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EFFECT OF RULES AND LAWS ON THE SUSTAINED AVAILABILITY OF GROUNDWATER (PHASE I PROJECT COMPLETION REPORT)

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and

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INTRODUCTION

Many possible alternative sustained groundwater withdrawal strategies exist for any aquifer system. With time, implementation of each strategy results in the evolution of a different steady state potentiometric surface. Peralta and Peralta (1984b) describe the physical and legal feasibility of implementing a sustained groundwater withdrawal strategy in a critical groundwater region within Arkansas. Yazdanian and Peralta (1985) demonstrate how quadratic goal programming can be used to develop a regional sustained yield strategy that will maintain a potentiometric surface as close to preselected elevations as possible. Peralta and Killian (1985) demonstrate how a least cost regional conjunctive water use/sustained groundwater yield strategy can be developed. Each of these papers describe the development of strategies for the Grand Prairie region of Arkansas (Figure 1), an important rice, soybean and aquacultural producing area.

Historically, most of the region's water requirements have been obtained from a Quaternary aquifer, part of the Mississippi Plain alluvial aquifer. Groundwater levels have been dropping in the Grand Prairie for most of this century. Peralta et al (1985) predict continued declines and an increasing area in which saturated thicknesses will be so small that groundwater yields may be inadequate. Groundwater levels are declining in other portions of the same aquifer as well, but in no other region is the problem as severe as in the Grand Prairie. Since the Grand Prairie problem is representative of situations that will soon

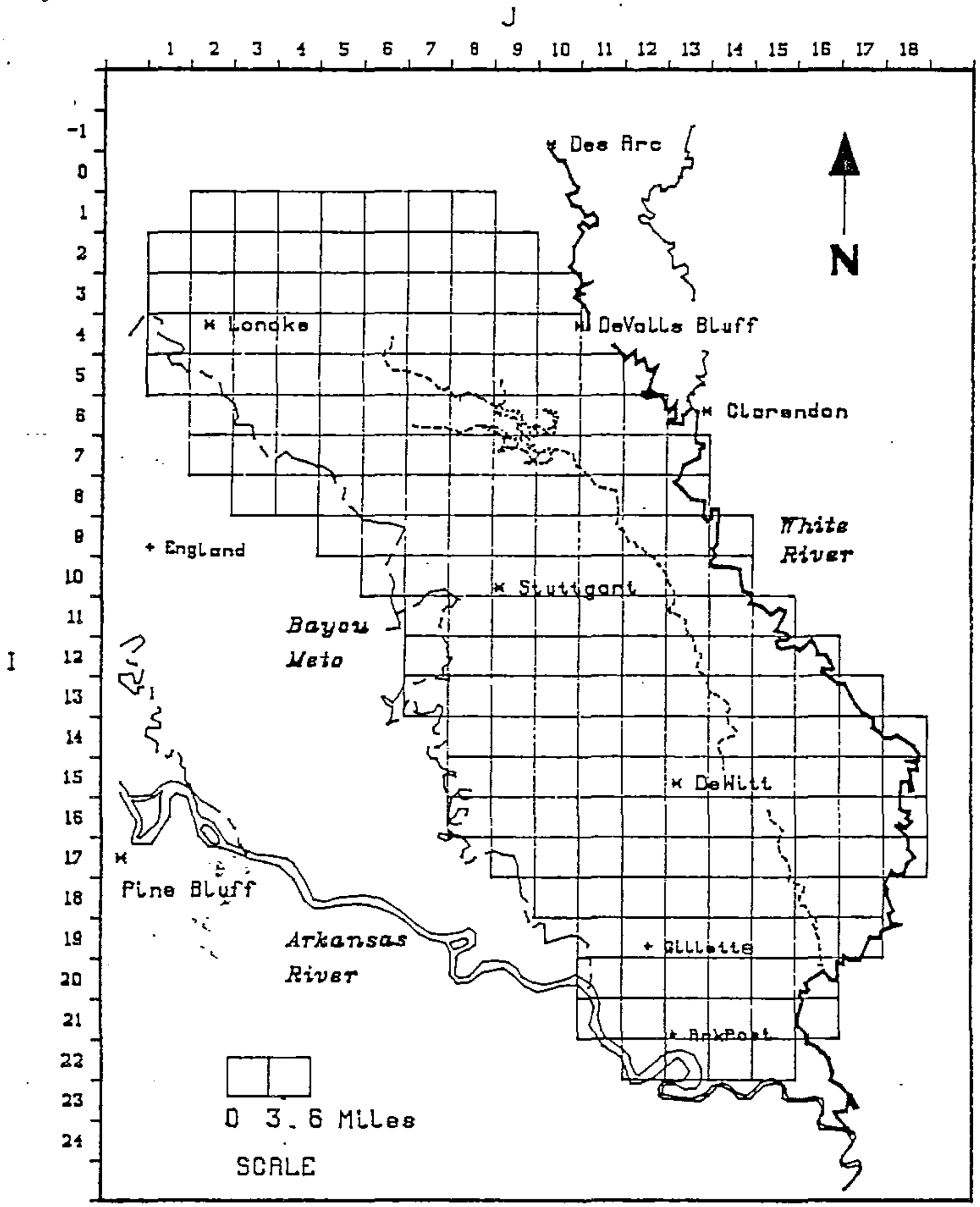

Figure 1: The Grand Prairie Study Area.

exist for other parts of eastern Arkansas, the effect of water policy on how the Grand Prairie water problem can be solved is of widespread interest.

