Intertemporal Farm Response to Limited Groundwater Conditions

by

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AAEA paper presented at its annual meetings.
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Intertemporal farm-level irrigation planning decisions associated with a policy mandated limited water supply are examined with a two-state dynamic programming model. The model uses a backward solving algorithm with farm and field level data. General conclusions on policy structure and producer response are drawn from a test application.
Intertemporal Farm Response to Limited Groundwater Conditions

Pressure to manage groundwater resources for the public interest is increasing, as reflected in the increasing body of literature devoted to the discovery of a socially "optimal" rate of groundwater extraction. Kim, et.al., Feinerman and Knapp, Burt, Gisser and Sanchez, Nieswiadomy, and Worthington, et.al., among others, have developed "optimal" extraction rates for a wide variety of conditions. The search for an "optimal" extraction rate from a common property aquifer has been somewhat inconclusive, but most of these studies suggest that the social optimum is less than the private profit maximizing rate of extraction. This finding is reflected in public policy movement toward at least some control of groundwater resource extraction rates in some areas. The Arizona Water Plan (Arizona Department of Water Resources), establishment of three groundwater control areas in Nebraska, and a recent congressional hearing on linking federal water development dollars to the presence of a state water plan (Reclamation States Ground Water Protection Act, H.R.2320) are evidence of policy changes.

Significant differences exist between irrigation management with policy limited supplies and existing irrigation management practices. Previous studies assumed that land is the limiting input and have focused on either the yield-maximizing water application (Ahmed, et. al.; Stegman, et. al.) or the profit maximizing water application (Lansford, et. al.; Dudley, et. al.; Zavaleta, et. al.). This research effort begins with the premise that policy limited water, not land, is the limiting input. As a result, the goals and operating rules of current irrigation scheduling techniques (elimination of crop moisture stress) are no longer valid, since they are based on land as the limited input.
Current irrigation management methods are inadequate for a policy-limited groundwater supply analysis because current methods fail to consider; (1) temporal inter-dependence of irrigation decisions; and, (2) deficit irrigation\(^1\). Under conditions of policy limited groundwater availability, current usage reduces the water available in the near-term future, resulting in temporal inter-dependence in irrigation water use decisions over a planning horizon. Because future period water supply is directly related to current period water use, the optimal intertemporal farm-level response at any point in time must include the evaluation of both current and future periods. Deficit irrigation, as well as the number of acres irrigated and the number of irrigation systems should be in the producer's decision set for each time period. This assures maximum flexibility in irrigation decisions by having the capacity to serve all or part of the irrigable acres with full or less-than-full irrigation levels.

A few previous studies have addressed farm-level irrigation management with limited groundwater supplies (Martin and van Brocklin, Hardin and Lacewell). However, none of these studies led to the development of criteria for on-farm management decisions with policy limited groundwater supplies. Identification of optimal intertemporal groundwater use strategies along with criteria for on-farm management decisions, are useful to producer's who must adjust to changing groundwater supply conditions. Knowledge of the optimal producer response is also useful for formulation of groundwater management policy, because it enables policy makers to more accurately estimate the

\(^1\)Per-acre water application of less-than-full yield maximizing quantities will be referred to as "deficit" irrigation. This should not be confused with the term "limited water supply" which is used in this analysis to mean a policy limited supply of groundwater available for a specified time period.
economic implications of withdrawal restrictions and other demand management policies.

Therefore, the objective of this analysis was to determine the optimal farm-level intertemporal irrigation planning decisions associated with a limited water supply. This is done within a specified groundwater policy structure where water and not land is the limiting factor of production.

Irrigation Management Framework

A useful farm-level response model must simulate the producer's decision process under actual or realistic conditions. One cannot assume perfect knowledge of such stochastic events as crop prices or weather. A realistic model must rely on expected values of historic events, when known, or producer's expectations, when distributions of events are unknown.

Accordingly, the decision framework for this analysis assumed the producer would begin the planning process with quantifiable expectations for crop yields, weather conditions, crop prices and production costs. It also assumed the producer knew the amount and timing of groundwater withdrawal limits. Based on this information, a producer made several irrigation management decisions. Planning decisions were made on temporal water use, weighing the benefits of using a marginal unit of water in the current period versus a future period in the planning horizon. Decisions were also made on which alternative crop to plant and per acre water application for each crop, given a planned seasonal groundwater allocation and available irrigation application systems.

