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OPTIMIZING IRRIGATION SYSTEM DESIGN---SUMMARY REPORT

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Summary Report

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ABSTRACT

A linear-programming (LP) framework and computer routines for systems design and cost estimating are presented for design and planning of irrigation systems from the farmer's or developer's point of view on an after-tax basis. The framework allows planners to evaluate economics of deficit irrigation in system design and to optimize the size and operation of irrigation system components.

The framework includes linear crop evapotranspiration production functions and simulates crop evapotranspiration and resulting crop yield according to irrigation application levels and simulates soil moisture availability with time of season. The LP framework simulates irrigation system costs and requirements including costs for capital, labor, energy and water, and provides for hydraulic and economic continuity throughout the system. Sprinkler, pipe, pump and canal systems are modeled. The LP model provides for parametric analyses on physical and economic parameters and system constraints to evaluate system resiliencies to parameter variation. Associated irrigation system design and cost estimating routines can be used independent of the LP framework.

The LP model and associated routines were applied to a study area in the proposed Bruneau Plateau Water Development project in southern Idaho. The study area irrigation system is composed of gravity, earthern canal conveyance sections with pipeline mains on 1.6 km grids pressurized from the canal with sprinkler systems on 260 ha farm units. The crop distribution for the study area is composed of equal distributions of potatoes, dry beans, spring wheat and sugar beets.

The systems with the highest net, after-tax annual profits were linear move systems with spray booms, with profits averaging -$245 per hectare per year. Net profits for these systems became positive as crop price estimates were increased by 18 percent or crop production costs were reduced by 20 percent. Optimization of system design for net-profit maximization resulted in canals, pipelines, pumps and sprinkler systems being sized at 90 percent of the 14-year average 15-day peak irrigation requirement. Reduction of peak design size resulted primarily from full usage of stored soil moisture during peak periods.

INTRODUCTION

This report summarizes development and application of a planning model which incorporates state of the art relationships between crop yield and water use, soil moisture, and irrigation application rates and amounts, and between application rates and amounts and system costs. The model formulates guidelines for allocating water during an irrigation season. These guidelines incorporate the opportunity costs of water and energy, so that an economic balance of resource use is maintained. The model defines flow of water through the irrigation system with continuity of flow at all points. Costs for all system components, labor, energy, and production are defined and sensitivity and parametric analyses are provided. Total system productivity and profitability are computed.

A detailed description of model development and application procedures are contained in a published dissertation by Allen (1983).

Objectives of this research were to:

1. Develop a linear-programming model to be used by planners and engineers to optimize irrigation system design, water application, and system operation strategies with the goal of maximization of after-tax farm profits.

2. Develop and apply supporting computer routines for linearizing costs and physiological and physical processes within crop/irrigation systems. Supporting routines calculate and express the following:

a) crop evapotranspiration and soil moisture as linear functions of system application rates for specified periods through the irrigation season;

b) farm irrigation application system costs and energy, hydraulic and labor requirements as linear functions of system application rates;

c) pipe conveyance and pumping system costs and energy requirements as linear functions of system application rates; and

d) open channel conveyance system costs as linear functions of conveyance flow rates.

3. Apply the supporting evapotranspiration modeling and cost-estimating routines and the linear-programming framework to a study area. Results of the application have indicated adequacy of the model formulation in simulating economic and physical and physiological relationships and processes to fulfill Objective 1.

PROCEDURE

A conceptual description of the overall modeling procedure is presented in Figure 1. Boxed items in the left-hand column in the figure represent supporting computer routines and information required to accomplish Objective 2. Results from operation of the model include the right-hand column of boxed items. Names of computer routines which accomplish Objectives 2a through 2d are enclosed within parentheses within the appropriate boxed items in Figure 1. A brief description of each routine and the linear-programming model follow.

Evapotranspiration and Soil Moisture Modeling

A computer routine was developed to estimate linear equations for describing relationships among crop ET, irrigation application rates and soil moisture. This routine, ETSM, models crop and root development, soil evaporation and plant transpiration processes from multilayered soils. Crops are "grown" with time over the available weather and evapotranspiration period of record to evaluate ranges and average values of crop evapotranspiration as functions of antecedent soil moisture and effective irrigation application rates during half-monthly periods. Reduction in evapotranspiration from crop potentials is modeled according to procedures outlined and reported by Hanks (1974) and Hill et al (1979) where ET is decreased proportional to soil moisture after a minimum threshold is reached. Evapotranspiration by crops was calculated using a modified Penman method developed by Wright (1981) and basal crop coefficients developed at Kimberly, Idaho by Wright (1979) and reported by Burman et al (1980). Irrigation frequency within half-monthly periods is optimized within ETSM to achieve maximum transpiration levels for specific application rates. Results of operating the ETSM model are multiple linear regression equations which relate average expected half-monthly evapotranspiration rates and ending soil moisture levels to antecedent soil moisture and effective irrigation application rate for half-monthly periods throughout the growing season.

The ETSM model was operated using daily reference ET estimates calculated over a fourteen-year period of weather record (1965-1978) for Kimberly, Idaho. Regression equations for evapotranspiration (ET) and half-monthly soil moisture levels (SM) were calculated for nine agricultural crops grown in the Bruneau Plateau area of southern Idaho.

Sprinkler Application System Modeling

Sprinkler application systems were sized and annual costs for ownership and operation were estimated using the computer routine APSYS. This routine models hydraulics, economics and irrigation system management for hand line, wheel line, solid set, center pivot and linear move irrigation systems from conveyance system turnouts through farm mainlines, manifolds and laterals. APSYS sizes all laterals and mainlines using life-cycle cost analyses where equivalent annual marginal costs for energy and pumping systems to cover friction losses are balanced against annual marginal capital costs for pipe. Multiple mainline/lateral configurations are resident in program memory for each sprinkler system type and are evaluated to obtain least cost design layouts. Hydraulic design utilizes a critical branch approach where those lateral-mainline-manifold branches which govern system head are sized first and "noncritical" branches are allowed to be reduced in size to reduce excess line pressures and capital costs. APSYS is a detailed planning tool which accounts for valves, water meters and other miscellaneous capital requirements. System design and layout is done on an after-tax basis. Linear regression equations are generated which describe capital, energy, and labor requirements as functions of peak system application rates.

Surface Irrigation System Costs

Costs for furrow and border irrigation systems at various levels of irrigation efficiency can be estimated using computerized procedures presented by Allen et al (1978). These routines include design of border systems using zero-inertia calculations presented by Strelkoff and Katapodes (1977). Surface application systems were not evaluated in this study application.

Pipe Conveyence System Costs

Costs and specifications for closed conveyance systems are calculated using the NWRKLN routine developed by Hill (1980). This routine applies life-cycle cost analyses in which incremental costs for pumping systems and energy are set equal to incremental costs for pipe capital. The NWRKLN routine was modified by Allen (1982) to include pump and energy cost subroutines used within the APSYS routine and to account for income taxes and effects of tax credits and deductions on system economics. A linear regression subroutine was added to express system pipe and pump costs and energy requirements as functions of system application rate in accordance with objective 2c. NWRKLN is a proprietary program. The modifided version of NWRKLN used within this study is commercially available from Hill (1983). Other computer packages which are available for life-cycle costing and pipeline design include a nonproprietary routine by Watters and Keller (1980). The

Watters and Keller routine is large and cumbersome to apply, but can be used in the absense of the NWRKLN routine.

Open Channel Conveyance System Costs

The CANAL computer routine used for sizing and estimating costs for lined or unlined earthen canals was developed by Galinato et al (1977) and modified by Allen et al (1978). This routine incorporates U.S. Bureau of Reclamation guidelines for sizing of canal structures and a U.S. Bureau of Reclamation subroutine for computation of earthwork quantities. Annual costs for canal sections are expressed as linear functions of canal flow rates. Regression coefficients were adjusted to account for income-tax analyses as a part of objective 2d.

Linear-Programming Model

The linear-programming framework accounts for fixed and variable crop production costs, crop evapotranspiration reduction resulting from moisture stress, average annual crop yields and after-tax income, and irrigation system costs for capital investment, labor, energy and water. Constraint equations have been included within the model to provide for hydraulic continuity between farm application systems, pumping systems and pipe and/or open channel conveyance systems and to govern evapotranspiration processes. The linear-programming framework allows the model operator to perform parametric and sensitivity analyses upon model results so that effects of changes in commodity and resource costs and constraints upon system design and profitability can be simulated. System constraints include limits upon system diversion rates, volumes of seasonal diversions, and labor and energy availability.

A linear-programming matrix generating program, MATRX, facilitates matrix generation. This routine contains all required information on constraint requirements and hydraulic and economic relationships to provide for automatic matrix formulation. The LP matrix is coded in a format usable by MPS360 or MPSX, which are proprietary LP programs marketed by IBM (International Business Machines, 1969).

APPLICATION

The computerized cost routines APSYS, NWRKLN and CANAL were applied to the proposed Little Pilgrim irrigation project study area in southern Idaho for testing and evaluation. The 2700 ha Little Pilgrim study area, is a proposed irrigation development on federal land in the Bruneau Plateau area of southern Idaho planned as a Desert Land Entry project by the U. S. Bureau of Land Management (1979). Delivery of water to the Bruneau Plateau project would be via wintertime diversions into the Twin Falls High Line Canal system at Milner, Idaho on the Snake River (114^{o} 00' longitude).

The proposed distribution system type for the Little Pilgrim project is an open-channel main canal supplying four pressurized pipe mainlines on a 1.6 km (1 mi) grid. Pressurized farm turnouts are located on 0.8 km (0.5 mi) spacings along the pipelines. A schematic of the Little Pilgrim system is included in Figure 2.

The Bruneau Project area is on predominantly gently rolling terrain bisected with dry stream beds, canyons and gullies. Because of varying land slope and discontinuities, surface irrigation is possible on only a minor portion of the project area. As a result sprinkler irrigation of all project lands was anticipated.

The crop distribution for the study area was modeled as equal proportions of potatoes, dry beans, spring wheat and sugar beets. These crops are predominately high-value, low to moderate water users. Annual farm production costs were obtained from the Department of Agricultural Economics of the University of Idaho (Rimbey, 1983). All economic analyses were performed on an after-tax, equivalent annual basis from the farmer's point of view. Costs were annualized using a 7 percent discount rate with a 12 percent annual interest rate on borrowed capital. General inflation from the viewpoint of project developers was projected to be 4.7 percent per year over the 30 year project life.

Linear Equations and Relationships

The following is a summary of linearized relationships between costs, receipts, yield responses and system requirements modeled in the LP framework. All relationships are expressed in half-monthly time periods (days 1 through 15 and days 16 through 30 or 31).

The objective of the linear-programming model is to maximize the expected equivalent annual net after-tax profit of the irrigation project development. The form of the objective function is:

$$\sum_{c=1}^{d} A_c(P_c Y_{ac} - C_{Pc} - C_{Cc} - C_{Ec} - V_L T_{Lc} - V_W T_{Wc}) - \sum_{s=1}^{q} (a_s + b_s Q_s) \quad [1]$$

where the objective function is expressed in equivalent annual after-tax dollars for the complete irrigation project, and

A_c = project area planted to crop c, ha (ac)
P_c = expected equivalent annual after-tax price for crop c, \$/unit
Y_{ac} = expected average annual yield for crop c, unit/ha (unit/ac)
C_{Pc} = expected average annual cost of production for crop c, \$/ha (\$/ac)
C_{Cc} = equivalent average annual cost for capital invested in application systems for crop c, \$/ha (\$/ac)
C_{Ec} = equivalent average annual cost for irrigation energy for crop c, \$/ha (\$/ac)
V_L = equivalent annual cost for irrigation labor, \$/hr
T_{Lc} = total annual irrigation labor requirement for crop c, hr/ha (hr/ac)
V_W = equivalent annual after-tax charge for water, \$/ha-mm (\$/ac-ft), for reservoirs, O&M or purchase
T_{Wc} = total annual irrigation water requirement at farm turnouts for crop c, mm
Q_s = maximum flow rate in conveyance section s, m^3/s (ft^3/s)
a_s, b_s = regression coefficients for conveyance sections
d = the number of crops in rotation
q = number of conveyance sections and service areas.

