THE ECONOMIC VALUE OF GROUNDWATER RECHARGE FOR IRRIGATION USE

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Abstract

A conceptual model is developed to evaluate the economic benefits from ground water recharge, under conditions where the major water use is irrigation. Both pumping cost savings and aquifer extension benefits are considered. This model is then applied to a Nebraska case where it was found that recharge benefits vary from less than $2 to nearly $20 as a function of aquifer response, the discount rate, commodity prices and energy prices.

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INTRODUCTION

Serious ground water mining problems exist in the High Plains from Nebraska to Texas, in south central Arizona, and in parts of California (U. S. Water Resources Council, 1978). In each of these severe problem areas, irrigated agriculture accounts for over 90 percent of total consumptive use of ground water (Williams and Murfield, 1977; U. S. Water Resources Council, 1978). Furthermore, irrigation provides a large proportion of the economic base in the regions where the most severe ground water declines are occurring (Mapp and Eidman, 1976; Bekure, 1967). This means that a major policy issue posed by the ground water mining problem is how to manage the available ground and surface water resources to provide for economic stability over time.

One of the principal management alternatives available to policy makers faced with this situation is artificial ground water recharge. Artificial recharge projects, either single-purpose or multi-purpose, utilize underground storage to augment available water supplies. Although artificial recharge is not a new idea, public interest in this option has been growing at least in part because of the environmental problems associated with conventional surface reservoirs. This growing public interest has created a need to critically examine the technical and economic feasibility of artificial recharge in regions where the only significant ground water use is irrigation.

The technical aspects of artificial recharge have been extensively investigated. Annotated bibliographies on artificial recharge by Todd (1959) and Signor, et al. (1969), briefly describe more than 800 published technical reports through 1967. Although much of this early work focused on geohydrologic conditions and water use situations not typical of those found in the major ground water irrigation regions, more recent research has addressed the issues of technical feasibility for the Texas High Plains and for Central Nebraska (Brown, et al., 1978; Hoskins-Western-Sondregger, 1978; Lichtler, 1978; Manbeck and Stork, 1975). From the literature it is evident that there are numerous situations in major ground water irrigation areas where artificial recharge, either ponding or well injection, is technically feasible. What remains to be examined more thoroughly is the question of economic feasibility.

Previous work on the economics of ground water recharge has generally been focused on two issues: the cost of recharge systems (Todd, 1965 and 1970; Bookman, 1968; Frankel, 1979; Mawer, 1970; Hajas and Swanson, 1979), and the economics of conjunctively managing surface and ground water (Chun, et al., 1964; Brown and Deacon, 1972; Nieswand and Granstrom, 1971). Very little, if any, definitive work appears to have been done on the value of benefits from artificial recharge. Until more is known about the potential benefits from artificial recharge, policy makers will be unable to determine when, where and if artificial recharge is a viable option to pursue.

The principal objectives of this paper are to develop a methodology for estimating ground water recharge benefits in irrigation use areas, and to use that methodology to estimate ground water recharge benefits for selected situations. These objectives were addressed using a Nebraska case for illustrative purposes, but the benefits methodology and general conclusions regarding the value of recharge under alternative conditions should be applicable to other ground water irrigation areas as well.

PROCEDURES FOR ESTIMATING RECHARGE BENEFITS

Economic benefits from groundwater recharge for irrigation purposes are only realized when water is withdrawn from the aquifer. The benefits occur in the form of reduced pumping costs and extension of aquifer life. Cost of pumping increases with depth to water and if recharge is able to stop or slow the rate of decline, one benefit of recharge is the difference in the amount spent on pumping with the project versus what would have been spent without the project. Recharge of a declining aquifer may also make it possible to irrigate for additional years. The economic value of this aquifer extension effect is equal to what an irrigator could afford to pay for the water and be at least as well off as he could be without it.

The magnitude of the economic benefits from recharge, per unit of recharged water depends on two sets of parameters: (1) the physical variables, which determine the impact of recharge on pumping depth, well yields and aquifer life; and (2) the economic variables, which determine the significance of the physical impacts in terms of reduced pumping costs and additional income from extended aquifer life. In the paragraphs which follow, these sets of relationships and the linkages between them are discussed and presented in the form of a mathematical model for estimating recharge benefits.

