An Irrigation Model for Management of Limited Water Supplies

Daniel J. Bernardo, Norman K. Whittlesey,
Keith E. Saxton, and Day L. Bassett

A two-stage simulation/mathematical programming model is presented for determining the optimal intraseasonal allocation of irrigation water under conditions of limited water supply. The model is applied to a series of water shortage scenarios under both surface and center pivot irrigation. Economically efficient irrigation management is shown to involve the coordination of a number of managerial decisions, including irrigation scheduling, crop substitution, the adoption of improved irrigation labor practices, and idling land. The results indicate that significant opportunities exist for conserving water in the study area under both surface and center pivot irrigation.

Key words: crop simulation, deficit irrigation, irrigation management, water supply limits.

Past policies of water resource management and inexpensive energy have encouraged many western irrigators to adopt irrigation practices consistent with an abundant and inexpensive water supply. Typically, these practices were designed to avoid moisture stress and strive for maximum yield. As competition for water becomes more acute and irrigation costs increase, a departure from traditional irrigation practices is required. Irrigation management must be reoriented toward increasing the precision of irrigation scheduling and application to maximize returns to the scarce water resource.

The economic analysis of farm-level irrigation management has been the subject of research for several years. Traditionally, these studies employed static water response functions relating crop yield to seasonal water application and thus ignored the temporal dimension of irrigation management. More recent studies have focused on efficient intraseasonal allocation of irrigation water (Flinn and Musgrave; Anderson and Maas; Zavaleta, Lacewell, and Taylor; and Mapp et al.). These studies have employed such techniques as linear programming, simulation, and dynamic programming to allocate a finite quantity of water over the irrigation season.

In developing intraseasonal water allocation models, several common problems have been encountered. Problems of computational tractability and unavailability of crop-water response information have often necessitated considerable simplification in the specification of response models relating crop yield to moisture stress. In addition, intraseasonal water allocation models have focused primarily on the time and depth of irrigation. Prior to their empirical application, irrigation management models must also consider the effect of practices that may be used in conjunction with irrigation scheduling to form efficient farm-level irrigation programs. For example, little consideration has been given to how irrigation labor and nonirrigation input use may be adjusted in responding to water shortage. Also, results from single-crop studies must be extended to incorporate the possibilities of crop substitution and reallocation of water among crops when responding to farm-level water supply limits.

The authors are, respectively, an assistant professor, Department of Agricultural Economics, Oklahoma State University; a professor, Department of Agricultural Economics, Washington State University; a U.S. Department of Agriculture research hydrologist, Washington State University; and an associate professor, Department of Agricultural Engineering, Washington State University.

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Economically efficient irrigation management requires the coordination of a number of irrigation and production practices which may affect water use. This study attempts to integrate available knowledge regarding yield response to water, irrigation scheduling, irrigation system design, and irrigation economics into a whole-farm irrigation management model. The specific objectives of this study are (*a*) to present a methodology for developing economically efficient seasonal irrigation plans and (*b*) to apply the model to limited water supply settings characterized by alternative irrigation conditions. Specific attention was focused on developing a formulation that accounts for the numerous economic adjustments available to producers operating in an environment of scarce water supplies.

The Farm-Level Irrigation Model

A two-stage simulation/mathematical programming model was developed to analyze farm-level irrigation management under conditions of limited water supplies. In the first stage, biophysical crop simulation is used to analyze yield response to specified irrigation schedules. Irrigation activities generated in the first stage are then entered into a farm-level mathematical programming model to maximize returns through the efficient allocation of the available water supply.

Crop Simulation Model

Biophysical crop simulation models that consider the interaction of climatic conditions, soil properties, agronomic characteristics, and production decisions have become important research tools. Recent applications of these models to the economic analysis of irrigation scheduling and investment include Mapp et al.; Boggess and Amerling; Harris and Mapp; and Zavaleta, Lacewell, and Taylor.

The SPAW-IRRIG model is the crop simulation model employed in the biological component of the analysis (stage one). The model is based upon the soil-plant-air-water (SPAW) model developed by Saxton, Johnson, and Shaw to estimate the effect of various environmental influences on crop development, water use, and crop yield. Later, the model was revised to derive seasonal estimates of water stress (Sudar, Saxton, and Sponer) and again to reflect the hydrologic conditions of irrigated agriculture (Bassett, Saxton, and Bluhm).

