DRAFT

CENTER PIVOT IRRIGATION

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INTRODUCTION

The first "Self-Propelled Sprinkling Irrigating Apparatus" was invented in 1948 and patented in 1952 by Frank Zybach in eastern Colorado. The early systems were the foundation of the development of modern self-propelled center pivot and linear move irrigation systems. These very adaptable water application methods have experienced tremendous growth around the world in recent years due to: 1) their potential for highly efficient and uniform water applications; 2) their high degree of automation requiring less labor than most other irrigation methods; 3) large areal coverage; and 4) their ability to economically apply water and water soluble nutrients over a wide range of soil, crop and topographic conditions. Most of the following discussion is directed towards center pivot machines although much will also apply to lateral move machines.

Approximately one third of all irrigation, or about 60% of all sprinkler irrigated lands (about 125,000 machines on approximately 19.5 million acres [7.9 million ha]) or about 29% of the total irrigated area, in the USA utilizes self-propelled irrigation systems, mostly center pivots (CP). These sprinkler irrigation systems have allowed agricultural development "marginal" lands unsuitable for surface irrigation ranging from light sandy soils and heavy clays with large variations in topography and soil types within the same field. For these reasons, center pivot irrigation in the USA has increased by more than 50% from 1986 to 1996.

A standard 125 ac (~50 ha) center pivot system will cost US$35,000 to US$45,000 excluding land and water supply development costs. Water development costs depend on the source of water and power (i.e., electric, diesel or natural gas). Generally, the largest annual costs for these machines are for power or fuel to pump water.

Because of the semi-automatic operation of center pivots and lateral moves, it is relatively easy to carefully manage soil water levels. Almost all crops including sugar cane, orchard and vines as well as more traditional field crops such as maize, potatoes, small grains, alfalfa, and vegetable crops can and have been successfully irrigated with center pivot water application systems under a wide range of conditions. Some center pivot irrigated crops require special cultural practices such as planting in circles or the use of small pits or reservoirs in the furrows to facilitate infiltration on heavy soils and prevent surface runoff. Application efficiencies can range as high as 80% or more depending on management and a properly designed installation for the site.

In this presentation, I will discuss the general characteristics of self-propelled center pivot and lateral move irrigation systems, their management and general design concerns. I will finish with a discussion of the future directions for center pivot irrigation including the potential for precision (site specific) irrigation and chemigation applications.

GENERAL CHARACTERISTICS

There are considerable variations in construction of these large machines between the different manufacturers. However, a center pivot or lateral move basically consists of pipeline (lateral) mounted on motorized structures (towers) with wheels for locomotion. A center pivot machine rotates around a "pivot" point in the center of the field whereas a lateral move machine travels along a straight path and has a separate guidance system. Sprinkler outlets are installed on the top a pipe supported by steel trusses between adjacent tower structures. The towers are usually 90 to 200 ft (30 to 60 m) apart and each tower has a 1 hp motor and sits on two large rubber or steel tires. The combination of pipe, truss and sprinklers between two towers is called a span. Flexible couplers at each tower connect the pipes of two adjacent spans. The maximum length of span is a function of pipe size, pipe thickness (strength), field slope and topography. Span length does not have to be uniform; in fact, it is often varied to match

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field dimensions or to provide adequate clearance between the truss and soil surface on rolling terrain. An "overhang" is a smaller pipe with sprinklers that is often suspended by cables beyond the outermost tower(s) to increase the wetted area. Large volume end guns and corner systems may also be added to the end of a machine to increase the wetted area in the corners or to cover additional areas. Machines can be more than 4900 feet (1000 m) long although the most common length of a basic machine is about 1300 ft (~400 m). The distance between the trusses and the ground can range from 4 to 14 ft (1.2 to 4.3 m) with most between 8 and 9 ft (2.5 and 2.8 m). Basic system life should be 15 to 20 years not including sprinkler heads, pumps and other ancillary equipment.

Most machines are powered by electricity, although some manufacturers use hydraulic motors which are more expensive. A one constant speed horsepower electric or hydraulic drive motor is used to propel each tower. Tower motors should always be covered to extend their useful life. Electric power wires and/or hydraulic lines run the length of the machine with control boxes or valves at each tower. A primary control panel is usually located at the pivot base or at the engine on lateral moves. Hydraulic powered systems have a higher initial cost but may have lower annual costs because of lower maintenance and operational costs. Various manufacturers are looking at using more expensive variable speed electric motors to reduce start-stop effects on uniformity, especially with chemigation systems.

Not including a pivot base structure, there can be one to fifteen or more towers on each system. Towers are usually identified by number starting with the tower closest to the pivot base or the linear move engine/pump assembly. The towers should always follow the same tracks through the field. Equipment crossings and problems with traction as well as runoff from the compacted, wet wheel tracks are sometimes serious concerns.

Keeping linear move and center pivot machines in good alignment is critical to proper operation. Substantial damage can occur to the equipment and the crops if the alignment system fails. Alignment sensors are located on the pipeline at each tower causing the tower motor to start or stop . Alignment is controlled by electronic strain gauges, radio or laser controlled sensor systems. Often the first tower (closest to primary controls) will have an additional adjustable timer that will turn off the entire system if that tower does not move at least once every two to five minutes for extra protection against alignment system failures. Inadequate traction at a tower will often cause alignment problems.

Generally, the tower farthest from the pivot point controls the movement of the entire machine. Minimum rotation times (maximum speed) are commonly between 14 and 20 hours (2 to 3 m/min at the outer tower). Special high speed gear boxes can be installed on each tower to reduce rotation times to less than 12 hours (i.e., 4.3 m/min at the outer tower) which is often desirable on sandy or cracking clay soils. Timing controls at the control panel determine the relative average speed of the outer tower. The on-off cycle time of the outer control tower is usually about 1 minute (i.e., on a 50% speed setting, the outer motor is on 30 seconds in every minute.) A 100% setting causes the machine to travel at maximum speed (minimum rotation time) whereas a 50% setting results in the outer tower moving at half the maximum speed. Of course, the slower the rotation speed, the greater the amount of water applied. All the other towers try to stay in alignment with the end tower as regulated by the alignment system. However, tower movement in the interior of the system is somewhat random and start and stop times of 1 to 3 minutes may occur. Thus, because of the start-stop action the uniformity coefficients in the direction of travel are largest near the pivot and the end tower and the smallest near the center of the irrigation system.

Since all the towers on standard electric systems typically have the same motors and gearing ratios, the towers start and stop to stay in alignment. The start-stop action of the towers is not usually a problem with water application uniformity which is averaged over several days. However, with pesticides becoming more specific, applied in small amounts and costing several dollars per gram, this jerky movement may present a concern if pesticides are to be applied through the irrigation water or if a separate system attached to the center pivot trusses. Costly variable speed electric motors on each tower may be justified for pesticide systems where uniformity is critical. Hydraulically powered tower motors can be adjusted so that there is no start-stop movement and applications are more uniform.

Flow requirements for center pivots and lateral move systems are defined in terms of total flow supplied to the system or the total system capacity, Q_T (gpm), for hydraulic requirements, and gross system capacity, Q_g (gpm/ac), for irrigation requirements and management. Q_g is defined as the total system capacity, Q_T, divided by the total irrigated area. Standard inside diameters of center pivot pipes are 5.31, 5.74, 6.38, 7.76, 8.37 and 9.76 inches (135 mm, 146 mm, 162 mm, 197 mm, 212.7 mm and 247.8 mm, respectively) with most (50-52 hectare)125-130 acre systems using 6.38 inch (162 mm) steel tubing with a wall thickness of 0.11 inch (2.77 mm).

The two types of sprinklers used with center pivot and linear move systems are "impact" and "spray" heads. Impacts (traditional, older style impact drive) are generally low pressure, low angle (6° to 15°) heads mounted directly on the top of the pivot lateral pipe. Spray heads are subdivided into sprayers and "rotators." Sprays provide a mist or small jets that can also be mounted on top of the pipe but are more commonly installed at the bottom end of flexible drop tube connected to a U-shaped "gooseneck" on the lateral pipe. The height of the sprinklers may be adjusted throughout the season to maintain them above the crop canopy but this may negatively affect uniformity. *The height, location, spacing, size and the discharge from each head are specified in the sprinkler "package" from the manufacturer.* A standard 1300 ft (400 m) long center pivot will have 100 to 110 sprinklers. Low pressure spray type sprinkler heads mounted close to the canopy are probably the most popular to reduce wind and evaporation losses although low pressure impact heads on the pivot lateral are still used in some areas. Use of high pressure impact heads is becoming rare. Use of pressure regulators or flow control nozzles is very common with low pressure systems.

Water losses from spray heads near the top of the canopy typically range from 0-2% due to droplet evaporation, wind drift is usually less than 5%, evaporation from crop canopy ranges from 4 to 8%, and soil evaporation less than 2% whereas runoff may range from 0 to 15% or more depending on slope and soil conditions. Spray heads and impacts mounted on top of the pipe lateral may have droplet evaporation and wind drift losses as high as 15%. Evaporation may slightly offset crop water use, but this amount is difficult to measure or calculate and is usually less than 15% of total ET. For spray irrigation on drops over a crop with a full canopy, application efficiencies of about 90 to 92% are attainable with no surface runoff whereas sprinklers on the top of the pipe may attain efficiencies from 80-85%.

