Valuing the Characteristics of Irrigation Water in The Platte River Basin

Eric Houk
Garth Taylor
Marshall Frasier[1]

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[1] Eric Houk is graduate research assistant at Colorado State University, contact at erichouk@lamar.colostate.edu. Garth Taylor is an assistant professor at the University of Idaho. Marshall Frasier is an associate professor at Colorado State University.

Introduction

Increased demands on water supplies are derived from a multitude of uses including recreational, industrial, municipal, environmental, and agricultural. Construction of new water storage and conveyance facilities to meet these demands is no longer feasible. Cost effective sites have already been developed (Turner and Perry 1997) and recent environmental concerns effectively prohibit new construction. Reallocation of water from current users is the lowest cost alternative to meet emerging higher valued water demands.

Population growth is responsible for many of these increased demands, but it is the recent emergence of environmental demands that is having the greatest impact on current water users (Michelsen and Taylor 1999). In the western United States water for irrigated agriculture is presently responsible for more than 85% of the total water resource withdrawals (Frasier et al. 1999, Taylor and Young 1995, Colby 1990, Gibbons 1987). Agriculture is the largest consumptive and least valued water user; it would generally be less costly to transfer water from agriculture than to develop new water supplies (Young 1884). Thus, agriculture will be targeted to fulfill endangered species habitat requirements.

The Platte River Basin has four species listed as threatened or endangered under the federal Endangered Species Act (ESA), and a 56-mile long section of the Central Platte River designated as critical habitat. To comply with the ESA mandate for species recovery, an estimated 373,000 acre-feet of additional water must be made available annually to augment the current flows through the critical habitat (Frasier et al. 1999). In 1997 Nebraska, Wyoming, and Colorado entered into a cooperative agreement with the United States Secretary of the Interior to develop and implement a program that would increase stream flows to aid species recovery (Frasier et al. 1999).

Finding new water to allocate for endangered species is prohibitively expensive and water in the Platte Basin is fully appropriated. The transfers of water from agriculture to instream flows for species recovery have proposed a myriad of conservation, water markets, water banking, and pricing solutions. All of these solutions require evaluation as to the foregone benefits of that water in agriculture, and/or the costs to agriculture.

To efficiently allocate water resources it must be done in a way that maximizes social welfare. Social welfare will be maximized when the marginal benefit of the resource is equal across all uses (Gibbons 1987). In the absence of working free markets for water it is difficult to identify the value (or marginal benefit) that should be placed on this ever-changing resource. It is critical to determine the value of water in agriculture so that the necessary information is available for these water allocation decisions. The goals of this study are to value agricultural irrigation water in the Platte River Basin over form, place and time: (1) over a cross section of agriculturally distinct regions of the Platte River Basin, which reflect climatic, agronomic, and crop markets influences; (2) over times of the growing season; (3) over differing institutional arrangements for water transfers; and (4) the risk response to changing water supplies.