SPAW-IRRIG utilizes two components to estimate the water use of crops and associated yield impacts. First, a crop simulation model is used to relate meteorological, crop, and soil-moisture relationships on a daily basis throughout the growing season. Next, yield estimates are calculated from measures of accumulated water stress derived from daily predictions of evapotranspiration (ET) and soil moisture distribution.

The SPAW-IRRIG model employs a three-step procedure in making daily soil-moisture calculations. These calculations are made using daily climatic, edaphic, and agronomic data programmed for each crop. First, an estimate of potential evapotranspiration (ET_p) is derived from daily meteorological data.[1] Potential ET is then distributed among the various components of the soil-plant system based upon the prevailing agronomic, edaphic, and hydrologic characteristics. Daily estimates of interception evaporation, transpiration, and soil-water evaporation combine to provide an estimate of actual evapotranspiration (ET_a). Actual ET approximates the energy component utilized by the plant for the physiological processes of crop growth and development. The quantity of water evapotranspired is then withdrawn from the multilayered soil profile based upon current water availability and root characteristics. The soil-plant system is initialized for the following day's calculations through application of a series of hydrologic relationships which redistribute the soil water among the various soil layers.

Four alternative measures of accumulated water stress were evaluated as to their ability to predict yield reductions resulting from deficit irrigation schedules. The model selected for application in this analysis expresses relative yield (the ratio of actual to maximum yield) as a function of ET deficit ($1 - ET_a/ET_p$) and was programmed using information provided by FAO Publication No. 33, *Yield Response to Water*. The model is based on the assumption that yield is affected not only by the magnitude of the ET deficit, but also the stage of crop growth in which the stress occurs. The model assumes a multiplicative relation-

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[1] Potential evapotranspiration represents the maximum ET of a healthy crop and approximates energy demand placed on the crop by the atmosphere.

ship between water stress sustained in each of the four growth periods and may be expressed

$$(1) \qquad Y_a/Y_m = \prod_{i=1}^{4} [1 - k_{yi}(1 - ET_{ai}/ET_{pi})],$$

where k_{yi} is the crop-response factor for the ith period, ET_{ai} is actual ET in period i, and ET_{pi} is potential ET in period i. An estimate of actual yield is derived by multiplying relative yield by maximum yield under farm-level production conditions.[2] Individual crop simulators were developed for four crops: dry beans, wheat, grain corn, and alfalfa.

Irrigation activities were constructed by running the individual crop simulators for a number of irrigation scheduling criteria available to irrigators. Each one-acre irrigation activity represents an alternative means of irrigating one of the four crops. Both time and depth of irrigation may be based on soil moisture levels, soil tension, time intervals, accumulated potential ET since the previous irrigation, and accumulated actual ET. For each criterion, a series of activities was generated by varying the relevant irrigation parameters. For example, to represent criteria based on soil moisture levels, an irrigation activity was generated for numerous levels of soil moisture depletion, dictating the time and depth of irrigation. Approximately 1,200 irrigation activities representing alternative ways of irrigating the four crops were generated using this procedure.

Figure 1 illustrates the data flow involved in the generation of the irrigation activities and linkage of the simulation and mathematical programming models. Output from the crop simulators is processed through an intermediate program to develop resource-allocation matrices for the mathematical programming model. The matrix generator is comprised of four parts: (*a*) a set of nutrient models, (*b*) a production cost model, (*c*) an irrigation application system model, and (*d*) an irrigation model. Irrigation applications are stated in terms of consumptive use per four-day subperiod, the number of irrigations, and seasonal water use. These factors are employed to estimate labor demands, repair and maintenance costs, and energy inputs. Nutrient applications are estimated from a series of equations relating nitrogen levels to the yield and quantity of deep percolation estimated for each irrigation activity. These relationships are premised on the assumption that nutrient stress cannot limit yield, but excessive nutrient application is also to be avoided.

