SPECIFICATION OF CENTER-PIVOT IRRIGATION BASED ON LOAD-CONTROL CONSTRAINTS

D. L. Armour, L. R. Massie, W. L. Bland, G. D. Bubenzer

ABSTRACT. *A numerical simulation (model) evaluated combinations of irrigation system capacity and scheduling protocol to minimize the risk associated with irrigating potato under the constraints of load-control programs in Wisconsin. Results from the model indicated that a center pivot irrigation system capacity of 4540 L/min operated with a scheduling program based on the soil water balance minimized the economic risks associated with irrigating potato under the constraints imposed by energy load-control programs. Increasing the system capacity from 3785 L/min provides greater flexibility in choosing and adjusting an irrigation scheduling program to variable seasonal and yearly weather conditions. This model clearly demonstrated that a system capacity of 2840 L/min is not sufficient to participate in a load-control program.*

Keywords. *Energy, Irrigation scheduling, Irrigation systems, Modeling.*

The design and management of a sprinkler irrigation system should not be based on average climatic values where the amount and distribution of rainfall varies significantly from year to year. In such regions, it is preferable to determine system capacity and scheduling techniques using long term actual weather data to predict the amount of stored water in the soil profile and future evapotranspiration and soil moisture depletion rates (Smith et al., 1985).

While annual electric use by irrigators is only about three percent of the total used in Wisconsin, the use of electricity to power irrigation pumping plants increases the peak electrical demand for generating capacity, especially since high irrigation demand coincides with high air conditioning use. To control peak demand, power suppliers are trying to shift agricultural energy use to off-peak periods with load-control ("time-of-day") programs which offer economic incentives for not operating irrigation systems during peak demand periods. However, growers perceive an increased level of risk associated with participation in load-control programs when growing high value crops, such as potato.

Heermann et al. (1974) determined irrigation system design capacities versus optimum soil water depletion as a function of water holding capacity for eastern Colorado. They showed that system capacity requirements decrease as soil water holding capacity increases, and as the probability of meeting peak ET decreases. In a study on the effect of management policies on irrigation system capacities, von Bernuth et al. (1984) showed a similar relationship between soil moisture depletion and system capacity as that determined by Heermann et al. (1974). A study of the season-to-season variability of weather on irrigation scheduling for wheat by Smith et al. (1985) demonstrated that fixed irrigation schedules based on mean climatic data caused inefficient use of water because it was not applied at the optimal time which resulted in over-application or excessive depletions. Young (1979) and Buchleiter (1979) demonstrated electrical loads could be shifted without reducing yield using an integrated load-control and irrigation scheduling program in Colorado. The Colorado load-control program considered two alternatives which restricted electrical use to either one day per week, or possibly everyday.

OBJECTIVE

The objective of this study was to determine combinations of irrigation system capacity and scheduling protocol to minimize the risk associated with irrigating potato under the constraints of a load-control program.

METHODS

A numerical simulation, driven by actual weather data, was developed to test combinations of well capacities and irrigation strategies over a range of historical climatic scenarios. The plant and soil portions of the model simulated canopy and rooting depth development, actual evapotranspiration (ET_a), and the soil-water balance for potato on two soils. The effect of system capacity on irrigation scheduling strategies was also simulated. Management options included "time-of-day" constraints on operation, and conditions to initiate irrigation and application depth. The entire simulation was driven by weather inputs of temperature, evaporative demand, and precipitation. Between 35 and 43 years of weather data were gathered for five locations in the state. Figure 1 summarizes the variables tested.

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CONCLUSIONS

1. Appropriate irrigation schedules will perform adequately with existing center-pivot irrigation system capacities in the 2840 to 4540 L/min range. With increasing capacity, irrigation scheduling options will permit participation in load-control programs. Also, with a larger well capacity, the grower can adapt irrigation scheduling to seasonal weather conditions.

   For installation of a new center-pivot irrigation system, this study found a 4540 L/min capacity preferable because:

   A. Irrigation scheduling and load-control combinations minimized seasonal energy use, losses, and costs.

   B. There was more flexibility in seasonal management decision.

   C. There was a small level of risk for both soils tested, and the Plainfield soil represents the extreme demand conditions likely to occur.