As a starting point for making irrigation planning decisions, groundwater withdrawals were limited to a maximum volume for a specified multi-year period.
The total farm allocation was less than the sum of the yield maximizing water withdrawals over the multi-year period. Such a groundwater withdrawal policy is presented in Figure 1 for a hypothetical producer with an N period planning horizon. (Note, year N is the first period.) A water allocation amount of Q1 is provided to the farm at the beginning of the current multi-year groundwater allocation period (N to k). In Figure 1, the producer used all available water over the first water allocation period, N to k. (The model was more flexible and allowed for transfers between allocation periods). This process is repeated in the next multi-year water allocation period (j to i) where Q2 water is available to the farm unit and continues in a similar manner over the remainder of the planning horizon.

Modeling Farm-Level Response

A model for determining the optimal planned water distribution of a multi-year water allocation was developed by considering annual field-level net returns, combined with a specified farm-level, time-specific groundwater regulation scenario. The annual net returns represent the estimated returns from the profit maximizing cropping pattern over a range of limited water availabilities with a fixed land base. The optimal intertemporal water distribution also depends on the producer's discount rate, the number of irrigated fields, and each field's irrigation system costs.

2This study does not examine the potential foundations of such regulations. Withdrawal regulations are just one of the options available to several states to reduce groundwater mining. If implemented, the regulations could be based on socially "optimal" extraction rates, political compromise or court ordered adjustments. There was also no attempt to evaluate the numerous forms that such withdrawal limitations could take. Regulations could be structured with a wide variety of water allocation periods, with provisions to "borrow" water from future periods, and to "carry-over" unused water from past periods.
This temporal distribution planning model was a backward solving two-state dynamic programming (DP) model that provided optimal temporal water allocation and irrigation capacity decisions over a specified planning horizon. A two-state model was necessary to enable temporal water allocation decisions that allowed the option of disinvestment (reducing irrigation capacity) on any field in any time period. This feature enabled concentration of a limited water supply on part of the farm, by either selling or idling unused irrigation equipment. The model design also allowed for restoring irrigation capacity before a future irrigation season.

The temporal groundwater allocation problem was solved by applying the following recursion equation over all stages from N to 1:

\[
R_n(w,s) = \max_{d_{sn}} \left[ C(d_{sn}) + r_n(d_{wn},(s+d_{sn})) + \alpha R_{n-1}((w-d_{wn}),(s+d_{sn})) \right]
\]

Subject to the boundary condition when \( n = 0 \) of: \( R_0(w,s) = 0 \).

Where: \( R_n(w,s) \) - The maximum returns from the utilization of the available water \( w \), with the current number of irrigation systems \( s \), from the current stage \( n \), to the end of the planning horizon.

\( C(d_{sn}) \) - The penalty cost of changing the number of irrigation systems in stage \( n \). (This value represents take-down and installation costs and other transaction costs.);

\( r_n(d_{wn},(s+d_{sn})) \) - The net returns in stage \( n \), from the water use decision \( d_{wn} \), given the current number of irrigation systems \( s+d_{sn} \);

\( R_{n-1}((w-d_{wn}),(s+d_{sn})) \) - The net returns from stage \( n-1 \) from the application of the water not used in stage \( n \) \( (w-d_{wn}) \), given the current number of irrigation systems \( s+d_{sn} \);

\( \alpha = (1 + \text{Real discount rate})^{-1} \);

\( R_0 \) - The value of unused water and owned irrigation systems in the \( N + 1 \) year;
n - Stage: Remaining years in producer's planning horizon, 
\( N \geq n \geq 0 \) (See Figure 1);

w - State variable: Amount of water remaining for 
allocation in the water allocation period, \( 0 \leq w \leq W \);

s - State variable: Number of irrigation systems at the 
beginning of stage n, \( 0 \leq s \leq S \);

N - Total number of years in planning horizon;

W - Maximum amount of water available for use in the 
specified water allocation period;

S - Maximum number of irrigation systems available;

d_{wn} - Decision: Amount of water to use in stage n, 
\( 0 \leq d_{wn} \leq W_n \);

d_{sn} - Decision: The number of irrigation systems to 
disinvest or reinvest in stage n, \(-S_n \leq d_{sn} \leq +S_n \);

W_n - Maximum quantity of water the farm can use in stage n. 
It was the minimum of either (1) the water remaining in 
the period \( w \) or (2) the maximum possible water use to 
the end of the water allocation period. (Proper 
specification of this variable enabled the model to 
bridge from one water allocation period to the next.);

S_n - Maximum number of systems that can be disinvested or 
purchased in stage n, \( 0 \leq S_n \leq S \).