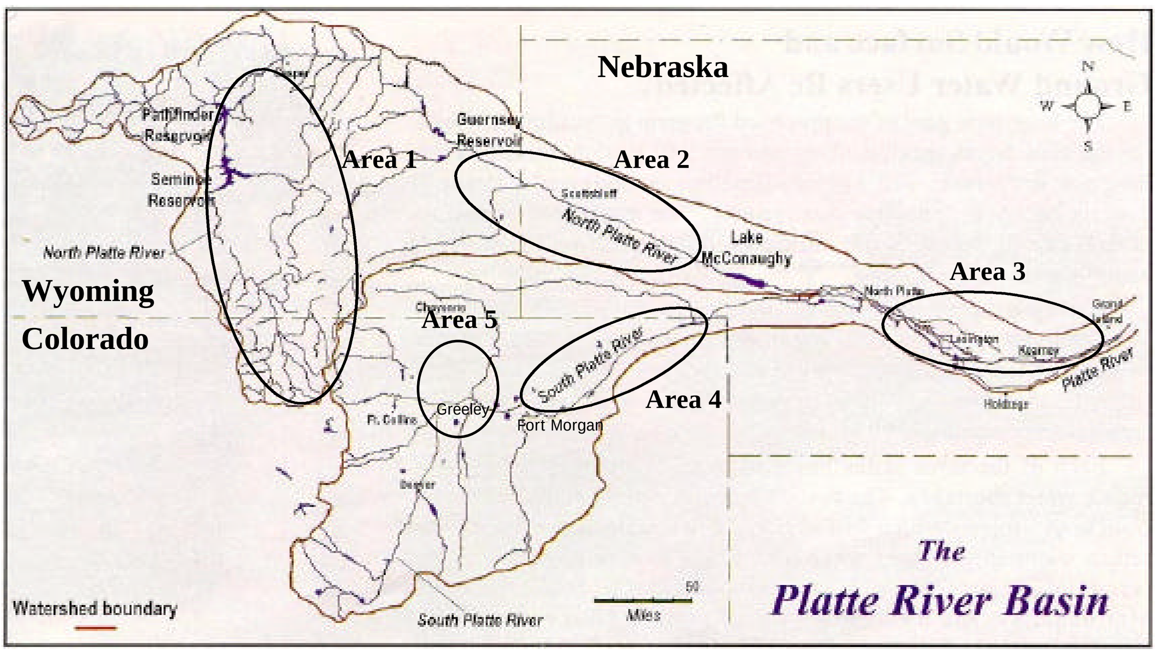
The results of this study will be useful to policy makers and individual farmers. Policy makers will be able to assess the impacts on farmers and the feasibility of changing water rights to meet the demands of recreational, industrial, municipal, and environmental water uses. Farmers will be able to quantify the relationship between their water supply and their income to better understand the impacts of entering into agreements that would change their current water supplies.

Methods

Both the North and South Platte Rivers originate in the Rocky Mountains of Colorado. The North Platte River flows north from Colorado, through Wyoming and then eastward into Nebraska. The South Platte flows northeast through Denver and continues towards the town of North Platte, Nebraska were the two converge to form the Platte River; the entire basin covers approximately 90,000 square miles (Eisel and Aiken, 1997).

Based upon producer and irrigation district employee interviews conducted in June 1999, the basin was segmented into five regions with similar agricultural practices, water deliveries, water institutions, and weather (Figure 1). Five representative farms were then constructed from survey and census farm data based upon these distinctive regions.

Figure 1: Platte River Basin:



The representative farm framework in each region varies in farm size, crops produced, crop rotations, types of irrigation used, amount of irrigation water available, precipitation, crop water requirements, cropping budgets, crop yields, and crop prices. In Area 1 agriculture is limited to flood irrigated alfalfa, wild or native hay, and pasture. The area is characterized by high elevation, short growing season, and limited water storage for late season irrigation. Area 3 produces high yields of corn and soybean with very secure water supplies. The major irrigated crops in Areas 2,4, and 5 are corn, alfalfa, sugarbeets, and drybeans.

Model Structure

Agricultural production is sequential in nature, where many farm decisions are influenced by earlier decisions and information that becomes available only after earlier choices have been made (Anderson, Dillon, Hardaker 1977). To account for the sequential nature of agricultural production a model was used that incorporates the risks of crop production into the objective function and allows for sequential decisions to be made. Discrete Sequential Stochastic Programming (DSSP) is a technique where decisions will be optimized through multiple stages of expected occurrences (McCarl and Spreen). DSSP was developed by Cocks in 1968 and was later applied in 1971 by Rae to agriculture (Taylor and Young 1995), but has been used very seldom since (Kaiser and Apland 1989).

The structure of the model can be viewed as a decision tree, where the decisions are linked in time sequence with their associated probabilities. As we move along the decision tree we are faced with forks representing possible outcomes or decisions, if these event forks (state of natures) are not limited the problem can quickly become too large to work with. Anderson, Dillon and Hardaker (1977) recommend limiting states of nature that are essentially continuous by approximating discrete distributions into two or three categories.

