WATER ALLOCATION MODEL FOR LIMITED IRRIGATION

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ABSTRACT. *For irrigation managers with limited water resources, irrigation management decisions begin well before the irrigation season. Irrigation managers with limited water supplies from restricted well capacities or water allocations need to anticipate crop selections, plan for crop rotations, and project water deliveries to each crop. A water allocation model [Crop Water Allocator (CWA) available at www.oznet.ksu.edu/mil] has been built to evaluate growing-season water allocations among two to six crops over five possible divisions of land area. Users input crop pricing, production costs, irrigation costs, and maximum crop yields. The program iterates all possible combinations of the water allocation by 10% increments over all possible crop combinations and a chosen land division. Net economic return to land, labor, and irrigation equipment is calculated for each crop mix/water allocation/land division combination. Net returns are ranked, and several of the highest are presented to the user for evaluation. The influence of one variable input on another, such as water allocation, commodity prices, crop yields, annual rainfall, irrigation system efficiency, and irrigation operating costs on net return can be evaluated through multiple executions of the model.*

Keywords. *Limited irrigation, Deficit irrigation, Decision model, Groundwater, Economic optimization.*

Irrigators are facing challenges of reduced water supplies. Groundwater declines and dwindling surface water deliveries are normal rather than infrequent. Irrigators have adjusted by turning to more efficient irrigation application techniques and water-conserving cropping practices. Both of these measures have given incremental improvement to the use and effectiveness of water at the farm level.

Irrigators tend to choose the crops that they produce on the basis of their production capabilities, economic returns, adaptability for the area, government programs, water use, and their production preferences. When water supply falls below the irrigation system's ability to meet full evapotranspiration demand, yield-irrigation relationships and related economic returns become critical inputs for management decisions. Under fully irrigated conditions, crop selection is driven by the prevailing economics and production patterns of the region. Crops that respond well to water, return profitably in the marketplace and/or receive favorable government subsidies are selected. These crops still may be considered for limited irrigation systems, but other crops need to be examined for their economic return at different levels of irrigation. Which of these crops need to come into the mix, what proportions of land should be devoted to each crop, and how much water should be apportioned to each crop are key questions for the analysis. The final outcome of these questions is the system returning the optimal net for the available inputs.

Factors that influence the possible outcome of limited-irrigation management decisions can be complex. Commodity prices and government programs can fluctuate and change advantages for one crop relative to another. Water availability, determined by governmental policy or by irrigation system capacity due to water supply, may also change with time. Precipitation probabilities influence the level of risk the producer is willing to assume. Production costs give competitive advantage or disadvantage to the crops under consideration.

Allocation of water to irrigate crops has taken many forms since man decided to divert water from a natural water course. Decisions were made about the timing and amount of water to be applied to a crop or probably to a mixture of crops. In modern times, irrigation managers have access to decision tools and input information that early irrigators sensed from their surroundings. For example, a model that is available on the internet, KanSched (Kansas State University, 2004), allows an irrigator to allocate water to crops daily from a soil water balance of daily evapotranspiration (ET), rainfall, and irrigation. Evapotranspiration is often derived from energy-balance and aerodynamic-combination equations requiring meteorological parameters (Penman, 1948). This program, along with predecessor programs dating from the 1970s, can optimize irrigation amounts for well-watered field conditions with adequate water supplies.

Another form of water allocation is from a sole source serving multiple users. Many irrigation managers have addressed this challenge. For large scale projects where a single source serves many independent users in a distribution network, irrigators have needs that vary in time, quantity, and space. Wardlaw and Barnes (1999) used quadratic programming as a basis to optimize crop production in a large river-basin project in Indonesia. They built the model on crop water requirements and a soil water balance. Gorantiwar and

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Smout (2005) allocated land and water resources optimally to a mix of crops in a variable irrigation scheme with limited water under a rotational scheme of water supply to a large project. They introduced variable depth irrigation to match cropping patterns, soils, irrigation interval, and reservoir storage volumes (Gorantiwar and Smout, 2003).

Water allocation also accounts for the variation in rainfall from one year until the next year. For irrigators who control their own water sources and have the option of pooling a regulated water resource over multiple years, management strategies could be advantageous. Bernardo et al. (1988) examined the conditions of limited water availability to a surface irrigated multi-cropped farm in the northwestern United States with a crop-water simulation including economic optimizations. Multi-year simulations showed that a combination of irrigation scheduling and labor practices minimized water shortages. Martin et al. (1989a) used dynamic programming to develop operating rules for irrigators in southwest Nebraska to manage their water that is allocated over a 5-year period. They simulated yield response of crops to irrigation for 27 years of climatic data and determined optimal cropping patterns for specific water allocations. These procedures apply to others in similar situations. Panda et al. (1996) worked with a large project of multiple users and linked a groundwater simulation model, a crop water-response model, and a linear programming model together. Results from these simulations were used to maximize net economic returns through managing conjunctive use of surface water and gypsum-treated groundwater.

