On-Farm Irrigation Scheduling Evaluations in Southeastern North Dakota

E. C. Stegman, Professor
Agricultural Engineering Department
North Dakota State University
CONTENTS

INTRODUCTION .............................................. 5
METHODS .................................................. 5
RESULTS
  Water Management Effects .................................. 7
  Crop Water Use ........................................... 10
  Corn Yield Trends ......................................... 10
  Seasonal Irrigation Requirements ......................... 16
  Root Zone Drainage ....................................... 16
  Corn Yield Relationship to Water Use ...................... 16
  Off-season Storage of Precipitation ....................... 17
SUMMARY .................................................... 17
REFERENCES ................................................ 17
On-Farm Irrigation Scheduling Evaluations in Southeastern North Dakota

E. C. Stegman, Professor
Agricultural Engineering Department
North Dakota State University

Introduction

Irrigation scheduling implies the use of a methodology for determining when to irrigate and the amount of water to apply during each period of water application. Many methods are available. Some rely on instruments for sensing soil or plant parameters that are indicators of water stress. Others utilize models for estimating the day-to-day progress of soil water level in given irrigated fields, and inputs are mostly in the form of weather data and crop information. With these latter methods and the rapid data processing capabilities of computers, large scale irrigation scheduling is possible. Jensen (1969) developed an applied water balance model and he subsequently introduced the concept of an irrigation scheduling service. This concept brings the professionally trained and experienced irrigationist to the farmer on a continuing basis and it makes possible a rapid transference of new technology to the points of application. Commercial scheduling consultants began their operation in the western United States. Scheduled area on an individual field basis has grown from less than 40,000 ha in 1971 to about 300,000 ha in 1978 (Jensen, 1979).

A trial scheduling service was begun by the author in 1973 to help provide an impetus for this form of scheduling in North Dakota. Methods for estimating evapotranspiration (ET) have been calibrated via the development of crop coefficient curves (Stegman, et al. 1977). These curves are in use by consultants now operating in North Dakota and western Minnesota. This study also has resulted in the development of a simplified water balance scheduling procedure that is called the "checkbook method" (Lundstrom and Stegman, 1977). This method is available to individual operators who desire to do their own irrigation scheduling.

The report that follows summarizes additional data that were taken during the conduct of this trial service.

Methods

A trial irrigation scheduling service was operated with cooperating farmers in the Oakes and LaMoure area. Cooperative fields have been numbered between four and six per season and numbers of scheduled fields have averaged near 15. The principal irrigated crops were corn, alfalfa, wheat, barley, pinto beans, sunflowers, navy beans, and potatoes.

Farms were selected to represent a range of soils. Principal soil series in the various fields were Hecla, Hamar, Emden, Perella, Maddock, Renshaw, Gardena, Claire, Arvilla, Glyndon, Tiffany, and Fordville. Water holding capacities to 120 cm depths in these soils range from less than 7.0 cm to over 20.0 cm. Basic intake rates range from about 1.0 to over 5.0 cm/hr.

Input data were obtained from and scheduling information was supplied to each cooperating farmer on a weekly basis from about the date of planting to mid-September of each season. Rainfall and irrigation data were supplied to the service by having farmers telephone their data to a recording system each Monday morning. Weather data (daily maximum and minimum temperature and solar radiation) were obtained from an observation site at the NDSU Oakes field trials site (located 7.2 km south of Oakes, ND). These data were then processed with a computerized water balance model (Stegman and Valero, 1972) to produce new scheduling recommendations for each field.

Scheduling recommendations were provided to each farmer via a postcard which was mailed each Monday afternoon or Tuesday morning. This postcard (see Figure 1) indicated: (1) the current allowable soil water depletion for the coarser textured soils in each field, (2) the updated estimate of soil water deficit, and (3) the projected increase in soil water deficit with time assuming no rainfall in the forthcoming period. This latter projection also reflected the net irrigation amount that would be required in the forthcoming period just to satisfy crop need.

