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A Simplified Statistical Method For Field Evaluation Of Sprinkler Irrigation Systems

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A SIMPLIFIED STATISTICAL METHOD FOR FIELD EVALUATION OF SPRINKLER IRRIGATION SYSTEMS

By

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ABSTRACT

A SIMPLIFIED STATISTICAL METHOD FOR FIELD EVALUATION OF SPRINKLER IRRIGATION SYSTEMS.

By

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Sprinkler irrigation has become increasingly popular in the recent years, because of continuous innovations and improvements in the method. However, water distribution uniformity is an important factor attracting the attention of many researchers, because of its direct impact on crop productivity and the environment.

In this thesis, a simplified statistical method for field evaluation of sprinkler irrigation systems is presented. The method is based on the estimated coefficient of variation CV (low/high) and estimated confidence limits. The method can be applied to the evaluation of any sprinkler irrigation system when 18 catch can depths are randomly selected. The coefficient of determination (R^2) together with 95% confidence limits were used to compare this method with methods already in practical use.

When the CV (low/high) of solid set sprinkler was compared to the CV (actual), $R^2 = 0.96$. On the other hand, when CV (18) was compared to CV(actual) $R^2 = 0.94$. Further comparison of CV (low/high) to CV (18) yielded $R^2 = 0.97$.

With regard to Turf grass sprinklers, a comparison of CV (actual) to CV (low/high) resulted in $R^2 = 0.99$. Comparing CV (actual) to CV (18) yielded, R^2=0.99. When CV (low/high) was compared to CV (18) gave $R^2 = 0.99$.

As for the center-pivot system, a comparison of CV (Heermann) to CV (low/high)

from simulated data yielded $R^2 = 0.94$. When the actual data were statistically analyzed , a comparison of CV (Heermann) to CV (SCS) resulted in $R^2 = 0.93$. In addition, when CV (Heermann) was compared to CV (low/high) $R^2 = 0.95$. Further comparison of CV (SCS) to CV (low/high) yielded $R^2 = 0.99$. Finally, a graphical technique for estimating the statistical uniformity of the the proposed method is presented.

It can be concluded that, the "three lowest and three highest" method is practically applicable for field evaluation of sprinklers irrigation systems. It includes the advantages of being very simple, easy to use and is based on statistical analysis. In addition, it is a very useful tool for conservation of energy used for crop production and conservation of water to the farmer and the environment.

To
my siblings Aisha and Balla, who sacrificed their lives for us

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ABBREVIATIONS

AW	available water holding capacity, which is the difference between field capacity and permanent wilting point, decimal.
ASAE	American Society of Agricultural Engineers.
C	Roughness coefficient, dimensionless.
CV	Coefficient of variation, percentage and equal $\sigma/\bar{x}$.
D	Diameter of pipe, mm (inch.).
DU	Soil Conservation Service, distribution uniformity.
E_a	Water application efficiency, percentage.
E_pLQ	Soil Conservation Service pattern efficiency.
E_u	Water application efficiency.
FAO	Food Agriculture Organization of the United Nations.
fc	Field capacity, percentage.
f	Dimensionless friction factor.
g	Acceleration due to gravity, m^2/s.
h_f	Head loss due to friction, m.
L	Pipe length, m.
Low/high	Sum of three-low depths and the sum of three-high depths method, based on the estimated coefficient of variation and estimated confidence limits.

MAD	Management-allowable deficit, decimal.
P	Operating pressure, Kpa (Psi).
PWP	Permanent wilting point, percentage.
PVC	Polyvinylchloride.
Q	Flow rate in L/s.
R_e	Reynold number, dimensionless.
R^2	Coefficient of determination.
SCS	Soil Conservation Service.
SMD	Soil moisture deficit equal 50% of the Available water.
SURFER	Computer software, version 4.5, 1991.
UC	Uniformity coefficient of variation of the irrigation system, percent.
UCC	Christiansen uniformity coefficient.
UCH	Hart uniformity coefficient.
UCW	Wilcox and Swailes uniformity coefficient.
UN	United Nations.
U.S.	United States of America.
σ	Standard deviation
$\bar{x}$	Average depth of application, mm (inch.).
α	Confidence level desired.

I. INTRODUCTION

A. Background

Irrigation has enabled many nations to establish ancient civilizations in the semiarid and arid regions, such as the Egyptian civilization on the River Nile and the Chinese civilization on the banks of the Yellow River. Irrigation is one of the oldest technologies, but improvements in irrigation methods and practices are still being made. The future will require even more innovations and improvements because of the competition for limited water resources.

Agricultural production in general, and the production of food in particular has not kept up with need. In 1977 the Food and Agriculture Organization (FAO) of the United Nations (UN) estimated that the total global irrigated area was 233 million hectares (ha), and that would increase to about 273 million ha by 1990, Jensen (1983). Buringh et al. (1975), estimated that, of 3419 million ha of potential agricultural land in the world, 470 million ha could be irrigated. A summary of irrigated area by regions and countries was presented by Zonn (1974) and reproduced by Fukuda (1976). A brief summary is presented in Table 1, (estimates in Table I differ slightly from those of the FAO). In 1979, the FAO estimated irrigated agriculture to represent only 13% but the value of its crop production was 34% of the total world arable land. Since the end of World War II, the development of sprinkler irrigation has been very extensive. One of the factors that helped in the successful development of sprinkler irrigation was the introduction of the light weight aluminum pipes. This basically reduced the initial investment cost in equipment. Other factors include, improvements in sprinkler design and couplings, and fittings. By 1950 Keller and Bliesner (1990) better sprinklers and more efficient pump, further reduced the cost and increased economic accessibility of sprinkler irrigation systems, hence accelerating widespread use of the method. More recently, the self-propelled center-pivot sprinklers, which gained popularity in the 1960s, have provided a means for relatively low cost, high frequency automatic irrigation with a minimum labor cost. Additional innovations are continually being introduced to reduce labor cost and increase the efficiency of sprinkler irrigation.

Table 2 shows the increase in U.S. irrigated land area since 1939. The largest recent percentage increases occurred in the subhumid and humid south and southeast states. But the largest increase in the total area occurred in the semiarid central and southern great plains, Table 3 Jensen (1983). He suggested that 32% of the total irrigated area in the US (20 million ha), was under sprinkler irrigation The largest increase in sprinkler irrigated areas are in the arid pacific northwest and the semiarid great plains. Furthermore, in the subhumid cornbelt and arid pacific northwest 84 and 54 percent, respectively of the total irrigated area are under sprinkler irrigation. Sprinkler irrigation has grown in popularity, because sprinkler irrigation systems are adaptable and suitable for a wide variety of cropping systems. Also, they are adaptable to all irrigable soils, different topographies, and because sprinklers are available in a wide range of discharge capacities.

Table 1. Major world irrigated areas.

	Agricultural Land		
Continent and Country	Cultivated	Cultivated Land Irrigated	Percent Irrigated
	ha (1000s)	ha (1000s)	
Africa	214,000	8,929	4.2
Asia, excluding USSR	463,000	164,640	35.5
Australia and Oceania	47,000	1,701	3.6
Europe, excluding USSR	145,000	12,774	8.8
North and Central America	271,000	27,431	10.1
South America	84,000	6,662	7.9
USSR	233,000	11,500	4.9
Total	1,457,000	233,637	16.0

Adopted from Jensen, (1983).

Table 2. Irrigated area in the United States.

	U.S. Census data			Irrigation Journal data		
Year	Total Irrigated Area in the US		Rate of Growth	Total Irrigated Area in the US		Rate of Growth
	ha (1000s)	ac (1000s)	percent	ha (1000s)	ac (1000s)	percent
1939	7,278	17,893	-	-	-	-
1944	8,312	20,539	2.7	-	-	-
1949	10,484	25,906	4.8	-	-	-
1954	11,960	29,552	2.7	-	-	-
1959	13,421	33,164	2.3	-	-	-
1964	14,997	37,057	2.2	-	-	-
1969	15,832	39,122	1.1	-	-	-
1971	-	-	-	-	-	-
1972	-	-	-	20,215	49,951	-
1973	-	-	-	20,834	51,480	3.1
1974	16,691	41,243	1.1	21,461	53,029	3.0
1975	-	-	-	21,871	54,044	1.9
1976	-	-	-	23,032	56,911	5.3
1977	-	-	-	23,658	58,459	2.7
1978	20,700	51,000	3.0	23,834	58,893	0.7
1979	-	-	-	24,746	61,148	3.8

Adopted from Jensen, (1983).

Table 3. Characteristics of irrigation development in the US from 1974 to 1979 by region .

	Total Area Irrigated			Sprinkler Irrigated			
	1974 to 1979			1974 to 1979			
Region	ha (1000s)		percent	ha (1000s)		Percent	percent of total
Arid Southwest, (AZ, CA)	4,010	4,470	11	561	835	28	19
Arid Pacific Northwest, (ID, OR, and WA)	2,963	3,153	7	1,006	1,664	65	53
Semiarid Central Mountains, (CO, MT, NV, UT, and WY)	4,587	4,280	-7	529	559	6	13
Semiarid Central and South Great Plains, (KS, NE, NM, OK, and TX)	7,343	8,987	22	1,766	2,884	63	32
Subhumid Cornbelt, (IL, IN, MN, MO, and WI)	261	602	131	172	504	193	84
Subhumid and Humid, South and Southwest, (AR, FL, GA, AL, MS, NC, and SC)	1,993	2,511	26	504	799	59	32

Adopted from Jensen, (1983).

B. Overview

Hydraulic design is the most important factor in the ultimate success or failure of a sprinkler irrigation system. A significant amount of research has been done in this area. To assist in the improved design of sprinkler irrigation, Christiansen (1942), developed the coefficient of uniformity as an indicator of a design's distribution uniformity. Heermann and Hein (1968) modified Christiansen's uniformity coefficient for center-pivot sprinkler systems. In addition to the coefficient of uniformity, Christiansen (1942) developed an adjustment factor for the head loss along a lateral due to sprinkler output. Merriam and Keller, (1978) developed the distribution uniformity concept. Bralts et al. (1983 a, and b), developed the statistical uniformity concept for evaluation of drip irrigation systems. The design of sprinkler irrigation submain units for optimal sprinkler uniformity is very important, because once the nozzles, the laterals and the main components have been chosen, very little additional flow control is possible. Thus, the engineer making the design decision regarding pipe size as well as nozzle and sprinkler selection, must have a method of determining submain unit sprinkler uniformity at the design stage.

Sprinkler irrigation systems, figure 1 (Solid set sprinkler) and figure 2 (Center-pivot), consist of water supply and a pump, followed by a network of mainlines, (mostly pipes of steel, asbestos or recently of polyvinylchloride (PVC), and laterals made of either aluminum, PVC, or polyethylene, and sprinklers. In addition to delivery for irrigation, sprinkler irrigation systems can be an effective means for the application of chemicals, i.e. fertilizers, pesticides, herbicides, descants, and defoliants.

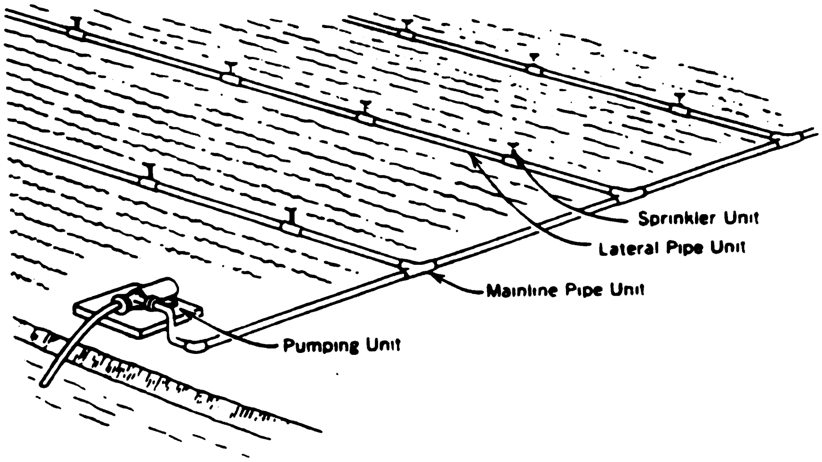


Figure 1. A typical solid set sprinkler layout. *(Adopted from Sichinga, 1975).*

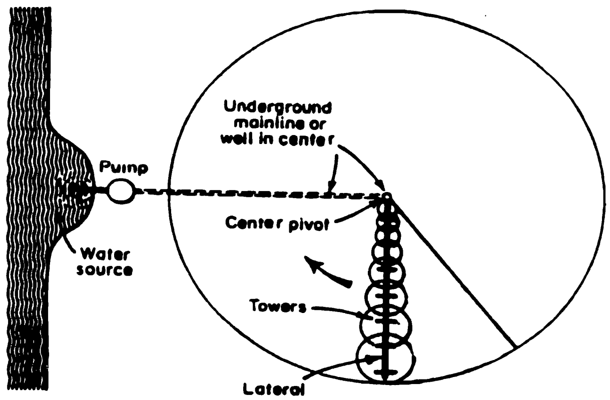


Figure 2. A Typical Center-pivot system layout. (*Adopted from Wallace, 1987*)

The advantages of the conjunctive application of chemicals with irrigation water include savings in labor and equipment, better timing, ease of split and multiple controlled application, greater flexibility of farm operations, and consequently enhanced crop production. Other functions of sprinkler irrigation systems may include crop and soil cooling, protecting crops from frost and freeze damage, delaying fruit and bud development, controlling wind erosion, providing water for seed germination by effective light watering and land application of wastes. Today, sprinkler irrigation systems are utilized on all types of soils, topographies and crops. However, the use of fertilizer injection through sprinkler irrigation has not been fully realized. This is because irrigators were not certain that their sprinkle systems were performing at an acceptable level of uniformity. The problem has been a lack of field evaluation tools.

The field evaluation of sprinkler irrigation submain units is important for the farmer to ensure acceptable performance of water distribution and chemical application; as well as a diagnostic tool for the engineer to confirm successful design.

In this thesis, a simplified method for the field evaluation of sprinkler irrigation system was evaluated. This work follows the comprehensive procedure used by Bralts et al (1983) to evaluate drip irrigation submain units by the using statistical uniformity concept. The same procedures were adopted to evaluate the design and uniformity of sprinkler irrigation. Then, the estimated coefficient of variation and the estimated confidence limits were developed for sprinkler irrigation systems based on one sixth maximum depths and one sixth minimum depths. Finally, the statistical uniformity was calculated. The method was compared to existing methods used to evaluate sprinkler irrigation systems, by using linear regression method and the results were validated. A nomograph of sum of three minimum depths to the sum of three maximum depths was generated to calculate the statistical uniformity of sprinkler irrigation systems.

C. Scope and objectives

The broad objectives of this study were to develop a simplified method to conserve water, chemicals, and energy used for crop production through improved field evaluation of sprinkler irrigation systems. Improvement of field evaluation techniques can conserve energy by maximizing the efficiency of water use. This simplified method is, also, a very useful tool to diagnose environmental concerns such as runoff water quality.

This study was, therefore, intended to develop a simplified method for field evaluation of sprinkler irrigation systems which can be useable by the farmers. The method described here uses uniformity estimates based upon the coefficient of variation, and the statistical uniformity concept together with estimated confidence limits.

The specific objectives of this research were:

1. To develop the statistical uniformity concept for sprinkler irrigation systems based on estimated coefficient of variation and estimated confidence limits;
2. To apply the estimated coefficient of variation and the statistical uniformity concept with estimated confidence limits to field evaluation of sprinkler irrigation systems; and

3. To evaluate the usefulness of the estimated coefficient of variation and the estimated confidence limits for the field evaluation of sprinkler irrigation systems by statistical comparison of the results to methods already adopted for field evaluation of sprinkler irrigation systems.

II. LITERATURE REVIEW

A. Soil-water-plant relations

Understanding the general concept underlying basic soil-water-plant relations and interactions is central to the ability to design and manage sprinkler irrigation system. It is therefore, worth clarifying the following important terms:

1. Soil water

The soil stores water needed by plants. Adsorptive and capillary forces, called *matric forces*, hold significant amounts of water which can be removed and used by plants. It is much easier for plants to obtain water from the soil when it is moist than when it is dry because these retention forces are more significant under low water content conditions.

Between saturation and absolute dryness are two important soil water contents relative to the plant. These water contents, *field capacity (fc)* and *permanent wilting point (pwp)*, are defined respectively as the upper and the lower limits of soil water that is available to the plants. In practice these parameters are defined as follows: Field capacity is the percentage of water remaining in a soil two to three days after the soil has been saturated and after free drainage has practically ceased, and permanent wilting point is the water content of the soil after plants can no longer extract water at a sufficient rate for wilted leaves to recover overnight when placed in a saturated environment. The water content when the soil is at field capacity is less than saturation, while the soil is not absolutely dry at the permanent wilting point. Neither field capacity nor wilting point is a sharply defined quantity.

Because water between field capacity and permanent wilting point is available to the plants, it is called the available water, (AW). The following equation is used to compute available water:

$$AW = D_{rz} \frac{(fc - pwp)}{100} \tag{1}$$

where:

AW = available water (mm, in.);

D_{rz} = depth of the root zone (cm, in.) the depth to the soil layer that restricts water movement;

fc = field capacity in percentage by volume; and

pwp = permanent wilting point, in percentage by volume.

Soils of various textures have varying abilities to retain water. Table 4, gives typical ranges of available water-holding capacities, (field capacity minus permanent wilting point) of soils of different textures adapted from Chapter I, Section 3, of Keller and Bliesner, (1990). These data are important to the farmer because any irrigation beyond field capacity is an economic loss. However, if field data were not available, these averages are very useful in preliminary designs.

2. Root depth

The total amount of water available for plant use in any soil is the sum of all available water-holding capacities of all horizons occupied by plant roots (Keller and Bliesner, 1990). Table 5. can be used to estimate the effective root depth if actual data are not available. The values represent the depth at which crops will obtain a major portion of their needed water when grown in a deep, well-drained soil that is adequately irrigated.

3. Consumptive use

To address the question of system capacity that, over the life of the system will maximize profit to the farmer, one must decide how much water the system should be able to deliver to a crop over a given period. It is necessary to know how much water the crop will use, not only over the entire growing season, but also during the part of the season when water use is at its peak. It is the rate of water use during this peak consumptive period that is the basis for determining what rate irrigation water must be delivered to the field. Examples of typical seasonal and peak daily crop water requirements are given in Table 6.

Table 4. Range in available water-holding capacity of soils of different texture.

Texture	water-holding capacity range mm/m	water-holding capacity average mm/m
1. Very coarse texture-very coarse sands.	33 to 62	42
2. Coarse texture-coarse sands, fine sands, and loamy sands.	62 to 104	83
3. Moderately coarse texture-sandy loams.	104 to 154	125
4. Medium texture-very fine sandy loams, loams and silt loams.	125 to 192	167
5. Moderately fine texture clay loams, silty clay loams and sandy clay loams	145 to 208	183
6. Fine texture -sandy clays, silty clays, and clays	133 to 208	192
7. Peat and mucks.	167 to 250	208

Note: 1 mm/m = 0.012 in./ft

Adopted from Keller and Bliesner, 1990.

Table 5. **Effective crop root depths that would contain approximately 80% of the feeder roots in a deep, uniform, well-drained soil profile.**

Crop	Root Depth (m)	Crop	Depth (m)	Crop	Root Depth (m)
Alfalfa	12 to 1.8	Chard	0.6 to 0.9	Peanuts	0.4 to 0.8
Almonds	0.6 to 1.2	Cherry	0.8 to 1.2	Pear	0.6 to 1.2
Apple	0.8 to 1.2	Citrus	0.9 to 1.5	Pepper	0.6 to 0.9
Apricot	0.6 to 1.4	Coffee	0.9 to 1.5	Plum	0.8 to 1.2
Artichoke	0.6 to 0.9	Corn (grain and silage)	0.6 to 1.2	Potato (Irish)	0.6 to 0.9
Asparagus	1.2 to 1.8	Corn (sweet)	0.4 to 0.6	Potato (sweet)	0.6 to 0.9
Avocado	0.6 to 0.9	Cotton	0.6 to 1.8	Pumpkin	0.9 to 1.2
Banana	0.3 to 0.6	Cucumber	0.4 to 0.6	Radish	0.3
Barley	0.9 to 1.1	Egg plant	0.8	Safflower	0.9 to 1.5
Bean (dry)	0.6 to 1.2	Fig	0.9	Sorghum	0.6 to 0.9
Bean (green)	0.5 to 0.9	Flax	0.6 to 0.9	Sorghum (silage)	0.9 to 1.2
Bean (lima)	0.6 to 1.2	Grapes	0.5 to 1.2	Soybean	0.6 to 0.9
Beet (sugar)	0.6 to 1.2	Lettuce	0.2 to 0.5	Spanish	0.4 to 0.6
Beet (table)	0.4 to 0.6	Lucern	1.2 to 1.8	Squash	0.4 to 0.9
Berries	0.6 to 1.2	Oats	0.6 to 1.1	Strawberry	0.3 to 0.5
Broccoli	0.6	Olives	0.9 to 1.5	Sugarcane	0.5 to 1.1
Brussels sprout	0.6	Onion	0.3 to 0.6	Sudan grass	0.9 to 1.2
Cabbage	0.6	Parsnip	0.6 to 0.9	Tobacco	0.6 to 1.2
Cantaloupe	0.6 to 1.2	Passion fruit	0.3 to 0.5	Tomato	0.6 to 1.2
Carrot	0.4 to 0.6	Pastures	0.3 to 0.8	Turnip (white)	0.5 to 0.8
Cauliflower	0.6	Pea	0.4 to 0.8	Watermelon	0.6 to 0.9
Celery	0.6	Peach	0.6 to 1.2	Wheat	0.8 to 1.1

Adapted from Keller and Bliesner, 1990.

Table 6. Typical peak daily and seasonal crop water requirements in different climates.