2. System capacity determines the ability to participate in load-control programs. The 2840 L/min system lacked sufficient capacity to permit participation in a full load-control program. Only on soils with larger water holding capacities, such as Richford, was participation in partial load-control programs possible. The 3785 L/min systems achieved economic savings with partial load-control programs. However, a larger depth per application was required to minimize the number of failures. Participation in a full load-control program resulted in an economic loss with a 3785 L/min system. For the soils tested, the best irrigation system capacity and schedule combination permitted full load-control program participation with a 4540 L/min well capacity.
3. Analysis of the trade-off between the capital and infrastructure costs, associated with higher capacity irrigation systems, and the desirability of full load-control participation is needed to meet producer and societal objectives.

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Estimation of Potential Evapotranspiration and Conversion to ET_a

Clothier et al. (1982) and Gunston and Batchelor (1983) show that in humid climates, like Wisconsin, the Priestley-Taylor and Penman equations produce estimates of potential evapotranspiration (ET_p) of similar accuracy. The reduction in the number and type of inputs required in the Priestley-Taylor method makes it an attractive alternative. The effect of partial cover on actual crop evapotranspiration (ET_a) was accounted for with a quadratic that increased the ratio of ET_a/ET_p from 0 at 0% cover to 0.8 at 50%, and to 1 at 80% cover (Curwen and Massie, 1992).

The Priestley-Taylor equation requires temperature and net radiation. Long-term daily temperature and precipitation data gathered by the Cooperative Observation Program of the National Oceanic and Atmospheric Association (NOAA) were available for the test locations. Net radiation was approximated from modeled daily solar radiation values (Petersen, 1990) and a temperature-driven long-wave calculation. Petersen (1990) modeled solar radiation at 58 first-order meteorological stations in the Midwest from the late 1940s through the early 1990s. The semi-physical model estimates were validated at four midwestern stations with measured data from 1987 to 1988. The mean, mean absolute, and relative mean square errors for all stations were 5.6, 11.7, and 15.7%, respectively. Given the incomplete and/or insufficient hourly data used to estimate solar radiation, the errors indicate excellent agreement between modeled and observed solar radiation values. The NOAA locations are not physically coincident with the first-order stations, so geostatistical methods were used to interpolate daily integrated solar radiation for these locations.

Bland and Clayton (1994) determined the spatial structure of solar radiation across Wisconsin. They found that the semi-variogram function from the day with the largest standard deviation of measured solar radiation best predicted the spatial structure and point estimates of insolation across the state for all days. This semi-variogram was applied to the modeled data to interpolate estimates at the test locations. The interpolated data reflect both the daily magnitude and spatial structure of insolation across Wisconsin. The estimates of integrated daily solar radiation and historical measurements of temperature provided the necessary data to calculate ET_p using the Priestley-Taylor equation.

Irrigation Management Strategies

The irrigation management strategies evaluated were load-control scheduling, field partitioning to permit efficient use of load-control programs, and scheduling the depth to be applied.

Three load-control options were evaluated. No-load control places no restrictions on the use of electricity. Growers pay full cost at all times for all the electricity used. Partial-load control limits electrical usage to 18 h per day Monday through Friday. The cost per kilowatt is reduced and a credit based on the horsepower of the pumping plant is also given. Full-load control limits electrical use to 12 h per day Monday through Friday with the cost per kilowatt further reduced. For either partial- or full-load control, a penalty in higher rates is charged if the grower uses electricity during the load control period. The higher penalty rates exceed the no load control cost of electricity.

