel @ standard to pump an acre-inch (from Table 20)	2.19	2.44	3.44		
K	Volume of water pumped, acre-inches: (multi- ply row C x row D)	1755	1664			
L	Gallons of diesel fuel needed at 100% Performance Rating (J x K)	3843	4060			
M	Multiplier for energy source (from Table 21)	1	14.12	1.814		
N	Energy used if at 100% pump rating (L x M)	3843	57,327			
O	Performance rating of pump (100 x N / E)	70	88			
P	Potential energy savings with repair, gallons, kWh, etc.: (E-N)	1657	7673			
Q	Annual cost savings, $ (G x P)	$4,971	$537			
R	Series present worth factor (Table 24)	3.89	7.02			
S	Breakeven repair investment (Q * R)	$19,337	$3,770			
3. Hourly Performance						
T	Pump discharge, gallons per minute			700		
U	Volume of water pumped per hour (Table 23), acre-inches/hour			1.55		
V	Energy use per hour if at 100% Performance Rating (J x M x U)			9.65		
W	Actual energy use rate (gal/hour, 1000 cubic feet/hr or kWh/hr)			11.0		
X	Pumping plant performance rating (100 x V/W)			88		

Figure 88. Irrigation energy use worksheet.

Comparing Energy Sources

The optimal type of energy for powering irrigation engines depends on the long-term relative price of one energy source to another. Energy prices have varied considerably over time. The nominal cost of energy per million BTUs is illustrated in Figure 89 for the types used to power irrigation systems for the period from 1970 through 2006. These results show that electricity was expensive relative to other energy sources from about 1983 through about 2000. Electricity has become more favorable especially recently when fossil fuels prices have increased rapidly. While diesel fuel once was very economical the situation has recently changed.

Two methods can be used to analyze power source alternatives for irrigation. The previous section illustrated how to determine the amount that could be saved through annual energy savings if one changed from an energy source to another type. More detailed analysis based on the annual ownership costs have also been developed (http://lancaster.unl.edu/ag/Crops/irrigate.shtml). Typical conditions were used to demonstrate the technique to compare diesel and electricity as energy sources for a center pivot. Representative costs are included in Figure 90 for an electrically powered pivot and in Figure 91 for a pivot powered with a diesel engine. The cost for the electric motor should include any extra expenses for control panels and to bring three-phase service to the motor. The diesel engine should include the cost of the fuel tank and an electric generator if one is not present. The costs listed in the figures are approximate values and local conditions should be use for specific comparisons.

Results of using the spreadsheet to compare the total annual cost of an electrically powered and a diesel powered irrigation system are shown in Table 25 for a range of electricity and diesel fuel prices. The annual savings is the difference between the annual costs for diesel minus the cost for an electrically powered system. The results show that electricity is generally preferred except when diesel is less than 2.25 $/gallon and electrical rates are above 8¢/kWh. If the price of electricity is 6¢/kWh and diesel fuel is $2.25 per gallon then switching to electricity could save over $3,000 annually as long as service can be brought to the field. Again, these are representative costs and producers should analyze their unique situation.

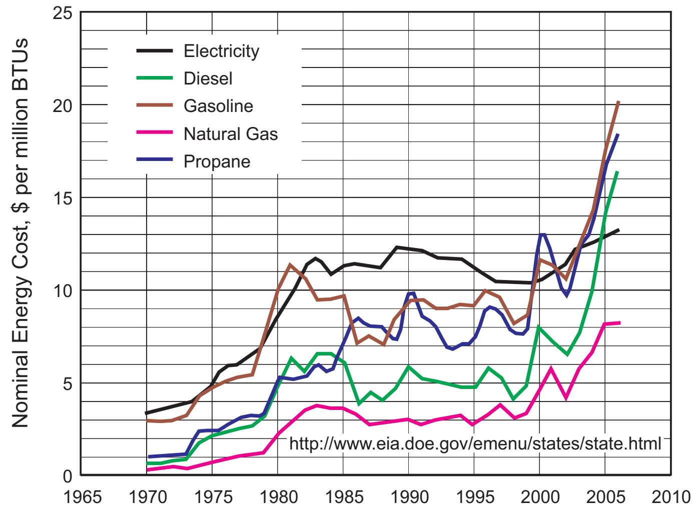


Figure 89. Historical prices of energy.

Table 25. Annual savings when using electricity

Electricity		Diesel Fuel Cost, $ / gallon			
		1.75	2.00	2.25	2.50
Price, $ / kWh	Total Annual Costs	$19,616	$20,625	$21,634	$22,643
0.06	$18,549	$1,067	$2,076	$3,085	$4,094
0.07	$19,119	$497	$1,506	$2,515	$3,524
0.08	$19,689	-$73	$936	$1,945	$2,954
0.09	$20,259	-$643	$366	$1,375	$2,384
0.10	$20,829	-$1,213	-$204	$805	$1,814

Summary

This publication demonstrates methods to estimate the potential for repairing pumping plants to perform at the Nebraska Pumping Plant Performance Criteria and the annual cost for varying energy sources. Producers frequently have several questions regarding the procedures.

First they want to know "Can actual pumping plants perform at a level equal to the Criteria". Tests of 165 pumping plants in the 1980s indicated that 15% of the systems actually performed at a level above the Criteria. So producers can certainly achieve the standard.

The second question is "What level of performance can producers expect for their systems?" Tests on 165 systems in Nebraska during the 1980s produced an average performance rating of 77% which translates to an average energy savings of 30% by improving performance. Tests on 200 systems in North Dakota in 2000 produced very similar results. These values illustrate that half of the systems in the Great Plains could be using much more energy than required. The simplified method can help determine if your system could be inefficient.

The third issue focuses on "What should I do if the simplified method suggests that there is room for improving the efficiency?" You should first determine if the irrigation system is being operated as intended. You need to know if the pressure, lift and flow rate are appropriate for the irrigation system. For example, some systems were initially designed for furrow irrigation systems and are now used for center-pivot systems. If the conditions for the current system are not appropriate for the system you need to work with a well driller/pump supplier to evaluate the design of the system.

Sometimes the system is simply not operated properly. An example occurred where a center-pivot sprinkler package was installed that used pressure regulators with a pressure rating of 25 psi. However, the end gun on the pivot was not equipped with a booster pump so the main pump was operated at a pressure of 75 psi to pressurize the entire system just to meet the needs of the end gun. Since end guns only operate about half of the time the pump was actually pumping against the pressure regulators half of the time, wasting a significant amount of energy. The problem here was not the pump or the power unit but the sprinkler design and its operation.

We recommend periodic evaluations by a well drilling /service company to measure the pumping plant performance. They conduct a test that determines pumping lift, discharge pressure and the efficiency of the pump for a range of conditions that would be expected for a system. They also use equipment to measure the power output of the engine or electric motor. While they don't usually measure the energy consumption rate the results of the test will indicate if the pump is performing efficiently. This provides an excellent reference for future analysis.

Annualized Cost of Owning and Operating an Irrigation System

Center Pivot with Electric Pump Motoı Written by: Tom Dorn, Extension Educator UNL-IANR Lancaster County, NE revised 02/02/2009

Select Distribution ;	Pivot			
Acres Irrigated	130			
Pumping water level, ft.	150			
System Pressure, PSI	50			
Gross Depth applied, inche	12			
Select Power Unit Type	Electricity			
$/kW-h	$0.070			
Labor Chrg, $/hour	$15.00			
Irrigation District, $/ac-ft	0			
Return on Invest. (R.O.I), %	6			
Drip Oil, $/gal	$4.50			
Increase in Property Tax Due to Irrig.Development, $/ac			$0.00	
Annual Elec Hookup Cost	$1,035	HP= 90	$/HP=	$11.50

Note: Users are encouraged to replace values in blue font with values that represent their unique situation.

Select Distribution system and energy source for the pump motor from pull down menus.

Component				Ownership Costs			Operating Costs				
	Initial Cost	Life	Salvage[4]	R.O.I.	Insurance + tax	Depr	Repairs[2]	Oper. labor	Electricity	Energy $[1]	Total Costs
Irrigation Well	$16,500	25	($825)	$470	$165	$693	$215	$23	Kw-hour	kW+Hookup	$1,566
Irrigation Pump	$11,163	18	$558	$352	$112	$589	$340	$94		$/kW-h	$1,486
Gear Head	$0	15	$0	$0	$0	$0	$0	$0		$0.09	$0
Pump Base, etc.	$0	25	$0	$0	$0	$0	$0	$0			$0
Electric Motor& Switches	$5,350	30	$268	$169	$107	$169	$405	$351	53,182	$4,758	$5,958
Center Pivot System	$52,000	20	$2,600	$1,638	$1,040	$2,470	$2,028	$702		$81	$7,959
	$0		$0	$0	$0	$0	$0	$0		$0	$0
											$0
Add'l Property Tax					$0						$0
Totals	$85,013		$2,601	$2,628	$1,424	$3,922	$2,987	$1,170		$4,839	$16,970

	Ownership Costs	Operating Costs	Total Costs
Total annual $	$7,974	$8,997	$16,970
Annual $/ Acre	$61.34	$69.21	$130.54
$/ac-in	$5.11	$5.77	$10.88

1 Energy Cost assumes operating at 100% of the NPC. Hookup charge added for Electric Units.
2 Drip oil added to repair costs. For internal combustion engines, 5% of energy costs added to repair costs for oil, filters, and lube.
3 Energy Cost for Center Pivot assumes 7/8 hp-h per acre inch of water . delivered. Other systems require no additional energy for distribution
4 End of life salvage value 5% of purchase price except for irrigation well. **End of life cost for well = 5% to plug the well.**

Figure 90. Example analysis for an electrically powered center pivot and pump system

Annualized Cost of Owning and Operating an Irrigation System

Center Pivot with Diesel Engine

Developed by : Tom Dorn, Extension Educator UNL-IANR Lancaster County, NE revised 4/09/2013

Select Distribution	Pivot
Acres Irrigated	130
Pumping water level, ft.	150
System Pressure, PSI	50
Gross Depth applied, inches	12
Select Power Unit Type	Diesel
$/Gallon	$2.500
Labor Chrg, $/hour	$15.00
Irrigation District, $/ac-ft	0
Return on Invest. (R.O.I), %	5
Drip Oil, $/gal	$4.50
Increase in Property Tax Due to Irrig.Development, $/ac	$30.00

Note: Users are encouraged to replace all values in blue font with values that represent their unique situation.

Select Distribution system and energy source for the pump motor from pull down menus.

Component				Ownership Costs			Operating Costs				
	Initial Cost	Life	Salvage[4]	R.O.I.	Insurance + tax	Depr	Repairs[2]	Oper. labor	Diesel	Energy $[1]	Total Costs
Irrigation Well	$16,500	25	($825)	$392	$165	$693	$215	$23	Gallons		$1,488
Irrigation Pump	$11,163	18	$558	$293	$112	$589	$340	$94			$1,428
Gear Head	$2,800	15	$140	$74	$28	$177	$36	$23			$339
Pump Base, etc.	$1,100	25	$55	$29	$11	$42	$17	$23			$122
Diesel Engine & Tank	$11,500	12	$575	$302	$230	$910	$829	$351	3,765	$9,413	$12,036
Center Pivot System	$75,000	20	$3,750	$1,969	$1,500	$3,563	$2,925	$0		$206	$10,162
	$0		$0	$0	$0	$0	$0	$0		$0	$0
											$0
Add'l Property Tax					$3,900						$3,900
Totals	$118,063		$4,253	$3,058	$2,046	$5,974	$4,363	$515		$9,619	$29,474

	Ownership Costs	Operating Costs	Total Costs
Total annual $	$14,978	$14,497	$29,474
Annual $/ Acre	$115.21	$111.51	$226.73
$/ac-in	$9.60	$9.29	$18.89

1 Energy Cost assumes operating at 100% of the NPC. Hookup charge added for Electric Units.

2 Drip oil added to repair costs. For internal combustion engines, 5% of energy costs added to repair costs for oil, filters, and lube.

3 Energy Cost for Center Pivot assumes 7/8 hp-h per acre inch of water . delivered. Other systems require no additional energy for distribution

4 End of life salvage value 5% of purchase price except for well.
End of life cost for well = 5% to plug the well.

Figure 91. Example analysis for a center-pivot irrigated field powered a diesel engine.

Chapter 8 Crop Water Use

When managing an irrigation system, it is important to have an understanding of crop water use. We need to know why crops use water and what factors affect the rate of water use. Then we must know how to calculated crop water use and manage the irrigation system accordingly. Also, leaving crop residue on the soil surface can reduce the amount of irrigation needed to meet crop water needs.

Evapotranspiration (ET)

Evapotranspiration (ET) can be defined as the transfer of water in the form of water vapor from the soil surface, a body of water and vegetative and other surfaces to the atmosphere. There are two components to ET: evaporation from the soil, a body of water, or plant leaves and transpiration from plants. During transpiration, water is taken up from the roots of the plant and moved to the leaves. Small openings in the leaf tissue called stomata allow water vapor to pass from the plant to the atmosphere. The transpiration of water cools the plant and maintains the productivity of photosynthesis. This results in a direct relationship between transpiration and yield. Although we are mainly concerned with transpiration, it is difficult to separate it from evaporation so the two components are measured or calculated together.

Factors that affect ET

Since the primary reason for transpiration is to cool the plant, it is to be expected that climatic conditions are the driving forces behind the rate at which plants transpire. Air temperature and solar radiation are the two primary factors in the rate at which transpiration occurs. As air temperature and solar radiation increase, so does transpiration. ET will also increase with increased wind speeds to a point. Conversely, as relative humidity increases, transpiration decreases.

Other factors that affect ET include plant species, canopy characteristics, plant population, degree of surface cover, plant growth stage, irrigation regime, tillage practices, planting date, maturity group of plant species, and soil water availability.

Effect of Residue

Leaving crop residue on the soil can have a significant effect on evaporation of moisture from the soil surface. In a University of Nebraska study, it was found that in plots with residue removed it would take 1.5-2.5 inches more of irrigation to achieve the same yield as plots with residue on the surface. Also, at the end of the growing season, the plots with residue on the surface contained 1.5 inches more water in the top 4 feet of soil than the bare plots. This means that the residue on the soil surface could save 3-4 inches of irrigation compared to bare soil.

Change in E vs. T during season

The ratio of evaporation to transpiration changes as the crop grows and more of the soil surface is shaded. When the crops are small, the portion of ET due to transpiration is minimal relative to soil evaporation. The surface area of the leaves is small and more of the soil surface is exposed. Figure 92 illustrates this idea with larger arrows representing more water leaving the soil through evaporation compared to the small amount being transpired by the small plants.

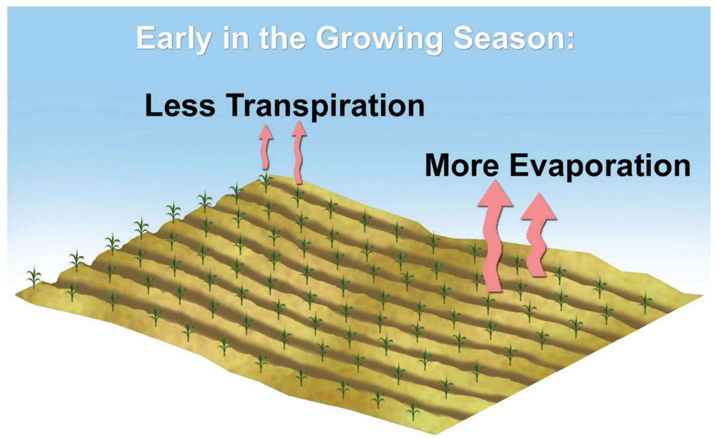


Figure 92. Source of ET early in the growing season.

By the time that the crop reaches full canopy, the soil is completely shaded and evaporation from the soil is minimized (Figure 93). Leaf area is now much larger than the exposed soil surface and transpiration becomes the more important component of ET as 90-98% of ET is now due to transpiration.

Calculating ET

When irrigation is managed to meet crop water needs, the amount of water used by the crop over a given time is needed. However, water use of a crop in a specific field is difficult to calculate. A simple calculation of crop ET can be made if the ET of a reference crop is known. In order to calculate the water use of a crop, we must first know the water used by the reference crop, typically grass or alfalfa. Once we calculate or estimate the reference crop, the ET for the crop in question can be determined by:

$$ET = ET \times K$$

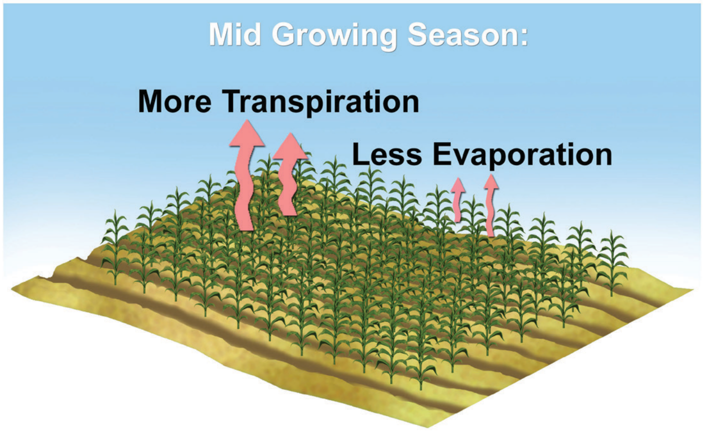


Figure 93. Source of ET in the middle of the growing season.