Types of climate and water requirements, mm										
Season	Cool		Moderate		Hot		High desert		Low desert	
Crop	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
Alfalfa	5.1	635	6.4	762	7.6	914	8.9	1016	10.2	1219
Grain	3.8	381	5.1	457	5.8	508	6.6	533	5.8	508
Beets	4.6	584	5.8	635	6.9	711	8.1	732	9.1	914
Beans	4.6	330	5.1	381	6.1	457	7.1	508	7.6	559
Corn	5.1	508	6.4	559	7.6	610	8.9	660	10.2	762
Cotton	-	-	6.4	559	7.6	660	-	-	10.2	813
Peas	4.6	305	4.8	330	5.1	356	5.6	356	5.1	356
Tomatoes	4.6	457	5.1	508	5.6	559	6.4	610	7.1	660
Potatoes	4.6	406	5.8	457	6.9	553	8.1	584	6.9	533
Truck vegetables	4.1	305	4.6	356	5.1	406	5.6	457	6.3	508
Melons	4.1	381	4.6	406	5.1	457	5.6	508	6.4	559
Strawberry	4.6	457	5.1	508	5.6	559	6.1	610	6.6	660
Citrus	4.1	508	4.6	559	5.1	660	-	-	5.6	711
Deciduous orchard	3.8	483	4.8	533	5.8	584	6.6	635	7.6	762
Vineyard	3.6	356	4.1	406	4.8	457	5.6	508	6.4	610

1 = Daily; **2** = Seasonal.
Adapted from Keller and Bliesner, 1990.

4. Soil moisture management

A general rule of thumb for many field crops in arid and semiarid regions is that the soil moisture deficit, (SMD), within the root zone should not fall below 50% of the total available water-holding capacity. This is the management allowable deficit; MAD = 50% of AW. Because it is desirable to bring the moisture level back to field capacity with each irrigation, the depth of water applied at each irrigation is constant (50% of total available water holding capacity) throughout the growing season (Keller and Bleisner, 1990). This means that the duration of each irrigation is also constant, although the frequency of application varies as a function of changes in the rate of water use over the growing season.

The situation is different in the humid regions, because it is necessary to allow for rains during the irrigation period. However, the 50% limitation on soil moisture depletion should be followed as a general guide for field crops.

Soil management, water management, and economic considerations determine the amount of water used in irrigation and the rate of water application necessary. The standard design approach has been to determine the amount of water needed to fill the entire root zone to field capacity, and then apply at one application a larger amount to account for evaporation, leaching, and inefficiency of application. The traditional approach to the frequency of application has been to take the depth of water in the root zone reservoir that can be extracted, assuming MAD = 50%, and, using the daily consumptive use rate of the plant, determine how long this supply will last. This approach is useful only as a guide to irrigation requirements, as many factors affect the volume, and the timing of application for optimal design and operation of a system.

Table 7. Guide for selecting management-allowable deficit, MAD, values for various crops.

MAD, %	Crop and root depth
25-40	Shallow-rooted, high-value fruit and vegetable crops
40-50	Orchards,* vineyards, berries and medium-rooted row crops
50	Forage crops, grain crops, and deep-rooted row crops

* Some fresh orchards require lower MAD values during fruit finishing for sizing

Adopted from (Keller and Bleisner, 1990)

5. Irrigation depth

The maximum net depth of water to be applied per irrigation, d_x, is the same as the maximum allowable depletion of soil water between irrigations. It is computed by:

$$d_x = \frac{MAD}{100} W_a Z \tag{2}$$

where:

d_x = maximum net depth of water to be applied per irrigation, mm (in.);

MAD = management allowed deficit, which can be estimated from Table 4;

W_a = available water-holding capacity of the soil, which can be estimated from Table 4, mm/m; and

Z = effective root depth, which can be taken from Table 5, mm (ft).

6. Irrigation interval

The appropriate irrigation interval, which is the time that should elapse between the beginning of two successive irrigations, is determined by:

$$f = \frac{d_n}{U_d} \tag{3}$$

where:

f = irrigation interval or frequency, days;

d_n = net depth of water application per irrigation, to meet consumptive use requirements, mm (in.); and

U_d = conventionally computed average daily crop water requirement, or use rate, during the peak-use month, which can be estimated from Table 6, mm/day (in./day).

The values selected for d_n will depend upon system design and environmental factors, and it should be equal to or less than d_x. When d_n is replaced by d_x in equation 2, f becomes the maximum irrigation interval, f_x.

B. Methods of irrigation

Farm irrigation systems must supply water at rates in quantities, and at times needed to meet farm irrigation requirements and schedules. It is essential that farm irrigation systems facilitate management by providing a means for measuring and controlling flow. The methods of applying water to the plants may be classified as subirrigation, surface irrigation, microirrigation, and sprinkler irrigation.

1. Subirrigation

In special situations, water may be applied below the soil surface by developing or maintaining a water table that allows water to move up through the root zone by capillary action. This is essentially the same practice as controlled drainage. Controlled drainage becomes subirrigation if water must be supplied to maintain the desired water level. Water may be introduced into the soil profile through open ditches, mole drains, or pipe drains. The open ditch method is most widely used. Water table maintenance is suitable where the soil in the plant root zone is quite permeable and there is either a continuous impermeable layer or a natural water table below the root zone. Since subirrigation allows no opportunity for leaching and establishes an upward movement of water, salt accumulation is a hazard; thus the salt content of water should be low.

2. Surface irrigation

This is the most common method of applying irrigation water, especially in arid regions. Surface methods include: wide flooding, where the flow of water is uncontrolled, and surface application, where the flow is controlled by furrows, corrugations, border dikes, contour dikes or basins. To conserve water, the rate of water application should be carefully controlled and the land properly graded.

3. Microirrigation

Increasing use is being made of microirrigation (trickle or drip) systems that apply water at very low rates, often to individual plants. Such rates are achieved through the use of specially designed emitters or porous tubes, usually installed on or just below the soil surface. These systems provide an opportunity for efficient use of water because of minimum evaporation losses, and because irrigation is limited to the root zone. Because of their high initial cost, their use is generally limited to high-value crops. They are, also well adaptable for application of agricultural chemicals.

4. Sprinkler irrigation

A sprinkler irrigation system uses pressure energy to form and distribute "rainlike" droplets over the land surface, (Larry G. James, 1988). In sprinkler irrigation systems water is conveyed from a pump through a network of pipes, called mainlines and submains, to one or more pipes with sprinklers called laterals. A typical sprinkler system is shown by figures 1 and 2. Sprinkler irrigation is a versatile means of applying water to any crop, soil, and topographic condition. It is popular because surface ditches and prior land preparation are not necessary and because pipes are easily transported and provide no obstruction to farm operations when irrigation is not needed. Sprinkling is suitable for sandy soils or any other topographic conditions where other methods may be expensive or inefficient, or where erosion may be particularly hazardous. Low rates and amounts may be applied, such as required for seed germination, frost protection, delay of fruit budding, and cooling of crops in hot weather. Fertilizers and soil amendments may be dissolved in water and applied through irrigation systems. The major concerns of sprinkler irrigation systems is the investment costs, labor requirements, and evaporation losses.

C. Types of sprinkler irrigation systems

There are 10 major types of sprinkler irrigation systems and several versions of each type. These types of systems may be divided into two basic groups:

1. Set systems

These operate with a sprinkler set in a fixed position. They can be further divided to the following subgroups:

a. Periodic move

Hand-move laterals, end-tow laterals, side-roll laterals, side-move laterals, gun, and boom sprinklers

b. Fixed sprinkler system

2. Continuous-move systems

These operate while the sprinklers are moving. They can be subdivided into: Traveling sprinklers, center-pivot system, linear-moving laterals.

D. Parameters for sprinkler irrigation evaluation

1. Basic hydraulics

The hydraulic principles of sprinkler irrigation are based upon the classical continuity and energy equations. The following developments will follow the theory and nomenclature used by Wu et., al., (1979) and Bralts et al. (1983 a, b).

a. Pressure and head relationships:

The pressure of water at rest in a container at any point is equal to the product of the unit weight of water (1000 Kg/m^3 at 20°C) and the height of water above the point, (head of water). Head is in meters (m) and pressure in Kilo-Pascal (KPa). One meter of water = 9.81 KPa of pressure. In an irrigation system the head consists of several components:

i. static head = difference in elevation between source and current position;

ii. pressure head = the pressure (P) divided by the unit weight of water;

iii. velocity head = the energy required to accelerate the water from rest to its velocity ($V^2/2g$); and

iv. friction head (h_f) = the energy required for water to flow (to overcome friction) between two points at the same elevation.

b. Pipe flow equation

The flow in a sprinkler irrigation manifold pipe or lateral will be considered to have reached a steady state. Flow will, therefore, vary spatially due to friction and pipe length, but not temporally (Bralts, et al. 1983). This means that the total flow in the pipe is changing, usually decreasing, with respect to length due to friction losses.

Head loss along a lateral is due to sprinkler output and friction. Any of several empirical equations can be used to calculate head loss due to friction. In this thesis, only two such equations will be discussed. The first equation, which is based on the Darcy-Weisbach equation is as follows:

$$h_f = f\,\frac{LV^2}{2gD}\,x \qquad (4)$$

Where:

h_f = head loss due to friction;

f = dimensionless friction factor;

L = length of the pipe;

D = diameter of the pipe;

V = velocity of water in the pipe; and

g = acceleration due to gravity.

Since sprinkler irrigation laterals are considered to be hydraulically smooth and their flow is fully turbulent then the Blasius empirical formula for turbulent flow in a smooth pipe can be substituted for the dimensionless friction factor (f), (Wu and Gitlin, 1974; Howell et. al. 1981; and Bralts et. al. 1983 a, b). Figure 3. represents the dimensionless energy gradient line, along a sprinkler irrigation lateral line, (Wu and Gitlin, 1974).

The Blasius formula for the friction fact f, is:

$$f = \frac{0.3164}{R_e^{0.25}} \qquad (4000 < R_e < 100000) \tag{5}$$

where:

f = friction coefficient; and

R_e = Reynold number.

Watters and Keller (1978) combined equations (4 and 5) at 20°C and found:

$$h_f = 7.89 * 10^5 \left(\frac{Q^{1.75}}{D^{4.75}}\right) * L \tag{6}$$

where:

h_f = head loss in meters;

Q = flow rate in L/s;

D = pipe diameter in millimeters; and

L = pipe length in meters.

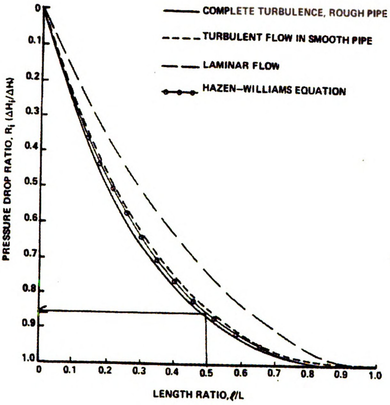


Figure 3. Dimendionless energy gradient curve, (Wu and Giltin, 1974)

The second empirical equation which is commonly used in hydraulic design is the Hazen-Williams formula (Keller and Karmeli, 1975; Jeppson 1982):

$$h_f = 1.221 * 10^{10} \left(\frac{Q^{1.852}}{C^{1.852} D^{4.871}}\right) * L \tag{7}$$

where: C = the roughness coefficient.

Table 8 shows typical values of C for use in the Hazen-Williams equation.

Table 8. Typical values of C used in Hazen-Williams equation

Pipe Material	C Value
Plastic	150
Epoxy-coated Steel	145
Cement Asbestos	140
Galvanized Steel	135
Aluminum, (with couplers every 30 ft)	130
Steel (new)	130
Steel (15 years old) or Concrete	100

Adoptd from James, (1988).

The Hazen-Williams equation was developed from the study of water distribution systems that used 75 mm (3 in.) or larger diameter pipes and discharges greater than 3.2 L/s (50 gpm). Under these flow conditions the, R_e is greater than 5 x 10^4, and the formula, therefore, predicts the friction losses satisfactorily.

The Reynold number at 20°C (68°F) for water flowing through a pipe is:

$$R_e = K \frac{Q}{D} \tag{8}$$

where:

K = conversion constant, (1.3×10^6, for metric system; 3214 for English system).

The friction factor f for flow in smooth pipes is given by the following classic equation for laminar flow where $R_e < 2000$

$$f = \frac{64}{R_e} \tag{9}$$

For turbulent flow, $R_e > 2000$.

For turbulent flow the friction factor f, taking Von Korman formula, becomes;

$$\frac{1}{f^{0.5}} = 1.14 + 2 \log \frac{D}{e} \tag{10}$$

and the relationship:

$$E = \frac{e}{D} \tag{11}$$

where:

E = relative roughness;

e = roughness size, (L); and

D = diameter of the pipe, (L).

An equation developed by Churchill (1977), perfectly handles the entire range of Reynold number for determining f in all types of pipes. It lends itself to numerical solutions:

$$f = 8\ \left(\left(\frac{8}{R_e}\right)^{12} + \frac{1}{(K_1 + K_2)^{1.5}}\right)^{\frac{1}{12}} \tag{12}$$

where:

$$K_1 = \left(2.457\ \ln\left(\frac{1}{\left(\frac{7}{Re}\right)^{0.9}}\right) + 0.27\ \frac{e}{D}\ \right)^{16} \tag{13}$$

$K_2 = (37530/Re)^{16}$

If the value of C for smooth pipe, of 150 is substituted in equation (4), the following empirical equation is obtained:

$$h_f = 11.38\ X\ 10^5 \left(\frac{Q^{1.852}}{D^{4.871}} \right) L \tag{14}$$

Equation 14 is the same as equation 7, but it incorporates a fixed value for C. The major difference between Darcy-Weisbach and Hazen-William equations is that, the Darcy-Weisbach equation has a friction factor which is dependent on Reynold Number while the Hasen-William equation has a constant smooth pipe friction factor. However, it is clear that, the Darcy-Weisbach equation represents the friction losses in small diameter pipes and hoses better than does the Hazen-William formula. Furthermore, when comparing the two equations at the same velocity, the *C*-value of the Hazen-Williams equation seems to be dependent upon pipe diameter.

Howell (1981) recommended the following *C*-values to use with plastic pipes:

Table 9. Recommended C-values for Plastic Pipes

C-value	Diameter
130	14 - 15 mm (0.58 inches)
140	18 - 19 mm (0.75 inches)
150	25 - 27 mm (1.0 inch)

Adopted from Howell, (1981).

Both equations (4) and (7) are generalized by Wu and Gitlin (1975), and Wu *et. al* (1979), as follows:

$$\Delta H = - a Q^m \qquad (15)$$

where:

ΔH = change in head due to friction;

Q = total lateral line flow;

a = pipe constant; and

m = pipe flow exponent.

*c. **Sprinkler Flow Equation***

In general, the relationship between pressure, or pressure head, and discharge from a sprinkler can be expressed by the orifice equation:

$$q = K_d (P)^{0.5} \qquad (16)$$

or

$$q = K_d (h)^{0.5} \qquad (17)$$

where:

q = sprinkler discharge L/m, (gpm);

K_d = appropriate discharge coefficient for sprinkler and nozzle combined and specific units used;

P = sprinkler operating pressure KPa (Psi); and

H = sprinkler operating pressure head, m (ft).

The design coefficient K_d can be determined for any combination of sprinkler and nozzle, if any value of *P* and the corresponding value of *q* are known. Because of the internal sprinkler friction losses, K_d decreases slightly as *P* and consequently *q* increase. However, over the normal operating range of most sprinklers, it can be assumed constant.

Equation (16) can be manipulated to yield;

$$P = P^{/} \left(\frac{q}{q^{/}}\right)^2 \tag{18}$$

where;

$P^{/}$ and $q^{/}$ can be supplied by the manufacturer's tables; and either P and q is not known. Also, equation (17) can be manipulated in a similar manner.

A special form of equation (16) and (17) can be modified to account for sprinkler and nozzle plugging, (Bralts, 1983):

$$q = (1-a)\, K_d\, P^{0.5} \tag{19}$$

$$q = (1-a)\ K_d\ H^{0.5} \tag{20}$$

where:

a = the fraction of nozzles likely to plug.

E. Sprinkler system capacity requirements

The required capacity of a sprinkler system depends on the size of the area irrigated, the gross depth of water applied at each irrigation, and the net operating time allowed to apply this depth.

1. System capacity

The capacity of the system can be computed by the formula presented by (Keller and Bliesner, 1990):

$$Q = K\ \frac{Ad}{fT} \tag{21}$$

where:

Q = system discharge capacity, L/s (gpm);

K = conversion constant, 2.78 for metric units, (453 for English units);

A = design area, ha (acre);

d = gross depth of application, mm (in.);

f = operation time allowed for completion of one irrigation, days; and

T = average actual operating time per day, hr/day

2. Sprinkler application rates

The rate at which water should be applied depends on the following:

a. The infiltration characteristics of the soil, the field slope, and the crop cover;

b. The minimum application rate that will produce a uniform sprinkler distribution pattern and satisfactory efficiency under the prevalent wind and evaporative demand conditions; and

c. The farm conditions and the type of sprinkler system used.

3. Computing set sprinklers application rates

The average application rate from a sprinkler is computed by:

$$I = \frac{K\,q}{S_e \, X \, S_l} \tag{22}$$

where:

I = average application rate, mm/hr, (in./hr);

K = conversion constant, 60 for metric units, (93.6 for English units);

q = sprinkler discharge, L/min, (gpm);

S_e = spacing of sprinklers along the laterals, m (ft); and

S_l = spacing of laterals along the main line, m (ft)

4. Computing instantaneous application Rate

To compute the average instantaneous application rate, I_i, for a sprinkler having a radius of throw, R_j, and wetting an angular segment, S_a, equation (23) can be modified as:

$$I_i = \frac{K\,q}{\pi\,(R_j)^2\,x\,\dfrac{S_a}{360}} \tag{23}$$

where:

K = same as above;

R_j = radius of wetted area, m (ft); and

S_a = angular segment, (from a top view) wetted by a stationary a sprinkler jet, degrees.

F. Sprinkler uniformity

Irrigation uniformity is a concept used extensively in system design and management. There are several factors that cause irrigation to be nonuniform under different methods of irrigation. However, there are specific factors that affect the water application efficiency of sprinkler irrigation systems:

i. Variation of individual sprinkler discharge throughout a lateral line;

ii. Variation in water distribution within the sprinkler-spacing area, which is caused primarily by wind;

iii. Losses of water by direct evaporation from the spray; and

iv. Evaporation from the soil surface before water is used by plants.

1. Solid sets sprinklers

The uniformity of application is of primary concern in a sprinkler design procedure. The areal distribution of irrigation depth from a sprinkler system is often a result of an overlapping application pattern of many individual sprinklers at a given spacing. The uniformity of sprinkler irrigation has been studied by many researchers. The first pioneer to address the problem of sprinkler uniformity as an important factor affecting the design and performance of sprinkler irrigation was Christiansen (1942). He was the first to assign an index to the variability of sprinkler irrigation depth, and introduced a measure of uniformity known as the Christiansen Uniformity Coefficient, (UCC), defined as:

$$UCC = 1 - \sum_{i=1}^{n} \frac{|(X_i - \bar{X})|}{n\bar{X}} \tag{24}$$

where:

$\bar{x}$ = average depth of irrigation;

X_i = observed irrigation depth; and

n = No. of observations.

The mean deviations are given by:

$$Mean\ Deviations = \sum_{i=1}^{n} \left| \frac{X_i - \bar{X}}{n} \right| \tag{25}$$

Keller and Bliesner (1990) suggested that the test data for UCC > 70% usually forms a bell-shaped normal distribution and is reasonably symmetrical about the mean. Therefore, UCC can be approximated by:

$$UCC = \frac{Average\ (low\text{-}half)\ depth\ of\ water\ received}{\bar{X}} \times 100 \tag{26}$$

However, the problem with the UCC measure is that it gives the same weight assigned to irrigation depths above and below the mean. The result is that too little and too much irrigation has the same effect on yield, which is not quite true. The bottom line of this definition of uniformity is that dispersion of irrigation water is related to the mean of the amount irrigated.

Wilcox and Swailes (1947) replaced the mean deviation of Christiansen by the standard deviation. The result was the coefficient of variation (CV), $\sigma/\bar{x}$, and becomes:

$$UCW = 1 - \frac{\sigma}{\bar{X}} \tag{27}$$

where:

σ = the standard deviation of the sample.

The coefficient of variation was extensively used by Bralts, et al.. (1981, 83, 84 and 87) to develop statistical uniformity concept to evaluate drip irrigation submain units. The coefficient of variation is defined as the ratio of the standard deviation to the mean of a sample or a population. The coefficient of variation was approached by estimating the mean and the standard deviation. The following is a summary of how they developed the estimation equations.

a. Estimating the standard deviation:

$$S_{qs} = \frac{2}{N} (Q_{us} - Q_{ls}) \tag{28}$$

where:

S_{qs} = the estimate of the standard deviation of the emitter (sprinkle) flow rate;

Q_{us} = the sum of the observations in the upper one sixth of the distribution;

Q_{ls} = the sum of the observations in the lower one sixth of the distribution; and

N = the number of observations in the sample.

b. Estimating the mean:

$$q_s = \frac{3}{N}(Q_{us} + Q_{ls}) \tag{29}$$

c. Estimating the coefficient of variation:

Using the above two equations, the coefficient of variation can be written as:

$$CV_{qs} = 0.667\,\frac{(Q_{us} - Q_{ls})}{(Q_{us} + Q_{ls})} \tag{30}$$

If 18 random measurements of sprinkler or emitter flow rate were made, it would only be necessary to sum the three highest and the three lowest values to estimate the coefficient of variation. The above equation can be rearranged to demonstrate the linear nature of the terms Q_{us} and Q_{is}:

$$Q_{us} = \frac{(0.667 + CV_{qs})}{(0.667 - CV_{qs})}\,Q_{ls} \tag{31}$$

Thus, for any given coefficient of variation CV_{qs}, the Q_{us} varies linearly with Q_{ls}.