For typical center-pivot irrigation systems, the area, system travel speeds, and net depth required are such that irrigating the field within a 12- or 18-h period requires partitioning the field into more than one management unit. The time of a complete rotation for the simulated systems to cover 51 ha was 15 h. Theoretically, for well capacities of 2840 L/min, 3785 L/min, and 4540 L/min, a depth of 5.1, 6.7, and 7.8 mm, respectively, can be applied in 15 h. However, delivery and application efficiencies (85% of the total) reduce the effective depths applied to 4.3, 5.7, and 6.6 mm for the 2840-, 3785-, and 4540-L/min pumping plant capacities, respectively. Actual peak ET rates can exceed 7.0 mm/day. Load-control programs limit time of daily operation to either 12 or 18 h. The systems modeled did not complete a full revolution in the 12-h load-control time block, and cannot deliver sufficient water to meet peak crop demand in 18-h periods for any well capacity tested. Partitioning the field into halves, with respect to irrigation scheduling, addressed both the insufficient time to complete a full-revolution in a 12-h period and insufficient capacity to meet crop demand in either load-control time block. The irrigation schedules tested in the model operated within the time blocks for each load-control program to test the viability of participation. A separate soil water balance was maintained for each field partition to determine when to apply and the depth of application. Irrigation schedules operating with no load-control irrigated the whole field during one day. The partial and full load-control irrigation schedules required two days, to irrigate the whole field with half the field covered each day.

For the single field partition, the condition to trigger an irrigation was:

$$\text{Irrigate if } RAW_{rz} - 1.2AET_a \leq 0.5AET_a \qquad (3)$$

where AET_a is the three-day average ET_a, or today's ET_a (15 June to 1 August) if today's ET_a is greater than either of the previous two days.

Table 1 lists the RAW_{rz} by soil type and layer. A reserve of up to 40% RAW_{rz} is required because the center-pivot irrigation system used most, if not all of the 24-h time block, to irrigate the 51 ha during peak ET_a periods.

The two-field partition trigger mechanism must include both the amount of stored RAW_{rz} in the half to be irrigated today and the amount of RAW_{rz} in the other half. The

Table 1. Readily available water by soil type and depth

Soil Depth (mm)	Readily Available Water (mm)	
	Plainfield Loamy Sand	Richford Sandy Loam
152.5	12.2	16.8
305.0	23.1	30.5
457.5	33.8	42.7
610.0	44.5	57.7
762.5	52.1	78.2
915.0	59.7	91.2
1067.5	71.1	98.8
1220.0	82.6	106.4

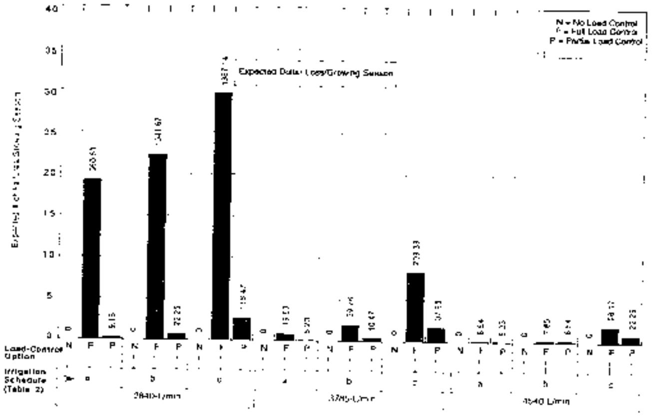

Figure 2–Average yearly number of failures and economic loss for all combinations of well capacity, irrigation schedule, and load-control program at all locations for the Plainfield soil.

corresponding average annual economic loss (AAEL) determined for the 51-ha field size for this level of probability of failure ranged from $40,500 to $63,000 on the Plainfield soil and from $29,000 to $42,750 on the Richford soil. With the partial load-control program and irrigation schedule 'a', the 2840-L/min system has a $603 AAEL on the Plainfield soil and $151 on the Richford soil.

The 3785-L/min system operating under full load-control had a P_f ranging from 0.25 to 1.95%, with the corresponding AAEL ranging from $330 to $3840 depending on soil type and irrigation schedule. The level of risk and loss is related. At three locations, irrigation schedules 'a' and 'b' with the partial load-control program had an AAEL between $330 to $990 which corresponds to a $P_f < 0.20 - 0.50\%$.

The 4540-L/min irrigation system permits more schedules to be used with smaller risk. The probability of failure for the full load-control program and schedules 'a' – 'b' was less than 0.14% at three locations and less than 0.35% at the other locations for both soil types. The range of AAEL was from $101 on the Richford for schedule 'a' to $680 on the Plainfield for schedule 'b'.