Single growing-season water allocation among several crops from a limited source of water is based on how each crop responds in terms of net economic return to water. The first step in this determination is the relationship between crop yield and water use. Researchers have developed relationships between ET and grain yields for many years (Stewart et al., 1975; Barrett and Skogerboe, 1978; Retta and Hanks, 1980; Stegman, 1982; Schneekloth et al., 1991). Martin et al. (1984) proposed a simulation model to estimate the effect of limited irrigation on crop yield by providing relative crop yield estimates for combinations of system, crop, and management parameters. This link between water use and irrigation application is necessary to achieve economic decisions. Martin et al. (1989b) went on to develop a method to determine optimal irrigation depth or land allocation for single season irrigation management of multiple crops or non-cropped alternatives. Martin and his colleagues (University of Nebraska, 2005) recently expanded their approach to optimizing limited water allocations to multiple crops using a spreadsheet as a platform for a user interface. The target users are those from counties in southwest Nebraska.

With powerful personal computers common to consumers in the last 5 years, another alternative to the same challenge is available. Personal computers have the capability to solve iterative approaches to complex questions. This approach can provide a seasonal planning tool to find the optimum net return from all of the combinations of crops, irrigation amounts, and land allocations that the program user wants to examine. Producers have been dividing their fields and growing more than one crop under one irrigated system when water supplies are limited. They have not been guided on the optimum amounts of water to apply to each crop or which crops to grow with different rates of water supply. The objective of this project has been to create a decision tool with user interaction to examine crop mixes and limited water allocations within land allocation constraints to find optimum net economic returns from these combinations. This decision aid is for intended producers with limited water supplies to allocate their seasonal water resource among a mix of crops. But, others interested in decisions concerning allocating limited water to crops may use it. Decisions are intended as a planning tool for crop selection and season allocations of land and water to crop rotations. These choices are not intended for scheduling water applications during the growing season.

BACKGROUND AND MODEL DEVELOPMENT

The model, called the Crop Water Allocator (CWA), calculates net economic return for each combination of water allocations for every crop combination of a chosen land split. The results are ranked so that the user can evaluate the options. Subsequent executions of land-split scenarios can lead to more comparisons. Irrigation system parameters, production costs, commodity prices, yield maximums, annual rainfall, and water supply were also held constant for each scenario executed. Crops eligible for consideration in the crop rotation could be equal to, or greater than, the number of land splits designated. Fallow is considered as a crop (cropping system selection) because a valid option is to idle part of a field or farm. Each crop selected is used in every combination of possible land splits. Overlying every crop combination, each combination of water allocation is iterated in 10% increments. The model has an option for larger water iteration increments to save computing time.

With each iteration, net return to land, management, and irrigation equipment is calculated:

$$\text{Net return} = (\text{commodity price}) \times (\text{yield}) - (\text{irrigation cost} + \text{production cost}) \qquad (1)$$

where commodity prices are determined by user inputs; crop yields are derived from yield-irrigation relationships from a simulation model based on field research; irrigation costs are a function of lift, water flow, water pressure, fuel cost, pumping hours, repair, maintenance, and labor for irrigation; and production costs are from user inputs or default values derived from Kansas State University projected crop budgets.

All of the resulting combinations are sorted on the basis of net returns from maximum to minimum and several of the top scenarios are summarized and presented to the user.

One of the features of CWA is that the user can choose among five land splits or fixed configurations of dividing the land resource (50-50; 25-75; 33-33-33; 25-25-50; 25-25-25-25). These splits reflect the most common probable crop-rotation patterns in western Kansas. The user can examine the results of each one of the land splits in sequential executions of the model, but the algorithm treats land split as a constant during an individual scenario. Producers divide their fields into discrete parcels and rotate their crops in this same pattern, which led to this simplifying assumption and to the possibility of an iterative solution of the model.

The CWA software finds every possible combination of water volume according to information supplied by the user.

Volume combinations are aggregates of volume amounts of water applied to each crop whose sum is the calculated gross water volume. To avoid an infinite number of volume combinations, CWA uses a "FineFactor" that defines the smallest percentage of the calculated gross water volume an individual volume amount can represent. The default FineFactor is 10, which is the individual volume amounts in 10% increments of the calculated gross water volume. By increasing the FineFactor to 20, CWA produces "finer" results by allowing individual volume amounts to be in 5% increments of the calculated gross water volume. Decreasing the FineFactor to 5 produces "coarser" results by limiting individual volume amounts to be in 20% increments of the calculated gross water volume.

A combination of volumes contains as many individual volume amounts as the number of land splits the user defined (e.g. 2, 3, or 4 splits). The CWA software quits adding individual volume amounts to the volume combination when the number of individual amounts equals the number of land splits.