Each of the components of the objective function are calculated or constrained according to the following matrix equations:

$$ET_{ci} = C_{Ec0i} + C_{Ec1i} R_{ci} + C_{Ec2i} AM_{ci} \quad [2]$$

$$SM_{ci} = C_{Sc0i} + C_{Sc1i} R_{ci} + C_{Sc2i} AM_{ci} \quad [3]$$

$$AM_{ci} = SM_{c(i-1)} \quad [4]$$

$$ET_{ck} = \sum_{i=j}^{l} L_i \, ET_{ci} / ET_{pck} \quad [5]$$

$$Y_{ac} = Y_{mc}(1 - \sum_{k=1}^{n} K_{Ick} - \sum_{k=1}^{n} K_{Ick} \, ET_{ck}) \quad [6]$$

$$C_{Pc} = a_{Pc} + b_{Pc} Y_{ac} \quad [7]$$

$$C_{Cc} = a_{Cc} + b_{Cc} R_{maxc} \quad [8]$$

$$C_{Ec} = \sum_{i=1}^{m} a_{Ec} + b_{Ec} \sum_{i=1}^{m} R_{ci} \quad [9]$$

$$T_{Ec} = \sum_{i=1}^{m} a_{Hc} + b_{Hc} \sum_{i=1}^{m} R_{ci} \quad [10]$$

$$T_{Lc} = \sum_{i=1}^{m} a_{Lc} + b_{Lc} \sum_{i=1}^{m} R_{ci} \quad [11]$$

$$T_{Wc} = \frac{1}{Aeff} \sum_{i=1}^{m} R_{ci}(L_i) \quad [12]$$

$$P = a_D + b_D \sum_{c=1}^{d} R_{maxc} \quad [13]$$

$$Q_s = Q_{s-1} / Ceff_s + c_q \sum_{c=1}^{d} A_{cs} R_{maxc} / Ceff_s \quad [14]$$

where:

ET_{ci} = average expected evapotranspiration during half-monthly period i for crop c, mm/day

R_{ci} = effective irrigation application rate (100% efficiency) during half-monthly period i for crop c, mm/day

AM_{ci} = antecedent soil moisture at start of half-monthly period i for crop c, mm

SM_{ci} = soil moisture at end of half-monthly period i for crop c, mm

C_{Ec0i}, C_{Ec1i}, C_{Ec2i} = regression coefficients for crop c, half-monthly period i, (from ETSM)

C_{Sc0i}, C_{Sc1i}, C_{Sc2i} = regression coefficients for crop c, half-monthly period i, (from ETSM)

ET_{ck} = ratio of average expected to average potential evapotranspiration during growth period k for crop c
ET_{pck} = average potential evapotranspiration for crop c during growth period k, mm
L_i = length of half-monthly period i, days
Y_{mc} = average potential yield for crop c, units/ha (units/ac)
K_{Ick} = crop water-yield response factor for individual growth period k and crop c
C_{Pc}, C_{Cc} and C_{Ec} are previously defined
a_{Pc} = annual fixed cost of production for crop c
b_{Pc} = annual variable (per unit of yield) cost of production for crop c
T_{Ec} = total annual irrigation energy requirement for crop c, kwh/ha (kwh/ac)
P = peak irrigation power demand over all crops
a_{Pc}, a_{Cc}, a_{Ec}, a_{Hc}, a_{Lc}, a_D = regression constants from APSYS or NWRKLN computer routines
b_{Pc}, b_{Cc}, b_{Ec}, b_{Hc}, b_{Lc}, b_D = regression coefficients from APSYS or NWRKLN computer routines
Aeff = irrigation application efficiency of farm application systems
Ceff = conveyance efficiency of conveyance section s
A_{cs} = area of conveyance section service area s planted to crop c, ha
c_q = conversion factor
R_{maxc} = maximum application rate R_{ci} for crop c
d = number of crops in rotation
j = number of first half-monthly period in growth stage k
l = number of last half-monthly period in growth stage k
n = number of growth stages for crop c
m = number of half-monthly periods in the irrigation season.

Crop evapotranspiration, in millimeters per day, is described in terms of antecedent soil moisture at the start of each half-monthly period and the soil moisture replacement rate (effective irrigation application rate), millimeters per day, over the same period. Antecedent soil moisture of a period, in millimeters, is based upon the soil moisture replacement rate, mm/day, and antecedent soil moisture, millimeters, of the previous period (equations 3 and 4).

Crop production functions are described in terms of relative yield (Y_{ac}/Y_{mc}) and relative evapotranspiration (ET_{ck}). The form of the linear relationship is expressed in equation 6, where K_{Ick} is the yield response factor relative to moisture stress for crop c during period k.

The response factors represent yield reductions and ET suppression during individual growth periods as presented by Doorenbos and Kassam (1979).

Model Operation

Cost equations for application systems and yield response factors are modeled for a fixed, user-defined crop distribution. However, crop distributions can be varied according to soil type. A maximum of ten crop distributions and a maximum of five soil types can be modeled within one linear-programming matrix. Each soil type can have unique crop distributions and irrigation system costs. A total of ten application system types can be considered by the matrix generator described in the following section. However, only one application system type can be modeled per LP matrix run.

The planner has the option of the form for expressing conveyance costs. Conveyance system costs (pipelines, canals or pumping systems) can be expressed in terms of fixed and variable annual costs per unit of system flow rate or per millimeter per day of soil moisture replacement rate over the area served. Conveyance system costs can also be expressed in terms of equivalent annual cost per unit volume of water diverted by project farms.

Capital costs for canal conveyance systems are expressed in terms of fixed and variable costs per unit of design flow rate. Coefficients for these equations are obtained by regression analysis using the CANAL routine.

System application and conveyance efficiencies are accounted for by sizing canal reaches according to efficiencies and flow requirements of all downstream reaches. The maximum canal flow rate is based upon the maximum cummulative irrigation application rate over all crop and soil types. The value of the cummulative R_{maxc} values is calculated within the LP matrix through a series of inequality rows. Each row requires the cummulative R_{maxc} to be greater than the cummulative R_{ci} over all crop and soil types during a particular period i. This results in the value of the cummulative R_{maxc} equal to the maximum cummulative R_{ci}.

Energy requirements are modeled in terms of both kilowatt hours per time period and season and in terms of peak kilowatt demand for specific crops and for the project. Water requirements are modeled in terms of half-monthly and seasonal volume requirements and in terms of peak use rates. Farm irrigation labor is accounted on a seasonal basis. Upper limits are assigned for total allowable project energy use and power demand along with water volumes and flow rates.

Equivalent annual after-tax costs for production, not including irrigation related costs, are expressed in terms of fixed and variable costs per acre. Variable costs are those that vary per unit of yield.

Crop evapotranspiration and soil moisture levels during individual time periods are bounded in the LP model by maximum values based on average annual maximums and are bounded on the lower end by zero. Crop relative ET ratios are bounded by a lower limit which is user-defined according to crop growth period and are bounded by an upper limit of 1.0. Relative yield ratios are bounded by limits of 0 and 1.

Six sprinkler system types were selected for analysis within the LP framework. These six types are hand line, wheel line (side roll), center pivot systems equipped with impact sprinklers at 410 kPa (60 psi) pressure, center pivot systems equipped with spray booms, linear move systems equipped with spray booms and 100 meter-long supply hoses, and linear move systems equipped with spray booms and automated "riser-catcher" drive towers. The spray boom machines were specified to operate at pressures of 100 kPa (15 psi) at the nozzles and hand line and wheel line systems were specified to operate at nozzle pressures of 280 kPa (40 psi).

Costs for project offstream storage reservoirs and supplemental water supply facilities are those estimated by Galinato and Packer (1981a). Costs for enlargement of the Twin Falls High Line Canal and construction of a new supply canal across Salmon Falls Creek to project reservoirs were estimated using CANAL. Reservoir, supplemental supply costs and reservoir supply canal costs were converted into an annual, after-tax cost per acre-foot of farm diversions. These costs totaled $325 per ha-m ($40 per ac-ft) after taxes.

RESULTS

Results of applying the linear-programming model to the six sprinkler system types are summarized in Tables 1 through 6 for hand line, wheel line, impact center pivots, spray-boom center pivots, hose-pull linear move and riser-catcher linear move systems. Average system capital costs in these tables include annual after-tax costs for sprinkler systems, pipe networks, pumping plants, and open-channel conveyance systems. These costs do not include costs for project reservoirs or construction of the gravity canal system to the Bruneau project which are included in the per-unit cost for water. Total annual after-tax costs include all production and irrigation costs of the project development.

Included within Tables 1 through 6 are target average application rates for each half-monthly period for profit maximization and resulting expected average crop evapotranspiration (ET) rates during each period. For all six systems, optimal ET levels are at maximum values during all periods for potatoes and dry beans and decrease from potential amounts for spring wheat and sugar beets during late June and July, depending on system type. Optimized yields for all crops are within 97 percent of potential, except for spring wheat under wheel lines where the estimated optimum average yield is only 85 percent of the potential 5.73 tons/ha (85 bu/ac). "Optimal" target effective application rates (100 percent efficiency) are presented for the four crops and for the average for wheel line systems in Figure 3 and for riser-catcher linear move systems in Figure 4. Optimal evapotranspiration rates for crops under linear move systems are presented in graphical form in Figure 5.

For all six systems, the most profitable effective application rates for both operation and design during the July 1-15 period are about 90 percent of the average peak period ET rates (7.4 mm/day). This result emphasizes the importance of soil moisture storage in reducing peak design requirements. The average effective application rate during June 16-30 is greater than the average ET during that period, indicating a build up of soil moisture reserve before the peak July 1-15 period.

The irrigation system design and management specified for the six systems in Tables 1 through 6 are strategies for maximization of net profits for the anticipated costs, prices and planning parameters used in the simulation. However, calculated net annual after-tax profits for the systems are negative, ranging from -$314 per ha (-$127 per ac) for wheel lines, to -$245 per ha (-$98 per ac) for the linear-move systems. These net profits include all after-tax costs for new land ownership, crop production, irrigation, and water delivery. Equivalent annualized prices for crops were projected to increase in value at the same rate as the composite growth rate (4.7 percent per year). Deviations from these price levels would significantly affect the profitability of the irrigation development. Economic results from this study are similar to those obtained by Galinato and Packer (1981) for the Bruneau Plateau irrigation development, thereby confirming model calculations.

Parametric Analyses

Predicted crop prices were varied from the 1977-1982 indexed averages used in the optimal analyses to determine effects of price variation on system design and economics. Prices were varied from a low of 25 percent of the 1977-1982 average to a high of 200 percent of the 1977-1982 average.

Net after-tax farm profits for hand line, center pivot-spray-boom and riser-catcher linear move systems are presented in graphical form versus relative composite crop prices in Figure 6. From this figure, it appears that an increase in current levels of crop prices of about 18 percent would be required to achieve a positive net, after-tax farm profit in the study area under any of the sprinkler types. This necessary increase for profitability assumes that crop prices will keep pace with inflation (the composite growth rate) which has been estimated to be 4.7 percent per year. The proximity of system cost curves in Figure 6 indicates that differences in capital and other costs between the system types are overshadowed by the larger magnitudes of production costs and crop revenues. A similar increase in profitability could also have been obtained by decreasing production costs 18 to 22 percent.

Irrigation management and design for spring wheat and sugar beets are more sensitive to changes in crop price levels than for potatoes and beans. Effective application rates (essentially irrigation schedules) specified for spring wheat watered with riser-catcher linear move systems are presented in Figure 7 over a range of crop price levels. The increase in application rate during early June for spring wheat as crop prices decrease results from the decrease in application rate during May, a less moisture-sensitive growth period. Soil moisture is depleted during April and May, and the crop is stressed during that period as shown in Figure 8. Soil moisture is recharged by higher application rates during June. Increases in crop prices to values greater than 100 percent of anticipated prices have no effect on application rates or evapotranspiration, as these rates reach maximum values at the 100 percent price level.