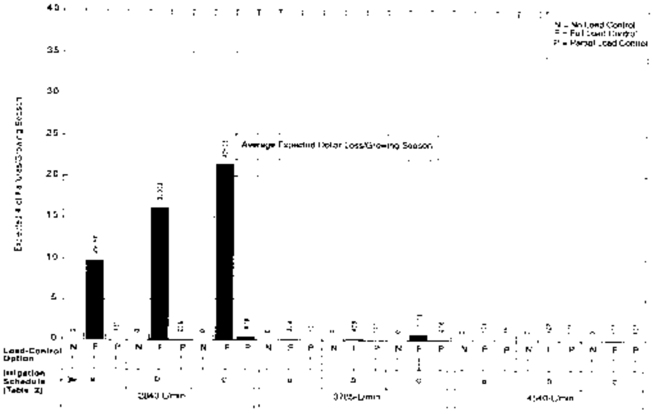

Figure 3–Average yearly number of failures and economic loss for all combinations of well capacity, irrigation schedule, and load-control program at all locations for the Richford soil.

Table 3. Recommended combinations of well capacity, irrigation schedule, and load-control program on the Plainfield Loamy Sand

Rank	Well Capacity (L/min)	Irrigation Schedule	Load-control Program
1	4540	a	Full
2	4540	b	Full
3	3785	a	Partial
4	3875	a	Full
5	4540	b	Partial

Table 4. Recommended combinations of well capacity, irrigation schedule, and load-control program on the Richford sandy loam

Rank	Well Capacity (L/min)	Irrigation Schedule	Load-control Program
1	4540	c	Full
2	4540	b	Full
3	4540	a	Full
4	3875	b	Full
5	3875	a	Full

The top five ranked combinations of well capacity, irrigation schedule, and load-control program are listed in tables 3 and 4 for the Plainfield and Richford soils, respectively. Assessing the different combinations in economic terms finds:

1. Best results are achieved with a system capacity of 4540 L/min, and an irrigation schedule which attempts to refill all or most of the soil moisture deficit under full load-control.
2. A 3785 L/min system can be operated under partial load-control with an irrigation schedule which attempts to refill all or most of the soil moisture deficit. On soils with a larger water-holding capacity this system may be operated under full load-control.
3. Increasing the pumping capacity provides greater flexibility in choosing and adjusting the irrigation scheduling program to annual climatic conditions; minimizes the number of soil moisture depletion failures and reduction in potato development, and cost of electricity.

For a center-pivot location on Plainfield loamy sand, the results of ranking of the linear combination of TEC, one-tenth TKWh, and EL are shown in table 3. The large capacity system (4540 L/min) managed with full load-control gave the best results followed by the medium (3785 L/min) and large capacity systems managed under partial load-control. These were the top ranked schedules at all locations, though the order varied at different locations. The best results were achieved with irrigation schedules 'a' and 'b' for all pumping plant capacities and either full or partial load-control programs. The full load-control management strategy produced the best results at all locations. The results from the 4540 L/min pumping plant indicate that the increased capacity lowered the number of failures for both the full and partial load-control programs. The reduction in the demand surcharge provided a net economic savings when there were only minimal costs associated with reduced yields.

The Richford sandy loam results (table 4) show the high capacity systems with full load-control produced the best economic results. These were followed by medium capacity systems with full load-control, and then low capacity systems with partial load-control. The top five schedules used full load-control, with three using the highest capacity pumping plant. The increased water holding capacity of the Richford sandy loam clearly affected the results.

