Welfare Differences Between Gross Water Pumped and Consumptive Use as Alternative Policy Control Variables to Meet Aquifer Management Objectives[1]

by

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ABSTRACT: The welfare cost of using gross water pumped instead of consumptive use as a control variable to meet consumptive use goal was estimated for Southwestern Nebraska. Crop simulation models for corn, grain sorghum, wheat and soybeans were estimated by EPIC. The models were then optimized for profit maximization under each irrigation scenario where groundwater is constrained through successive reductions. The results indicate that the social cost of reducing consumptive use is substantially overstated when using gross water pumped instead of consumptive use as the control variable, with the percentage difference declining as the size of the reduction increases. For example, the social cost of reducing consumptive use by 10 percent was 43 percent lower if it were achieved by directly controlling consumptive use instead of using the traditional approach of limiting gross water pumped. On a per acre basis, the average cost of a 10 percent reduction was $87.65 per acre foot of consumed water if consumptive use was controlled, and $156 per acre foot of consumed water if gross water was the control variable.

INTRODUCTION

Background

Economists have traditionally analyzed aquifer management problems using optimization models based on gross water pumped as the constrained input and many have recommended controlling gross water as an aquifer management strategy. Prominent examples include Young and Bredehoeft (1972), Haimes and Dreizin (1977), Morel-Seytoux, et al. (1980), Hardin and Lacewell (1980), Lacewell and Grubb (1971), Louise, et al. (1984), Feinerman and Knapp (1983), Supalla, et al.(1982), Worthington, et al. (1985) and Cory, et al. (1992). The only exception is He (1997) who emphasized the use of consumed water or net withdrawals rather than gross irrigation water as a policy variable involving the Great Lakes.

The economic consequences of using either gross water or consumptive use as policy control variables are the same for those circumstances where groundwater return flows have no economic value, or where return flows have economic value but the relationship between gross water pumped and consumptive use is a constant proportion. Although these conditions are met in some cases, irrigation return flows often have some economic value to either a stream or the aquifer and the relationship between gross water and consumptive use is always non-linear for irrigation uses. The relationship between water pumped and water consumed approaches one to one when crops are partially irrigated, but marginal consumptive use falls well below 50 percent of marginal gross water applied as the optimum full irrigation level is approached, even with a very efficient irrigation system, (Martin, et al.,1984). If return flows have value and the relationship between consumptive use and pumped water is not constant, then the economic optimum is different if consumptive use rather than gross water pumped is the control variable for achieving a given consumptive use goal. This means that policies based on gross water pumped may not be the least cost method of achieving public water management goals.

The welfare cost of using gross water pumped instead of consumptive use as the control variable to meet a consumptive use goal was estimated for Frenchman Creek, which is a tributary to the Nebraska-Kansas Republican River. Groundwater levels in this area have declined by 30 feet or more since 1955 (Steele and Wigley, 1994) and this has contributed to a 80 percent decline in streamflow at the mouth of the Frenchman. A U.S. Geological Survey (U.S.G.S) report in 1989 predicted a steady decline in the level of the aquifer from 1989 to 2030, resulting from long-term pumping at the current rate. The effect of the pumping scenario on streamflow was also estimated. The observed streamflow in Frenchman Creek near Imperial at the end of May 1989 was 32.6 cubic feet per second (cfs), while the simulated flow at the same location in May 2030 was only 10.2 cfs. Similar conclusions were reached by Peckenpaugh, et al. (1989), in their study of the High Plains Aquifer response to groundwater withdrawals in the Upper Republican Natural Resources District.

Study Area

Frenchman Creek Watershed is a subbasin of the Republican River Basin made up of Frenchman Creek, Spring Creek, Stinking Water Creek and Sandy Creek. The watershed is in the Upper Republican and Middle Republican Natural Resource Districts of Nebraska with over 70 percent of the area being in the Upper Republican Natural Resource District. The watershed covers Chase County, southern Perkins, a southwest section of Hayes, the northwestern quarter of Hitchcock and northern Dundy counties. The drainage area is 1,300 square miles (Nebraska Department of Water Resources, 1995).