The model in this study simplifies the farm decision process to two sequential time periods in which irrigation water can become available to the farm. The stochastic variable is the quantity of irrigation water available at these two stages throughout the growing season.

Irrigation water available in the first time period will be limited to two states of nature, either full water or no water. The use of run-off water is restricted to the early production of alfalfa (if alfalfa is a possible crop choice in that area). Full water represents an adequate supply to fully irrigate all available alfalfa based upon regional alfalfa rotations. The decision at this time period decides the amount of the farm's land that will be used to grow alfalfa. This decision limits future time periods because it causes less land to be available for other crops.

The second time period has three states of nature identified as full water, short water, and very short water. This time period commences with the announcement of growing season storage water available for the irrigation district. Irrigation water available in this period will be used to grow all crops on the available land for the entire growing season, if the state of nature provides an adequate supply. Full water, short water, and very short water supply represent water deficits of 0%, 25%, and 40% respectively. The decisions made at this point are the crop mix to be planted on the idle land available from the first time period, irrigation strategy based on the water supply available, and harvesting activities. Land can also be left idle (not farmed) if it is found to maximize expected farm profits.

Quantities of water will be allocated by crop growing stages throughout the season with the ability to deficit individual or all stages of growth if optimal, based upon the supply of water available. The model will produce optimal crop mix and optimal irrigation schedule based on the state of nature and period by maximizing the total expected profit of each representative farm. The marginal value of water will be estimated for each time period and for each representative farm.

The DSSP model maximizes total expected profit over two sequential stages, subject to acreage, agronomic, and irrigation water constraints:

$$\text{Max} \sum_{k=1}^{4}\sum_{i=1}^{81}\sum_{s1=1}^{2}\sum_{s2=1}^{3} \Big[ACRE_{k,i,s1,s2}\big(Y_{ki} * (P_k - HC_k) - NC_{ki}\big) + A_{s1}\big((Ap - Ahc) - Anc\big) - \big(I_{k,i,s1,s2} * Ic\big)\Big] * P1_{s1} * P2_{s1,s2}$$

$$\begin{aligned} \text{s.t. :}\quad & ACRE_{k,i,s1,s2} + I_{k,i,s1,s2} \le Land\ \ Available \\ & ACRE_{k,i,s1,s2} \le B_k \\ & A_{s1} * Awreq \le R1 \\ & ACRE_{k,i,s1,s2} * (Wreq_4 - P_E) \le R2 \\ & A_{s1} \ge A_{s2} \end{aligned}$$

where $ACRE_{k,i,s1,s2}$ is the quantity of acres planted for each crop k ($k = 1,\dots,4$) across all irrigation strategies i (i = 1,…,81), for both of the time periods and all possible states of nature $s1,s2$ ($s1$ = 1,2 ; $s2$ = 1,2,3). The quantity of acres is multiplied by the difference in crop price, P_k, and the per unit cost of harvesting HC_k to get a per acre value of production that then has the per acre non-harvest costs subtracted NC_{ki}, the value of non-harvest costs is dependent upon crop (k) and irrigation strategy (i). The value associated with the first cutting of alfalfa is then added to the value of all other crops. A_{s1} is the acreage of alfalfa that is irrigated with run-off water and then cut, it is multiplied by the difference in alfalfa price (Ap) and alfalfa per unit cost of harvesting (Ahc), then has the alfalfa non-harvest costs (Anc) subtracted. The cost of maintaining idle land is then subtracted from the total value of all crop production. The quantity of idle land ($I_{k,i,s1,s2}$) is a function of all crops produced, irrigation strategies used, and all time periods and is multiplied by the cost of idle land (Ic). The last step of the objective function is to include the probabilities ($P1_{s1}$, $P2_{s1,s2}$) of each state of nature in each of the two time periods. The objective function is subject to many constraints, the first constraint is making total acreage used by crops and idle land equal to the total land available. B is the minimum rotational requirements for each of the crops. The quantity of water used by alfalfa in the first cutting ($Awreq$) must be less than the amount of run-off water available ($R1$). The second water constraint requires that the total water required for each crop ($Wreq_4$) less the areas effective precipitation (P_E) be less than the total quantity of water available in the second time period ($R2$). The last constraint links the quantity of alfalfa in the first period (A_{s1}) to afalafa in the second time period (A_{s2}).