Mathematical Programming Model

Irrigation activities developed in the simulation stage provide the physical component of a farm-level irrigation management model developed to examine the effects of alternative water supply restrictions on farm income. The mathematical programming model was designed to represent several irrigation practices currently available to producers operating in an environment of scarce water supplies. The model may be applied to a variety of production scenarios differing in terms of input and output prices, water supply limits, water delivery rules, and irrigation system properties.

The specific objective of the mathematical programming model was to allocate a finite land area, water supply, and other limiting resources among the various irrigation activities so as to maximize returns to fixed factors of production. Farm-level net returns are estimated as total revenue from the production of the four crops less three cost components: (*a*) preharvest cultural costs, (*b*) irrigation costs, and (*c*) remaining endogenous production costs (harvest, hauling, and nutrients). Irrigation costs (labor, energy, and repairs) are estimated based upon the number of irrigations and quantity of water applied, irrigation system characteristics, and the irrigation labor practices employed. Harvest and hauling costs are represented as nonlinear functions of crop yield. The objective function is maximized subject to water availability limits imposed by the irrigation system, on-farm conveyance system, and water delivery rules; constraints on annual water availability; limits on total and individual crop acreage; and constraints on subperiod labor availability.

Water supply limits in the mathematical programming model may be represented as follows:

$$(2) \qquad \sum_j \sum_k w_{ijk} X_{jk} \le b_i \cdot E(l) \qquad (i = 1, 2, \ldots, 50),$$

$$(3) \qquad \sum_j \sum_k W_{jk} X_{jk} \le b_t \cdot E(l),$$

where X_{jk} is the process of producing the kth crop with the jth irrigation activity; w_{ijk} is crop

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[2] Maximum yield estimates are based upon the agronomic practices, soil type, and climatic characteristics of the study area.