Figure 9 provides a summary for riser-catcher linear move systems where seasonal diversions are limited to a project average of 0.27 ha-m/ha (0.90 ac-ft/ac) which is 40 percent of the optimal diversion requirement. Application rates during half-monthly periods for the four crops and mean are presented in Figure 9, and evapotranspiration rates are presented in Figure 10. The spiking of application rates as shown in Figure 9 is caused by higher magnitudes of yield response factors during moisture-sensitive growth periods. Some water application is required throughout the season on all crops due to the minimum constraint placed on the ET ratio (actual ET / potential ET) during each growth stage, necessitated by the need to keep the crops alive. The minimum ET ratio constraint ranges from 0.5 to 0.6 for potatoes, 0.5 to 0.65 for dry beans, 0.5 to 0.6 for spring wheat and 0.25 for sugar beets, as specified in the bounds section of the LP matrix. The average net annual after-tax farm profit for riser-catcher linear move systems would decrease by $550 per ha with the 0.27 ha-m/ha limitation.

Constraints were placed upon allowable project diversion rates to evaluate changes in design, management and economics of project irrigation systems. LP design solutions for riser-catcher linear move systems are summarized in Figures 11 through 14 for diversion rates of 94, 78, 67, and 54 percent of the optimal diversion rate. It should be noted that as the peak allowable diversion rate is decreased, economics suggest extension of the average peak rate later into the season. Individual crops are targeted to peak much higher than the average during moisture-sensitive growth periods, similar to effects from reducing seasonal diversion volumes.

The recommended changes in scheduling of irrigation applications on sugar beets for linear move systems are presented in graphical form in

Figure 15 over the range of 40 to 100 percent of optimal diversion rates. As the diversion rate is constrained to lower rates, irrigation of sugar beets is delayed later into the season. The corresponding reduction in evapotranspiration by sugar beets is presented in Figure 16. Evapotranspiration by beets is reduced beginning at 94 percent of optimal diversion capacity (2.58 m^3/s) with very large stresses at diversion rates less than 67 percent of optimal. Target yields for sugar beets were 55.2, 53.4, 49.0, 45.4, 43.3 and 39.7 metric tons per hectare when diversion capacity was limited to 100, 94, 78, 67, 54 and 40 percent of maximum.

Figure 17 indicates sensitivity of farm profit to constraints on peak diversion requirements. Net after-tax profits are not significantly reduced until diversions are limited to less than about 75 percent of optimal requirements (duty of 1270 ha/m^3/s or 95 ac/cfs). The shape of curves included in Figure 18 indicates that the reductions in diversion volumes do not decrease linearly with diversion rate, but that diversion earlier and later in the season can partially offset effects of reduced peaks. Decreases in seasonal diversion volumes are accelerated at diversions less than 2.0 m^3/s for the 2700 ha project.

Because costs for irrigation energy for pressurization and lifting water to project farms were only 4 percent of total annual production costs for hand lines and 2.5 percent of production costs for riser-catcher linear move systems, doubling of energy costs decreased net after-tax profit by only $32 per ha ($13/ac) per year for the linear move system and $52 per ha ($22/ac) per year for hand lines.

As the annual charge for water diverted by project farms was increased from $325/ha-m to a total charge of $570/ha-m, it became economical to underirrigate spring wheat, with average annual yields decreased by 0.42 metric tons per ha (6.2 bu/ac). The net farm after-tax profit was reduced by $188 per ha ($75 per ac) per year for hand line systems, and project diversions were decreased from 0.81 ha-m/ha to 0.74 ha-m/ha (2.66 ac-ft/ac to 2.43 ac-ft/ac).

Shadow Pricing

Shadow prices on soil moisture equations within the linear-programming model were used to indicate the value of increasing available soil moisture, in millimeters, during a half-monthly period. These prices can be useful in estimating the importance or value of selecting or developing deeper-rooted crop varieties or of increased use of seasonal rainfall. In the case of riser-catcher linear move systems, the increase in net after-tax profit obtained by increasing available soil moisture for potatoes averaged $180/ha-m ($4.65 per ac-in) for the optimal solution and approached $1170 per ha-m ($30/ac-in) per year when project diversion capacity was limited to 54% of optimal. This indicated that the 2700 ha project, if under limited diversion capacity, could afford to invest a present worth of about $400,000 on research, conservation, or varietal development if available soil moisture on the 680 ha (1670 ac) of potatoes grown in the project were increased as a result of the investment by 0.025 ha-m/ha (1 ac-in/ac) per year. This sensitivity analysis on soil moisture also indicates the economic importance of obtaining accurate soil moisture data and accurately assessing the role soil moisture plays in fulfilling irrigation water requirements and in dampening irrigation requirement peaks.

SUMMARY

The LP model was applied to six irrigation system types: hand lines, wheel lines, center pivots with impact sprinklers, center pivots with spray booms, linear move systems with spray booms and hose attatchments and linear move systems with spray booms and riser-catching drive towers. The systems with the highest net, after-tax annual profits were the linear move systems, with profits averaging -$245 per ha (-$98 per ac) per year. Net profits for these systems became positive as crop price estimates were increased by 18%. None of the crops evaluated have positive net profits with cost and price estimates used within the analysis. Dry, commercial beans were calculated to have the least negative profit, averaging about -$55 per ha ($22 per ac) for linear move systems. Potatoes and sugar beets were the least profitable crops due to high production costs.

Parametric analyses were performed on hand line, center pivots with spray boom attachments and linear move systems with riser-catchers. These analyses indicate resiliencies of design, management, and economics of the various systems to changes in planning parameters or system constraints.

CONCLUSIONS

The ETSM model which was developed to calculate expected reduction in crop evapotranspiration resulting from moisture stress produced good results over a broad range of soil moisture levels and irrigation system application rates. Annual estimates of half-monthly ET were found to be normally distributed about mean (expected) values over the available weather record. Comparison of ETSM model runs using daily, half-monthly and long-term average ET and precipitation data indicated that the model may be used in areas where only long-term averages of weather data are available.

The cost estimating routines APSYS, CANAL and NWRKLN provided linear equations with high coefficients of determination (r^2) over ranges of application and system flow rates modeled. The APSYS routine is a good, detailed model for design and planning of sprinkler and mainline systems. It considers soil, crop, climatic, hydraulic, economic and management requirements. One limitation of APSYS is that it does not consider specific variations in land elevation or topography. However the model was developed to be used for general planning studies over a project area. In addition, the NWRKLN model does consider topography in laying out pipe distribution systems, so that only elevation changes on individual farms are not considered.

The NWRKLN routine provided good estimates of pipe network costs, pipe specifications and pumping system and energy requirements. Results from this routine were used within the LP procedure to describe costs for pipe distribution systems.

The MATRX matrix generater functions well by freeing the planner from the tedious task of manually designing and formulating the linear-programming matrix. In addition, MATRX includes all information required to combine system cost and hydraulic information and ET-application rate information into a working model, thereby assisting the planner in understanding the workings of the linear-programming model and set up. MATRX is flexible and able to model most project layouts.

The linear-programming model provides optimal results for irrigation project planning and management from the stand point of irrigation system size and water application for a fixed crop distribution. The linearity of the model allows for ease of parametric analyses, resulting in a flexible, "what if" model. Many assumptions and estimates of physical and economic conditions are required in calculating system and crop production costs and yield, ET and hydraulic relationships. These assumptions and estimates along with the model linearity precludes formulation of "exact" system designs and management strategies. However, model results appear to be realistic and very usable for systems planning and sensitivity analyses.

The linear-programming model presents design and management strategies for the average year case. If farmers follow the optimal application rate schedule outlined by the LP model, there will be some years in which ET demands are lower and resulting yields are greater than model predictions. Correspondingly, there will be years in which ET demands and resulting deficits are greater with lower than predicted yields. With the indication of normality of ET deficits about the long-term mean, yields during individual years and operating costs and crop revenues should average out to values equivalent to those estimated by the model. Cash flow problems are likely to occur under most of the strategies suggested by the LP model, especially under some of the constrained paratmetric conditions evaluated. However, the long term economic result will be equivalent to the LP estimate with a possible difference in net annual profit equal to interest on short term loans less interest on short term savings times average flucuations in production costs and revenues. Since the sequence of high and low ET and precipitation years is not known over the project life, there is no good way to quantify the financial feasibility of the project without involved stochastic or time series analyses and without knowing the financial health and backing of the developer.

The modeling procedure developed and described should be useful in systems planning in water short areas such as the Texas High Plains region. The LP framework can be applied to currently installed irrigation systems by setting capital costs equal to current costs and limiting the system size to that of the current system. System management strategies, economics and sensitivities to price and water constraints and fluctuations should provide useful planning and management information.

According to results of application of the model to the Little Pilgrim study area, development of the project as formulated in this study should not be pursued. However, if development is pursued, farmers should attempt to acheive full production on all crops, since the net annual profit under full production would be less negative than if deficit irrigation were employed. Water management and irrigation scheduling should be implemented according to system type. Linear move systems appear to be the least-cost system under the modeled conditions.

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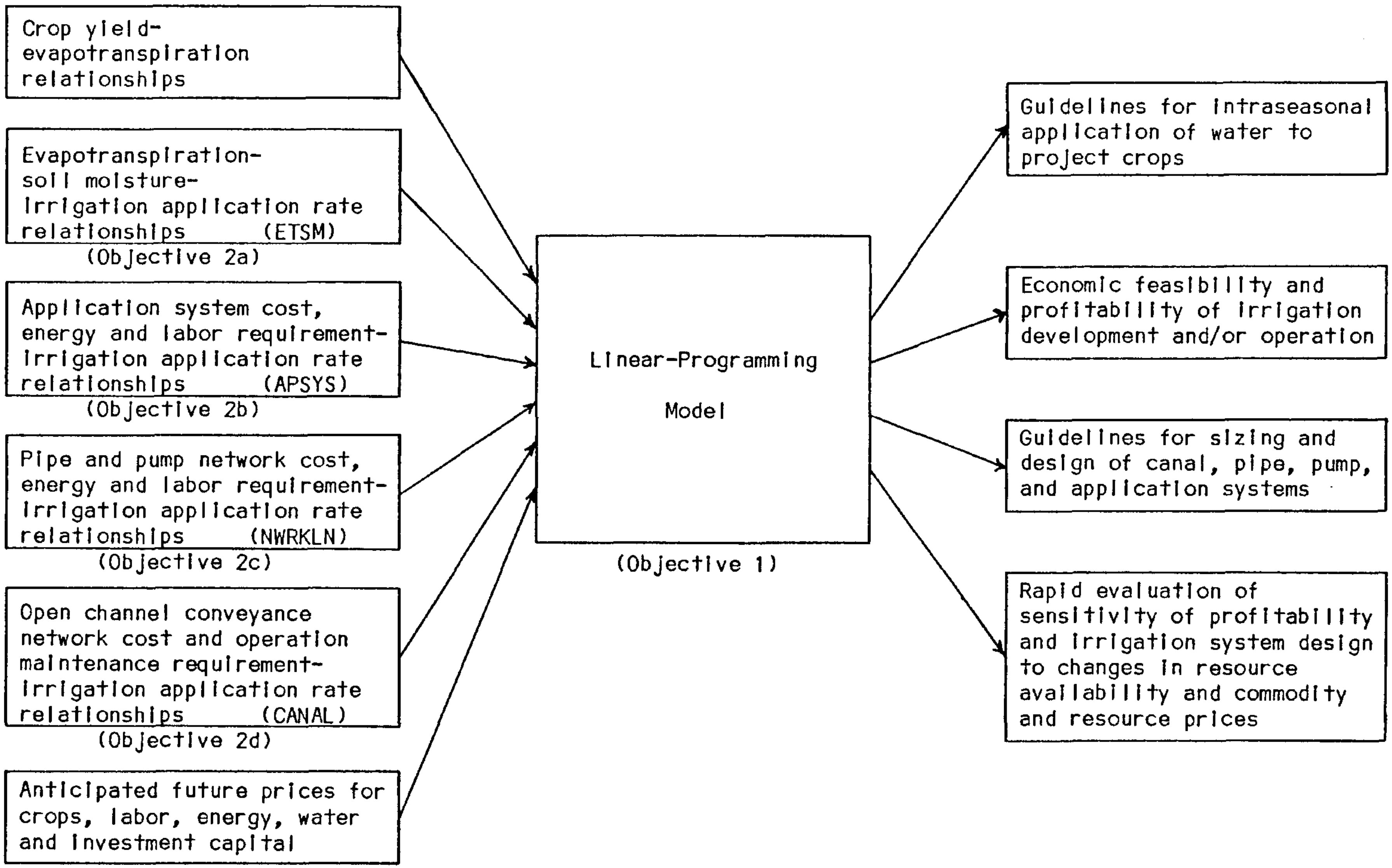

Figure 1. Conceptual description of the modeling and optimization procedure.