Bralts, et al., (1983), also used, the inverse relationship of minimum time to maximum emitter flow rate, so the above equation can be written as:

$$T_{max} = \frac{(0.667 + CV_{qs})}{(0.667 - CV_{qs})} T_{min} \tag{32}$$

where:

T_{max} = the sum of the top one sixth of the emitter flow times required to fill a specific volume with water; and

T_{min} = .the sum of the bottom one sixth of the emitter flow times required to specific volume with water.

d. Confidence Limits:

The confidence limits for the coefficient of variation (CV_{qs}) on samples from a normal population, (Bralts and Kesner, 1983, after Sokal and Rohlf, 1969) can be expressed as:

$$p\,(V_q - t_{\frac{\alpha}{2}} S_{V_q} \leq V_q^* \leq V_q + t_{\frac{\alpha}{2}} S_{V_q}) = 1 - \alpha \tag{33}$$

Where:

CV_q = sample coefficient of variation;

$t_{\alpha/2}$ = student t value for given α;

α = confidence level desired;

CV^*_q = Actual coefficient of variation for the full submain; and

S_{Vq} = standard deviation of the coefficient of variation is calculated from the equation:

$$S_{V_q} = \frac{CV_q}{\sqrt{2N}} \sqrt{1 + 2\,(CV_q)^2} \tag{34}$$

Using these two equations, the confidence limits for the sample coefficient of variation, CV_q, can be found. Since the confidence limits of the estimated coefficient of variation are dependent on the assumption of a normal distribution, the above confidence limits can only be used as the approximate confidence limits of estimated coefficient of variation.

They translated this relationship into a nomograph figure 4, for drip irrigation field uniformity estimation. The same procedure will be followed for sprinkler irrigation uniformity estimator.

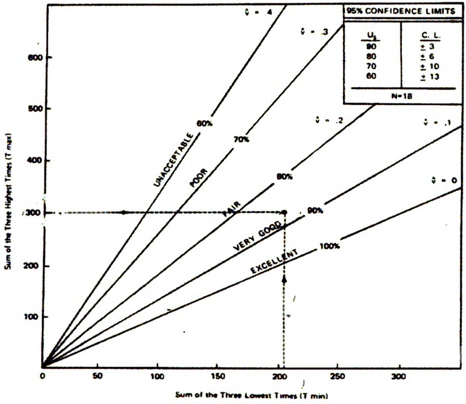


Figure 4. Nomograph for drip irrigation uniformity estimation, (Bralts, 1983).

Hart, (1961) described a uniformity similar to UCC:

$$UCH = 1 - \left(\frac{2}{\pi} \right)^{0.5} \left(\frac{\sigma}{\bar{X}} \right) \tag{35}$$

Hart and Reynolds (1965) from the Hawaiian Sugar Planters' Association proposed a uniformity coefficient similar to UCC called Hawaiian Sugar Planters' Association (HSPA). Hart et al. (1980) showed these two coefficients are essentially the same.

A useful term placing a numerical value on the uniformity for agricultural irrigation is the distribution uniformity, DU, (Merriam and Keller, 1978). DU indicates the uniformity of application throughout the field and is computed by:

$$DU = \frac{\text{Average low-quarter depth of water received}}{\text{Average depth of water received}} * 100$$

The average low-quarter depth of water received is the average of the lowest one-quarter of measured values, where each value represents an equal area.

The relationship between UCC and DU was approximated by, Keller and Bleisner(1990), as:

$$UCC = 100 - 0.63 \left(100 - DU \right) \tag{36}$$

or

$$DU = 100 - 1.59 \ (\ 100 - UCC \ ) \tag{37}$$

And the relationship between UCC and the standard deviation of individual depth of catch observations can be approximated by:

$$UCC = 100 \ (\ 1.0 - (\frac{\sigma}{\bar{x}}) \ (\frac{2}{\pi})^{0.5} \ ) \tag{38}$$

Emmanuel, (1992), referred to the postulation of (Karmeli, 1977, 1978. Karmeli, Salazer and Walker, 1978), that observations drawn from the cumulative distribution are approximately linear and could be defined as:

$$Y = a + bX \tag{39}$$

where:

Y = dimensionless irrigation depth;

X = dimensionless area received Y depths or less; and

a and b are the intercept and the slope on the Y-axis respectively.

Noting that the uniform distribution provides a linear cumulative distribution, they defined the uniformity coefficient by:

$$UCL = 1.0 - 0.25\ b \tag{40}$$

where:

b = transformed range of dimensionless irrigation depth; and

0.25 = is the mean deviation, dividing the mean for uniform distribution.

2. Center-pivot System

The center-pivot sprinkler system is a versatile method of applying water to a large scale agricultural area which covers about one-quarter section of a land area. The method developed because of an increased demand for agricultural labor. The effectiveness of this method can be evaluated using the guidelines of ASAE. Bittinger and Longenbough (1962) were the first to develop a mathematical model for center-pivot uniformity. Heerman and Hein (1968), solved the mathematical expression for the application rate and the application depth to develop a weighted coefficient of uniformity for center-pivot system in the form of:

$$C_u = \left[1.0 - \frac{\sum_s S_s \left| D_s - \frac{\sum_s D_s S_s}{\sum_s S_s} \right|}{\sum_s D_s S_s} \right] \tag{41}$$

where:

C_u = coefficient of uniformity (Heermann and Hein);

D_s = catch can depth at distance S from the pivot center; and

S_s = distance from catch point to the center of the pivot.

Marek et al (1986) used the coefficient of variation to develop an areal-weighted uniformity coefficient in the form of :

$$C_u = 100 \left[1.0 - \frac{\sqrt{\dfrac{\sum_{i=1}^{N} \left[x_i \, r_i - \left(r \, \dfrac{\sum_{i=1}^{N} x_i \, r_i}{\sum_{i=1}^{N} r_i} \right) \right]^2}{N-1}}}{\dfrac{\sum_{i=1}^{N} r_i \, x_i}{N}} \right] \qquad (42)$$

G. Irrigation Efficiency Terms

1. SCS Pattern Efficiency

The on-farm irrigation committee, (Kruse 1978), defines pattern efficiency as:

$$E_p LQ = \frac{\text{Average low-quarter depth of water applied and stored}}{\text{Average depth of water applied}}$$

This is not an efficiency term as the name suggest but a distribution index and it is similar to the low quarter distribution.

2 Irrigation Efficiency

There are many different irrigation efficiency concepts now in existence and they are widely used. However, the most commonly used definition is the ratio of beneficially used water to total water applied, Chaurdry (1978).

Application efficiency is different from irrigation efficiency and is the ratio of water stored in the root zone to total water applied. Many attempts have been made to standardize irrigation efficiency terms, e.g. The On Farm Irrigation Committee, and Kruse (1978).

3. Application Efficiency

There are different available definitions in the literature, which vary according to the particular use. However, this term should include the effect of losses due to nonuniformity of application, spray drifts, evaporation, and pipe losses.

4. Water Use Efficiency

Irrigation efficiency sometimes is defined as water use efficiency. Israelsen and Hansen (1962) defines water use efficiency as:

$$E_u = 100 \frac{W_u}{W_d} \tag{43}$$

where:

E_u = water use efficiency;

W_u = water is beneficially used; and

W_d = water delivered to the farm.

5. Water Application Efficiency

Water application efficiency is defined as:

$$E_a = 100 \frac{W_s}{W_f} \tag{44}$$

where:

E_a = water application efficiency;

W_s = water stored in the root zone during irrigation; and

W_f = water delivered to the farm or irrigation system.

Wallace (1987) also refers to common sources of losses of irrigation water during water application including surface runoff, (R_f), and deep percolation below the root zone, (D_f). The sum of these losses and water used is equal to total water delivered.

$$W_f = W_s + R_f + D_f \tag{45}$$

According to this equation water application efficiency (E_a) can be defined as:

$$E_a = 100 \frac{W_f - (R_f + D_f)}{W_f} \tag{46}$$

When the incorporation of leaching these definitions are radically changed, because water in this case is considered to be beneficially used.

Application efficiency is not an indication of irrigation uniformity or adequacy. Figure 5, illustrates how, with deficit irrigation, an application efficiency of 100% may be achieved under sprinkler irrigation (Wallace 1987, refers to Wu and Gitlen, 1981). Figure 6, shows a common application efficiency found under sprinkler irrigation. In figure 6, area A is adequately irrigated, area B is in deficit irrigation, while area C is excessively irrigated. Using these areas, then, application efficiency may be defined as:

$$E_a = \frac{A}{A + C} \tag{47}$$

Bralts et al., (1984) have defined application efficiency for drip irrigation as:

$$E_a = 100 \frac{V_r (1 - P_D)}{V_a} = 100 \frac{V_r (1 - P_D)}{3600 \, Q_a \, T} \tag{48}$$

where:

V_r = the volume of water applied, m^3;

P_D = irrigation deficit expressed as decimal;

V_a = irrigation volume required, m^3;

Q_a = the actual discharge to the submain per second, m^3 ; and

T = irrigation time in hours.

The above equation is illustrated in figure 7. Wallace (!987).

Bralts (1984) used the coefficient of variation when the irrigation volume applied equals the irrigation volume required, then the irrigation deficit is equal to 0.40 times the coefficient of variation. As a result the application efficiency can be determined by the equation:

$$E_a = 100 \frac{V_r (1 - P_D)}{V_a} = 100 (1 - 0.4\, CV) \tag{49}$$

Figure 8, shows this relationship.

Hart and Reynolds, (1965) assumed that the standard deviation and the mean drawn from a population sample adequately represent the actual mean and the variance of the total population. Then, they used the coefficient of variation to analyze irrigation system design. They used the normal probability density function:

$$y = \frac{Nq}{s\sqrt{2\pi}} \; e^{-0.5 \frac{(x - \bar{x})^2}{s}} \tag{50}$$

Where:

N = number of observations;

q = class interval;

x = the value of an occurrence;

$\bar{x}$ = the mean of the sample; and

s = the standard deviation.

They, also, assumed that the population is continuous and that it is possible to determine the fraction of the total number of observations falling between two points with an equation:

$$\Delta y = \frac{1}{s\sqrt{2\pi}} \int_{\alpha}^{\beta} e^{-0.5 \frac{(x - \bar{x})^2}{s} dx} \tag{51}$$

Replacing Δy with a, α with $\bar{x}H_a$, and β with ∞, the equation becomes:

$$a = \frac{1}{s\sqrt{2\pi}} \int_{\bar{x}H_a}^{\infty} e^{-0.5 \frac{(x-\bar{x})^2}{s}} dx \qquad (52)$$

where:

a = the fraction under the normal curve from x = $\bar{x}H_a$ to x = ∞;

$\bar{x}H_a$ = minimum application on the area a; and

H_a = the fraction of the mean application ($\bar{x}$) ≥ over the area a.

This equation can be used to compute the fraction of irrigated area in excess or deficit.

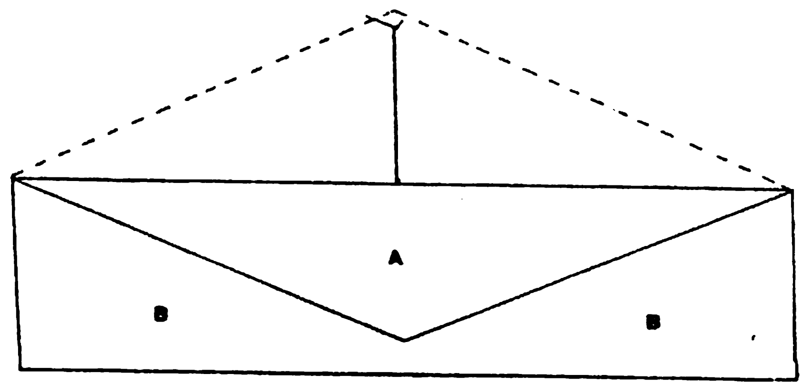


Figure 5. Application efficiency under sprinkler irrigation, (Wallace, 1987)

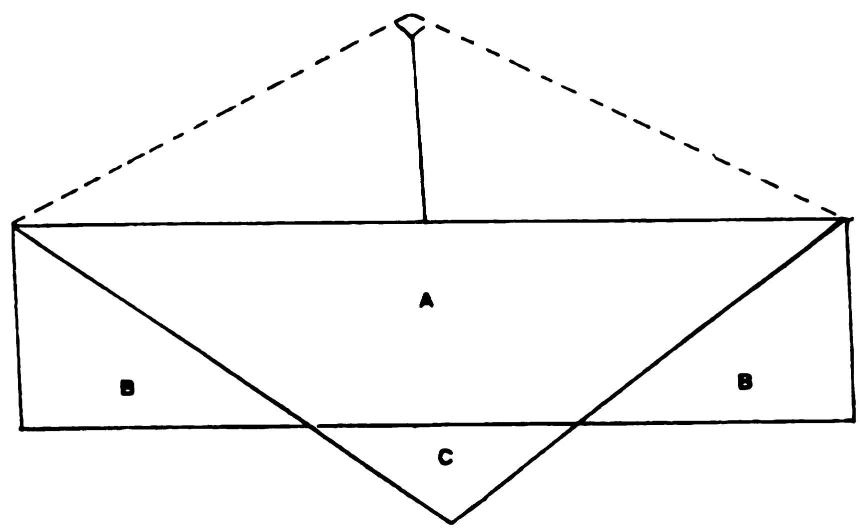


Figure 6. Deficit irrigation for 100% efficiency, (Wallace, 1987)

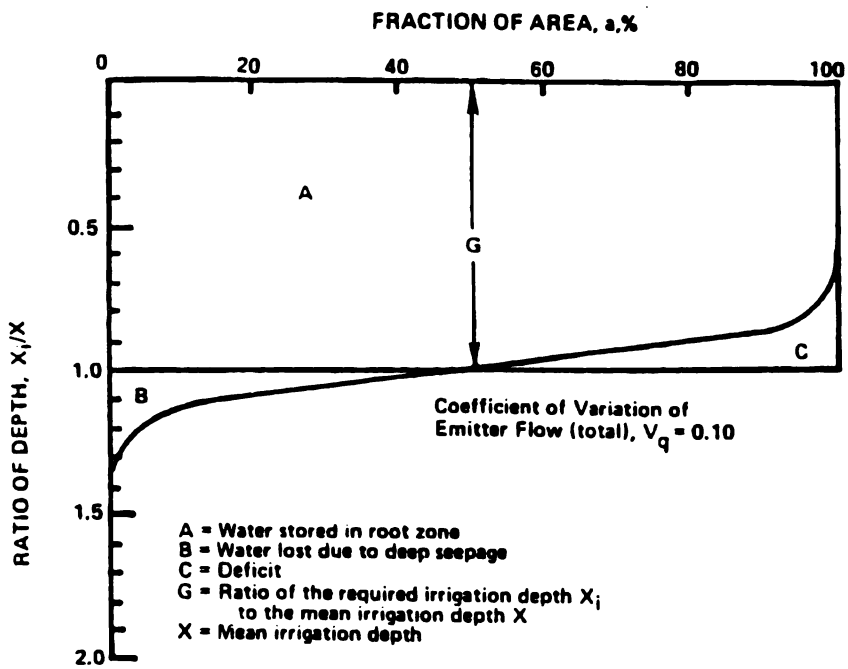


Figure 7. Application efficiency relationships (Bralts, 1984)

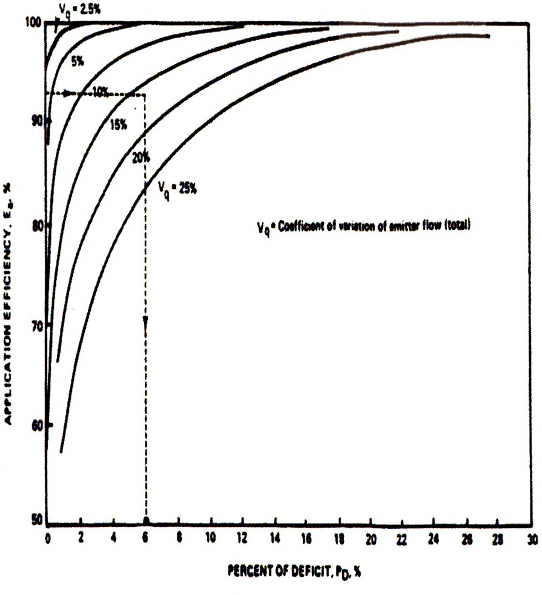


Figure 8. Application efficiency, coefficient of variation, and percentage deficit relationships, (Bralts, 1984).

H. Summary

Sprinkler irrigation uniformity is the measure of spatial variability of the application of water to an irrigated area. Although a large number of uniformity measures have been in widespread use, none of them can claim to absolutely represent all the characteristics of a real distribution. An extensive research has been done in this area. However, the most common statistical measures are Christiansen's uniformity and the coefficient of variation. The problem with Christiansen uniformity, is its susceptibillity to arbitrariness of performance measurement. On the other hand, the coefficient of variation uses the squares of the deviation from the mean rather than the deviations themselves. It uses two statistical moments, the standrd deviation and the mean. Therefore, it gives a better measure of dispersion.

The On-Farm Irrigation Committee was trying to provide standardized definitions for irrigation efficiency terms, (Kruse, 1978). However, all the definitions of efficiency terms are based on theoretical studies and lack empirical investigation and statistical techniques. In addition, there are statistical relations between irrigation uniformity and efficiency. Therefore, there is no simple or efficient method for field evaluation of sprinkler irrigation systems. In this thesis, a simplified statistical method based on the estimated coefficient of variation and statistical uniformity conceptwill be presented for the field evaluation of sprinkler irrigation systems.

III. METHODOLOGY

A large body of theoretical research has been published regarding the various aspects of sprinkler irrigation uniformity. The Literature Review indicated that most of the work was concentrated in the area of variability of water distribution. However, there is a lack of empirical research in this area. It was also apparent that a number of studies followed traditional procedures advocated in the past by the Soil Conservation Service, (SCS), and the American Society of Agricultural Engineers, (ASAE). These procedures, despite their usefulness, were tedious and laborious as well as time consuming. Many attempts have been made to apply the coefficient of variation and the statistical uniformity concept to evaluation of sprinkler irrigation, however, there was no extensive research made to investigate the practical usefulness of these concepts. In this study, 18 randomly selected application depths were compared to the methods already in practical use by applying the estimated coefficient of variation and estimated confidence limits. The latter is called three low and three high method.

A. Research approach

There was a need to develop a simple, easy, quick, and relatively accurate method to evaluate the irrigation uniformity of sprinkler irrigation systems. The ultimate goal was to conserve water and energy for the irrigator as well as to maximize his profit.

The following approaches were adopted to achieve the stated research objectives.

Objective 1.

Develop the statistical uniformity concept for field evaluation of sprinkler irrigation systems based on the estimated coefficient of variation and estimated confidence limits

Research approach:

The procedure presented by Bralts and Kesner (1983) to develop an equation for determining the coefficient of variation for drip irrigation from randomly selected times to fill a specific container was applied to estimate the coefficient of variation for sprinkler irrigation systems from similarly selected depths..

The estimated coefficient of variation was calculated by first, independently estimating the standard deviation and the mean. The coefficient of variation was then obtained by dividing the standard deviation by the mean. The method used for estimating the standard deviation uses the difference between two quantities drawn from the tails of the normal distribution curve of observed values. The same method will be applied to develop an equation for estimating the mean. A complete procedure to develop equations for estimated coefficient of variation and estimated confidence limits was presented in the theoretical development.

Objective 2.

Apply the estimated coefficient of variation and the statistical uniformity concept with estimated confidence limits to field evaluation of sprinkler irrigation systems.

Research approach

During this stage of analysis, collected data from sprinkler irrigation were analyzed according to ASAE recommendation to compute the coefficient of variation. Then the estimated CV was calculated for 18 randomly selected depths from the actual data. The three-low and three-high method will be applied to calculate the estimated CV. Finally, the coefficient of variation was also computed for 18 depths by the standard deviation method.

The software "SURFER, version 4.15. 1989." and hand picked methods were used to randomly select 18 depths for solid set sprinklers and center-pivot system respectively.

The software "SURFER" was used for the following reasons:

1. It shows topographic and surface maps of the water distribution as illustrated by figures 9 and figure 10;
2. It gives better chance of random selection; and
3. It closely estimates the unrecorded data points during the time of data collection, because it uses "minicurve" method with an accuracy of (0.995).

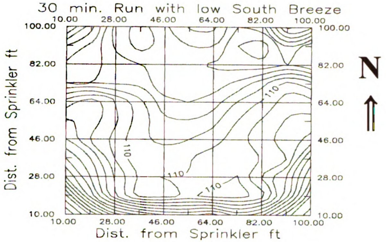
Objective 3.

Evaluate the usefulness of the estimated coefficient of variation and the estimated confidence limits for field evaluation of sprinkler irrigation systems by statistical comparison of the results to the methods already adopted to evaluate sprinkler systems.

Research approach

The coefficient of variation from the actual data was compared to the estimated coefficient of variation calculated by the "three-low and three-high method". Then the coefficient of variation resulted from 18 depths was, also, compared to the CV actual and CV (low/high). The results were statistically tested using the coefficient of determination, (R^2) for field evaluation of sprinkler irrigation systems..

A nomograph was constructed by plotting the sum of three-lowest depths against the sum of three-highest depths. Then, either the statistical uniformity or the coefficient of variation can easily be found if one knows the required inputs.



The sprinklers were located in the corners of the square.

Figure 9. Topographic distribution of water from solid set sprinklers.

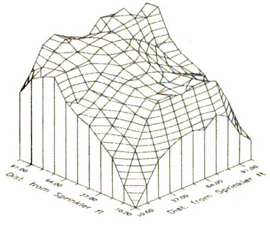


Figure 10. Surface distribution of water from solid set sprinklers.

B. Theoretical development

The procedure presented by Bralts and Kesner (1983) to develop an equation for determining the coefficient of variation for drip irrigation from 18 randomly selected times to fill a specific container will be followed to estimate the coefficient of variation for sprinkler irrigation systems.

The development of a statistical method for estimating the coefficient of variation, i.e the standard deviation over the mean, was approached by first, considering methods, for independently estimating the standard deviation and the mean.

1. Estimating the standard deviation:

The method used for estimating the standard deviation uses the difference between two quantities drawn from the tails of the normal distribution curve of observed values, Figure 11.