Farmers were instructed to begin irrigation when the projected soil water deficit approached the indicated allowable depletion. If rainfall occurred they were to decrease the soil water deficit by the amount of rainfall on the date of each occurrence. Then, from this new estimate of soil water deficit they could re-project the increase in deficit with time by paralleling the initial projection line as is illustrated in Figure 1. This approach proved to be an instructive method by which farmers could manually adjust an issued schedule for rainfall; a very significant water balance input in the North Dakota climate.

Sites were established in each field for measurement of soil water deficits to 120 or 150 cm depths. Initial measurements determined the starting deficit levels for the water balance computations. Subsequent measurements were made at 7 to 14 day intervals to monitor the service and to obtain crop water use and phenologic data. The neutron probe served as the primary method for moisture measurement. Tensiometers were occasionally used. Additional sampling was done with hand probes (Oakfield type) and deficits were estimated by the feel or appearance method.

Rainfall and irrigation amounts were measured at the soil moisture sampling sites. Raingauges of the test tube type were placed in stands that could be extended to maintain location above the crop canopy. Evaporation was suppressed by adding kerosene each time the gauges were read.

Crop yields and other agronomic data were obtained from each cooperating farm at the end of each season. Guidance relative to agronomic and cultural practices was not a strong emphasis of the service. Farmers were encouraged to soil test and fertilize for their yield goals. Part of the nitrogen fertilizer commonly was applied with the irrigation water. Guidelines for control of weeds, insects, diseases, etc., were primarily provided via NDSU Cooperative Extension Service workshops that were periodically conducted in the area.

Non-weighing lysimeters were installed in some fields in 1976 to obtain samples of root zone drainage. Lysimeters were located in Hecla, Renshaw, Maddock, and Claire soil series near Oakes and in a Lohnes series near Karlsruhe, ND. The lysimeters were installed by hand excavating 117 cm diameter holes to depths of 150 cm below the ground surface. A waterproofed steel pan of 114 cm diameter and 30 cm wall height was placed at the bottom of each hole. A porous cylinder for water extraction was placed within a coarse (pea-rock) gravel layer at the bottom of the pans. The cylinder was connected to a butyl rubber tube of sufficient length to
FIGURE 1. Example of post card mailed to farmer each week indicating allowable deficit, estimated deficit as of first day in the period, and the projected water use rate for the next 14 days. Also illustrated is an assumed adjustment in projected deficit as resulted from rainfall on June 8. A new card was sent out each week.

FIGURE 2. A soil water deficit (SWD) regime that was typical of inexperienced irrigators, showing a tendency toward inadequate irrigation.
reach the ground surface. The side walls of each excavation were lined with nylon reinforced plastic from pan level to about the plow depth below ground surface. An access tube for soil moisture measurements was placed at the center of each lysimeter. The lysimeters were backfilled with disturbed soil but care was taken to replace the profile by horizons that were consistent with the surrounding natural soil. Compaction was achieved by hand tamping.

Results

Water management effects:
A post season analysis of soil water deficit (SWD) versus time was a primary method for evaluating the degree of water management that was likely attained in given fields. Day-to-day soil water deficits were estimated with the relationship:

\[ \text{SWD}_d = \text{SWD}_{d-1} - P_i - IR_i + ET_i + DR_i \]  

where \( \text{SWD}_d \) = soil water deficit on day \( d \), cm; \( \text{SWD}_{d-1} \) = soil water deficit on day \( d-1 \), cm; \( IR \) = net irrigation depth, cm; \( ET \) = daily evapotranspiration estimate, cm; and \( DR \) = root zone drainage, cm.

The water balance computation was begun at or near crop emergence. Initial SWD was based upon measured deficits at soil moisture sampling sites. ET was calculated with the 1963 equation and crop coefficient (\( k_c \)) curves that were developed for each season from neutron probe and associated water balance data. Daily ET estimates were additionally adjusted for water stress and wetness of soil surface effects with computational procedures of Jensen et al. (1970). Drainage losses (DR) were accumulated whenever rainfall or irrigation amounts exceeded the prevailing soil water deficit.