As concern for the worsening crisis increases, three questions are commonly asked by water users, water managers and those involved in the water policy formation process. The first is: what across-the-board percentage reduction in current groundwater use is necessary in order to achieve a sustained yield? This question arises because an owner of land overlying groundwater in Arkansas has the right to use the water to the "full extent of his needs if the common supply is sufficient, and to the extent of a reasonable share thereof, if the supply is so scant that the use by one will affect the supply of other overlying users" (Jones v. OZ-ARK-VAL Poultry Co., 228 Ark. 76, 306 S.W. 2nd 111 (1957).) In times of scarcity, the California correlative rights doctrine governs, allowing each overlying landowner a proportionate or pro-rated share of the available supply (Hudson v. Dailey, 156 Cal. 617, 105 (1909). As groundwater continues to become less accessible, an across-the-board percent reduction in groundwater withdrawal could conceivably be mandated by court order under the correlative rights doctrine (Peralta and Peralta, 1984a).

The second question is whether the implementation of on-farm conservation measures can cause sufficient reduction in demand to assure the sustained availability of groundwater in the Grand Prairie without other, more drastic, measures. Among the additional actions that are possible is the diversion of river water to non-riparian lands. Agriculture, including aquaculture, uses 99 percent of the Quaternary groundwater withdrawn in that region. Since rice and aquaculture producers generally use 2 and 7 ac-ft of water per acre respectively, Grand Prairie agriculture, like agriculture elsewhere, is occasionally criticized because of its high consumptive water use. Whether improving presumedly wasteful on-farm practices can, by itself, assure a sustained yield is a question that needs answering. Policy decisions concerning how to address the Grand Prairie water supply problem, and how to fund the solution, may pivot on the answer.

The third question arises from the recent formation of the first irrigation district in Arkansas and its authorization to distribute diverted river water to the region. At this time, both approval for diversion of the necessary flowrate or cumulative volume and funding for the necessary works must be obtained. Assuming that adequate surface water can be diverted to replace current groundwater use in the cells to which it can be delivered, can all current regional water demand be satisfied on the long-term? In other words, can a sustained yield strategy be developed that replaces all current groundwater use with a combination of groundwater use and diverted river water use, and, if necessary, on-farm water conservation measures?

Each of these questions can be answered by formulating an appropriate optimization problem and incorporating the problem statement in a sustained yield simulation model similar to those previously mentioned. The results of using such models are regional water allocation strategies. Before such strategies can be properly evaluated, the economic consequences of their implementation must be determined. Presentation of the hydrologic and economic consequences of implementing any of the sustained yield strategies is the a priori demonstration of the effect of implementing certain policy decisions.

The purposes of this paper are to describe the methodology used to answer the stated questions, and to present the results of its application. In doing so, we test six alternative policy scenarios. Optimal sustained groundwater yield strategies and the annual economic consequences for the period immediately following strategy implementation are presented for each scenario. The three objective functions that are used include minimization of unsatisfied water demand, minimization of regional cost and minimization of the common percentage of reduction in groundwater use necessary to achieve a sustained yield. Also considered are the reduction in water needs achieved through on-farm water conservation measures and the use of diverted river water. The economic evaluation is of necessity, simple, and provides merely a means of comparing the relative annual economic impacts of implementing one strategy as opposed to another.

At some time in the future voters will decide whether they wish to pay the price needed to assure the sustained availability of groundwater, or whether they prefer to risk the more uncertain future of continued aquifer mining. In addition, they will have a voice in determining water policies that in turn affect what sustained yield strategies are institutionally feasible. This study was undertaken in order to provide information pertinent for those decisions.

THEORY AND MODEL FORMULATIONS

Governing Equations

Development of a regional steady-state set of target groundwater levels requires the use of a steady-state equation for each cell. The following has been developed for two-dimensional steady flow in a heterogeneous isotropic aquifer from both the linearized Boussinesq equation (Pinder and Bredehoeft, 1968; Illangasekare et al, 1984) and the Darcy equation (Peralta and Peralta, 1984a):

$$
\begin{aligned}
q_{i,j} = &- t_{i-1/2,j}\, s_{i-1,j} - t_{i+1/2,j}\, s_{i+1,j} \\
&+ [t_{i-1/2,j} + t_{i+1/2,j} + t_{i,j-1/2} + t_{i,j+1/2}]\, s_{i,j} \\
&- t_{i,j-1/2}\, s_{i,j-1} - t_{i,j+1/2}\, s_{i,j+1} \quad \ldots\ldots\ldots\ldots\ldots\ldots 1
\end{aligned}
$$

where $q_{i,j}$ is the net volume flux rate of groundwater moving into or out of the aquifer in cell (i,j). It is positive when flow is out of the aquifer, negative when flow is into the aquifer, (L^3/T).

$s_{i,j}$ is the vertical distance between a horizontal datum located above the ground surface, and the potentiometric surface. In this paper $s_{i,j}$ is a steady state drawdown, (L).

$t_{i-1/2,j}$ is the geometric average of the transmissivities of cells (i,j) and $(i-1,j)$, (L^2/T).

To express this equation in matrix form for a groundwater system, the row-column notation is replaced with single integer identification of each cell. Thus for a groundwater flow system of n cells:

$$(Q) = [T](S) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

where (Q) is an n x 1 column vector of net steady-state volume flux values, (L^3/T).

[T] is an n x n symmetric diagonal matrix of finite difference transmissivities, (L^2/T).