The internal system structure of CWA uses a "stack" to create every possible combination of water volumes. The stack uses a "first in, last out" principle; the first volume combination created is the last one to be completed. The CWA program starts the volume combination process by iterating through each possible individual volume, according to the FineFactor used. Each individual volume calculated is added to the stack object. After the first set of iterations is complete, CWA looks at the last individual volume added to the stack and repeats the iteration process by adding a new individual volume amount, one for each possible individual volume. This process repeats until CWA creates a combination of individual volume amounts that has a total volume equal to the calculated gross water volume. When this condition is met, the combination is removed from the stack and added into a collection of valid water volume combinations. Combinations of water volumes that do not equal the calculated gross water volume amount are discarded.

Grain Yield-Irrigation Relationship

Grain yields for corn, grain sorghum, sunflower, and winter wheat were estimated by using the "KS Water Budget v. T1" software. Software development and use are described in Stone et al. (1995), Khan (1996), and Khan et al. (1996). Yield for each crop was estimated from relationships with irrigation amount for annual rainfall and silt loam soils with loess origins derived from research in the High Plains of western Kansas (Khan, 1996). Annual rainfall amounts were reduced within the software by runoff fractions of 0.12, 0.13, 0.15, and 0.02 for corn, grain sorghum, sunflower, and winter wheat, respectively (Khan et al., 1996). In the development of the grain-yield estimates, annual rainfall was varied from 280 to 530 mm (11 to 21 in.) in 25-mm (1-in.) increments (Stone et al., 1995). Irrigation application amounts were adjusted to account for application efficiency, such that the model uses the amount of irrigation water that enters into the soil profile. For development of the grain-yield estimates, irrigation application amounts (at 100% application efficiency) were varied from 0 through 510 to 610 mm (20 to 24 in.) in 25-mm (1-in.) increments, with the upper irrigation amount varying by crop. Each irrigation event was either a 25- or 51-mm (1- or 2-in.) application amount to achieve the total irrigation level sought.

Yield estimates for continuous dryland cropping were found with the Kansas Water Budget (KSWB) software by going through each amount of rainfall [25-mm (1-in.) increments] with no irrigation added. Next, a 25-mm (1-in.) irrigation was applied (at 100% application efficiency) on the best date for yield enhancement of each crop. In the KSWB software, the most benefit from a 1-in. application of water occurs at silking in corn, head emergence in grain sorghum, head opening in sunflower, and head emergence in winter wheat (Khan et al., 1996). This philosophy was used as water was added until the crop was fully irrigated.

Resulting yield-irrigation relationship for corn (fig. 1) shows a convergence to a maximum yield of 14.1 Mg ha^{-1} (210 bu acre^{-1}) from the various combinations of rainfall and irrigation. A diminishing-return relationship of yield with irrigation applied was typical for all crops. Each broken line represents normal annual rainfall for an area.

Crop Production Budgeting

For western Kansas, cost-return budgets for center-pivot irrigation of crops (Dumler and Thompson, 2004) provided the basis for default production-cost values for CWA. Results can be sensitive to production costs, which require realistic production inputs. Table 3 shows early 2005 default production-cost inputs from Kansas Farm Management Guides.

User Interface with Model

The program was designed with user-friendly, customized interface screens with discrete input information cells or keyed actions. Input cells have drop-down choices, where appropriate, and direct links to help information. A help library is also available that serves as a technical guide for the program. The flow of information through the program is shown in figure 2. Information inputs are categorized into general, irrigation, and crop production, according to the input screens receiving the data (see details in the Inputs to Model section). Each crop has a separate production-cost screen.

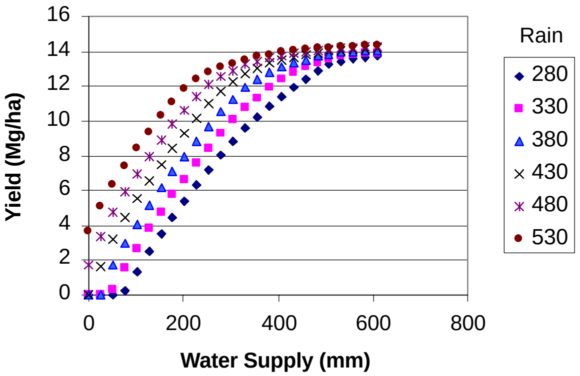

Figure 1. Yield-irrigation relationship for corn with annual rainfall from 280 to 530 mm (11 to 21 in.).