The first center pivots had sprinkler spacings of about 32 ft (9.75 m) using impact heads. Later versions had variable spacings with sprinklers closer together as they approached the distal end of the lateral. Most modern machines have a constant outlet spacing ranging from 3 to 9 ft (1 to 3 m) depending on the manufacturer and the type of system. Machines can be ordered for almost any outlet spacing although 6 to 8 ft (2 to 2.4 m) spacings are typical, although LEPA machines (discussed later) may have outlets as close as every 2 to 3 feet (0.6 to 1 m). Sprinklers are installed in every outlet for linear move machines. However, on center pivots near the pivot where machine movement is slow, not every outlet has a sprinkler installed in order to reduce application depths. Generally, after the first tower all outlets have sprinklers installed. Uniform water applications depend on the *careful matching of spacing, the particular sprinkler heads to be used and their height above the crop canopy.*

Older machines and sprinkler packages often required pressures in excess of 70 psi (500 kPa) to operate, but modern machines are generally designed to operate at 35 psi (250 kPa) or less. These pressures are often too low for high volume-high pressure end guns and small electric booster pumps are often installed at the last tower. Discharge from end guns and corner systems should be controlled to avoid water applications to roads, streams or drainage facilities (especially when chemicals are being applied) by switches at the pivot base.

Pipe sizes range from about 4 inches (100 mm) to more than 12 inches (300 mm) in diameter. Pipe sizes on center pivots may decrease along the length of the lateral with increasing distance from the pivot. Linear move systems have uniform pipe sizes except for overhangs past the end towers. However, minimum pipe size is determined by strength rather than hydraulic considerations.

Regardless of the type of system, strict annual or weekly maintenance and lubrication schedules are required for all motors, gear boxes, alignment systems, couplers, seals and other parts. Sprinkler heads and pressure regulators should be replaced on a regular basis, usually every 3 to 4 years.

Lateral Move Systems

A lateral move machine travels in a straight line to irrigate up to 95% of square or rectangular shaped fields, and is supplied water through a carefully constructed open ditch that runs parallel to the direction of travel or large flexible hose-buried pipeline system. Some land is lost to production because of area needed for the supply ditch or supply hose drag lanes (30-40 ft [10-15 m] wide for the length of the field). Generally, linear move systems are used on land with slopes less than 6%.

Many lateral move systems have large diesel engines connected to a generator that powers the pump (open ditch supply) and tower motors. A hose drag system is pressurized by pumps off the field. The engine/pump/control assembly can be located in the center of the lateral move or at the edge of the field. These systems are guided by buried electrical cables, lasers or wire on stakes. All the sprinklers on a lateral move are usually the same size except for large end guns on some systems. The design of a lateral move system is a simplified case of center pivots although the management and operation is more complex with higher labor requirements. The average intensity of application, I (in/hr), for lateral move systems is given by:

$$I = \frac{K * Q_T}{W * L} \qquad \textbf{Eq. (1)}$$

where Q_T is the total water delivered to the system also called the total system capacity (gpm) , K is a units conversion factor equal to 96.25 in English units (K is 6.0 for metric units using $l\ s^{-1}$ and m with I in mm/min), W is the width of the sprinkler pattern in feet, and L is the total length of the lateral pipe including overhangs in feet. The actual depth applied during an irrigation event for a lateral move system is given by:

$$d = \frac{K * Q_T}{L * S} \qquad \textbf{Eq. (2)}$$

Where d is the applied depth in inches, K is a units conversion equal to 1.604 in English units (equals 1.0 in metric with mm, m and $m\ s^{-1}$) and S is the speed of movement of the machine in ft/min.

Lateral move systems are often used where productive land is limited and valuable. Capital costs of lateral move machines will vary from US$500 to over US$1200 per acre (US$1250 to over US$3000 per hectare) not including water source or land costs. Labor can be a significant annual cost factor.

Center Pivot Systems

The remainder of this paper is directed towards center pivots although the two systems have many similarities. A center pivot machine rotates in a circle around a base pipe structure in the center of the field so that the irrigated section is any circular shape including parts of circles less than 360°. They can cover 80% to 90% of the area of a square field. Center pivots can operate on widely variable terrain with slopes as much as 30% with proper design although an upper limit of 15% slopes is generally recommended. A service road is usually necessary for control adjustment and maintenance as well as refilling, operation and monitoring of any chemigation supply tanks and injection pumps located at the pivot.

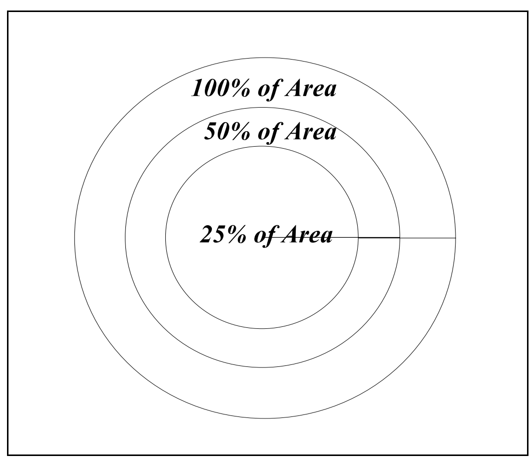

Figure 1. **Percent of areas covered at various radii of a center pivot irrigation system without end guns or corner systems.**

The pivot base structure is also the source of water, power and control wires. Pivot bases are usually permanent for large systems but may be portable for towable systems. Electrical power is supplied to tower motors, hydraulic and booster pumps through the slip ring connection at the pivot base.

The percent of area irrigated at various radii of a center pivot are illustrated in **Figure 1** where the innermost circle is at 50% of the radius but only contains 25% of the total irrigated area. It is important to realize that 75% of the total cropped area occurs in the outer half of the radius. Thus, management concerns tend to focus on outer towers, but many of the disease and water distribution problems will occur in the inner portions of the circle. The current state of the technology basically treats the entire field as a uniform soil and crop system. Some of the new control panels do allow changes in speed in selected sectors, but field variations are seldom pie shaped.

Center pivots are available to irrigate from 5 to 500 ac (2 to 200 ha) although a typical machine will generally irrigate about 125 to 130 acres (50-52 ha) . Economic considerations usually limits their application to irrigated areas larger than 50 ac (20 ha). The area irrigated with a center pivot depends on the radius of the main lateral plus the radius increase due to end guns and corner systems. If the center pivot is positioned in the middle of a square piece of land without an end gun, the machine will irrigate about 80% of the total area. Machines are often nested (clustered) together if several center pivots are installed on one large piece of land so that 85% to 95% of the total area is irrigated (**Figure 2**).

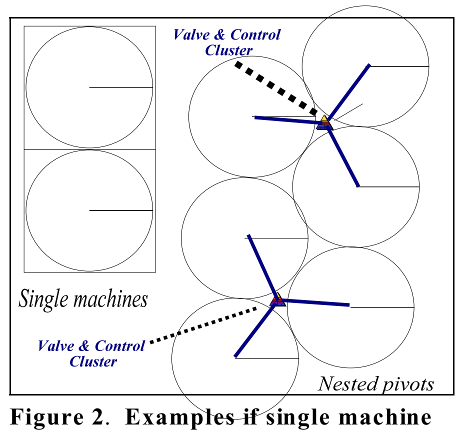

Figure 2. Examples if single machine placement and the increase in cropped area achieved by nesting pivots.

The average operating pressure of a center pivot lateral will vary significantly depending on whether the pipeline is going up hill or down hill. This can result in large variations in sprinkler discharge so that pressure regulators or flow control nozzles are often required on every sprinkler head.

The area irrigated by a machine can be extended by the addition of relatively inexpensive high volume end guns and expensive "corner systems." Center pivot capital costs can range from US$400 to more than US$1000 per acre (US$1000-US$2500 per hectare) not including land and water development cost depending on options such as size, sprinkler packages, corner systems and end guns.

<u>Corner Systems.</u> Corner systems (also called corner "catchers" or swing spans) may be installed on center pivot systems to increase the irrigated, productive areas in the corners and other non-symmetrical regions along the field boundaries by adding 17-25 acres (7 to 10 ha) without buying or renting more land (**Figure 3**) in areas where circles cannot be clustered. They usually consist of an additional tower and pipe system that is connected to the last tower of the main system. Corner systems normally follow behind the main system which tends to fix system rotation direction (rotation direction can be changed with great caution). The corner system tower generally has a guidance system such as phased-lock-loop circuitry that detects a low frequency radio signal from a guidance wire that is buried directly below where the tower will run. Signals are received by a high resolution antenna and receiver and fed into a microprocessor which continually monitors tracking and activates the steering motors. Sprinklers on the corner system are likewise controlled by the same microprocessor which also activates individual solenoid valves depending on their location with respect to the main end tower and the edge of the field. Use of corner systems on slopes greater than 15% may be problematic. Some corner systems use variable speed motors to improve water distribution and operation.

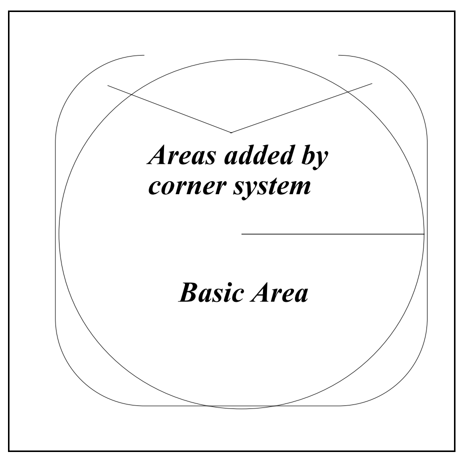

Figure 3. Schematic showing additional land covered by a corner system compared to a standard machine.

The incremental cost per hectare for the additional land covered by a corner systems may be two to three times as expensive as land covered by the main system. Therefore, corner systems are usually only added when land values are high. In addition, a corner system can cause large fluctuations in demand from the water supply system as it turns sprinklers on and off resulting in large, undesirable pressure fluctuations and poor water distributions. Pressure and flow problems may require the installation special controls and valves or expensive variable speed pump motors. These corner system sections also tend have fairly high maintenance costs due to the complexity and many moving parts. In general, corner systems should be added only after careful analysis of all the economic benefits.