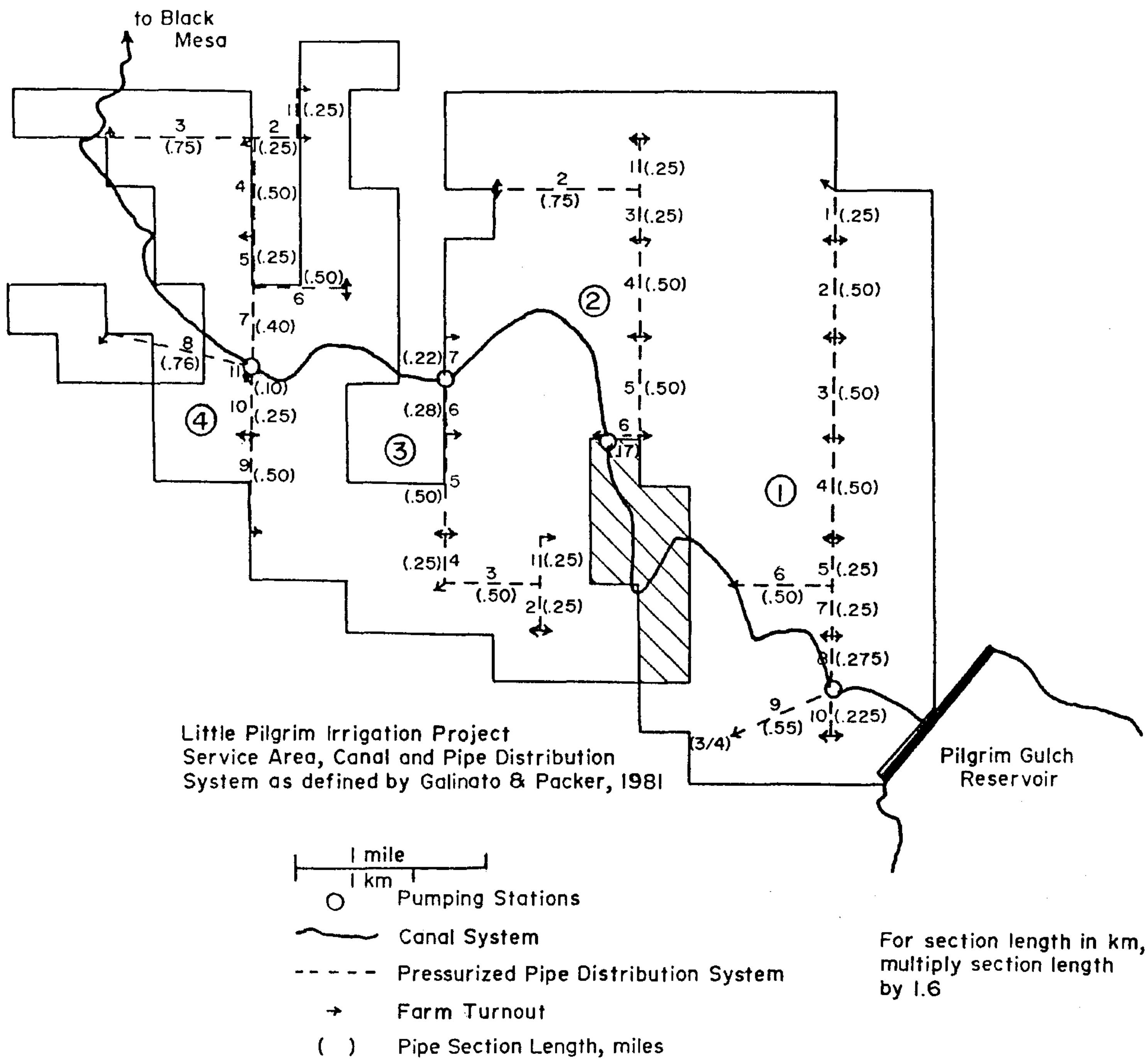

Figure 2. Schematic diagram of the canal and pipe distribution system of the Little Pilgrim study area and section numbering and lengths for the pipe distribution system.

Table 1. Optimal design solution for hand line, high pressure pipe and canal systems for the Little Pilgrim study area.

	ET, mm/day					Eff. Application Rate, mm/day				
Period	Pot.	Beans	Sp.Gr	S.Bt	Ave.	Pot.	Beans	Sp.Gr	S.Bt	Ave.
4/ 1-15			.61		.15			1.34		.33
4/16-30	.71		1.09	.64	.61	.83		1.31		.53
5/ 1-15	.87		1.81	.54	.81	2.59				.65
5/16-31	1.28	.97	5.77	.68	2.18	2.96	1.24	7.29		2.87
6/ 1-15	2.93	1.38	7.02	2.02	3.34	4.71	1.86	5.65	1.97	3.54
6/16-30	5.50	3.79	8.10	5.58	5.74	6.97	5.26	7.54	6.55	6.58
7/ 1-15	6.32	7.18	7.54	7.85	7.22	6.22	7.54	6.34	6.40	6.63
7/16-31	6.17	7.56	4.94	8.03	6.68	6.48	6.55	4.33	7.39	6.19
8/ 1-15	5.76	6.09	1.40	7.23	5.12	6.03	4.57	.35	5.87	4.20
8/16-31	4.82	2.54		5.90	3.32	5.48	2.16		4.48	3.03
9/ 1-15	4.07	.41		4.81	2.32	3.70			3.14	1.71
9/16-30				3.75	.94				3.02	.76
10/1-15				2.31	.58					

	Pot.	Beans	Sp.Gr	S.Bt	Ave.
Estimated yield, metric tons/ha	33.7	2.45	5.57	55.0	Ave.
Irrigation labor req., hours/ha/yr	15.76	7.73	5.41	4.10	8.25
Irrigation energy req., kwh/ha/yr	2250.	1430.	1670.	1900.	1810.
Farm diversions, ha-m/ha/yr	1.01	.64	.75	.85	.81
Irrigation energy costs, $/ha/yr	67.	43.	50.	57.	54.
Variable production costs, $/ha/yr	541.	42.	123.	252.	240.
Fixed production costs, $/ha/yr	1870.	600.	330.	1600.	1100.
Average system capital costs, $/ha/yr					155.
Total annual after-tax costs, $/ha	3020.	1080.	920.	2360.	1850.
Net after-tax farm profit, $/ha/yr	-427.	-87.	-288.	-369.	-293.
Peak project power req., kw (2700 ha)					2430.

Canal sections (0) 3.37 (1) 3.03 (2) 2.01 (3) 1.27 (4) .79 m^3/s. ($57./ha/yr)

Table 2. Optimal design solution for wheel line, high pressure pipe and canal systems for the Little Pilgrim study area.

	ET, mm/day					Eff. Application Rate, mm/day				
Period	Pot.	Beans	Sp.Gr	S.Bt	Ave.	Pot.	Beans	Sp.Gr	S.Bt	Ave.
4/ 1-15			.61		.15			3.12		.78
4/16-30	.71		1.09	.64	.61	.83		.82		.41
5/ 1-15	.87		1.82	.54	.81	2.59				.65
5/16-31	1.28	.97	5.77	.68	2.18	2.96	1.24	7.28		2.87
6/ 1-15	2.93	1.38	7.02	2.02	3.34	4.71	1.86	5.65	1.97	3.55
6/16-30	5.50	3.79	8.10	4.04	5.36	6.97	5.26	7.54	2.77	5.64
7/ 1-15	6.33	7.18	4.60	8.34	6.61	6.22	7.54		9.51	5.82
7/16-31	6.16	7.56	4.94	5.85	6.13	6.48	6.55	7.36	2.09	5.62
8/ 1-15	5.76	6.09	1.40	7.23	5.12	6.03	4.57	.43	8.38	4.85
8/16-31	4.82	2.54		5.90	3.32	5.48	2.16		4.50	3.04
9/ 1-15	4.07	.41		4.81	2.32	3.70			3.14	1.71
9/16-30				3.75	.94				3.02	.76
10/1-15				2.31	.58					

	Pot.	Beans	Sp.Gr	S.Bt	Ave.
Estimated yield, metric tons/ha	33.7	2.45	4.85	52.8	Ave.
Irrigation labor req., hours/ha/yr	7.06	3.90	2.49	1.21	3.68
Irrigation energy req., kwh/ha/yr	2250.	1430.	1220.	1730.	1650.
Farm diversions, ha-m/ha/yr	1.01	.64	.71	.77	.78
Irrigation energy costs, $/ha/yr	67.	43.	47.	52.	52.
Variable production costs, $/ha/yr	541.	42.	109.	242.	235.
Fixed production costs, $/ha/yr	1870.	600.	330.	1600.	1100.
Average system capital costs, $/ha/yr					172.
Total annual after-tax costs, $/ha	3010.	1080.	900.	2320.	1830.
Net after-tax farm profit, $/ha/yr	-408.	-89.	-346.	-413.	-314.
Peak project power req., kw (2700 ha)					2130.

Canal sections (0) 2.95 (1) 2.66 (2) 1.76 (3) 1.13 (4) .68 m^3/s. ($56./ha/yr)

Table 3. Optimal design solution for impact-center pivot, high pressure pipe and canal systems for the Little Pilgrim study area.

Period	ET, mm/day Pot.	Beans	Sp.Gr	S.Bt	Ave.	Eff. Application Rate, mm/day Pot.	Beans	Sp.Gr	S.Bt	Ave.
4/ 1-15			.61		.15			3.17		.79
4/16-30	.71		1.09	.64	.61	.83		1.31		.53
5/ 1-15	.87		1.81	.54	.81	2.59				.65
5/16-31	1.28	.97	5.77	.68	2.18	2.96	1.24	7.29		2.87
6/ 1-15	2.93	1.38	7.02	2.02	3.34	4.71	1.86	5.65	1.97	3.54
6/16-30	5.50	3.79	8.03	5.58	5.72	6.97	5.26	7.36	6.55	6.54
7/ 1-15	6.32	7.18	7.53	8.34	7.34	6.22	7.54	5.22	7.40	6.60
7/16-31	6.17	7.56	4.94	8.03	6.68	6.48	6.07	4.35	6.92	5.95
8/ 1-15	5.76	6.09	1.40	7.23	5.12	6.03	4.60	1.30	5.87	4.45
8/16-31	4.82	2.54		5.90	3.32	5.48	2.16		4.48	3.03
9/ 1-15	4.07	.41		4.81	2.32	3.70			3.14	1.71
9/16-30				3.75	.94				3.02	.76
10/1-15				2.31	.58					
Estimated yield, metric tons/ha						33.7	2.45	5.55	55.2	<u>Ave</u>.
Irrigation labor req., hours/ha/yr						1.23	.52	.74	.91	.86
Irrigation energy req., kwh/ha/yr						2580.	1610.	2000.	2210.	2100.
Farm diversions, ha-m/ha/yr						.88	.55	.68	.75	.72
Irrigation energy costs, $/ha/yr						77.	48.	60.	66.	63.
Variable production costs, $/ha/yr						541.	42.	123.	252.	240.
Fixed production costs, $/ha/yr						1870.	600.	330.	1600.	1100.
Average system capital costs, $/ha/yr										198.
Total annual after-tax costs, $/ha						2980.	1070.	940.	2370.	1840.
Net after-tax farm profit, $/ha/yr						-383.	-80.	-306.	-371.	-285.
Peak project power req., kw (2700 ha)										2730.