(S) is a column vector of steady-state drawdowns, (L).

In applying this equation to the Grand Prairie, one considers the peripheral cells as constant-head cells. Validation of an unsteady state groundwater simulation model AQUISIM, developed by Verdin et al (1981), demonstrated that the study area can be treated as a groundwater system surrounded by constant-head cells (Peralta et al, 1985). In the validation, the groundwater level in each constant-head cell equalled the average of ten years of observed springtime groundwater levels in that cell.

The value in (Q) corresponding to a constant-head cell is the annual volume of water entering (-) or leaving (+) the aquifer at that cell. Since no groundwater withdrawal by wells is considered at constant-head cells, for those cells the value in (Q) represents the annual volume of water moving between the aquifer and either the surrounding aquifer system or a stream located within the cell.

Vertical recharge of the aquifer in the Grand Prairie is negligible for interior cells (non-constant-head cells). Therefore, the net annual vertical volume flux for each interior cell equals its groundwater pumping volume, p, and the value in the (Q) vector corresponding to an interior cell is nonnegative. The following equation describes the range of acceptable flux values that are in harmony with a regional aquifer volume balance.

$$(L_q) \leq (Q) = [T](S) \leq (U_q) \quad .....3$$

where (L_q) and (U_q) are n x 1 column vectors whose elements respectively are the lower and upper bounds on volume flux in all cells in the system, (L^3/T).

The appropriate range of potentiometric surface values is described by:

$$(L_s) \leq (S_*) \leq (U_s) \quad .....4$$

where (L_s) and (U_s) are m x 1 column vectors of the lower and upper bounds, respectively, on the optimal steady-state drawdowns in the m internal cells, (L).

(S_*) is an m x 1 vector of optimal drawdowns, (L).

*

Both Equations 3 and 4 are used as constraints within the models discussed below. In the discussions, the policy scenarios for which each model is used are also referenced. Optimization within the models was accomplished using the QPTHOR subroutine (Lieffson et al, 1981).

Maximizing X (Scenario I)

A common question is: by what percentage do all groundwater users need to reduce their current withdrawals in order to achieve a sustained yield? The management model of Scenario I addresses this question indirectly by maximizing the common proportion X, of their current groundwater withdrawals, that all cells can pump in a sustained yield setting. The result is a single value of X for all cells. One minus X is the answer to the stated question. Assuming that current groundwater withdrawal represents the upper limit on pumping in any cell, the model for determining X is:

$$\max X \qquad .....5$$

subject to Equations 3, 4, 6 and 7:

$$(U_{qi}) X = (P_{*i}) \qquad ....6$$

$$0.0 \leq X \leq 1.0 \qquad .....7$$

where X is the maximum common proportion of current pumping that all cells may continue to pump in a sustained yield setting, (%/100).

(U_{qi}) is the m x 1 column vector of upper limits on pumping in internal cells, (L^3/T).

(P_{*i}) is the vector of optimal pumping values for the internal cells, (L^3/T).

Minimizing Unsatisfied Demand (Scenarios II-IV)

In cells in which no diverted surface water is available, only groundwater is used. Minimizing unsatisfied water needs for such cells is accomplished by maximizing groundwater usage in those cells. The linear objective function used to maximize regional groundwater pumping is similar to formulations used by Aguado et al (1974), Alley et al (1976) and Elango and Rouve (1980) for small systems:

$$\max z = \sum_{i=1}^{mm} p(i) \qquad .....8$$

subject to Equations 3 and 4,

where z is the total volume of groundwater annually pumped from mm cells.

In Scenarios II and III no diverted surface water is available and mm equals the number of internal cells, m. In Scenarios IV-VI surface water is available in mc cells. The number of cells without the alternative source, mm, equals m-mc. As previously stated, it is assumed that divertable water supplies are adequate to satisfy water needs in those cells to which the water can be delivered.

Minimizing Regional Cost of Conjunctive Water Supply (Scenario V)

In this paper, we make use of a quadratic optimization model (Peralta and Killian, 1985) that minimizes the total cost of attempting to satisfy regional demand from conjunctive water resources. The model uses the costs of groundwater and diverted surface water in cells in which diverted water is available. It uses the cost of groundwater and the opportunity cost of unsatisfied water needs in cells in which diverted water is unavailable. A simple statement of the model is:

$$\min y = \sum_{i=1}^{n} c_e(i)\, p(i)\, f(s(i)) + c_m(i)\, p(i) + c_a(i)\, p_a(i) \quad \ldots\ldots 9$$

subject to Equations 3 and 4,

where:

y = the total annual cost of the water supply and the opportunity costs of inadequate supply, (\$/yr).

$c_e(i)$ = the pumping plant energy, repair and lubrication costs associated with raising a volume of groundwater one unit distance, ($\$/L^4$).

$f(s(i))$ = a linear function of steady state drawdown which describes the total dynamic head at cell i, (L).

$c_m(i)$ = the pump maintenance cost of pumping a unit volume of groundwater, ($\$/L^3$).

$c_a(i)$ = either the cost per unit volume of river water used in cell i to which water can be diverted, or, the opportunity cost associated with each unit volume of unmet needs in that cell, ($\$/L^3$).

$p_a(i)$ = either the annual volume of diverted water or the annual volume of unsatisfied demand in cell i, (L^3/yr).