End Guns. End gun systems composed of one or more large, high pressure heads are often used to extend the area in the corners of single machines on square blocks of land. These are used as a low cost alternative to corner systems to expand irrigated area as much as 21% in corners over a 35° to 42° arc. Considering the amount of land added by a relatively small increase in radius (**Figure 1**), end guns are popular as an inexpensive way to add significant irrigated acreage to the field, however, they are not without problems. A major consideration with end guns is that they are a basically a single large sprinkler and the application depth tapers off with distance and severe drought stress may occur at the field edges. This may not be significant for biomass production (e.g., forage crops) but can be a major problem when deficit soil water conditions negatively affect crop quality. For this reason, many irrigators will turn off the end guns on their center pivots when potatoes are being grown. Booster pumps are usually required to operate the end guns which can result in the same pressure and flow problems experienced with corner systems.

Towable Systems. Towable systems can irrigate from one to four adjacent fields and are often smaller systems than fixed machines. These systems are typically used as supplemental irrigation in humid areas and used on more than one field when rainfall is insufficient for good crop production. In these cases, the machine is typically moved at least daily during the drought periods. They are often not practical in arid areas on more than one field at a time because of the high labor required for the frequent moving of them from field to field. In more arid areas the towable systems are usually moved once or twice a year as part of rotation program or on leased land.

Orchards and Vineyard Irrigation. Orchards and vineyards can be irrigated with center pivot and linear move machines. However, if the water cannot be applied below the canopy there are a number of cultural and fungal disease problems that may develop. Consequently, the fields must be designed and planted so that center pivot or linear move systems apply the water below the canopy using small sprinklers or bubblers similar to the LEPA sysems described below. Vineyards can be irrigated with standard height machines. Orchards, on the other hand, have been successfully irrigated with high clearance (i.e., 4.3^{+} m high) machines.

Orchards and vineyards are generally planted in circular rows for center pivots and in straight rows for linear move systems (similar to the LEPA systems below). The irrigation machines are usually special orders to fit each specific installation. Sprinkler, spray or bubbler heads are suspended between rows on long drops with heads that apply water below the tree or vine canopy almost at ground level. As a water conservation measure and to ensure good coverage (and no cover crop between rows), there are typically two 180° flat or downward spray heads directed towards the plant row are located on each side of the plants. Fertilizers, systemic pesticides and pre-emergent herbicides can be applied with the irrigation water.

LEPA Systems

A special adaptation of the technology is the Low Energy Precision Application (LEPA) method that can be installed on both center pivot and linear move systems. LEPA has “drop” tubes about every meter that extend to the soil surface where a low pressure bubbler is attached in place of a sprinkler. Water is applied directly to the furrow and evaporation losses are minimized since the canopy is not wetted. These systems can be very efficient (e.g., 95-98%) since evaporation losses (soil evaporation generally less than 2% with alternate row irrigation, although runoff may be as much as 50% with poorly designed and operated systems) are minimal although initial capital costs are higher than standard systems.

Crops are usually planted in a circle so that the drops do not damage plants. Sometimes a canvas “sock” or other fabric energy dissipation device is used to prevent soil erosion in the furrows. The use of a machine such as the Dammer-Diker™ is often used to create small reservoirs to store water until it has infiltrated on heavy or steeply sloping soils under both LEPA and regular application techniques. Typical quarter mile long (400 m) LEPA systems will have 350 to 450 heads.

OPERATIONAL CHARACTERISTICS OF CENTER PIVOT IRRIGATION SYSTEMS

Many consider the current center pivot technology to be mature. They are mechanically reliable, simple to operate and require little supervision. However, the management for these systems is much different and unique compared to other types of irrigation systems. These systems are inherently characterized by light, frequent irrigations (e.g., daily) which offers numerous water and nutrient management advantages as well as numerous cultural disadvantages.
From a benefits standpoint, water and water soluble nutrients can be carefully applied in amount to exactly meet plant needs. The light applications can potentially reduce leaching in sandy soils (or cracking clays). Culturally, the frequent wetting of the canopy often creates ideal conditions for many fungal diseases, especially inside the tower closest to the pivot base. Shallow root development is encouraged on many crops by the frequent, light irrigations so there is often little buffering against drought stresses in the event of a mechanical breakdown of the system. For this reason, soil water contents in the upper regions of the root zone generally have to maintained at relatively high levels.

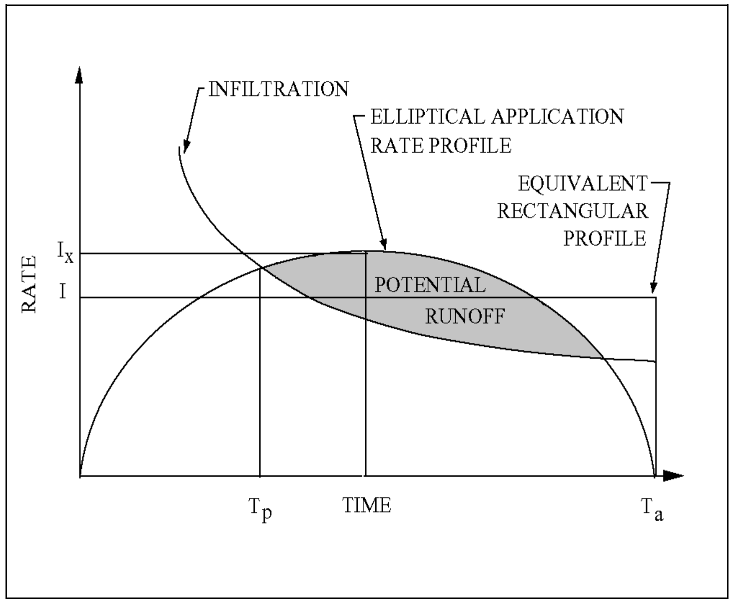

Figure 4. Illustration of the interaction between the infiltration function and the application rate pattern (Tp is time to ponding, Ta is the application time).

The frequent irrigations require adjustment of rotation times such that the machine is not in the same spot in the field every day at the same time to "average" losses and over applications across the field over time. Thus, rotation times that are 12 hour multiples are avoided.

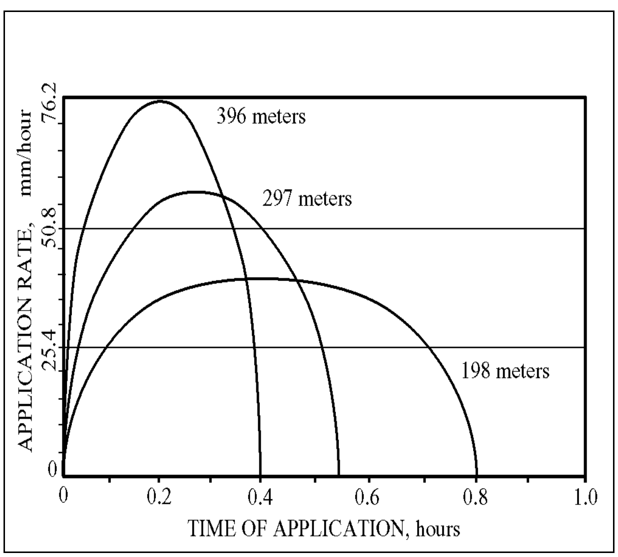

Figure 5. Application rate profiles and time of wetting showing the wetted diameters of the sprinkler heads depending on their position along the lateral length relative to the pivot base with a uniform width of wetted strip.

Matching Application and Infiltration Rates. A major physical phenomena that center pivots take advantage of is that initial water infiltration rates into soils are high. Light, quick applications take maximum advantage of this phenomenon. To illustrate, the outermost tower of a basic 125^+ ac (50^+ ha) center pivot can travel 3 to 15 ft per minute (1 to 4 m min^{-1}). However, the innermost tower travels only about 10% of that speed. This means that sprinklers at the outer tower are applying water 10 times faster than those near the first tower in order to have the same depth of application applied along the entire length of the pivot. With some sprinkler packages the application rate at the outer tower may exceed 4 in./hr (100 mm/hr).

Thus, the sprinklers at the end of the machine generally cover larger diameters even at higher system rotation speeds to avoid exceeding the infiltration rate of the soils. **Figure 4** shows the interaction between the application rate and the infiltration function. The intensity of application is illustrated in **Figure 5** relative to position in the field assuming the same amount of water is being applied showing the different wetting times. The rate of water application reaches a peak when the sprinkler passes directly overa locations at ⅓, ⅔ and the full radius of a basic system. The objective of proper nozzle selection and system operation is to ensure that the application rates do not exceed the respective infiltration rates at various points along the lateral.

In order to meet the application depth requirements, the discharge from sprinklers basically increases linearly with the radius as shown in **Figure 6.** In addition, as can be seen in **Figure 6**, the majority of the pressure loss occurs in the first one-third of the lateral pipe. A sprinkler at 985 feet (300 meters) from the pivot base will have twice the discharge of a sprinkler at 492 feet (150 m). Thus, the required discharge for any individual sprinkler along the pivot lateral is:

$$q_s = \frac{2\pi RSQ_g}{K} \qquad \text{Eq. } \mathbf{(3)}$$

where q_s is the individual sprinkler discharge in gpm, R is the radial distance from the pivot base in feet, S is the spacing between adjacent sprinklers along the pipe lateral in feet, and Q_g is the gross system capacity for the irrigation system in gpm per acre, K is a units conversion of 43560.0 in English units (equals 10000. 0 in metric units of L s^{-1}, m, and L $s^{-1}ha^{-1}$) . Special soil cultural practices may have to be implemented if the system capacity results in runoff in various areas of the field. **Table 1** presents sprinkler discharge requirements with length as a function of gross system capacity .