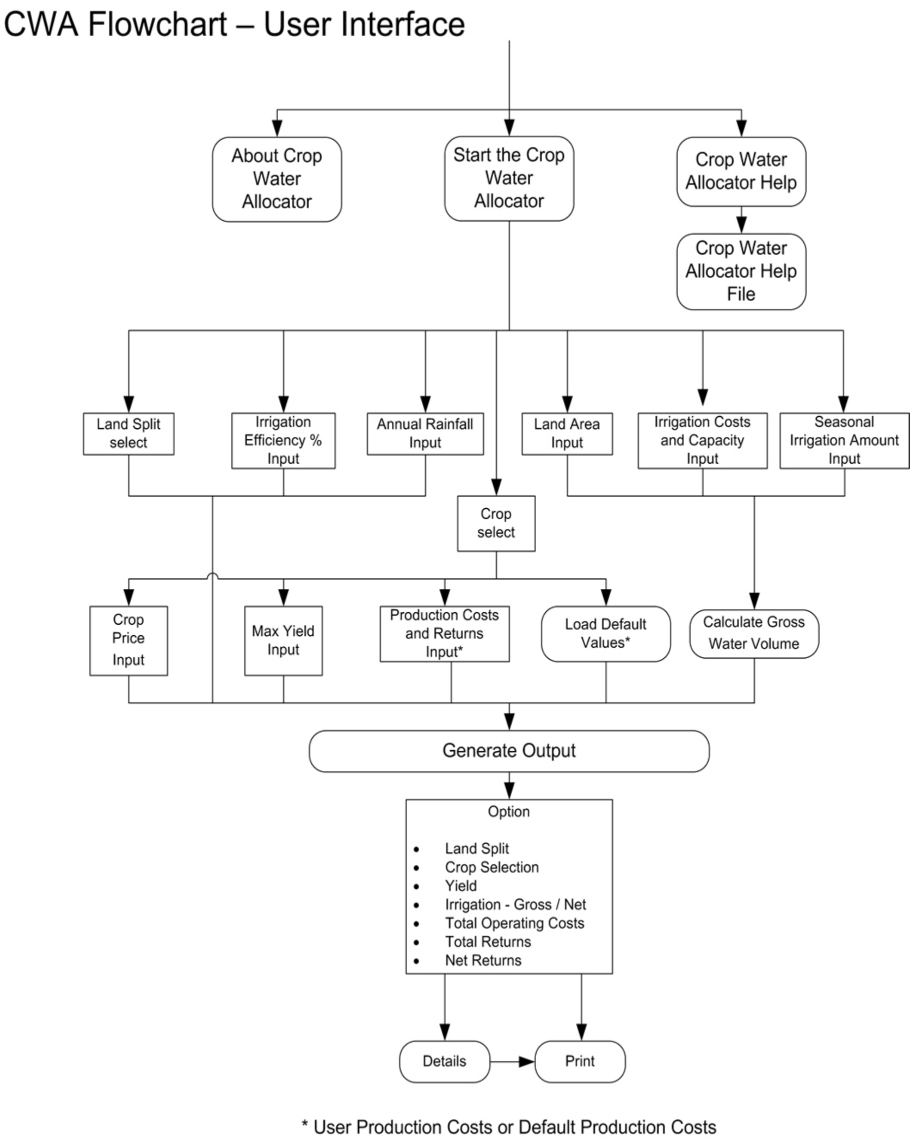

Figure 2. CWA flow chart of user interface.

INPUTS TO MODEL

GENERAL INPUTS

The general-input interface screen allows the user to define the various field, water, and cropping-system inputs along with their desired land-split scenario for each simulation.

Water Iteration "Water Split Factor:" (Access through Edit/Options)

This feature allows the user to change how "coarse or fine" the iteration of water is over crops and land. The default and recommended value is 10. Larger values increase the fineness of the iterations and slow the program, whereas smaller values are coarser iterations. For example, a value of 10 divides the entered water allocation into 10 equal amounts that are sequentially added to one another as one iteration builds to the next. A value of 5 divides the water allocation into five equal amounts, leading to fewer iterations. If more crops are to be compared at one time with more land splits, coarser water iterations (lower split values) will shorten program run time.

Total Land Area

Land area may be a field, farm, watershed, or river basin. The program is not scale dependent. The original intent in designing the program was for the field or farm scale because of the assumption for limited land splits. The designers of the program projected that producers would divide their land in finite, rather than infinite, patterns; thus, the decision was made to limit choices to convenient arrangements of fields.

Irrigation Application Efficiency

Irrigation efficiency reflects the relationship between gross irrigation (delivered to the field or pumped) and net irrigation (delivered to the ground and available for evapotranspiration). The user is free to enter a custom number. Suggested efficiencies (table 1) are provided as management suggestions. Actual efficiencies will depend on local design, site conditions, and system management.

Table 1. Irrigation system efficiencies suggested in Crop Water Allocator.

Irrigation System	Efficiency (%)[a]
Average surface irrigation	50
Surface with surge valve	60
Surface with tail water recovery	70
Surface with surge valve and tail water recovery	80
Sprinkler with heads on top of mainline	85
Sprinkler with heads at top of canopy	88
Sprinkler with heads in canopy	90
Drip irrigation	95

[a] Assumes no surface runoff or leaching.