For a normal distribution using the sprinkler flow rates, q (liters per hour), as the random variable, the sum of the observations in the upper portion of the distribution can be expressed as:

$$Q_u = N p \, [\bar{q} + S_q \, (Z_{up})] \tag{53}$$

where:

Q_u = the sum of the observations in the upper portion of the distribution;

N = the number of observations in the sample;

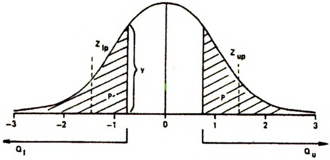
p = the proportion of the observations in the upper portion of the distribution($0<p<0.5$);

= the mean sprinkler flow rate;

S_q = the standard deviation of sprinkler flow rates; and

Z_{up} = the mean abscissa in the upper portion of the standard normal variate, ($\mu = 0$, $\sigma = 1$).

It can be shown that $Z_{up} = y/p$, where y is the ordinate height of the normal probability density function.



$$y = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} \tag{54}$$

Figure 11. Standard normal distribution curve, (Bralts, 1983).

Np represents the number of observations in the upper portion of the distribution. Expressing the sum of the lower portion in similar manner:

$$Q_l = Np\ [\ \bar{q} - S_q\ (Z_{lp})] \tag{55}$$

Where:

Q_l = the sum of observation in the lower portion of the distribution; and

Z_{lp} = the mean abscissa in the lower portion of the standard normal variate.

Based on these equations and the observation that Z_{up} = y/p = Z_{lp} the estimate of the standard deviation of sprinkler flow rate, S_q is derived in the equation of the form:

$$S_q = \frac{1}{2\ y\ N}\ [Q_u - Q_l] \tag{56}$$

An example of this method is presented by Bralts (1983). He used p equal to one sixth, (p = 0.167), for which y = 0.25. In this case, S_q can be expressed as the difference between the sums of the upper and the lower one-sixth of the distribution divided by one half of the number of observations. Then the estimated standard deviation is given by the equation:

$$S_{qs} = \frac{2}{N} [Q_{us} - Q_{ls}] \tag{57}$$

Where:

S_{qs} = the estimate of the standard deviation of sprinkler flow rate when p = 0.167:

Q_{us} = the sum of the observation in the upper one sixth of the distribution; and

Q_{ls} = the sum of the observation in the lower one sixth of the distribution.

2. Estimating the mean:

Since we assumed a normal distribution which is symmetrical about the mean, the estimated mean sprinkler flow rate $\bar{q}$, can be found by:

$$\bar{q} = \frac{1}{2\,p\,N} [Q_u + Q_l] \tag{58}$$

Setting p = 0.167, the above equation becomes:

$$\bar{q} = \frac{3}{N} [Q_{us} + Q_{ls}] \tag{59}$$

Where all variables were as previously defined

3. Estimating the coefficient of variation:

The coefficient of variation (CV_q) is defined as the standard deviation (S_q) divided by the mean(q^{-}). Then the equation for CV_q becomes:

$$ {}_{q} = \frac{S_q}{\bar{q}} = \frac{\frac{1}{2\,y\,N}\,[\,Q_u - Q_l\,]}{\frac{1}{2\,p\,N}\,[\,Q_u + Q_l\,]} \tag{60}$$

or

$$ CV_q = \frac{p\,[\,Q_u - Q_l\,]}{y\,[\,Q_u + Q_l\,]} \tag{61}$$

Setting p = 0.167, for which y = 0.25, will result in the estimated coefficient of variation as follows:

$$ CV_{qs} = 0.667\,\frac{(\,Q_{us} - Q_{ls}\,)}{(\,Q_{us} + Q_{ls}\,)} \tag{62}$$

If 18 random measurements of sprinkler or emitter flow rate were made, it would only be necessary to sum the three-highest and the three-lowest values to estimate the coefficient of variation. The above equation can be rearranged to demonstrate the linear nature of the terms Q_{us} and Q_{is}:

$$Q_{us} = \frac{(0.667 + CV_{qs})}{(0.667 - CV_{qs})} Q_{Is} \tag{63}$$

Thus, for any given coefficient of variation CV_{qs}, the Q_{us} varies linearly with Q_{Is}.

Bralts, et al., (1983), also used, the inverse relationship of minimum time to maximum emitter flow rate, so the above equation can be written as:

$$T_{max} = \frac{(0.667 + CV_{qs})}{(0.667 - CV_{qs})} T_{min} \tag{64}$$

The above equation can be modified to replace the time to fill specific container by the depths collected in each catch can. As a result equation (61) becomes:

$$D_{max} = \frac{(0.667 + CV_{qs})}{(0.667 - CV_{qs})} D_{min} \tag{65}$$

4. Estimating the confidence limits:

The confidence limits for the estimated coefficient of variation are in the literature review using equations (42). The confidence limits for the coefficient of variation (CV_q) on samples from a normal population, (Bralts and Kesner, 1983, after Sokal and Rohlf, 1969) can be expressed as:

$$(CV_q - t_{\frac{\alpha}{2}} S_{V_q} \le CV_q^* \le CV_q + t_{\frac{\alpha}{2}} S_{V_q}) = 1 - \alpha \tag{66}$$

The standard deviation of the coefficient of variation can be calculated from the equation:

$$S_{CV_q} = \frac{CV_q}{\sqrt{2N}} \sqrt{1 + 2\,(CV_q)^2} \tag{67}$$

Since these estimated confidence limits of estimated coefficient of variation are dependent on the assumption of normal distribution,, these, limits can only be used as approximate confidence limits of the estimated coefficient of variation.

IV. RESULTS AND DISCUSSION

A. Solid set sprinklers test

In this part of the analysis, data from Sichinga thesis (1975), Appendix A, were input to the software "SURFER" to select 18 catch can depths. The coefficients of variation were calculated from the actual data by the standard deviation method, the by three-low and three high method, and finally, CVs were computed from 18 depths using the standard deviation method all with 95% confidence limits, Table 10.

The objective was to apply the estimated coefficient of variation to field evaluation of solid set sprinklers. Then to compare the results of estimated coefficient of variation to the method already in practical use. Figure 12, illustrates the relationship between the estimated CV from (low/high) to the CV from actual data calculated by standard deviation method. Then the CV from actual data were compared to CV(18) calculated by standard deviation method, as can be viewed by Figure 14. In addition, CV (low/high) was compared to CV (18).

From figure 12 it can be seen that the estimated CV (low/high) is highly correlated to the coefficient of variation from actual data with $R^2 = 0.956$ with 95% confidence limits.

Figure 13 shows the estimated confidence limits between the CV (low/high) and the actual data. A comparison of CV from actual data to CV (18) yielded $R^2 = 0.94$ with

95% confidence limits as it can be seen from figure 14 and figure 15.

Figures 16 and figure 17 show the relationships between the CV computed by the three-low and three-high method compared to the CV from 18 depths for set sprinklers. The coefficients of variation are highly correlated with $R^2 = 0.97$ at 95% confidence limits. From the above analysis of the linear regression of the CVs calculated by the three methods, it is clear that there was no significant difference to use either of these methods for the calculation of the coefficient of variation. It can be concluded that, the three-low and three-high method is highly applicable for the field evaluation of solid set sprinklers, it is very simple, easy and based on statistical background. In addition, it is quick, and could conserve time and money for the farmer. Furthermore, it is a very useful tool for conservation of energy and water to the farmer and the environment.

Table 10. Coefficient of variation of solid set sprinklers.

Sample Number	CV (Actual)	Number of Points	CV (low/high)	CV (18)
1	0.109769	79	0.135037	0.144037
2	0.143215	79	0.135333	0.147215
3	0.14791	79	0.156848	0.148938
4	0.16619	79	0.166750	0.176876
5	0.1721	79	0.170628	0.185219
6	0.176896	79	0.173960	0.187173
7	0.184164	79	0.175526	0.190243
8	0.1855	79	0.182231	0.190909
9	0.189543	79	0.183667	0.194137
10	0.193973	79	0.188600	0.195064
11	0.19494	79	0.191877	0.210257
12	0.251356	79	0.204519	0.218163
13	0.26348	79	0.253648	0.265199
14	0.285035	79	0.276561	0.295780
15	0.356115	79	0.325366	0.310588

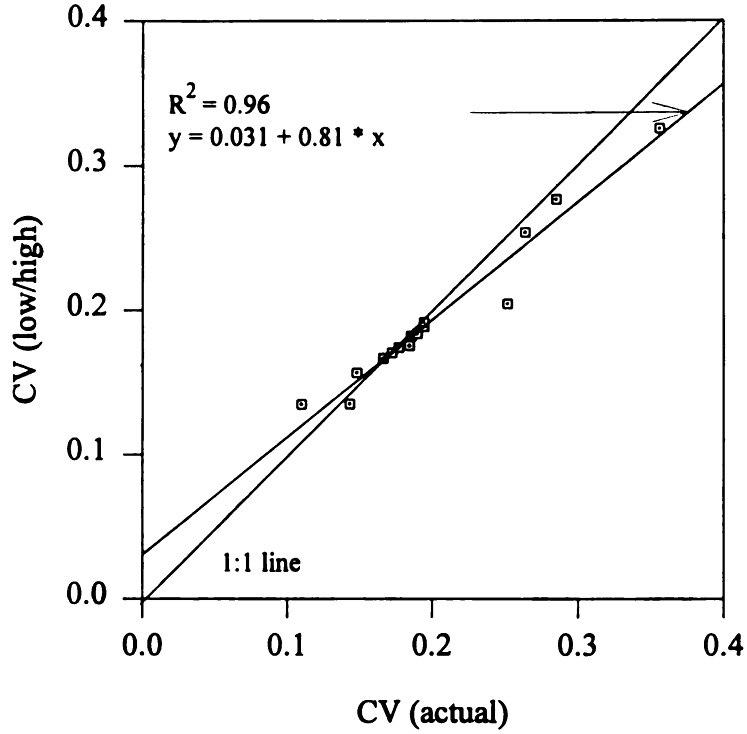


Figure 12. A comparison of CV (actual) to CV (low/high).

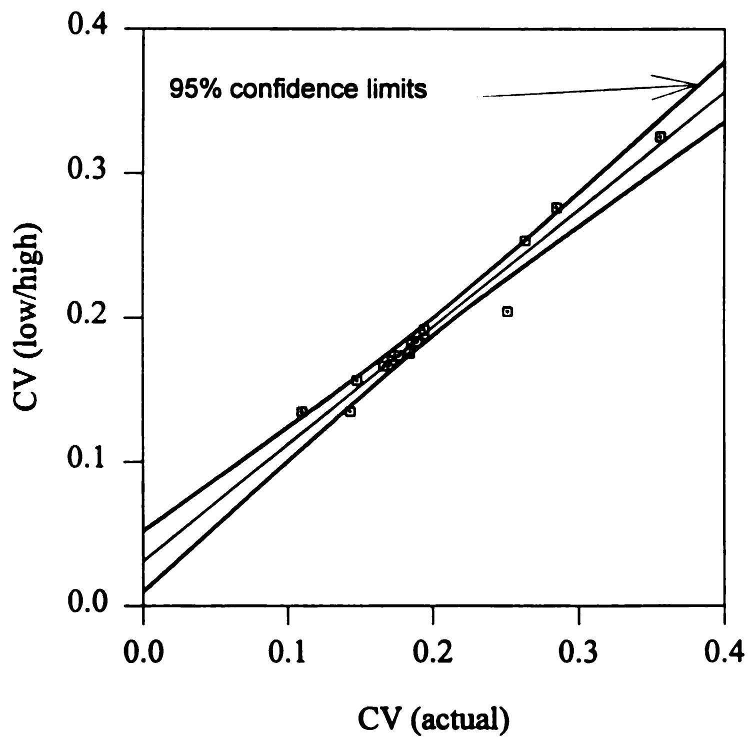


Figure 13. A comparison of CV (actual) to CV (low/high) with 95% confidence limits.

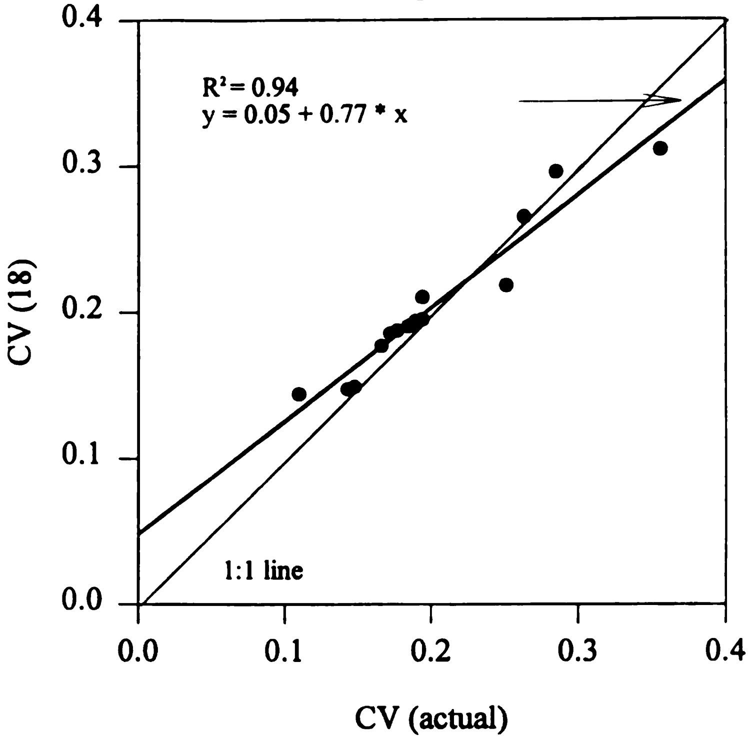


Figure 14. A comparison of CV (actual) to CV (18).

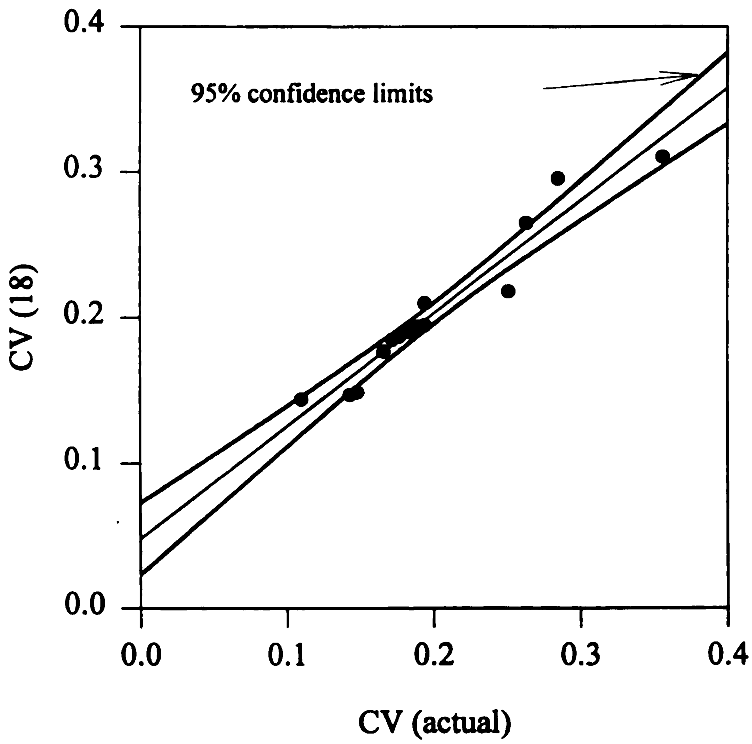


Figure 15. A comparison of CV (actual) to CV (18) with 95% confidence limits.

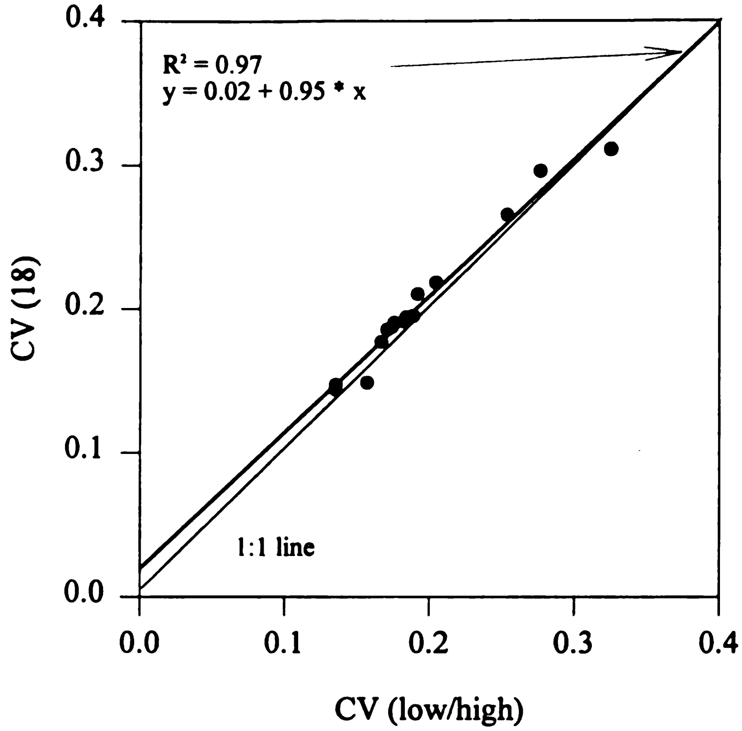


Figure 16. A comparison of CV (low/high) to CV (18).

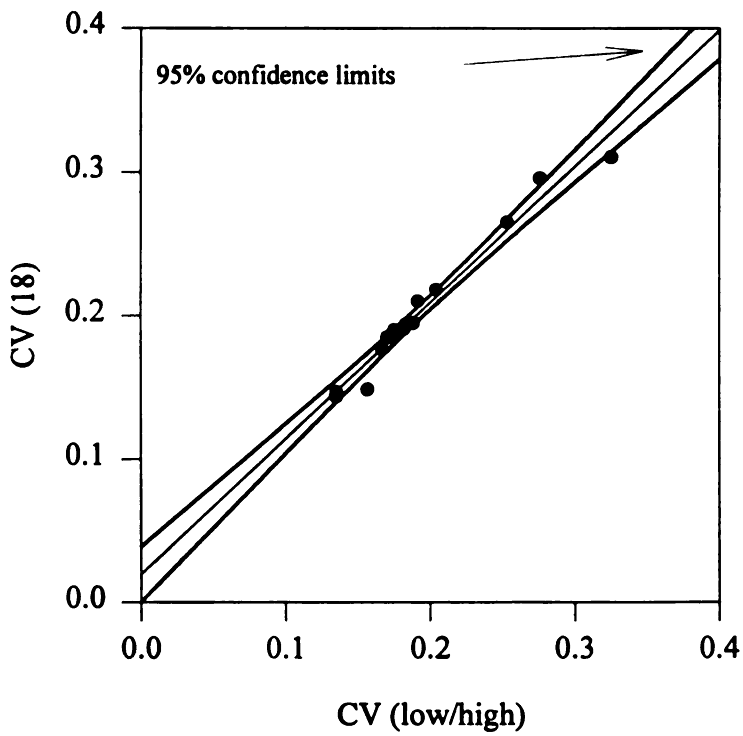


Figure 17. A comparison of CV (low/high) to CV (18) with 95% confidence limits.

B. Turfgrass sprinklers

Data for this part of the results were obtained from Saffel, 1993, Hancock Turfgrass Research Center, Department of Crop and Soil Science, MSU, Appendix B. Actual data were entered into the software "SURFER" to select 18 catch can depths. The coefficients of variation were calculated for the actual data, three-high and three-low for 18 depths, and from 18 depths by standard deviation methods. Table 11 shows the coefficients of variation for each method.

The objective of this part of the research was to apply the estimated coefficient of variation to the field evaluation of sprinkler irrigation on the turfgrass. Also the estimated coefficient of variation was compared to methods already in practical use. The linear regression analysis was used to statistically compare these coefficients of variation methods.

Figures 18 and figure 19 illustrate the relationship between the CV from the actual data to the estimated CV calculated by three-low and three-high from 18 randomly selected depths. As it can be seen, the estimated CV (low/high) is highly correlated to the CV of the actual data with $R^2 = 0.99$ at 95% confidence limits.

Figures 20 and figure 21 show the relationships between the CV calculated from 18 randomly selected depths and the CV calculated from actual data with both computed by the standard deviation method. These two methods are, also, highly correlated with $R^2 = 0.99$ at 95% confidence limits.

When the estimated CV calculated by the three-low and three-high method was compared to the CV from 18 depths computed by the standard deviation methods, the two methods show a close relationship, with $R^2 = 0.99$ at 95% confidence limits, as shown by figure 22 and figure 23.

Table 11. Coefficient of variation for sprinklers on turf.

Sample Number	CV (Actual)	Number of Points	CV (low/high)	CV (18)
1	0.162	100	0.152	0.161
2	0.249	100	0.259	0.249
3	0.269	100	0.279	0.269
4	0.272	100	0.281	0.272
5	0.279	100	0.282	0.280
6	0.288	100	0.283	0.288
7	0.303	100	0.301	0.303
8	0.306	100	0.319	0.305
9	0.306	100	0.324	0.307
10	0.307	100	0.333	0.307
11	0.341	100	0.333	0.341
12	0.357	100	0.356	0.356
13	0.387	100	0.392	0.388
14	0.413	100	0.415	0.413
15	0.432	100	0.437	0.432
16	0.456	100	0.453	0.456

Data were obtained from the Turfgrass Hancock Research Center, Saffel 1993.

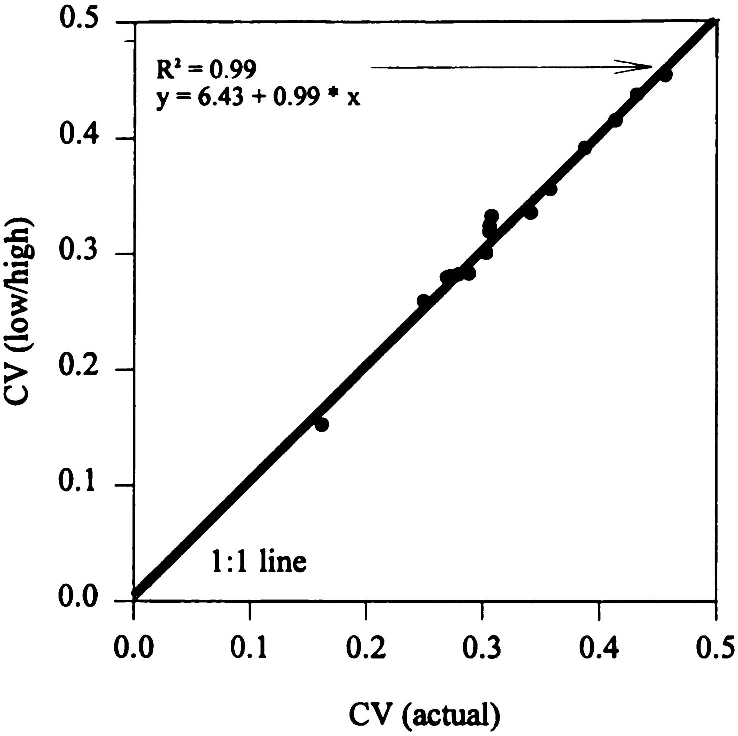


Figure 18. A comparison of CV (actual) to CV (low/high) on turf.