Assuming uniform crop, soil, microclimate and topographic conditions, the goal of irrigation is to have the most uniform water application pattern possible. Two major variables with selection of sprinklers are spacing and the type or size of the heads. Sprinklers must be spaced close enough to have good overlapping of wetting patterns. The sprinkler type and discharge must be selected to avoid runoff. They must be matched to the soil and crop. The kinetic energy and power with which droplets impact the soil can have a large effect on soil compaction and sealing which can greatly increase runoff (a major problem with end guns), and small droplets may be beneficial in reducing soil sealing. However, small droplets are subject to wind drift and evaporative losses. Thus, selection of best sprinkler heads is, at best, a compromise between often conflicting criteria and additional measures such as creating small storage reservoirs in the furrows may be required.

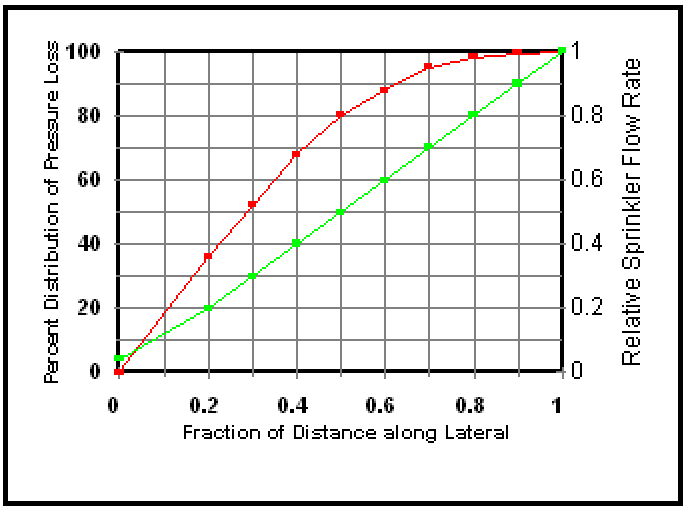

Figure 6. Typical distributions of pressures (upper line) and flow rates (lower line) from individual sprinklers along the lateral length.

Generally, nozzle sizes are small near the pivot base and gradually increase in size and discharge as the radius increases. Corner systems generally have similar or slightly larger nozzles as the end tower of the basic system. On very long systems, the largest nozzles may not have enough flow capacity and two or more sprinklers must be installed or the system flow requirements reduced and system pressure increased. Infiltration problems are often reduced by spreading water applications over are larger area through placement of drop tubes on alternating sides of the pivot lateral truss structure or having two to four small heads on a small boom mounted almost perpendicular to the pivot lateral.

Table 1. Sprinkler discharge requirements in gpm per foot along the length of the lateral for various system capacities.

	System Capacities (gpm/ac)					
Radius, ft	4.0	5.0	6.0	7.0	9.0	10.0
300	0.17	0.22	0.26	0.30	0.39	0.43
600	0.35	0.43	0.52	0.61	0.78	0.87
900	0.52	0.65	0.78	0.91	1.17	1.30
1200	0.69	0.87	1.04	1.21	1.56	1.73
1500	0.87	1.08	1.30	1.51	1.95	2.16
1800	1.04	1.30	1.56	1.82	2.34	2.60
2100	1.21	1.51	1.82	2.12	2.73	3.03
2400	1.38	1.73	2.08	2.42	3.12	3.46

Sprinkler discharge requirements in L/s per meter (1 L $s^{-1}ha^{-1}$ equals 6.414 US gallons per acre) .

	System Capacities (L $s^{-1}ha^{-1}$)					
Radius, m	0.6	0.8	1.0	1.2	1.4	1.6
100	0.038	0.050	0.063	0.075	0.088	0.101
200	0.075	0.101	0.126	0.151	0.176	0.201
300	0.113	0.151	0.188	0.226	0.264	0.302
400	0.151	0.201	0.251	0.302	0.352	0.402
500	0.188	0.251	0.314	0.377	0.440	0.503
600	0.226	0.302	0.377	0.452	0.528	0.603
700	0.264	0.352	0.440	0.528	0.616	0.704
800	0.302	0.402	0.503	0.603	0.704	0.804

Soil infiltration functions must be determined prior to the design and nozzle selection process and related to opportunity time. The opportunity time is less towards the outer towers since the sprinklers are traveling faster which must be offset by higher flow rates and wider wetted diameters per head with increasing distance from the pivot base. Thus, to have the same application depth, sprinkler selection and rotation speed are dependent on bare soil (no crop) and topographic factors to avoid soil erosion and wasting water and energy. The speed, S_j, at point j on the radius r is $2\pi r_j \;/\; t_{rotation}$ where $t_{rotation}$ is the time required for a complete rotation in minutes. The infiltration opportunity time t_j is defined as the wetted diameter of the nozzle, W_j, divided the speed, S_j. The average intensity (application rate in./hr), I_j, of application at radius (r) at point j which can be calculated as:

$$I_j = \frac{d_g}{t_j} = \frac{K\, r_j\, Q_g R_e}{W_j\, L^2} \qquad \text{Eq. } \mathbf{(5)}$$

where K is a units conversion factor equal to 192.3 for English units (7200.6 in metric units of $l\ s^{-1}$ and m), Q_g is the gross system capacity for a basic circle (no end guns or corner systems) in gpm, L is the radius of the basic circle in feet and W_j is the width in feet of the sprinkler application pattern at j. R_e is a loss factor equal to 1.0-fraction of estimated evaporation and wind drift losses (e.g., 0.10 to 0.15). Thus, this equation must be solved in a trial-and-error procedure until the selected nozzles and minimum system rotation speed do not cause runoff. Use 50% or less of the maximum system rotational speed for these calculations to allow for changing conditions through the season and management flexibility. Thus, the average application rate, I_L, in in/hr at the end of the basic pivot, L, is:

$$I_L = K \frac{L\ d_g}{W\ t_{rotation}} \qquad \text{Eq. (6)}$$

where $t_{rotation}$ is in hours, d_g is the gross daily application depth in inches, L and W are in feet, and K is a units factor of 6.2832 (same in metric units of mm/hr and meters). The average depth of water applied, d_g, per revolution is given by:

$$d_g = K\ Q_g\ h_r \qquad \text{Eg. (7)}$$

where K is the units conversion equal to 0.00221 (K is 0.36 in metric units of mm and $l\ s^{-1} ha^{-1}$), Q_g is the gross system capacity in gpm/ac, and h_r is the hours per revolution

The speed control setting, C_s, is a ratio of the depths at 100% speed (minimum depth per revolution) to the desired depth at a lower speed. It can also be determined as the ratio of the depth per revolution at the 100% speed, d_g, to the application depth per revolution at a given speed, S, in percent, which is:

$$C_s = K \frac{R_l * v_m * d_g}{Q_T} \qquad \text{Eq.(8)}$$

where K is a units factor equal to 31.168 (0.84 in metric units of $l\ s^{-1}$, meters, meters per minute and mm per revolution), Q_T is the total system capacity in gpm, R_l is the distance from the pivot base to the end tower in feet, v_m is the velocity of the end tower in feet per minute for that revolution, and d_g is in inches applied at the 100% speed setting that should not result in runoff . Substituting equation 6 into equation 7 gives C_s in terms of velocity and hours per revolution (K would be 0.01667 in both English and metric units).

SYSTEM SELECTION CONSIDERATIONS

Because center pivot technology is so well developed, it may seem that design concerns are minimal. However, this is absolutely not the case! The machines must be designed to match each site. Information must be collected to characterize the variability of the soils (physical and chemical), topography, infiltration rates, microclimates across a field, and expected crop water use patterns over the season. Water supply (quality, quantity, timing and long term availability) must be investigated as well as any other potential physical, legal or social constraints must be identified. Steepness of slopes along wheel tracks can affect performance and long system life. Potential losses such as wind drift, evaporation, runoff, and deep percolation need to be estimated. Sprinkler spray and distribution patterns characteristics must match the soil. Machine operational criteria and strategies must be developed. A more complete discussion of the full design process can be found in Allen et al (1998).

Total system flow requirement is needed for hydraulic calculations and proper selection of pumps, main lines and lateral sizes. The calculation for total system flow, Q_T (gpm), is:

$$Q_T = K * A * d_g \qquad \text{Eq. (9)}$$

where K is a units factor of 18.86 (0.1158 in metric units of $L\ s^{-1}$, hectares and mm), A is the total area irrigated in acres and d_g is the daily gross depth applied per unit area in inches over the irrigation period of 24 hours. The total system flow, Q_T, can also be calculated based on the amount of water to be applied over a fixed time period, f, as:

$$Q_T = K \frac{A * d}{f * T} \qquad \text{Eq. } \mathbf{(10)}$$

where f is in days, d is the average depth applied in inches, T is hours per day of operation, and K is a units factor equal to 452.6 (use 2.78 in metric units of $l\ s^{-1}$, hectares and mm).