<u>Recharge Benefits Due to Reduced Pumping Costs</u>

When recharge occurs from either well injection or ponding, the basic effect is the development of a "water mound" which spreads radially as recharge continues. The first question which must be addressed in an economic analysis is how this phenomenon affects pumping lift and well yields per unit of water recharged. Answers to this question are, of course, aquifer specific and depend upon geohydrologic parameters such as storage coefficients, transmissivity values, existence of impermeable zones, the presence of base flow streams which might intercept recharge water, etc. A detailed and complete assessment of the physical effects of recharge would therefore require an extensive data collection and modeling effort. It is important to note, however, that in some instances it may be possible to adequately approximate the effects with a much more basic approach.

In cases where irrigation wells are distributed at a near equal density throughout the affected area, when pumping costs as a function of lift are linear, and when well yields do not change appreciably until near the point of aquifer exhaustion, one does not have to know for purposes of computing pumping cost effects how far and how fast the recharged water dissipates into the aquifer. All that one needs to know in order to estimate the impact of a unit of recharge water on lift per unit area of land affected is the average long term storage coefficient and the approximate size of the affected area. In mathematical terms, the change in lift may be expressed as:

$$L = \frac{R}{SA} \qquad (1)$$

Where: L = change in lift in feet per year
S = average long-term storage coefficient
R = quantity of water recharged in acre feet per year
A = affected land area in acres

With the lift affect specified, one can proceed to convert lift changes to pumping cost savings. Pumping cost savings from recharging R amount in year one can be represented as follows:

$$C = PLrAI \qquad (2)$$

Where: C = pumping cost savings
P = pumping cost per acre foot per foot of lift
L = average lift change per acre of affected area
r = proportion of affected area which is irrigated
I = acre feet of water pumped per acre

The above approach provides a method of estimating pumping cost changes for a single year. When expanding the above to encompass a multi-year recharge project recharging R acre feet per year for n years, but only considering the pumping cost component, two additional factors are involved: the cumulative nature of lift changes and the time value of money.

Lift affects are cumulative in the sense that the affect on average lift in year two is twice the affect in year one; in year three, it is three times year one and so on for the life of the project, given that a constant amount R is recharged each year. Thus, the lift effects for each year of a recharge project can be estimated by multiplying equation 1 by t, for t = 1 to n. The conversion of changes in lift to annual pumping cost savings can then be expressed as:

$$C_t = PLt\,[f(t)]; \quad t = 1 \text{ to } n \qquad (3)$$

Where: P, L and t are as specified before
f(t) = a relationship indicating the amount of water pumped within an affected area over time.

The form of the equation f(t) will depend upon the state of the aquifer. If declines in pumping are not expected over the life of the project, f(t) will be constant. One would expect, however, that in the usual case a recharge program would not be contemplated unless some reduction in annual pumpage is eminent. Indeed, the most common case would probably be reductions occurring at an increasing rate over time.

Specifically how much water is pumped from an affected area over time will depend on: whether any new lands are developed for irrigation, whether there are any changes over time in the average amount pumped per acre, how recharge affects the amount of water pumped, and how much land is withdrawn from irrigation because of an inadequate water supply. Estimating this relationship is a difficult process requiring a great deal of data concerning such things as groundwater declines as a function of withdrawals and remaining saturated thickness estimates. In cases where good models of the affected area exist, estimating these parameters may not be too much of a problem. In other cases, one may have to be content with rough approximations based on observed changes in water levels over time.

The expression C = PLt [f(t)] gives us the pumping cost savings for each year of the project. Expressing this in present value terms to reflect the time value of money yields:

$$PV = \sum_{t=1}^{n} \frac{PLt[f(t)]}{(1+r)^t} \qquad (4)$$

Where: PV = present value of pumping cost savings
r = discount rate
n = life of recharge project and length of planning horizon
All other variables as specified earlier.

These present value computations reveal what one could afford to pay in current dollars for a recharge program where the only benefits are reduced pumping cost. The next step is to expand the analysis to encompass the benefits from extended aquifer life.

Recharge Benefits from Extended Aquifer Life

In situations where ground water mining is occurring, recharge may have the effect of extending aquifer life by some amount over the planning period. When this occurs, the economic benefits from recharge are the reduced pumping costs, plus the value of the additional water available for irrigation as a result of recharge.