Biobjective Optimization between Minimizing Cost and Minimizing Unsatisfied Water Needs (Scenario VI)

The constraint method of multiobjective optimization (Haimes, 1973) is commonly used to develop the pareto optimum for the simultaneous consideration of multiple objectives. Datta and Peralta (1985) and Killian and Peralta (1985) both describe different ways of applying this method to the bicriterion problem of minimizing cost and maximizing groundwater withdrawal. The procedure described by Killian and Peralta (1985) was used in this paper to address the problem of minimizing cost while minimizing unsatisfied water demand (maximizing pumping in those cells to which diverted surface water is not available). To avoid having nonlinear constraints in the optimization formulation, the linear maximum pumping function (Equation 6) is used as the constrained objective and the quadratic least-cost objective function (Equation 7) is the primary function.

APPLICATION AND RESULTS

Hydrologic Assumptions and Constraints

Aquifer characteristics within the study area are relatively well known. Finite difference models of the Quaternary aquifer underlying the Grand Prairie have been successfully utilized by Griffis (1972) and Peralta et al (1985). The models employed a hydraulic conductivity of 267 and 270 ft/day respectively and an effective porosity of 0.3 (Engler et al, 1945). A hydraulic conductivity of 270 ft/day was used in this study. Estimates of the elevation of the top and bottom of the aquifer in the center of each cell were determined by kriging from records of water well construction. Estimates of the water table elevation in the center of each cell were made by kriging from U.S. Geological Survey records (Edds, 1982). Cell by cell transmissivities were calculated from spring 1982 saturated thicknesses and the assumed hydraulic conductivity.

The acreages of rice, soybeans and aquacultural production existing in each cell in 1982 were estimated using a procedure reported by Peralta et al (1983). The water needs for these crops and municipalities were estimated for average climatic conditions for each cell. Then, the portion of these needs that was being withdrawn from the Quaternary aquifer in each cell were estimated, based on U.S. Geological Survey studies (Halberg, 1977; Holland and Ludwig, 1981). These resulting cell by cell volumes are the water needs that the models attempt to satisfy in Scenarios I and II. The total of the water needs for all the cells is 288,000 ac-ft.

A second set of water needs represent the volumes that the models attempt to satisfy if simple on-farm water conservation measures are implemented for each of the major crops. Through a survey of literature and water users, Harper (1983) concluded that regional water needs for rice and soybeans can be reduced, without reducing yields or increasing production expense. For example, 19.7 percent of the rice acreages in the region are maintained at a flood depth of 6-8 inches. On those acreages, 6 inches per year can be saved without adversely affecting yields by changing to a 2-4 inch flood depth (Ferguson, 1970).

Harper also reported that 20.5 percent of the soybean acreage was furrow irrigated. He estimated that a 35 percent reduction in water use can be obtained for those acres by irrigating only alternate furrows, instead of every furrow.

For this paper, we arbitrarily assumed that aquacultural consumptive use can be reduced by 20 percent from 7 feet per year to 5.6 feet per year, Assuming that these three conservation measures can be implemented, at no cost and without reduction in production, for the acreages supported by groundwater, the regional groundwater needs can be reduced by 29,000 ac-ft per year to 259,000 ac-ft. Apportioning this value appropriately to all cells in accordance with their acreages, a new set of cell by cell water needs is calculated. These are used in Scenarios III-VI.

The models attempt to satisfy the water needs described above, either from groundwater alone (Scenarios 1-3) or from groundwater and diverted surface water (Scenarios 4-6). Dixon and Peralta (1984) demonstrate that there are significant divertable water resources available in the Arkansas River and White River for this purpose. U. S. Army Corps of Engineers (1984a, 1984b) investigations indicate the cells to which surface water can be

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realistically diverted. For this paper it is assumed that adequate surface water is available to completely replace groundwater use in each cell to which river water can be diverted. In all scenarios, any current groundwater use that cannot be replaced by a combination of groundwater and surface water is considered to be unsatisfied demand.

Through the use of constraints, Equation 3, the models assure that only physically and institutionally satisfactory recharge and discharge values can occur in any cell. The greatest annual recharge that is permitted to occur in any of the peripheral constant head cells is the greatest value that was calculated to occur based on the springtime hydraulic gradients of the years 1972-1983. The lower limit on groundwater withdrawal in any internal cell is zero. The upper limit on groundwater withdrawal is the water need of the specific strategy.

Satisfactory groundwater table elevations and saturated thicknesses are assured to result from all optimizations by appropriately bounding the steady state drawdowns via Equation 4. In each cell, the optimal water level is constrained such that it never exceeds the ground surface elevation. In addition, the optimal saturated thickness is constrained to be at least 20 feet. Peralta et al (1985) determined 20 feet to be the minimum saturated thickness needed for a representative 500 gpm well irrigating 50 acres of rice to remain operable throughout the pumping season. They assumed a zero hydraulic gradient existing initially across the site of the well.

Economic Assumptions

The annual economic consequence in the period immediately following implementation of a particular strategy is demonstrated by estimating the <u>change</u> in net economic return for the strategy from that assumed for a base agricultural production and water use strategy. The base net return is calculated considering only those acreages supported by Quaternary groundwater in 1982. It is assumed that acreages currently supported from other water sources will continue to be supported by those sources. It should be emphasized that the calculated change in net economic return resulting from implementation of a particular strategy is the sum of the changes for all the acres supported by Quaternary groundwater in 1982, and relates only to those acres. Both the base economic return and the changes in net return are calculated using a modified version of a post-processing program written by W. D. Dixon.