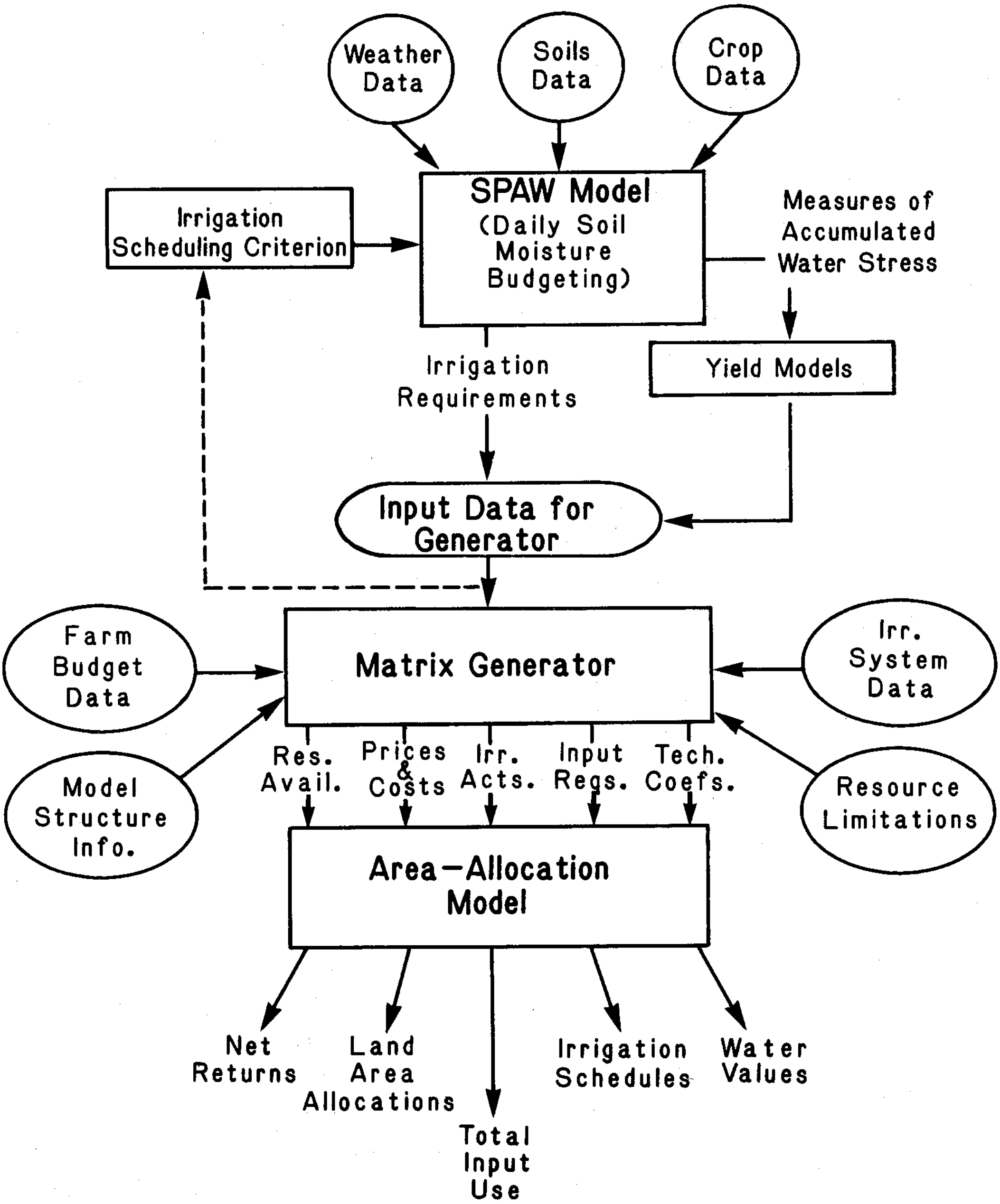

Figure 1. Schematic of the data flow of the two-stage mathematical model

consumptive use in subperiod i by irrigation activity X_{jk}; W_{jk} is annual consumptive use by activity X_{jk}; b_i and b_t are limits on subperiod and annual water availability, respectively; and $E(l)$ is the application efficiency expressed as a function of the labor-intensity of irrigation applications.[3] The right-hand-side values indicate the portion of the total water that enters the crop root zone and is made available for consumptive use (net irrigation). Thus, water supply limits state that consumptive use

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[3] Application efficiency is defined as the percentage of irrigation water applied that is stored in the root zone and made available for consumptive use by the crop. Thus, the right-hand sides of equations (2) and (3) give the quantity of water available for consumptive use, given the optimal application efficiency, i.e., net irrigation.

summed over all crop acreage not exceed net irrigation. Equation (2) imposes a restriction on subperiod water availability and may be used to represent flow-rate restrictions. Equation (3) requires that total farm-level water demand not exceed the annual water allotment.

Efficient irrigator response to water supply limits includes the adoption of labor-intensive irrigation practices to increase application efficiency.[4] Because the labor wage rates and application efficiencies are embodied in the objective function and right-hand-side coefficients, respectively, the parameters can be varied using the PARARIM procedure of the MPSX mathematical programming package. The function of PARARIM was to "sweep out" a series of solutions in which irrigation labor, energy, repair and maintenance costs (objective function coefficients), and water supply limits (right-hand-side levels) are varied incrementally and simultaneously. Thus, a series of application efficiency and labor rate (hours/acre/irrigation) combinations along a production isoquant are surveyed, and the combination that maximizes returns is selected.

In addition to the adoption of labor-intensive irrigation practices, several additional alternatives available to the producer responding to water supply limits are represented. Irrigation scheduling modifications are incorporated through the availability of the 1,200 alternative irrigation schedules. Four levels of scheduling sophistication can be assessed in the mathematical programming model: *a*) the use of criteria based on specified dates, depths, and fixed time intervals; (*b*) the addition of soil moisture criteria; (*c*) the addition of soil tension criteria; and (*d*) the addition of criteria based on ET_a and ET_p. Crop substitution, reallocating water among crops, and idling land represent additional adjustments to water supply restrictions.

Specific attention was focused on developing a formulation which could be applied to a variety of irrigation technologies. The researcher may specify system type, including its application efficiency, peak-flow rate, and minimum and maximum irrigation depths. Thus, irrigation activities are restricted to those which are compatible with the currently prevailing irrigation system.