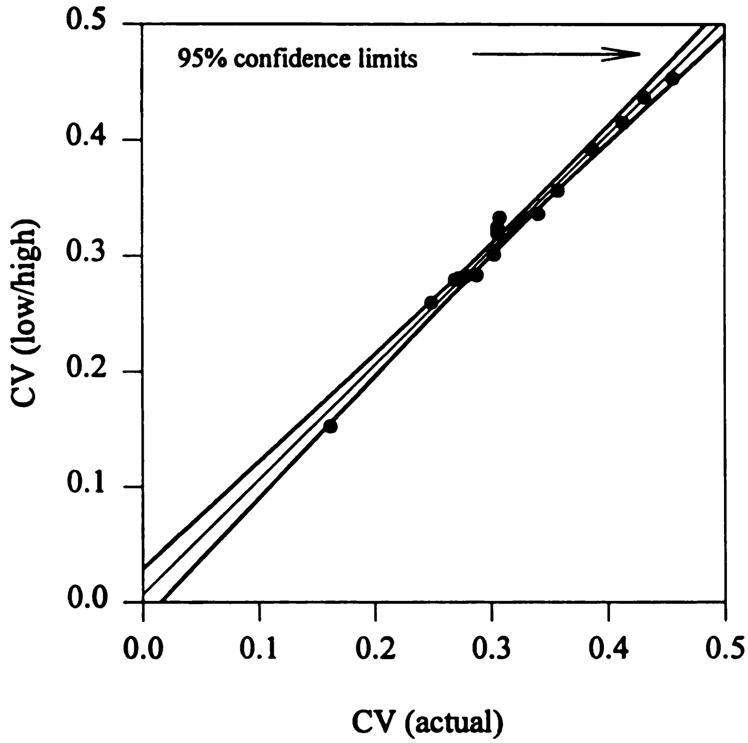


Figure 19. A comparison of CV (actual) to CV (low/high) with 95%confidence limits on turf.

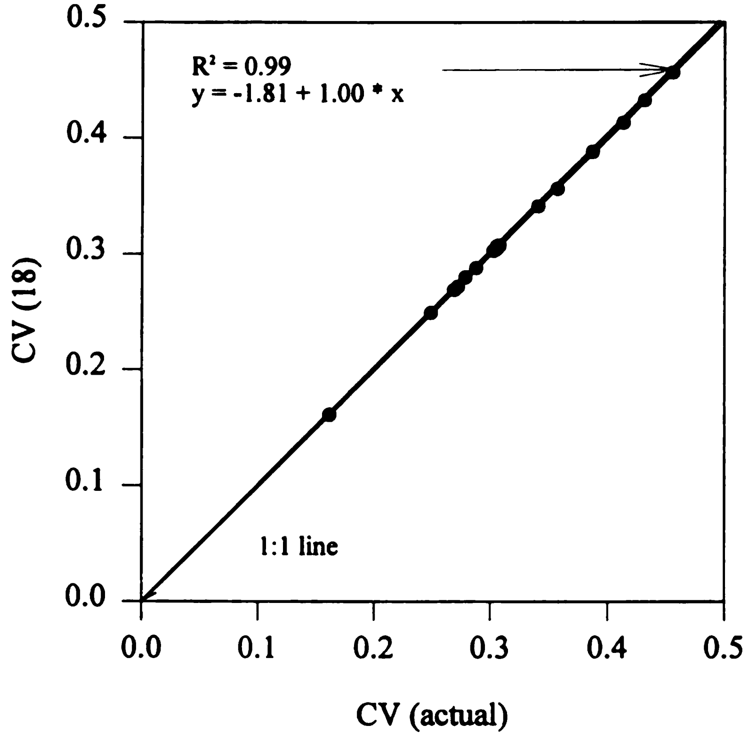


Figure 20. A comparison of CV (actual) to CV (18) on turf.

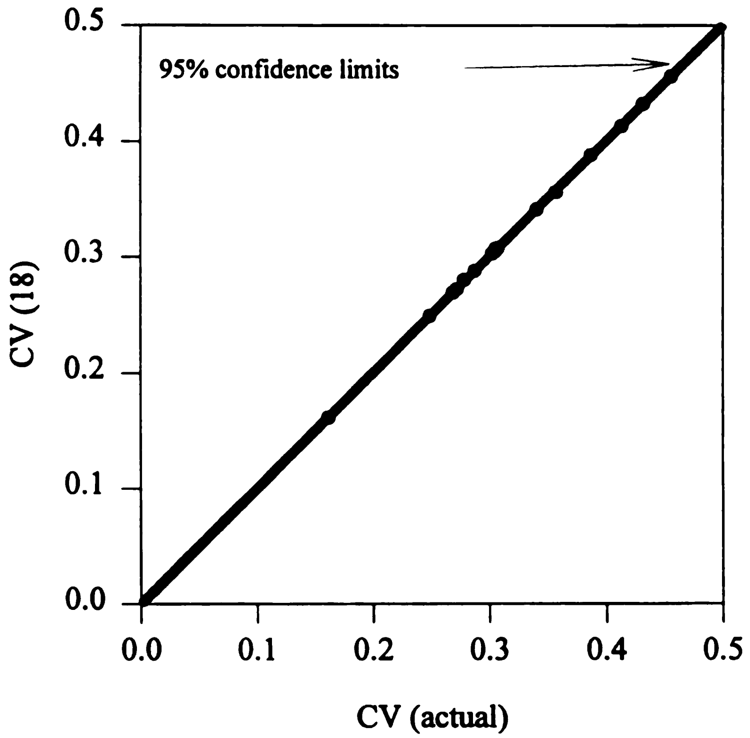


Figure 21. A comparison of CV (actual) to CV (18) with 95% confidence limits on turf.

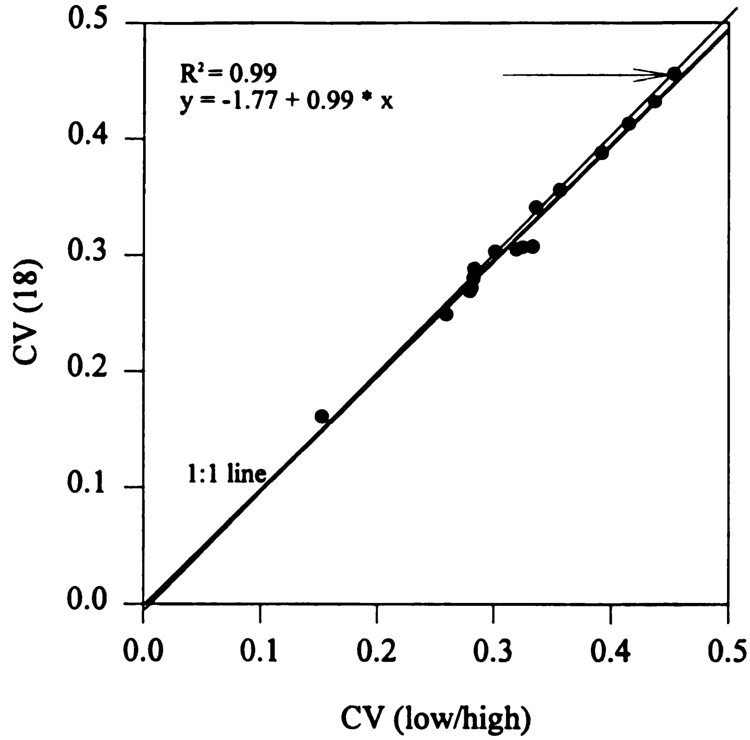


Figure 22. A comparison of CV (low/high) to CV (18) on turf.

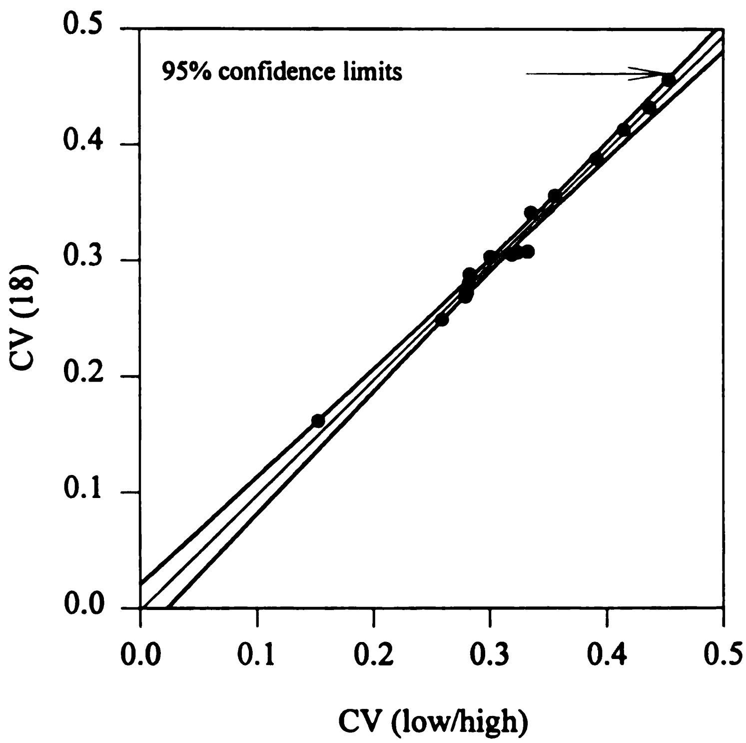


Figure 23. A comparison of CV (low/high) to CV (18) with 95% confidence limits on turf.

C. Center-pivot system

The coefficients of variation for this analysis were computed from the simulated data from Pandey,(1989, Appendix C. using the Heermann equation, and the estimated coefficients of variation using the three-low and three-high method without weighting as done by Heermann and Hein and are presented in table 12.

Table 12. Coefficients of variation for center-pivot from simulated data.

Sample Number	CV (Heermann)	Number of Data Points	CV(low/high)
1	0.155	135	0.146
2	0.259	34	0.262
3	0.289	34	0.275
4	0.346	34	0.277
5	0.46	40	0.456

Data were obtained from Pandey 1989.

Actual data collected by Soil Conservation Service (SCS) at St Joseph, Appendix C, were analyzed and the coefficients of variation were computed by, the Heermann equation, the Soil Conservation Service (SCS) equation, and the three-low and three-high method as shown in Table 13.

Table 13. Coefficient of variation for center pivot from actual data.

Sample Number	CV (Heermann)	Number of Data Points	CV (SCS)	CV (low/high)
1	0.135	61	0.150	0.160
2	0.16	49	0.180	0.196
3	0.261	27	0.260	0.272
4	0.278	27	0.280	0.287
5	0.334	25	0.280	0.296

Data were obtained from Soil Conservation Service, St. Joseph, 1995.

The objective was to apply the estimated CV to the field evaluation of center-pivot system. The CV calculated by the Hermann method from simulated data was compared to the coefficients of variation computed by the three-low and three-high method from selected catch can depths. The two methods were closely correlated with $R^2 = 0.93$ at 95% confidence limits as can be seen in figure 24 and figure 25.

When the actual data were analyzed, a comparison of CV (Heermann) to CV (SCS) resulted in $R^2 = 0.93$ with 95% confidence limits as illustrated by Figure 26 and Figure 27. When the same CV (Heermann) was compared to CV (low/high) resulted in $R^2 = 0.95$ with 95% confidence limits as can be viewed in Figure 28 and Figure 29. Further comparison of CV (SCS) to CV (low/high) yielded $R^2 = 0.99$ with 95% confidence limits as can be seen in figure 30 and figure 31.

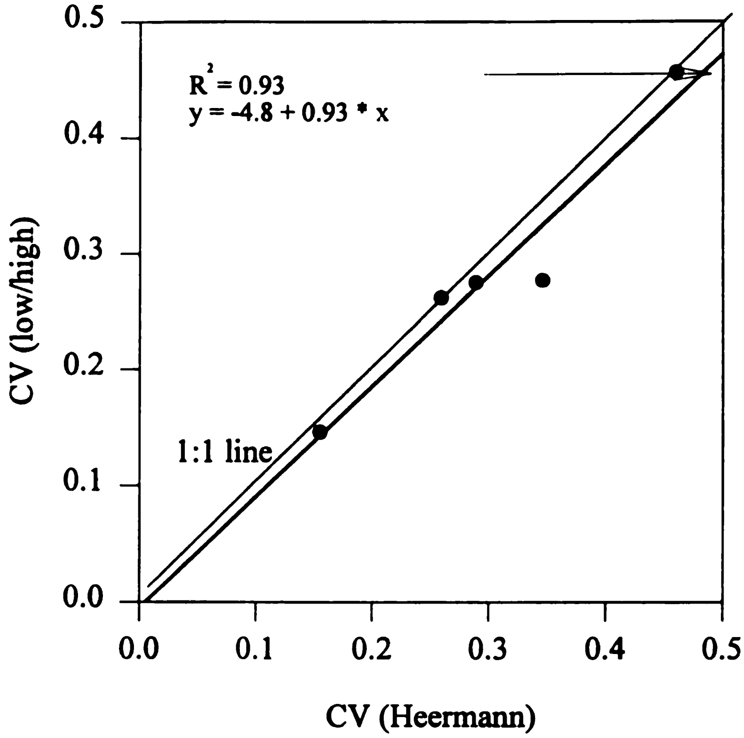


Figure 24. A comparison of CV (Heermann) to CV (low/high).

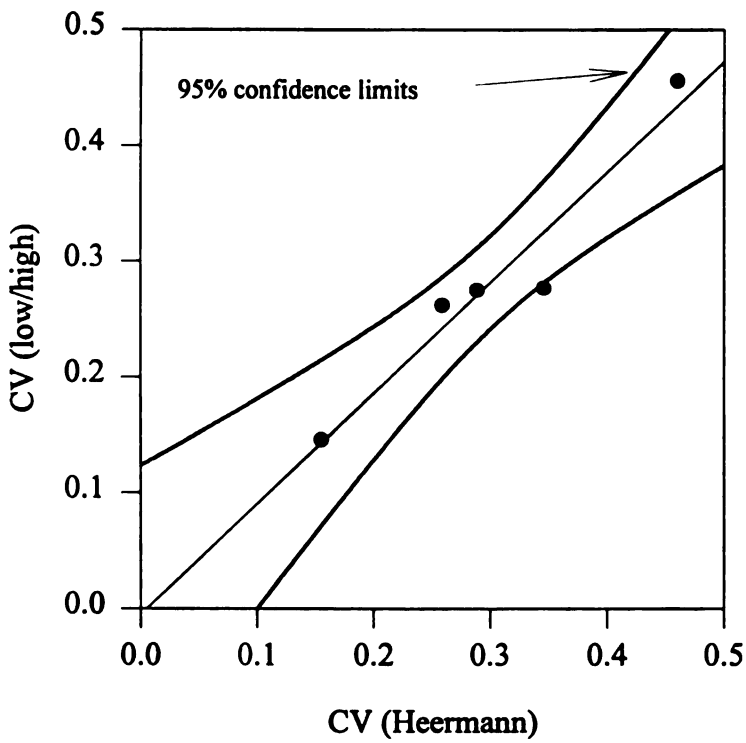


Figure 25. A comparison of CV (Heermann) to CV (low/high) with 95% confidence limits.

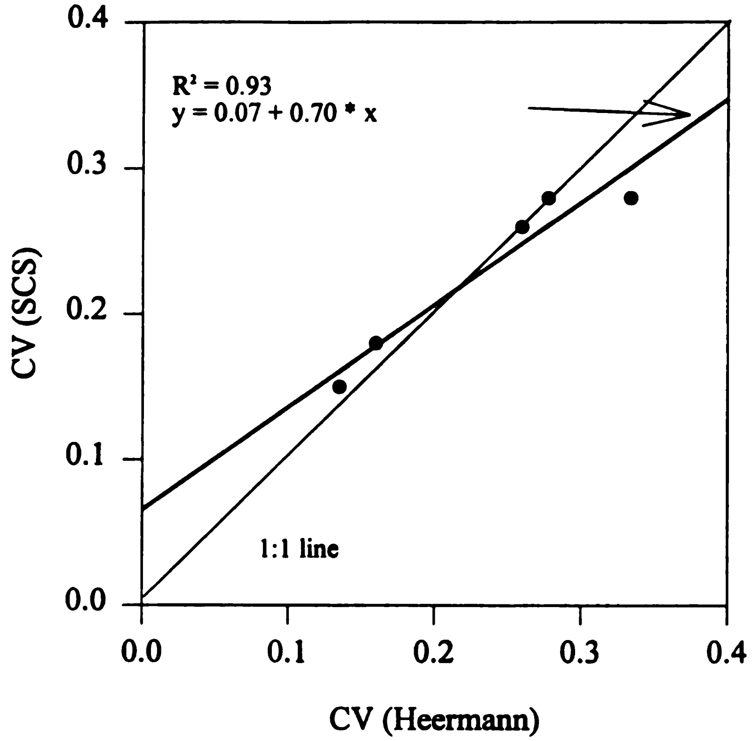


Figure 26. A comparison of CV (Heermann) to CV (SCS).

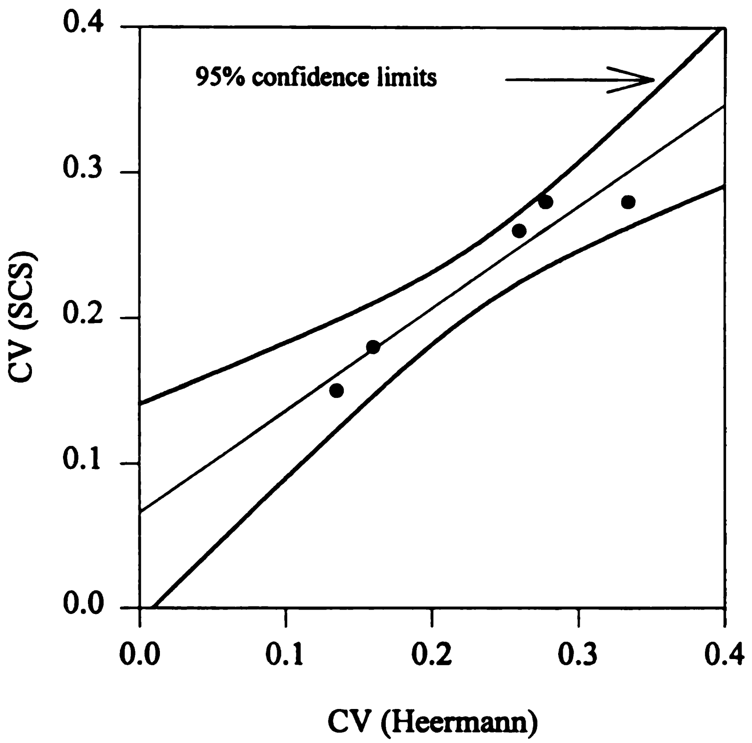


Figure 27. A comparison of CV (Heermann) to CV (SCS) with 95% confidence limits..

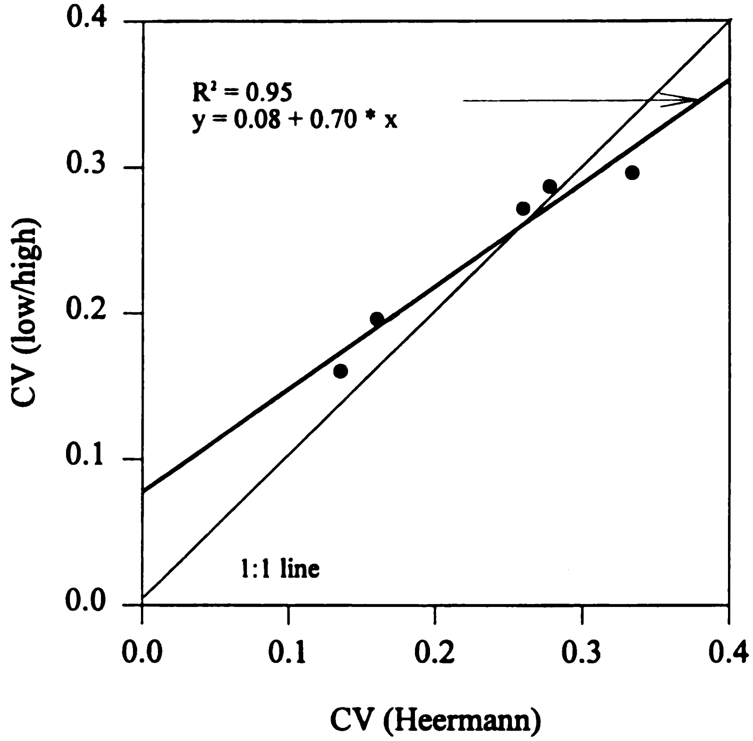


Figure 28. A comparison of CV (Heermann) to CV (low/high).