The factors included in estimating the base net economic return include yields, market prices, water demand, fixed and variable costs exclusive of the water supply and variable costs of the water supply. Economic factors for aquaculture are derived from an unpublished budget for catfish production in Alabama. Factors for rice and soybeans are obtained from published crop budgets (respectively, Smith et al, 1983; and Stuart et al, 1983).

Assumed yields are 1110 lb of fish per acre, 4410 lb of rice per acre and 40 bu/ac for irrigated soybeans. Assumed market prices are 1.12 $/lb of fish, 0.1055 $/lb of rice and 6.25 $/bu of soybeans. The supplemental water requirements are 7 ac-ft/ac for aquaculture, 2 ac-ft/ac for rice and 0.4 ac-ft/ac for irrigated soybeans. Fixed costs are 227.23 $/ac for aquaculture, 117.75 $/ac for rice and 119.28 $/ac for irrigated soybeans. Variable costs, not including the variable cost of supplied water, are 604.37 $/ac for aquaculture, 245.57 $/ac for rice and 171.56 $/ac for irrigated soybeans. The variable cost of groundwater in each cell for the base strategy is a function of the total dynamic head estimated for the saturated thickness and the 1982 groundwater levels at the center of the cell (Peralta et al, 1985). The function makes use of the cost coefficients $c_e(i)$ and $c_m(i)$ values, 0.18 $/ac-ft-ft and 1.65 $/ac-ft respectively, found in Equation 7. The f(s(i)) describing total dynamic head as a function of static lift is discussed by Peralta and Killian (1985).

The estimated net economic return for the base strategy is $9,030,000. It should be recognized that this value is an estimate based on the specified costs in the crop budgets. The cost of land, the value of the labor of the farmer and his family and general farm overhead are not included in these costs.

If, in accordance with a particular sustained yield strategy, there is inadequate water in a cell to satisfy demand, it is assumed that nonirrigated soybeans will replace aquaculture or an irrigated crop. In this paper it is assumed that irrigated soybean acreages would be the first to be switched to dryland soybeans, followed by aquacultural and rice acreages respectively. It is assumed that the equipment for the original crop is adequate to produce unirrigated soybeans, and therefore, that the fixed expenses for the original crop will continue for a few years, even after a crop change is implemented. Therefore, when the crop switch is made, the fixed production costs of the original crop are used for the replacement crop.

The net return of a particular sustained yield strategy is calculated based on the crop acreages that the strategy can support with water plus any unirrigated soybean acreages made necessary by inadequate water supply. In calculating this return, a 27 bu/ac yield and a variable cost (exclusive of supplying water) of 165.96 $/ac is assumed for nonirrigated soybeans. As stated above, when a crop switch is made, the fixed costs associated with the original crop are assumed to carry over to the unirrigated soybeans in the first years after the switch is made. The actual fixed costs of unirrigated soybeans is 90.43 $/ac, about 40 percent that of aquaculture and 75 percent that of rice or irrigated soybeans. Therefore, during the years until the fixed costs of the original crop are paid for, there is some penalty associated with making the crop switch. It is for this period of time that our "short-term" economic analysis is valid.

The next two paragraphs in this section discuss how the c_a values used in Equation 7 and Scenarios V and VI are estimated. The values are shown on a cell by cell basis in Figure 2.

Based on the returns and variable costs of production at a representative cell in 1982, the decrease in net economic return (opportunity cost) of switching from aquaculture to dryland soybeans is 79 $/ac-ft. Figure 2 shows this value in cells for which aquaculture is the dominant water user and diverted river