Objective Function, Costs of Production, and Crop Prices

The objective function maximizes the total expected profit over all possible states of nature. It is a summation of all activities for each time period in the model, calculated by the value of crop sales minus per unit costs of harvesting and the non-harvest acreage costs accrued throughout the growing season. The value of crop sales will reflect the regional crop prices and non-harvesting acreage costs will vary according to the different irrigation strategies and crop mixes. Crop budgets for Nebraska and Colorado were used to find area specific costs of production. Establishment costs for alfalfa were amortized over a four-year period.

States of Nature

It was assumed that the decision maker's beliefs or perception of an uncertain event would dictate how he or she would behave in the long run. Probabilities for each state of nature and for each time period were identified. Producers and irrigation district employees were consulted as to the likelihood of receiving run-off water, and the likelihood of having short, very short, or full water supply from irrigation districts. Probabilities were based on the historical occurrences for each area.

Agronomic and Water Constraints

The possible crops are alfalfa, sugarbeets, drybeans, soybeans, corn, and meadow hay with no one area growing more than four of these crops. Rotational practices for each area were determined by interviews with producers in each region. Water constraints were constructed using the evapotranspiration requirements for each crop in each region. In addition to irrigation water fulfilling these ET requirements, the average effective precipitation during the growing season for each region was estimated.

Crop-Water Production Functions and Crop Yields

The generalized production function used in this study was from Doorenbos and Kassam (1979) and quantifies the relationship between relative yield decrease (1-Ya/Ym) and relative evapotranspiration deficit (1-ETa/Etm):

$$(1-Ya/Ym) = Ky\ (1-ETa/Etm)$$

Where:	Ya	=	Actual Yield
	Ym	=	Maximum Yield
	Ky	=	Yield Response Factor
	ETa	=	Actual Evapotranspiration
	ETm	=	Maximum Evapotranspiration

The yield response factor (Ky) is dependent upon crop species, magnitude of water stress, and timing. Values of the yield response factor (Ky) were used as found by Doorenbos and Kassam (1979). Evapotranspiration (ET) represents the actual quantity of water used by the soil-plant system and was used because it has been found to be a better predictor of yield than applied water (Vaux and Pruitt, 1983). When actual evapotranspiration is less than the maximum evapotranspiration required a relative evapotranspiration deficit occurs resulting in decreased yields. The use of relative evapotranspiration will allow the model to have site transferability so that it can be used along different areas of the Platte River Basin (Vaux and Pruitt, 1983). The quantity of water that is actually applied for crop production will be adjusted to represent the quantity of water available for evapotranspiration through the use of area specific irrigation efficiencies.