Estimating the value of extended aquifer life, where the only significant water use is irrigation, requires that one compute the difference between the amount pumped with and without recharge over the length of the planning horizon being considered. Gross pumpage over time without recharge is the f(t) relationship discussed earlier. To compute additional pumpage due to recharge one must estimate a pumpage relationship g(t) for the with recharge situation and calculate the difference between the two. Estimation of the effect of recharge on pumpage is often difficult, but it can be made reasonably manageable, provided one is willing to make two simplifying assumptions: (1) the effect of recharge on aquifer decline is the same as an equivalent reduction in pumpage; and (2) the affected area is well enough specified to be assured that the areas where irrigation would cease without recharge fall within the impact zone of the recharge program. Given these assumptions, gross pumpage with recharge can be approximated by relating ground water declines to gross pumpage and treating recharge as a reduction in pumping, which means that the additional water pumped due to recharge can be represented by g(t) - f(t).

Given f(t) and g(t) one can proceed to specify the present value of the aquifer life extension benefits of recharge. This involves placing a per acre foot value on the difference between withdrawals with and without recharge and discounting back to the present. Thus, multiplying the additional water pumped due to recharge times a value per acre foot (V) and discounting at some rate yields:

$$PV = \sum_{t=1}^{n} \frac{V[g(t) - f(t)]}{(1+r)^t} \qquad (5)$$

Where: PV = present value of recharge benefits due to aquifer exhaustion
V = value of an acre foot of irrigation water
g(t) = gross pumpage over time with recharge
f(t) = gross pumpage over time without recharge
r = discount rate
n = project life and length of planning horizon in years

At this point, a methodology for estimating the present value of a flow of recharge benefits, including both pumping cost and aquifer extension effects, is completely specified, assuming that a project recharges a constant annual amount R beginning in year one and continuing throughout the entire n-year planning horizon. When stated in summary form with all variables as defined earlier the suggested approach can be expressed as:

$$PV = \sum_{t=1}^{n} \frac{PLt\,[f(t)] + V[g(t) - f(t)]}{(1+r)^t} \qquad (6)$$

Recharge Benefits as a Function of Project Life

There may be circumstances where the length of the planning horizon in years (m) is longer than the project life (n). When this is the case, the present value of recharge benefits includes the flow of benefits for years 1 to n as indicated above, plus the benefits which continue for m minus n years after recharge ceases. In mathematical terms they may be expressed as:

$$PV = \sum_{t=1}^{n} \frac{PLt[f(t)] + V[g(t) - f(t)]}{(1 + r)^t}$$

$$+ \sum_{t=n+1}^{m} \frac{PLn[f(t)] + V[h(t) - f(t)]}{(1 + r)^t} \qquad (7)$$

Where: h(t) = the amount pumped from the affected area during years t = n+1 to m, given that recharge of R amount occurred during each year from t = 1 to n

m = length of planning horizon in years
n = project life
All other variables are as specified earlier.

Annual benefits due to both reduced pumping costs and extended aquifer life will continue throughout an entire planning horizon, or until the aquifer is totally exhausted, whichever comes first. This phenomenon occurs because the accumulated reduction in lift is advantageous as long as pumping continues, and because the additional water made available by recharge will remain in the aquifer when the recharge program ceases.

The fact that recharge benefits continue after recharge ceases raises a final issue which must be considered before the benefits model is applied. This is the question of project starting date. With conventional surface water projects, the expected starting date does not matter as long as it is reasonable to assume constant relative prices over time. With recharge projects, however, benefits vary over time because of changing aquifer conditions and thus project starting date is very important. Generally speaking, the nearer one is to the point where without recharge there would be substantial reductions in pumpage the higher the present value of benefits will be. What this means is that when applying the above model, one should specify the functional relationships such that year one is the point in the future when the project comes on line. Indeed, it may be appropriate in some instances, to consider benefits as a function of alternative starting times.

RECHARGE BENEFITS IN CENTRAL NEBRASKA

The foregoing model was applied to a Nebraska situation to determine the approximate magnitude of the economic benefits from recharge and how they vary as a function of aquifer response and selected economic parameters. The results of the analysis also serve as a test of the benefits model and provide an indication of what recharge benefits are in areas where irrigation is the major use of water.