Where ETc is the crop ET, ET_r is the reference crop ET and K_c is the crop coefficient. The crop coefficient is a conversion factor that relates the ET of the reference crop to the crop of interest. The conversion is not constant throughout the season. It changes depending on the growth stage of the crop.

The High Plains Regional Climate Center (HPRCC) monitors weather stations (Figure 94) throughout the region. Some stations measure only high and low temperature and precipitation but others monitor more variables that influence ET. Along with temperature and precipitation, these stations monitor solar radiation, relative humidity, and wind speed. These measurements allow HPRCC to make daily ET estimates for a reference crop at these locations. This information can be found at: http://www.hprcc.unl.edu/.

The equipment needed to measure the variables required for computing ET_r can be expensive and complicated to measure for growers, crop consultants, and extension educators. A simpler method for estimating reference crop ET is an atmometer (Figure 95). More information on ETgages can be found in University of Nebraska-Lincoln Extension publication G1579, a NebGuide entitled Using Modified Atmometers for Irrigation Management.

Once the reference crop ET has been estimated that data is combined with a crop coefficients to calculate the crop ET. Table 26 shows the K_c for corn, soybeans, and wheat. Suppose the change in the water level in the sight gage on an ETgage is 2.10 inches for a week and the soybean crop of interest is in the full pod stage. The K_c found in Table 26 can be used with the previous crop ET equation to estimate the crop ET. In this case the crop water use would be approximately 2.31 inches for the week.

$$ETc = 2.10 \text{ inches} \times 1.10 = 2.31 \text{ inches}$$

Figure 94. Weather stations for computing reference ET.

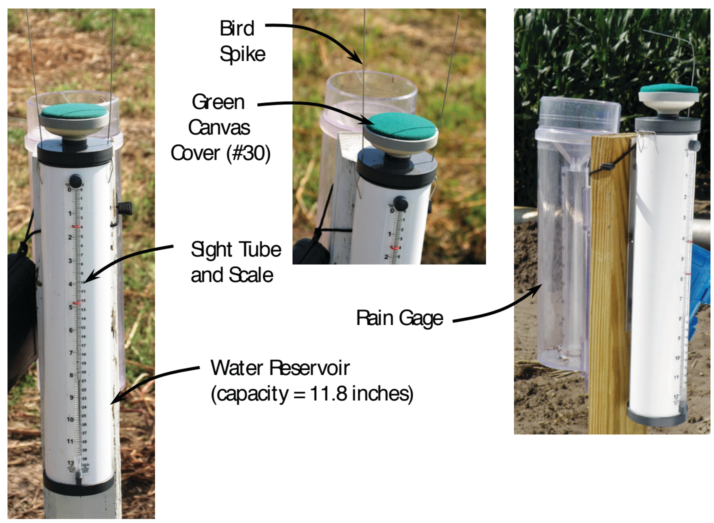


Figure 95. ETgage

Crop ET calculations can be performed daily or weekly. The University of Nebraska-Lincoln CropWatch website provides estimated values of ET_c for a week or a three-day period. The site provides values for regional crops for a range of crop emergence dates for approximately 20 weather station distributed across the state. This allows growers to select local climate information and crops near the growth stage of the producer's crop. The information can be found at: http://cropwatch.unl.edu/gdd-etdata.

Table 26. Crop Coefficients for corn, soybeans, and wheat.

Stage	Corn	K_c	Soybean	K_c	Wheat	K_c
1	2 leaves	0.10	Emergence	0.10	Emergence	0.10
2	4 leaves	0.18	Cotyledon	0.10	Visible crown	0.50
3	6 leaves	0.35	First node	0.20	Leaf elongate	0.90
4	8 leaves	0.51	Second node	0.40	Jointing	1.04
5	10 leaves	0.69	Third node	0.60	Boot	1.10
6	12 leaves	0.88	Begin bloom	0.90	Heading	1.10
7	14 leaves	1.01	Full bloom	1.00	Flowering	1.10
8	16 leaves	1.10	Beginning pod	1.10	Grain fill	1.10
9	Silking	1.10	Full pod	1.10	Stiff dough	1.00
10	Blister	1.10	Beginning seed	1.10	Ripening	0.50
11	Dough	1.10	Full seed	1.10	Mature	0.10
12	Begin Dent	1.10	Begin maturity	1.10		
13	Full Dent	0.98	Full maturity	0.90		
14	Black Layer	0.60	Mature	0.20		
15	Full Maturity	0.10		0.10		

Partial listing from High Plains Regional Climate Center at the University of Negbraska-lLincoln..

Seasonal ET

As we look at crop ET throughout the growing season, we see that daily ET varies significantly but when averaging many years together a trend is easily identified. Also, daily ET varies with the crop being grown. Results in Figure 96 show that the peak ET for corn tends to be earlier in the growing season than soybeans.

When considering the total growing season ET of a crop, the local climatic conditions will also be important factors. Figure 97 shows how ET varies across the state of Nebraska. It is highest in the southwest portion of the state, the area that typically has lower humidity and higher temperatures.

Summary

To make timely irrigation applications and at a proper application depth, we must know the previous evapotranspiration from the field. Evapotranspiration (ET) consists of both water evaporation from the soil surface as well as transpiration from crops. In order to calculate ET, we need to measure the weather conditions that affect the rate of ET. Once we have determined crop water use of a reference crop we can then, by using a crop coefficient, calculate the water use of the crop we are interested in. This information can then be used to make informed decisions about irrigation applications.

Example 3. Crop Water Use

A producer wants to estimate how much water a corn crop used over the previous week. The corn is in the 10 leaf stage of growth and an ETgage has been installed near the field. The ETgage indicates water use of 2.4 inches for the week. To calculate the water use of the corn crop we use the crop coefficient found in Table 26 to convert the reference ET from the ETgage to the crop ET:

$$ET_c = ET_r \times K_c$$

$$ET_c = 2.4 \text{ inches} \times 0.69$$

$$ET_c = 1.66 \text{ inches}$$

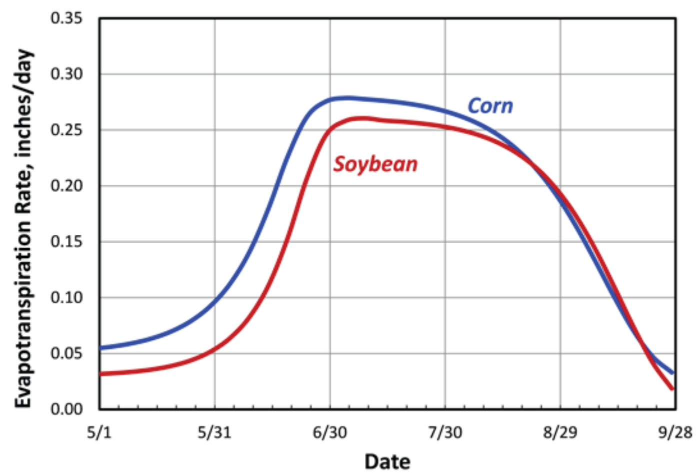


Figure 96. Average daily ET for corn and soybeans in Central Nebraska.

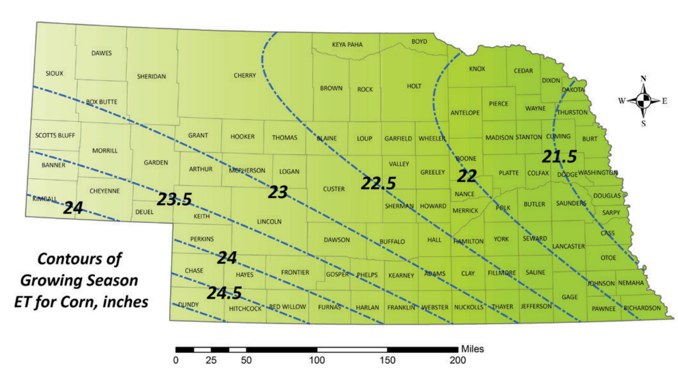


Figure 97. Average seasonal ET for corn in Nebraska.

Chapter 9. Water Resource Management

Background

To understand water use it is helpful to consider the fate of water as depicted in the hydrologic cycle (Figure 98). There is a constant amount of water on earth; however, the supply is continuously recycled when viewed from a global perspective. Precipitation that reaches the earth's surface either infiltrates into plant root zones, runs off to streams and rivers, or is intercepted by plants. Some of the water that infiltrates is used to supply water that evaporates from the soil or that transpires through plant leaves. When more water infiltrates the soil than plant root zones can store, the excess infiltration flows through the unsaturated zone toward the groundwater aquifer. Water that reaches the groundwater is usually called recharge. Recharge causes the local groundwater level to rise which creates a gradient that causes groundwater to flow away from the recharge area. Groundwater may flow toward streams, lakes and rivers if groundwater aquifers are connected to the stream. In other cases the elevation of the stream may be higher than the groundwater surface and water may flow from the stream to the groundwater. Water also reaches streams and lakes by direct overland runoff.

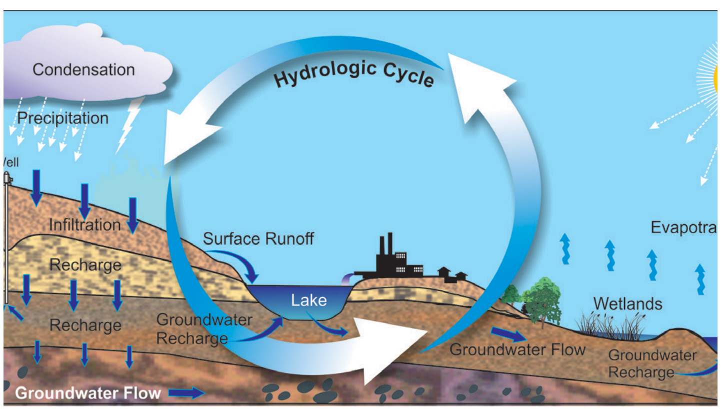


Figure 98. Diagram of the hydrologic cycle (adapted from www.sws.uiuc.edu/docs/watercycle).

Thus, water in streams and lakes can come from either runoff or groundwater. The contribution of flow due to groundwater is frequently called base flow. Energy from the sun and dry winds causes water in streams, lakes and the ocean to evaporate, and water to evaporate from the soil and or transpire through plants. Water vapor in the atmosphere condenses as it cools and returns to the earth as precipitation, and the hydrologic cycle is complete.

Watersheds

We are generally concerned with watersheds at the local scale. A watershed is the land whose runoff drains into a particular stream (Figure 99). All land uses in the watershed affect its water balance. Many processes included in the hydrologic cycle also apply to the watershed. The primary difference is that water vapor as evapotranspiration generally does not return to the same watershed where the ET occurred. Thus evapotranspiration represents a loss for the watershed. In the Great Plains the jet stream transports air from more arid regions into the area and the evapotranspiration that occurs is often transported toward more humid regions.

Precipitation is the primary source of renewable water supplies for most watersheds in the Great Plains. Some watersheds benefit from inflow from surface water in streams and rivers from upstream regions. Groundwater may also flow into the watershed area. Precipitation and inflow to the watershed produces outflow (streamflow or groundwater discharge) or evapotranspiration within the watershed. Some water is also temporarily stored within the watershed as water in reservoirs or groundwater aquifers. Water is also stored in the unsaturated soil (i.e. the root zone and the vadose zone) above the groundwater aquifer. Water in storage can increase or decrease over time depending on the balance between inflow, outflow and evapotranspiration.

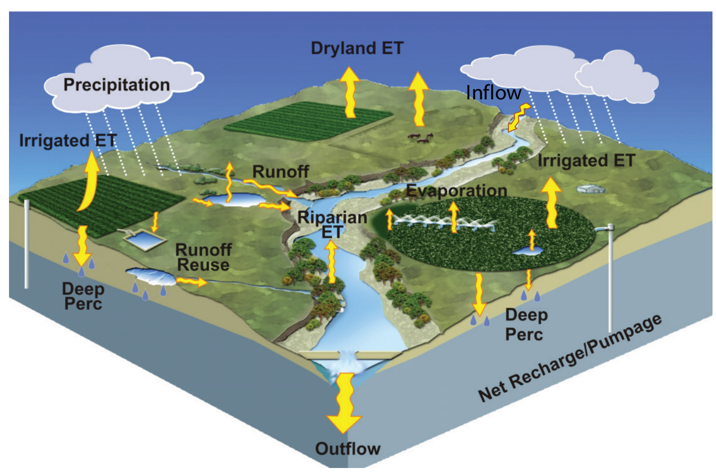


Figure 99. Water balance of agricultural watershed

Man can affect the hydrologic cycle and the water balance of a watershed by diverting surface water in lakes or streams and pumping groundwater. Some applications, such as irrigating crops, increase evapotranspiration. The increase in evapotranspiration due to irrigation is called the consumptive use of irrigation water and represents a conversion of liquid water to water vapor that ultimately leaves the watershed. Some of the water diverted from streams or pumped from groundwater for irrigation may percolate through root zones of irrigated fields or seep from water delivery systems. Seepage and drainage usually recharge the groundwater aquifer. Some water may run off irrigated fields or may be spilled from delivery systems. If the runoff and/or spills flow to a stream or lake, the water is usually referred to as return flow because it becomes available downstream.

Water Use

Use is the act of utilizing something for a particular purpose. For water we generally think of diverting water from streams or reservoirs, or pumping from groundwater, to supply an intentional use. Evapotranspiration that occurs due to natural activities is not generally considered to be a "use". Thus, evapotranspiration from native range or evaporation of natural lakes would not normally be referred to as a use. The act of moving water from its original location to a different location or time ("i.e., using the water") has an intended purpose. For example we irrigate to cool crops and to reduce water stress during dry periods to sustain crop yields. We might also use streamflow or groundwater to cool electrical power generation systems or to produce ethanol. When we "use" water we generally increase evapotranspiration.

Not all of the water "used" is consumed (i.e., converted from a liquid to water vapor). For example, consider the sprinkler and surface irrigation examples shown in Figure 102. Water supplied to the irrigated field as either rain or irrigation furnishes water for crop evapotranspiration, but may also result in runoff which may return to the streams of the watershed or may percolate through the crop root zone and recharge the groundwater aquifer. Thus, the amount of water pumped for irrigation is not all consumptively used. Data from the USGS (2005) lists the relative consumptive use of water by major sectors in Nebraska. The data show that up to 90% of the water consumed in the state is for irrigation. Cooling of power plants represents approximately 8% of the total consumptive use in the state. These data show that little water is consumed for domesticate or municipal uses.

Consumptive Use

A widely used term today is consumptive use. The meaning of consumptive use is often different between individuals, especially those that are new to hydrology. Various scientific and engineering organizations have developed definitions for consumptive use that vary slightly but that usually have a consistent message. The Glossary of Meteorology defines consumptive use as "The total amount of water taken up by vegetation for transpiration or building of plant tissue, plus the unavoidable evaporation of soil moisture, snow, and intercepted precipitation (interception) associated with the vegetal growth. Consumptive use is primarily applied to a single type of vegetation in a given area and does not include evaporation from water surfaces in or adjacent to the area; thus, it is not as general in scope as evapotranspiration or duty of water." The United States Geological Survey defines consumptive use as "that part of water withdrawn that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment." The United States Bureau of Reclamation adds that "water whose state, chemical, or biological characteristics are altered sufficiently to render it useless to further beneficial uses" is also referred to as water consumption. The Irrigation Association lists definitions of use that are partially based on terminology from the American Society of Civil Engineers and the American Society of Agricultural and Biological Engineers as:

Consumptive: Total amount of water taken up by vegetation for transpiration or building of plant tissue, plus the unavoidable evaporation of soil moisture, snow, and intercepted precipitation associated with vegetal growth.
Nonconsumptive: Water that leaves the selected region and not considered consumptive. Examples are runoff, deep percolation, and canal spills.

Beneficial Use: Beneficial use of water supports the production of crops: food, fiber, oil, landscape, turf, ornamentals, or forage.

Nonbeneficial Use: Water utilized in plant growth which cannot be attributed as beneficial.

Reasonable Use: In the context of irrigation performance, all beneficial uses are considered to be reasonable uses. Non-beneficial uses are considered to be reasonable if they are justified under the particular conditions at a particular time and place.

Unreasonable Use: Unreasonable uses are non-beneficial uses that, furthermore, are not reasonable; that is, they are without economic, practical, or other justification.

The State of Utah considers consumptive use to be the portion of water withdrawn from a surface or groundwater source that is consumed by particular use(s) and does not return to a natural water source or another body of water."

The common theme within these definitions is that water which is converted from liquid to water vapor by evapotranspiration is consumptive use since it represents a loss from the watershed and is not available to downstream users in the watershed or neighboring watershed. There is a subtle difference in the definitions regarding how water is made available for consumptive use. Some include all water and other organizations focus on water that is withdrawn from the source for a use. The latter definition seems to be more appropriate for managing watersheds.

Consumptive use is more subtle if we alter evapotranspiration due to changes in land use and/or agricultural production practices. Consider expanded use of conservation tillage in agriculture. It is widely recognized that reduced tillage contributes to higher infiltration rates that supply water for crop evapotranspiration and groundwater recharge. The increased infiltration diminishes the amount of runoff that contributes to streamflow leaving the watershed. So, as one compares to earlier times the changes in farming practices could be considered an increase in consumptive use. However, the individual producer did not intentionally move water from one location to another in this process, so in that sense it may not be an increase in consumptive use even though it results in an increase in evapotranspiration.