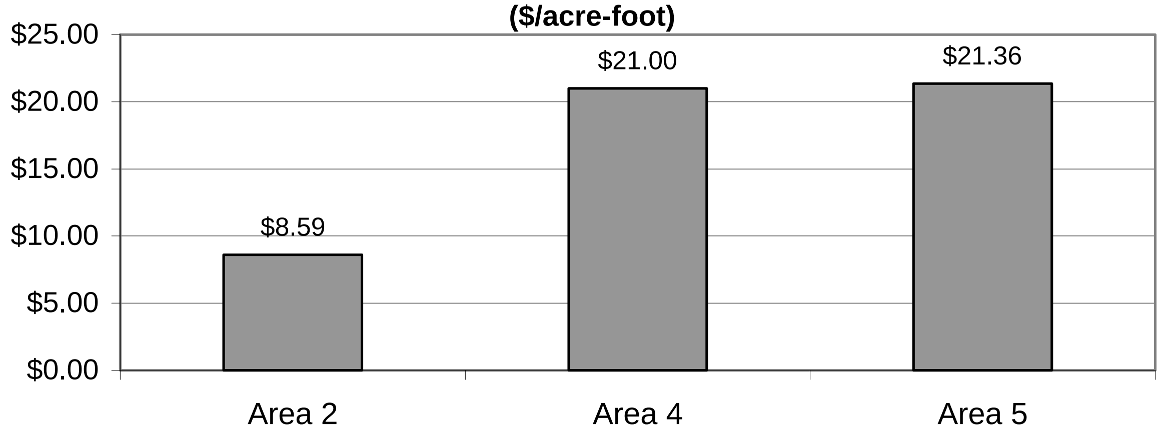
Results

Incentive based techniques such as early spring run-off water transfers, long term growing season transfers, and dry year leases are analyzed in the following sections by identifying the marginal value of irrigation water under these possible conditions.

Value of Spring Run-off

Alfalfa's first and largest cutting is assured by spring run-off diversions. The expected marginal value of run-off water is thus related to this first cutting of alfalfa and ranged from as little as $8.59/acre-foot in Area 2 to as high as $21.36/acre-foot in Area 5. The only other area that was using spring run-off to irrigate alfalfa was Area 4, where the value was $21.00/acre-foot (Figure 3). The difference in value between Area 2 and Areas 4 and 5 could be associated with the lower prices received for alfalfa in Area 2 and the lower percentage of alfalfa grown. The values in Area 4 and 5 are almost exactly equal because the crop budgets and percentage of alfalfa grown on a representative farm are similar.

Figure 3: Expected Marginal Value of Run-off Water ($/acre-foot)



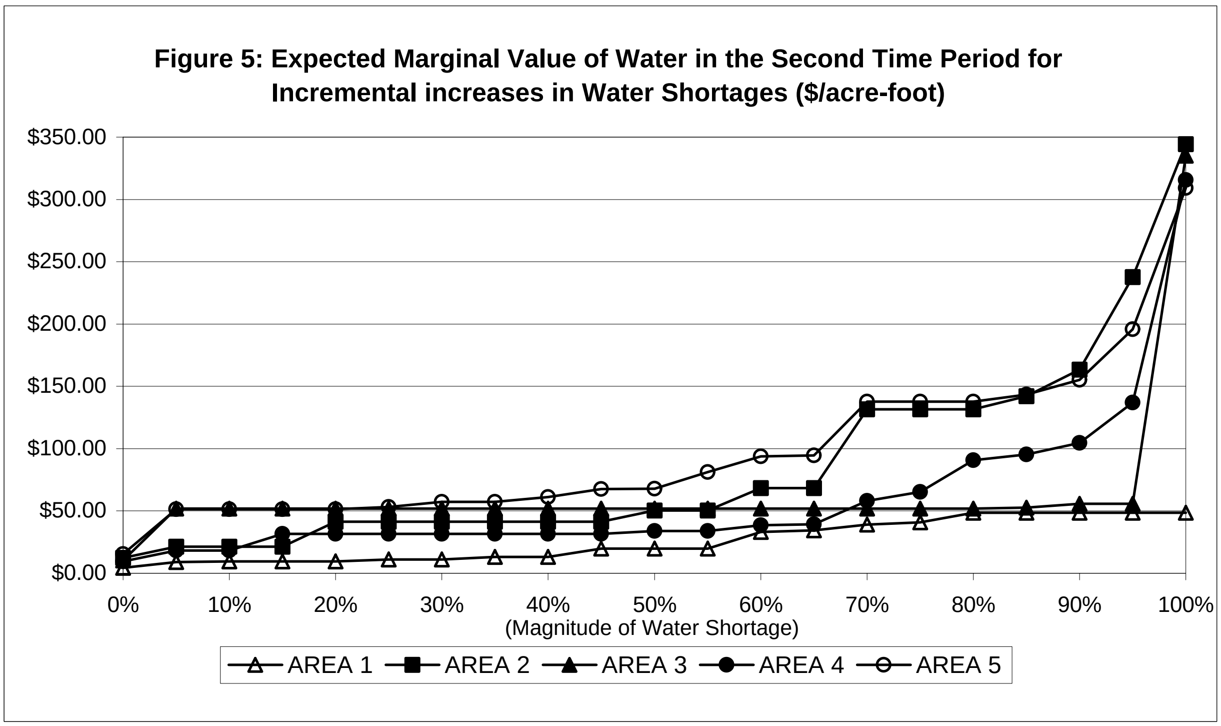
Value of Water in the Second Time Period