Producers faced with limited groundwater supplies must decide several 
irrigation management questions. The decision order is of critical importance 
in modeling a producer's response. As specified above, the temporal 
distribution model assumed prior producer decisions regarding irrigation system 
improvements and cropping patterns. Determining the cropping pattern before 
planning temporal irrigation decisions allows more accurate net returns 
estimation, since net returns vary by crop and water application. This 
assumption provided the same basic conceptual starting point as in Anderson and 
Maass, Martin and van Brocklin, and Beckure and Eidman.
Outputs of the temporal distribution model provide the optimal planned water use decisions \((d_{w_n})\) and irrigation investment/disinvestment decisions \((d_{s_n})\) over the planning horizon. Implicit from the recursion equation and boundary condition, the calculation of \(R_n(w,s)\), and therefore, determination of \(d_{w_n}\) and \(d_{s_n}\) occur starting at \(N - 1\) and proceeding sequentially to \(n = N\). As specified, \(R_n(w,s)\) will be determined for the last year in the planning horizon first, and the first year in the planning horizon last; thus, a backward calculating algorithm. The planned decisions depend on a known starting position, which requires specification of the initial model states (water endowment and current number of irrigation systems). After calculation of an initial solution, changes in planning decisions as a result of stochastically induced changes in either state variable may be determined without further calculation.

Application and Results

The temporal planning model was applied to a representative farm situation based on conditions in South Central Nebraska. This area was analyzed because the problem was germane to the region, and the necessary data were available. However, it is important to note that the analysis was conducted for methodological development, and not a definitive assessment of limited water management strategies for South Central Nebraska.

The representative farm situation used to evaluate selected water allocation periods and water allocation quantities was four, homogeneous 130 acre fields. Each field had the cropping options of irrigated and dryland corn, grain sorghum and soybeans. The penalty costs for reducing irrigation capacity, \(C(d_{s_n})\) was $5,000, (compare with calculated annual ownership costs of
$4,600). The model operated over a 20 year planning horizon with a real discount rate of 6 percent. A 500 acre inch water supply evaluation increment was the basis for the temporal farm allocation decisions.

An important required input was the field-level net returns and cropping pattern response to limited water supplies. For the representative farm, estimated field net returns\(^3\) for an electric powered irrigation system ranged from about $9,000 to $23,600 per year for water allocations of zero to 1,800 acre-inches annually (Figure 2).

To achieve these optimal field-level net returns, the cropping pattern and per acre water application required significant adjustment as water availabilities changed. The dryland crop grown with zero water availability was soybeans. With 100 acre-inches of water available, irrigated corn entered the cropping pattern and the estimated field-level net returns declined below dryland values. The initial decrease in net returns with irrigation was due to irrigation costs which were not fully offset by increased returns from irrigation. As water availability increased, more irrigated corn entered the cropping pattern and net returns increased steadily (Figure 2).

The economic logic behind the rate of substitution between irrigated and dryland crops is an important management issue. The profit maximizing per acre water application level with limited water supplies occurs at an application level that maximizes the technical efficiency of the water application. This level corresponds to the maximum average returns to water, and is consistent with the principle that as long as the marginal return from the application of a unit of water to an acre of land exceeds the average return, producers increase per acre applications. Likewise, when the marginal

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\(^3\)Net returns were computed as the contribution to land, management and general farm overhead.
return per unit of water drops below the average return, profit maximizing producers seek to expand irrigated acreage if non-irrigated acres are available.

The substitution between irrigated and dryland crops for the representative farm was consistent with the anticipated maximization of the average returns to water. The per acre water application to irrigated corn remained stable at the maximum average return level of about 11.25 inches per acre until all acres were irrigated at a field availability of 1500 acre-inches. (On the representative farm, a full water supply was 14 inches per acre or 1800 acre-inches per field.) The constant per acre water application of near 11.25 inches meant that an additional 9 acres could be irrigated for each 100 acre-inch increase in the limited water supply. Over the range of water availability from 100 to 1500 acre-inches, linear increases in the acres irrigated with constant per acre water applications translated into linear increases in net returns to the field (Figure 2). After irrigating all acres at the field availability of 1500 acre-inches, per acre water applications increased, reaching the nonlimiting full supply at 1800 acre-inches. Over this range (1500 to 1800 acre-inches), the marginal net returns to water slowed visibly, since all acres were irrigated and increases in net returns were due to marginal yield increases.