Annual Rainfall

Annual rainfall is the total amount of effective precipitation that can be expected, on average, during the calendar year. The program was developed for western Kansas with rainfall conditions of 280 to 530 mm (11 to 21 in.) annually. Rainfall totals can be altered to reflect other probabilities for occurrence (NOAA, 2000) and, as a result, reflect different levels of risk for the outcome of the results.

Seasonal Gross Irrigation or Water Allocation

Seasonal gross irrigation is the amount of total seasonal water applied, which could be limited by a regulation or well capacity . This input is in terms of gross irrigation depth. A warning will be issued by the program if the entered irrigation depth cannot be achieved with the input specifications of pumping volume and pumping hours.

Calculated Gross Water Volume

Calculated gross water volume is the total amount of water pumped during the season, which is calculated by the program from the product of total acres and seasonal irrigation amount. If this volume is more than the one derived from pumping hours and pumping discharge, a warning is given to the user.

Land Split

Total irrigated or non-irrigated areas have been divided into five different sets of proportions in this program: 50%-50%; 75%-25%; 33%-33%-33%; 50%-25%-25%; and 25%-25%-25%-25%. These land splits were chosen as convenient ways to divide fields or farms for crop rotations. Because farmers usually do not divide their land in an infinite number of ways, the model assumes these sets of probable choices. The user can choose one land split for each run of the model or hold it fixed and vary other factors.

Select the Crops to Evaluate

The user can select from a minimum of two, or up to all of the crops listed, to consider in the proposed rotations. More crops can be selected than can fill the land parcels at one time. The program will consider each crop selected for every possible combination of crop and water allocation. Fallow, in which nothing is grown, is considered a crop. As water availability dwindles, one alternative may be to withhold water from part of the field. Concentrating water on another crop may lead to more economic return. Production costs are associated with fallow and should be entered into the appropriate production cost screen, but, this option can be used with a positive net return that may exist with a water "buyout" program or other income such as grazing leases.

Price per Unit

Commodity prices are important for determining the optimal crop mix in the model. Prices need to be realistic if the user intends to predict reasonable outcomes. Results in the model can be sensitive to price relationships among commodities. For USDA farm program crops, the loan rate should be the minimum price entered.

Maximum Yield

The recommended maximum yield is similar to the yield goal for calculating fertilizer needs for a crop. Appropriate maximum yields fall between the average yield obtained over the past 3 to 5 years and the highest yield ever obtained in the particular field. (Leikam et al., 2003). This value is used to tailor the program's yield predictions to the user's experience. The relationships between yield and irrigation built into the program are based on Kansas State University research in western Kansas. The maximum yield information further customizes the yield-irrigation relationships for the user. The maximum yield defined by the user and the maximum yield defined in the program is used as a ratio to proportionally adjust all of the points of the yield-irrigation relationship up or down. Therefore, the selection of maximum yield is important to the outcome. Equation 2 defines the maximum yield adjustment and figure 2 illustrates its effect with corn.

$$Y_{iu} = Y_{ic} (Y_{mu})/(Y_{mc}) \tag{2}$$

where

Y_{iu} = incremental adjusted yield for user yield-irrigation relationship,
Y_{ic} = incremental yield-irrigation relationship from Crop Water Allocator (CWA),
Y_{mu} = user entered maximum yield, and
Y_{mc} = maximum yield for CWA yield-irrigation relationship.

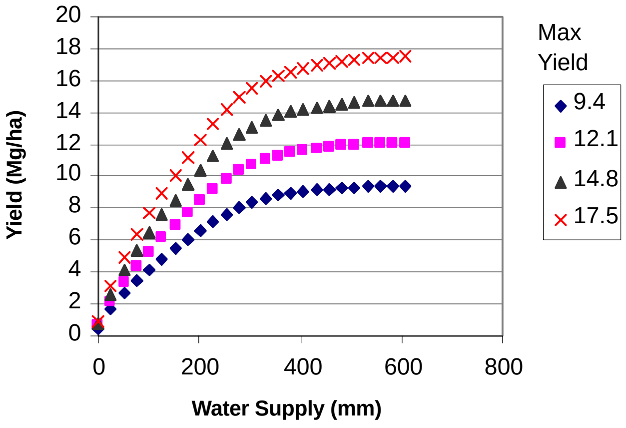

Figure 3. Adjustment of maximum yield for corn by Crop Water Allocator.

IRRIGATION COSTS

Irrigation costs are determined from input factors that combine to estimate energy use according to the Nebraska pumping plant performance criteria (Fischbach and Schroeder, 1982). These criteria were developed for well engineered and properly maintained power plants, drive trains, and irrigation pumps. Not all irrigation systems are performing at the level of the criteria. It is possible that there may be exceptional systems, possibly diesel-powered systems, that may exceed the performance criteria. The user is furnished with a preliminary operating cost for irrigation so that an adjustment in an input could be made to match operating cost.