Canal sections (0) 2.92 (1) 2.66 (2) 1.76 (3) 1.10 (4) .68 m^3/s. ($56./ha/yr)

Table 4. Optimal design solution for spray-boom center pivot, high pressure pipe and canal systems for the Little Pilgrim study area.

Period	ET, mm/day Pot.	Beans	Sp.Gr	S.Bt	Ave.	Eff. Application Rate, mm/day Pot.	Beans	Sp.Gr	S.Bt	Ave.
4/ 1-15			.61		.15			1.34		.33
4/16-30	.71		1.09	.64	.61	.83		1.31		.53
5/ 1-15	.87		1.81	.54	.81	2.59				.65
5/16-31	1.28	.97	5.77	.68	2.18	2.96	1.24	7.29		2.87
6/ 1-15	2.93	1.38	7.02	2.02	3.34	4.71	1.86	5.65	1.97	3.54
6/16-30	5.50	3.79	8.10	5.58	5.74	6.97	5.26	7.54	6.55	6.58
7/ 1-15	6.32	7.18	7.12	8.34	7.24	6.22	7.54	5.44	7.40	6.65
7/16-31	6.17	7.56	4.94	8.03	6.68	6.48	6.55	4.76	6.92	6.18
8/ 1-15	5.76	6.09	1.40	7.23	5.12	6.03	4.57	.36	5.87	4.21
8/16-31	4.82	2.54		5.90	3.32	5.48	2.16		4.48	3.03
9/ 1-15	4.07	.41		4.81	2.32	3.70			3.14	1.71
9/16-30				3.75	.94				3.02	.76
10/1-15				2.31	.58					
Estimated yield, metric tons/ha						33.7	2.45	5.47	55.2	<u>Ave</u>.
Irrigation labor req., hours/ha/yr						1.58	.64	1.04	1.16	1.11
Irrigation energy req., kwh/ha/yr						1480.	940.	1080.	1270.	1190.
Farm diversions, ha-m/ha/yr						.88	.56	.65	.75	.71
Irrigation energy costs, $/ha/yr						44.	28.	33.	38.	36.
Variable production costs, $/ha/yr						541.	42.	121.	252.	240.
Fixed production costs, $/ha/yr						1870.	600.	330.	1600.	1100.
Average system capital costs, $/ha/yr										207.
Total annual after-tax costs, $/ha						2960.	1060.	910.	2350.	1820.
Net after-tax farm profit, $/ha/yr						-361.	-71.	-284.	-353.	-267.
Peak project power req., kw (2700 ha)										1580.

Canal sections (0) 2.95 (1) 2.66 (2) 1.76 (3) 1.13 (4) .68 m^3/s. ($56./ha/yr)

Table 5. Optimal design solution for hose-pull linear move, high pressure pipe and canal systems for the Little Pilgrim study area.

Period	ET, mm/day Pot.	Beans	Sp.Gr	S.Bt	Ave.	Eff. Application Rate, mm/day Pot.	Beans	Sp.Gr	S.Bt	Ave.
4/ 1-15			.61		.15			1.34		.33
4/16-30	.71		1.09	.64	.61	.83		1.31		.53
5/ 1-15	.87		3.07	.54	1.12	2.59		3.93		1.63
5/16-31	1.28	.97	5.77	1.06	2.27	2.96	1.24	5.33	1.31	2.71
6/ 1-15	2.93	1.38	7.02	2.02	3.34	4.71	1.86	5.82	1.74	3.53
6/16-30	5.50	3.79	8.10	5.58	5.74	6.97	5.26	7.53	6.54	6.57
7/ 1-15	6.32	7.18	7.54	7.71	7.19	6.22	7.54	6.34	6.12	6.56
7/16-31	6.17	7.56	4.94	8.03	6.68	6.48	6.55	4.33	7.53	6.23
8/ 1-15	5.76	6.09	1.40	7.23	5.12	6.03	4.57	.35	5.87	4.20
8/16-31	4.82	2.54		5.90	3.32	5.48	2.16		4.48	3.03
9/ 1-15	4.07	.41		4.81	2.32	3.70			3.14	1.71
9/16-30				3.75	.94				3.02	.76
10/1-15				2.31	.58					
Estimated yield, metric tons/ha						33.7	2.45	5.73	55.2	<u>Ave</u>.
Irrigation labor req., hours/ha/yr						1.31	.74	.91	.96	.99
Irrigation energy req., kwh/ha/yr						1620.	1030.	1280.	1400.	1330.
Farm diversions, ha-m/ha/yr						.83	.53	.65	.72	.68
Irrigation energy costs, $/ha/yr						49.	31.	38.	42.	40.
Variable production costs, $/ha/yr						541.	42.	128.	252.	240.
Fixed production costs, $/ha/yr						1870.	600.	330.	1600.	1100.
Average system capital costs, $/ha/yr										193.
Total annual after-tax costs, $/ha						2930.	1040.	910.	2330.	1800.
Net after-tax farm profit, $/ha/yr						-336.	-52.	-257.	-333.	-245.
Peak project power req., kw (2700 ha)										1720.

Canal sections (0) 2.75 (1) 2.49 (2) 1.64 (3) 1.05 (4) .65 m^3/s. ($55./ha/yr)

Table 6. Optimal design solution for riser-catcher linear move, high pressure pipe and canal systems for the Little Pilgrim study area.

Period	ET, mm/day Pot.	Beans	Sp.Gr	S.Bt	Ave.	Eff. Application Rate, mm/day Pot.	Beans	Sp.Gr	S.Bt	Ave.
4/ 1-15			.61		.15			1.34		.33
4/16-30	.71		1.09	.64	.61	.83		1.31		.53
5/ 1-15	.87		3.07	.54	1.12	2.59		3.93		1.63
5/16-31	1.28	.97	5.77	1.06	2.27	2.96	1.24	5.33	1.31	2.71
6/ 1-15	2.93	1.38	7.02	2.02	3.34	4.71	1.86	5.82	1.74	3.53
6/16-30	5.50	3.79	8.10	5.58	5.74	6.97	5.26	7.53	6.54	6.57
7/ 1-15	6.32	7.18	7.54	7.70	7.19	6.22	7.54	6.34	6.09	6.55
7/16-31	6.17	7.56	4.94	8.03	6.68	6.48	6.55	4.33	7.54	6.23
8/ 1-15	5.76	6.09	1.40	7.23	5.12	6.03	4.57	.35	5.87	4.20
8/16-31	4.82	2.54		5.90	3.32	5.48	2.16		4.48	3.03
9/ 1-15	4.07	.41		4.81	2.32	3.70			3.14	1.71
9/16-30				3.75	.94				3.02	.76
10/1-15				2.31	.58					
Estimated yield, metric tons/ha						33.7	2.45	5.73	55.2	<u>Ave</u>.
Irrigation labor req., hours/ha/yr						.15	.10	.12	.10	.12
Irrigation energy req., kwh/ha/yr						1390.	880.	1100.	1210.	1140.
Farm diversions, ha-m/ha/yr						.83	.53	.65	.72	.68
Irrigation energy costs, $/ha/yr						42.	27.	33.	36.	34.
Variable production costs, $/ha/yr						541.	42.	128.	252.	240.
Fixed production costs, $/ha/yr						1870.	600.	330.	1600.	1100.
Average system capital costs, $/ha/yr										201.
Total annual after-tax costs, $/ha						2930.	1040.	910.	2330.	1800.
Net after-tax farm profit, $/ha/yr						-334.	-55.	-258.	-333.	-245.
Peak project power req., kw (2700 ha)										1490.

Canal sections (0) 2.75 (1) 2.49 (2) 1.64 (3) 1.05 (4) .65 m^3/s. ($55./ha/yr)

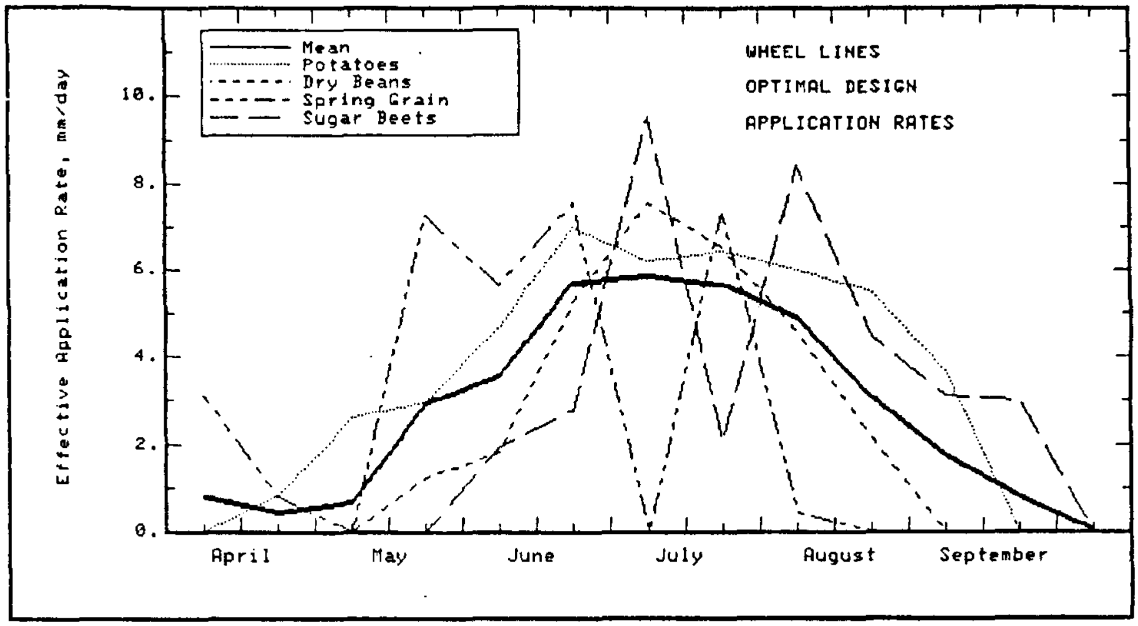

Figure 3. Optimal effective application rates during half-monthly periods for potatoes, dry beans, spring grain and sugar beets for wheel line systems in the Little Pilgrim study area.

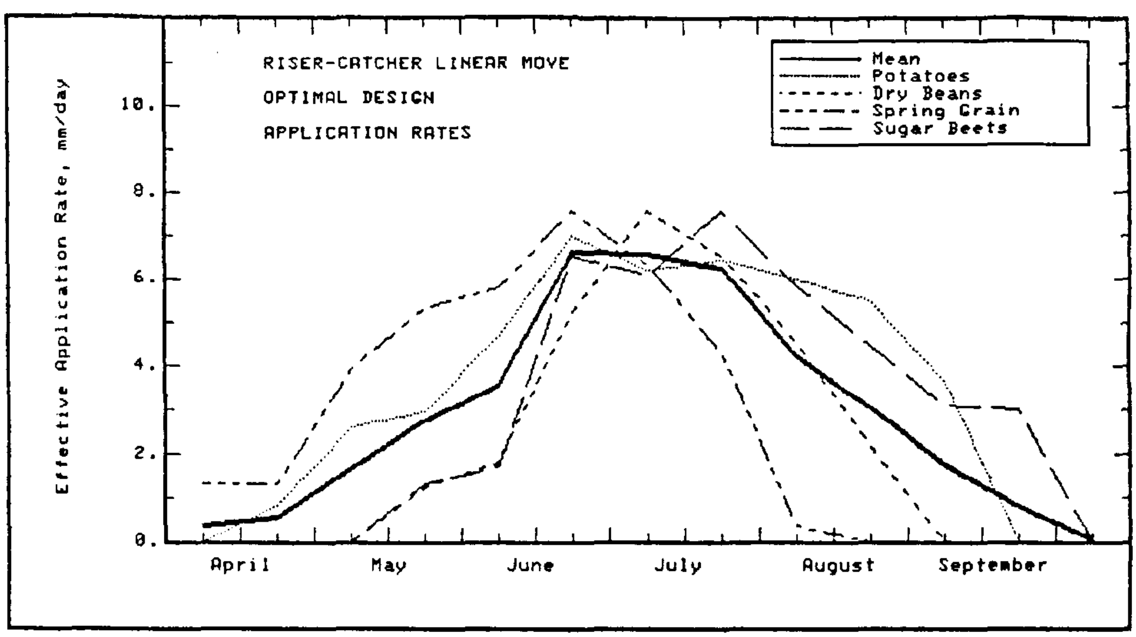

Figure 4. Optimal effective application rates during half-monthly periods for potatoes, dry beans, spring grain and sugar beets for riser-catcher linear move systems in the Little Pilgrim study area.