The second time period is the water available from irrigation districts for the entire growing season excluding the first cutting of alfalfa. The expected marginal value of water in this time period ranged from $4.38/acre-foot in Area 1 to as high as $15.44/acre-foot in Area 5 (Figure 4). These values of water are lower than those of most other studies for water in this area, however these are the expected marginal values for water. These values represent the long-run value of water at the margin; in most years these farms expect to have abundant water supplies, which would cause the marginal value to be zero in those years. This value is what a producer should be willing to accept to be compensated for an acre-foot of water for a long-term water lease regardless of the current years water condition. In water short years this value would be less than the actual value and in a wet year it would be higher than the actual value.

Figure 4: Expected Marginal Value of Water in the Second Time Period ($/acre-foot)

Area 1, characterized by the shortest growing season and limited crop choice, had the lowest value of water in the basin. This result was expected due to the much lower yields and efficiencies in this area. The model estimates that over four acre-feet of water is applied, which is approximately twice as much as all other areas, but only receives half of the yield for their alfalfa. Area 5 had the highest value of water in the basin; this was most likely associated with the higher production of profitable sugarbeets and drybeans. Although Area 2 had a similar crop rotation as Area 5 the value of water was lower because the crop budgets reflected a higher cost of production in that area.

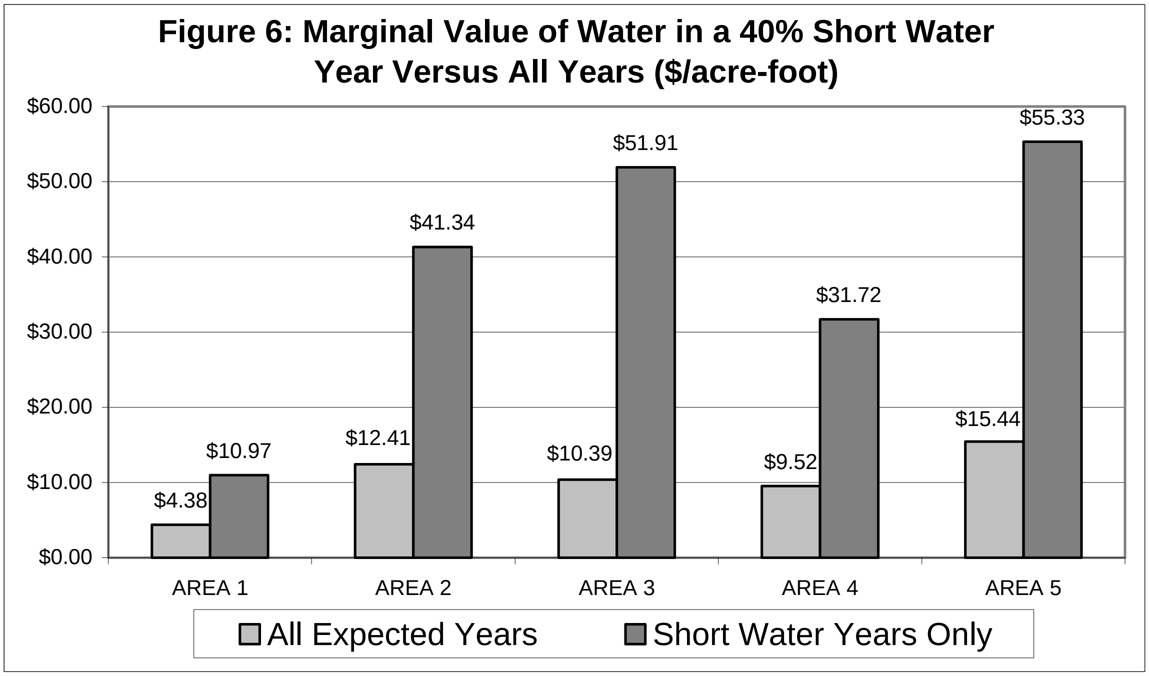
The model was used to estimate the marginal value of water for water reductions up to 100% in 5% increments. These values represent a demand schedule for irrigation water for each of the areas. The highest expected marginal value of water when all water was diverted away from the farm was in Area 4 at a value of $344.38/acre-foot (Figure 5).