Figure 2 illustrates a SWD regime that was quite typical of the attained degree of water management with the first year irrigator. The tendency was to under-irrigate, probably because the beginning irrigator is preconditioned to think in terms of the rainfall that is available for rainfall in the period when it is usually most abundant. Studies (Stegman and Aflatouni, 1978) at the Oakes field trials station have indicated, that when the SWD begins near zero at planting, the subsequent storage depletion can safely approach 60-70 percent in the vegetative period. Thereafter, in the reproductive period, irrigations should be increased to reduce the SWD (like in Figure 6). High soil water levels, particularly in the surface 30 cm, are needed to prevent yield reducing stress. Total water supply must be sufficient to meet evaporative demands. In the latter season (after soft dough in small grains, early dent in corn) irrigations can be reduced. However, SWD should not approach excessive levels before crop physiologic maturity. If rainfall and irrigations significantly reduce the root zone water deficit in the reproductive period (like in Figure 6), then subsequent irrigations can be reduced in a programmed manner. SWD can approach a 50-60 percent depletion of the available water capacity.
FIGURE 3. Measured soil water suction vs. time in the field associated with Figure 2.

FIGURE 4. A soil water deficit regime that typically resulted in highest yields. SWD tended not to exceed 40 percent of the root zone available water capacity and irrigation amounts were sufficient to meet crop ET rates.
FIGURE 5. A soil water regime that produced a high (5.5 T/HA) wheat yield. SWD was not reduced to zero nor allowed to increase with time. Irrigations plus rainfall were therefore sufficient to satisfy ET. The soil profile throughout the season had a storage capacity for about 5 cm of rainfall.

FIGURE 6. A soil water regime that resulted in a high (7.5 T/HA) barley yield. Irrigations were limited in early vegetative period as root zone advanced into zones well supplied with water. Irrigations reduced the SWD to low levels in the critical heading to soft dough period.
In this case, a wheat field was sufficiently irrigated until half of the root zone available water capacity before crop water needs. The high soil water depletions caused reduced crop water use rates and less than potential yield. In fields where soil textures are very coarse, the soil profile water content should be brought to high levels before cutting and then the harvest period should be kept as short as possible.

Figure 9 illustrates a frequently observed SWD regime when a center pivot system is used to irrigate two fields. In this case, a wheat field was sufficiently irrigated until mid-July or about the early soft dough stage. In the second field, spring rains and off-season precipitation storage provided adequate water for a near potential first cutting of alfalfa. However, soil water deficit increased rapidly in the subsequent period to completely exhaust the root zone available water capacity before the second cutting. Little regrowth took place until the irrigation system was moved. Total yield from the alfalfa field was well below potential. Near optimum economic return for this type of center pivot management requires an adequate pumping rate, soils with medium to high water storage capacity, and the willingness of operators to move their systems as required to satisfy crop water needs.

Crop water use:

Table 1 summarizes seasonal evapotranspiration (from emergence date to physiologic maturity) estimates for the regularly grown crops. These data were estimated with the previously described methods for equation 1.

Seasonal water use averaged 50.3 cm for corn, 63.5 cm for alfalfa, 39.9 cm for wheat, 36.8 cm for barley, 43.2 cm for pinto beans, and 44.7 cm for sunflowers. Highest use occurred in the driest season (1976) with ET estimates averaging 55.4, 68.6, and 43.6 cm for corn, alfalfa, and wheat, respectively.

The average seasonal distribution of corn ET rates and the 1976 season distribution are given in Figure 10 as functions of time after crop emergence. ET rates for corn typically averaged near 0.1 cm/day at emergence. On average, the ET rate peaked near 0.64 cm/day at 65-75 days after emergence and then it declined gradually to near 0.25 cm/day at about 110 days after emergence. For a center pivot area of 53.4 ha and an application efficiency of 80 percent, the average peak ET rate equals a 46.9 l/sec pumping rate. At the peak ET rates of the 1976 season (Figure 10), the daily water loss equaled a 64.6 l/sec pumping rate for a standard center pivot area.

