Sprinkler system installation and monitoring of plant microclimate
by Douglas John Oellermann

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Agricultural Engineering
Montana State University

Abstract:
A sprinkler irrigation system to irrigate 24 10 m. x 10 m. individual test plots of alfalfa and spring wheat at precise rates was designed and installed. This was accomplished by using quick coupler valves on the corner of each plot in conjunction with quick coupler keys using quarter-circle sprinkler heads. Plots could thus be selectively irrigated for any chosen duration of time. The offseason use of irrigation water was investigated, including late fall irrigation in spring wheat and alfalfa and early spring irrigation on alfalfa, as well as normal seasonal irrigation. Parameters monitored included daily maximum and minimum soil temperatures at 5 and 20 cm., soil moisture levels before and after irrigation during the growing season and monthly during the dormant season, crop yields and weather parameters such as daily maximum and minimum air temperatures, precipitation, solar radiation, wind run, relative humidity and standard pan evaporation. The project investigated the efficiency of storage of water in the off-season, the effects of off-season irrigation on soil temperature regimes and crop yield and possible energy or equipment savings by lengthening of the irrigation season. The relationship between spring wheat yield and total water applied during the 1977 season was evaluated. A second order regression equation with r2 = 0.7804 was determined which indicates that yield increases with increased water to a certain point, then decreases.

Some plots had a gross gain in water over-winter while others had a gross loss. No relationship could be established. The efficiency of irrigation water storage over-winter was calculated for the plots. The spring wheat plots had higher overall efficiencies than the alfalfa since the former were drier prior to fall,irrigation. Positive spring wheat efficiencies ranged from 43-65%. Alfalfa efficiencies were all negative with one exception, 25%. Negative efficiencies indicate more water was lost than was applied by irrigation. Fall irrigation is beneficial if the soil profile is dry prior to fall irrigation and spring precipitation and runoff are not excessive.

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ABSTRACT

A sprinkler irrigation system to irrigate 24 10 m. x 10 m. individual test plots of alfalfa and spring wheat at precise rates was designed and installed. This was accomplished by using quick coupler valves on the corner of each plot in conjunction with quick coupler keys using quarter-circle sprinkler heads. Plots could thus be selectively irrigated for any chosen duration of time. The off-season use of irrigation water was investigated, including late fall irrigation in spring wheat and alfalfa and early spring irrigation on alfalfa, as well as normal seasonal irrigation. Parameters monitored included daily maximum and minimum soil temperatures at 5 and 20 cm., soil moisture levels before and after irrigation during the growing season and monthly during the dormant season, crop yields and weather parameters such as daily maximum and minimum air temperatures, precipitation, solar radiation, wind run, relative humidity and standard pan evaporation. The project investigated the efficiency of storage of water in the off-season, the effects of off-season irrigation on soil temperature regimes and crop yield and possible energy or equipment savings by lengthening of the irrigation season. The relationship between spring wheat yield and total water applied during the 1977 season was evaluated. A second order regression equation with $r^2 = 0.7804$ was determined which indicates that yield increases with increased water to a certain point, then decreases. Some plots had a gross gain in water over-winter while others had a gross loss. No relationship could be established. The efficiency of irrigation water storage over-winter was calculated for the plots. The spring wheat plots had higher overall efficiencies than the alfalfa since the former were drier prior to fall irrigation. Positive spring wheat efficiencies ranged from 43-65%. Alfalfa efficiencies were all negative with one exception, 25%. Negative efficiencies indicate more water was lost than was applied by irrigation. Fall irrigation is beneficial if the soil profile is dry prior to fall irrigation and spring precipitation and runoff are not excessive.

Chapter 1

BASIS OF INVESTIGATION

As water becomes more and more valuable in man's daily life, every drop must be utilized to its maximum. Agriculture is in increasing competition with industry, recreation, wildlife, municipalities and many other interests for the use of a renewable, but annually finite resource. Even in the West, where irrigators have enjoyed almost exclusive use of the waters, industries, especially energy-related companies, are demanding and receiving rights to the use of these waters. Irrigators are increasingly efficient with their limited rights, due to modern sprinkler systems and better utilization of existing systems. By knowing the properties of the soils under irrigation and monitoring the soil moisture levels, they can apply the right amount at the right time.