The major crops under groundwater irrigation are corn, soybeans, alfalfa, wheat and grain sorghum. The climate of the study area is continental subhumid and semiarid conditions predominant in most years. Average annual precipitation is around 19 inches. About 75 percent of the annual precipitation occurs during the growing season (April-September).

Approach and Procedures

The approach used here to compare the welfare effects of restricting net withdrawals versus gross pumping of irrigation water as alternative policy scenarios consists of two major parts: (a) a crop simulation model, and (b) an economic optimization model.

The Erosion-Productivity Impact Calculator (EPIC), a biophysical simulator developed by the Agricultural Research Service (Williams, et al.) was used to estimate yield-water production functions for the economic analysis. EPIC simulates crop growth and nutrient flow under varying conditions with respect to climate, soil and farming system characteristics. The physically-based components of EPIC include hydrology, weather simulation, erosion simulation, nutrient cycling, plant growth, tillage and soil temperature.

EPIC has been applied to a number of biophysical-economic models. Recent examples include an evaluation of conservation compliance on Tennessee farms (Thompson, et al.) and cropping strategy assessment in the Texas Trans-Pecos region (Ellis, et al.).

EPIC results for the Frenchman Creek Valley were compiled in the following manner. Simulated runs for typical operations were made for corn, grain sorghum, wheat and soybeans for conventional dryland, ecofallow and full irrigation over a 46 year time period. Average annual crop yields, evapotranspiration and irrigation water applied were estimated for these crops on the major soils found in the area: Valentine (sandy), Rosebud (loamy) and Keith (silt). Sprinkler irrigation using center pivots was assumed. The EPIC results were used to estimate water-yield production functions using a methodology developed by Martin, et al. The functions were of the form:

where:

$$Y = Y_d + (Y_m - Y_d) [1 - (1 - I_r) (\frac{1}{\beta})] \qquad \textbf{(1)}$$

Y = yield, bu/ac ;
Y_d = dryland yield, bu/ac;
Y_m = maximum irrigated yield, bu/ac;
I_r = ratio of irrigation water applied (I) to maximum irrigation requirement (IM),decimal
β = ratio of the ET due to irrigation (ET_m - Et_d) to the maximum irrigation requirement (IM), decimal
Et_m = Et at maximum irrigation, inches
Et_d = Et with no irrigation, inches

β represents the portion of the irrigation that is used by the crop as evapotranspiration when producing maximum yield. The value of β is highly dependent on the application efficiency of the irrigation system. However, the effects of irrigation scheduling, soil characteristics and other irrigation management factors are included in β. In general, β values close to 1 indicates efficient irrigation and low β values represent inefficient irrigation.

Estimating sprinkler irrigated water-yield functions for each crop and soil requires estimates of the maximum ET (ET_m), the dryland ET (ET_d), the maximum irrigation requirement (I_m) and the maximum yield (Y_m). All of these values were estimated using EPIC (Table 1). The resulting equations were used to provide grain yield by irrigation level for discrete activities within a linear programming model. For gravity irrigated alternative, the same parameters were used to estimate the function except that irrigation efficiency of 80 percent was used instead of 90 percent.

The linear programming model was a regional model which maximizes return to land and management, subject to land and water constraints. Mathematically, the model can be described as:

$$\max \ \left(\sum_{t=1}^{2} \sum_{c=1}^{4} \sum_{j=1}^{23} C_{tcj} X_{tcj} \right) - \sum_{n=1}^{2} \sum_{T=1}^{2} \left(W_n \, IR_n + K_n \, T_n \right) \qquad \textbf{(2)}$$

where subscripts t = irrigation technology = (center pivot and gravity irrigation with reuse irrigation systems); c = crop (corn, sorghum, winter wheat and soybeans); j = irrigation level of crop c, inches; n = water source, in this case n = (groundwater and surface water); C_{tcj} = net revenue (gross revenue less variable production costs) \$ per acre; X_{tcj} = acres of crop activity; IR_n = annual irrigation activity in acre-feet (ac-ft); W_n = cost of irrigation water in \$ per acre-inch; K = acres of irrigation technology; and T = capital cost of irrigation in \$/acre for irrigation technology.