Results

An application of the two-stage model to an irrigated production region in Washington State's Columbia River Basin is presented in this section. The representative irrigated farm is comprised of 520 acres of sandy loam soil available for production. The irrigation system is assumed fixed and consists of either (*a*) four 130-acre center pivot circles, or (*b*) a 520-acre conventional gravity system consisting of open ditches, siphon tubes, and furrows. Prices and costs are representative of 1985 production conditions. Net returns to land, fixed costs of irrigation, and management are maximized through the production of four crops (dry beans, grain corn, spring wheat, and alfalfa) and selection of the irrigation schedules and practices applicable to the prevailing irrigation system.[5]

Application of the SPAW-IRRIG model requires the specification of three general classes of data related to climatic, crop, and soil characteristics. Daily pan evaporation and precipitation values specify the representative climatic conditions. Agronomic data for the SPAW-IRRIG model include a series of canopy cover, root distribution, phenology, and crop susceptibility relationships. The growth periods, response factors, and maximum yields used in equation (1) to estimate actual yield for the four crops are given in table 1. Soil profile characteristics and initial soil moisture levels are the remaining input required for application of the model. The model was verified using available field data from the study area.

The model is applied to analyze the efficient management of alternative annual water allotments when producers have complete flexibility in allocating the allotment over the irrigation season. Such restrictions may be indicative of those imposed by a water district in years of water shortage, physical limits on water availability, or voluntary forfeiture of a portion of a water right in a water market setting.

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[4] Alternative levels of irrigation management and corresponding application efficiency/labor rate combinations (%, hr/Ac./irrig.) are: surface irrigation: base level (45, .70); improved runoff monitoring (50, .75); reduced set-time (55, .80); and cutback methods (65, 1.10). Center pivot irrigation: base level (78, .05); improved labor/management (83, .08); and improved monitoring of set-time and irrigation losses (86, .14) (English, Kraynick, and Eakin; Gossett).

[5] Crop rotation and diversification considerations dictate the use of 260-acre upper limits on individual crop acreage, equivalent to two center pivot irrigation circles.

Table 1. Input for ET-Deficit Yield Model, Columbia Basin, Washington

Crop	Maximum Yield	Period Number[a]	Growth Period	K_y[b]
Dry beans	25 cwt.	1	6/3–6/28	.20
		2	6/29–7/15	1.10
		3	7/16–8/10	.75
		4	8/11–8/30	.20
Spring wheat	90 bu.	1	4/15–5/12	.20
		2	5/13–6/2	.65
		3	6/3–7/19	.55
		4	7/20–8/10	.00
Grain corn	5 tons	1	6/1–7/18	.40
		2	7/19–8/8	1.50
		3	8/9–9/9	.50
		4	9/10–9/30	.20
Alfalfa	6.5 tons	1	3/23–5/30	.80
		2	5/31–7/13	.80
		3	7/14–8/28	.80
		4	8/29–10/10	.80

[a] Growth periods 1 through 4 refer to vegetative, flowering, yield formation, and ripening stages, respectively.

[b] From Doorenboos and Kassam.

Center Pivot Irrigation

Currently, irrigators in the study area pay a fixed per-acre water delivery charge that entitles them to divert and apply as much water as they deem necessary. To approximate this condition, a base model solution was derived with an unlimited annual water supply. These results are presented in column one of table 2. Under an unlimited water supply, the profit-maximizing producer allocates 260 acres each to dry beans and alfalfa, resulting in a return to land, management, and fixed irrigation costs of $106,420. A total of 17,160 acre-inches is applied, of which 13,042 acre-inches are made available for consumptive use (net irrigation). These results support the proposition that under sufficient water availability and low irrigation costs, profit-maximizing yields approach the maximum attainable.