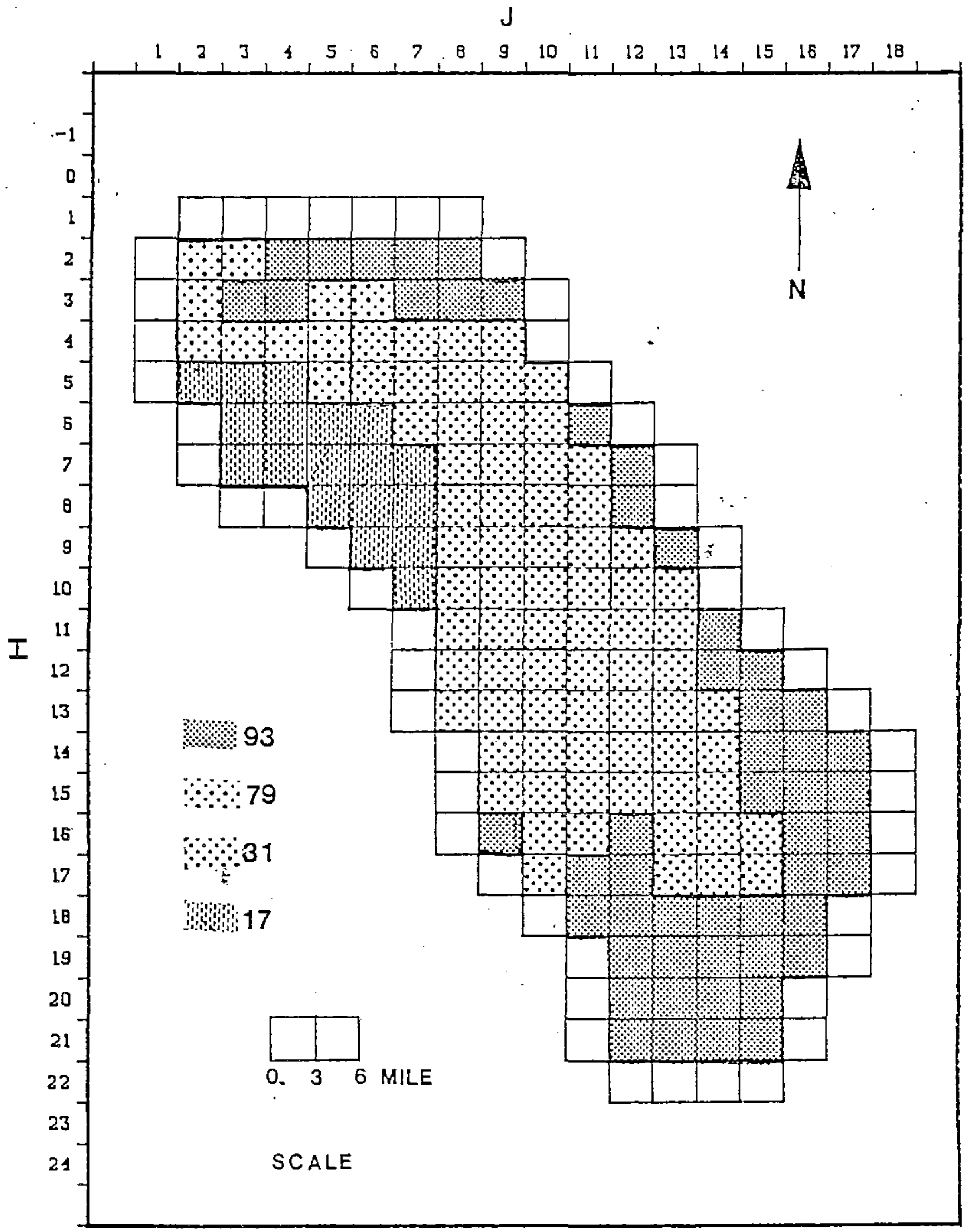

Figure 2: Cost of Alternative Water and Opportunity Cost ($/ac-ft).

water is not available. The opportunity cost of switching from rice to dryland soybeans is 93 $/ac-ft. In Figure 2 this value identifies those cells in which rice is the dominant user and diverted river water is not available. It is recognized that the opportunity cost of a crop switch can more accurately be performed on a cell by cell basis, since the variable cost of groundwater varies with cell depending on the depth to water and saturated thickness. This level of refinement is not used while performing the optimization. Instead, after a particular sustained yield strategy is developed and its target water levels are determined, the economic post-processing program mentioned above is used to determine the cell by cell and total change in net economic return resulting from the crop switches required for that strategy.

The value of c_a for cells in which diverted river water is potentially available is the cost of delivering that water to fields in those cells. Reconnaissance level studies by the U. S. Army Corps of Engineers estimate costs of 14 $/ac-ft for diverting Arkansas River water through the Bayou Meto and 28 $/ac-ft for distributing White River water through a canal system (respectively, U.S. Army Corps of Engineers, 1984a; and personal communication Dwight Smith). For this paper we assume an additional 3 $/ac-ft expense to move the water from a waterway to the field. Figure 2 shows the resulting costs of 17 $/ac-ft and 31 $/ac-ft in those cells to which Arkansas River water and White River water may be diverted. No economy of scale is considered in the prices of diverted water.

Peralta and Killian (1985) describe the simulated evolution of water levels in the Grand Prairie from 1982 elevations to an optimal set of target levels. In the current paper, the fact that water levels must evolve from current levels to the appropriate steady-state levels is ignored when estimating the change in economic return resulting from strategy implementation. In actuality, all the target steady-state water table elevations are higher than the 1982 levels. Therefore, during the first years after strategy implementation, the actual costs of groundwater will be slightly greater than the values assumed in the optimization. This underestimation in developing optimal strategies however, is somewhat counteracted by the fact that the fixed costs associated with an initial crop will be gradually replaced with the lesser fixed cost of unirrigated soybeans during the same initial period after strategy implementation.

Alternative policy scenarios and results

Table I contains a summary of the six sustained yield strategies that are developed. As an aid in recalling the characteristics of a particular scenario, one can inspect the values in the first and third rows. The first row values indicate whether a particular strategy attempts to satisfy current groundwater needs or groundwater needs reduced by conservation measures. A value of zero in the third row indicates that no surface water is available for diversion in that strategy. The following is a discussion of Table I.

In Scenario I we assume: that no improvement in water conservation is practiced, that river water is not available for

Table 1: Short term annual consequences of strategy implementation

	CURRENT GROUNDWATER USE	STRATEGIES I	II	III	IV	V	VI
WATER NEEDS (1000 AC-FT)	288	288	288	259	259	259	259
GROUNDWATER USE (1000 AC-FT)	288	40	119	118	63	92	86
SURFACE WATER USE (1000 AC-FT)	0	0	0	0	164	134	140
UNMET WATER NEEDS (1000 AC-FT)	0	248	169	141	31	33	32
CHANGE IN NET ECONOMIC RETURN FROM CURRENT GROUNDWATER USE # (1000 DOLLARS)	NA	-8,359	-5,077	-4,416	-3,019	-2,792	-2,803

Based on published crop budgets and including only specified costs.

diversion to the area, and that the policy is to be absolutely egalitarian from a percentage perspective. Accordingly, only 40,000 ac-ft can be withdrawn per year from the aquifer, 14 percent of the base strategy withdrawal rate. Thus, X, the percent reduction in current pumping or the percent of unsatisfied demand, is 86 percent. The consequence of reducing production to that extent is an annual reduction in net economic return of $8,359,000. This is 93 percent of the assumed return for the base strategy, $9,030,000. A policy incorporating this objective, representing one possible application of the correlative rights doctrine, would have a serious impact on the region.