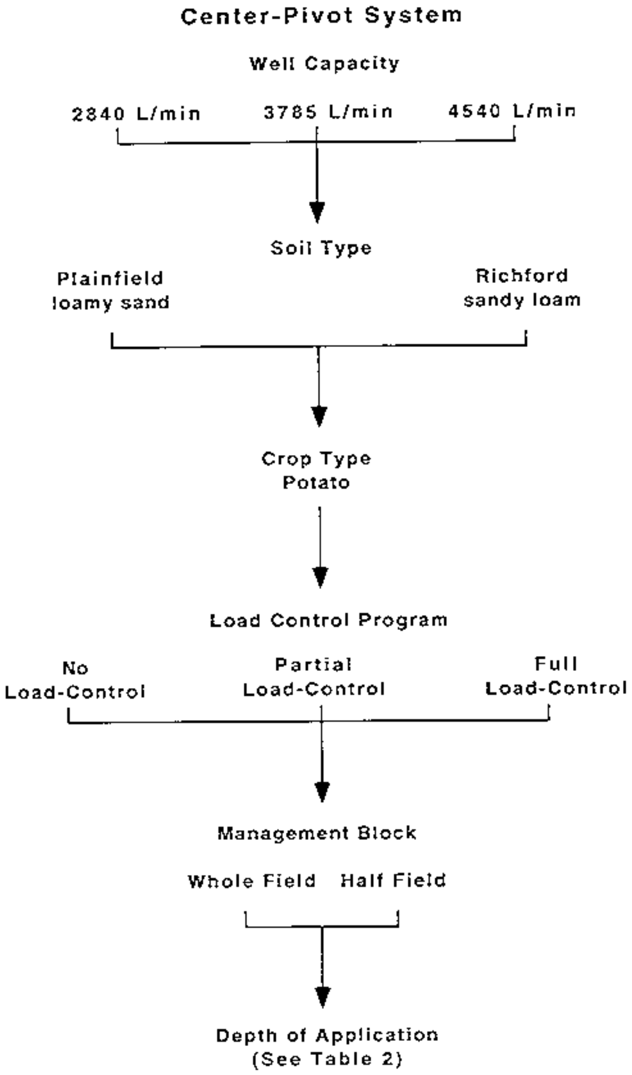

Figure 1–Summary of research variables.

SOIL WATER BALANCE MODEL

Dividing the soil profile into 152-mm-thick layers provided sufficient resolution with respect to an expanding root zone for computing the total and readily available water stored. The methodology of Chesness et al. (1986) was used to account for infiltration and redistribution of water by layer in the soil profile. Modifications were made to the precipitation and irrigation terms to account for canopy, surface storage, and interception. Surface runoff was not simulated because the irrigated soils in Wisconsin are predominantly sandy loams to loamy sands with high infiltration and permeability rates. The soils tested were the Plainfield loamy sand and Richford sandy loam.

The readily available water stored in a layer (RAW_i) is a function of the water-holding capacity (WHC_i) and total available stored water (TAW_i) of layer *i*, and the crop's response to soil-water depletion at that time. The amount of readily available stored water is given as:

$$RAW_i = TAW_i - [WHC_i \times (1 - CSC_k)]$$

$$1 \leq i \leq \text{maximum root depth layer} \qquad (1)$$

where

RAW_i = water stored in layer i readily available to the crop (mm)
TAW_i = total available water stored in layer i (mm)
WHC_i = potential water holding capacity of the soil in layer i (mm)
CSC_k = crop sensitivity coefficient during the k*th* crop development phase (Werner, 1993) $0.4 < CSC_k \leq 0.6$

A crop exhibits a unique water stress relationship in terms of the amount of water which it can easily extract and the length of time a relatively uniform level of water stress sensitivity exists (Werner, 1993). The crop sensitivity coefficient (CSC_k) varies throughout the growing season in response to the physiological development of the crop, and its ability to extract water from the soil and response to water stress over discrete stages (Werner, 1993). The subscript, k, identifies the stage. This is a refinement over previous modeling efforts, which determined RAW as a fixed percent of TAW throughout the entire growing season (Gregory and Schottman, 1982; Swaney et al., 1983; Smith et al., 1985).

When $RAW_{rz} > 0\%$, water is available for crop use without stressing the plant, so crop development and potential yield are not limited. A $RAW_{rz} \leq 0\%$ indicated a failure of the center-pivot, pumping plant, and irrigation schedule combination. Crop development was delayed causing a reduction in the quality and/or quantity of yield.