Some consumptive use may be beneficial in that they increase crop yields and profitability, allow for production of electrical energy or provide for increased recreation at lakes, or provide for some other purpose. In other cases consumptive use may be nonbeneficial. Examples of nonbeneficial uses would be evapotranspiration from weeds in road ditches that are wetted due to uncontrolled runoff from irrigated lands, evapotranspiration from artificially wetted areas adjacent to canals, or evaporation of water applied to streets and pavements in urban areas. The fate of an irrigation water withdrawal relative to these considerations is illustrated in Figure 100. Identification and reduction of nonbeneficial uses of water offers potential to enhance water supplies with little loss of economic or environmental impact.

Farm Scale

Water use at the farm or field scale differs slightly from considerations for the hydrologic cycle and/or water management at the watershed scale. The fate of water for an irrigated field located in a watershed is illustrated in Figure 101.

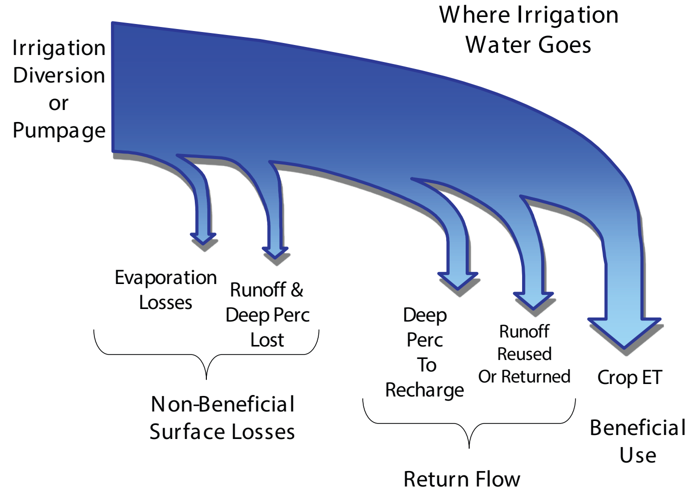


Figure 100. Fate of irrigation water.

The rectangular dashed line represents the water balance for an irrigator. Additions to the field water balance include rainfall, and irrigation water from ground or surface water sources. Losses of water from the field represent runoff, deep percolation from the field and evapotranspiration from the field and evaporation from on-farm storage or conveyance systems. Farmers profit by increasing efficiency to obtain as much evapotranspiration by irrigated crops as is profitable. Thus, runoff, deep percolation and evaporation from storage are losses. . Water that percolates from the field or that runs off and returns to the stream would not be seen as a loss at the watershed scale as they are still in the system for use elsewhere.

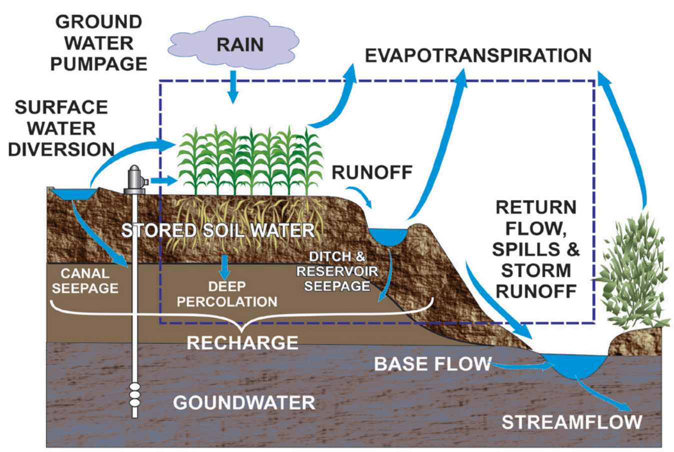


Figure 101. Water balance of an irrigated field.

Application of water from an irrigation system can result in several outcomes as illustrated in Figure 102. The goal of the irrigator is to produce the maximum of crop ET from the irrigation as it is generally linearly related to crop yield as shown in Figure 103. Irrigators can improve their efficiency by a range of activities and management practice changes. Actually the only truly beneficial use of water for the farmer is the transpiration from the crop. However, it is difficult to separate the transpiration from soil evaporation, so evaporation is included with transpiration as a beneficial use. Reduced tillage and other practices that reduce evaporation from the soil reduce consumptive use without reducing transpiration. This can reduce the amount of water that must be extracted from the source to fully irrigate the field.

Improving irrigation efficiency can reduce the other surface water losses and recharge and/or return flow as shown in Figure 101. Practices that reduce surface losses will reduce nonbeneficial consumptive use. Irrigation water that goes to recharge and/or return flow represents losses to the producer but not to the watershed per se. Thus, improving irrigation efficiency will usually leave more water at the ground or surface water source, and may reduce nonbeneficial use. Extracted (pumped or diverted) water that is recycled back to the aquifer or stream is not a loss to the watershed, thus improving irrigation efficiency will not "save" all of the reduction in extraction that was accomplished through improved irrigation efficiency.

Deficit irrigation can also affect crop water use and yield. Deficit irrigation is the intentional stressing of the crop during the season to reduce water use while minimizing yield reduction. The process of deficit irrigation is illustrated in Figure 103. We normally find a linear relationship between crop yield and evapotranspiration (ET) from the crop for most crops that are raised in the Great Plains. The relationship between irrigation and yield for an efficient and inefficient irrigation system is shown in Figure 103 also.

A portion of the irrigation water is consumed for ET while the rest goes to other surface losses, recharge or return flow. If the yield is the same for an efficient and inefficient irrigation system the crop water use will be the same but the nonconsumptive uses will be larger for the inefficient system. If the amount of irrigation water is limited an efficient irrigation system will generally produce more yield and will require more in-field consumptive use than a less efficient system. Figure 103 also illustrates that irrigation systems become more efficient, i.e. a larger portion of the applied water will go to ET, when deficit irrigation is employed.

Summary

Water use can be viewed at several scales and each perspective offers a different conclusion regarding water balances and the impact of man's activity. It is essential to consider these perspectives in managing water and to clearly define the perspective to avoid misunderstanding and false expectations. Practices that reduce nonproductive/nonbeneficial use of water benefit the producer and improve the water balance of the watershed if the amount of water extracted is reduced. Improving irrigation efficiency can contribute to reduced nonbeneficial uses. In other cases improving irrigation efficiency can lead to consumptive of a larger portion of the applied water which can increase consumptive use. To evaluate the long-term impacts it is essential to distinguish between consumptive use, surface losses and return flow or recharge. We are working on methods to account for these effects in the future as we face new challenges in managing the watershed in the future.

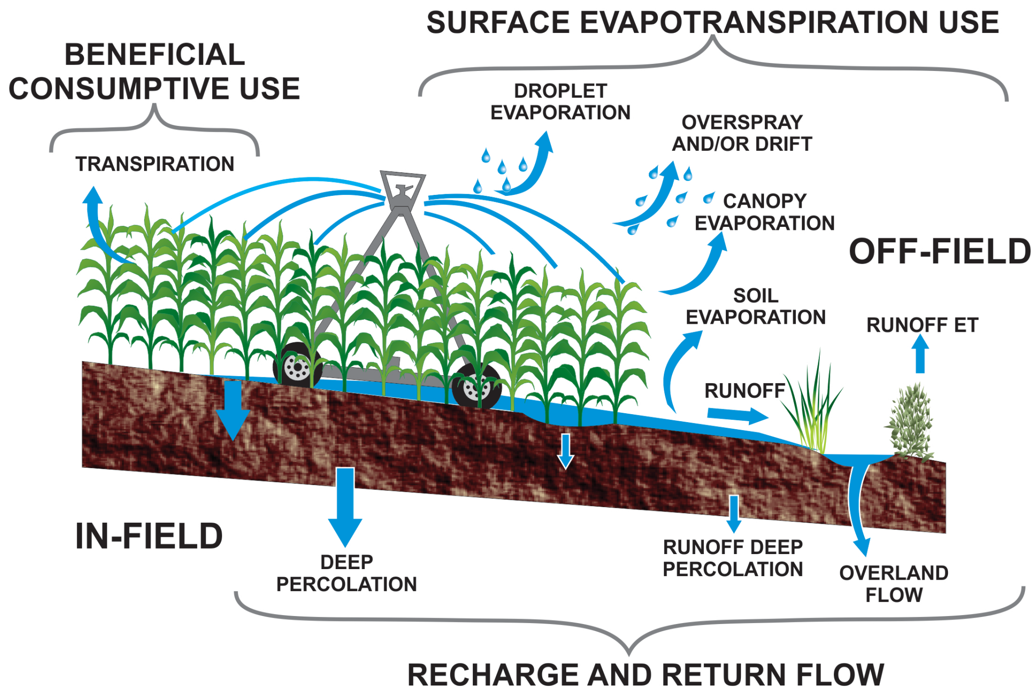


Figure 102. Water balance for a center pivot irrigated field.

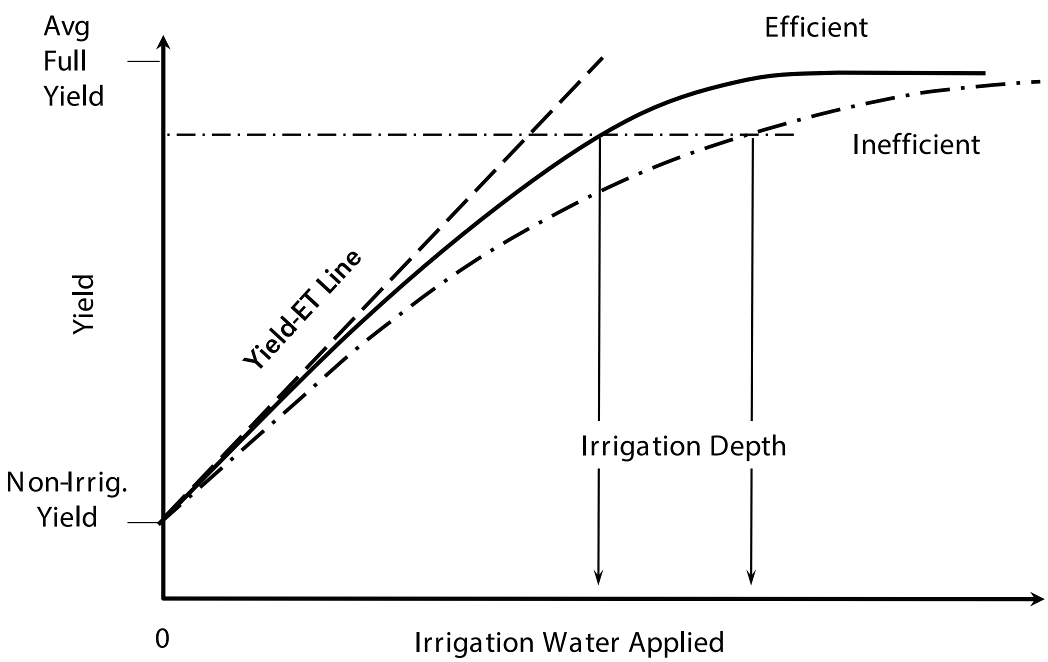


Figure 103. Effect of application efficiency on irrigation depth.

Chapter 10. Limited Irrigation

A growing number of water users are competing for a limited supply of water. In some cases, restrictions have been placed on irrigators to protect fully and over-developed water supplies. Water allocations may not meet the irrigation requirement of crops like corn. There are many strategies to manage limited water supplies. Some of these are water conservation practices designed to reduce the irrigation needed. Other methods are designed to provide the greatest return from limited irrigation water supplies.

Water conservation practices

Several practices can conserve water. Limiting water application during non-critical growth stages can reduce water use without reducing yield significantly. The crop can be stressed somewhat during the vegetative growth stages as long as permanent damage is not done to the plant. Also, allowing the soil to dry at the end of the growing season will reduce irrigation application and leave room for rainfall to refill the profile before the next growing season.

Another strategy to stretch limited water supplies is to grow a crop that doesn't require as much water. For instance, grain sorghum and sunflowers require less irrigation water to reach their full potential than corn. However, corn produces a large amount of grain per unit of ET and deficit irrigation of corn will often be optimal rather than fully irrigating a crop such as grain sorghum.

Using a cropping rotations that provide good residue cover maximizes rainfall stored in the soil profile and reduces evaporation early in the growing season and during the off-season. A fallow system that allows rainfall to replenish the soil profile can reduce the irrigation water needed to produce the same crop in an intense cropping system. This can be accomplished using winter wheat after corn or soybeans and allowing a fallow period between the summer wheat harvest and planting the following spring. Analysis of the economic returns for rotations is critical as they may produce suboptimal returns.

Plant Population Effects

Reducing the plant population can also reduce the water needs of the crop; however, the plant population generally must be reduced significantly to reduce ET. Results generally show that it is infeasible to reduce the plant population to the extend required to decrease water use of a corn crop. Irrigated corn develops more leaf area than needed to absorb the available radiation or to exchange water vapor with the environment. Therefore, the plant population of corn must be reduced to about 18,000 plants per acre before crop water use decreases materially. Reducing the population to that extent often results in a significantly smaller yield potential. Populations between this level and the desirable population for well-watered conditions generally reduce the potential yield yet do not reduce water use significantly.

The important question for deficit irrigation is: "What plant population is needed to produce the target yield expected when water is limited?" For exampled, if water limitations reduce yield potentials below that for well-watered crops, then a population of 32,000 plants per acre for corn is probably excessive. So, the goal becomes predicting the expected yield and then selecting a population that will likely achieve that goal. The resulting population will usually be well above the population that reduces the crop water use rate. Thus, irrigators can save seed costs while achieving the expected yield. Unfortunately, we do not have adequate data for all aspects of this decision. Some results show that crop varieties react differently to plant populations especially when stressed. Growers are encouraged to consult their seed suppliers to address population and variety selection.

Deficit Irrigation Management

The Great Plains depends heavily on groundwater to supply irrigated agriculture. In some areas of the Great Plains, irrigation has been developed to an extent that withdrawals for irrigation exceed the annual recharge of the aquifer from precipitation. The result has been declining groundwater levels. The flow of water in streams also decreases if the streams are hydraulically connected to the groundwater. Several water use allocation systems have been developed in the region due to groundwater declines and/or streamflow reductions. The allocation systems generally limit the volume of water that can be pumped annually and/or during a multi-year period. Water supplies for lands irrigated with surface water have become limited due to drought and streamflow depletions. Irrigators faced with limited surface water supplies may encounter annual or multi-year allocations as well. The capacity of some irrigation wells in the Great Plains may be too small to meet peak water requirements of crops during the growing season. In such areas, the annual pumpage may be limited by the well capacity rather than regulation, especially in years with little precipitation. These factors, plus high input costs, are causing irrigators to ask several questions, such as:

- How much water should I apply this year?
- How much land should I irrigate?
- What crops should I irrigate?
- How much profit can I expect from irrigating?
- Should I invest in more efficient irrigation systems and can I pay that investment cost?

When the available water supply is limited, farmers are faced with different planning decisions than historically encountered. When ample water supplies are available in sufficient flow rates, producers are primarily interested in scheduling irrigation to determine the depth and timing of water application needed to maintain crop water use rates near those required to produce the maximum yield. High water costs may reduce the annual application slightly below the yield maximizing amount; however, reductions are generally not a large percentage of the full irrigation requirement. When water supplies are limited, the decisions required are much different. This situation is called deficit irrigation and involves more analysis.

We highlight some decisions that must be considered in managing deficit irrigation. We also present results of experiments and modeling studies that provide some information for addressing these considerations. Certain decisions will be specific to an individual farmer's situation, while more general, conclusions can be made regarding some alternatives.

Yield-ET Relationships

The relationship between crop yield and the amount of water used by the crop forms the basis for deficit irrigation analysis. Water that evaporates from soil and plant surfaces, and that transpires through the plant stomata, is referred to as evapotranspiration which is abbreviated as ET. Evapotranspiration is the conversion of liquid water into water vapor. This process requires large amounts of energy. Transpiration is necessary to cool plants during hot summer days and is closely related to photosynthesis rates of crops. The stomata on crop leaves close during water stress which prevents transpiration and limits the intake of carbon dioxide which is necessary for photosynthesis and ultimately plant growth and yield. Thus, many researchers have shown that crop yields are closely related to transpiration. Unfortunately, it is difficult to measure the amount of transpiration during the year, so many relationships have been developed between crop yield and ET as illustrated in Figure 104. Results from many experiments all over the world have shown that there is a linear relationship between the seasonal amount of ET and yield for the crops typically grown in the Great Plains.