Input factors for the irrigation cost inputs are:

- Pump Discharge: Outflow of the pump for the field or the sum of the flow for the pumps operating over the field(s) considered in the total land area.
- Hours of Pumping: Total hours of pumping over the entire season for the greatest amount of water application to be considered. If more than one field was considered, enter the average hours pumped by the wells over the season.
- Pumping Lift: Static water level plus drawdown of the aquifer are combined for pumping lift. The pump must lift this distance to the surface.
- System Operating Pressure: After the water reaches the surface, the pump must pressurize the water for the irrigation system.
- Fuel Type: Select from diesel, propane, natural gas, or electricity.
- Labor: Labor charges are for irrigation-system management and maintenance.
- Repair and Maintenance: This reflects the increase or decrease in usage of the irrigation system on the basis of irrigation requirements. The suggested default value is \$0.005 ha^{-1} mm^{-1} (\$0.33 $acre^{-1}$ in^{-1}).

CROP-PRODUCTION COSTS

Each crop has a separate screen for crop-production cost entry. Grain crops (corn, soybean, wheat, grain sorghum, and sunflower) have similar screens, whereas alfalfa and fallow have customized screens.

- General Input Costs: The primary, crop-specific, input costs including, nitrogen, phosphorus, and seeding rates, can be calculated by the program on the basis of water use of the particular option or can be entered manually on the basis of user's practices. Herbicide and insecticide costs are the total cost per acre for all treatments used for the crop from the harvest of the previous crop to the current harvest. Application costs are not included in the general input section.
- Land Usage Returns: The model allows users to enter income from non-cash crop enterprises such as grazing,, crop residue effects, or government payments. Because government payments (direct and counter-cyclical) are the same, regardless of the crop planted, this information is irrelevant in terms of determining the optimal crop mix, but it can be entered for cash-flow purposes.
- Operation Costs: Tillage, planting, and herbicide, and insecticide application costs are identified in this section. For each item, the number of operations is multiplied by the cost per operation.
- Miscellaneous Costs: Any costs not covered in the other categories can be entered.
- Default Crop Values: If users do not know their specific costs per operation, representative costs can be entered by selecting "Load Default Crop Values." These default values are acquired from the Kansas Agricultural Statistics Service (2004). Typical costs for farms in western Kansas were obtained from the Kansas State University Farm Management Guide crop budget series. These crop budgets are updated annually, and are available at www.agmanager.info or at local county Extension offices.

TREND ANALYSIS RESULTS

Several model simulations or scenarios were executed to examine the effects of various input factors on net return when annual water allocations were varied from 102 to 610 mm (4 to 24 in.). Kansas's water has appropriated water rights from 460 to 610 mm (18 to 24 in.) on an annual basis, depending on water resource availability and user density. However, in areas of depleted aquifers or limited surface water sources, producers face reduced water supplies for irrigation. In these areas annual irrigations are below appropriated water rights. A water allocation of 610 mm (24 in.) was used in this example to apply the full annual water rights of western Kansas and to show the diminishing net returns of extended pumping. Applying more than 410 to 460 mm (16 to 18 in.) of water may not be practical since the well and pump capacity of the example was 31.5 L s^{-1} (500 gpm), given the operating hours in the growing season.

Single input factors considered were irrigation pumping costs, commodity prices, maximum crop yield, and rainfall probability. Initial inputs for this example (table 2) include crop, system, and commodity price values typical for western

Table 2. Inputs to the Crop Water Allocator for baseline conditions.

Table 2a. Initial Conditions

Land area	53 ha
Land split	33−33−33
System efficiency	90%
Rainfall	432 mm

Table 2b. Crop Inputs

Crop	Price (\$ Mg^{-1})	Max Yield ($Mg\ ha^{-1}$)
Alfalfa	13.64	12.4
Corn	17.05	13.2
Sorghum	16.67	7.5
Sunflower	50.00	2.5
Soybean	31.82	3.8
Wheat	24.24	4.1
Fallow	0	0

Table 2c. Irrigation Inputs

Flow rate	31.5 L s^{-1}
Lift	61 m
Pressure	240 kPa
Natural gas	2.12 \$ 10,000L^{-1}
Labor	10 \$ h^{-1}
Repair	0.005 \$ ha^{-1} mm^{-1}
Irrigation cost	0.06 \$ ha^{-1} mm^{-1}

Table 3. Default production costs and prices for Crop Water Allocator (December 2004).