A series of alternative water withdrawal policies (water allocation periods and water allocation levels) were evaluated to determine the effect on temporal water use and irrigation system disinvestment/reinvestment decisions. Examined alternatives used three limited groundwater allocation levels (90, 70 and 50 percent of full water supply) for each of three water allocation periods (2, 5 and 10 years). The periods selected had a common planning
horizon for computational ease. All other inputs were held constant in order to focus on the temporal water distribution decisions. To convey the essence of the results with limited article length, only selected cases will be discussed.

The temporal water allocation results were grouped into three categories; equal, rapid or transition use (Table 1). Equal use was characterized by equal water use across time. This sometimes requires an immediate system disinvestment decision (during the first allocation period) leading to optimal water use over the allocation period (Figure 3). Situations under each evaluated water level and each allocation period which appear to produce this resource allocation pattern, include: a short (two year) allocation period at any water level; a small reduction in water availability (ten percent) with any allocation period, or; a high disinvestment penalty cost that severely limits the profitability of adjusting irrigation capacity.

Rapid use was characterized by the condition that optimal water use over the water allocation period required multiple irrigation system disinvestment or reinvestment decisions. This occurred with both longer water allocation periods and greater water reductions. Optimal producer response generally consisted of a period of intensive water use (using the entire water allocation on a only part of the allocation period), followed by complete disinvestment in irrigation capacity and a period of dry farming (Figure 4). However, as a precondition for this pattern to develop, the irrigation system disinvestment penalty must be low enough to allow recovery of the penalty $(C(d_{sn}))$ through foregone annual ownership costs. Shifting between an

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4 For a complete discussion of the results, see Gollehon, 1987.
Table 1. Summary of the Water Use Strategies for the Representative Farm from the Multi-Season Planning Model With Four Initial Systems

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<thead>
<tr>
<th>Percent of Full Groundwater Allocation</th>
<th>Water Allocation Period</th>
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<tbody>
<tr>
<td></td>
<td>2 Years</td>
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<tr>
<td>--------------------------------------</td>
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<td>90</td>
<td>Equal</td>
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<tr>
<td>70</td>
<td>Equal</td>
</tr>
<tr>
<td>50</td>
<td>Equal</td>
</tr>
</tbody>
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a/ "Equal" refers to a strategy of water use that is even across time periods using the same number of irrigation systems each year. "Transition" refers to cases where some combination of irrigation system disinvestment and reinvestment occurs before stabilizing for the remainder of the planning horizon. "Rapid" refers to cases where the water is used rapidly followed by complete disinvestment in irrigation systems and dryland farming until the next allocation.

intensive irrigation period followed by dry farming periods, maximized the net returns but the strategy introduces planned income variability.

Transition use was characterized by the dominance of initial resource endowments on optimal water use over the first water allocation period. This occurred when the endowed number of irrigation systems were used in the first allocation period before a permanent disinvestment, resulting in different water use patterns for different water allocation periods.

Policy Conclusions

The temporal planning model was a backward-solving, two-state dynamic programming model that provided optimal temporal water distribution and
irrigation system investment decisions over a specified planning horizon. The model was developed for a micro-computer and was limited to farm situations consisting of less than seven fields, a planning horizon of no more than twenty years, and a water allocation for up to ten years.

This model was successfully applied to a hypothetical South Central Nebraska farm consisting of four homogeneous fields each equipped with a sprinkler irrigation system. Water allocation periods of two, five, and ten years were considered at water allocation levels of 90, 70 and 50 percent of full water supply.

The results for the representative farm indicate that the optimum strategy with lower allocation levels and short allocation time periods was to permanently disinvest in one or more irrigation systems and concentrate the water on the remaining fields. With the lower water supply allocations and longer time periods, disinvestment occurred part way through the allocation period, with reinvestment occurring at the start of the next allocation period. These results suggest that one must consider the size distribution of irrigated farms when recommending response strategies for water limiting conditions, or when evaluating alternative public policies which limit water availability. These results question the impact analysis of water management studies which use only a single model farm approach whenever allocation periods are long and/or the amount allocated is very low. Results also suggest that public water management policies which limit water availability should consider the length of the allocation time period in addition to the average annual irrigation amount.
Figure 1. Hypothesized Relationship Between Water Allocation Period and Planning Horizon.

Figure 2. Field Net Returns for the Representative Farm.
Figure 3. Representative Farm Intertemporal Water Allocation for a Two-Year, Seventy Percent Water Allocation with Four Initial Irrigation Systems.

Figure 4. Representative Farm Intertemporal Water Allocation for a Ten-Year, Fifty Percent Water Allocation with Four Initial Irrigation Systems.
REFERENCES