CROP SIMULATION MODEL

Development of the potato canopy and root system is predicted on simple thermal time models. The unit of thermal time is the P-Day (Pscheidt and Stevenson, 1986). The function estimates mean daily temperature ($T_{average}$) weights from the daily maximum and minimum temperature to approximate a typical diurnal trace, then multiplies $T_{average}$ by a coefficient which increases from 0 at 7°C to 10 at 21°C and decreases again to 0 at 31°C. Percent canopy cover was approximated by a quadratic equation in accumulated P-Days:

$$\%\ \textit{Canopy Cover} = -4.8128804 + (0.427898643\ ADPD)$$

$$+ (-0.000439134\ ADPD^2) \qquad (2)$$

where *ADPD* represents the summation of P-Days from emergence until the current day.

Root development was simulated using the sigmoidal function of Borg and Grimes (1986). The function determined the number of days after planting for the roots to reach 15, 30, 45, and 60 cm of depth. A mature rooting depth of 60 cm and growth period from planting to maturity of 18 weeks (Werner, 1993) were assumed.

To participate in the full load-control program and achieve the largest net economic benefit required a 4540 L/min capacity well. The medium capacity system with full load-control met the grower's objective with a smaller net economic benefit. The data show that as well capacity increased, greater flexibility in irrigation scheduling in conjunction with the load-control programs was achieved. The ability to adapt to yearly conditions, therefore minimizing the number of failures, electrical use, and total cost of electricity was an important factor in achieving maximum net economic benefit. Also seasonal application depths were reduced, increasing the storage and effective use of precipitation and minimizing the potential for deep percolation.

Figures 4, 5, and 6 show the difference in average annual costs between the no load control irrigation schedules and the partial and full load control schedules for both soil types and the 2840 L/min, 3785 L/min, and 4540 L/min capacity wells, respectively. The average annual costs include electrical usage, pump horsepower charge, and economic losses from system failures. The base annual cost (x-axis) is the no load control cost for each irrigation schedule. The cost differential (y-axis) shows the difference in average annual costs between the base cost (no load control) and the two load-control options for the same irrigation schedule and soil. Negative cost differential values indicate greater cost to use full or partial load-control schedules (a loss), and positive cost differential values represent a savings for using either of the load-control options (full or partial load-control).

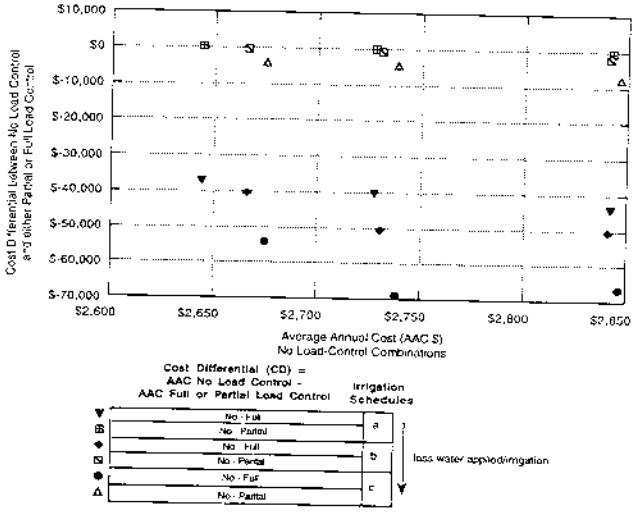

Figure 4–Average annual cost differential between no-load and partial- or full-load-control schedules for 2840 L/min irrigation systems on both soil types.

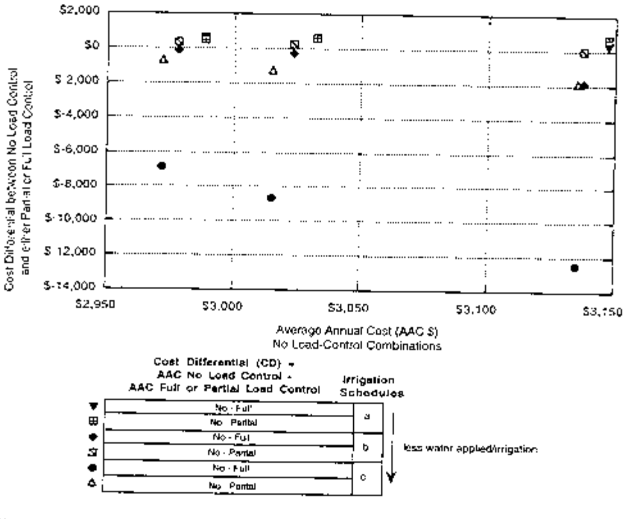

Figure 5–Average annual cost differential between no-load and partial- or full-load-control schedules for 3785 L/min irrigation systems on both soil types.