Item	Unit Value	Wheat	Sorghum	Corn	Soybean	Sunflower	Alfalfa
N	\$ kg^{-1}	0.10	0.10	0.10	0.10	0.10	0.10
P	\$ kg^{-1}	0.13	0.13	0.13	0.13	0.13	0.13
Seed	\$ 1000^{-1}	0.04[a]	1.23[a]	1.55	0.18	0.96	1.62[a]
Herbicide	\$ ha^{-1}	2.09	10.71	11.91	5.48	6.08	6.10
Insecticide	\$ ha^{-1}	0.00	0.00	15.84	0.00	5.50	3.30
Tillage	\$ ha^{-1}	7.68	8.33	8.33	8.33	8.33	7.68
Planting	\$ ha^{-1}	2.98	3.45	3.62	3.66	3.54	4.16
Herb appl	\$ ha^{-1}	1.56	3.11	3.11	3.11	1.56	1.56
Insect appl	\$ ha^{-1}	0.00	0.00	1.58	0.00	3.17	1.58
Fert appl	\$ ha^{-1}	2.50	2.50	2.50	2.50	2.50	1.49
Harvest							
Base	\$ ha^{-1}	5.67	6.14	7.88	7.82	7.64	
Extra	\$ Mg^{-1}	1.05	1.05	0	0	0	
High yield	\$ Mg^{-1}	3	4.6	0	0	0	
Hauling	\$ Mg^{-1}	0.98	1.05	0.83	0.90	0.92	
Contracting	\$ Mg^{-1}	24.30	17.18	19.20	41.10	46.00	17.80

[a] \$ kg^{-1}.

Kansas in 2004. Default crop-production-cost values used in this example analysis are shown in table 3.

Net returns over the range of water allocation for the baseline inputs are in table 4a and figure 3. Net returns continuously increased from 102- to 406-mm (4- to 16-in.) water allocations but decreased with additional irrigation. Between and including water allocations of 610- and 305-mm (24- and 12-in.) continuous corn produced the most net return. At water allocations of 203 and 102 mm (8 and 4 in.), the crop rotation shifted from continuous corn to include wheat. Wheat was used as a dryland crop to shift water to favor irrigated corn production at both of the lower water allocations.

Irrigation cost increases from \$0.06 to \$0.10 ha^{-1} mm^{-1} (\$3.8 to \$6.3 acre^{-1} in.$^{-1}$)] had a negative impact on net return when compared with the baseline scenario (table 4b). Continuous corn was recommended except at the two lowest pumping levels, where wheat was included in rotation. At water allocations more than 406 mm (16 in.), high irrigation costs along with other input costs cause reduced pumping below allocations for best net returns. The best options were to fallow 1/3 of the field rather that apply the large allocations. Irrigation costs are increasing with energy costs. Great Plains irrigators are reporting costs of \$0.16 ha^{-1} mm^{-1} (\$10 acre^{-1} in.$^{-1}$), which will cause more pressure on irrigated production.

An upward shift in soybean price was the next deviation from the baseline example (table 4c). Soybean was selected for all of the corn selections of the baseline examples, with wheat becoming a companion crop when water allocation dropped to 102 mm (4 in.). The magnitude of the net return increased as a result of the price increase. The “shape” of the net return relationship to maximum economic returns (fig. 3) mimicked the yield-irrigation relationship for maximum return for water (fig. 1). The challenge with this solution is whether or not it is practical from an agronomic viewpoint. Continuous cropping of soybeans is generally not a recommended cropping practice. Crop rotations with soybean were program alternatives produced lower net returns. These crop rotations with soybeans included wheat for a water application of 200 mm (8 in.) and corn for 305 to 610 mm (12 to 24 in.) of water. Adding wheat to a soybean rotation, irrigated with 204 mm (8 in.), decreased net return by 1% from the continuous cropping. Adding corn to a rotation with soybean decreased net returns by 13% and 16% for the 508- and 610-mm (20- and 24-in.) allocations, respectively. Fine tuning commodity price selections, however, can give an indication of price relations where parity among crops may exist at different water allocations.

Producer expectation of crop yields can be important in crop selections. An individual’s ability for producing different crops and the capabilities of their farms is important. The example scenario in table 4d shows the influence of reducing the maximum expected corn yield. With this shift, soybeans took over as the option for returning the most economic gain, except at the lower water amounts. For this example, soybean had relatively good commodity prices and low input costs. Wheat and sunflowers were selected when water was severely limited and soybean yields were also limited. The user would also be looking into other options with less net return if continuous soybean was not a viable system.

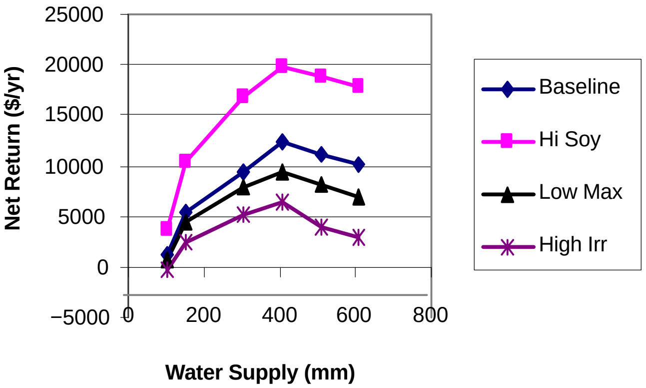

Figure 3. Net return in response to water allocation for irrigation when input variables of commodity price, maximum crop yield, irrigation system efficiency, irrigation costs, and rainfall probabilities are independently changed.