The ET distributions in Figure 10 show peak ET rates do not persist for very long during the season and that wide day-to-day fluctuations also occur. Thus, the actual adequacy of a particular pumping rate is affected by the weather, irrigation scheduling, the available soil water holding capacity, and the crop sensitivity to stress. Rainfall effects are perhaps best evaluated by simulating irrigation programs over periods of many seasons. Figure 11 demonstrates a simulated SWD regime that could have been attained with a 50.5 l/sec pumping rate in the 1976 season. Associated assumptions were: crop = corn, available soil water holding capacity = 14.0 cm, safe allowable depletion = 5.1 cm, and water application efficiency = 85 percent. The SWD regime suggests this pumping rate was successfully managed to maintain less than a 5.1 cm deficit. The associated seasonal ET accumulation was estimated at 59.4 cm, only 1.3 cm less than for a simulation with a much higher pumping rate. However, the system operated almost continuously (note, each field revolution took 3 days) from day 65 to day 123. If operating time had been lost due to system breakdown, some yield loss would have been likely.

Further simulations (Stegman and Ness, 1974) were run for a 37 year period of weather record from 1929 to 1965 at Oakes, ND. Seasonal soil water deficit regimes were computed for assumed combinations of variables and pumping rate adequacy was estimated by computing likely ET deficit accumulations. ET deficits were summed during each simulation when soil water deficits limited ET rate. Results of this simulation study are given in Figure 12, wherein, pumping requirements can be estimated as a function of allowable soil water depletion between irrigations. For example, if for the soils in a given field the safe allowable depletion is estimated at 5.0 cm, a 44.2 l/sec pumping rate (assumes 53.4 ha system) can likely be scheduled to achieve near zero seasonal ET deficits in 90 percent of the years. In coarser textured soils with only a 2.5 cm allowable depletion, the pumping rate should be increased to about 53.6 l/sec. An assumption associated with these results is that center pivot systems can be operated for 24 hours per day without interruption. The probabilities of successful management are lower for given pumping rates if part time shutdown is necessary to reduce peak electric energy demand.

Corn yield trends:

The trend in average corn yields for the scheduled farm fields is compared in Figure 13 with the corresponding yield trend (averages for hybrid trials) for the Oakes field trials site. The two trend lines exhibit a similar pattern. Both show a decline in the 1974 season yield from the 1973 level. This result was believed due to a cool August (2.8°C below normal) and an early frost on September 3 in the 1974 season. The 1975 season yield at the Oakes Station recovered to about the 1973 level, whereas the farm average continued to decline. This latter result was believed due to a low average application of N (see Figure 14) and the occurrence of three large rainfall events of nearly 10 cm each during this growing season. Considerable N was likely leached.

Figure 13 shows a sharp upward trend in the 1976 and 1977 season for both the farms and the Oakes field trials site. Weather conditions in these two seasons were very favorable to corn production, i.e., early springs, warm summers, and long frost free growing seasons. Production practices on the farms also improved noticeably with time.

Farm yields in the 1978 season about equalled the 1977 yields, and a slight decline occurred in the 1979 season. This reduction appears attributable to a somewhat lower
FIGURE 7. A soil water regime that frequently occurs when center pivot pumping rate is insufficient to satisfy mid-season ET rates. Yields can be near potential if SWD is near zero in early season, soils are deep, and irrigations are frequently applied.

FIGURE 8. A soil water regime in an alfalfa field where harvest period was excessively long following each cutting. Deficits approached complete exhaustion of available water holding capacity.
FIGURE 9. A soil water regime that is frequently observed when a center pivot system is towed between two fields. In this case, soil water was excessively depleted before the system was moved to this field. Total yield was considerably reduced from potential.