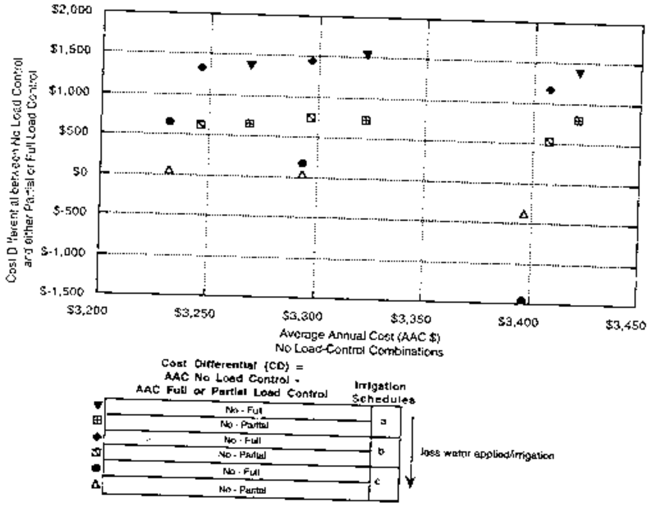

Figure 6–Average annual cost differential between no-load and partial- or full-load-control schedules for 4540 L/min irrigation systems on both soil types.

Figure 4 shows that operating the 2840 L/min system with full load-control incurred costs significantly greater than the no load-control schedules. Large economic losses were associated with insufficient capacity which could not deliver enough water to the crop in the restricted irrigation time blocks, thereby causing a large number of failures. Partial load-control with the smallest capacity cost approximately the same as the base case of no load-control. For both full- and partial load-control, economic loss due to reduced yield offset savings from lower demand surcharges.

The partial load-control program in conjunction with irrigation schedule 'a' and 'b', saved between $500.00 and $750.00/year on the 3785 L/min system (fig. 5). The full load-control schedules either cost more or roughly the same as the no load-control program.

The 4540 L/min system showed that savings can be achieved with the full load-control schedules (fig. 6). Full load-control operating with a routine irrigation schedule cost less per year than the no load-control program. The savings ranged from $100.00 to $1500.00. The 4540 L/min pumping plant had sufficient capacity to minimize risk (economic loss) and total electrical cost, achieving the best economic results for the grower. In general, the partial load-control program cost approximately $500.00/year less than the no load-control program.

second partition must have enough stored RAW_{rz} to meet another full day of ET_a because irrigation does not begin until the following evening. The management strategy must anticipate the water balance in both partitions. The trigger condition is:

$$\text{If}\left\{\begin{matrix} RAW_{rz}(i) - 2.0AET_a \le 0.5AET_a \\ RAW_{rz}(j) - 1.0AET_a \le 0.5AET_a \end{matrix} \; or \right\}$$

$$\text{then irrigate partition } i \qquad (4)$$

In the model, the center-pivot system was never rotated dry to the next partition even if the current one did not require an irrigation. In those cases, the smallest depth was applied to minimize over-application of water.

Table 2 presents the formulae for determining the depth to be applied for the partition strategies. The actual application depth may be less than desired because the model requires the center-pivot to irrigate the whole partition in a load-control time block. In table 2, the second of the two formulae in "Amount to Apply — 2 Field Partitions" is used when partition i has sufficient stored water to offset expected crop demand in the next 48 h, yet will be irrigated so partition j can be irrigated during the next time block. This technique also helped maximize the unfilled storage capacity in the root zone, thus increasing effective storage of rainfall. In this simulation the entire area of a single partition was completely irrigated in a time block, whether it was 12, 18, or 24 h and either the whole field or half. The option of partially watering a single partition and then completing it during the next irrigation period was not investigated.