As mentioned previously, the gross system capacity, Q_g, is a useful quantity for easy comparisons of the adequacy of design and management of different sizes of center pivots and lateral move systems. It should be the amount of water continuously delivered to the machine per acre that is sufficient to meet peak evapotranspiration (ET) requirements as well as losses. Q_g typically ranges from 4 gpm/ac (0.65 $l\ s^{-1}ha^{-1}$) to as much as 10 gpm/ac (1.6 $l\ s^{-1}ha^{-1}$) although the average is around 6 to 8 gpm/ac (1.0 to 1.2 $l\ s^{-1}ha^{-1}$) which allows some flexibility in case of breakdowns. Some systems are specifically designed to operate at a deficit during the peak water user periods to stretch water supplies or add additional center pivots to increase the total irrigated area, but this should be done only after careful consideration of all factors. **Figure 8** shows the relationship between d and Q_g **(Figure 11** at the end of the paper presents these data in metric units). A properly selected Q_g should account for local crop, climate and soil characteristics.

Some systems are deliberately under designed (gross system capacity too small) in order to stretch water supplies and irrigate more area, realizing that the plants may be stressed during peak water use requirement periods. Designing for less than 6 gpm/ac (~1 L $s^{-1}ha^{-1}$) is not recommended in arid areas of the Pacific Northwest since many crops would be stressed during peak water use periods. A design gross system capacity value of 8 gpm/ac (1.2 L $s^{-1}ha^{-1}$) is more appropriate.

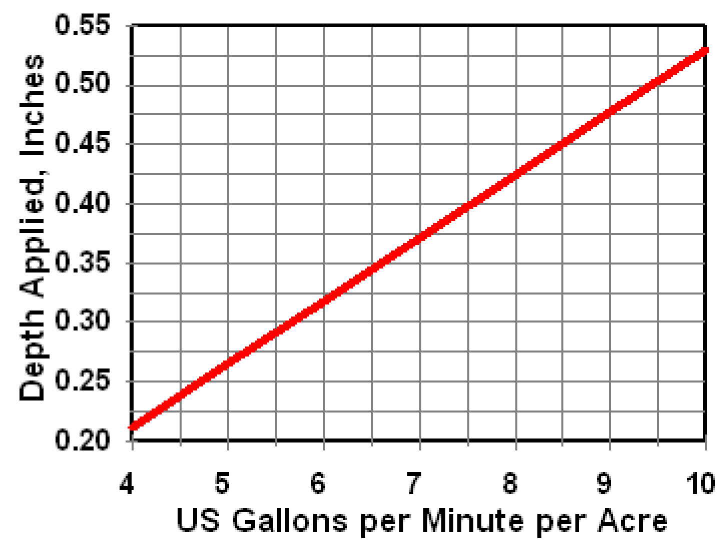

Figure 7. Water application depths in a 24 hour period for center pivots as related to the gross system capacity with no losses (100% efficiency).

Irrigation Scheduling.

Center pivots and lateral move sprinkler systems will usually *use* more water than other sprinkler methods because the frequent irrigations have more evaporation losses from the plant canopy and soil as well as wind drift which occur with every application (see **Equation 9**) rather than once every 7 to 10 days. LEPA systems will be more efficient. Irrigations should be scheduled based on soil water levels to avoid undesirable levels of crop stress. This is compounded by the light frequent applications, shallow rooting and cultural operations such as fertigation, spray and tillage programs. If system capacity is not adequate to meet peak water use requirements, it may be necessary to build up soil water reserves and encourage deeper rooting prior to any water short periods, however, this it is often difficult to limit over-watering and avoid deep percolation losses.

Pressure variations due to static topographic differences and changes in system flow rate by the operation of end guns or corner systems can easily result in greater than 10% variations (±5%) in water applications across a field. These differences in application depths are small on a daily basis, but the effects are additive over the season and may have serious consequences on water sensitive crops such as potatoes. Thus, the actual daily variation in application depths and the actual distribution of water must be considered in irrigation scheduling. General irrigation scheduling concerns are presented in the adjacent box.

Irrigation Scheduling

- Frequent applications that match plant water use
- Calculate daily and forecasted ET based on current measured nearby climatic data
- Check ET based water applications using soil water (2 or more depths) and/or plant monitoring
- Adjust water applications, if necessary
- May be complicated by chemigation and other cultural activities
- Use aerial photography and ground observations to check for water distribution problems

Water Requirements. Center pivot and linear move systems inherently provide frequent, small water applications. Consequently, the volume of water stored in the soil and available for crop use can be considerably less than the wetted soil volume under other types of sprinkler irrigation. However, this practice can maintain higher, less variable soil water contents than other irrigation methods and reduce the occurrence of plant water stresses if the system capacity and management are appropriate.

The basic philosophy of center pivot and linear move systems is to *replace* water in the root zone in small increments as it is used by a plant at frequent intervals rather than *refilling* a much larger soil water reservoir after several days or weeks. Thus, the major concern for scheduling center pivot systems is primarily how much to apply during an irrigation since the irrigation interval is often fixed by other factors, including design. The actual seasonal water requirements of a crop can be obtained from various technical sources including the Cooperative Extension Service.

The gross required depth, d_g, in inches (in metric use mm per day of ET and P) of application per day is given by:

$$d_g = \frac{k_f\, ET_c - P_e}{E_a / 100} \qquad \text{Eq. } \mathbf{(11)}$$

where k_f is a frequency factor to adjust the actual daily crop evapotranspiration (Et_c) in inches during the period for high frequency water applications which is typically about 1.2 for daily irrigations, 1.1 for irrigations every two days and 1.0 when irrigations are every 5 days or more. ET_c can be calculated from the Modified Penman, Penman-Monteith or other suitable estimating equation depending on data availability. This adjustment is necessary because of increased evaporation losses from the plant canopy and soil surface inherent in high frequency irrigation regimes. P_e is the effective precipitation during the period in inches and E_a is the application efficiency as a percent.

Using the same variables as previously defined except that d is the net depth applied, the maximum time between

$$f = \frac{d}{k_f\, ET_c - P_e} \qquad \text{Eq } \mathbf{(12)}$$

irrigations, f, can be calculated as:

The estimated crop water use (ET) combined with amount of the area to be irrigated, will determine the total volume of water to be applied in an irrigation subject to system capacity. The system should be able to apply the maximum depth of water needed during peak water use periods accounting for all losses. The maximum interval between irrigations is primarily controlled by soil hydraulic characteristics, soil profile layering, and maximum allowable deficit levels for the crop. The depth of root zone soil, saturated hydraulic conductivities and soil water holding capacities may the volume applied in a single irrigation to avoid runoff or excessive deep percolation.

It is sometimes not possible to achieve optimum irrigation schedules because of irrigation system limitations. These include inflexibility in controls and instrumentation, inadequate system hydraulic capacities (including fill times and system drainage), and the quantity and quality of available water throughout the season.

Management considerations such as the quality and quantity of available labor can affect the ability to implement irrigation schedules. Timing, amount and label requirements for chemigation may also negatively influence optimum schedules. Irrigation schedules may have to be adjusted because of cultural or harvesting considerations or to take advantage of lower "off peak" electrical power rates.

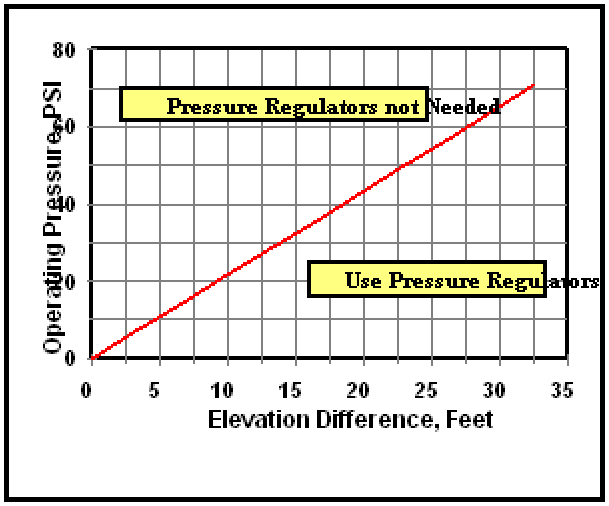

Figure 8. Suggested recommendations for the determination of the need for pressure regulators on center pivots and linear move systems.

Depth and Pressure Distributions. Sprinkler flow rates will vary as the lateral rotates on sloping land unless pressure regulators are used. Pressure regulators will be needed on each sprinkler head if the pressure varies by more than ±10% oven the length of the pivot at any point in the field. Pressure regulators are almost always required on low pressure systems on sloping land. **Figure 9** shows general recommendations on whether or not pressure regulators are needed on a system (Use **Figure 12** at the end of the paper for metric units). The selection of specific regulators depends on system pressures and the sprinkler selection. Flow control nozzles may also be an option but large fluctuations in pressures may adversely affect distribution patterns and droplet sizes.

Selection of the proper nozzles requires a knowledge of the pressure distribution along the pivot lateral. This is complicated by the fact that the sprinkler discharges increase as you move toward the end of the pivot lateral while the pipe diameter remains constant (e.g., 6.38 inches [162 mm] diameter until the overhang after the last tower). The pressure, P_j, at point j in psi along the lateral is given by:

$$P_j = P_o - \frac{P_{lp} * L * f_p(R)}{100} - K\,E_g \qquad \text{Eq. (13)}$$

where P_o is the pressure at the inlet to the pivot in psi, P_{lp} is the pressure loss in the pivot lateral pipe in psi per 100 ft, L is the radial length in feet to j, E_g is the elevation gain in feet at j, K is a units conversion factor of 0.4484 (use 0.1017 with meters and kPa) and $f_p(R)$ is the dimensionless pressure distribution factor at distance R (at j). R is about 0.555 for most center pivots without an end gun (**Figure 9**) and 0.56 with an end gun. A value of 0.36 is used for R on linear move systems due to the more equal distribution of flow from the outlets along the lateral. This can relationship also be calculated by the Hazen-Williams equation using a C factor of 140 or 145 for galvanized or epoxy lined steel pipe.