TABLE 1. ESTIMATED SEASONAL EVAPOTRANSPIRATION (EMERGENCE-MATURITY) FOR OAKES SCHEDULED FARMS (1973-1979)

<table>
<thead>
<tr>
<th>CROP</th>
<th>AVERAGE</th>
<th>HIGHEST SEASON</th>
<th>LOWEST SEASON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>50.3 cm</td>
<td>55.4 cm</td>
<td>45.7 cm</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>63.5 cm</td>
<td>68.6 cm</td>
<td>61.0 cm</td>
</tr>
<tr>
<td>Wheat</td>
<td>39.9 cm</td>
<td>43.7 cm</td>
<td>37.1 cm</td>
</tr>
<tr>
<td>Barley</td>
<td>36.8 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pinto Beans</td>
<td>43.2 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sunflowers</td>
<td>44.7 cm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FIGURE 10. Seasonal ET distribution for irrigated corn in SE North Dakota.
**FIGURE 11.** A soil water deficit regime as generated by a simulation model to estimate the likely adequacy of a 50.5 L/sec center pivot pumping rate for the indicated combination of variables.

<table>
<thead>
<tr>
<th>Q</th>
<th>Rev. time</th>
<th>Net applic.</th>
<th>AWHC</th>
<th>Dep.</th>
<th>ΣET</th>
<th>Revs</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.5 L/s</td>
<td>3 days</td>
<td>2.1 cm</td>
<td>14.0 cm</td>
<td>5.1 cm</td>
<td>59.4 cm</td>
<td>24</td>
</tr>
</tbody>
</table>

Location - Oakes, ND  
Year - 1976  
Crop - Corn

**FIGURE 12.** Center pivot pumping requirement as a function of allowable soil water depletion between irrigations. The curves indicate pumping rates that would likely be required to achieve near zero seasonal ET deficits in 50, 90, or 95 percent of the years if the system is properly managed.

IRRIGATED AREA = 53.4 HA  
APPLICATION EFFICIENCY = 85 PERCENT

- 53.6 L/s  
- 44.2 L/s  
- 41.0 L/s

95% PROBABILITY  
90%  
50%
FIGURE 13. Comparison of corn yields for the scheduled farms vs. yield levels at the Oakes Field Trials Station.

FIGURE 14. Average corn yield vs. average applied Nitrogen (NO₃) Fertilizer for the scheduled farms.
TABLE 2. GROSS APPLIED IRRIGATION AMOUNTS FOR OAKES SCHEDULED FARMS
(1973-1979)

<table>
<thead>
<tr>
<th>CROP</th>
<th>AVERAGE</th>
<th>HIGHEST SEASON</th>
<th>LOWEST SEASON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>34.8</td>
<td>49.5</td>
<td>22.4</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>46.5</td>
<td>61.0</td>
<td>28.2</td>
</tr>
<tr>
<td>Wheat</td>
<td>19.1</td>
<td>32.3</td>
<td>6.1</td>
</tr>
</tbody>
</table>

TABLE 3. SEASONAL DISTRIBUTION OF GROSS WATER APPLIED ON CORN—OAKES SCHEDULED FARMS
(1973-1979)

<table>
<thead>
<tr>
<th></th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.4 cm</td>
<td>6.3 cm</td>
<td>16.4 cm</td>
<td>13.0 cm</td>
<td>0.8 cm</td>
</tr>
<tr>
<td>3.8</td>
<td></td>
<td></td>
<td>19.3</td>
<td>19.8</td>
<td>2.5</td>
</tr>
</tbody>
</table>

1973-1979 averages over all farms for each month
Highest observed average over all farms for each month

TABLE 4. ESTIMATED GROWING SEASON ROOT ZONE DRAINAGE LOSS FOR OAKES SCHEDULED FARMS (1974-1979)*

<table>
<thead>
<tr>
<th>CROP</th>
<th>AVERAGE</th>
<th>HIGHEST SEASON</th>
<th>LOWEST SEASON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>6.9 cm</td>
<td>16.3 cm</td>
<td>2.3 cm</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>4.6</td>
<td>13.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Wheat</td>
<td>3.6</td>
<td>7.6</td>
<td>0.0</td>
</tr>
</tbody>
</table>

* Estimates based upon computed water balance

TABLE 5. MEASURED DRAINAGE IN NON-WEIGHING LYSIMETERS FOR OAKES SCHEDULED FARMS (1976-1979)