There is always room for improvement to any system. One such improvement suggested is to utilize waters not normally used for irrigation. These are waters now going down the stream from fall and spring precipitation and early spring snow melt. Can fall and spring applied water be stored in the soil for seasonal use? What efficiencies can be attained? This thesis will address some of these questions.

STATEMENT OF PROBLEM

The problem is to determine the feasibility of off-season irrigation (i.e., late fall and early spring irrigations) on irrigated crops in relation to the disposition of off-season applied water in the soil profile, soil temperatures, climatic variables, system size and power requirements.

Storage of Irrigation Water

Can irrigation water applied during the off-season be stored for seasonal use? If it can be stored, it is important to know how much. Is it efficient? Water which is stored in the soil can be used as a reserve to draw upon during peak demand periods when the irrigation system cannot supply all of the crop's demands. This is analogous to a city water system when both the water reservoir and the pumping station supply the needs at peak use rates.

Effects on Soil Temperatures

Will soil temperatures be adversely affected? All crops have an optimum soil temperature at which they grow the best. Soil temperatures which are significantly lowered could have a harmful effect on the crop, reducing yields and thus adding to the cost of off-season irrigation.

Effects on System Size

Will a savings be realized by using a smaller system over a longer period of time, that is, both in-season and off-season? A smaller system will use less energy per hour, but the duration of use is longer. The same total amount of water for a certain crop still needs to be supplied, be it in-season, or off-season.

Climatological Effects

The variations of climate from one year to the next will certainly have significance on the practicability of off-season irrigation. What are the effects of a dry fall or a wet spring on this practice, or vice-versa? These questions need to be answered.

REVIEW OF SELECTED LITERATURE

In order to understand better what is known on the subject and to identify areas lacking in knowledge, several areas were reviewed. It is of interest to investigate research already done in such areas as the efficiency of storage of fall and spring applied water, the movement of water in the soil profile in all seasons, and the soil moisture requirements of crops and the effects of soil moisture stress on them. Also of interest are the optimum growing temperatures of crops, the effect of irrigation on soil temperatures and the specific effects of these variables on spring wheat and alfalfa, the crops to be grown in this experiment.

Storage Efficiencies

It is of primary interest to know how much water due to an off-season fall or spring (preseason) irrigation is stored in the soil and utilized. It has been found that carryover from fall to spring is affected by the soil moisture content (Timmons, 1968). Moreover, Hobbs (1971) states that the storage efficiency is inversely related to soil moisture content.

Fall irrigation. A variety of storage efficiencies have been found for fall irrigation. In Saskatchewan, Staple (1960) determined an efficiency of 37% on stubble fields while Timmons (1968) estimated that 1/3 of the total dormant season precipitation in Minnesota was stored. A similar 31% efficiency was found in a dry profile by Hobbs (1971). A late fall irrigation in Texas yielded a high 54% efficiency (Musick, 1971). Raney (1960) says that from tests made from 1953-57 in Kansas, he can conclude that fall irrigation is profitable in a dry fall.

It would appear that as much as 1/3-1/2 of water applied to a dry soil profile in the fall can be conserved over-winter. The amount conserved is a function of the soil moisture level at the time of irrigation.

Preseason irrigation. Preseason irrigation efficiencies are similar to those of fall irrigation. In order to increase efficiencies, Musick (1970) suggests cutting off seasonal irrigation at an early date, no later than early grain filling, to dry out the profile. As in fall irrigation, the efficiency was highest when the soil moisture content was lowest. Musick (1971) also states that low evaporative potential at the time of irrigation raised efficiencies. In this test, the efficiencies were believed to be affected by low soil permeability and difficulty of wetting the soil to a considerable depth. Musick (1970) found efficiencies of stored rainfall of 30-50% on dry soils to 10% on wet soils. A late spring irrigation yielded a 33% efficiency (Musick, 1971). He also states that preseason irrigation did not appreciably increase yields, but did delay the need for early seasonal irrigation one out of three years.

Again, 1/3-1/2 of spring applied water, be it rainfall or irrigation, was conserved in a dry profile. The efficiencies drop drastically in a wet profile, since the applied water is partly lost to deep drainage.