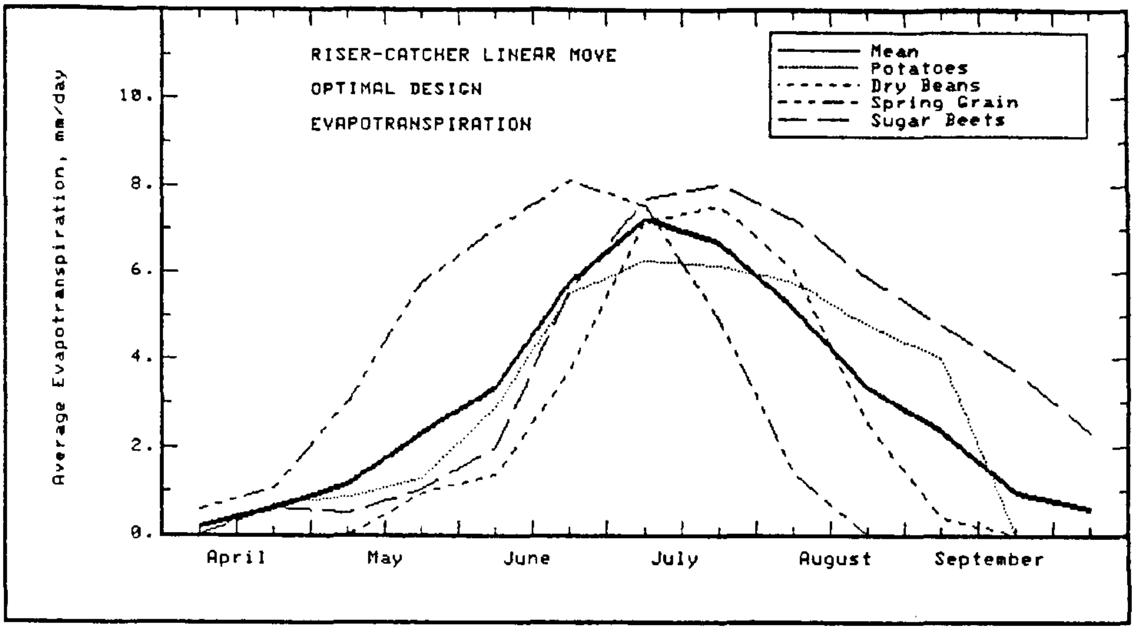

Figure 5. Optimal evapotranspiration rates for half-monthly periods for potatoes, dry beans, spring grain and sugar beets for riser-catcher linear move systems in the Little Pilgrem study area.

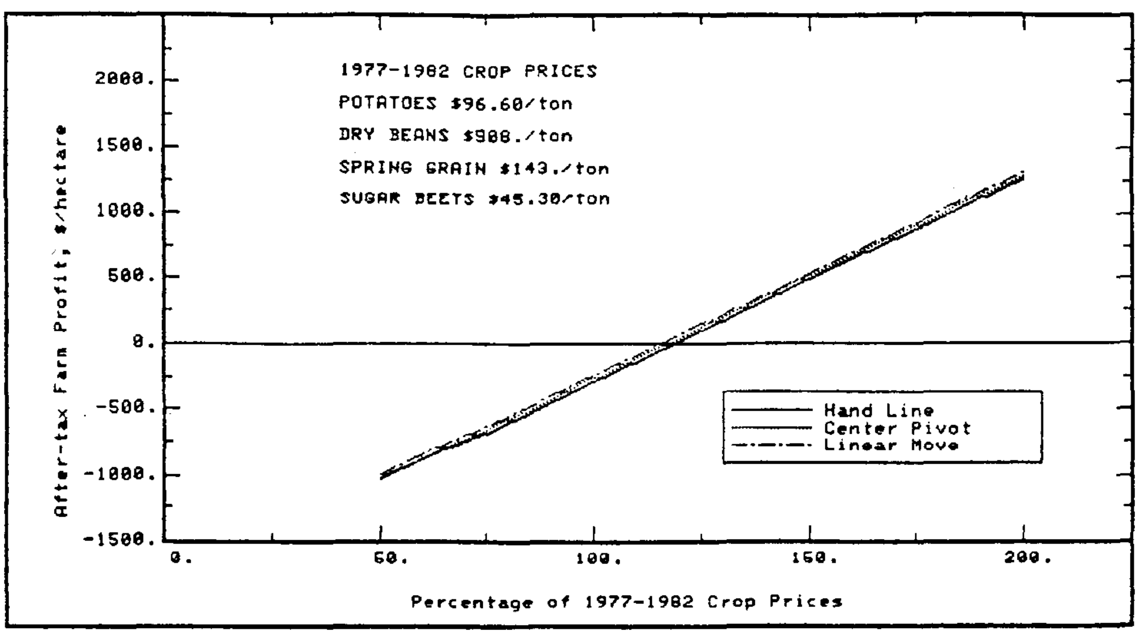

Figure 6. Net after-tax farm profit for hand line, spray-boom center pivot, and riser-catcher linear move systems with pressurized pipe and canal conveyance systems versus crop price levels for the Little Pilgrim study area.

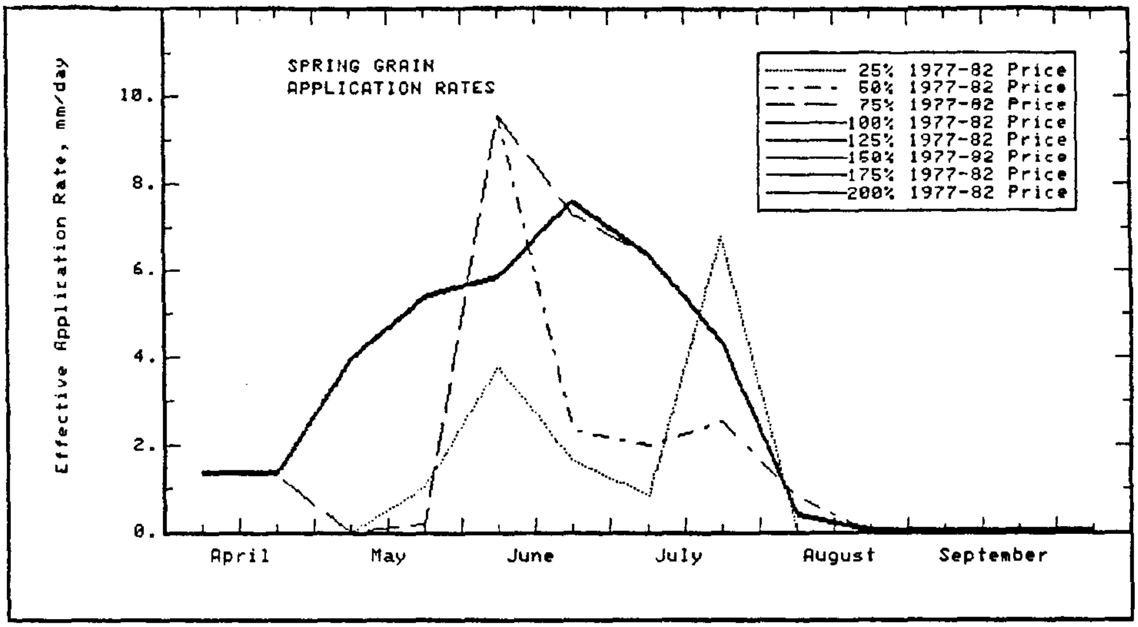

Figure 7. Optimal effective application rates during half-monthly periods at varying levels of crop prices for riser-catcher linear move systems on spring grain in the Little Pilgrim study area.

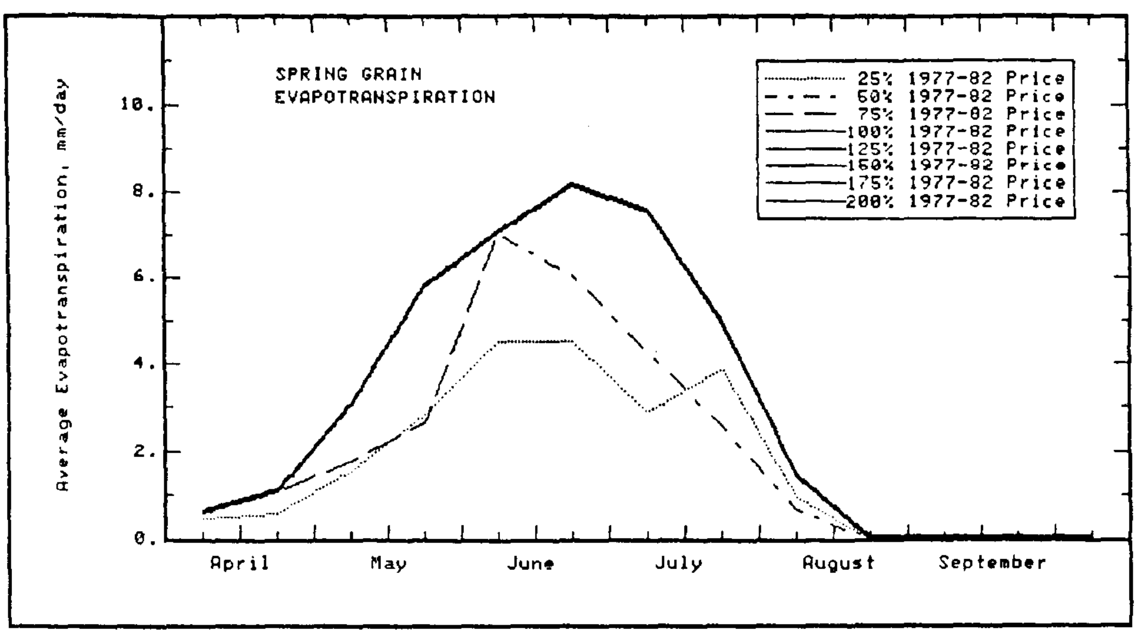

Figure 8. Optimal average evapotranspiration rates for half-monthly periods at varying levels of crop prices for riser-catcher linear move systems on spring grain in the Little Pilgrim study area.

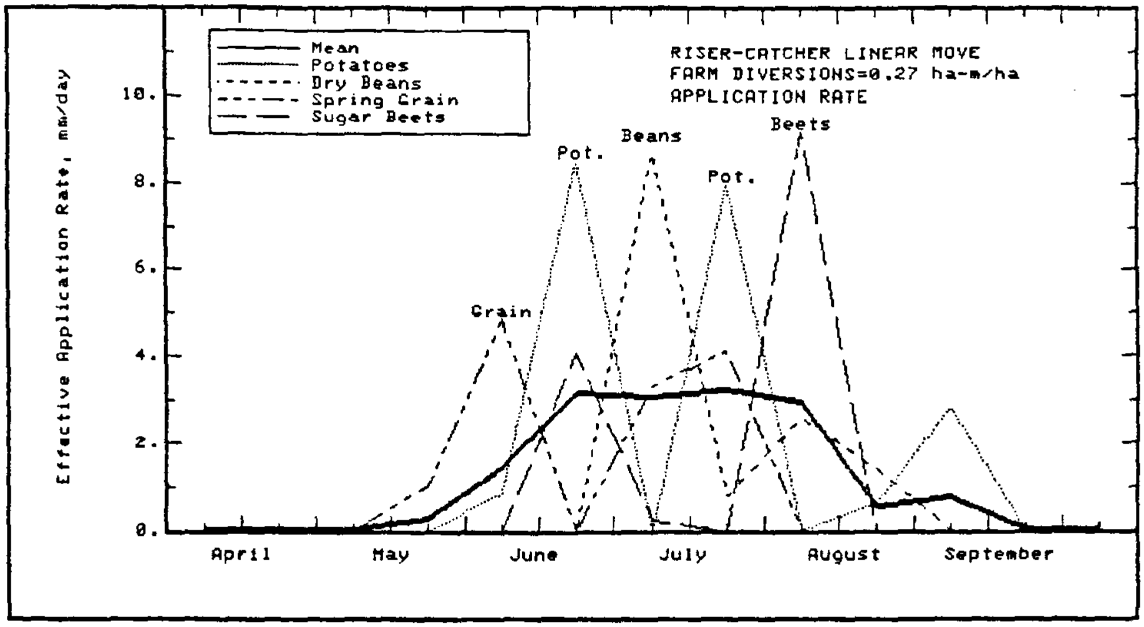

Figure 9. Effective application rates during half-monthly periods for potatoes, dry beans, spring grain and sugar beets for riser-catcher linear move systems in the Little Pilgrim study area when average annual farm diversions are limited to 0.27 ha-m/ha (optimal=0.68 ha-m/ha).