Incremental reductions in seasonal water supply are met through the conjunctive adoption of a number of available water conservation strategies. The first supply reduction is met by the employment of a less water-intensive irrigation schedule for alfalfa. The quan-

Table 2. Optimal Solutions for Alternative Annual Water Allotments on a 520-Acre Center-Pivot Irrigated Farm, 260-Acre Crop Limits

	Annual Water Allotment (Acre Inches)			
	17,160	14,000	11,000	8,000
Net irrigation requirement (AI)	12,870	10,140	9,130	6,640
Net returns ($)	106,420	102,310	98.432	82,423
Land (acres)	520	520	520	502
Application efficiency (%)	78	78	83	83
Labor use (hr/acre/irr.)	.05	.05	.08	.08
Dry beans				
Avg. water applied (AI/a)	24.4	24.4	19.5	18.3
Avg. yield (cwt/a)	23.8	23.8	23.6	22.4
Acreage	260	260	260	260
Grain corn				
Avg. water applied (AI/a)			22.0	
Avg. yield (cwt/a)			4.36	
Acreage			248	
Wheat				
Avg. water applied (AI/a)				13.5
Avg. yield (cwt/a)				76.8
Acreage				242
Alfalfa				
Avg. water applied (AI/a)	41.6	30.5	28.0	
Avg. yield (cwt/a)	6.48	6.28	6.16	
Acreage	260	260	12	
Marginal value product of applied water ($/AI)	.0	1.05	3.48	8.10

tity of water applied is reduced 11.1 acre inches per acre, resulting in a .2 ton per acre decrease in yield. Achieving the next reduction requires adopting irrigation practices that increase the application efficiency in conjunction with employing less water-intensive irrigation schedules for both alfalfa and beans. Farm-level application efficiency is increased from 78% to 83% through closer monitoring of set-time and field runoff. In addition, 248 acres of grain corn are substituted for alfalfa.

Analysis of individual crop results presented in table 2 indicates that large decreases in average water applications may be attained while incurring only small yield reductions. In meeting the 11,000 acre-inch allotment, average water applications to dry beans and alfalfa are reduced 25% and 33%, respectively; however, yield decrements associated with these reductions are less than 6% for each crop. Although water applications have decreased considerably, only marginal reductions in crop consumptive use (as measured by actual evapotranspiration) have occurred. For example, the consumptive use of alfalfa in the 11,000 acre-inch supply scenario is 30.9 acre-inches, only 5.3 acre-inches below the crop's annual "full-yield" water requirement. As water allotments are reduced, the application efficiency is increased by adopting labor- and management-intensive irrigation practices and employing irrigation schedules that minimize deep percolation, runoff, and residual water in the soil profile at the conclusion of the irrigation season. Finally, irrigation schedules are adopted to apply water deficits when the crop yield is least affected by water stress.

In meeting the 8,000 acre-inch water allotment, substitution toward low water-use crops continues—12 acres of alfalfa and 248 acres of grain corn are removed from production, 242 acres of wheat are added, and 18 acres are idled. Irrigation schedules employed are deficit irrigation schedules that efficiently utilize available soil moisture and water applied during the irrigation season. For example, consumptive use of wheat in the final solution is 15.6 acre-inches per acre, approximately 74% of the crop's annual water requirement; however, the resulting yield is about 85% of maximum. Yield reductions are minimized by timing irrigations such that the majority of the water deficit occurs in the final growth period, when crop susceptibility to water stress is at a minimum.

Irrigation scheduling criteria change considerably as water becomes more limiting. Under an unlimited water supply, optimal irrigation schedules are based on fixed time intervals and fixed irrigation depths. These schedules lead to relatively large amounts of water use and deep percolation because irrigations do not correspond to the crop's changing water requirement over the growing season. As water becomes more limiting and its opportunity cost increases, the optimal irrigation scheduling increases in sophistication. Irrigation activities appearing in the 8,000 acre-inch solution are generated using high-frequency irrigation schedules based on soil moisture percentage and actual ET accumulated since the previous irrigation. These criteria tend to maximize water-use efficiency by relating irrigations to water consumed since the previous irrigation.[6] Irrigation frequency increases an average of two applications per crop in moving from an unlimited water allotment to an annual water supply of 8,000 acre inches.

The results presented in table 2 demonstrate a large potential for water conservation by sprinkler irrigators in the study area. For example, the return to land, management, and fixed cost of irrigation declines less than 8% when water supply is reduced in excess of 36% and consumptive use is reduced to 29%.[7] In the study area, reductions in consumptive use are frequently the best indicator of conservation potential because water not consumptively used is generally available to other users. Through the conjunctive development and application of efficient irrigation programs, significant reductions in seasonal water application and consumptive use can be attained with small losses in producer returns.