Distribution Patterns. Water application uniformity is an important performance criterion for the design and evaluation of center-pivot sprinkler irrigation systems. However, the water application depth of a center-pivot irrigation system is not uniform across a field. It depends on the sprinkler package, field topography, movement of the machine, and many other factors. Wind distortion of sprinkler distribution patterns is a major and dynamic factor.

Numerous coefficients of uniformity (CUs) have been developed over the past few decades. In general, all CUs can be divided into two categories: non-weighted and areal-weighted. Non-weighted CUs are calculated directly from the observations (actual or simulated catch-can data), and each observation is assumed to represent the same land area. Non-weighted CUs include Christiansen's CU_C (1942), Wilcox and Swailes (1947), Benami and Hore (1964). Areal-weighted CUs are determined from both observations and the land area each observation represents. Areal-weighted CUs include CU_H by Heermann and Hein (1968) and the USDA-Soil Conservation Service pattern efficiency (1982). For irrigation systems where each sprinkler covers the same amount of land area, non-weighted CUs can be used. On the other hand, if each sprinkler in an irrigation system covers different sized area, such as in a center-pivot irrigation system, areal-weighted CUs are preferred. The uniformity coefficient can range from 0.0 to 1.0, but the minimum desirable uniformity is about 0.85 for a center pivot irrigation systems . Both the application efficiency and uniformity coefficients are affected by the depth of irrigation.

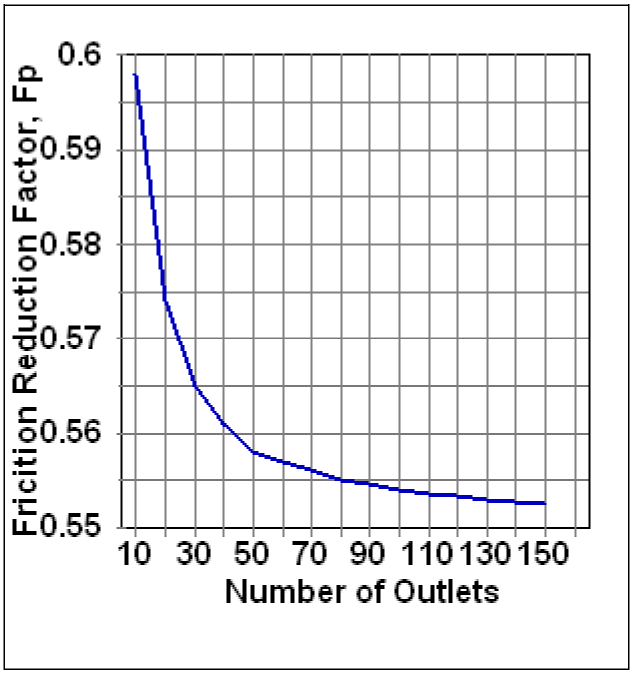

Figure 9. Friction reduction factors for multiple outlet pipelines.

Although a coefficient of uniformity can be used to compare different systems, it does not provide a functional description of actual applied water distribution. Therefore, statistical distribution functions are often used to represent the actual water application distribution. Many distribution functions have been proposed. Among them are the normal distribution (Hart, 1961; Seniwongse et al., 1972), log normal, uniform and specialized power distributions (Elliott et al., 1980; Warrick, 1983; Heermann et al., 1992). Comparisons among these distribution functions for application to sprinkler systems can be found in many papers (Elliott et al., 1980; Heermann et al., 1992).

One advantage of using distribution functions over a CU is that matching raw data to a theoretical function results in better estimation of the performance compared to the direct use of the raw data (Warrick et al., 1989). When a distribution model is known, raw data are used to fit the distribution function and to obtain the function coefficients. en, the coefficient of variance (CV) is calculated and used to compute the CU. The CV approach has been stated to be more appropriate than the CU approach in some cases (Solomon, 1984; Marek et al., 1986). Distribution functions can also be used to determine the volume of over and under irrigation. This is done by simply integrating the product of the application depth and depth distribution function (Walker, 1979; Elliott et al., 1980; Heermann et al., 1992).

In using a distribution function to evaluate a sprinkler system design, two important points must be kept in mind. First, the distribution function is the probability distribution, not the actual **spatial** distribution, of water application depths. It can tell the probability of a given application depth, but it cannot tell which locations of the field actually receive the given amount of water. A distribution function may be adequate for evaluating the overall system performance, but it is not sufficient when a spatial water distribution is required as is needed, for example, in managing chemigation. Secondly, the distribution function is developed based on the assumption that water application depth is a random variable. That assumption may not be true if sprinkler distribution patterns have highly predictable shapes. In such a case, application depth may be directly calculated, and assuming a random distribution of application depth is vulnerable to errors and misinterpretations.

A center pivot irrigation model (CPIM) was developed to study the non-uniform distribution of irrigation water/nitrogen from the center pivot system. CPIM is a basic hydraulic model that considers topography and predicts nozzle pressures at any water emission point in the field. An empirical shape-pressure function specific to each sprinkler head is used to predict the water distribution from each head. CPIM overlaps the patterns and can produce maps showing the spatial distribution of water application depths (**Figure 10**). Complete field information on a center pivot system including actual topography and hydraulic data can be entered into the program's databases. There are also several "default" sprinkler (impacts only, at this time) packages and topographic options that can either be used directly or edited. CPIM is currently structured to fit within our defined GIS framework.

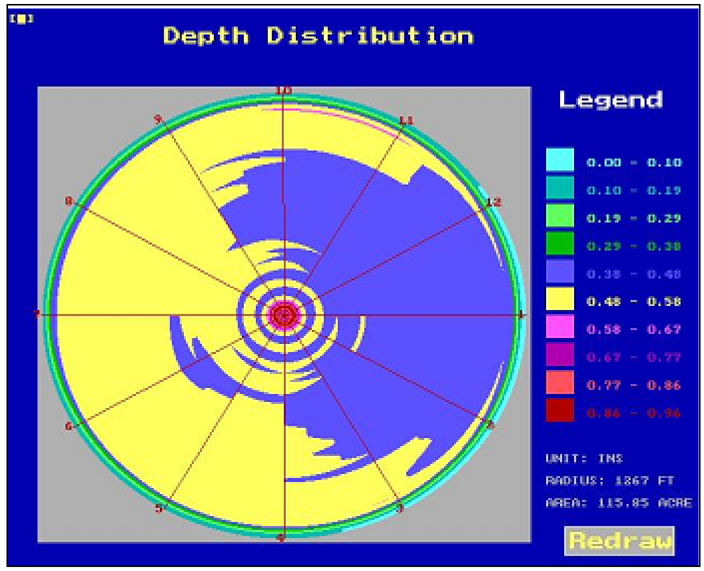

Figure 10. Example of water distribution from the CPIM model on steeply sloping field without pressure regulators.

The application uniformity of the whole field can also be assessed. The CPIM results can be graphically compared with actual catch-can test results, if available. Results of the CPIM analysis could be used to target areas of highest potential nitrate leaching within a field for specific management practices. **Figure 10** shows the simulated water application results for one system on steeply sloping land without pressure regulators based on one meter catch can data along three rays.

Chemigation. Center pivots provide an excellent vehicle to apply some chemicals and many fertilizers to exactly match plant requirements. In some areas with very light soils as much as 80% of nitrogen fertilizer is applied through the center pivot system. Substantial crop quality and pest control benefits may accrue when using this method.

The first rule of chemigation is safety. Special chemigation safety devices, check valves and air relief valves are required for <u>all</u> chemical injection systems under federal and state regulations. Well heads must be protected from reverse flows, system drainage or back siphoning. Electric and hydraulic interlocks with time delays must be installed between the injectors and irrigation pumps to prevent chemical injection when the irrigation system is not operating.

Personnel must be specifically trained and, in many areas, licensed for chemical applications. Injection of any pesticide into an irrigation system must be specifically permitted by the pesticide label and may also be subjected to additional state regulations. Detailed records of all chemical applications need to be maintained for safety, evaluation, legal and regulatory requirements.

All chemicals and chemical-water mixtures must be checked to avoid phytotoxic effects before any injection occurs. In addition, it is critical that all the chemicals being injected at one time are compatible with each other and the water chemistry and concentration limits are not exceeded so that precipitates do not form. Emulsifiable pesticide concentrates and wetable powders may require special design and management considerations (e.g., mechanical supply tank agitation) to help ensure uniform applications. Acidification to lower water pH may sometimes be required prior to injection of the chemical.

Injection installations should always provide for complete mixing and uniform concentrations before the chemicals reach the field. Materials should be injected into the center of the water flow to ensure quick dilution to reduce deterioration of piping, valving or other components. Generally, injection rates should not exceed 0.1% of the system water flow rate although concentration limits and label requirements for pesticides are usually less.

The use of positive displacement pumps is highly recommended for liquid chemical injections. The pumps should be adjustable and able to inject any water soluble chemical at low concentration levels (e.g., $\leq$100 ppm). The use of an in-line mixing chamber after injection may be necessary in some cases. A flow meter or other flow detection device can be connected to a controller that is programed to inject a specified amount of chemical from a nurse tank into the irrigation system at specific times based on flow rate. Estimating the amount of nitrogen injected at various concentrations is presented in graphs at the end of the paper.

Maintenance. Because center pivot and lateral move systems inherently supply small amounts of water on a frequent basis, soil water storage is usually limited. Consequently, an extended breakdown can be very serious in terms of yield reduction and expensive service calls.

Some system maintenance will always be required during the irrigation season. This typically involves replacing or repairing sprinkler heads or sprayers, leaky valves, flat tires, electrical shorts, oil leaks in gear boxes and breakdowns in gear boxes or drive line U-joint couplers.