Soil Water Movement

Frozen soil. The effects and movement of water in the soil after fall irrigation through the winter season is of interest. It has been found that dry soils freeze deeper and faster than wet soils and that the former thaws upward while the latter thaws from both directions (Willis, 1961). The percolation rate of water in frozen soil decreases with increasing moisture content. When the soil is alternately frozen and thawed, there is no change in the percolation rate at 15 atmospheres pressure, an increase in the rate at field capacity and a decrease in the percolation rate at high moisture contents (0.1 atm.). The decrease at high moisture contents is believed due to the destructive effects of freezing and thawing on the soil aggregates (Hinman, 1973). Ferguson (1964) states that at depths in frozen soil as deep as 180 cm. and 235 cm., water held at low tensions (5 atm.) moved to the frozen zone from the unfrozen zone. For every centimeter of available water, a decrease of 0.22 cm. of stored water was found.

If the soil profile is below or equal to field capacity at the time of freezing in the fall, it appears that water may be frozen without deleterious effects.

Deep drainage. The movement of water in the soil profile should also be considered to help determine where the water losses occur. Miller (1971) ascertained that deep drainage decreased as evapotranspiration increased. In a 31-day field study, 6 cm. of water was lost to deep drainage in a 150 cm. profile. It was also found that there was an upward movement of water whose rate reached a maximum of

0.20 cm./day (Stone, 1973). Wilcox (1959) discovered that with increased depth, the total drainage increased, but the net rate of loss per meter decreased. Miller (1972) performed tests which showed a delay between the end of irrigation and the start of drainage. Van Schaik (1970) noted that on Chin loam and Cavendish loamy sand soils, much of the soil moisture loss over winter is due to the capillarity of the soil.

Soil Moisture Stress Effects on Spring Wheat and Alfalfa

What are the effects of soil moisture stress on a crop? Dubetz (1970) states that with increasing soil moisture in spring wheat, an increase in yield but a decrease in protein content was achieved. In alfalfa, lower temperatures and low soil moisture stress gave a higher yield and digestibility of alfalfa (Vough, 1971). Constant soil moisture stress has a tendency to lower the yield approximately as a linear function of the severity of stress. The magnitude of reduction of yield from occasional stress is dependent on the evapotranspiration rate, the severity of stress and most importantly, the physiological stage of growth of the plant. The most critical physiological stage is from flowering to maturity (Downey, 1972). Lucey (1965) found that for forage, the moisture absorption is greatest in the upper 15 cm. of soil. The absorption decreases when the soil moisture reaches less than 25-30%

of the available moisture and at a value of less than 15%, plant stress is apparent.

Since it is obvious that causing moisture stress during the reproductive stage of the plant reduces yields, one will have to be careful at which stage he cuts off irrigation in order to dry out the profile, as suggested by some investigators.

Optimum Soil Temperatures for Crop Growth

The application of off-season irrigation is expected to have an effect on soil temperature. Such changes may or may not have an adverse effect on plant growth. Various investigators have determined optimum temperatures for the growth of different crops. Mack (1965) found that barley, regardless of soil moisture, grew best at 18°C. For spring wheat, Mack (1973) determined a range of 10-18°C for optimum growth, while temperatures from 18-28°C significantly reduced yields. Sosulski (1966) reports that Thatcher wheat yielded more at 18°C than at 24°C. Smika (1974) tested two spring wheat varieties, Lee and Crim, and found a somewhat lower optimum soil temperature at crown depth, 12.5 and 14.5°C, respectively, than other investigators. Wheat emergence was 100% at 20-25°C while it was very low at 5°C (Singh, 1972). In yet another experiment, Boatwright (1976) found that spring wheat has an optimum surface soil temperature (0-3 cm.) of 19-22°C. At less than these temperatures, yields were reduced significantly. He further states that the crown seems to be the most sensitive part of the plant to low soil temperatures. For barley, Power (1963) determined an optimum temperature of 15°C. Alfalfa, subjected to day and night temperatures of 18° and 10°C, respectively, gave higher yields than when under a 32/24°C regime (Smith, 1969).

For spring grains, a mean optimum temperature of 18°C appears to be the best. A wide range was found which resulted in optimum temperatures from 10-25°C. Alfalfa has not been tested as extensively but a reasonable value would also be in the 18°C range for optimum growth.