Shadow prices on the water supply constraint given in equation (3) provide estimates of the marginal value product of water at each allotment. These values are reported at the bottom of table 2 and reflect the value of an additional acre-inch of water to the center pivot irrigator who responds to water supply reductions in an efficient manner. Such infor-

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[6] The term "water-use efficiency" refers to the physical efficiency of irrigation water (i.e., yield per acre-inch of water applied).

[7] Income losses are expressed as a percentage of returns to land, management, and fixed cost of irrigation and reflect the consequences of short-run water deficit. Under recurring shortages, a long-run measure of economic consequences would be applicable. Removing the irrigation system as a residential claimant on short-run income would increase the percentage reduction in returns resulting from water supply reductions.

Table 3. Optimal Solutions for Alternative Annual Water Allotments on a 520-Acre Surface Irrigated Farm, 260-Acre Crop Limits

	Annual Water Allotment (Acre Inches)			
	27,846	22,000	16,000	12,000
Net irrigation requirement (AI)	12,520	10,560	8,800	7,800
Net returns ($)	98,490	96,399	88,125	74,030
Land (acres)	520	520	520	520
Application efficiency (%)	45	48	55	65
Labor use (hr/acre/irr.)	.70	.73	.80	1.10
Dry beans				
Avg. water applied (AI/a)	39.6	36.1	26.7	19.5
Avg. yield (cwt/a)	23.8	23.4	21.4	20.9
Acreage	260	260	260	260
Grain corn				
Avg. water applied (AI/a)				26.7
Avg. yield (cwt/a)				4.21
Acreage				260
Wheat				
Avg. water applied (AI/a)				
Avg. yield (cwt/a)				
Acreage				
Alfalfa				
Avg. water applied (AI/a)	67.5	48.6	34.6	
Avg. yield (cwt/a)	6.46	6.16	5.58	
Acreage	260	260	260	
Marginal Value product of applied water ($/AI)	.0	.45	2.43	4.05

mation is useful when evaluating the participation of irrigators in water markets and other water reallocation mechanisms.

Surface Irrigation

Table 3 summarizes efficient seasonal irrigation plans for four alternative annual water allotments to the surface irrigated farm. Conditions of unlimited water supply are represented in column one. When an abundant water supply is available at a low marginal cost, the efficient seasonal irrigation plan consists of high water-use schedules resulting in crop yields approaching the maximum attainable.

As in the center pivot scenario, water supply reductions are met through the adoption of several irrigation management practices. In meeting the first two reductions (22,000 and 16,000 acre-inches), two types of adjustments are made. First, less water-intensive irrigation schedules are adopted for both the alfalfa and dry bean crops, reducing crop yield. A second response involves the use of improved irrigation labor practices to increase the application efficiency with which irrigations are applied. Meeting the final water supply allotment (12,000 acre-inches) requires the employment of both of these practices, in addition to substituting 260 acres of grain corn for alfalfa.

Surface irrigation provides the irrigator less flexibility than sprinkler systems in terms of application rates or timing. Thus, the high-frequency, deficit irrigation schedules employed in the center pivot scenario may not be used to meet water supply reductions to surface irrigators. In addition, the labor requirements of surface irrigation make these types of schedules uneconomical. Two forms of scheduling adjustments are adopted: (*a*) reducing the number of irrigations and (*b*) discontinuing irrigations in growth stages in which crop yield is least susceptible to water stress. The number of irrigations decreased an average of three per crop in moving from the unlimited water supply to an allotment of 12,000 acre inches. Water applications were also redistributed to later periods of the irrigation season because beans and corn are least sensitive to water stress in the establishment and vegetative stages.

The labor and application efficiency coefficients presented in rows 4 and 5 of table 3 indicate modifications in irrigation practices as water supplies become more constraining. Under present management practices, a base-level application efficiency of 45% prevails. As water supply is reduced and water takes on a higher value, labor is substituted for the scarce water input by increasing application efficiency through the adoption of labor-intensive irrigation practices. In meeting the 22,000 acre inch allotment, a 3% increase in application efficiency is attained through improved runoff monitoring. The application efficiency is increased to 55% in the following solution (16,000 acre-inches) by monitoring runoff and adjusting the irrigation set-time to meet field needs. Finally, in meeting the 12,000 acre-inch supply, labor use is increased to 1.1 hours per acre per irrigation by adopting cutback methods to increase application efficiency to 65%. Thus the full-range of attainable increases in application efficiency is employed in meeting the 12,000 acre-inch allotment.