In Scenario II we again assume no significant increase over current water conservation measures and that river water is not available for diversion. The objective of this policy however, is to minimize unsatisfied demand. With this goal, 119,000 ac-ft of groundwater can be withdrawn, resulting in 169,000 ac-ft of unsatisfied demand. The reduction in economic return is $5,077,000, 56 percent of the base strategy and a significant improvement over the $8,359,000 of Scenario I. Although neither strategy offers a satisfactory solution to the Grand Prairie problem, comparison between these two scenarios indicates clearly that the selection of an appropriate policy objective is important for voters and/or decision-makers.

Scenario III differs from Scenario II in that we assume the implementation of the described conservation measures for rice, soybeans and aquaculture. Once again, no diversion water is available and the policy objective is to minimize unsatisfied demand. Note that groundwater use is 1,000 ac-ft less than in the previous strategy, but since water needs are reduced by 29,000 ac-ft, unsatisfied water needs are 28,000 ac-ft less. The reduction in net return from the base strategy, 49 percent or $4,416,000, is $661,000 less than the previous strategy in which no new conservation measures are implemented. Dividing $661,000 by 29,000 ac-ft, we find an improvement of $22.79 $ for each ac-ft of reduced water demand. (The average variable cost of groundwater in the base strategy is $22.19.) Thus there are reductions both in unsatisfied demand and in regional expense if reasonable conservation measures are implemented.

Scenario IV differs from Scenario III in that river water is available for diversion. As a result, groundwater use is cut almost in half and 164,000 ac-ft of surface water are used each year. Unsatisfied demand drops from 141,000 ac-ft to 31,000 ac-ft. The reduction in net return from the base strategy is $3,019,000, 33 percent of the base net return. The use of diverted river water can have a significant effect on the regional economy in a sustained yield scenario.

Scenario V differs from Scenario IV in that the policy objective is to minimize the regional expense of attempting to satisfy water demand. While achieving a comparable unsatisfied demand, this strategy requires the use of significantly more groundwater and less diverted water than Scenario IV. The increase in 2,000 ac-ft of unsatisfied demand from that of Scenario IV results in a $227,000 reduction in regional expense, a $113.50 /ac-ft tradeoff. The net return of Strategy V is 31 percent below the base scenario.

Scenarios IV and V represent policy objectives that conflict over part of the range of feasible regional strategies. Choosing one or the other of the strategies may not be as satisfactory as selecting a compromise strategy between them. Use of the constraint method of multiobjective optimization mentioned previously results in the pareto optimum shown in Figure 3. A compromise strategy lying on the pareto optimum was selected arbitrarily for purposes of this paper, although rigorous means of determining the compromise strategy may be utilized (Haimes and Hall, 1974; Datta and Peralta, 1985). Notice that the compromise strategy, Scenario VI, has values lying between those of Scenarios IV and V for the last four rows of Table I.