__Value of Water in Short Years__

Currently the most common plan for acquiring water from agriculture for endangered species recovery is the use of short-term water leases in low water years. The DSSP model can be used as a deterministic linear programming model that will value water in short years only. To do so it is necessary to change the probabilities for each of the states of nature so that the model is forced to solve for a solution when it is a short water year, in other words when the probability of a short water year is equal to 1.

The results from this procedure indicate that the marginal value of water increases approximately 350% in a short water year (40% reduction in water)(Figure 6).



The value of water in a short water year depends directly upon the magnitude of the water shortage. These values which range from $10.97/acre-foot to $55.33/acre-foot represent what the farmers in these area should be willing to accept for compensation of one acre-foot of water when water supplies are 40% less than required.

Conclusions

The value of irrigation water in the Platte River Basin is dependent upon the water supplies that are available to the farm and how producers respond to these changing conditions. The DSSP indicated that alfalfa and sugarbeets are the only crops that use water deficit irrigation strategies in short water years. Corn, soybean, and drybeans were not irrigated with water deficit irrigation strategies in short years because of their relatively high responses to water deficit. It was more profitable for the model to reduce the quantity of irrigated acreage and fully irrigate the crops rather than water-stressing all of the possible acreage. The result that alfalfa was deficit irrigated in short water years was supported by producer behavior, according to interviews, alfalfa was the first crop to be water stressed.

Current supplies for irrigation water in the Platte River Basin have been very secure with relatively high allocations, the expectation of these conditions continuing causes the long run expected values of water to be considerably less than some other studies found. If the likelihood of receiving full water supplies were to decrease in the basin the expected marginal value of water would increase. Optimal crop acreage and irrigation strategies produced from the DSSP model was similar to what is currently occurring in these areas of the Platte River Basin, these results give confidence in the accuracy of the values of water produced.

If water was to be acquired from agriculture for species recovery at this time, assuming that the costs of water transport to the critical areas was low or non-existent, it would be most efficient to reallocate water from its lowest valued current use in agriculture. If water were to be targeted early in the year it would be most efficient to transfer spring run-off water from Area 2. It would be much less costly to acquire water from Area 2 because the marginal value of run-off water in Area 2 was lower than in Areas 4 and 5. Water transfers during the regular growing season would be done most efficiently from Area 1. The producers in this region should be willing to be compensated for their water supplies at a much lower price than producers in the other regions. Reducing the water supply to these areas should increase the efficiency of water use and cause their expected marginal values to increase. If it would be necessary to continue reallocating water from agriculture it would be most efficient to continue doing so from the next lowest valued water user until all of the water users in the basin were receiving the same marginal benefits from their water supplies.

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