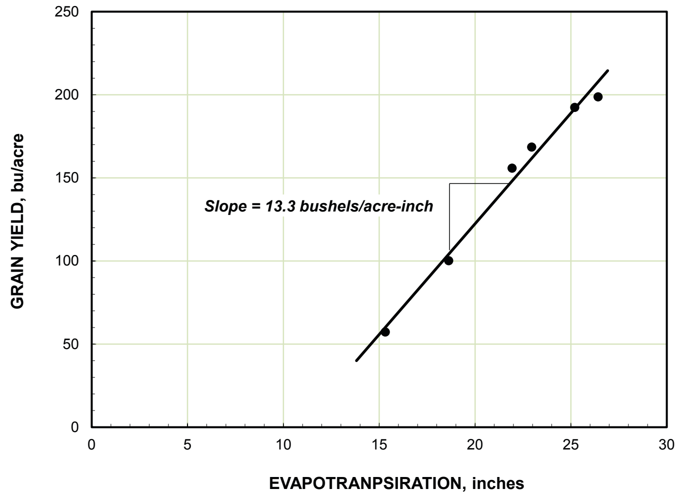


Figure 104. Relationship of seasonal ET to grain yield for corn in west central Nebraska.

Note that extending the yield-ET line to the bottom of the graph will show that about 10 inches of water is needed before any yield can be produced. Thus, for this experiment about 10 inches of ET were needed in the development of leaves and stalks to the point where some yield would be produced. Some of the 10 inches is also used as direct evaporation of water from the soil.

Once enough precipitation, irrigation or stored soil water is provided to exceed the 10-inch requirement, there is a linear increase in yield for each unit of ET. Eventually, the maximum annual amount of ET that is required for achieving the maximum yield is reached. About 26 inches of ET during the growing season was needed to produce the maximum amount of yield in the example. It is essential to realize that the ET shown in Figure 104 is the amount that occurred during the growing season. Additional evaporation occurs during the non-growing season, but that evaporation is not related to crop yield. Evaporation during the non-growing season depends on the amount and frequency of rainfall, the soil type and the amount crop residue on the soil surface. Simulation results show that four or six inches of evaporation may occur during the nongrowing season which increases the total annual ET to 30 to 32 inches for typical corn crops.

The ET and yield values vary annually; therefore, the shape of the ET-yield line also varies from year to year depending on rainfall and climatic distribution. The general shape however generally remains the same.

Irrigation Production Function

It is not possible to apply irrigation water efficiently enough so that the depth applied just equals the amount of ET. As illustrated in Figure 102 some irrigation water is lost to runoff, deep percolation, and evaporation or drift during irrigation. Attaining maximum yields requires that soil water levels be maintained above a level where water stress affects crop yields. Thus, some irrigation water must be left in the root zone at the end of the season to avoid stress at the end of the year.

Irrigation systems are not capable of applying the exact amount of water that is needed at every point in the field. Due to the nonuniformity of application, it is often necessary to apply more water on average than needed to produce the maximum yield. Figure 105 illustrates that deep percolation may occur in the valleys of the field due to runoff from hillslopes. The tops and sides of hills may not receive enough infiltration to satisfy the target depth. Center pivots, cannot apply with perfect uniformity; thus, the amount of water needed to irrigate a field will exceed that consumed for ET.

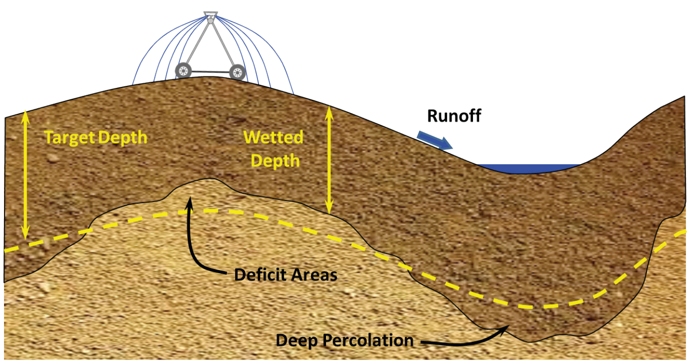


Figure 105. Water distribution uniformity from a center pivot.

The need to apply more irrigation water than needed for ET for a given amount of yield is illustrated in Figure 106. The diagram shows that the amount of irrigation needed for a specific yield equals the amount of ET for the crop, plus what are referred to as non-ET losses. Non-ET losses represent the extra application needed for nonuniformity, deep percolation, runoff and the soil water reserve needed for reducing water stress. Non-ET losses become a smaller portion of the amount of irrigation water applied when irrigation amounts are reduced. So, irrigating to achieve maximum yields requires some runoff, deep percolation and increased levels of soil water reserves. As water stress occurs and yields drop due to deficit irrigation, the amount of deep percolation, runoff and soil water reserves decrease. When only the first unit of irrigation water is applied almost all of the irrigation water will be used for ET. Thus, the fraction of the irrigation application that goes to ET decreases as the amount of irrigation water applied increases.

The term irrigation efficiency, or application efficiency, is often used in irrigation management. Application efficiency is referred to as the fraction of the irrigation water that remains in the crop root zone following irrigation. Irrigation efficiency is used in many ways and one must be careful to know the context of each situation. Frequently irrigation efficiency means the same thing as application efficiency, while in other situations irrigation efficiency means the fraction of the irrigation that is used for crop ET. Regardless of the definitions for irrigation efficiency, Figure 106 illustrates that both the application efficiency and the irrigation efficiency increase as irrigation applications are reduced leading to deficit irrigation. Application efficiency is often used to estimate the maximum amount of irrigation required for achieving the maximum crop yield. Many guidelines are available for the application efficiency for various systems. These refer to the efficiency when irrigating to achieve the maximum yield and are smaller than for deficit irrigation where some water stress occurs.

Figure 106 also illustrates that some rainfed yield generally occurs for most conditions in the Great Plains when no irrigation water is applied. In severe droughts some crops may not produce a harvestable yield on some soils. However, this is rare in the Great Plains due to the annual rainfall amounts and patterns that are typical for the region.

The maximum yield shown in Figure 106 represents an achievable yield on a particular farm when enough irrigation water is applied to avoid crop water stress. The maximum yield varies with production practices, soils and other factors. The maximum yield is not a hypothetical upper limit of the production potential of a crop species, it should be achievable if there was enough water.

The maximum irrigation requirement shown in Figure 106 represents the amount of irrigation water needed to achieve the maximum yield. The maximum irrigation amount is usually determined through irrigation scheduling. The maximum irrigation requirement depends on the crop ET, precipitation, soil type and the application efficiency of the irrigation system. The maximum requirement will naturally be larger for inefficient irrigation systems than for efficient systems.

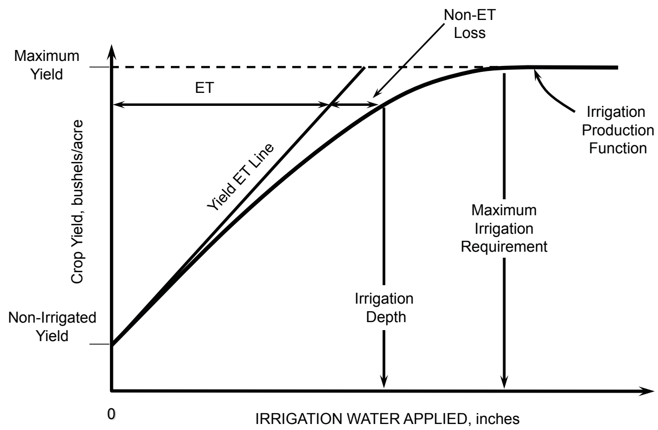


Figure 106. Illustration of the relationship between crop yield and ET or irrigation.

Some irrigators apply more irrigation water than needed to provide the maximum yield for their field and irrigation system. The yield-irrigation function shown in Figure 106 shows that yields are not affected much by overirrigating. Most soils in the Great Plains have adequate drainage so that soils do not become water logged with excess irrigation. If excess irrigation results in leaching of crop nutrients, it is possible to increase the level of fertilization, thus crop yields can be sustained with excess irrigation. While this is not good for groundwater quality, the fact remains that yields can be sustained.

The relationship between the irrigation depth and crop yield is called the irrigation production function or simply the production function. Irrigation management decisions depend on how crops respond to irrigation. The shape of the production function has a great deal to do with answering questions related to deficit irrigation.

Experiments were conducted at the West Central Research and Extension Center at North Platte, Nebraska in 1998 through 2000 to evaluate the crop response to irrigation (Schneekloth, et. al, 2004). The rainfall patterns for the three years are shown in Figure 107. The rainfall for the 1998 water year was about normal, while 1999 was wetter than normal and 2000 was quite dry. The crop production functions for each year are shown in Figure 108 for corn irrigated with furrow irrigation.

For a typical year (1998) the dryland yield was about 110 bushels/acre while the maximum yield was about 210 bushels per acre. The maximum irrigation requirement for that year was about 10 inches of water. The wet year (1999) produced higher dryland yields and required only about 6 inches of water for the maximum yield. In 2000 the precipitation for the year was about half of normal and no dryland yield was produced. The full irrigation requirement for 2000 was about 12 to 13 inches. The maximum yield did not vary much for the three years with only a range of about 10 bushels/acre.

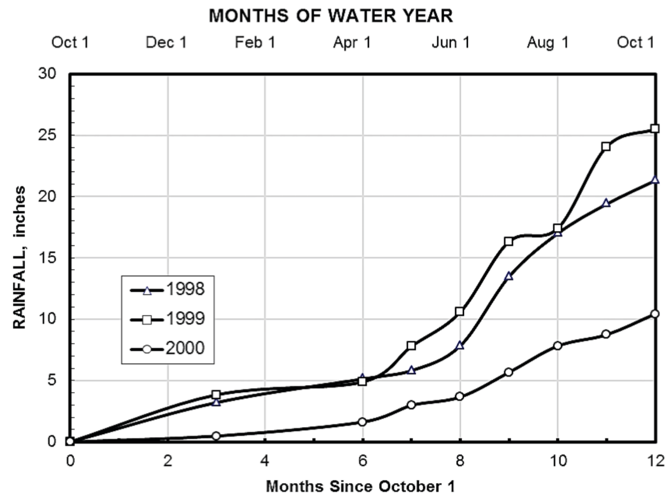


Figure 107. Precipitation patterns for three years at a furrow irrigated field near North Platte, NE.

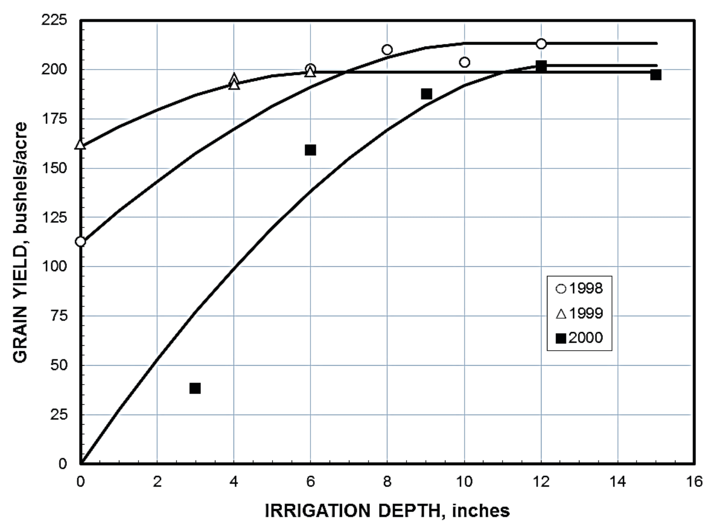


Figure 108. Crop production functions for three years for a surface-irrigated field near North Platte, NE.

Consumptive Use

For a given irrigation level the amount of crop ET exceeds that for dryland, or rainfed, conditions. The increase of ET is called consumptive use. From a watershed perspective consumptive use is the amount of liquid water in the basin that is converted to vapor and lost from the basin due to irrigation. Water policy makers and resource managers must balance the benefits of irrigation against the consumptive use to arrive at policies that achieve watershed management goals. Consumptive use is often the focus of interstate and interbasin deliberations concerning total watershed management. Deficit irrigation reduces ET which reduces consumptive use and is one method to manage consumptive use within basins. The total consumptive use for a watershed is the product of the amount of land irrigated and the amount of consumptive use per unit area. An alternative to deficit irrigation is to reduce the amount of land irrigated, or to combine acreage and deficit irrigation decisions. Thus, it is important to consider how deficit irrigation enters into watershed management as well at field or farm management.

Effective Precipitation

The impact of deficit irrigation depends on how producers manage precipitation. Effective precipitation is water retained in the soil that ultimately reduces irrigation requirements. Producers can increase effective precipitation by managing tillage and cropping systems to increase crop residues and enhance infiltration. This can minimize yield reductions that may result from irrigation water supply allocations. If these practices also reduce the amount of water that directly evaporates from the soil surface, especially just after rains or tilling, the water supply for the watershed could be enhanced. Deficit irrigation usually increases effective precipitation since soils are generally drier which increases infiltration rates and provides more storage in the root zone for large rains that could cause deep percolation when irrigating for maximum yield.

Net Return

Managing limited water supplies requires determination of how much area to irrigate and what depth of water to apply across the irrigated field. This decision requires analysis of the profitability of the dryland crop compared to the irrigated crop. To do this, we define a quantity called the net return from irrigation. The net return is not profit, as it only considers those costs directly associated with irrigation. If a cost does not change with irrigation depth or amount of irrigated area, then that cost will not affect how water is distributed. For the land that is irrigated, we compute the net return using the following equation:

$$NR_{irr} = \left[V_{irr} Y_{irr} - PC_{irr} - C_w \times D \right] \times A_{irr} - C_s$$

where;

NR_{irr} = net return for irrigated area ($)
A_{irr} = area of land irrigated (acres)
V_{irr} = net value of irrigated crop ($/bushel)
Y_{irr} = yield of irrigated crop (bushels/acre)
PC_{irr} = production cost for irrigated crop ($/acre)
C_w = cost to pump or buy a unit of water ($/acre-inch)
D = depth of irrigation water applied (inches)
C_s = startup cost for irrigation ($)

The startup cost includes connect charges for electrically powered irrigation wells and other costs that are necessary regardless of the amount of water applied for the year. The expressioin for the net return for dryland production is about the same as for an irrigated crop, except there are no costs for irrigation water. For dryland, the net return is:

$$NR_{dry} = \left(V_{dry} \times Y_{dry} - PC_{dry} \right) \times A_d$$

where;

NR_{dry} = net return from dryland area ($)
A_{dry} = area of dryland production (acres)
V_{dry} = net value of dryland crop ($/bushel)
Y_{dry} = yield of dryland crop (bushels/acre)
PC_{dry} = production cost for dryland crop ($/acre)

The total net return for the field is the sum of the net return for the irrigated and dryland areas:

$$NR_t = NR_{irr} + NR_{dry}$$

Some crop production costs are directly related to yield and are not a constant cost per acre. An example might be the cost of nitrogen fertilizer. The amount of nitrogen fertilizer needed per acre depends on the yield goal you establish. To account for input costs that are related to yield, the value of the crop is reduced from the selling price. For example, if you expect to need 1.2 pounds of nitrogen per bushel of crop produced, and if nitrogen costs $0.40/pound, then the value of the crop should be reduced by about $0.48/bushel. Other examples of yield related costs are expenses for hauling, handling and drying crops.

The amount of water available for the year must be distributed over the area irrigated. The area irrigated and the depth of water applied are related by:

$$A_{irr} = \frac{W_s}{D}$$

where W_s is the available water supply in acre-inches. For example, if you have 1,700 acre-inches of water available, you could apply 17 inches to 100 acres, or 13 inches to 130 acres.

The area that can be irrigated with a given water supply and irrigation depth can be calculated using the equation above. However, there are limits on the amount of land that can be irrigated. The upper limit is the size of the field. The lower limit is the amount of area that could be irrigated if the maximum yield was produced. Once the irrigated area has been determined, the area of dryland production can be determined:

Cost of Pumping Irrigation Water

The cost of pumping irrigation water is always important to producers and enters into the determination of the appropriate depth of irrigation water when water supplies are not limiting. In deficit irrigation management it is important to compute the cost of irrigation water and then determine if the depth of allocated water limits production or if high water costs make it more profitable to apply less water than needed to produce the maximum yield. The cost of pumping irrigation water (C_w) can be computed from procedures in chapter 7.

Water Miser Best Management Practices (BMP)

The Water Miser approach has been developed and tested to manage irrigation water applications when water supplies are limited. The method involves four fundamental steps. First, it is important to install and use good soil moisture monitoring equipment. As described in the Soil Water Management chapter, soil moisture monitoring equipment is a valuable tool that will enable an irrigation system operator to know and track how much water is available to the crop.

Secondly, it is important to evaluate when to begin irrigation. The Water Miser strategy delays irrigation during the reproductive growth stages. The crop is allowed to be stressed during the vegetative growth stages but irrigation application during the reproductive and grain fill stages attempt to preserve full yield potential. This is where it is important to know the capabilities of the irrigation system in terms of the time it takes to apply a given amount of water. Also, knowing how much available water is stored in the soil, how much water the crop is using, and what depth of application will allow room for possible rainfall will help in determining the proper start time.

It is also important to keep good rainfall and irrigation records. If the water holding capacity of the soil is known, rainfall and irrigation records can be useful in gauging the amount of water in the soil profile. For instance if we know that we received 1.2 inches of rainfall and the crop ET is approximately 0.3 inches/day, we know that this rain will give us 4 days of crop ET. Recording and tracking rainfall and irrigation applications can be just as important as monitoring soil moisture and crop water use.