Recharge benefits were estimated for a portion of the Upper Big Blue Natural Resources District in East Central Nebraska. Topographically the region is a broad loessial plain of low relief with local shallow depressions. The principal aquifer system underlying the study area is composed of pleistocene sands and gravels, having transmissivity values ranging from about 7 to 20 cubic feet per day per foot and an average long term storage coefficient of about .25 (Cady and Ginsberg, 1979). Over 95 percent of total withdrawals from the aquifer are for irrigated agriculture.

The agriculture in the region consists primarily of cash grain operations, with about 50 percent of the available cropland under irrigation. Approximately, 90 percent of the irrigated acreage is devoted to corn, with an average gross application of 15 inches and an average yield of 139 bushels per acre. The dominant dryland crop is grain sorghum accounting for about 56 percent of the dryland acreage and yielding an average of 60 bushels per acre.

The first step in applying the recharge benefits model to the study region consisted of specifying the size, exact location and type of project(s) to be analyzed. Based on the foregoing benefits model, one would not expect benefits to vary much as a function of project size and perhaps not at all as a function of recharge technique. Thus, only one set of project specifications was considered at it was selected primarily on the basis of data availability.

The data base for this analysis was drawn primarily from ground water modeling work by Cady and Ginsberg (1979). The model is essentially a simulation of aquifer response to selected withdrawal scenarios projected to the year 1990. By treating recharge as negative withdrawals, one can use the results of earlier model runs as a basis for determining pumpage with and without recharge over time and for estimating lift changes and other parameters needed for the recharge benefit analysis.

Using data available in part from Cady's model and in part from other sources, a part of the Upper Big Blue basin consisting of 186 square miles (118,900 acres) where severe ground water declines have been occurring was selected for analysis. It was assumed that a project recharging 16,800 acre feet annually for 25 years would be implemented in this area. This recharge quantity is equivalent to 3 inches per acre per year for each of the 67,217 irrigated acres that lie within the impact area.

The next step in the analysis consisted of specifying the length of the planning horizon and a starting date for the hypothetical project. With discount rates as high as they are presently (greater than 10 percent), there seemed little reason to consider a planning horizon longer than the 25 year project life because a dollar received 25 years hence discounted at 10 percent is worth only $0.09. For a starting date it was assumed that the project began in 1980. Thus, the appropriate equation to use for estimating benefits is equation 6.

To estimate equation 6, one needs to know the annual change in lift, the cost savings associated with a one foot change in lift per acre foot pumped, the value of an acre foot of water, the appropriate discount rate and the amount of water pumped as a function of time. Several of these parameters are difficult to estimate and/or can be expected to vary as economic conditions and other external factors change. Therefore, several sets of values were considered, but a base case which corresponds to current cost-price relationships and the most likely lift affect was used as the starting reference point.

Recharge Benefits: The Base Case

The estimated base values for each of the parameters in equation 6 were:

1. Annual lift change of .5652 feet. This value was estimated using equation 1, L = 16,800/(.25)(118,900).
2. Pumping cost savings per foot of lift per acre foot pumped of $0.25, assuming a diesel powered pump with $0.95 per gallon diesel fuel. Costs were estimated using a computerized pump program developed by AGNET, University of Nebraska-Lincoln.
3. A value of water per acre foot of $10.25. This value was determined by estimating average per acre net returns to land and management for the most profitable dryland and irrigated crops, with the difference being a return to water. Continuous corn was assumed to be the most profitable irrigated crop and continuous grain sorghum the most profitable dryland crop. The expected yields are those typical of the area; 139 bushels per acre for corn and 60 bushels per acre for grain sorghum. The commodity prices used were normalized U.S.D.A. prices; $2.20 per bushel for corn and $1.92 per bushel for grain sorghum. Production costs and returns were as estimated by Bitney, et al. (1980), assuming irrigation was with a diesel powered system, weighted 50 percent center pivot and 50 percent gated pipe.
4. Amount of water pumped in acre feet as a function of time without recharge was $f(t) = 84838 - 220.0t$, and with recharge, $g(t) = 84296 - 100.6t$. These equations were estimated by using Cady's simulation model of the area to predict pumpage with and without recharge. A regression technique was then used to fit a line through the simulated pumpage figures.
5. A discount rate of 10 percent, based on the current yield on long term government bonds.