ANALYSIS

Considered in the evaluation of alternative scenarios were: (1) the frequency of failure to maintain adequate water in the root zone ($RAW_{rz} \le 0$ mm); (2) total seasonal electrical usage; (3) total seasonal electrical costs; (4) probability of failure (Pf); and (5) cost differential of alternative combinations. Failure to maintain $RAW_{rz} > 0$ mm was tallied for each field partition, and the associated economic losses were normalized with respect to area (ha).

The Pf is the annual number of failures expected throughout the entire irrigation season. It was determined by taking all the failures for a particular combination of soil, well capacity, and irrigation schedule and dividing by the number of days in the irrigation seasons. This was computed from the results for the entire historical record at a particular location.

The estimate of the economic loss assumed an average yield for potatoes of 38 tonnes/ha, valued at $200/t. Tuber bulking occurs over a 90-day period. The cost of a single day of water stress (a failure) was assumed to reduce bulking by 1/90th, or one days worth of tuber development over the management area. Thus, a daily failure reduced yield by 0.42 t/ha/day, which equals a loss of $84.40/ha/day. The average yearly economic loss for a given soil was averaged over the number of years and locations. The $84.40 penalty was applied for failure to maintain adequate RAW_{rz} regardless of the size of the deficit below zero. The size of water deficit should affect yield proportionally, but no clear relationship between level and duration of water stress and potato yield has been determined which could have been used in the simulation.

The best irrigation system and schedule minimizes total seasonal electrical use and costs, and the risk of economic loss. Weighting these criteria in an objective function depends on numerous externalities. However, as a first approximation, each was equally weighted by summing the one tenth the average yearly total kilowatts used (TKWh), average yearly total electrical cost (TEC) and economic loss (EL). The TKWh is scaled by one-tenth to produce the same order of magnitude as TEC. The new random variable, "linear expectation", minimizes TKWh, TEC, and EL, by sorting in ascending order.

RESULTS

Figures 2 and 3 show the average number of failures for potato grown on the Plainfield and Richford soils at all locations and for averaged identical combinations of well capacity, irrigation schedule, and load-control program. Operating all systems with a "no-load" control condition produced 0 irrigation failures regardless of the irrigation scheduling program. However, the "no-load" control combinations did not minimize the average yearly costs even with zero or no risk or economic loss.

As shown in figures 2 and 3 the pumping capacity for a 2840 L/min system was not sufficient to participate in a full load-control program. All irrigation schedules operating with full load-control produced a high P_f ranging from 10 to 15% on the Plainfield soil and 8 to 12% on the Richford soil. The

Table 2. Depth of application algorithms by irrigation schedule

Label	Trigger Mechanism	Irrigation Application Depth (ID) 1 Field Partition	Irrigation Application Depth (ID) 2 Field Partitions
a	Eq. 3 (1 partition) Eq. 4 (2 partitions)	$(WHC_{root\ zone} \times CSC_k) - RAW_{root\ zone}$	$\begin{cases} (WHC_{root\ zone} \times CSC_k) - RAW_{root\ zone} \\ 0.5 \times [(WHC_{root\ zone} \times CSC_k) - RAW_{root\ zone}] \end{cases}$
b	Eq. 3 (1 partition) Eq. 4 (2 partitions)	$0.8 \times [(WHC_{root\ zone} \times CSC_k) - RAW_{root\ zone})$	$\begin{cases} 0.8 \times [(WHC_{root\ zone} \times CSC_k) - RAW_{root\ zone}] \\ 0.4 \times [(WHC_{root\ zone} \times CSC_k) - RAW_{root\ zone}] \end{cases}$
c	Eq. 3 (1 partition) Eq. 4 (2 partitions)	$0.6 \times [(WHC_{root\ zone} \times CSC_k) - RAW_{root\ zone})$	$\begin{cases} 0.6 \times [(WHC_{root\ zone} \times CSC_k) - RAW_{root\ zone}] \\ 0.3 \times [(WHC_{root\ zone} \times CSC_k) - RAW_{root\ zone}] \end{cases}$