Finally, one of the best ways to reduce water use with the Water Miser approach is to deplete the crop root zone at the end of the growing season. When crops are in the reproductive stage, the total water needed to get the crop to maturity should be determined. The University of Nebraska-Lincoln Extension NebGuide "Predicting the Last Irrigation of the Season" provides a worksheet to determine the amount water needed to supply a crop from a given growth stage to physiological maturity. Knowing the available water in the root zone at a given growth stage and the required crop water use to reach maturity allows determination of the irrigation required for the remainder of the growing season. This can facilitate pumping reduction by depleting soil water to the maximum extent at the end of the growing season. It is likely in the Great Plains that the root zone will be replenished by precipitation during the off season.

Water and Land Allocation

Crop yield will be reduced if a crop does not have adequate water for full ET. When the available water supply for irrigation is not enough to fully irrigate the crop, a decision must be made as to how to best use the limited supply. One possible scenario like this might be a field of 100 acres and an allocation of 6 inches (Figure 109). We need to determine if using deficit irrigation on the entire field will produce higher net returns than applying all of the water to part of the field and leaving the rest dryland.

This practice of applying less water than the crop needs to fully meet ET is called deficit irrigation. In a deficit irrigation system, the timing of irrigation applications becomes critical to the successful use of the limited irrigation water. Deficit irrigation attempts to get the most return for the irrigation water resource.

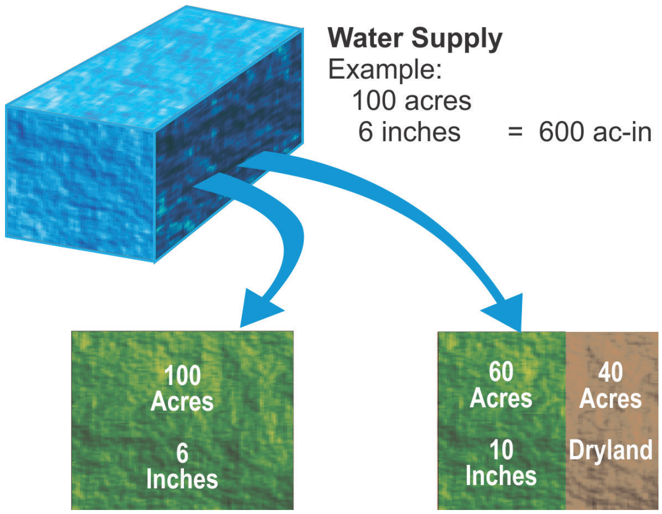


Figure 109. Water and land allocation trade-offs for deficit irrigation.

Optimal Annual Irrigation Depth Land-Limiting Conditions

When water is unlimited, you only need to decide if the yield increase will pay for the cost of pumping or purchasing the water. For example, suppose going from 14 to 16 inches produces an extra four bushels of crop and that the price of the crop is $2.50/bushel. This would increase income by $10/acre for using two inches of water. If the water costs $2.00/acre-inch, then the cost was only $4.00/acre. Since you received $10.00/acre and spent $4.00/acre, it pays to apply the extra water. You would continue to increase the application until the cost to apply an additional unit of water equaled the cost to apply the additional unit. We call this determining when the marginal cost equals the marginal return to irrigation. The depth of water applied in this case is called the land-limiting depth of irrigation (D_L).

The slope of the irrigation production function times the net value of the crop determines the marginal return. The land-limiting irrigation depth occurs where the marginal net return equals the marginal cost, or where the slope of the production function times the net value of the water equals the cost of pumping water:

$$V_{irr} \times \frac{\Delta Y}{\Delta D} = C_w$$

where $\Delta Y/\Delta D$ is the change in the yield for a unit change in irrigation depth (i.e., the slope of the production function at irrigation depth D_L.).

When land limits production, and not water, all of the irrigable area would normally be irrigated; thus the irrigated area equals the total area ($A_{irr} = A_t$). Irrigation will be practical if the net return is greater than zero. For most cases the value of yield produced from irrigation is high compared to the price or irrigation water and the optimal irrigation depth when water is not limited is usually near the full irrigation requirement.

Water-Limiting Conditions

If there is a limit on how much water can be applied for the season, the problem of how much water to apply is more complicated. If irrigation is profitable, then all of the available water supply will be used. The economic goals shifts from equating marginal costs to marginal net returns. The optimal strategy for water-limiting conditions is to maximize the average value of the irrigation water. The question is how to distribute the water supply over the area that can be irrigated in order to maximize the average value of the irrigation water. With deficit irrigation you should determine the amount of land area to irrigate and the amount of the field to plant to a dryland crop (Figure 109). It may not be optimal to irrigate the entire field, or to plant a smaller area that produces the maximum yield per acre.

For example, consider an average year for the furrow irrigated field at the West Central Research and Extension Center near North Platte shown in Figures 107 & 108. Research results show that 10 inches of irrigation produced a yield of about 210 bushels/acre and 6 inches produced about 185 bushels/acre. Suppose that you had a 100 acre field and that the amount of water available was only 600 acre-inches. One scenarios would be to irrigate the entire field with 6 inches of water which would produce 18,500 bushels of grain. A second alternative would be to apply 10 inches to 60 acres and to plant the rest of the field to a crop that was not irrigated. For the second scenario the total yield of the irrigated corn would be 12,600 bushels. Deficit irrigation of the field produced 5,900 more bushels of corn on the portion of the field that was irrigated.

To analyze water-limiting conditions it is important to consider the profitably of the dryland portion of the field. If the 40 acres of dryland cropping produces less profit than derived from the increased yield of irrigated corn (i.e., 5,900 bushels) then the first scenario using the deficit irrigation strategy would be preferred and the whole field should be irrigated at the 6 inch level. If the dryland crop was very profitable, then it would be optimal to irrigate nearer the 10 inch level that produced maximum yield. Of course, a range of irrigation levels is possible between the 6 and 10-

inch levels for this problem and the optimal depth could lie within this range. The goal of this section is to develop methods to determine the optimal depth of irrigation for water-limiting conditions.

The process for optimizing the net return for water-limiting conditions is illustrated in Figure 110. These results are for a 130 acre field that has a supply of water equivalent to a supply of 12 inches per acre for a total supply of 1560 inches. The irrigated crop is corn with the costs and yield function presented in a latter section of the paper. The net return per acre of land is plotted as a function of the depth of irrigation water applied. For this example the startup cost was distributed over the irrigated area to provide the net return per acre. The net return per acre of dryland is shown to be $98/acre on the vertical axis. The net return per acre of land increases until a depth of approximately 18 inches. This depth corresponds to the land-limiting depth of irrigation (D_L) and the net return per unit of land areas reaches a maximum of approximately $240/acre. The results show that applying more water for this case only increases pumping costs and net returns per acre decrease when more than 18 inches are applied. The problem here is that there is not enough water to apply 18 inches to 130 acres. That would require 2340 acre-inches and we only have 1560. If an irrigation depth of 18 inches was applied, the water allocation would only supply 87 acres (i.e., 1560 /18) and 43 acres would be devoted to the dryland crop (i.e., 130 - 87). The total net return for the field would be the sum of the net return for the irrigated land plus the dryland areas :

$$240\ \$/\text{acre} \times 87\ \text{acres} + 98\ \$/\text{acre} \times 43\ \text{acres} = \$25{,}094$$

The alternative of irrigating the whole 130 acres at a depth of 13 inches gives a net return per acre of 213 $/acre. In this case there would be 120 acres of irrigated land (1560 /13) and 10 acres of dryland. The total net return would be:

$$213\ \$/\text{acre} \times 120\ \text{acres} + 98\ \$/\text{acre} \times 10\ \text{acres} = \$26{,}540$$

The second scenario produced $1,446 more net return than the first option, or $11.12/acre more when averaged over the whole field.

The average net return per unit of irrigation water is the increase in net return above dryland conditions divided by the amount of water applied. For this example the total net return from the field if it were not irrigated would be 98 $/acre × 130 acres = $12,740. The average net return for the second scenario where the whole field was deficitly irrigated would be:

$$\frac{\$26{,}540 - \$12{,}740}{1560\ \text{acre-inches}} = 8.84\ \$/\text{acre-inch}$$

If the first scenario was used (i.e., 18 inches) the average net return would be 7.91 $/acre-inch.

The average net return of the water is also illustrated in Figure 110. The average net return per unit of water is equal to the slope of the line from the dryland point to a point on the irrigation net return curve. When 13 inches are applied the slope of the line would be:

$$\frac{213\ \$/\text{acre} - 98\ \$/\text{acre}}{13\ \text{inches}} = 8.84\ \$/\text{acre-inch}$$

This net return is the same as the average net return determined above for the whole field.

The optimal irrigation depth for water-limiting conditions can be determined graphically by pivoting a line through the dryland net return per acre to the angle where the line is tangent to the net return curve for irrigation. The point where the line is tangent to the irrigation net return curve will be the optimal water-limiting depth (D_w). Any other point on the irrigation net return function will produce a smaller slope and less total net return.

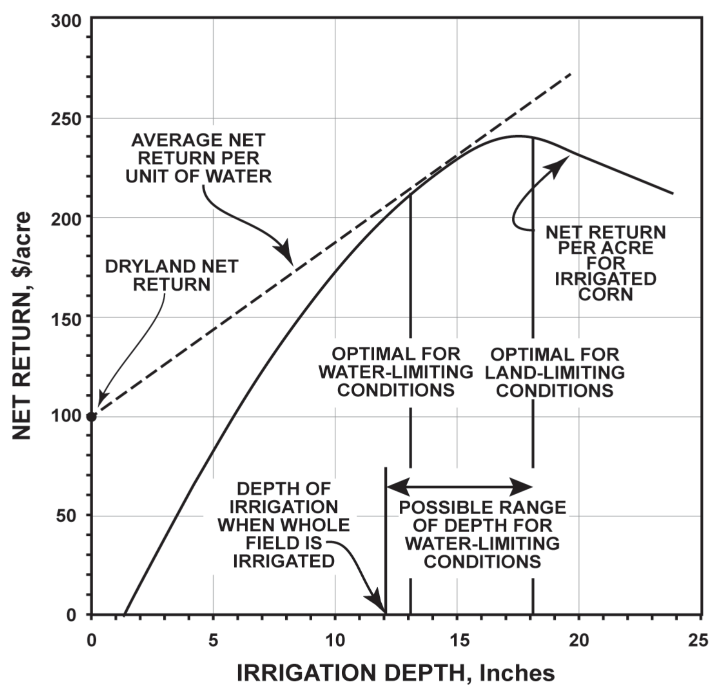


Figure 110. Example analysis needed to determine optimal depth for water-limiting conditions.

The net return for dryland is very important in determining the optimal water-limiting depth of irrigation and the amount of land to irrigate. When the dryland net return is high, the average net return to irrigation will be less and the irrigation depth will be closer to the land-limiting optimum. This will result in less irrigated area and more dryland production. When the dryland alternative is less profitable the average value of the irrigation water will be higher which will generally result in smaller irrigation depths and larger irrigated areas.

The optimal depth of irrigation for water-limiting conditions is constrained by the volume of the water supply and the land-limiting depth of irrigation. If the available water supply is spread across the entire field the smallest depth of irrigation per acre would occur, (i.e., for the example 1560 acre-inches / 130 acres = 12 inches). The optimal water-limiting depth should always be larger than or equal to this value. The optimal water-limiting depth will always be smaller than or equal to the land-limiting depth. These constraints can be expressed as:

$$\frac{W_s}{A_t} \le D_W \le D_L$$

where; W_s is the available irrigation water supply, A_t is the total land area that can be irrigated, D_W is the optimal water-limiting irrigation depth and D_L is the optimal land-limiting irrigation depth. Ultimately, the shape of the crop production function, the water supply, field size and the economics of productions will determine the optimal irrigation depth.

Basic concepts regarding crop responses to irrigation, irrigation efficiencies, computation of water costs and determination of the optimal irrigation depth for land-limiting and water-limiting conditions were presented in this section. Data used for illustrations are representative of conditions in the Great Plains; however, the results are for illustration and cannot be generalized to management recommendations. Analysis of conditions unique to individual operations are needed to develop deficit irrigation strategies. Strategies involve planning for annual and multi-year limitations and an in-season scheduling procedures to distribute a limited seasonal water supply throughout a growing season. The next section describes a program we have developed to assist with planning decisions.

Water Optimizer

Water Optimizer is a decision support tool developed to incorporate different crops, limited irrigation water, and the economics involved to determine the combination of crops and depths of irrigation to achieve the highest net return. The focus is to achieve the highest return from a limited supply of water. There are also options to perform either a multi-year analysis or a multi-field analysis. The multi-year program is useful when working within a multi-year water allocation, such as 60 inches of water for use over 5 years. The multi-field program can determine the best use of limited water supplies if trading water between fields is an option. All of the versions of Water Optimizer and the user guides can be downloaded at:
http://water.unl.edu/cropswater/optimizer

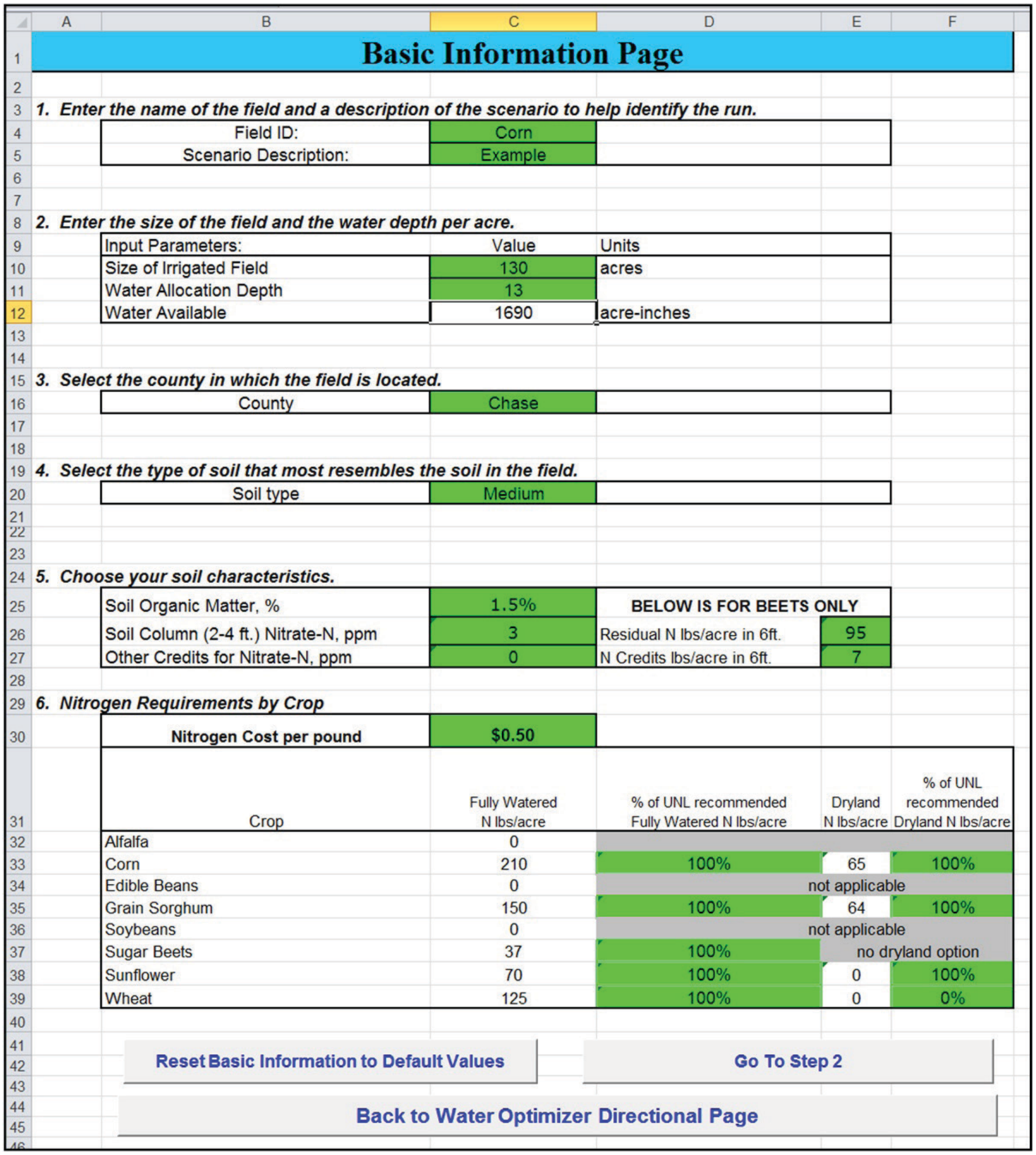
Here we will show an example of a single year, single field analysis. The first step, shown in Figure 111, is to input information about the field in question. The size of the field, the soil type and the county in which the field is located is needed. In this example, we have a field of 130 acres located in Chase County with a medium texture soil. This field has an irrigation allocation of 13 inches of water. Default fertility recommendations are included on the Basic Information page as well. These values can be changed as needed to represent production practices.

Next, your expected fully irrigated and dryland yields can be added for the crops you will consider growing. Default yields are used if you do not input your own expected yields. Figure 112 shows the selection of crops that growers would accept. One must select the crops that might be grown under irrigation and potential crops for dryland. For this case corn, edible beans, grain sorghum, and wheat were selected as potential irrigated crops, while corn, grain sorghum, sunflower, and wheat fallow or ecofallow rotations were chosen as dryland alternatives. There is also an option to set a minimum area for a crop. If it is undesirable to plant small areas of a crop, then a constraint can be set to limit that crop. For example , suppose the smallest area of alfalfa that is acceptable is 40 acres. In this case, the minimum irrigated area for alfalfa would be set to 40 acres.