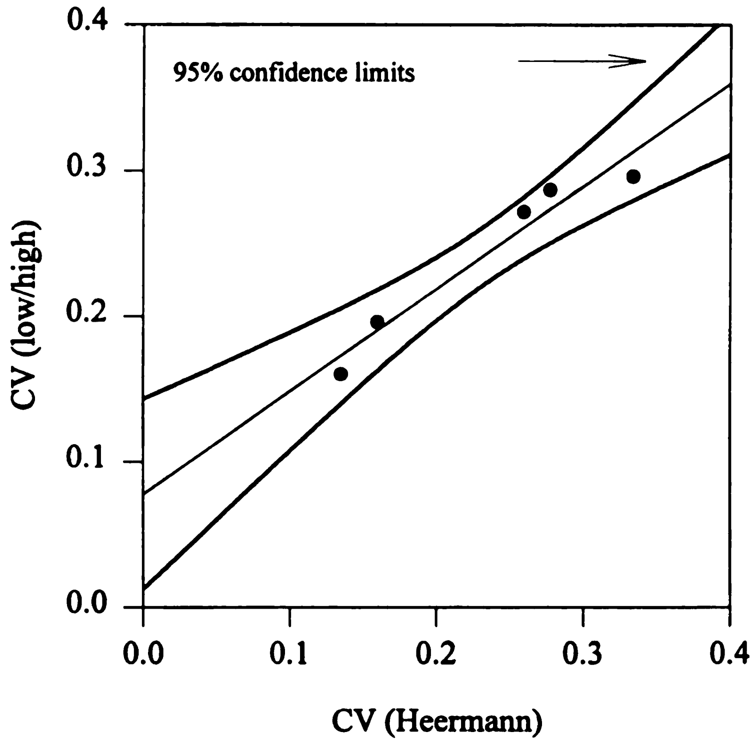


Figure 29. A comparison of CV (Heermann) to CV (low/high) with 95% confidence limits.

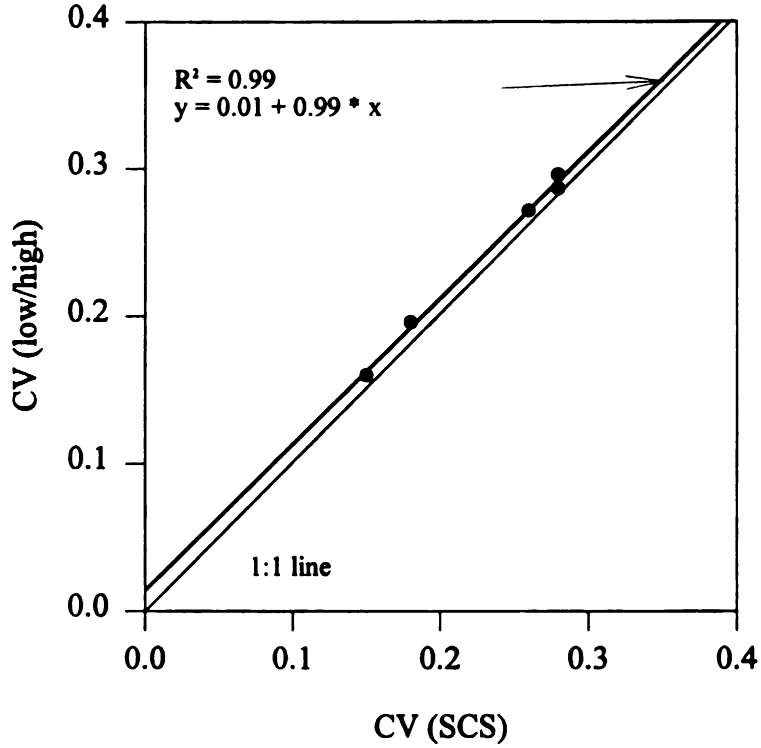


Figure 30. A comparison of CV (SCS) to CV (low/high).

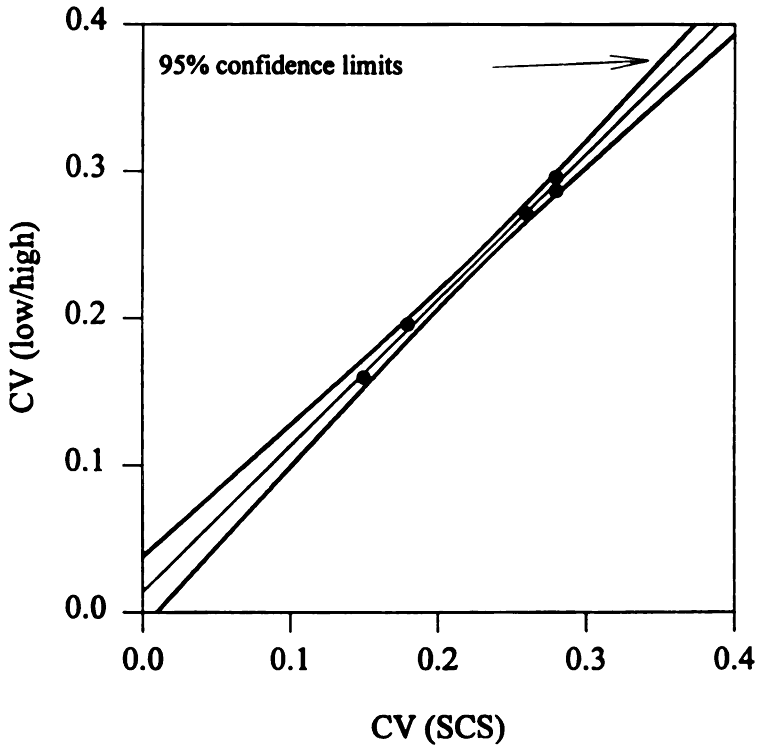


Figure 31. A comparison of CV (SCS) to CV (low/high) with 95% confidence limits.

D. A nomograph for sprinkler irrigation uniformity estimation.

The following equation will be used to construct a nomograph for sprinkler irrigation systems.

$$D_{max} = \frac{(\ 0.667\ +\ CV_{qs})}{(\ 0.667\ -\ CV_{qs})}\ D_{min} \tag{66}$$

The following values of maximum depths were obtained, if the values for the minimum depths were taken from the randomly selected 18 depths at different confidence limits and different estimated coefficient of variations.

Table 14. Values of maximum depths at different coefficient of variations and known minimum depths.

D_{min}	D_{max} CV = 0%	D_{max} CV = 10%	D_{max} CV = 20%	D_{max} CV = 30%	D_{max} CV = 40%
0	0	0	0	0	0
50	50	67.65	92.83	131.70	199.80
100	100	135.30	185.65	263.50	399.60
150	150	203.00	278.48	395.00	599.40
200	200	271.00	371.31	527.00	799.25
250	250	338.00	464.00	658.72	999.06
300	300	406.00	556.95	790.50	1198.88

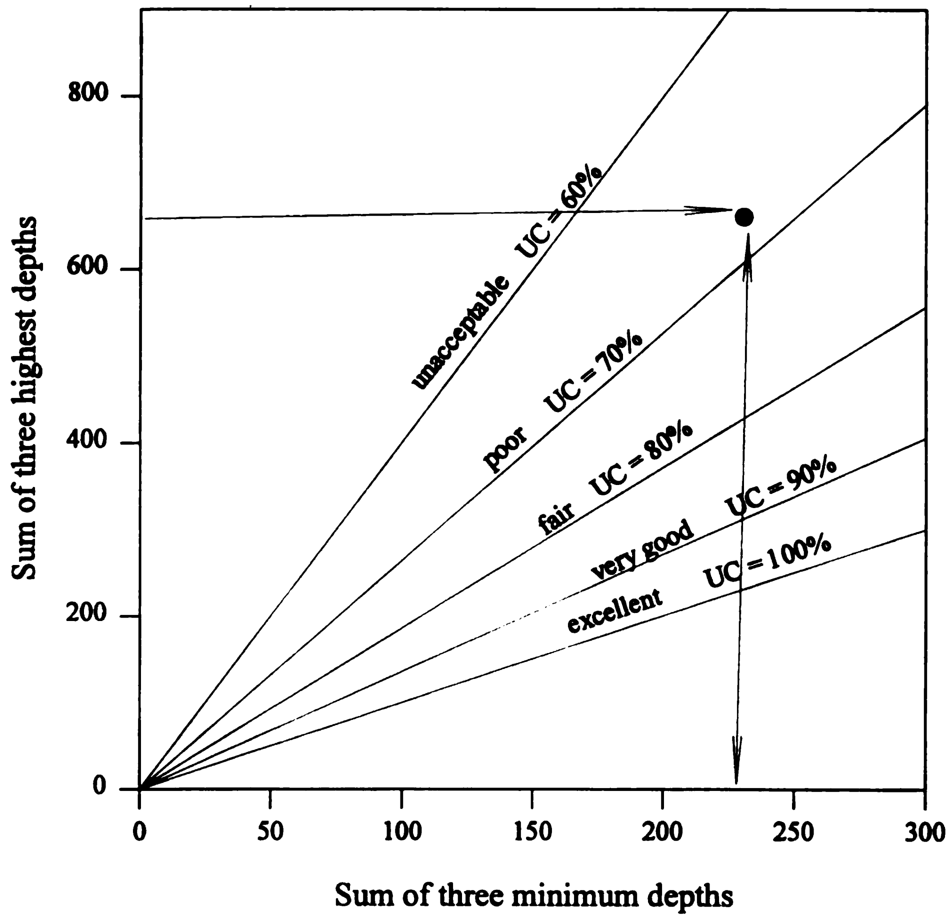


Figure 32. A nomograph for sprinkler irrigation systems uniformity estimation.

Example:

If we take the first 18 randomly selected set of depths from appendix B, as follows:

42, 86, 98, 100, 101, 104, 133, 136, 142, 156, 161, 184, 189, 202, 203, 204, 223, 227.

Sum of three lowest depths = 42 + 86 + 98 = 226 ml
Sum of three highest depths = 204 + 223 + 227 = 654 ml

From the x-axis (sum of three lowest depths) we read a value of 226, then we read from the y-axis (sum of three highest depth) a value of 654, then we proceed untill the two lines intersect where the uniformity coefficient of the system = 67%

V. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The objectives of this research have been addressed in full. The estimated coefficient of variation has been developed for the field evaluation of sprinkler irrigation systems. The estimated coefficient of variation has been applied to evaluate the distribution uniformity of sprinkler irrigation systems. In addition, the estimated coefficient of variation was found to be very useful tool for the field evaluation of sprinkler irrigation systems. The method has been verified for the field evaluation of sprinkler irrigation systems, by using the linear regression method with the estimated coefficient of variation statistically correlated to the method already in practical use.

The method was found to be very simple, applicable to sprinkler irrigation systems, and easy to handle by the farmer. In addition, it conserves time and money for the farmer and conserves water and energy for crop production. As a result it is environmentally sound

The specific conclusions were:

1. Solid set sprinklers: the estimated coefficient of variation from 18 random depths for this system was statistically correlated to the coefficient of variation from the actual data. The two methods were highly correlated at 95% confidence limits. The method could be easily applied for the field evaluation of this system.

2. Turfgrass sprinklers: the estimated coefficient of variation was statistically compared to coefficient of variation from the actual data, and there was no significant difference at 95% confidence limits to use either of these methods for the field evaluation of this system.

3. For center-pivot system: the estimated coefficient of variation closely approximated the statistical uniformity when compared to coefficient of variation from actual data computed by the Heermann method.

4. A simplified statistical method for the field evaluation of sprinkler irrigation systems has been developed from randomly selected 18 catch cans depths using the three-low and three-high method.

5. A nomograph to estimate the coefficient of variation or statistical uniformity for sprinkler irrigation systems has been presented.

Recommendations

1. Analysis of other factors affecting irrigation uniformity such as pressure, sprinkler spacing, nozzle diameter, and wind speed in the comparison.

2. Incorporation of other environmental factors, such as spacial variability of soil type which may also affect the irrigation uniformity.

3. Comparison of coefficient of variation from Heermann equation to coefficient of variation from Mariek equation together with estimated coefficient of variation.

REFERENCES

APPENDIX A

Solid Set Sprinklers Irrigation Data

Appendix A

Solid set sprinklers irrigation data

Data were obtained from Sichinga, 1975. M.S. thesis, Depart. of Agr. Engineering, MSU. Water distribution from Rainbird 30 E-TNT sprinklers, at varied nozzle diameter, pressure and wind speed.

set1

X						X						X
0.05		0.04		0.04		0.04		0.05		0.05		0.07
0.05	0.05	0.05	0.06	0.07	0.07	0.07	0.08	0.05	0.05	0.07	0.07	0.08
0.03	0.04	0.06	0.08	0.07	0.07	0.07	0.06	0.05	0.07	0.07	0.07	0.07
0.04	0.04	0.06	0.07	0.07	0.07	0.07	0.06	0.06	0.07	0.07	0.07	0.07
0.05	0.05	0.06	0.06	0.07	0.07	0.08	0.07	0.06	0.07	0.07	0.06	0.07
0.05	0.06	0.06	0.05	0.06	0.06	0.07	0.08	0.07	0.05	0.05	0.06	0.05
0.05		0.04		0.04		0.08		0.05 .		0.03		0.05
X						X						X

Figure 1. Water distribution from Rainbird 30 E-TNT sprinklers, 1/8 inch (3 mm) nozzle
X = position of sprinklers

Set 2

X						X						X
0.08		0.03		0.07		0.07		0.04		0.07		0.08
0.06	0.04	0.04	0.06	0.07	0.08	0.07	0.04	0.05	0.07	0.07	0.07	0.08
0.03	0.03	0.04	0.04	0.06	0.04	0.07	0.03	0.05	0.06	0.06	0.05	0.07
0.04	0.03	0.03	0.04	0.04	0.04	0.04	0.03	0.05	0.07	0.07	0.04	0.04
0.04	0.03	0.03	0.04	0.04	0.05	0.08	0.07	0.04	0.05	0.06	0.05	0.05
0.04	0.03	0.04	0.04	0.05	0.07	0.07	0.06	0.05	0.04	0.04	0.07	0.05
0.04		0.03		0.04		0.07		0.04		0.04		0.05
X						X						X

Figure 2. Same as Figure 1, except wind speed was 3.23 mph (1.44 m/s).

Set 3

X						X						X
0.04		0.04		0.03		0.04		0.03		0.04		0.04
0.08	0.04	0.04	0.03	0.04	0.04	0.08	0.08	0.04	0.04	0.05	0.06	0.06
0.03	0.04	0.04	0.02	0.03	0.04	0.05	0.05	0.05	0.04	0.05	0.06	0.07
0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.06	0.05	0.04	0.04	0.05	0.06
0.05	0.04	0.04	0.04	0.04	0.06	0.07	0.06	0.04	0.04	0.05	0.05	0.05
0.08	0.05	0.03	0.04	0.05	0.06	0.07	0.07	0.05	0.04	0.04	0.04	0.05
0.05		0.03		0.03		0.03		0.04		0.03		0.04
X						X						X

Figure 3. Same as above except wind speed was 2.5 mph (1.12 m/s).

Set 4

X						X						X
0.09		0.07		0.07		0.16		0.08		0.08		0.09
0.08	0.1	0.09	0.09	0.08	0.1	0.16	0.14	0.11	0.1	0.09	0.09	0.09
0.08	0.09	0.1	0.11	0.09	0.09	0.1	0.11	0.12	0.11	0.1	0.09	0.09
0.08	0.09	0.11	0.12	0.11	0.09	0.1	0.11	0.12	0.12	0.11	0.1	0.09
0.08	0.1	0.11	0.11	0.11	0.11	0.12	0.12	0.12	0.12	0.12	0.11	0.08
0.07	0.09	0.11	0.12	0.14	0.13	0.12	0.14	0.14	0.12	0.12	0.11	0.09
0.09		0.09		0.14		0.16		0.12		0.11		0.09
X						X						X

Figure 4. The nozzle diameter was changed to 5/32 inch, (4 mm).

Set 5

X						X						X
0.08		0.07		0.09		0.1		0.08		0.09		0.09
0.08	0.09	0.09	0.1	0.1	0.1	0.1	0.12	0.09	0.09	0.1	0.1	0.1
0.08	0.08	0.09	0.1	0.1	0.09	0.09	0.1	0.1	0.11	0.11	0.1	0.09
0.07	0.09	0.11	0.11	0.1	0.11	0.1	0.1	0.12	0.12	0.11	0.11	0.1
0.08	0.09	0.11	0.12	0.12	0.11	0.11	0.11	0.14	0.12	0.13	0.12	0.09
0.07	0.09	0.11	0.12	0.14	0.12	0.12	0.12	0.14	0.13	0.13	0.12	0.1
0.07		0.1		0.14		0.16		0.1		0.12		0.09
X						X						X

Figure 5. Nozzle diameter 5/32 inch (4 mm), pressure 60 psi, wind speed 3.76 mph (1.67 m/s), N.W.

Set 6

X						X						X
0.1		0.06		0.08		0.1		0.07		0.07		0.07
0.14	0.09	0.1	0.07	0.08	0.1	0.17	0.12	0.09	0.09	0.08	0.08	0.08
0.08	0.08	0.08	0.08	0.08	0.08	0.1	0.1	0.09	0.1	0.09	0.08	0.07
0.08	0.09	0.1	0.09	0.09	0.09	0.1	0.1	0.1	0.1	0.09	0.09	0.07
0.08	0.1	0.1	0.1	0.11	0.11	0.13	0.11	0.1	0.1	0.09	0.08	0.07
0.07	0.09	0.1	0.11	0.12	0.12	0.12	0.11	0.11	0.09	0.09	0.08	0.07
0.08		0.09		0.11		0.15		0.1		0.05		0.08
X						X						X

Figure 6. Same as above except, wind speed 0.45 mph (0.20 m/s), N.W.

Set 7

X						X						X
0.08		0.05		0.06		0.1		0.06		0.05		0.07
0.08	0.08	0.07	0.05	0.07	0.1	0.1	0.09	0.07	0.07	0.07	0.07	0.07
0.07	0.07	0.07	0.06	0.07	0.09	0.1	0.09	0.07	0.07	0.07	0.07	0.07
0.07	0.07	0.07	0.07	0.07	0.09	0.1	0.09	0.07	0.07	0.08	0.07	0.07
0.08	0.08	0.07	0.07	0.08	0.11	0.13	0.1	0.07	0.07	0.07	0.07	0.05
0.07	0.08	0.08	0.08	0.1	0.1	0.11	0.11	0.09	0.07	0.07	0.07	0.06
0.08		0.09		0.1		0.12		0.11		0.08		0.06
X						X						X

Figure 7. Nozzle diameter 5/32 inch (4.0 mm), pressure 30 psi, wind speed 0.45 mph

Set 8

X						X						X
0.14		0.05		0.09		0.2		0.14		0.06		0.08
0.17	0.09	0.07	0.09	0.08	0.11	0.17	0.12	0.08	0.09	0.09	0.08	0.08
0.09	0.09	0.09	0.08	0.1	0.1	0.11	0.09	0.08	0.08	0.1	0.09	0.08
0.1	0.1	0.09	0.09	0.11	0.11	0.11	0.1	0.1	0.09	0.09	0.09	0.08
0.1	0.1	0.1	0.1	0.11	0.14	0.15	0.11	0.1	0.1	0.09	0.09	0.08
0.09	0.09	0.1	0.1	0.11	0.11	0.12	0.11	0.11	0.08	0.1	0.09	0.08
0.1		0.09		0.11		0.09		0.09		0.08		0.09
X						X						X

Figure 8. Same as above.

Set 9

X						X						X
0.1		0.1		0.12		0.14		0.1		0.13		0.1
0.09	0.1	0.09	0.1	0.1	0.14	0.14	0.13	0.1	0.15	0.12	0.14	0.11
0.08	0.08	0.09	0.1	0.1	0.12	0.12	0.11	0.1	0.15	0.12	0.14	0.12
0.08	0.1	0.09	0.09	0.1	0.12	0.12	0.12	0.11	0.14	0.11	0.12	0.1
0.08	0.1	0.11	0.1	0.11	0.13	0.14	0.14	0.12	0.13	0.11	0.1	0.09
0.09	0.1	0.1	0.1	0.12	0.12	0.14	0.15	0.14	0.11	0.1	0.1	0.1
0.1		0.08		0.1		0.15		0.1		0.07		0.1
X						X						X

Figure 9. Nozzle diameter 3/16 inch (4.75 mm), pressure 30 psi, wind speed 3.9578

Set 10

X						X						X
0.09		0.13		0.16		0.16		0.14		0.16		0.14
0.08	0.12	0.13	0.15	0.16	0.16	0.16	0.15	0.15	0.15	0.16	0.14	0.12
0.08	0.11	0.13	0.15	0.15	0.15	0.13	0.14	0.15	0.15	0.15	0.14	0.12
0.08	0.11	0.13	0.13	0.13	0.13	0.12	0.13	0.15	0.14	0.15	0.12	0.09
0.07	0.1	0.12	0.11	0.12	0.14	0.14	0.15	0.14	0.13	0.13	0.1	0.09
0.07	0.09	0.11	0.11	0.13	0.11	0.13	0.13	0.13	0.11	0.1	0.1	0.08
0.07		0.09		0.1		0.13		0.11		0.09		0.09
X						X						X

Figure 10. Same as above except pressure 40 psi.

Set 11

X						X						X
0.06		0.03		0.04		0.04		0.06		0.04		0.08
0.07	0.04	0.03	0.03	0.04	0.07	0.13	0.07	0.04	0.03	0.04	0.05	0.06
0.03	0.04	0.02	0.03	0.04	0.06	0.08	0.08	0.05	0.04	0.04	0.07	0.08
0.06	0.06	0.06	0.06	0.07	0.07	0.1	0.08	0.07	0.06	0.07	0.08	0.1
0.06	0.07	0.08	0.07	0.06	0.1	0.1	0.1	0.11	0.1	0.09	0.1	0.12
0.07	0.07	0.07	0.06	0.1	0.12	0.13	0.12	0.12	0.1	0.09	0.1	0.1
0.06		0.07		0.07		0.1		0.08		0.1		0.08
X						X						X

Figure 11. Nozzle diameter 1/8 inch (3.175 mm), pressure 60 psi, wind speed 7.72 mph

Set 12

X						X						X
0.05		0.04		0.05		0.04		0.03		0.04		0.06
0.05	0.05	0.05	0.06	0.07	0.08	0.08	0.08	0.06	0.06	0.06	0.08	0.07
0.04	0.05	0.05	0.07	0.07	0.08	0.07	0.07	0.06	0.07	0.07	0.08	0.08
0.05	0.05	0.05	0.07	0.07	0.08	0.08	0.07	0.06	0.07	0.08	0.08	0.08
0.05	0.05	0.05	0.06	0.07	0.06	0.07	0.07	0.06	0.07	0.07	0.08	0.08
0.04	0.04	0.04	0.04	0.06	0.07	0.07	0.07	0.07	0.06	0.08	0.06	0.07
0.05		0.04		0.07		0.08		0.05		0.05		0.05
X						X						X

Figure 12. Same as above except wind speed 5.21 mph (2.33 m/s), N.W.