<table>
<thead>
<tr>
<th>NO. OF SITES</th>
<th>CROP</th>
<th>AVE. ANNUAL</th>
<th>HIGHEST SEASON</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WATER LOSS</td>
<td>NO₃-N LOSS</td>
<td>WATER LOSS</td>
</tr>
<tr>
<td>3</td>
<td>Corn</td>
<td>8.6 cm</td>
<td>3.5* kg/ha-cm</td>
</tr>
<tr>
<td>1</td>
<td>Alfalfa</td>
<td>3.0</td>
<td>1.0**</td>
</tr>
<tr>
<td>1</td>
<td>Wheat</td>
<td>6.1</td>
<td>0.3***</td>
</tr>
</tbody>
</table>

* Lysimeters located in Claire and Lohnes series
** Lysimeters located in Maddock series
*** Lysimeters located in Emden series
average N application relative to the 1978 season, a tendency towards reduced irrigation as a reaction to rapidly escalating pumping costs, and a season with less potential evapotranspiration than the 1977 or 1978 years.

For the last four years (1976-1979) corn yields averaged near 11.2 T/ha at the Oakes site and 8.2 T/ha for the scheduled fields, or a field to plot ratio of 0.73. In the earlier 1972-1975 period, the farm yields are believed to be reasonably typical of beginning farmers who were learning the production practices attendant to irrigation farming.

Seasonal irrigation requirements:
Season irrigation amounts (Table 2) averaged 34.8, 46.5, and 19.1 cm for corn, alfalfa, and wheat, respectively. Rainfall in the May-September period averaged near the long term mean of 31.1 cm, thus these irrigation amounts probably represent average needs. Highest amounts were applied in the 1976 season, averaging 49.5, 62.7, and 32.3 cm for the corn, alfalfa, and wheat crops, respectively.

The seasonal distribution of applied water to corn is illustrated in Table 5. Irrigation requirement averaged less than 1.4 cm in either May or September. The peak requirement occurred in July and averaged 16.4 cm. The “highest” observed averages by months are also given. These data indicate water need can approach 20 cm of gross irrigation in both July and August.

Root zone drainage:
The water balance procedure of equation 1 assumes that drainage losses will occur when rainfall or irrigation amounts exceed the prevailing SWD. No attempt was made to separate excess water into components of surface runoff and root zone drainage. Rather, all losses were assumed to be drainage. This assumption is believed to be realistic because the scheduled fields did not have defined surface drainage systems. Most surface water during high intensity rainfall tended to collect in closed depressions for subsequent infiltration.

The estimated drainage losses over the emergence to physiologic maturity time period averaged 6.9, 4.6, and 3.6 cm per season for corn, alfalfa, and wheat crops, respectively (Table 4). The 1975 season, with three very large rainfall events, produced the highest losses. Average losses in this season were estimated at 16.3, 16.5, and 17.6 cm for these three crops.

The drainage loss of NO₃-N losses from the non-weighing lysimeter sites in the 1976-1979 period are summarized in Table 5. Drainage losses, although for different periods, are in reasonable agreement with the estimated losses in Table 4. NO₃-N losses from three sites that were in continuous corn averaged 3.5 kg/ha-cm of drainage. In the season with highest water loss, the average NO₃-N loss was 4.4 kg/ha-cm. Much lower losses are indicated in Table 5 for either alfalfa or wheat.

It should be noted that the lysimeter sites represent a very limited sampling of the potential drainage loss. The three sites in continuous corn were located in coarse textured Claire and Maddock series near Oakes and in a Lohnes series near Karlsruhe. Much lower losses would, therefore, be expected from finer textured soils. The average seasonal NO₃-N loss (8.6 cm x 3.48 kg/ha-cm) under corn of 30.0 kg/ha does compare favorably with the 30-35 kg/ha range that was reported by Watts et al. (1978) in Nebraska studies involving sandy soils.

Corn yield relationship to water use:
For given seasons, experimental water regimes frequently demonstrate that corn grain yield is linearly related to the accumulated seasonal ET. This linear relationship is also indicated in Figure 15 for the observed farm yields and corresponding estimates of seasonal ET. Data points for the 1976, 1977, and 1978 seasons predominate near the top of this relationship, thus indicating the seasons with greatest ET potential produced the higher yields. The considerable Y vs. ET variation tends also to show that some fields were less than adequately irrigated.