Table 4. Example of input-variable influences on the outcome of Crop Water Allocator.

Water Allocation (mm)	Crop Selection			Water Distribution for Selected Crop (mm)			Net Return[a] ($\$$ Year^{-1})	Δ Net Return[b]
	1/3	1/3	1/3					
Table 4a. Baseline−influence of water allocation								
102	wheat	wheat	corn	0	0	305	1260	−−
203	wheat	corn	corn	0	305	305	5424	−−
305	corn	corn	corn	305	305	305	9489	−−
406	corn	corn	corn	406	406	406	12262	−−
508	corn	corn	corn	457	610	457	11167	−−
610	corn	corn	corn	610	610	610	10119	−−
Table 4b. Influence of high pumping costs				Irrigation Costs $\$0.10$ ha^{-1} mm^{-1}				
102	wheat	wheat	corn	0	0	279	−176	−1436
203	wheat	corn	corn	0	305	305	2551	−2873
305	corn	corn	corn	305	305	305	5180	−4309
406	corn	corn	corn	406	406	406	6517	−5745
508	corn	corn	corn	305	305	0	3986	−7181
610	corn	corn	corn	368	368	0	2959	−7160
Table 4c. Influence of change in soybean price from $\$36.3$ to $\$47$ mg^{-1}								
102	wheat	wheat	soybean	0	0	305	3667	2407
203	soybean	soybean	soybean	185	246	185	10315	4891
305	soybean	soybean	soybean	305	305	305	16826	7337
406	soybean	soybean	soybean	406	406	406	19685	7423
508	soybean	soybean	soybean	508	508	508	18923	7756
610	soybean	soybean	soybean	610	610	610	17841	7722
Table 4d. Influence of dropping corn maximum Yield from 14.1 to 11.8 m ha^{-1}								
102	wheat	sunflower	sunflower	0	152	152	758	−502
203	wheat	soybean	soybean	203	203	203	4324	−1100
305	soybean	soybean	soybean	305	305	305	7895	−1594
406	soybean	soybean	soybean	406	406	406	9498	−2764
508	soybean	soybean	soybean	508	508	508	8249	−2918
610	soybean	soybean	soybean	610	610	610	6934	−3185
Table 4e. Influence of changing rainfall probability to 80% (356 mm)								
102	fallow	fallow	sunflower	0	0	305	−1006	−2266
203	fallow	sunflower	corn	0	246	368	2202	−3222
305	fallow	corn	corn	0	462	462	5502	−3987
406	corn	corn	corn	406	406	406	9305	−2957
508	corn	corn	corn	508	508	508	10124	−1043
610	corn	corn	corn	610	610	610	9997	−122

[a] Net Return = Net return to land, management, and irrigation equipment.

[b] Δ Net Return = Change in net return from baseline scenario to test scenario.

The standard annual rainfall recommendations for the model are based on average rainfall. For long-range planning, a user, who is "risk averse" or "risk seeking," may want to use a range of rainfall probabilities. Substituting a different rainfall amount (NOAA, 2000), as in the example in table 4e, gave an indication of change from the baseline scenario. The rainfall probability of 80% is a "risk-averse" planning strategy because the expected rainfall was less than normal. Fallow was used to concentrate more water on corn in the low water allocation amounts. Unfortunately, the program does not answer all questions from a hydrologic prospective. The water carried over by fallow to the next year does not get credit unless it is given credit manually by the user in the production cost input page. When compared with the baseline scenario, net returns were less for all water allocations except 610 mm (24 in.), which was over-irrigation management for the irrigation system efficiency of this scenario. The comparison demonstrated that, with less rainfall, the economic optimum occurs with greater water allocation. Irrigation simply replaced the rainfall to redefine the optimum return.

CONCLUSIONS

A computerized decision aid has been developed to assist irrigators in finding optimum allocations of limited water supplies for crop mixes that will maximize net returns. User inputs including water supply, irrigation costs, crop production costs, commodity prices, and maximum crop yields can be tailored to user circumstances. These inputs influence the selection of the optimum crop rotation, water allocation among those crops, and ultimate net return of the cropping system.

Multiple executions of the model with incremental input of one variable can lead to trend analysis. An example simulation demonstrated that large water allocations led to monoculture cropping systems, whereas limited water allocations promoted crop rotations. Above normal commodity prices and lower maximum yields shifted crop choices. All scenarios led to diminishing net returns with added irrigation at the same point that the yield-irrigation relation reached a maximum. Many "what if" questions can be raised, but care must be taken with realistic input information because there are multiple input variables that could be selected.

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