Using the above values to estimate equation 6 yields a present value of total recharge benefits for the base case of $954,424, where $901,188 is due to reduced pumping costs and $53,236 is due to extended aquifer life. The estimated value of recharge expressed in terms of dollars per acre foot recharged is $2.27 (Table 1).

Sensitivity of Recharge Values to Changes in Selected Parameters

The uncertainty associated with some of the parameter values used in calculating recharge benefits and the fact that external forces may change

Table 1. Economic value of artificial recharge, given variations in the discount rate, agricultural commodity prices, energy prices and aquifer response.

Benefits[1]	Most Likely Lift Change[2]				High Lift Change[3]		Low Lift Change[4]
	Current Crop Prices, Current Energy Prices	Current Crop Prices, High Energy Prices	High Crop Prices, Current Energy Prices	High Crop Prices, High Energy Prices	Current Crop Prices, Current Energy Prices	High Crop Prices, High Energy Prices	Current Crop Prices, Current Energy Prices
r = .10							
PV_t	954,424	2,631,582	1,145,759	2,822,918	1,179,720	3,467,504	774,186
PV_e	53,236	53,236	244,572	244,572	53,236	244,572	53,236
PV_l	901,188	2,578,346	901,188	2,578,346	1,126,484	3,222,939	720,950
PV_t/ac.ft.	2.27	6.27	2.73	6.72	2.81	8.25	1.84
r = .05							
PV_t	1,847,242	5,547,411	2,261,402	5,961,571	2,280,244	7,319,616	1,500,840
PV_e	115,233	115,233	529,393	529,393	115,233	529,393	115,233
PV_l	1,732,009	5,432,178	1,732,009	5,432,178	2,165,001	6,790,233	1,385,607
PV_t/ac.ft.	4.40	13.21	5.38	14.19	5.43	17.43	3.57

[1]Present value of benefits at two discount rates; PV_t = present value of total benefits, PV_e = present value of benefits due to delay of aquifer exhaustion; PV_l = present value of benefits due to lift change; PV_t/ac.ft. = present value to total benefits per acre foot recharged.

[2]Most likely lift change is the one calculated using L = R/SA; current crop prices means that the value of water was estimated using USDA normalized prices (1980); current energy is using $0.95 price of diesel; high energy prices increased the price of diesel (8 percent per year) when estimating benefits due to lift change; high price are the normalized prices increased by 25 percent.

[3]High lift change increased the lift estimated by L = R/SA by 25 percent.

[4]Low lift change decreased the lift estimated by L = R/SA by 25 percent.

some of the values makes it appropriate to consider how sensitive recharge benefits are to various factors. The principal parameters of concern are the discount rate, the lift change effect, energy prices and agricultural commodity prices. Space and time limitation preclude considering all reasonable changes and combinations of changes, but by considering at a few possibilities one can get a good idea of a reasonable range of possible recharge values.

Recharge benefits were estimated for thirteen combinations of parameter values in addition to the base case (see Table 1). The results indicate a range of recharge values from $1.84 to $17.42 per acre foot. The smallest estimated value corresponds to the base case with a 25 percent decrease in the estimated lift effect. The largest estimated value for the cases considered occurred when it was assumed that the appropriate discount rate was 5 percent, energy prices would increase 8 percent each year in real terms, lift change was 25 percent greater than the base case, and agricultural commodity prices would average 25 percent higher than 1975 to 1979 normalized U.S.D.A. prices. These extremes provide an indication of how sensitive recharge benefits in irrigation use areas are to combinations of widely varied parameter values. Of perhaps greater interest, however, is the question of what impact particular parameters have on recharge values when considered separately.

The effect of the discount rate on recharge benefits for the cases considered was essentially an inverse proportion; decreasing the discount rate by 50 percent approximately doubled recharge benefits. It is important to note, however, that the effect of the discount rate depends on the relative importance of the pump cost savings component and the aquifer extension effects and it is nonlinear across discount rates. From the benefits model one can see that the larger the relative importance of the aquifer extension component the larger the impact of a discount rate change. It is also apparent from the discounting equation that as the discount rate gets larger a given change in the rate has a smaller and smaller impact. For example, a change from 5 to 6 percent for the base case would reduce the present value of benefits by $246,663 whereas an increase from 9 to 10 percent would only reduce them by $122,889.