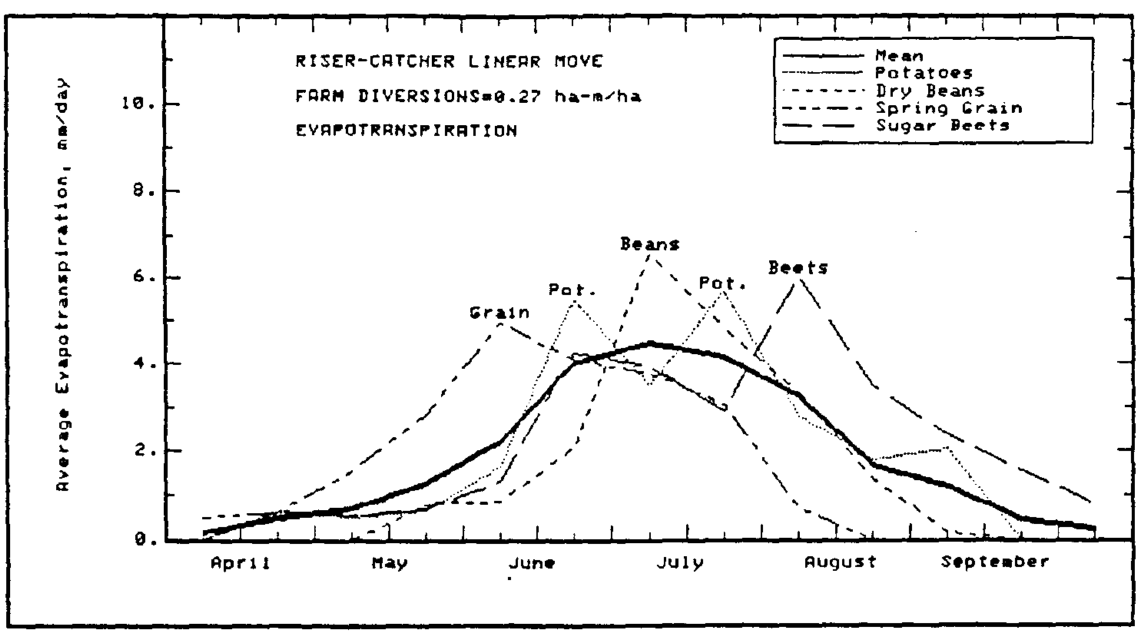

Figure 10. Average evapotranspiration during half-monthly periods for potatoes, dry beans, spring grain and sugar beets for riser-catcher linear move systems in the Little Pilgrim study area when average annual farm diversions are limited to 0.27 ha-m/ha (optimal=0.68 ha-m/ha).

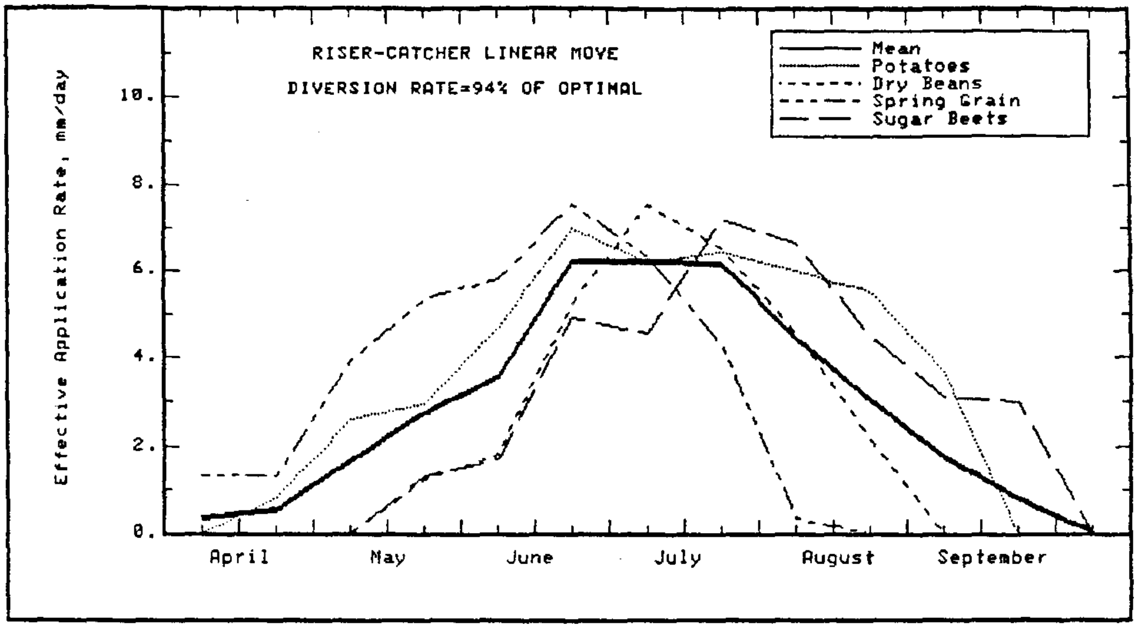

Figure 11. Effective application rates during half-monthly periods for potatoes, dry beans, spring grain and sugar beets for riser-catcher linear move systems in the Little Pilgrim study area when peak project diversions are limited to 2.58 cubic meters/second (optimal=2.75 cubic meters/second).

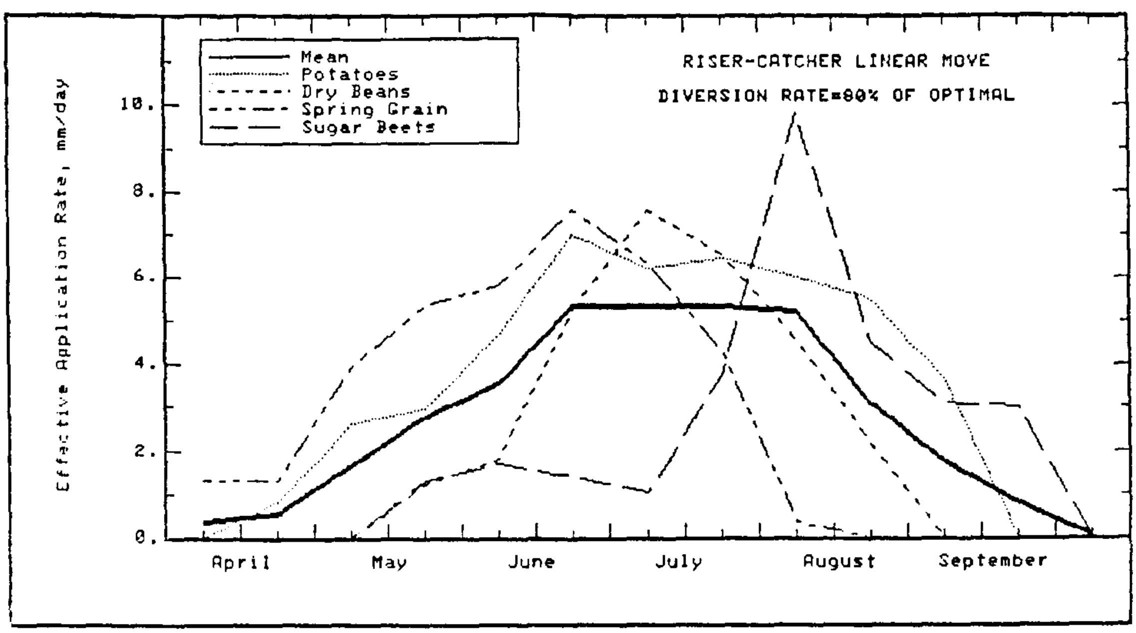

Figure 12. Effective application rates during half-monthly periods for potatoes, dry beans, spring grain and sugar beets for riser-catcher linear move systems in the Little Pilgrim study area when peak project diversions are limited to 2.21 cubic meters/second (optimal = 2.75 cubic meters/second).

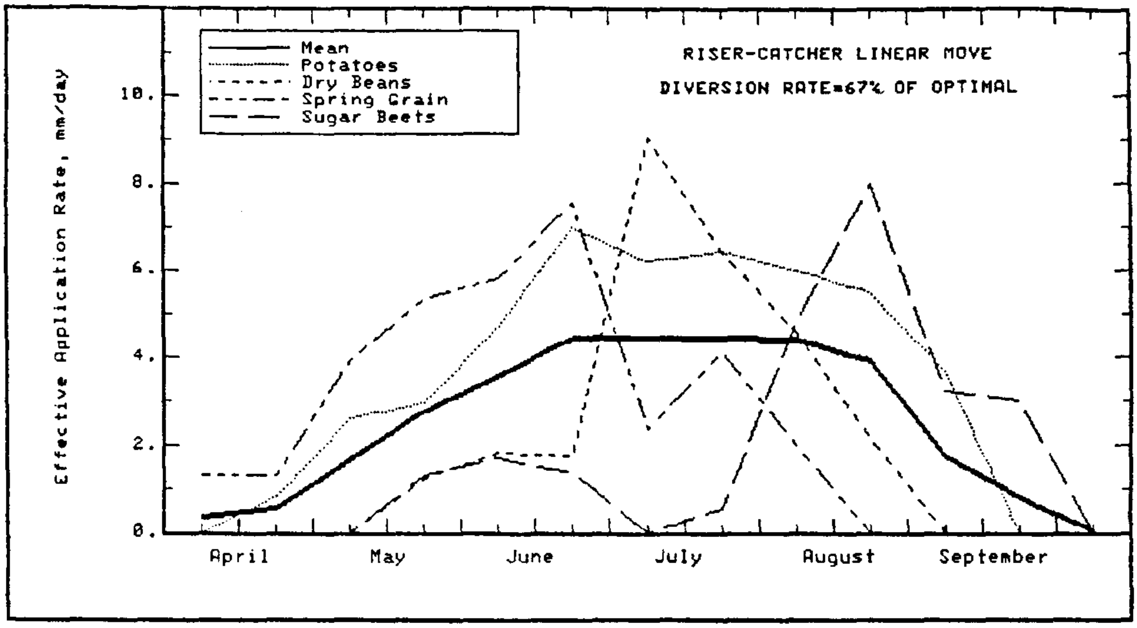

Figure 13. Effective application rates during half-monthly periods for potatoes, dry beans, spring grain and sugar beets for riser-catcher linear move systems in the Little Pilgrim study area when peak project diversions are limited to 1.84 cubic meters/second (optimal = 2.75 cubic meters/second).