Three constraints were used in the model: land use, gross water use and consumptive water use. The land use constraints represent the amount of land available for crop c, at irrigation level j, soil types s, under irrigation system types i, using water source n.

$$\sum_{c=1}^{4} \sum_{j=1}^{23} \sum_{s=1}^{3} \sum_{t=1}^{2} \sum_{n=1}^{2} X_{cjstn} \leq L_{cstn} \qquad \textbf{(3)}$$

The gross water constraint was defined as the amount of irrigation water applied summed across all irrigation activities as depicted in equation (3).

$$\sum_{t=1}^{2} \sum_{c=1}^{4} \sum_{j=1}^{23} \sum_{s=1}^{3} R_{tcjs} X_{tcjs} \leq \sum_{n=1}^{2} IR_{n} \qquad \textbf{(4)}$$

where:

R_{tcjs} is water applied to crop c; at irrigation level j; on soil s; with irrigation technology t in feet,

X_{tcjs} is number of acres under irrigation system t; crop irrigation level j; and

IR_n is irrigation water applied; from source n; in acre feet.

Estimating consumptive use constraint was more problematic. Consumptive use from irrigation was defined as crop transpiration, plus evaporation from the soil surface, plus the evaporation which occurs before the water reaches the soil surface, less dryland ET. All return flows from deep percolation and runoff were assumed to return to the aquifer or contribute to desired streamflow and, thus, were defined as non-consumptive. Dryland ET was assumed to equal precipitation over the long-term and, thus, was not explicitly incorporated in the constraint.

Consumptive use due to irrigation was calculated as:

$$CU_{scjt} = (Y_{scjt} - Yd) / b_{sct} + AW_{scit}(1 - IE_t) \quad \textbf{(5)}$$

where:

CU_{scjt} = consumptive use from irrigation crop c at level j on soil s using irrigation technology t; feet per acre;

AW_{scit} = gross water applied, inches per acre;

IE_t = irrigation efficiency defined as the proportion of pumped water which reaches the soil surface, assumed at 90 percent for sprinklers and 100 percent for gravity systems, decimal;

b_{sct} = yield per unit ET, defined as the ratio of (Ymax - Yd) over (ETmax - Etd), bushels; and

all other variables specified earlier.

The consumptive use constraint was then defined as equation (3) by substituting CU_{scjt} for R_{tcjs}.

The changes in profit and crop mix between the unrestricted (unregulated gross or consumed water) model in the base case and that model under imposed water policies provides a measure of water policy effectiveness and farm-level cost.

Prices and Production Costs

Crop prices were based on average prices, unadjusted for inflation or transfer payments, received by Nebraska farmers during the last five years. The average prices used were $2.49, $2.28, $3.42 and $5.80 for corn, grain sorghum, wheat and soybeans, respectively.

The production costs were divided into non-irrigation production costs and irrigation costs. The non-irrigation production costs were obtained from Nebraska Crop Budgets prepared by Bitney, et al. (1996). The irrigation costs which include both fixed costs and water dependent costs were estimated using an irrigation cost program prepared by Selley, et al. (1996). These costs vary with system type, well depth, well yield, pumping depth, pressure, acreage per system and energy type. Irrigation costs were estimated for center pivot sprinklers and gravity irrigation with reuse pits. The center pivot system was assumed to be an electric powered seven tower system irrigating 130 acres at a pivot point pressure of 40 psi. The gravity system was gated pipe system requiring 10 psi and used to irrigate 90 acres with an electric powered pump with one-half of the system having reuse pits and one-half diked ends. The 130 acres was assumed for the center pivot system because nearly all center pivots are used to irrigate a quarter section of land, which after corner loss, result in about 130 acres per system. For gravity systems, 90 acres per system was used.

Results and Discussions

Eight scenarios were evaluated, designated as A to H and originally defined in terms of gross water applied. Scenario A was the unconstrained baseline, while scenarios B to H were respectively defined as 5, 10, 15, 20, 25, 30 and 35 percent reductions in gross water. These scenarios were further defined in terms of consumed water by computing the percentage changes in consumed water which corresponded to the constrained gross water solutions. The corresponding percentage reductions in consumed water were 1.76, 4.33, 7.05, 10.75, 16.22, 21.71 and 27.21, for scenarios B to H, respectively.