The slope of the yield vs. ET relationship in Figure 15 is estimated at 0.27 T/ha-cm. If represented on a relative scale of Y/ETₜₐₓₑₚₛₛ vs. ET/ETₜₐₓₑₚₛₛ, this relationship indicates a 1.6 percent yield decline is likely per one percent decline in seasonal ET from the ETₜₐₓₑₚₛₛ potential. This degree of yield sensitivity to ET stress compares favorably with data from the Oakes field trials site (Stegman and Aflatouni, 1978).

A second curve in Figure 15 illustrates the probable relationship of corn yield to total water supply. This curve separates from the Y vs. ET relationship by the amount of non-ET losses. These losses were estimated to equal 15 percent of the gross seasonal irrigation amount plus the estimated seasonal root zone drainage loss.

When analyzed from a water management perspective the Y vs. ET relationship indicates yield will increase until sufficient water is supplied to attain the ETₜₐₓₑₚₛₛ for a given season. Irrigations, if sufficient in amount and properly timed to minimize water stress, make an ETₜₐₓₑₚₛₛ attainment possible. However, the second curve in Figure 15 shows that non-ET losses typically increase as more and more water is applied. At some point, an additional increment of water no longer returns its cost of application. A breakeven point occurs on the second curve (for unlimited water supply) at the point where the slope of the applicable price ratio (P₁RR/P₁Y) becomes tangent to the curve. P₁RR equals the variable cost of water application and P₁Y equals the unit crop price. Price ratio slopes have inherently been flat, thus, with center pivot systems profit generally increases with increased water application until yields approach the Yₜₐₓₑₚₛₛ potential. This is because non-ET losses are typically not excessive with these systems.

Price ratio slopes are illustrated in Figure 15 for assumed variable costs of water application equaling $2.91/ha-cm and $5.83/ha-cm and a unit price for corn of $7.50/MT. Tangency points of the price ratio slope with the second curve indicate that the normal non-ET losses are low enough to justify irrigating for yields near the Yₜₐₓₑₚₛₛ level. Efficient scheduling of irrigations is, however, desirable because relative profitability improves substantially as non-ET losses are reduced.

One can argue that with increasing energy costs the price ratio slope will increase thus tending to lower the optimal depth of water application. Skogerboe et al. (1979), however, also argue that the price of water can usually only rise a small amount without a rise in price received for the crop before irrigation simply becomes uneconomical. This is because irrigation farmers, like other farmers, operate on sufficiently slender margins so that the price ratio cannot increase substantially without irrigation becoming uneconomical. Thus, as price of water application escalates, so must selling price of the crop or other ways must be found to maintain a rather flat slope of the price ratio such as by improving scheduling efficiency, reducing pressure or head on pumped water, improving system application efficiency, maintaining high pump efficiency, reusing tail water, producing higher value crops, etc.
Off-season storage of precipitation:
Non-growing season precipitation in the period from September 30 to May 1 averages about 15.5 cm in the Oakes area. In the 1973-1979 period of this study, the non-growing season precipitation averaged 17.5 cm. The potential root zone recharge was analyzed by comparing the estimated soil water deficits in the fall with the beginning deficits in the following spring near date of crop emergence. Figure 16 illustrates the average recovery or reduction in deficit that was observed following corn. The plotted points indicate the average deficit recovery as a percentage of the fall deficit when in crop emergence. Figure 16 illustrates the average recovery or reduction in deficit that was observed four to six cooperating farmers from 1973 to 1979 near Oakes, ND. In-field observations indicated a range of the estimated soil water deficits in the fall with the beginning deficits in the following spring near date of September 30 to May 1 averaging about 15.5 cm in the 0.64 cm/day with short term peaks in individual years of 68.6 cm was estimated for alfalfa in the very droughty 1976 season. ET rate, on average, peaked near 0.64 cm/day with short term peaks in individual years approaching 0.85 cm/day. Evaluations, by simulation methods, indicated that required center pivot pumping rates (given a standard irrigated area = 53.4 ha, and irrigation efficiency = 85 percent) range from 41.0 to 54.0 1/sec depending upon the allowable safe soil water depletion between irrigations.