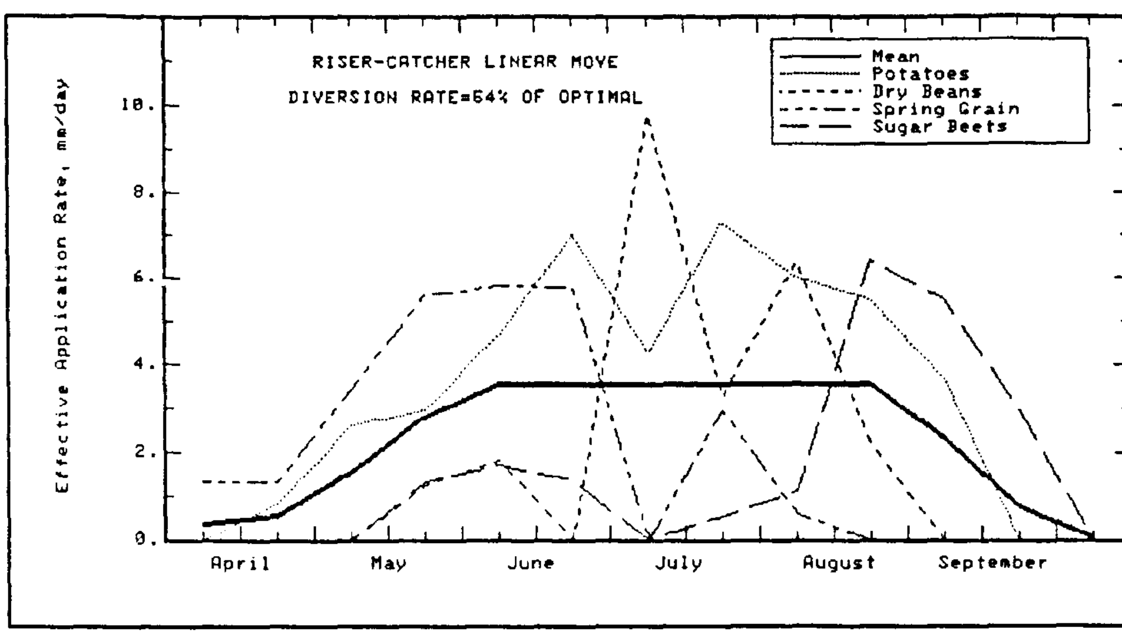

Figure 14. Effective application rates during half-monthly periods for potatoes, dry beans, spring grain and sugar beets for riser-catcher linear move systems in the Little Pilgrim study area when peak project diversions are limited to 1.47 cubic meters/second (optimal - 2.75 cubic meters/second).

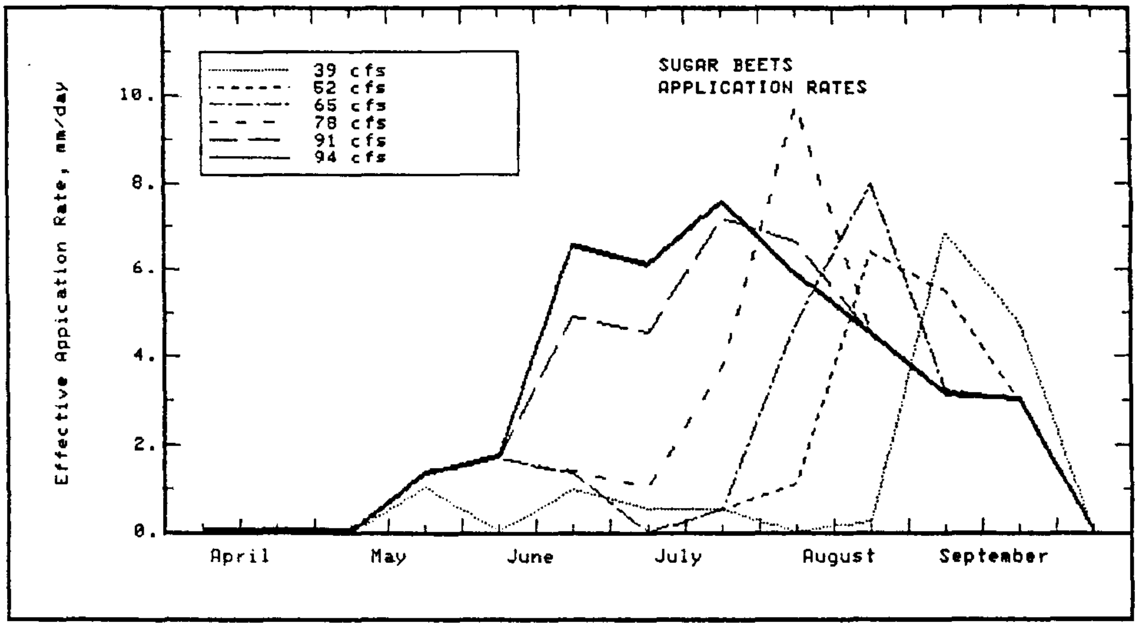

Figure 15. Optimal irrigation scheduling for sugar beets for varying maximum allowable project diversion rates for riser-catcher linear move systems in the Little Pilgrim study area.

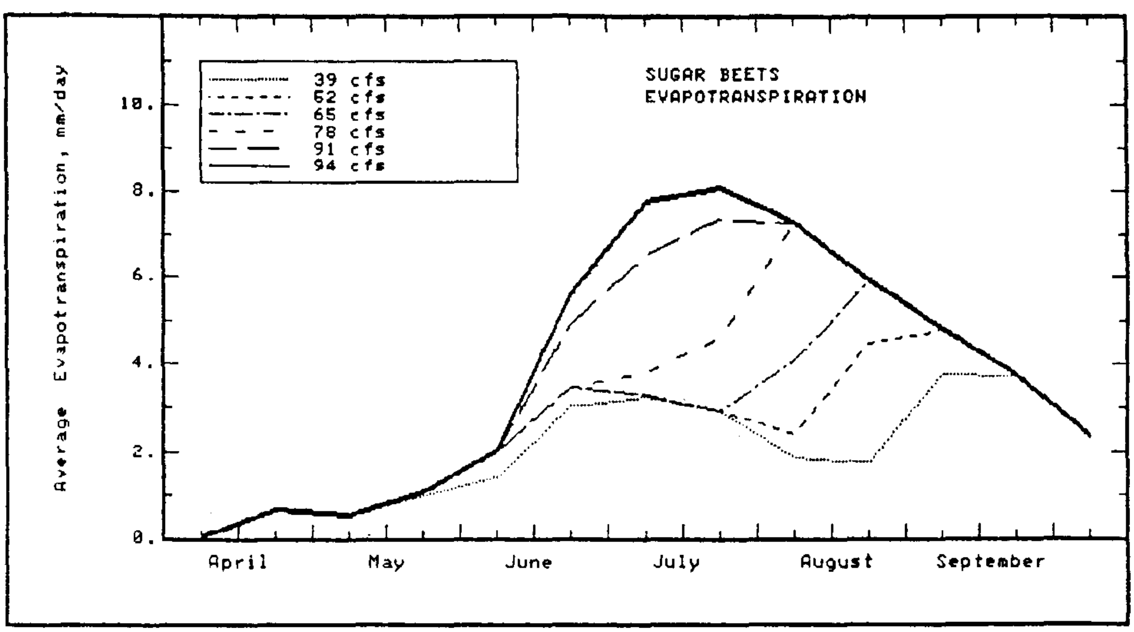

Figure 16. Optimal evapotranspiration from sugar beets for varying maximum allowable project diversion rates for riser-catcher linear move systems in the Little Pilgrim study area.

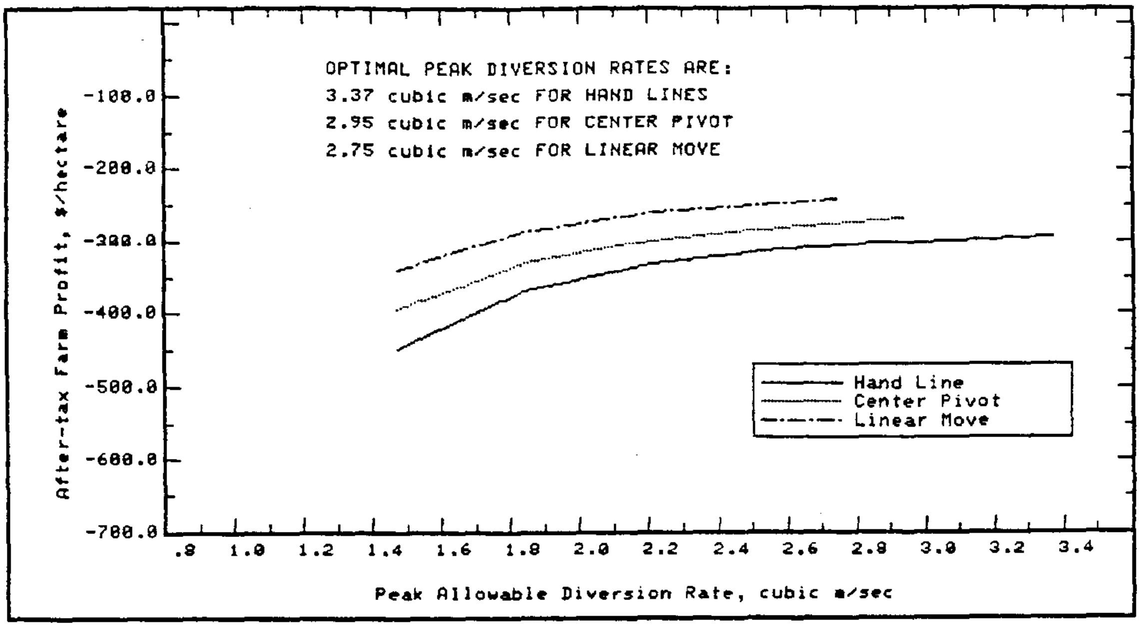

Figure 17. Net after-tax farm profit for hand line, spray-boom center pivot, and riser-catcher linear move systems with pressurized pipe and canal conveyance systems versus maximum allowable project diversion rate for the Little Pilgrim study area (2700 ha).

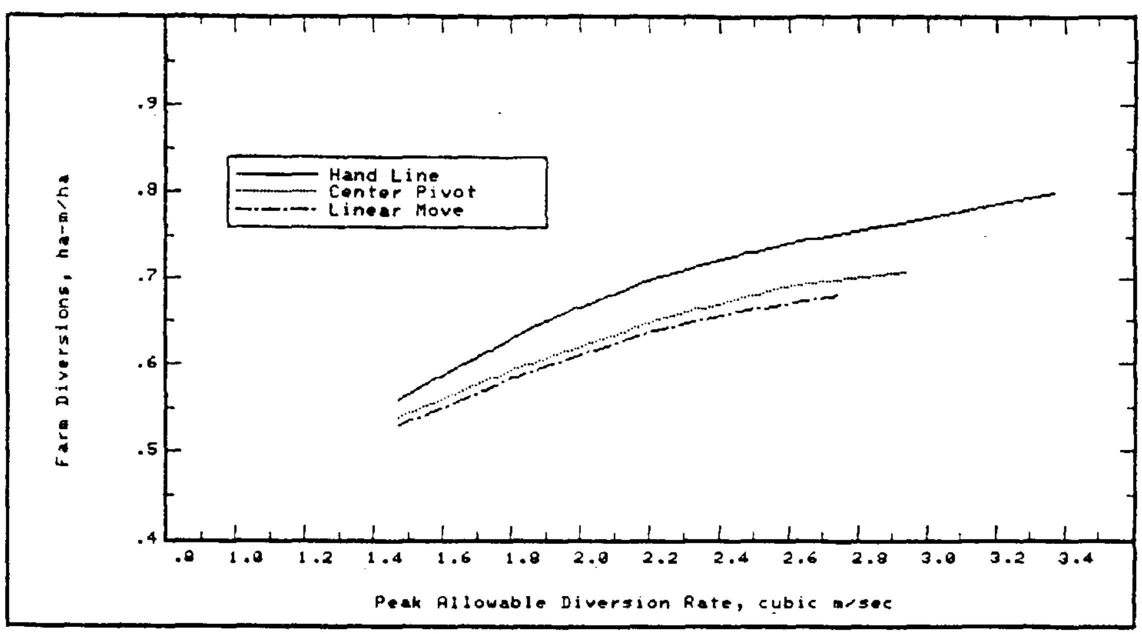

Figure 18. Average seasonal farm diversions versus maximum allowable project diversion rate for hand line, spray-boom center pivot, and riser catcher linear move systems with pressurized pipe and canal conveyance systems for the Little Pilgrim study area.