Soil Temperature Changes Due to Irrigation

Several investigators have measured soil temperature changes due to irrigation. At a 10 cm. depth, soil irrigated daily was 2°C below that of a soil which had been irrigated one week earlier (Kohl, 1973). Wierenga (1971) states that soil temperatures at 5 and 10 cm. depths were affected for less than 24 hrs. by warmer (27°C) and cooler (14°C) irrigation water. At a depth of 30 cm., the effects of the cooler and warmer water lasted less than 60 hrs. He also found that soil temperatures were reduced by evaporative cooling in mid-April but not in mid-February. He concludes that early spring irrigation would delay warming of the soil profile. In New York on forest soils, Leonard (1971) measured the effects of water which was 0-5.5°C warmer than the surface temperature. He found, at the 300 cm. depth, that the soil warmed to 10°C 1-1½ months sooner than nontreated areas and the soil cooled to 10°C about one week later than non-treated areas.

The effects of water temperature on the soil temperature depends on whether the water is of a higher or lower temperature than the soil. Using warm water warmed up the profile sooner while cooler water will tend to delay warming of the profile. This needs to be investigated more thoroughly.

Cultivation and Irrigation of Crops

Alfalfa. The irrigation and cultivation of alfalfa and spring wheat is important to understand. Ditterline (1976) recommends an irrigation on alfalfa in Montana before fall freezeup and 2-3 seasonal irrigations. He adds that an irrigation early in the spring is desirable unless there is available moisture. However, another investigator states that the first spring irrigation should be delayed until the soil warms up (Stanberry, 1955). Daigger (1970) found that, in western Nebraska, the average evapotranspiration ratio over a three-year period was 680. It was found that the first cutting was most profitable. Daigger recommends filling the soil profile to a depth of 2.5 m. early in the season. Evapotranspiration varies throughout the season and it is thought that it increases from early spring to late spring, then decreases through the summer. Advection, the horizontal movement of drier air over a crop, is an important factor which contributes to the late spring peak (Rosenberg, 1969). With three different levels of irrigation through three seasons in southern Alberta, Krogman (1965) determined evapotranspiration rates of 0.31-0.91 cm./day with an average of 0.51 cm./day. Ditterline (1976) emphasizes the importance of avoiding severe soil moisture stress in alfalfa while permitting slow, steady growth. With water in the soil profile immediately before freezeup, heaving of the soil may be a problem. Stanberry (1955) states that winterkilling is dependent on variety, plant vigor, the soil moisture and soil type. Soils which are fine-textured and saturated heave plants, leaving them exposed to low temperatures and dessication. In well-drained soils, the problem of heaving is less serious. Holmes (1960) determined that the severity of heaving at Ottawa, Canada, increases with alternate thawing and freezing, which moves water to the soil surface. A layer of snow is good protection against occurrences of this type. In a poorly drained soil in Illinois, Portz (1967) found that damage due to heaving was moderate to severe in a moderate winter. Soils at or near field capacity seemed to be more susceptible.

If a soil is well-drained where heaving is not a problem, fall irrigation may be feasible. Early spring irrigation may also be desirable if there is a shortage of water in the profile to take advantage of efficient water use by alfalfa early in the season.

Spring wheat. Early spring irrigation of spring wheat at Pullman, Washington, prior to the boot is not economical unless wilting is evident, according to Robins (1962). It has been recommended to irrigate winter wheat in the fall to a depth of 180 cm., thereby avoiding early spring (March and April) irrigation (Grimes, 1962). He further states that irrigation is beneficial at the boot stage if rainfall is below normal and is especially necessary at the milk stage in extremely dry years. Dougherty (1974) arrived at a rather surprising conclusion that irrigation of wheat in New Zealand just before and after ear emergence reduced yields. Robins (1962) reports that moisture stress caused yield reductions of 10-35% and was maximum during and after heading. He adds that the soil moisture should not be totally depleted before maturity. El Nadi (1969) supports this finding in reporting from the Sudan that flowering, grain filling and maturation are more sensitive to moisture stress than the vegetative phase of plant development. In comparing one fall irrigation with one spring irrigation, Koehler (1974) reports that the latter yielded 9 q/Ha. more than the former at Pullman, Washington. Raney (1960) recommends early spring irrigation on winter wheat during a dry spring in north central Kansas. However, he adds, care must be taken to prevent lodging if rainfull should occur after irrigation.