Average seasonal irrigation requirements were 34.8 and 46.5 cm for corn and alfalfa, respectively. Peak irrigation requirement normally occurred in July, averaging 16.4 cm. However, requirements did occasionally approach 20 cm in both July and August.

Root zone drainage losses in the growing season were estimated to average 6.9 cm in corn fields with lower losses likely for alfalfa or wheat. NO3-N losses were sampled by installing several non-weighing lysimeters. Annual losses from soils of the Lohnes or Claire series approached 30 kg/ha when the irrigated crop was corn.

Corn yields for the scheduled farms typically averaged 73 percent of the observed average yields for the hybrid corn trials at the Oakes field trials station. Corn yields were linearly related to seasonal ET with a slope of 0.27 T/ha-cm. When yield is related to seasonal water supply, the associated non-ET losses appear low enough to economically justify applying the seasonal irrigation amounts that are needed to approach Ymax, yield levels.

Off-season storage of precipitation may normally be sufficient to negate the need for off-season irrigation, particularly when deficits in late September are less than 7.5 cm.

Summary
A trial irrigation scheduling service was operated with four to six cooperating farmers from 1973 to 1979 near Oakes, ND. In-field observations indicated a range of water management regimes can be used to achieve near potential yields. Highest yields were most consistently achieved when irrigations were scheduled to maintain high levels of water availability and application amounts were sufficient to maintain potential ET rates throughout the growing season. Alternate management regimes were also illustrated for attaining high yields with reduced seasonal water application.

Average seasonal evapotranspiration was observed to range from 36.8 cm for barley to 63.5 cm for alfalfa. A high of 68.6 cm was estimated for alfalfa in the very droughty 1976 season. ET rate, on average, peaked near 0.64 cm/day with short term peaks in individual years approaching 0.85 cm/day. Evaluations, by simulation methods, indicated that required center pivot pumping rates (given a standard irrigated area = 53.4 ha, and irrigation efficiency = 85 percent) range from 41.0 to 54.0 1/sec depending upon the allowable safe soil water depletion between irrigations.

Average seasonal irrigation requirements were 34.8 and 46.5 cm for corn and alfalfa, respectively. Peak irrigation requirement normally occurred in July, averaging 16.4 cm. However, requirements did occasionally approach 20 cm in both July and August.

Root zone drainage losses in the growing season were estimated to average 6.9 cm in corn fields with lower losses likely for alfalfa or wheat. NO3-N losses were sampled by installing several non-weighing lysimeters. Annual losses from soils of the Lohnes or Claire series approached 30 kg/ha when the irrigated crop was corn.

Corn yields for the scheduled farms typically averaged 73 percent of the observed average yields for the hybrid corn trials at the Oakes field trials station. Corn yields were linearly related to seasonal ET with a slope of 0.27 T/ha-cm. When yield is related to seasonal water supply, the associated non-ET losses appear low enough to economically justify applying the seasonal irrigation amounts that are needed to approach Ymax, yield levels.

Off-season storage of precipitation may normally be sufficient to negate the need for off-season irrigation, particularly when deficits in late September are less than 7.5 cm.

*This work was supported by North Dakota Agricultural Experiment Station projects 1432 and 1435 and by funds provided by the U. S. Department of Interior. Water and Power Resources Service.

ACKNOWLEDGEMENTS: The author acknowledges the cooperation of the following farmers: L. Rehovsky, D. Roney, N. Haak, K. Klever, O. Streich, R. Fenno, L. Black, and H. Pare.

References

Example price ratio slopes

a. pumping cost = $2.91/ha-cm

b. pumping cost = $5.83

\[ Y = -6.07 + 0.27 (\xi ET) \]

\[ R^2 = 0.68 \]


FIGURE 16. Average soil water deficit reduction from non-growing season precipitation in the period from 9/30 to next planting date.