Many in-season problems could be averted by a strong preseason maintenance program that includes: checking flanges, rubber flex boots, collector ring base drain and system drain valves for leaks; tightening nuts and bolts on flanges, trusses, tower supports, flex boot bands, lug nuts, etc.; greasing the pivot swivel, changing oil in gear boxes and replacing leaky gaskets as necessary; cleaning the pump panels and screens; cleaning or replacing filters, screens and ventilation/drain holes on engines, gear boxes and electrical panels; checking electrical systems including power cables, grounding conductors, power and pump shutdown wires, swivel connectors, pivot contactors; testing, replacing and repairing defective sprinkler heads, end gun bearings and pressure regulators; and checking that system operational water pressures are appropriate and pressure gauges are accurate.

Aggressive nozzle "management" and leak prevention programs can save water and energy. Nozzles become worn by silt and sand particles in the irrigation water leading to higher flow rates, less efficient pump operation and possible decreases in system pressures. Replacing worn nozzles on a regular basis, checking that the appropriate nozzles are installed in the correct locations and the installation of flow control nozzles/pressure regulators where needed will help ensure good uniformities of application and reduce overall water use.

SPECIAL HARDWARE SELECTION CONSIDERATIONS

Control Panels and Communications. There are a tremendous number of options available for control and operation of center pivots. Panels can be operated and adjusted manually or remotely by phone or radio. Rapid advances in computer and communications technologies have made it possible to remotely monitor as well as turn machines and injection pumps on and off from the farm office or even the front seat of the grower's pickup truck. As many as 100 or more machines may be controlled at one time. Alarms may sound when a machine stops for a multitude of reasons.

All the main manufactures are supplying advanced control panels at the pivot with remote communications capabilities. These are primarily digital devices with minimal electro-mechanical parts. Graphical interfaces can set system speed, run the system wet or dry, rate of application, system direction, end gun valves, fertilizer pumps, and other ancillary equipment. Different rotation speeds can be easily pre-programmed for different sections of a circle. The control panel will also keep a digital record of events for later analysis and record keeping.

These technologies are not inexpensive and the irrigator must determine the economic tradeoffs when selecting which panel and communication system (if any) will be purchased. Growers must evaluate their operation and maintenance costs and compare these with anticipated productivity gains and/or labor savings from various remote control options.

Tire Selection and Gear Boxes. Proper tire selection is critical to avoid problems with traction, deep ruts and easy crossing of the wheel tracks by farm equipment. Tires will vary with width and diameter ranging in size from about

24 to 38 inches (610 to 965 mm) in height and 11 to 17 inches (280 to 430 mm) in width . Generally, narrow larger diameter tires are used on heavy clay or loamy soils while wider tires are used on lighter sandy soils for greater flotation. Row crop farmers will often choose narrow tires where as growers of permanent crops such as alfalfa will normally select wide tires. Turf or tractor treads can be ordered although steel tires with heavy lugs or steel traction rims with heavy duty lugs mounted inside a regular rubber tire may be used on heavy clay soils where traction is a concern.

Obtaining good flotation can be a compromise of tire width and diameter. A narrow large diameter tire may have the same soil contact area or “foot print” as a wider small tower and provide equal flotation. Narrower tire tracks are usually easier to cross with equipment.

Gear boxes selection can be difficult. Worm gear systems are more expensive used on widely variable, steep terrain situations and on heavy soils with traction problems. Planetary and spur drive gear boxes are used in less demanding situations.

Screens and Sand Traps

When water is pumped directly from rivers, lakes or canals, the intakes should be equipped with self-cleaning screens. The stainless steel screens should be about twice the diameter of the attached pipeline and a mesh opening of about 0.25 inches (6 mm) or less. Cleaning is often accomplished with internal pressurized water jets that rotate inside the intake screen and push debris away from the mesh openings.

The pivot point should also have a stainless steel or galvanized screen with a mesh size of 0.1 inch (3 mm) or less to keep debris, algae, weed seeds, etc from plugging nozzles. There needs to be a way to hydraulically isolate the screen from the rest of the system. These screens can be self-cleaning or manually cleaned. There should be a pressurized water supply for a hose to manually wash the screen in both cases.

Since sand and small gravel tend to collect at the distal end of pipelines, sand traps should also be placed at the distal end(s) of the center pivot or linear move system. These typically consist of a short section of 4-inch (100 mm) pipe pointing downward from a tee near the end of the mainline (near the end gun). These pipes have a 4-inch (100 mm) spring loaded valve or other method to quickly flush the collected sand from the system. Sometimes a special hose and large diameter (e.g., 0.25 in [6 mm] diameter) nozzle-spray plate arrangement is used to continuously flush the sand while the system is operating.

NEW ADVANCES IN CENTER PIVOT TECHNOLOGY

Despite the inherent high frequency and fairly uniform applications of self-propelled CP irrigation systems, considerable yield variations still exist which are often attributed to spatial variability in soil water holding capacities and related nutrient availability. Variations in water availability across a field result in a farmer managing to: 1) ensure that areas with the lowest water holding capacity maintain adequate water levels; 2) managing the whole field based on average soil water depletions; or 3) managing to avoid overirrigation in wettest areas. All of these cases will cause overirrigation or underirrigation of other areas due to the current inability to differentially irrigate based on soil and plant factors within a single CP irrigated field. Some chemical leaching below the root zone, surface runoff and potential yield decreases may occur in different areas under each management practice.

Yield variability is also increased by pest and pathogen effects on crop growth, which causes further variability in water and nutrient utilization. Thus, irrigation and nitrogen management are central to improved crop production and improved environmental stewardship on center pivot irrigated lands.

Economics dictate large field sizes for irrigated row crop production in many areas of the world. But, field and farm size are inherently highly spatially variable resulting in significant production differences and environmental consequences. Current center pivot technology basically treats the whole field one dimensionally (as a high “average” condition) assuming that the whole area has uniform water application requirements and soil types. This typically results in over irrigation of much of the area to compensate for non-uniformity to reduce risk of crop water deficits in portions of the field. However, surface and subsurface flows from higher to lower elevations will occur depending on slope, soil type, soil layering, infiltration rates and application rates, and can also substantially affect spatial crop water requirements. Application rates vary linearly along the pivot to a peak at the distal end. Infiltration rates vary spatially and temporally. In addition, recommendations for inputs of water, fertilizers, and pest control chemicals, of necessity, results in consistent practices being applied across diverse conditions where response may not be uniform.

Today, the goal of most designers is to have the most uniform water application pattern possible along the entire length of the center pivot. However, this criteria is not necessarily the best in terms of crop quality and environmentally. For example, our research and the research of others has shown that, *in grossly simplified terms*, that about 75% of the leaching occurs in about 25% of the area in many center pivot irrigated fields in the central Pacific Northwest. Thus, it is evident that the ability to more precisely manage small areas of the field will be necessary to reduce groundwater degradation. *Thus, the next advances in center pivot and lateral move irrigation will involved being able to vary water and chemical applications along the length of the pipe depending on its position in the field.*

The concept of varying crop protection chemicals, fertilizer and water applications to meet the specific crop needs in unique zones within a single field has been a dream of many people for years. However, the necessary "components" to implement precision agriculture or Site-Specific Crop Management (SSCM) on irrigated lands have recently become readily and economically available. These include: 1) Global Positioning Systems (GPS); 2) Geographic Information Systems (GIS); 3) improved techniques for real-time remote sensing of soil and crop status; and, 4) improved computers, pattern recognition software, communications, “smart” sensors and monitoring systems to provide adequate feedback and control capabilities. Some of these technologies have been combined to provide Variable Rate Technologies (VRT) for directed applications of fertilizer spreaders, precision field planters, and real time yield monitoring, but they have had limited application to water and nutrient management in irrigated farming systems.

Microprocessor controlled self-propelled center pivot and linear move systems linked to a central integrating computer provide a unique platform as well as control capabilities for precision crop management and are an effective and economical means to deliver SSCM under irrigated conditions.

Center pivots are especially suitable for site specific water application since one pipeline and 100^+ sprinklers can irrigate 125 acres (50^+ hectares). Automation of a sprinkle irrigation system for SSCM requires the ability to individually control the net application rate from each head depending on its location in the field. In addition to improved water management and reduced leaching, another obvious advantage of automating individual heads is that the very high application depths near the pivot point can be reduced to levels matching the rest of the system by using larger, non-plugging heads with better water distribution characteristics, and which would also reduce the incidence of fungal diseases.

We have been working on SSCM concepts for center pivot irrigated potatoes in central Washington since 1993 starting with the evaluation of three commercial fields on sand and fine sandy loam soils. The fields were topographically surveyed, grid soil sampled and sprinkler application uniformity tests conducted. An extensive GIS database was created for the three fields using these data and output from computerized CPIM irrigation model and various plant growth models. This study clearly showed that some increases in yields and large reductions in leaching could be achieved if irrigation and nutrient applications could be optimized in discrete areas of the field (e.g., < 25% of area).

In 1995, we began development of procedures and software to generate irrigation “management maps" or prescriptions, and applied these depending on the position of the center pivot in the field. A computer in the farm office communicated with 30 addressable controllers along a center pivot distribution pipe, an on-site weather station (every hour) and soil water monitoring stations via spread spectrum radio modems. These data were entered into the GIS and linked to existing computer simulation models (center pivot hydraulics, scheduling, etc.) for two more center pivot irrigated fields on sandy soils to generate optimum water and nutrient application rate maps. Communications and hardware to control sprinklers and implement management maps for water and fertilizer (N) applications were field validated and shown to be practical. We are also working with industrial process programmable logic controllers (PLC) for irrigation control. These are “off-the-shelf” and have their own communication protocols developed. This work is continuing.