Set 13

X						X						X
0.13		0.15		0.16		0.17		0.15		0.16		0.13
0.17	0.14	0.15	0.17	0.17	0.17	0.17	0.17	0.15	0.14	0.15	0.15	0.12
0.1	0.12	0.14	0.17	0.16	0.16	0.16	0.16	0.15	0.15	0.15	0.15	0.13
0.12	0.13	0.14	0.15	0.16	0.16	0.16	0.15	0.16	0.15	0.16	0.14	0.11
0.12	0.14	0.14	0.14	0.15	0.18	0.18	0.16	0.15	0.15	0.15	0.13	0.11
0.1	0.13	0.14	0.14	0.16	0.17	0.17	0.16	0.16	0.15	0.14	0.12	0.12
0.08		0.13		0.16		0.17		0.13		0.11		0.13
X						X						X

Figure 13. Nozzle diameter 3/16 inch (4.75 mm), pressure 60 psi, wind speed 2.5 mph

Set 14

X						X						X
0.12		0.13		0.2		0.21		0.17		0.23		0.18
0.17	0.12	0.14	0.19	0.21	0.23	0.22	0.2	0.17	0.2	0.23	0.23	0.18
0.1	0.1	0.13	0.18	0.2	0.2	0.15	16	0.16	0.17	0.21	0.22	0.18
0.09	0.08	0.11	0.15	0.2	0.18	0.16	0.14	0.13	0.16	0.19	0.18	0.14
0.07	0.08	0.08	0.14	0.17	0.15	0.13	0.13	0.12	0.17	0.16	0.16	0.14
0.05	0.08	0.1	0.13	0.18	0.15	0.13	0.13	0.11	0.14	0.16	0.14	0.12
0.08		0.08		0.13		0.11		0.1		0.12		0.13
X						X						X

Figure 14. Same as above except wind speed 7.06 mph (3.16 m/s), S.W.

Set 15

X						X						X
0.13		0.12		0.15		0.13		0.12		0.17		0.15
0.13	0.09	0.13	0.15	0.15	0.17	0.17	0.12	0.12	0.15	0.17	0.16	0.13
0.06	0.09	0.13	0.14	0.15	0.13	0.1	0.09	0.13	0.16	0.15	0.16	0.13
0.06	0.1	0.13	0.15	0.13	0.12	0.11	0.11	0.14	0.16	0.15	0.12	0.1
0.07	0.09	0.12	0.13	0.12	0.13	0.12	0.14	0.13	0.12	0.11	0.11	0.11
0.09	0.1	0.1	0.11	0.11	0.09	0.11	0.11	0.11	0.11	0.1	0.1	0.1
0.1		0.07		0.09		0.09		0.09		0.08		0.1
X						X						X

Figure 15. Nozzle diameter as above, pressure 30 psi, wind speed 2.98 mph

Interpolation of observed data using topographic maps by software SURFER.

Set No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.06	0.06	0.04	0.09	0.08	0.08	0.07	0.1	0.1	0.1	0.07	0.05	0.12	0.13	0.12
2	0.05	0.04	0.04	0.09	0.08	0.08	0.08	0.08	0.1	0.1	0.05	0.04	0.13	0.09	0.1
3	0.04	0.04	0.04	0.08	0.09	0.08	0.07	0.07	0.09	0.11	0.05	0.04	0.14	0.11	0.1
4	0.04	0.08	0.03	0.09	0.1	0.08	0.07	0.08	0.1	0.12	0.05	0.05	0.15	0.14	0.11
5	0.05	0.05	0.03	0.11	0.12	0.1	0.08	0.1	0.11	0.08	0.06	0.06	0.16	0.17	0.12
6	0.06	0.05	0.03	0.14	0.13	0.11	0.1	0.13	0.14	0.14	0.07	0.07	0.17	0.18	0.12
7	0.07	0.07	0.04	0.16	0.13	0.13	0.11	0.15	0.15	0.15	0.07	0.06	0.17	0.16	0.11
8	0.05	0.07	0.05	0.14	0.11	0.11	0.1	0.11	0.13	0.14	0.07	0.05	0.16	0.15	0.1
9	0.04	0.05	0.04	0.1	0.09	0.09	0.09	0.07	0.1	0.13	0.07	0.04	0.14	0.14	0.11
10	0.04	0.04	0.03	0.09	0.09	0.07	0.07	0.06	0.09	0.12	0.07	0.04	0.13	0.16	0.12
11	0.05	0.05	0.04	0.1	0.11	0.06	0.07	0.07	0.1	0.13	0.07	0.05	0.14	0.18	0.13
12	0.06	0.05	0.04	0.1	0.1	0.07	0.07	0.08	0.1	0.12	0.07	0.05	0.13	0.18	0.13
13	0.05	0.03	0.07	0.09	0.09	0.11	0.08	0.13	0.1	0.1	0.07	0.06	0.15	0.18	0.13
14	0.06	0.03	0.05	0.09	0.09	0.08	0.07	0.09	0.1	0.1	0.06	0.06	0.12	0.14	0.1
15	0.06	0.03	0.05	0.09	0.09	0.08	0.07	0.09	0.09	0.09	0.08	0.07	0.12	0.12	0.08
16	0.05	0.03	0.05	0.08	0.09	0.08	0.07	0.09	0.1	0.08	0.09	0.07	0.12	0.11	0.09
17	0.07	0.04	0.07	0.08	0.09	0.07	0.07	0.09	0.09	0.08	0.09	0.06	0.11	0.09	0.1
18	0.06	0.04	0.05	0.09	0.09	0.09	0.08	0.09	0.1	0.09	0.07	0.04	0.13	0.08	0.1
19	0.05	0.03	0.04	0.1	0.09	0.1	0.08	0.1	0.1	0.1	0.07	0.05	0.14	0.08	0.09
20	0.04	0.03	0.04	0.09	0.09	0.09	0.07	0.1	0.1	0.11	0.06	0.05	0.13	0.08	0.1
21	0.04	0.04	0.04	0.09	0.08	0.08	0.07	0.09	0.08	0.11	0.04	0.05	0.12	0.1	0.09
22	0.05	0.04	0.04	0.1	0.09	0.09	0.08	0.09	0.1	0.12	0.04	0.05	0.14	0.12	0.09
23	0.06	0.04	0.03	0.11	0.11	0.1	0.08	0.1	0.1	0.11	0.07	0.04	0.14	0.1	0.1
24	0.06	0.04	0.04	0.11	0.11	0.1	0.07	0.1	0.11	0.12	0.08	0.05	0.14	0.08	0.12
25	0.06	0.04	0.04	0.11	0.11	0.1	0.07	0.09	0.09	0.13	0.06	0.05	0.14	0.11	0.13
26	0.06	0.04	0.04	0.1	0.09	0.08	0.07	0.09	0.09	0.13	0.02	0.05	0.14	0.13	0.13
27	0.05	0.06	0.04	0.09	0.09	0.1	0.07	0.07	0.09	0.13	0.03	0.05	0.15	0.14	0.13
28	0.05	0.05	0.04	0.12	0.12	0.11	0.08	0.1	0.1	0.11	0.06	0.04	0.14	0.13	0.11
29	0.06	0.04	0.04	0.11	0.12	0.1	0.07	0.1	0.1	0.11	0.07	0.06	0.14	0.14	0.13
30	0.07	0.04	0.04	0.12	0.11	0.09	0.07	0.09	0.09	0.13	0.06	0.07	0.15	0.15	0.15
31	0.08	0.06	0.02	0.11	0.1	0.08	0.06	0.08	0.1	0.15	0.03	0.07	0.17	0.18	0.14
32	0.06	0.07	0.03	0.09	0.1	0.07	0.05	0.09	0.1	0.15	0.03	0.06	0.17	0.19	0.15
33	0.06	0.07	0.05	0.14	0.14	0.12	0.1	0.11	0.12	0.13	0.1	0.06	0.16	0.18	0.11
34	0.07	0.05	0.04	0.11	0.12	0.11	0.08	0.11	0.11	0.12	0.06	0.07	0.15	0.17	0.12
35	0.07	0.04	0.04	0.11	0.1	0.09	0.07	0.11	0.1	0.13	0.07	0.07	0.16	0.2	0.13
36	0.07	0.04	0.03	0.09	0.1	0.08	0.07	0.1	0.1	0.15	0.04	0.07	0.16	0.2	0.15
37	0.07	0.08	0.04	0.08	0.1	0.08	0.07	0.08	0.1	0.16	0.04	0.07	0.17	0.21	0.15
38	0.06	0.07	0.06	0.13	0.12	0.12	0.1	0.11	0.12	0.11	0.12	0.07	0.17	0.15	0.09
39	0.07	0.08	0.06	0.11	0.11	0.11	0.11	0.14	0.13	0.14	0.1	0.06	0.18	0.15	0.13
40	0.07	0.04	0.04	0.09	0.11	0.09	0.09	0.11	0.12	0.13	0.07	0.08	0.16	0.18	0.12
41	0.07	0.07	0.04	0.09	0.09	0.08	0.09	0.1	0.12	0.15	0.06	0.08	0.16	0.2	0.13
42	0.07	0.07	0.04	0.1	0.1	0.1	0.1	0.11	0.14	0.16	0.07	0.08	0.17	0.23	0.17
43	0.07	0.06	0.07	0.12	0.12	0.12	0.11	0.12	0.14	0.13	0.13	0.07	0.17	0.13	0.11
44	0.08	0.07	0.07	0.12	0.11	0.13	0.13	0.15	0.14	0.14	0.1	0.07	0.18	0.13	0.12
45	0.07	0.03	0.04	0.1	0.1	0.1	0.1	0.11	0.12	0.12	0.1	0.08	0.16	0.16	0.11
46	0.07	0.03	0.05	0.1	0.09	0.1	0.1	0.11	0.12	0.13	0.08	0.07	0.16	0.15	0.1
47	0.07	0.04	0.08	0.16	0.1	0.17	0.1	0.17	0.14	0.16	0.13	0.08	0.17	0.22	0.17
48	0.08	0.05	0.07	0.14	0.12	0.11	0.11	0.11	0.15	0.13	0.12	0.07	0.16	0.13	0.11
49	0.07	0.04	0.06	0.12	0.11	0.11	0.1	0.11	0.14	0.15	0.1	0.07	0.16	0.13	0.14
50	0.06	0.05	0.06	0.11	0.1	0.1	0.09	0.1	0.12	0.13	0.08	0.07	0.15	0.14	0.11

51	0.06	0.05	0.05	0.11	0.1	0.1	0.09	0.09	0.11	0.14	0.08	0.07	0.16	0.16	0.09
52	0.08	0.05	0.08	0.14	0.12	0.12	0.09	0.12	0.13	0.15	0.07	0.08	0.17	0.2	0.12
53	0.07	0.04	0.05	0.14	0.14	0.11	0.09	0.11	0.14	0.13	0.12	0.07	0.16	0.11	0.11
54	0.06	0.05	0.04	0.12	0.14	0.1	0.07	0.1	0.12	0.14	0.11	0.06	0.15	0.12	0.13
55	0.06	0.07	0.05	0.12	0.12	0.1	0.07	0.1	0.11	0.15	0.07	0.06	0.16	0.13	0.14
56	0.05	0.06	0.05	0.12	0.1	0.09	0.07	0.08	0.1	0.15	0.05	0.06	0.15	0.16	0.13
57	0.05	0.07	0.04	0.11	0.09	0.09	0.07	0.08	0.1	0.15	0.04	0.06	0.15	0.17	0.12
58	0.05	0.04	0.04	0.12	0.13	0.09	0.07	0.08	0.11	0.11	0.1	0.06	0.15	0.14	0.11
59	0.07	0.06	0.04	0.12	0.12	0.1	0.07	0.1	0.11	0.13	0.1	0.07	0.15	0.17	0.12
60	0.07	0.07	0.04	0.12	0.12	0.1	0.07	0.09	0.11	0.14	0.06	0.07	0.15	0.16	0.16
61	0.07	0.06	0.04	0.11	0.11	0.1	0.07	0.08	0.1	0.15	0.04	0.07	0.15	0.17	0.16
62	0.05	0.07	0.04	0.1	0.09	0.09	0.07	0.09	0.1	0.15	0.03	0.06	0.14	0.2	0.15
63	0.05	0.07	0.04	0.12	0.13	0.09	0.07	0.1	0.1	0.1	0.09	0.08	0.14	0.16	0.1
64	0.07	0.05	0.05	0.12	0.13	0.09	0.07	0.09	0.11	0.13	0.09	0.07	0.15	0.16	0.11
65	0.07	0.04	0.04	0.11	0.11	0.09	0.08	0.09	0.11	0.15	0.07	0.08	0.16	0.19	0.15
66	0.07	0.05	0.05	0.1	0.11	0.09	0.07	0.1	0.12	0.15	0.04	0.07	0.15	0.21	0.15
67	0.07	0.07	0.05	0.09	0.1	0.08	0.07	0.09	0.12	0.16	0.04	0.06	0.15	0.23	0.17
68	0.06	0.03	0.04	0.11	0.12	0.08	0.07	0.09	0.09	0.1	0.1	0.06	0.12	0.14	0.1
69	0.06	0.06	0.05	0.11	0.12	0.08	0.07	0.09	0.1	0.1	0.1	0.08	0.13	0.16	0.11
70	0.07	0.07	0.05	0.1	0.11	0.09	0.07	0.09	0.11	0.12	0.08	0.08	0.14	0.18	0.12
71	0.07	0.04	0.06	0.09	0.1	0.08	0.07	0.09	0.12	0.14	0.07	0.08	0.15	0.22	0.16
72	0.07	0.06	0.06	0.09	0.1	0.08	0.07	0.08	0.12	0.14	0.05	0.08	0.15	0.23	0.16
MEAN	0.06	0.05	0.05	0.11	0.11	0.09	0.08	0.1	0.11	0.13	0.07	0.06	0.15	0.15	0.12
STD	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.01	0.02	0.04	0.02
CV actual	0.18	0.29	0.26	0.17	0.14	0.19	0.19	0.19	0.15	0.17	0.36	0.19	0.11	0.25	0.18

18 Randomly selected depths using Topographic distribution from software SURFER, (using MinCurve Method)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.05	0.03	0.04	0.07	0.09	0.07	0.06	0.08	0.09	0.08	0.04	0.04	0.09	0.06	0.08
2	0.05	0.04	0.04	0.08	0.09	0.08	0.07	0.08	0.09	0.09	0.04	0.04	0.11	0.07	0.09
3	0.05	0.04	0.04	0.1	0.09	0.08	0.07	0.08	0.1	0.09	0.04	0.05	0.12	0.08	0.09
4	0.05	0.04	0.04	0.1	0.09	0.08	0.07	0.08	0.1	0.1	0.04	0.05	0.13	0.09	0.1
5	0.06	0.05	0.04	0.1	0.09	0.09	0.07	0.09	0.1	0.11	0.05	0.05	0.14	0.13	0.11
6	0.06	0.05	0.04	0.11	0.1	0.09	0.07	0.09	0.1	0.12	0.05	0.05	0.14	0.14	0.11
7	0.06	0.06	0.04	0.11	0.1	0.1	0.07	0.09	0.1	0.12	0.06	0.06	0.15	0.14	0.12
8	0.06	0.06	0.04	0.11	0.11	0.1	0.07	0.09	0.1	0.13	0.06	0.06	0.15	0.15	0.12
9	0.07	0.06	0.04	0.11	0.11	0.1	0.08	0.09	0.1	0.13	0.06	0.06	0.15	0.16	0.13
10	0.07	0.07	0.05	0.11	0.11	0.1	0.08	0.09	0.1	0.13	0.06	0.06	0.15	0.16	0.13
11	0.07	0.07	0.05	0.11	0.12	0.1	0.08	0.09	0.11	0.14	0.07	0.06	0.15	0.16	0.13
12	0.07	0.07	0.05	0.12	0.12	0.1	0.08	0.09	0.11	0.14	0.07	0.07	0.15	0.17	0.13
13	0.07	0.07	0.06	0.12	0.12	0.11	0.08	0.1	0.11	0.15	0.07	0.07	0.16	0.18	0.14
14	0.08	0.07	0.06	0.12	0.13	0.12	0.09	0.1	0.12	0.15	0.07	0.07	0.16	0.2	0.14
15	0.08	0.08	0.06	0.12	0.14	0.12	0.09	0.11	0.12	0.15	0.08	0.07	0.17	0.2	0.15
16	0.08	0.08	0.06	0.13	0.14	0.13	0.1	0.1	0.13	0.15	0.09	0.07	0.17	0.2	0.15
17	0.08	0.08	0.07	0.14	0.15	0.14	0.1	0.14	0.14	0.16	0.1	0.07	0.17	0.2	0.16
18	0.08	0.09	0.07	0.16	0.16	0.15	0.1	0.15	0.15	0.16	0.1	0.08	0.18	0.21	0.16
AVG.	0.07	0.06	0.05	0.11	0.11	0.1	0.08	0.1	0.11	0.13	0.06	0.06	0.15	0.15	0.12
STD	0.01	0.02	0.01	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.01	0.02	0.05	0.02
CV std	0.19	0.27	0.22	0.18	0.19	0.21	0.15	0.2	0.14	0.19	0.3	0.19	0.15	0.31	0.19
CV low/high	0.18	0.25	0.17	0.18	0.17	0.2	0.14	0.16	0.14	0.19	0.28	0.18	0.16	0.33	0.19

APPENDIX B

Turfgrass Sprinklers Irrigation Data

Appendix B

Turfgrass sprinklers irrigation data

These sprinkler irrigation data were obtained from Hancock Turfgrass Research Center, Saffel, 1993. Dept. of Crop and Soil Science, MSU. The cups diameters were 11.46 11.4 cm. The application rates were in mls. The sprinklers were spaced 10 m X 10 m .

Set 1	46	46	46	42	46	42	42	44	50	100
	64	88	70	86	96	98	102	104	104	11
	40	78	74	106	114	129	146	170	135	126
	30	70	90	140	152	164	170	190	160	140
	30	70	112	165	184	196	190	220	180	144
	40	108	169	196	214	210	220	236	180	170
	50	130	194	234	250	250	236	202	184	160
	70	142	206	234	270	273	260	229	186	154
	98	156	226	246	274	270	263	224	220	210
	101	188	186	210	244	220	222	183	154	179
Set 2	89	100	120	126	122	114	108	99	98	152
	61	108	148	158	162	160	162	149	146	138
	23	84	140	180	205	216	205	200	176	142
	21	92	154	200	222	238	236	226	198	150
	30	100	160	212	227	250	240	194	206	162
	34	110	172	218	240	250	255	236	210	169
	52	138	180	230	222	247	260	240	210	160
	70	130	178	210	222	237	249	237	192	156
	76	139	160	170	187	180	170	160	150	166
	64	150	106	114	120	107	109	101	96	40
Set 3	68	98	120	125	129	126	121	115	111	95
	98	126	132	145	146	141	138	121	121	110
	96	135	140	150	149	142	137	135	122	122
	109	128	132	138	142	138	132	122	116	125
	109	120	124	130	135	128	126	112	102	107
	101	118	122	126	125	126	121	114	105	96
	92	113	120	120	112	114	114	112	100	88
	74	97	112	115	112	110	116	106	96	76
	63	84	102	118	120	122	118	105	88	59
	39	68	84	99	100	99	90	85	63	44
Set 4	94	108	127	132	126	119	130	127	104	110
	110	116	126	132	128		135	138	125	134
	116	118	122	123	127	133	130	132	130	135
	120	120	120	120	133	127	124	114	108	113
	103	97	104	114	124	124	112	110	102	105
	90	100	106	116	118	118	109	102	98	93
	80	90	110	118	112	106	110	106	100	78
	70	85	102	110	105	103	112	96	90	75
	49	77	99	112	112	112	112	108	87	66
	35	50	68	75	80	78	87	81	62	52

Set 5	107	125	140	144	140	129	126	116	107	80
	120	130	144	148	140	140	145	125	114	112
	125	128	135	134	137	144	142	136	124	123
	120	118	123	130	131	133	132	120	119	119
	106	104	111	118	124	126	114	112	107	102
	94	98	112	114	114	112	108	110	101	80
	88	93	103	110	110	106	108	106	94	80
	73	85	100	102	106	112	112	100	88	71
	58	72	92	100	110	110	112	98	84	60
	52	65	77	80	78	75	74	63	50	41
Set 6	82	114	115	118	124	126	138	138	130	130
	96	123	130	124	128	131	135	140	136	127
	95	132	123	122	132	123	120	118	127	125
	104	114	118	122	120	118	108	102	102	110
	94	107	110	112	105	108	99	93	90	94
	84	94	103	106	105	97	90	92	80	79
	68	86	94	100	95	93	92	87	73	67
	50	70	90	100	104	103	100	88	72	64
	35	60	82	105	116	116	121	97	81	45
	20	32	48	66	74	80	83	77	64	45
Set 7	66	90	115	133	133	138	145	147	139	152
	76	112	121	134	147	150	150	154	137	125
	80	124	122	128	141	146	143	140	133	122
	72	118	115	114	127	130	125	114	108	111
	62	99	99		110	117	110	107	-	93
	52	83	90	96	99	94	95	99	94	87
	45	70	74	86	88	90	93	100	90	70
	32	50	67	78	87	90	105	97	83	58
	21	36	56	77	96	102	115	104	86	56
	29	25	38	54	64	69	74	78	59	38
Set 8	79	92	105	127	142	142	157	150	142	144
	117	113	120	137	148	154	167	159	146	140
	136	123	130	134	142	147	146	138	138	134
	125	115	115	120	127	-	124	114	118	115
	102	96	100	106	108	96	104	100	94	92
	90	90	99	95	96	94	96	97	93	80
	72	78	87	90	86	92	97	96	85	67
	52	64	81	88	90	101	108	96	85	66
	40	45	70	85	93	102	-	98	81	66
	26	52	55	53	54	63	70	66	57	52