As under center pivot irrigation, significant water conservation opportunities also exist for surface irrigators in the study area. At the 16,000 acre-inch supply level, the return to land, management, and fixed costs of irrigation decrease less than 11% from a 42% reduction in water availability. However, to achieve an additional 15% reduction in water supply to the 12,000 acre-inch level, net farm returns decrease an additional 14%.

Shadow prices from the annual water supply constraint are reported at the bottom of table 2. Because of the lower application efficiency of surface irrigation, the derived water values are much lower than for center pivot irrigation. In both cases, however, we believe these values to be more accurate than those provided by the production function approach or mathematical programming models that do not properly account for the temporal dimension of crop water response or the options of irrigation management.

It is clear in both the center pivot and surface irrigation results that the flexibility constraints on crop production did influence the selection of crops and their acreage. However, these constraints are not unlike those imposed by agronomic and market conditions in the study region. Other model applications, not discussed here, looked at alternative constraints on the delivery system capacity. Such model results were useful in showing the marginal value of investment in irrigation system capacity in addition to the value of seasonal water quantities.

The results of this modeling process are, of course, conditional upon the specific economic conditions, resource supplies, irrigation system properties, and environmental data employed in the two-stage model. The derived irrigation plans do, however, give an indication of the types of responses involved in efficient irrigator response to annual water supply reductions. The model has also been applied to investigate the effect of alternative factor cost, output price, and water supply scenarios on optimal seasonal irrigation management plans. Water conservation opportunities were shown to be available over a range of economic and resource conditions; however, specific adjustments employed to meet water supply reductions are conditional upon the production setting.

Summary and Conclusions

Increased water scarcity and escalating energy costs have provided the impetus for irrigators to increase the efficiency of agricultural water use through improved irrigation management. The effect on producer returns, irrigation schedules, production practices, and resource use of alternative water supply conditions were evaluated using a simulation/optimization model. A representative irrigated farm in Washington State's Columbia River Basin was used to analyze both center pivot and surface irrigation scenarios.

Economically efficient irrigation management was shown to involve the coordination of a number of managerial decisions affecting water use. In the case of center pivot irrigation, crop substitution, the employment of improved irrigation labor practices, and the adoption of deficit, high-frequency irrigation schedules represent important adjustments in responding to reduced annual water supplies. Efficient seasonal irrigation plans for surface irrigators differ considerably from those derived in the center pivot scenario. A primary response of surface irrigators to water supply reductions involves the adoption of labor-intensive irrigation practices to increase application efficiency. Although irrigation system characteristics prevent surface irrigators from employing high-frequency schedules, annual water applications may be reduced by decreasing irrigation frequency, reducing the depth of individual applications, and eliminating irrigations in noncritical stages of crop growth.

Despite considerable differences in the strategies used to meet water supply reductions, results indicate that significant opportunities exist for conserving water in the study area under both surface and center pivot irrigation. In the setting of this analysis, reductions in water applications of over 36% under center pivot irrigation and 32% under surface irrigation were obtained with relatively small losses in producer net returns. Smaller but significant reductions in consumptive use were also attained.

The modeling approach presented provides improved guidance for irrigation management under conditions of limited water supply. Through detailed simulation of crop water use and response and representation of a number of available irrigation management alternatives, the model should provide improved estimates of the income consequences associated with various water supply reductions. From these results, realistic estimates of water conservation potential and water value may be derived for irrigators operating under a variety of production settings. Such information should be of interest to policy makers investigating the feasibility of private or public water reallocation policy alternatives.

Despite recent advances in crop-water modeling, uncertainty remains regarding the ability to predict yield over a wide range of environmental and water stress conditions. Although the response models employed in this analysis were validated with available primary data, additional field testing is required before prescriptions derived from the model could be applied confidently to actual situations of water shortage.

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