Multipurpose Systems

Center pivot and lateral move systems have the potential to be more than water application devices. Other uses that have been discussed include site specific pesticide applications, planting of crops and mounting sensors and cameras for field scouting for pests and diseases.

Center pivot systems provide an especially suitable platform on which to mount various types of sensors since the lateral potentially passes over every part of the field every day. Color video, infrared and reflected wavelength specific sensors could be combined and coupled with pattern recognition software and GPS for early detection of stresses due to water, nutrients, disease and insects as well as potentially identify various weed species as well as other problems.

Site-Specific Pesticide Applications. Because many pest problems begin in localized areas within a field, site-specific pesticide application has a large potential for reducing inputs, more efficient utilization of existing resources, increased environmental benefits, and improved profitability. Pesticide use is reduced and IPM programs are greatly enhanced by reducing negative impacts of agrichemicals on non- target organisms and biocontrol agents in nonsprayed areas.

Utilization of early detection technologies (e.g., remote sensing) combined with the ability to “spot” spray and adjust rates depending on special conditions in discrete portions of an self-propelled irrigated field, can potentially save growers millions of dollars in reduced pesticide use. In addition, site-specific pesticide applications could: 1) reduce pesticide costs to growers which makes them more competitive in global markets; 2) reduce the potential for resistant pest populations; 3) reduce total use and minimize negative impacts of pesticides on the environment and non-target organisms; and, 4) reduce potential for leaching of pesticides and increase chemical efficacy. Site-specific pesticide applications could also enhance IPM programs by reducing negative impacts of agrichemicals on non-target organisms and biocontrol agents in nonsprayed areas. Variable water and nutrient applications would require the addition of a parallel nutrient/chemical distribution system(s) along the lateral, with controlled chemical injections at each sprinkler outlet.

Other reasons for site specific pesticide applications include: 1) pesticides can be applied after full cover (row closure) at a much lower cost per hectare than aerial applications (the current most common method) not counting the cost of the pesticide system; 2) the pesticide (as well as some fertilizers) is applied in much less water (i.e., 50-400 gallons per acre compared to 1500-5000 gallons per acre for applications through a center pivot irrigation system) which is often required for many pesticides; and, 3) the grower has a very expensive system (the center pivot) sitting in the field and it is desirable and economically advantageous to use this system for more than just irrigation and nitrogen fertilizer applications (note that some herbicides and a few fungicides are applied in the irrigation water but the water application amounts are often too high for many other registered pesticides). In addition, several commercial systems are in development. It is only a matter of time before site specific pesticide systems are readily available and we must be able to advise growers and help direct their management of these systems if growers are to be able to use them appropriately.

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Some Helpful Internet Web Sites

http://www.irrigation.org (The Irrigation Association)
http://www.irri-gate.com/cgi-bin/intro.cgi (The Irrigation Association Search Engine)
http://www.wiz.uni-kassel.de/kww/projekte/irrig/irrig_i.html#different (irrigation library)
http://www.valmont.com/irr/irr.html (Valmont center pivots and linear moves)
http://www.valmont.com/irr/uswwc/wcindex.html (Information on various crops)
http://zimmatic.com/zimmatic/zimmatic/zis.shtml (Lindsay center pivots and linear moves)
http://www.reinke.com/page2.html (Reinke center pivots and linear moves)

http://pierce-irrigation.com (Pierce center pivots and linear moves)
http://www.tlirr.com/systems.htm (T-L Irrigation — hydraulic drive center pivots and linear moves)
http://www.nelsonirr.com (Nelson Irrigation--Sprinklers)
http://www.senninger.com/pivotpa.htm (Senninger — Sprinklers)
http://www.northerndesigns.com/irrquip.html (list of irrigation equipment related web sites)
http://www.wco.com/~rteeter/waterlib.htm l (general water resources)
http://www.nal.usda.gov/ttic/tektran/data/000007/97/0000079746.html (Sprinkler selection software)
http://www.wcc.nrcs.usda.gov/nrcsirrig/ (USDA-NRCS Irrigation home page)
http://www.ag.ndsu.nodak.edu/abeng/chem/index.htm (chemigation)
http://www.ianr.unl.edu/pubs/irrigation/
http://www.colostate.edu/Depts/CoopExt/PUBS/CROPS/pubcrop.html#irr
http://ageninfo.tamu.edu/extension/pubs/engineering/index.html
http://www.engineering.usu.edu/iic/
http://www.northerndesigns.com/irrquip.htm l
http://www.nal.usda.gov/ttic/cgi-bin/tektran-absV3.pl?kincaid+and+kimberly
http://www.cprl.ars.usda.gov/ars.htm
http://cahedb.wsu.edu/infoPub/scripts/webListing.asp?category=340
http://www.oznet.ksu.edu/library/ageng2/welcome.htm#VII.Irrigation
http://universityextension.ucdavis.edu/_vti_bin/shtml.dll/search.html
http://www.handilinks.com/cat1/i/i44.htm (General irrigation related company listing)
http://www.nal.usda.gov/wqic/preci.html (Precision agriculture)

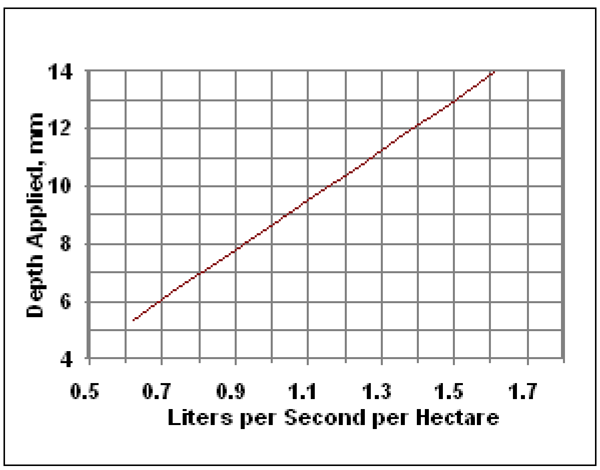


Figure 12. Water application depths in a 24 hour period for center pivots related to gross system capacity with no losses (100% efficiency).

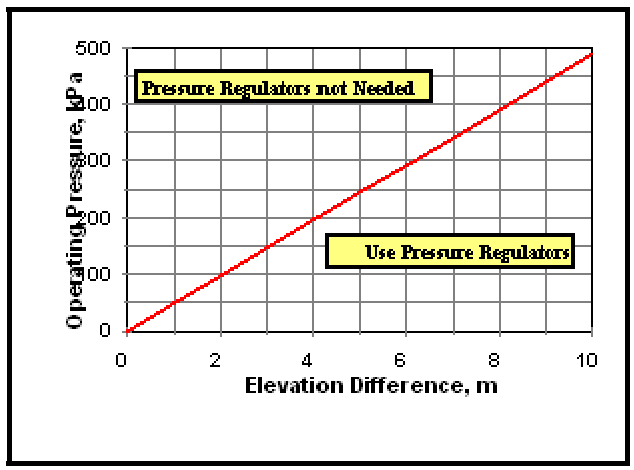
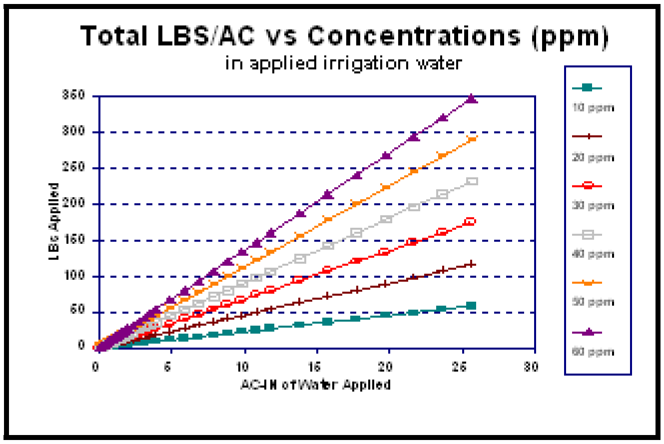
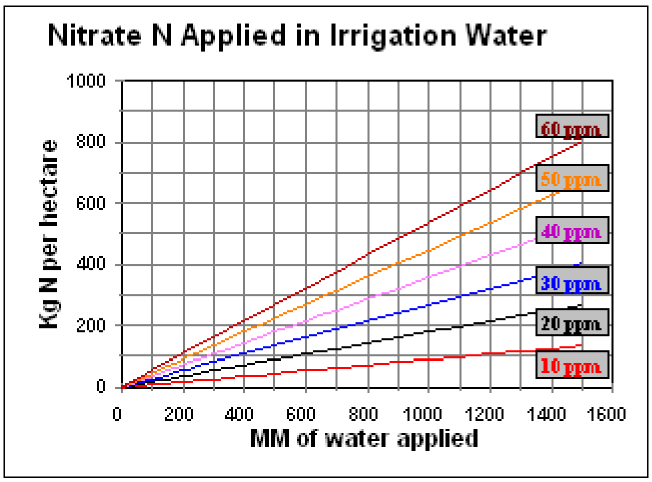


Figure 11. Suggested recommendations for determination of the need for pressure regulators on center pivot and linear move systems.

USEFUL UNITS CONVERSIONS

1 acre = 0.4047 ha
1 lb = 454 gm
1 ft = 0.3048 m
1 in = 25.4 mm
1 US gallon = 3.785 l
1 ft min^{-1} = 0.00508 m s^{-1}
1 gpm = 0.006308 l s^{-1}
1 gpm/ac = 0.1559 l s^{-1} ha^{-1}





Amount of nitrate fertilizer applied through an irrigation system at various concentrations.