Set 9	106	132	150	157	130	124	125	110	110	117
	130	147	170	170	144	126	130	130	125	130
	138	157	136	158	144	130	120	122	124	140
	132	137	140	146	137	131	112	97	106	125
	110	124	130	128	112	116	98	91	89	89
	106	115	123	120	113	108	98	84	84	91
	92	112	122	114	100	91	90	80	72	78
	80	98	111	116	107	108	93	78	60	45
	47	85	107	123	120	112	108	86	48	35
	50	48	52	60	60	78	70	59	39	35

Set 10	102	141	147	142	120	120	128	120	114	98
	130	140	153	138	124	125	130	125	130	135
	138	138	140	140	130	125	125	130	137	158
	116	110	118	128	141	126	116	108	120	127
	100	98	110	122	123	118	104	100	100	112
	97	101	116	114	112	107	98	92	95	93
	84	96	102	116	110	100	94	84	80	83
	75	94	111	120	112	106	98	78	68	60
	52	80	115	125	125	114	105	76	60	41
	38	72	102	122	115	108	100	76	61	40

Set 11	128	134	140	140	128	125	125	120	116	120
	127	137	148	144	130	120	134	123	130	138
	140	145	148	144	132	120	111	118	130	140
	132	130	133	132	131	119	108	92	106	118
	119	122	123	120	120	110	88	84	88	98
	110	120	120	115	106	120	82	74	70	73
	96	120	126	130	114	107	85	72	52	60
	75	110	124	125	118	112	93	66	60	53
	68	94	119		136	122	111	77	60	41
	40	60	66	68	60	52	52	44	42	48

Set 12	38	62	86	102	112	122	144	144	142	114
	44	94	110	128	128	134	142	156	148	132
	41	119	128	132	116	118	125	149	159	138
	40	126	124	124	127	126	137	131	142	133
	55	129	128	124	137	132	124	120	119	120
	78	124	116	122	132	124	126	118	118	127
	88	120	114	116	122	126	127	115	113	114
	82	110	114	122	120	118	126	128	117	107
	65	88	102	120	114	120	122	128	109	138
	40	60	89	115	130	133	152	132	106	60

Set 13	42	43	50	60	71	82	105	122	136	106
	26	58	66	76	91	110	131	162	160	133
	26	70	88	100	92	112	112	146	164	154
	30	90	102	106	104	114	124	134	150	154
	38	104	114	100	102	115	122	132	140	130
	54	121	116	103	105	105	122	130	124	116
	76	124	110	110	104	104	110	120	116	120
	70	100	106	108	104	104	111	119	134	118
	56	70	84	92	99	84	106	142	140	111
	40	38	50	84	94	105	140	156	145	99

Set 14	13	18	38	47	101	136	140	135	101	26
	34	50	50	55	97	136	136	120	83	54
	52	80	74	72	93	130	132	110	96	98
	60	99	90	90	92	122	142	124	112	122
	60	112	108	100	101	122	140	130	152	137
	50	106	97	97	100	116	130	130	130	123
	50	72	70	74	98	116	118	108	104	104
	36	58	52	62	90	116	116	104	90	72
	30	40	34	58	100	126	114	110	90	50
	14	20	40	60	106	120	120	115	70	37

Set 15	36	62	78	97	100	112	110	116	116	100
	52	86	100	112	120	120	129	136	140	126
	64	105	120	124	122	119	128	140	141	132
	64	115	120	120	1116	119	125	130	136	126
	60	112	116	112	111	120	122	122	123	119
	66	114	120	104	113	118	118	112	114	105
	64	110	121	113	110	110	105	105	115	106
	54	107	110	111	111	108	111	112	110	100
	46	90	110	110	110	110	110	118	107	91
	36	64	84	94	100	97	104	109	100	78

Set 16	84	114	140	152	152	160	152	156	192	220
	75	138	180	198	198	197	285	189	202	160
	46	136	210	243	240	232	323	212	220	190
	40	143	214	251	256	262	260	269	250	230
	34	130	210	240	242	249	270	290	294	280
	32	90	194	198	212	226	259	295	296	274
	31	69	142	144	152	193	234	280	280	249
	47	78	107	99	120	170	230	253	255	232
	60	106	90	80	103	154	200	218	212	222
	50	86	60	44	50	72	98	122	145	103

Actual data were input into the software SURFER for random selection of depths.
MiniCurve method was used for higher accuracy of 0.995.

	Actual data sets															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	101	64	39	35	52	20	29	50	50	38	40	40	40	14	36	50
2	98	76	63	49	58	35	21	47	47	52	68	65	56	30	46	60
3	70	76	74	70	73	50	32	80	80	75	75	82	70	36	54	47
4	50	52	92	80	88	68	45	92	92	84	96	88	76	50	64	31
5	40	34	101	90	94	84	52	106	106	97	110	78	54	50	66	32
6	30	30	109	103	106	94	62	110	110	100	119	55	38	60	60	34
7	30	21	109	120	120	104	72	132	132	116	132	40	30	60	64	40
8	48	23	96	116	125	95	80	138	138	138	140	41	26	52	64	46
9	64	61	98	110	120	96	76	130	130	130	127	44	26	34	52	75
10	46	89	68	94	107	82	66	106	106	102	128	38	42	13	36	84
11	188	150	68	50	65	32	25	48	48	72	60	60	38	20	64	86
12	156	139	84	77	72	60	36	85	85	80	94	88	70	40	90	106
13	142	130	97	85	85	70	50	98	98	94	110	110	100	58	107	78
14	130	138	113	90	93	86	70	112	112	96	120	120	124	72	110	69
15	108	110	118	100	98	94	83	115	115	101	120	124	121	106	114	90
16	70	100	120	97	104	107	99	124	124	98	122	129	104	112	112	130
17	70	92	128	120	118	114	118	137	137	110	130	126	90	99	115	143
18	78	84	135	118	128	132	124	157	157	138	145	119	70	80	105	136
19	88	108	126	116	130	123	112	147	147	140	137	94	58	50	86	138
20	46	100	98	108	125	114	90	132	132	141	134	62	43	18	62	114
21	186	106	84	68	77	48	38	52	52	102	66	89	50	40	84	60
22	226	160	102	99	92	82	56	107	107	115	119	102	84	34	110	90
23	206	178	112	102	100	90	67	111	111	111	124	114	106	52	110	107
24	194	180	120	110	103	94	74	122	122	102	126	114	110	70	121	142
25	169	172	122	106	112	103	90	123	123	116	120	116	116	97	120	194
26	112	160	124	104	111	110	99	130	130	110	123	128	114	108	116	210
27	90	154	132	120	123	118	115	140	140	118	133	124	102	90	120	214
28	74	140	140	122	135	123	122	136	136	140	148	128	88	74	120	210
29	70	148	132	126	144	130	121	170	170	153	148	110	66	50	100	180
30	46	120	120	127	140	115	115	150	150	147	140	86	50	38	78	140
31	210	114	99	75	80	66	54	60	60	122	68	115	84	60	94	44
32	246	170	118	112	100	105	77	123	123	125	100	120	92	58	110	80
33	234	210	115	110	102	100	78	116	116	120	125	122	108	62	111	99
34	234	230	120	118	110	100	86	114	114	116	130	116	110	74	113	144
35	196	218	126	116	114	106	96	120	120	114	115	122	103	97	104	198
36	165	212	130	114	118	112	100	128	128	122	120	124	100	100	112	240
37	140	200	138	120	130	122	114	146	146	128	132	124	106	90	120	251
38	106	180	150	123	134	122	128	158	158	140	144	132	100	72	124	243
39	86	158	145	132	148	124	134	170	170	138	144	128	76	55	112	198
40	42	126	125	132	144	118	133	157	157	142	140	102	60	47	97	152
41	244	120	100	80	78	74	64	60	60	115	60	130	94	106	100	50
42	274	187	120	112	110	116	96	120	120	125	136	114	99	107	110	103
43	270	222	112	105	106	104	87	107	107	112	118	120	104	90	111	120
44	250	222	112	112	110	95	88	100	100	110	114	122	104	98	110	152
45	214	240	125	118	114	105	99	113	113	112	106	132	105	100	113	212
46	184	227	135	124	124	105	110	112	112	123	120	137	102	101	111	242
47	152	222	142	133	131	120	127	137	137	141	131	127	104	92	116	256
48	114	205	149	127	137	132	141	144	144	130	132	116	92	93	122	240
49	96	162	146	128	140	128	147	144	144	124	130	128	91	97	120	198
50	46	122	129	126	140	124	133	130	130	120	128	112	71	101	100	152

51	220	107	99	78	75	80	69	78	78	108	52	133	105	120	97	72
52	270	180	122	112	110	116	102	112	112	114	122	120	84	126	110	154
53	273	237	110	103	112	103	90	108	108	106	117	118	104	116	108	170
54	250	247	114	106	106	93	90	91	91	100	107	126	104	116	110	193
55	210	250	126	118	112	97	94	108	108	107	120	124	105	116	118	226
56	196	250	128	124	126	108	117	116	116	118	110	132	115	122	120	249
57	164	238	138	127	133	118	130	131	131	126	119	126	114	122	119	262
58	129	216	142	133	144	123	146	130	130	125	120	118	112	130	119	232
59	98	160	141	125	140	131	150	126	126	125	120	134	110	136	120	197
60	42	114	126	119	129	126	138	124	124	120	125	122	82	136	112	160
61	222	109	90	87	74	83	74	70	70	100	52	152	140	120	104	98
62	263	170	118	112	112	121	115	108	108	105	111	122	106	114	110	200
63	260	249	116	112	112	100	105	93	93	98	93	126	111	116	111	230
64	236	260	114	110	108	92	93	90	90	94	85	127	110	118	105	234
65	220	255	121	109	108	90	95	98	98	98	82	126	122	130	118	259
66	190	240	126	112	114	99	110	98	98	104	88	124	122	140	122	270
67	170	236	132	124	132	108	125	112	112	116	108	137	124	142	125	260
68	146	205	137	130	142	120	143	120	120	125	111	125	112	132	128	232
69	102	162	138	135	145	135	150	130	130	130	134	142	131	136	129	185
70	42	108	121	130	126	138	145	125	125	128	125	144	105	140	110	152
71	183	101	85	81	63	77	78	59	59	76	44	132	156	115	109	122
72	224	160	105	108	98	97	104	86	86	76	77	128	142	110	118	218
73	229	237	106	96	100	88	97	78	78	78	66	128	119	104	112	253
74	202	240	112	106	106	87	100	80	80	84	72	115	120	108	105	280
75	200	236	114	102	110	92	99	84	84	92	74	118	130	130	112	295
76	190	194	112	110	112	93	107	91	91	100	84	120	132	130	122	290
77	160	226	122	114	120	102	114	97	97	108	92	131	134	124	130	269
78	136	200	135	132	136	118	140	122	122	130	118	149	146	110	140	212
79	104	149	121	138	125	140	154	130	130	125	123	156	162	120	136	189
80	44	99	115	127	116	138	147	110	110	120	120	144	122	135	116	156
81	154	96	63	62	50	64	59	39	39	61	42	106	145	70	100	145
82	220	150	88	87	84	81	86	48	48	60	60	109	140	90	107	212
83	186	192	96	90	88	72	83	60	60	68	50	117	134	90	110	255
84	184	210	100	100	94	73	90	72	72	80	52	113	116	104	115	280
85	180	210	105	98	101	80	94	84	84	95	70	118	124	130	114	296
86	180	206	102	102	107	90	100	89	89	100	88	119	140	152	123	294
87	160	198	116	108	119	102	108	106	106	120	106	142	150	112	136	250
88	135	176	122	130	124	127	133	124	124	137	130	159	164	96	141	280
89	104	146	121	125	114	136	137	125	125	130	130	148	160	83	140	202
90	50	98	111	104	107	130	139	110	110	114	116	142	136	101	116	192
91	179	40	44	52	48	45	138	34	34	40	48	60	99	37	78	103
92	210	166	59	60	60	45	56	35	35	41	41	138	11	50	91	222
93	154	156	76	70	72	64	58	45	45	60	53	107	118	72	100	232
94	160	160	88	78	80	67	70	78	78	83	60	114	120	104	106	249
95	170	169	96	93	80	79	87	91	91	93	72	127	116	123	105	274
96	144	162	107	103	103	94	93	89	89	112	98	120	130	137	119	280
97	140	150	122	113	119	110	11	125	120	123	118	133	154	122	126	230
98	126	142	123	135	123	125	122	145	140	155	140	130	154	98	132	190
99	110	138	110	134	112	129	125	130	130	138	138	132	133	54	126	160
100	100	152	95	110	80	132	152	117	117	98	120	114	106	26	100	220
mean	150	159	112	106	108	99.1	96.9	107	107	108	106	115	102	89.7	106	174
STD	58.9	48.6	17	16.7	18.5	20.4	26.8	24.6	24.6	19.3	25.4	18.3	25.5	29.9	16	65.7
CVactual	0.39	0.31	0.15	0.16	0.17	0.21	0.28	0.23	0.23	0.18	0.24	0.16	0.25	0.33	0.15	0.38

18 Catch can depths were randomly selected using the software SURFER .

1	42	64	39	52	48	20	29	19	34	38	40	38	40	14	36	50
2	86	100	44	87	52	32	36	26	50	40	52	40	42	26	66	84
3	98	130	64	94	63	45	37	45	78	60	61	88	58	37	78	99
4	100	139	68	99	72	81	50	52	85	76	63	110	70	40	86	103
5	101	146	88	101	80	82	63	54	89	91	71	113	83	49	90	106
6	104	148	106	109	84	82	81	78	100	98	73	114	99	68	100	128
7	133	152	114	110	97	85	91	88	111	99	79	117	102	71	107	130
8	136	158	118	110	99	88	94	88	111	101	81	118	103	83	107	186
9	142	166	121	112	107	93	102	92	112	102	93	126	104	95	111	197
10	156	170	122	112	110	94	105	99	112	110	94	126	105	97	113	202
11	161	190	126	113	112	95	119	101	114	113	94	127	108	103	114	220
12	184	202	128	116	114	104	121	102	117	115	110	129	109	109	114	225
13	189	209	130	116	119	109	127	120	117	116	114	129	110	109	115	229
14	202	214	132	120	125	112	134	123	118	127	116	132	112	112	121	235
15	203	227	135	122	126	116	137	127	124	130	120	135	118	120	122	248
16	204	230	137	123	133	122	142	142	125	130	121	138	126	130	128	253
17	223	244	140	123	133	123	144	144	126	140	128	148	140	136	140	254
18	227	244	140	125	134	128	152	146	149	143	130	153	153	138	141	260
Mean	150	174	108	108	100	89.5	98	91.4	104	102	91.1	116	99	85.4	105	178
STD	53.4	50.1	33.2	17.4	28	30.5	40.5	39.5	28	31.1	27.6	31.5	30.4	38.9	26.1	69
CV18	0.36	0.29	0.31	0.16	0.28	0.34	0.41	0.43	0.27	0.31	0.3	0.27	0.31	0.46	0.25	0.39
CVlow/high	0.32	0.28	0.32	0.15	0.28	0.39	0.42	0.44	0.28	0.33	0.28	0.3	0.33	0.45	0.26	0.36

APPENDIX C

Center-pivot Irrigation System Data

Appendix C

Center-pivot sprinkler irrigation data

Data were obtained from Pandey, 1989. M.S. thesis, Dept. of Agr. Engineering, MSU.

No	Distance ft	Depth1 inch 1	Depth2 inch 2	Depth3 inch 3	Depth4 inch 4	Depth5 inch 5
1	25	0.403	0.418	0.528	0.463	0.413
2	50	0.491	0.507	0.623	0.550	0.511
3	75	0.303	0.313	0.385	0.341	0.336
4	100	0.217	0.223	0.263	0.239	0.356
5	125	0.239	0.243	0.308	0.276	0.295
6	150	0.265	0.271	0.342	0.306	0.332
7	175	0.283	0.290	0.350	0.308	0.356
8	200	0.296	0.306	0.358	0.326	0.387
9	225	0.301	0.308	0.355	0.326	0.391
10	250	0.293	0.300	0.364	0.317	0.382
11	275	0.28	0.291	0.363	0.316	0.357
12	300	0.263	0.272	0.325	0.293	0.338
13	325	0.219	0.230	0.299	0.262	0.285
14	350	0.227	0.238	0.313	0.261	0.284
15	375	0.256	0.267	0.350	0.300	0.335
16	400	0.301	0.314	0.385	0.342	0.381
17	425	0.323	0.337	0.414	0.367	0.411
18	450	0.346	0.361	0.444	0.393	0.437
19	475	0.337	0.353	0.433	0.384	0.427
20	500	0.307	0.323	0.397	0.352	0.404
21	525	0.279	0.292	0.359	0.318	0.365
22	550	0.274	0.286	0.352	0.312	0.337
23	575	0.274	0.288	0.354	0.313	0.363
24	600	0.28	0.294	0.362	0.320	0.360
25	625	0.283	0.297	0.365	0.324	0.341
26	650	0.285	0.302	0.374	0.331	0.342
27	675	0.284	0.300	0.372	0.329	0.371
28	700	0.278	0.292	0.358	0.317	0.374
29	725	0.266	0.275	0.331	0.293	0.357
30	750	0.232	0.239	0.284	0.251	0.307
31	775	0.184	0.190	0.224	0.199	0.249
32	800	0.203	0.141	0.169	0.150	0.177
33	825	0.150	0.087	0.105	0.093	0.084
34	850	0.103	0.038	0.065	0.057	0.037
35	875	0.067				
36	900	0.063				
37	925	0.061				
38	950	0.058				
39	975	0.054				
40	1000	0.049				

Set 6	Station ft	0	10	20	30	40	50	60	70	80	90
0					1.045	1.503	1.888	1.863	1.708	1.620	1.464
100		1.427	1.428	1.327	1.187	1.23	1.212	1.109	1.149	1.170	1.084
200		1.083	1.123	1.057	1.018	1.057	1.021	0.958	0.967	0.967	0.927
300		0.948	0.974	0.935	0.934	0.988	0.95	0.935	0.958	0.922	0.903
400		0.91	0.915	0.907	0.922	0.945	0.916	0.907	0.917	0.890	0.884
500		0.898	0.892	0.893	0.904	0.900	0.89	0.884	0.891	0.893	0.888
600		0.892	0.899	0.902	0.904	0.915	0.904	0.909	0.93	0.94	0.937
700		0.936	0.943	0.937	0.924	0.931	0.925	0.909	0.909	0.901	0.882
800		0.88	0.883	0.874	0.868	0.879	0.878	0.872	0.884	0.881	0.869
900		0.876	0.868	0.846	0.849	0.857	0.854	0.843	0.828	0.801	0.763
1000		0.705	0.641	0.579	0.563	0.551	0.543	0.586	0.645	0.712	0.788
1100		0.826	0.851	0.886	0.875	0.845	0.834	0.838	0.824	0.814	0.827
1200		0.821	0.795	0.769	0.753	0.742	0.716	0.676	1.311	1.277	1.191
1300		1.063	0.912	0.758	0.626	0.517	0.408	0.279	0.132		

18 hand-picked random depths:

	1	2	3	4	5	6
	0.054	0.087	0.105	0.093	0.084	0.579
	0.061	0.141	0.169	0.150	0.177	0.753
	0.067	0.230	0.299	0.262	0.285	0.788
	0.203	0.239	0.284	0.251	0.307	0.801
	0.219	0.267	0.350	0.300	0.335	0.821
	0.232	0.271	0.342	0.306	0.332	0.827
	0.256	0.272	0.325	0.293	0.338	0.828
	0.265	0.275	0.331	0.293	0.357	0.845
	0.274	0.288	0.354	0.313	0.363	0.851
	0.274	0.292	0.359	0.318	0.365	0.88
	0.278	0.297	0.365	0.324	0.341	0.882
	0.28	0.300	0.364	0.317	0.382	0.89
	0.285	0.300	0.372	0.329	0.371	0.892
	0.296	0.306	0.358	0.326	0.387	0.912
	0.301	0.313	0.385	0.341	0.336	0.924
	0.307	0.337	0.414	0.367	0.411	0.935
	0.323	0.353	0.433	0.384	0.427	0.948
	0.337	0.418	0.528	0.463	0.413	1.427
CV Low/high	0.4557	0.277	0.275	0.274	0.262	0.146

CV Heermann		CV low/high
1	0.460	0.456
2	0.259	0.277
3	0.346	0.275
4	0.288	0.274
5	0.289	0.262
6	0.155	0.146

Appendix C Cont.

Data were obtained from Soil Conservation Service (SCS), St Joseph, Michigan, 1995, for field evaluation of center-pivot irrigation systems

Sample number	Distence ft	System 1 Depth 1 ml	System 2 Depth 2 ml	System 3 Depth 3 ml	System 4 Depth 4 ml	System 5 Depth 5 ml
1	30	0	214	59	83	90
2	60	120	50	80	104	105
3	90	130	70	60	91	140
4	120	120	190	60	70	140
5	150	90	105	64	85	97
6	180	84	154	60	64	56
7	210	82	88	56	78	75
8	240	136	80	51	75	74
9	270	110	80	59	76	76
10	300	234	116	54	70	91
11	330	118	69	54	78	84
12	360	120	82	60	70	40
13	390	116	82	55	70	56
14	420	104	89	58	72	55
15	450	108	89	38	74	68
16	480	98	73	44	70	69
17	510	97	92	58	74	48
18	540	122	80	59	70	43
19	570	100	72	55	67	63
20	600	112	80	60	70	62
21	630	120	81	49	59	62
22	660	172	80	20	80	57
23	690	180	85	40	73	69
24	720	210	96	65	59	79
25	750	216	93	63	46	56
26	780		95	16	10	60
27	810		87	0	8	56
28	840		92			55
29	870		93			61
30	900		104			56
31	930		88			62
32	960		91			60
33	990		96			61
34	1020		95			66
35	1050		78			57
36	1080		94			64
37	1110		92			64
38	1140		106			61
39	1170		85			56
40	1200		93			58
41	1230		87			69
42	1260		98			19

43	1290	87
44	1320	91
45	1350	98
46	1380	86
47	1410	124
48	1440	87
49	1470	112
50	1500	114
51	1530	107
52	1560	125
53	1590	100
54	1620	82
55	1650	58
56	1680	123
57	1710	98
58	1740	0

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