It appears to be questionable if early spring irrigation of spring wheat is desirable. Most investigators do not recommend it save in case of a severe water shortage because of the delay in warming the soil profile. Fall irrigation may be a better alternative. Hobbs

(1971) notes that at Vauxhall, Alberta (p. 17):

> Spring irrigation is not feasible throughout most of the area because water is not available in the distribution systems. It is also difficult to irrigate uniformly and adequately the bare soils of unseeded or newly seeded fields. Consequently, in the irrigated areas of the Canadian prairies, if fall soil moisture content is in the lower half of the available range, it is advisable to fall-irrigate.

Musick (1971) says of preseason irrigation on sorghum on the southern High Plains of Texas (p. 97):

> Preseason irrigation did not influence grain yields appreciably where all treatments received the same two or three seasonal irrigations. Preseason irrigation, which increased total irrigation-water application by one-fourth to one-third, was inefficiently used for grain production and reduced the water use efficiency of total irrigation water applied.

Soil Moisture Depletion--Jensen Equation

Numerous equations have been formulated to predict soil moisture depletion. Jensen (1969) developed one such equation based on four parameters: (1) daily minimum and maximum air temperatures, (2) daily solar radiation, (3) average dew-point temperature at 8:00 a.m., and (4) daily wind run at a known height. He states that in the absence of parameters 3 and 4, a two-parameter equation based on parameters 1 and 2 can be used if advection is not severe.

Conclusion

From previous research, most areas of interest to the present project have been investigated to some extent. The question of seasonal carryover has been partially answered. Whether the efficiencies already determined are high enough to make off-season irrigation economical remains to be seen. Much work has to be done yet in determining the effects of lowered soil temperatures on crops. Some work has been done on optimum temperatures for crops and on the changes on soil temperature due to irrigation, but a combination of the two effects has not been studied. Findings seem to indicate that irrigation system size may not be affected to a large extent, but this needs to be determined more thoroughly. With the data from the experiment, some of the now-unanswered questions should be satisfied.

DEFINITIONS

Available moisture--Total soil moisture available for plant use as determined by the difference in measured soil moisture level and wilting point.

Efficiency of over-winter storage--The amount of fall-applied water stored in the soil profile over-winter divided by the total amount of fall irrigation, multiplied by 100.

Field capacity--Moisture content of soil after gravitational water is removed, usually two days after irrigation.

Gain-ratio--The ratio of precipitation stored in the soil profile to the total precipitation received during a period.

Late fall irrigation--Application of water to the soil after removal of the crop and before freezing with the intent of storing a portion of the water over-winter for seasonal use.

Preseason irrigation--Early spring irrigation after thawing of the soil profile but before active growing of the crop, with the intent of storing a portion of the water for seasonal use.

Soil profile--The portion of the soil from which the roots of the plant actively withdraw water.

Wilting point--Moisture content of soil at which plants can no longer remove water.

Chapter 2

PROCEDURES

The experimental procedures and physical characteristics of the project need to be outlined to gain a better understanding of the basis for the results of the experiment. These include the location, soil properties, plot layout, irrigation system and instrumentation to monitor soil moisture, soil temperatures and climatological variables.

LOCATION AND SOIL PROPERTIES

The site selected for the experiment is on the Montana State University Field Research Laboratory farm located six miles west of Bozeman, Montana, on U. S. Highway 191. The soil is an Amsterdam silty clay loam with an approximate slope of 1-2% in a northerly direction. The characteristics of the soil are given in Table 1, p. 17.

DISPOSITION OF PLOTS AND TREATMENTS

The two crops grown were alfalfa and spring wheat in plots measuring 10 meters by 10 meters. Three different irrigation treatments were applied to the alfalfa plots with three replications of each treatment, resulting in nine plots of alfalfa. The spring wheat plots received five different treatments, three replications per treatment, for a total of fifteen plots. The treatments for the spring wheat and alfalfa are summarized in Table 2, p. 18. These plots were laid out

Table 1

Water Holding Properties and Bulk Densities of Amsterdam Silty Clay Loam at Research Site

Depth, cm.	Field Capacity, %	Wilting Point, %	Bulk Density
30	22.9	11.7	1.27
60	22.4	10.4	1.25
90	22.4	9.2	1.24
120	24.0	12.4	1.27
150	23.0	12.2	1.24
180	21.4	10.0	1.24
210	19.0	8.5	1.24