The most profitable irrigated crop was always continuous corn. For the dryland alternative, the optima were wheat-corn-ecofallow for silt soil and continuous grain sorghum on loam and sandy soils. When gross water is restricted, the optimum response was initially to keep all irrigated land in production and move slightly to the left on the yield-water production function. At higher restrictions it becomes economic to shift irrigated land to dryland production. The first land to shift to dryland was gravity irrigation on sandy soil. This occurred at a 25 percent gross water restriction. There was also a shift of gravity irrigated acres to center pivots on loam soil at a 30 percent gross restriction. On the other hand, when net water was constrained, there was no movement down the production functions. Instead, there was a shift of acres from the less efficient irrigation system; in this case gravity to the more efficient sprinkler irrigation at 1.76 % reduction of consumed water. When the restriction was extended to 4.33 percent, all the medium textured acres under gravity went to pivot and the corresponding coarse textured acres went to dryland. At further restrictions (i.e. 7.05 percent and above), about two-thirds of the coarse acres under pivot also went to dryland, but all the heavy soil under gravity and sprinkler, medium soil under sprinkler and the remaining third of coarse acres under sprinkler were still fully irrigated. Thus, when consumed water is restricted, crops are still at full irrigation with less acres.

The cost of reducing consumptive use was calculated as the difference in net returns for the alternative scenarios. Comparing the results for scenarios A and B, for example, indicates that it would cost $140.95 per acre foot to reduce consumptive use by 5 percent if the result was achieved using gross water as the policy control variable, but only $42.84 per acre foot if the control variable was consumptive use (Table 1). As the size of the reduction was increased, however, it was found that the control variable used made less and less difference. The marginal cost of reducing consumed water under the most restrictive scenario was $142.09 when using gross water as the control and $127.15 when using consumed water, a relatively small difference. On an average cost basis, using gross water instead of consumed water as the control variable cost over 200 percent more at low levels of reduction, but only 16 percent more for the most restrictive scenario considered.

Table 1. Costs of Reducing Consumptive Use of Groundwater Using Alternative Control Variables

		Cost When Control Variable is Consumptive Use		Cost When Control Variable is Gross Water	
Scenario	**% Reduction in Consumed Water**	**Average**	**Marginal**	**Average**	**Marginal**
A	–	–	–	–	–
B	1.76	42.84	42.84	140.95	140.95
C	4.33	87.65	118.29	156.03	166.34
D	7.05	102.92	127.14	171.64	196.39
E	10.75	111.25	127.15	178.48	168.28
F	16.22	116.61	127.15	154.04	140.91
G	21.71	119.28	127.15	145.74	142.08
H	27.21	120.87	127.15	140.79	142.09

Conclusions and Policy Recommendations

Most previous studies of the cost of limiting groundwater pumping for irrigation use have used gross water pumped as the control variable. The results from this analysis suggest that this is a very inefficient approach when irrigation return flows are not lost to the basin of interest. When irrigation return flows, either deep percolation or runoff, are not lost, there is a large difference between consumptive use and gross water pumped. In such cases, the widespread use of gross water as the policy control variable substantially overstates the welfare cost of reducing consumptive use.

The most important policy implication is that when the objective is to limit consumptive use and the difference between consumptive use and gross water pumped is large, one should use consumptive use rather than gross water as the control variable. However, it may be difficult to administer such a program because consumptive use varies by crop and irrigation level and is not easily measured and modeled at the field level.

A simple method of controlling consumptive use would be to directly limit irrigated acres of all crops. This would work relatively well if the cropping pattern is dominated by a single crop, or if the crop alternatives all consume similar amounts of water. A somewhat more sophisticated option that in some cases would lead to a more efficient outcome, would be to constrain consumptive use based on a consumptive use coefficient for each crop and the number of acres produced. This would allow the producer to choose more acres of a less consumptive crop if it was more economic to do so and still consume the same amount of water. Because the relationship between consumptive use and yield is linear, less than full irrigation of a given crop is never an attractive economic choice when consumptive use is limited.

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