Crop prices can be adjusted in the next screen (Figure 113). In this screen, default prices can be changed to reflect current or expected market prices for the crops. Any expected loan deficiency payment (LDP) or miscellaneous returns, such as grazing corn stalks, can also be added. The energy prices for the upcoming period can also be updated.

The cost of production per acre and the yield dependent production costs are also included on this page. Users can adjust the default production costs for each crop. This includes any input costs, field operations, and yield dependent costs. These adjustments can also be useful in analyzing which combination of crops will provide the highest return as input costs change.

Other steps include evaluating how much it costs to pump the irrigation water as in Figure 114. Documentation in the user manual explains the associated costs for pumping water and other parameter used in the program.



Basic Information Page

1. Enter the name of the field and a description of the scenario to help identify the run.

Field ID:	Corn
Scenario Description:	Example

2. Enter the size of the field and the water depth per acre.

Input Parameters:	Value	Units
Size of Irrigated Field	130	acres
Water Allocation Depth	13	
Water Available	1690	acre-inches

3. Select the county in which the field is located.

County	Chase

4. Select the type of soil that most resembles the soil in the field.

Soil type	Medium

5. Choose your soil characteristics.

		BELOW IS FOR BEETS ONLY	
Soil Organic Matter, %	1.5%		
Soil Column (2-4 ft.) Nitrate-N, ppm	3	Residual N lbs/acre in 6ft.	95
Other Credits for Nitrate-N, ppm	0	N Credits lbs/acre in 6ft.	7

6. Nitrogen Requirements by Crop

Nitrogen Cost per pound	$0.50

Crop	Fully Watered N lbs/acre	% of UNL recommended Fully Watered N lbs/acre	Dryland N lbs/acre	% of UNL recommended Dryland N lbs/acre
Alfalfa	0			
Corn	210	100%	65	100%
Edible Beans	0		not applicable	
Grain Sorghum	150	100%	64	100%
Soybeans	0		not applicable	
Sugar Beets	37	100%	no dryland option	
Sunflower	70	100%	0	100%
Wheat	125	100%	0	0%

Reset Basic Information to Default Values

Go To Step 2

Back to Water Optimizer Directional Page

Figure 111. Water Optimizer basic Information sheet.

Cropping Options and Information

Remember, this model is a single year planning model. Take into account what your last year's crop was on this field.
Do not choose both Corn Continuous and Corn After Beans OR Soybeans Continuous and Soybeans After Corn!

Cropping Options	Minimum Acres	Maximum Acres	Maximum Yields	Units	Market Price	LDP Payment	Total Value of Crop	Misc. Returns	Nitrogen lbs/acre	Fixed Costs	Dependent Costs
Irrigated Alfalfa											
Irrigated Corn, Continuous	0.0	130.0	201.3	Bushels	$3.75	$0.00	$3.75	$0.00	210.3	$228.82	$0.08
Irrigated Corn, After Beans											
Irrigated Edible Beans	0.0	130.0	2188.6	Pounds	$0.28	$0.00	$0.28	$0.00	0.0	$217.21	$0.08
Irrigated Grain Sorghum	0.0	130.0	139.5	Bushels	$3.05	$0.00	$3.05	$0.00	150.3	$149.10	$0.08
Irrigated Soybeans, Continuous											
Irrigated Soybeans, After Corn											
Irrigated Sugar Beets											
Irrigated Sunflowers											
Irrigated Wheat, After Row Crop	0.0	130.0	83.2	Bushels	$4.00	$0.00	$4.00	$0.00	124.9	$158.28	$0.08
Irrigated Canola											
Irrigated Camelina											
Dryland Alfalfa											
Dryland Corn, Continuous	0.0	130.0	54.8	Bushels	$3.75	$0.00	$3.75	$0.00	65.3	$196.38	$0.08
Dryland Corn, After Beans											
Dryland Grain Sorghum	0.0	130.0	60.8	Tons	$3.05	$0.00	$3.05	$0.00	63.7	$132.22	$0.08
Dryland Soybeans, Continuous											
Dryland Soybeans, After Corn											
Dryland Sunflower	0.0	130.0	0.0	Pounds	$0.16	$0.00	$0.16	$0.00	0.0	$111.43	$0.08
Dryland Wheat, After Row Crop											
Dryland Wheat - Fallow	0.0	130.0	45.3	Bushels	$4.00	$0.00	$4.00	$0.00	0.0	$130.84	$0.08
Dryland Eco-Fallow (Corn/Fallow/Wheat)	0.0	130.0	-	Bushels	-	-	-	$0.00	-	$237.60	$0.08

Figure 112. Water Optimizer crop selection sheet.

Water Optimizer Costs (Defaults are all Minimum Tillage)

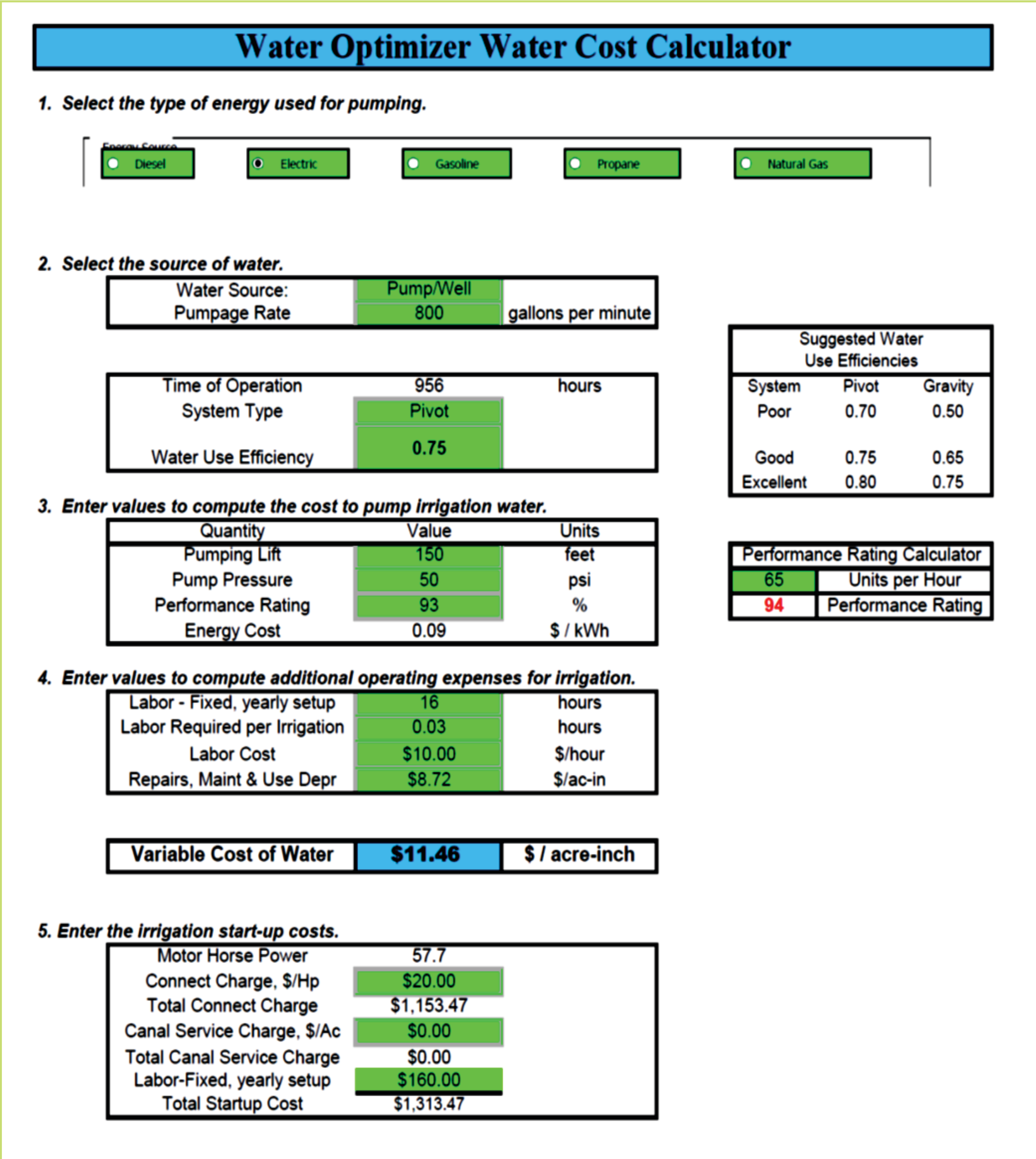
		Total Production Costs per acre	Total Dependent Costs per acre
Irrigated Crops	Alfalfa	$169.22	$5.92
	Corn, Continuous	$228.82	$0.08
	Corn, After Beans	$242.34	$0.08
	Edible Beans	$217.21	$0.08
	Grain Sorghum	$149.10	$0.08
	Soybeans, Continuous	$133.30	$0.08
	Soybeans, After Corn	$133.30	$0.08
	Sugar Beets	$357.10	$0.08
	Sunflower	$111.43	$0.08
	Wheat, after beans	$158.28	$0.08
	Canola	$164.64	$0.08
	Camelina	$107.59	$0.08
Dryland Crops	Alfalfa	$169.22	$5.92
	Corn, Continuous	$196.38	$0.08
	Corn, After Beans	$168.64	$0.08
	Grain Sorghum	$132.22	$0.08
	Soybeans. Continuous	$114.78	$0.08
	Soybeans, After Corn	$114.78	$0.08
	Wheat-Fallow	$130.84	$0.08
	Wheat, After Row Crop	$198.18	$0.08
	Sunflowers	$111.43	$0.08
	EcoFallow, C-W-F	$237.60	$0.08

Market Prices

Crop	Price at time of Sale	LDP Payment	Miscellaneous returns per acre	Units
Alfalfa	$120.00	$0.00	$0.00	Tons
Corn	$3.75	$0.00	$0.00	Bushels
Edible beans	$0.28	$0.00	$0.00	Pounds
Grain Sorghum	$3.05	$0.00	$0.00	Bushels
Soybeans	$9.25	$0.00	$0.00	Bushels
Sugar Beets	$32.00	$0.00	$0.00	Tons
Sunflower	$0.16	$0.00	$0.00	Pounds
Wheat	$4.00	$0.00	$0.00	Bushels
Canola	$0.15	$0.00	$0.00	Pounds
Camelina	$0.15	$0.00	$0.00	Pounds

Energy Input Costs	
Diesel Fuel ($/gal)	$2.40
Electric	$0.09
Gasoline	$2.20
Propane	$1.87
Natural Gas	$7.00

Figure 113. Water Optimizer crop prices sheet



Water Optimizer Water Cost Calculator

1. Select the type of energy used for pumping.

Energy Source

- ( ) Diesel
- (•) Electric
- ( ) Gasoline
- ( ) Propane
- ( ) Natural Gas

2. Select the source of water.

Water Source:	Pump/Well	
Pumpage Rate	800	gallons per minute

Time of Operation	956	hours
System Type	Pivot	
Water Use Efficiency	0.75	

Suggested Water Use Efficiencies		
System	Pivot	Gravity
Poor	0.70	0.50
Good	0.75	0.65
Excellent	0.80	0.75

3. Enter values to compute the cost to pump irrigation water.

Quantity	Value	Units
Pumping Lift	150	feet
Pump Pressure	50	psi
Performance Rating	93	%
Energy Cost	0.09	$ / kWh

Performance Rating Calculator	
65	Units per Hour
94	Performance Rating

4. Enter values to compute additional operating expenses for irrigation.

Labor - Fixed, yearly setup	16	hours
Labor Required per Irrigation	0.03	hours
Labor Cost	$10.00	$/hour
Repairs, Maint & Use Depr	$8.72	$/ac-in

Variable Cost of Water	**$11.46**	**$ / acre-inch**

5. Enter the irrigation start-up costs.

Motor Horse Power	57.7
Connect Charge, $/Hp	$20.00
Total Connect Charge	$1,153.47
Canal Service Charge, $/Ac	$0.00
Total Canal Service Charge	$0.00
Labor-Fixed, yearly setup	$160.00
Total Startup Cost	$1,313.47

Figure 114. Water Optimizer production costs sheet

The results screen (Figure 115) shows the combination of crops and irrigation depths to achieve the highest net return. In this case, Water Optimizer predicts a total net return of $25,015 from this field. It recommends 128 acres of continuous irrigated corn with an irrigation depth of 13.2 inches of irrigation. That leaves a small area of dryland wheat. It is impractical to plant such a small area individually, so a producer would likely irrigate the whole field with an average depth of 13 inches.

There is also a sensitivity analysis page that will show the effects that changing crop prices have on the combination of crops and irrigation depths.

These results serve as an application of the program for a specific field, location and set of parameters. Producers must ensure they have accurately obtained reliable information for their specific applications.

Summary

Limited water supplies are a growing challenge in irrigation management. Many techniques have been developed to help producers reduce their irrigation water use maximize the value of their available water supplies. Increasing residue cover, growing crops that require less water, and using a fallow rotation will decrease the water needed from irrigation. Deficit irrigation, the Water Miser strategy, and the Water Optimizer program have been developed to help irrigation system managers achieve the greatest return from the limited irrigation water supplies.

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Water Optimizer Crop Activates Summary Page

Field ID:	Corn
Scenario:	Example
County:	Chase
Soil Type:	Medium

CROP CHOICES AND RETURNS

	Crops	Was the Crop Evaluated?	Minimum Acres	Maximum Acres	Acres in Production	Water Applied	Yield Unit / Acre	Gross Return $/Acre	Total Cost $/Acre	Nitrogen Cost $/Acre	Net Return $/Acre	Total Net Return
Irrigated Crops	Alfalfa	No										$ -
	Corn, Continuous	Yes	0	130	128	13.2	183.03	$686.36	$395.20	$96.10	$195.06	$ 24,901
	Corn, after Beans	No										$ -
	Edible Beans	Yes	0	130	0	0.0	-	$345.18	$315.83	$0.00	$29.35	$ -
	Grain Sorghum	Yes	0	130	0	0.0	-	$154.75	$153.16	$26.31	-$24.71	$ -
	Soybeans, Continuous	No										$ -
	Soybeans, After Corn	No										$ -
	Sugar Beets	No										$ -
	Sunflowers	No										$ -
	Wheat, After Row Crop	Yes	0	130	0	0.0	-	$196.22	$162.20	$36.79	-$2.77	$ -
	Canola	No										$ -
	Camelina	No										$ -
Dryland Crops	Alfalfa	No										$ -
	Corn, Continuous	Yes	0	130	0		-	$205.57	$200.77	$32.64	-$27.83	$ -
	Corn, after Beans	No										$ -
	Grain Sorghum	Yes	0	130	0		-	$185.41	$137.08	$31.83	$16.49	$ -
	Soybeans, Continuous	No										$ -
	Soybeans, After Corn	No										$ -
	Sunflowers	Yes	0	130	0		-	$0.00	$111.43	$0.00	-$111.43	$ -
	Wheat, After Row Crop	No										$ -
	Wheat, after Fallow	Yes	0	130	2		45.33	$181.32	$134.46	$0.00	$46.86	$ 110
	Eco-Fallow	Yes	0	130	0		-	$128.96	$81.87	$18.43	$28.66	$ -
											Total Net Return	**$ 25,011**

PRICES, COSTS, & DRYLAND YIELDS

Crops	Dryland Yields	Total Price Received ($/Unit)	Misc. Returns (per acre)	Irrigated Costs Per Acre: Production Costs	Irrigated: Yield Dependent Costs	Irrigated: Nitrogen Cost	Dryland Costs Per Acre: Production Costs	Dryland: Yield Dependent Costs	Dryland: Nitrogen Cost	Dryland Net Return
Alfalfa	2.63	$120.00	0	$169.22	$5.92	$0.00	$169.22	$5.92	$0.00	$130.24
Corn, Continuous	54.82	$3.75	0	$228.82	$0.08	$96.10	$196.38	$0.08	$32.64	-$27.83
Corn, after Beans	60.30	$3.75	0	$242.34	$0.08	$32.81	$168.64	$0.08	$35.35	$17.31
Edible Beans	-	$0.28	0	$217.21	$0.08	$0.00				
Grain Sorghum	60.79	$3.05	0	$149.10	$0.08	$26.31	$132.22	$0.08	$31.83	$16.49
Soybeans, Continuous	19.68	$9.25	0	$133.30	$0.08	$0.00	$114.78	$0.08	$0.00	$65.65
Soybeans, After Corn	21.86	$9.25	0	$133.30	$0.08	$0.00	$114.78	$0.08	$0.00	$85.70
Sugar Beets	-	$32.00	0	$357.10	$0.08	$0.00				
Sunflowers	0.00	$0.16	0	$111.43	$0.08	$3.98	$111.43	$0.08	$0.00	-$111.43
Wheat, After Row Crop	34.00	$4.00	0	$158.28	$0.08	$36.79	$198.18	$0.08	$0.00	-$64.91
Canola	-	$0.15	0	$164.64	$0.08	$0.00				
Camelina	-	$0.15	0	$107.59	$0.08	$0.00				
Wheat, after Fallow	45.33	$4.00	0	$130.84	$0.08		$130.84	$0.08	$0.00	$46.86

Figure 115. Water Optimizer results.