The effect of the lift change on benefits is proportional for the pumping cost component of recharge benefits. Thus, when the lift effect relative to the base case was increased by 25 percent, benefits due to pumping cost savings increased by 25 percent. How large the impact in percentage terms is on total benefits depends, of course, on what proportion of total benefits is accounted for by the pumping cost components.

Perhaps the most important parameter to consider when estimating recharge benefits is future energy prices; the results are extremely sensitive to the price scenario used and at the same time it is very difficult, if not impossible, to specify what future energy prices will be. The illustrative cases depicted in Table 1 indicate that if one expects energy prices to increase by 8 percent each year in real terms, recharge benefits increase by 176 percent relative to the base case, where energy prices were held constant in 1980 dollars. Although this extremely large impact may be significantly over stated because the analysis did not allow for variations in the amount of water pumped as a function of energy price, it is nevertheless apparent that energy price estimates are a crucial component of any attempt to estimate recharge benefits.

The last parameter considered which significantly influences recharge benefits is agricultural commodity prices. If commodity prices are higher, an acre foot of irrigation water is worth more, thus increasing the value of benefits from aquifer extension. The importance of this impact depends on the size of the aquifer extension benefits relative to the total and on the differential between irrigated and dryland yields. If aquifer extension benefits are a small part of the total, it makes little difference how closely one estimates commodity prices. Likewise, if dryland-irrigated yield differences are small, proportional commodity price changes (corn and grain sorghum are close substitutes) will have much less of an impact than if the yield difference is large. For the project under consideration, a 25 percent increase in expected average commodity prices would increase aquifer extension benefits by 322 percent and total benefits by 20 percent relative to the base case. Although not explicitly considered, variations in estimated crop yields would have an impact on recharge values similar to that for commodity prices. Both variables directly change the value of an acre foot of irrigation water.

It is very important to note at this point that the range of benefit estimates considered above ignore important differences that might result from varying aquifer conditions and/or project starting dates. If the case study area were nearer or more distant from the point of aquifer exhaustion, or if another aquifer was considered, the benefits would clearly be different. Consideration of these factors would be interesting if the data were available, but it is sufficient for purposes of this analysis to note that in no circumstances could the benefits per acre foot recharged exceed the value of an acre foot withdrawn. Using this criterion, the highest possible recharge benefit for the Nebraska case is about $10.25 per acre foot, at current agricultural commodity prices. According to research conducted for the National Water Commission, one would expect this value to be similar for all major irrigation regions, with the possible exception of areas where specialty crops are grown extensively (National Water Commission, 1973).

SUMMARY AND CONCLUSIONS

Artificial recharge as a means of augmenting water supplies for irrigation is a management alternative which policy makers in ground water decline areas are beginning to seriously consider. This paper provides policy makers and analysts with a relatively easy to apply method of estimating recharge benefits and illustrates the approximate value of recharge benefits as a function of selected key parameters.

The methodology presented separates recharge benefits into two components: pumping cost savings and aquifer extension benefits. Simplified procedures designed for use by state and federal water planning agencies are then presented for each recharge benefits component. Experience in applying the model indicates that the required data, time and computer resources are within a range which would permit use of the model for even first-round, reconnaissance level studies as well as for more comprehensive analysis.

The results of recharge benefit calculations indicate that benefits in irrigation use areas could range from less than $2 to nearly $20 an acre foot, with the most likely value being in the $5 to $10 range. These recharge benefit values are most sensitive to energy price variations, the lift affect to be expected in any given aquifer and the discount rate. Agricultural commodity prices impact substiantially on recharge values only for those situations where the aquifer is relatively near the point of exhaustion when recharge begins.

State and federal water planning agencies have historically ignored recharge values when considering water developments in irrigation use areas. This has been the case in part because of the absence of a manageable methodology for estimating benefits and in part because recharge benefits were thought to be insignificant. It appears from this analysis that artificial recharge values can and ought to be considered by water planners in the major ground water irrigations areas of the nation.

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