Chapter 11. Center Pivot Management

Management Issues

Problems frequently occur in management of center pivots. Some of the issues that we observe include:

- Lack of knowledge regarding the depth of water applied per irrigation.
- Sprinkler installation and maintenance problems that reduce uniformity or efficiency.
- Inappropriate pressure to provide desired flow rate and uniformity.
- Sprinkler placement that decreases uniformity and does not provide expected evaporation savings.
- Runoff due to inappropriate sprinkler selection or system operation.
- Inappropriate monitoring of systems to ensure proper operation.
- System c apacity is not appropriate for crop needs.

We discuss some of these issues and provide simple evaluations that help identify problems and solutions.

Depth of Application

Accurate control of the depth of application is one of the advantages of center pivots. Utilizing this capability is difficult when the operator does not know how much water is applied each irrigation. Pivot manufacturers provide guides that describe the percent timer setting or other parameter to apply a specified depth of water. They also provide the time required to make a revolution of the pivot in the field for those settings. Occasionally these guides are lost or not passed along with the sale of irrigated land. We recommend that operators contact their dealer to get a replacement copy of the guide. If the manufacturer's guide is unavailable, the data in Table 27 provides a guide to the amount of water applied per day or week and the time to apply one inch of water for a range of system capacities. For example, if the system capacity was 5 gpm/acre, 0.27 inches per day would be applied by the system. This is equivalent to 1.9 inches of water per week or 3.8 days to apply one inch of water.

Sprinkler Installation/Maintenance Problems

Improper installation and maintenance of sprinkler packages can be an issue with center pivots. Installing sprinklers, regulators and/or nozzles at the wrong location along the lateral leads to reduced uniformity. Irrigators often over-irrigate the wet areas of the field when the uniformity of application is low. Measuring the depth of water caught in containers placed at short intervals under the pivot lateral provides a method to measure the uniformity of application. Plotting the depth of water caught in the containers along the lateral shows the location of dry and wet areas as illustrated in a test conducted by Rogers, et al. (2009), see Figure 116. The depth of water applied in zone A shows an average depth of application of about 0.4 inches. The depth oscillates in zone A but the pattern is reasonably uniform. A leak was observed at point B where the depth peaked at twice the depth in zone A. Zones C and D contain nozzling problems. In zone C sprinklers that should have been installed on the outer portion of zone C were installed on the inner portion of the Zone while the inner sprinklers were installed in the outer portion of the zone. The nozzle size should increase with distance from the pivot point. The installation problem results in excessive application of water in the inner portion of zone C while the outer half of Zone C received about 0.3 inches or 75% of the depth applied in zone A. Recall that about 24% of the field area is located under the seventh span of that pivot. Thus, the shortage of water in the outer portion of zone C represents a significant portion of the field. Most likely, this irrigator would over-irrigate the inner portion of the field due to signs of water stress in the outer portion of the pivot. The depth of application in zone D is excessive, more than twice the depth applied in the outer portion of zone C. The excessive application under zone D appears to be due to an improperly adjusted end-gun that probably had a larger arc of operation than called for in the design of the end-gun. The application is often excessive when the gun sweeps out too large of angle of rotation or the end-gun is set to throw water back onto the area under the outer portion of the pivot lateral.

Irrigators should obtain and use the sprinkler chart for their pivot. An example of the sprinkler chart is shown in Figure 117. The chart lists the distance of outlets from the pivot point, the flow rate needed from the sprinkler in that outlet, the nozzle size and color at that location along with the type of sprinkler device and regulator used at the sprinkler location. The sprinkler chart also includes the required pressure at the inlet to the pivot and the corresponding system flow. The sprinklers and nozzles installed on the pivot lateral should be compared to the sprinkler chart to ensure that the right devices are installed along the lateral. This will prevent the uniformity problem illustrated in Figure 116. The sprinkler installation only needs to be verified once.

Table 27. Depth of water applied during a day or week by system capacity, and time required to apply one inch of water.

System Capacity, gpm/acre	System Flow Rate for Field Size, acres 120	130	160	240	Depth Applied per Day, inches/day	Depth Applied per Week, inches/week	Days Required to Apply One Inch of Water
3	360	390	480	720	0.16	1.1	6.3
3.5	420	455	560	840	0.19	1.3	5.4
4	480	520	640	960	0.21	1.5	4.7
4.5	540	585	720	1080	0.24	1.7	4.2
5	600	650	800	1200	0.27	1.9	3.8
5.5	660	715	880	1320	0.29	2.0	3.4
6	720	780	960	1440	0.32	2.2	3.1
6.5	780	845	1040	1560	0.34	2.4	2.9
7	840	910	1120	1680	0.37	2.6	2.7
7.5	900	975	1200	1800	0.40	2.8	2.5
8	960	1040	1280	1920	0.42	3.0	2.4
8.5	1020	1105	1360	2040	0.45	3.2	2.2

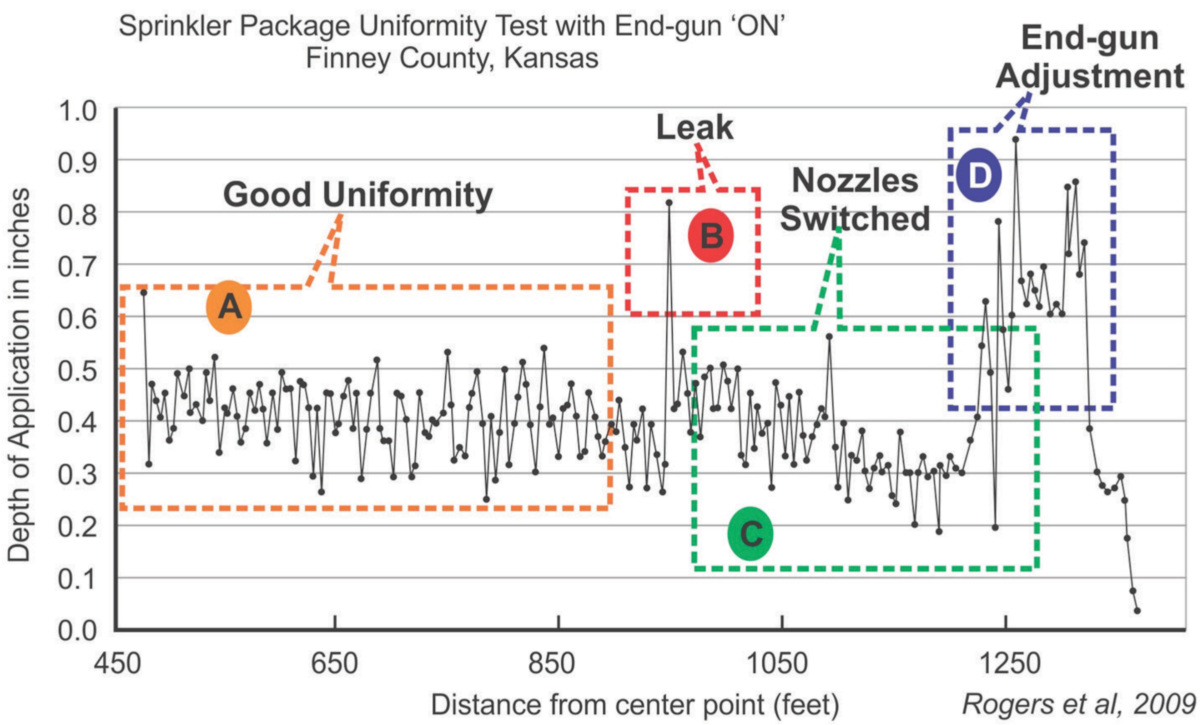

Figure 116. Results of a catch-can uniformity test for a center pivot in Kansas.

The sprinkler chart is also useful when a sprinkler is lost or broken. If a sprinkler is blown out and/or lost in the field, (Figure 118), determining the proper nozzle size for the replacement sprinkler is simple. If a sprinkler chart is not available, check the nozzle size of the sprinklers on either side of the sprinkler with the missing nozzle. The correct replacement is likely the same size as one or both of the neighboring nozzles.

Pressure Problems

Center pivots cannot operate properly if the pressure available at the inlet to the pivot is not appropriate. Two problems occur when the pressure at the pivot inlet is too low. First, the water available for the outer end of the pivot is inadequate and the depth of application tapers off in the outer spans which contains the majority of the area (top of Figure 119). The design pressure for the pivot was 40 psi with a system flow of 750 gpm. When the pressure at the pivot drops to 30 psi the average discharge at a point 1200 feet from the pivot is only 8 gpm while the design calls for 9.4 gpm. The reduced discharge will result in under irrigation at the end of the pivot.

Reduced pivot inflow is the second problem that occurs when the inlet pressure is too low. When pressure is 30 psi at the pivot inlet the flow through the pivot drops to 665 gpm instead of the intended flow of 750 gpm. Therefore, when irrigators thought they were applying an inch of water each irrigation they actually applied only 0.89 inches. This shortage would build throughout the season. Obviously, irrigators should monitor soil moisture to ensure that they keep up with crop water use during the season.

The summary in the lower portion of Figure 119 illustrates that both the depth of application and the system inflow rate both drop when the inlet pressure is too low. This will cause a reduction of uniformity as well.

The cost of pumping water increases substantially when the pressure is above the design value at the inlet to the pivot. The pivot pressure was three times the value of the pressure regulator for another field that we evaluated. The cost of pumping water for that situation was very expensive.

We recommend installing good pressure gages at the inlet to the pivot to ensure that the pivot is operating at the required pressure. The required pressure is available from the system chart for the pivot. It is also advisable to install a second pressure gage at the distal end of the pivot to check the available pressure when the outer portion of the pivot is on the highest hill in the field. Pressure gages are relatively inexpensive and are well worth their cost. You should also maintain the pressure gages from season to season, or given their modest cost you might just replace the pressure gage every few years.

```
 AS5054-1  24 Apr 2014 LINDSAY ,     7 TOWER,   740 gpm,    22 psi         PAGE  3

  ----OUTLET----    -REG-   PSI     ---GPM---   ----SPRINKLER-----   ---NOZZLE---
   No     Loc   Sep  Model  RegIn    Req     Del   Model  Plate   SpNo.

  111   271.3    9.8   LB10   27.8    2.1     2.1   A3000  Navy     26   #19 Gray w/trqu
  -x-                                               PLUG 3
  115   281.0    9.8   LB10   27.7    2.3     2.3   A3000  Navy     27   #20 Turquoise
  -x-                                               PLUG 3
  119   290.8    9.8   LB10   27.6    2.3     2.3   A3000  Navy     28   #20 Turquoise
  -x-                                               PLUG 3
  123   300.7    9.8   LB10   27.5    2.4     2.3   A3000  Navy     29   #20 Turquoise
  -x-                                               PLUG 3
  127   310.3    9.6   LB10   27.4    2.5     2.5   A3000  Navy     30   #21 Trqu w/yllw
  -x-                                               PLUG 3
  131   320.2    9.8   LB10   27.3    2.6     2.5   A3000  Navy     31   #21 Trqu w/yllw
  -x-                                               PLUG 3
  135   329.9    9.8   LB10   27.2    2.7     2.8   A3000  Navy     32   #22 Yellow
  -x-                                               PLUG 3
  139   339.7    9.8   LB10   27.1    3.1     3.0   A3000  Navy     33   #23 Yllw w/red
  -x-                                               PLUG 3

        349.6   TOWER NO.  2          INLINE PRESSURE:  27.0 psi

  143   350.6                                       PLUG
  144   352.5   12.8>  LB10   26.9    3.3     3.3   A3000  Navy     34   #24 Red
  -x-                                               PLUG 3
  148   362.3    9.8   LB10   26.8    2.9     3.0   A3000  Navy     35   #23 Yllw w/red
  -x-                                               PLUG 3
  152   372.0    9.8   LB10   26.7    2.9     3.0   A3000  Navy     36   #23 Yllw w/red
  -x-                                               PLUG 3
  156   381.8    9.8   LB10   26.6    3.0     3.0   A3000  Navy     37   #23 Yllw w/red
  -x-                                               PLUG 3
  160   391.7    9.8   LB10   26.5    3.1     3.0   A3000  Navy     38   #23 Yllw w/red
  -x-                                               PLUG 3
  164   401.3    9.6   LB10   26.5    3.2     3.3   A3000  Navy     39   #24 Red
```

Figure 117. Sprinkler chart for a center pivot.

Figure 118. Center pivot with a missing sprinkler.

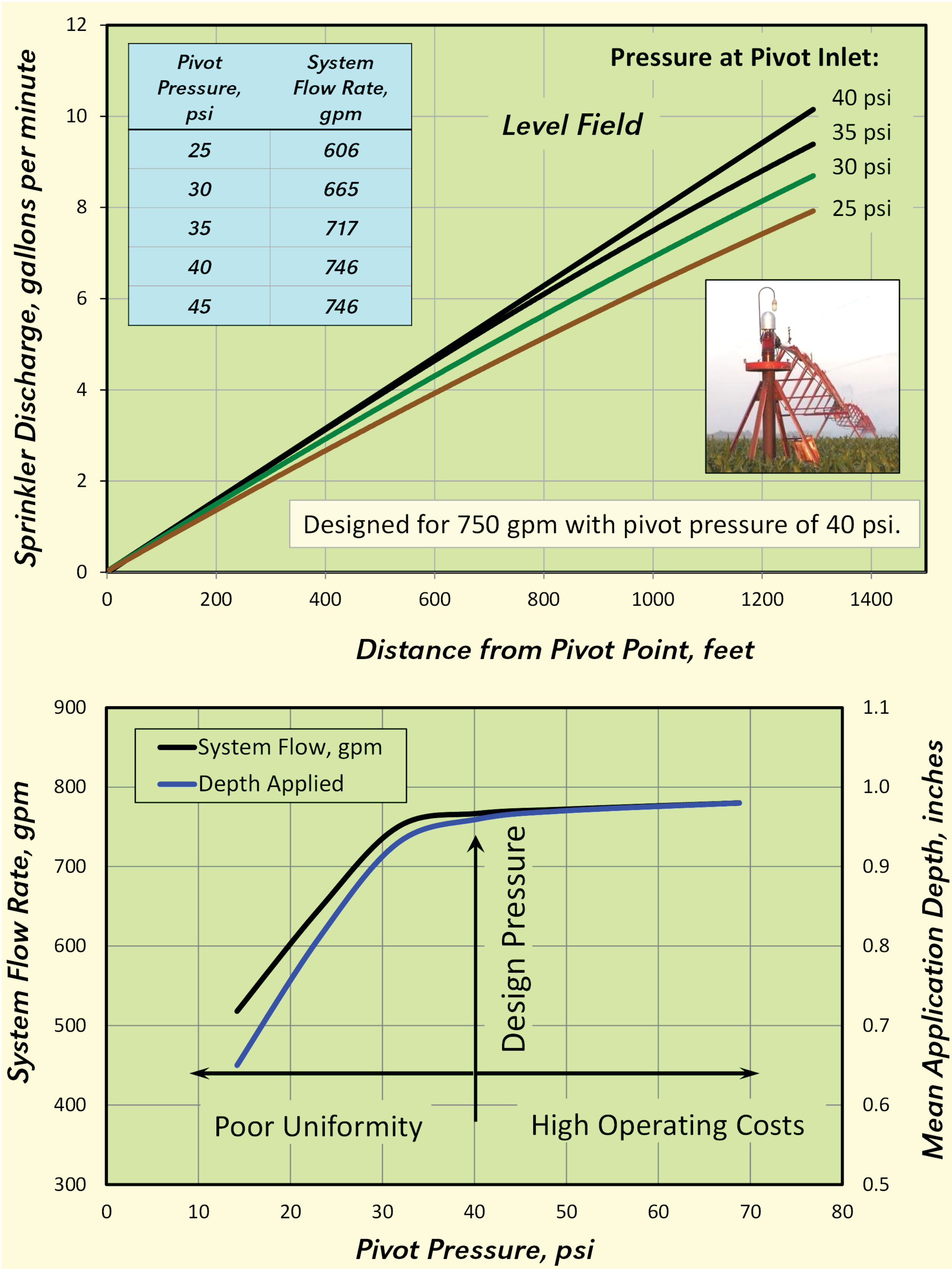

Figure 119. Effect of pivot pressures on the rate of flow into the pivot and the mean depth of application.

Reducing Runoff

Runoff is often the major problem for center pivot management. The following suggestions may assist in dealing with runoff issues.

1 Short term solutions

- Speed up the pivot to apply less water per application. We generally do not recommend irrigations smaller than about 0.7 inches per application to minimize the loss of water from increased evaporation from the soil and crop canopy.

2 Long term solutions

- Increase wetted diameter of sprinkler package. Usually requires a new sprinkler package. You can also use boom systems for severe conditions to expand the wetted diameter.

- Reduce gpm into pivot to reduce the peak application rate of the sprinkler package. However, be careful that the reduced system capacity is adequate to meet crop needs especially if the electric motor is on electrical load management and to provide for system downtime.

- Increase surface storage

  - Special tillage can increase surface storage by making small basins or reservoirs on the soil surface. These methods often require fields with little slope and involve extra tillage operations that increase fuel costs and require significant time to create storage.

  - Management systems to increase residue on the soil surface provide more surface storage and allow more time for infiltration.

- Increase soil infiltration rate

  - Reduced tillage generally enhances soil infiltration. Soil improvement may require several years after changing tillage practices.

The following checklist includes some activities that can help ensure that your pivot is operating efficiently.

Checklist of Pivot Maintenance and Management Activities

☐ 1. Obtain the sprinkler chart for your center pivot and ensure that the package was installed properly. Check with your dealer for a replacement copy if the sprinkler chart has been lost.

☐ 2. Determine if system capacity is adequate for your location using the procedures in Chapter 1. It may be necessary to adjust cropping patterns and scheduling practices when increasing capacities to recommended values is not possible.

☐ 3. Ensure that pump and pivot are properly matched. Make sure that the engine and pump speeds are correct for needed voltage or hydraulic pressure and for pressure at the pivot inlet, as well as for engine performance.

☐ 4. Buy a good pressure gage and operate the center pivot system at the design pressure. It is also a good idea to install a pressure gage at the distal end of the pivot. Periodically check the pressure at the far end of the pivot at its highest elevation. Pressure in the pivot lateral should be at least 5 psi above pressure regulator rating. The distal end of the pivot on the highest hill is often the most critical location in the field for monitoring.

☐ 5. Operate the system when crops are small and look for broken or plugged sprinklers or pressure regulators and leaks. If you have questions about the suitability of the existing sprinkler/regulator package, install a new regulator and sprinkler (with the proper nozzle) in the middle of each span and observe any differences between performance of new components and existing devices.

☐ 6. Observe water application under the outermost span on the steepest portion of the field and the soils with the lowest infiltration rate to see if you have runoff problems. If problems exist:
   - Reduce the application depth.
   - Use reduced tillage to enhance surface storage and infiltration.
   - Eventually evaluate if a different sprinkler package is necessary. Select sprinkler devices that provide at least as much wetted diameter as required in selection procedure.
   - Select devices with large droplet sizes when renozzling. If you irrigate a significant portion of the year on soils (especially fine sandy loam and silt loam soils) without residue cover, you may want to choose devices that provide medium diameter droplets.

☐ 7. Routinely maintain mechanical/electrical/hydraulic components.

☐ 8. Monitor annual or hourly energy use to determine if the pumping plant is operating efficiently.

☐ 9. When water supplies are limited special planning and in-season strategies are required to optimize the value of the water resource.

Appendix I. Pumping Cost Forms

Nebraska Lincoln EXTENSION

ESTIMATING IRRIGATION PUMPING COSTS
for Diesel Engines

1. Determine gallons of diesel fuel needed to pump an acre-inch of water if pump has a 100% performance rating.

		Your System			
	Example	**1**	**2**	**3**	**4**
Pressure at Pump Discharge, psi	50				
Pumping Lift, feet	125				
Diesel Needed Per Acre-Inch At 100% Rating	2.19				

Gallons of diesel fuel required to pump an acre-inch of water

	Pump Discharge Pressure, psi							
Pump Lift	10	20	30	40	50	60	70	80
0	0.21	0.42	0.63	0.84	1.05	1.26	1.47	1.69
25	0.44	0.65	0.86	1.07	1.28	1.49	1.70	1.91
50	0.67	0.88	1.09	1.30	1.51	1.72	1.93	2.14
75	0.89	1.11	1.32	1.53	1.74	1.95	2.16	2.37
100	1.12	1.33	1.54	1.75	1.97	2.18	2.39	2.60
125	1.35	1.56	1.77	1.98	2.19	2.40	2.61	2.83
150	1.58	1.79	2.00	2.21	2.42	2.63	2.84	3.05
175	1.81	2.02	2.23	2.44	2.65	2.86	3.07	3.28
200	2.03	2.25	2.46	2.67	2.88	3.09	3.30	3.51
250	2.49	2.70	2.91	3.12	3.33	3.54	3.75	3.97
300	2.95	3.16	3.37	3.58	3.79	4.00	4.21	4.42
350	3.40	3.61	3.82	4.03	4.25	4.46	4.67	4.88
400	3.86	4.07	4.28	4.49	4.70	4.91	5.12	5.33

2. Field Information:	**Example**	**1**	**2**	**3**	**4**
Annual Depth of Irrigation Applied, inches	13.5				
Irrigated Area, acres	130				
Total Volume of Water Pumped, acre-inches	1755				
3. Diesel Fuel Needed if at 100% of Performance Rating (multiply gallons needed per ac-inch times volume pumped)	3843				
4. Energy Actually Used Last Year, gallons	4800				
5. Potential Energy Savings (Subtract 3 from 4), gallons	957				
6. Price of Fuel, (Cost $ / gallon)	3.50				
7. Potential Annual Savings, $, (Multiply 5 by 6)	3350				

Notes:

1. Determine kilowatt-hours of electricity needed to pump an acre-inch if at 100% performance rating.

	Your System: Example	1	2	3	4
Pressure at Pump Discharge, psi	50				
Pumping Lift, feet	125				
Electricity required per acre-inch if at 100% performance rating	30.98				

Kilowatt-hours per acre-inch of water pumped

	Discharge Pressure, psi							
Lift	10	20	30	40	50	60	70	80
0	2.98	5.95	8.93	11.90	14.88	17.85	20.83	23.80
25	6.20	9.17	12.15	15.12	18.10	21.07	24.05	27.03
50	9.42	12.39	15.37	18.34	21.32	24.29	27.27	30.25
75	12.64	15.61	18.59	21.56	24.54	27.51	30.49	33.47
100	15.86	18.83	21.81	24.78	27.76	30.73	33.71	36.69
125	19.08	22.05	25.03	28.00	30.98	33.96	36.93	39.91
150	22.30	25.27	28.25	31.22	34.20	37.18	40.15	43.13
175	25.52	28.49	31.47	34.44	37.42	40.40	43.37	46.35
200	28.74	31.71	34.69	37.67	40.64	43.62	46.59	49.57
250	35.18	38.15	41.13	44.11	47.08	50.06	53.03	56.01
300	41.62	44.60	47.57	50.55	53.52	56.50	59.47	62.45
350	48.06	51.04	54.01	56.99	59.96	62.94	65.91	68.89
400	54.50	57.48	60.45	63.43	66.40	69.38	72.35	75.33

2. Field Information:	Example	1	2	3	4
Annual Depth of Irrigation Applied, inches	13.5				
Irrigated Area, acres	130				
Volume of Water Pumped, acre-inches	1755				
3. Electricity Needed if at 100% Performance Rating (multiply kW-hr needed per acre-inch by the water pumped)	54,369				
4. Energy Actually Used Last Year, kW-hr	68,000				
5. Energy Savings (Subtract 3 from 4), kW-hr	13,631				
6. Electricity Cost, $ / kW-hr	0.07				
7. Potential Annual Savings, $ (Multiply 5 by 6)	954				

Notes:

1. Determine gallons of gasoline needed to pump an acre-inch if pump has a 100% performance rating.

	Example	Your System 1	2	3	4
Pressure at Pump Discharge,, psi	50				
Pumping Lift, feet	125				
Gasoline Needed Per Acre-Inch At 100% Rating	3.17				

Gallons of gasoline required per acre-inch of water pumped

	Discharge Pressure, psi							
Lift	10	20	30	40	50	60	70	80
0	0.30	0.61	0.91	1.22	1.52	1.82	2.13	2.43
25	0.63	0.94	1.24	1.55	1.85	2.15	2.46	2.76
50	0.96	1.27	1.57	1.87	2.18	2.48	2.79	3.09
75	1.29	1.60	1.90	2.20	2.51	2.81	3.12	3.42
100	1.62	1.92	2.23	2.53	2.84	3.14	3.45	3.75
125	1.95	2.25	2.56	2.86	3.17	3.47	3.77	4.08
150	2.28	2.58	2.89	3.19	3.50	3.80	4.10	4.41
175	2.61	2.91	3.22	3.52	3.82	4.13	4.43	4.74
200	2.94	3.24	3.55	3.85	4.15	4.46	4.76	5.07
250	3.60	3.90	4.20	4.51	4.81	5.12	5.42	5.72
300	4.25	4.56	4.86	5.17	5.47	5.77	6.08	6.38
350	4.91	5.22	5.52	5.82	6.13	6.43	6.74	7.04
400	5.57	5.87	6.18	6.48	6.79	7.09	7.39	7.70

2. Field Information:	Example	1	2	3	4
Annual Depth of Irrigation Applied, inches	13.5				
Field Size, acres	130				
TotalVolume of Water Pumped, acre-inches	1755				
3. Gasoline Needed if at 100% of Performance Rating (multiply gallons needed per acre-inch by volume pumped)	5556				
4. Energy Actually Used Last Year, gallons	7000				
5. Energy Savings (Subtract 3 From 4), gallons	1444				
6. Gasoline Cost, $/gallon	2.75				
7. Potential Annual Savings, $, (Multiply 5 by 6)	3971				

Notes:

1. Determine amount of natural gas (1000 ft^3) needed to pump an acre-inch if at 100% performance rating.

	Example	Your System 1	2	3	4
Pressure at Pump Discharge, psi	50				
Pumping Lift, feet	125				
Natural Gas Needed Per Acre-Inch At 100% Rating, 1000 ft^3	0.444				

Thousand cubic feet of natural gas per acre-inch of water pumped

	Discharge Pressure, psi							
Lift	10	20	30	40	50	60	70	80
0	0.043	0.085	0.128	0.171	0.213	0.256	0.299	0.341
25	0.089	0.132	0.174	0.217	0.260	0.302	0.345	0.388
50	0.135	0.178	0.220	0.263	0.306	0.348	0.391	0.434
75	0.181	0.224	0.267	0.309	0.352	0.395	0.437	0.480
100	0.227	0.270	0.313	0.355	0.398	0.441	0.484	0.526
125	0.274	0.316	0.359	0.402	0.444	0.487	0.530	0.572
150	0.320	0.363	0.405	0.448	0.491	0.533	0.576	0.619
175	0.366	0.409	0.451	0.494	0.537	0.579	0.622	0.665
200	0.412	0.455	0.498	0.540	0.583	0.626	0.668	0.711
250	0.505	0.547	0.590	0.633	0.675	0.718	0.761	0.803
300	0.597	0.640	0.682	0.725	0.768	0.810	0.853	0.896
350	0.689	0.732	0.775	0.817	0.860	0.903	0.945	0.988
400	0.782	0.824	0.867	0.910	0.952	0.995	1.038	1.081

2. Field Information:	Example	1	2	3	4
Annual Depth of Irrigation Applied, inches	13.5				
Field Size, acres	130				
TotalVolume of Water Pumped, acre-inches	1755				
3. Natural Gas Needed if at 100% Performance Rating (multiply 1000 ft^3 needed per acre-inch by volume pumped)	780				
4. Energy Actually Used Last Year, 1000 ft^3	1000				
5. Energy Savings (Subtract 3 From 4), 1000 ft^3	220				
6. Price of Fuel, (Cost $ / 1000 ft^3)	9.00				
7. Potential Annual Savings, $, (Multiply 5 by 6)	1980				

Notes:

ESTIMATING IRRIGATION PUMPING COSTS
for Propane Engines

1. Determine gallons of propane needed to pump an acre-inch if pump has a 100% performance rating.

	Example	Your System 1	2	3	4
Pressure at Pump Discharge, psi	50				
Pumping Lift, feet	125				
Propane Needed Per Acre-Inch At 100% Rating	3.98				

Gallons of propane required to pump an acre-inch of water

	Discharge Pressure, psi							
Lift	10	20	30	40	50	60	70	80
0	0.38	0.76	1.15	1.53	1.91	2.29	2.68	3.06
25	0.80	1.18	1.56	1.94	2.32	2.71	3.09	3.47
50	1.21	1.59	1.97	2.36	2.74	3.12	3.50	3.88
75	1.62	2.01	2.39	2.77	3.15	3.53	3.92	4.30
100	2.04	2.42	2.80	3.18	3.57	3.95	4.33	4.71
125	2.45	2.83	3.21	3.60	3.98	4.36	4.74	5.13
150	2.86	3.25	3.63	4.01	4.39	4.78	5.16	5.54
175	3.28	3.66	4.04	4.42	4.81	5.19	5.57	5.95
200	3.69	4.07	4.46	4.84	5.22	5.60	5.98	6.37
250	4.52	4.90	5.28	5.67	6.05	6.43	6.81	7.19
300	5.35	5.73	6.11	6.49	6.87	7.26	7.64	8.02
350	6.17	6.56	6.94	7.32	7.70	8.08	8.47	8.85
400	7.00	7.38	7.76	8.15	8.53	8.91	9.29	9.68

2. Field Information:	**Example**	**1**	**2**	**3**	**4**
Annual Depth of Irrigation Water Applied, inches	13.5				
Irrigated Area, acres	130				
Total Volume of Water Pumped, acre-inches	1755				
3. Propane Fuel Needed if at 100% of Performance Rating (multiply gallons needed per acre-inch by volume pumped)	6984				
4. Energy Actually Used Last Year, gallons	8500				
5. Potential Energy Savings (Subtract 3 from 4), gallons	1516				
6. Price of Fuel, (Cost $ / gallon)	1.70				
7. Potential Annual Savings, $ (Multiply 5 by 6)	2577				

Notes:

INVESTMENT ANALYSIS

The breakeven investment for improving a pumping plant is the potential annual savings in energy costs due to improvement multiplied by the series present worth factor.

Series Present Worth Factors

Period, years	Annual Interest Rate 5%	6%	7%	8%	9%	10%	12%
3	2.72	2.67	2.62	2.58	2.53	2.49	2.40
4	3.55	3.47	3.39	3.31	3.24	3.17	3.04
5	4.33	4.21	4.10	3.99	3.89	3.79	3.60
6	5.08	4.92	4.77	4.62	4.49	4.36	4.11
7	5.79	5.58	5.39	5.21	5.03	4.87	4.56
8	6.46	6.21	5.97	5.75	5.53	5.33	4.97
9	7.11	6.80	6.52	6.25	6.00	5.76	5.33
10	7.72	7.36	7.02	6.71	6.42	6.14	5.65
12	8.86	8.38	7.94	7.54	7.16	6.81	6.19
15	10.38	9.71	9.11	8.56	8.06	7.61	6.81
20	12.46	11.47	10.59	9.82	9.13	8.51	7.47
25	14.09	12.78	11.65	10.67	9.82	9.08	7.84

Breakeven Cost = Annual Savings * Series Present Worth Factor

	Example	Your System 1	2	3	4
Annual Savings, $	1,980				
Interest, %	9				
Recovery Period, years	5				
Series Present Worth Factor, Table Above	3.89				
Breakeven Investment, $	7,702				

(Annual Savings times Series Present Worth Factor)

Notes:

Appendix II. Unit Conversions for Irrigation Mmanagement.

Volume, weight, and flow units			
1 gallon (gal)	= 231 cubic inches (in3)		
	= 0.13368 cubic feet (ft3)		
1 gallon of water weighs	= 8.345 pounds (lb)		
1 million gallons (mg)	= 3.0689 acre-feet (ac-ft)		
	= 133,700 cubic feet (ft3)		
1 cubic foot water	= 1728 cubic inches (in3)		
	= 7.48 gallons		
1 cubic foot of water weighs	= 62.4 pounds (lb)		
1 acre-foot (ac-ft)	= amount of water to cover 1 acre 1 foot deep		
	= 43,560 cubic foot (ft3)		
	= 325,850 gallons		
	= 12 acre-inches (ac-in)		
1 acre-inch per day (ac-in/da)	= 18.7 gallons per minute (gpm)		
1 million gallons (mg)	= 3.0689 acre-feet (ac-ft)		
1 million gallons per day (mgc	= 1.547 cubic feet per second (ft3/s),		
	= 695 gallon per minute (gpm)		
1 cubic foot per second	= 448.83 (typically rounded to 450) gallons per minute (gpm)		
	= 7.48 gallons per second		
	= 0.646 million gallons per day (mgd)		
	= 0.992 (typically rounded to 1) acre-inch per hour (ac-in/hr)		
	= 1.983 (typically rounded to 2) acre-feet per day (ac-ft/d)		
Pressure units			
1 atmosphere (1 bar)	= 14.697 pounds per square inch (lb/in2)		
	= 2116.3 pounds per square foot (lb/ft2)		
	= 33.93 feet of water		
	= 29.92 inches of mercury		
1 pound per square inch	= 144 pounds per square foot		
	= 2.31 feet of head of water		
1 pound per square foot	= 48 Pa = .0048 kPa		
1 foot head of water (ft)	= 0.433 pounds per square inch		
	= 0.0295 atmospheres (bars)		
Energy units			
	1 hp = 0.746 kw		
	1 kw = 1.3405 hp		
Soil and water chemistry units			
1 meq/liter	= 1 mg/liter/equiv. weight	1 milligram (mg) / Lite	= 1 ppm
1 milliter (mL) water	= 1 cubic centimeter (cc) water	1 milliliter (mL) water	= 1 milligram (mg)
Element	Equivalent weight	Element	Equivalent weight
Ca	2	CO3	30
Mg	12.2	HCO3	61
Na	23	SO4	48
Cl	35.4	NO3-N	14
10 ppm Nitrate – Nitrogen	= 27.1 lb of N /ac-ft of water	= 2.26 lb of N/ac-in of water	

Notes

Notes

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