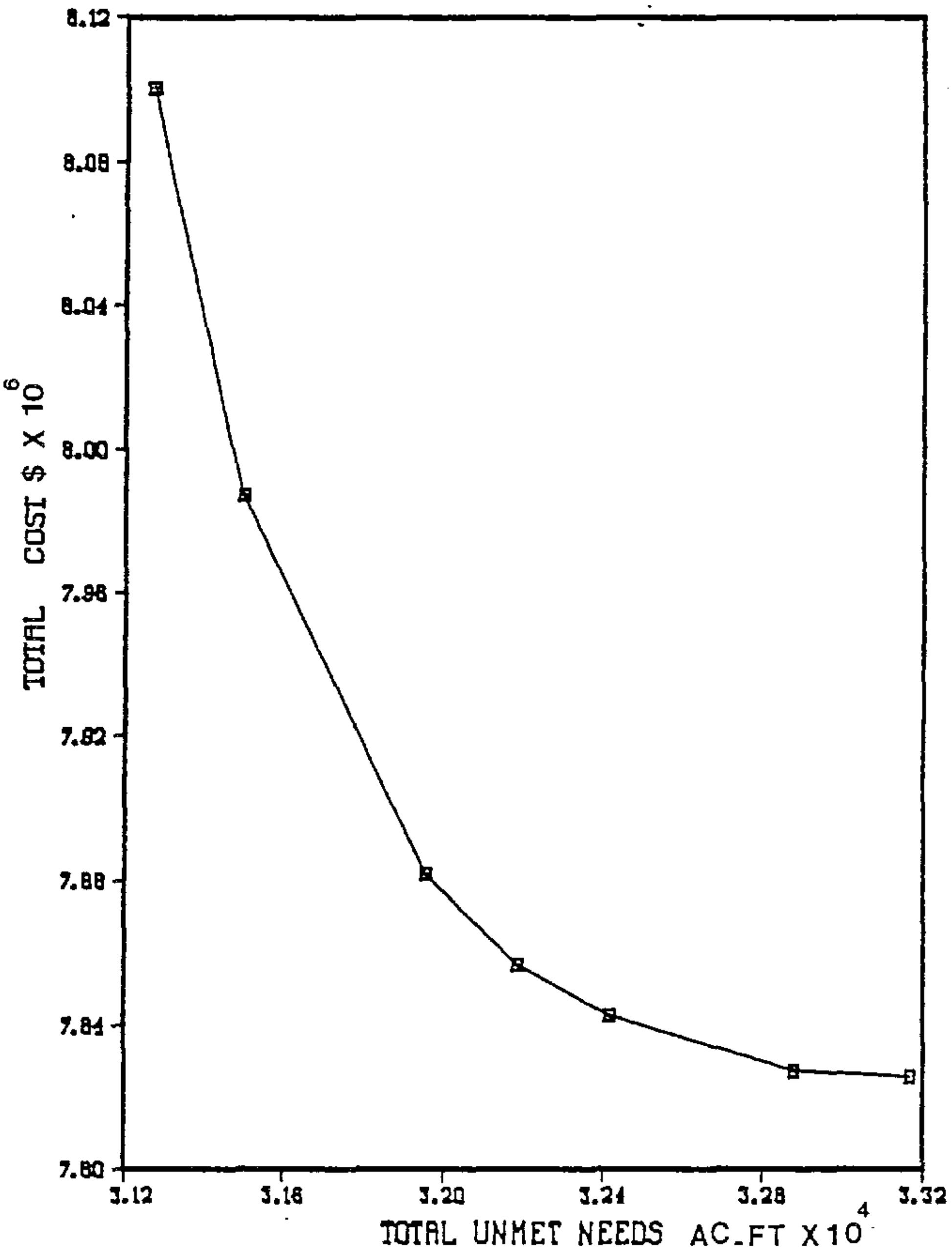

Figure 3: Pareto Optimum of Minimizing Cost and Minimizing Unmet Needs.

SUMMARY

We have demonstrated how sustained yield groundwater management models can be formulated to simulate hydrologic and short-term economic response to alternative water resource policy environments. The methodology was applied in testing six potential policy scenarios for the Arkansas Grand Prairie. Sustained groundwater withdrawal strategies were developed for each scenario. Before summarizing the results, it is appropriate to review the policy characteristics and assumptions under which the strategies were developed.

The annual water need assumed for the first two strategies is the volume of groundwater that was used for 1982 production levels and average climatic conditions, 288,000 ac-ft. Annual water need for the last four scenarios, 259,000 ac-ft, is the assumed demand after the implementation of simple on-farm water conservation methods.

The first three strategies utilize groundwater solely, while the last three coordinate the use of groundwater and water diverted from nearby rivers. In the development of all strategies, the sustained withdrawal of groundwater is limited to be less than the assumed sustainable recharge to the aquifer. It is assumed that historical recharge to the region will continue and that the water table elevations of the peripheral cells will be maintained.

Implementation of any one of the sustained yield strategies will result in unsatisfied water demand and a corresponding decrease in acreages that use supplied water. The economic consequence of the decrease is a reduction in net economic return from the 1982 base level. The base level, \$9,030,000, is the assumed net economic return of the acres supported by Quaternary groundwater in 1982. This estimated value is based on 1982 pumping lifts and published crop budgets and includes only specified costs.

The change in annual regional net return during the initial period after implementation of any one of the sustained yield strategies is calculated using: the dynamic pumping lifts appropriate for the steady state potentiometric surface that will result from implementation of the strategy, and the same crops used in the 1982 strategy, as long as adequate water is available to satisfy their water needs. If water supply is inadequate in any cell, water demand in that cell is reduced by changing appropriate crop acreages from aquaculture, rice or irrigated soybeans to dryland soybeans. The calculation of the net return properly reflects all necessary crop changes for the scenarios described below, but considers only variable production costs. It is assumed that the fixed cost associated with the initial crop continue to exist after a crop switch is made.

Scenario I represents the situation in which no new conservation methods are implemented, no river water is diverted to the region, and all groundwater users are limited to a common percentage of their current groundwater use. It answers the first of the three questions posed in the Introduction. A reduction of 86 percent of current groundwater use is necessary in every cell in order to achieve a sustained yield, subject to the assumed feasible recharge rates. Implementation of this strategy would result in 86 percent of water needs being unsatisfied and annual net economic return being a staggering 93 percent less than the base return on the short-term.

Scenario II represents the effort to minimize unsatisfied demand without improving water conservation or diverting river water. This is identical to maximizing groundwater use without changing husbandry practices or importing water. Fifty-nine percent of water needs are unsatisfied and the reduction in net return from base value is 56 percent.

Scenario III minimizes unsatisfied demand, after demand is reduced by the implementation of simple on-farm water conservation measures. No surface water is available for diversion. Forty-nine percent of the original water needs are unsatisfied and the reduction in net return is 49 percent of base value. This answers the second of the posed questions. Obviously, the use of the assumed on-farm conservation measures by themselves cannot reduce water demand sufficiently to achieve a sustained yield that will satisfy the remaining demand.

Scenario IV minimizes unsatisfied demand after both conservation measures are practiced and river water is diverted to the area. Eleven percent of the original demand is unsatisfied and the reduction in net return is 33 percent of the base value.

Scenario V minimizes the total expense of attempting to satisfy the reduced water needs from groundwater and diverted river water. Eleven percent of the original demand is unsatisfied and the reduction in net return is 31 percent of the base value.

Scenario VI is a compromise between the different regional objecives of Scenarios IV and V. It is presented merely to demonstrate that compromise strategies can be determined and reaffirms the concept that there are an infinite number of possible sustained yield strategies for the region.

Scenarios IV-VI each represent possible answers to the third posed question. Certainly, the "best" conjunctive use of groundwater and surface water in the region depends on the specific objectives of the water users and decision makers. Procedures have been developed to aid the process of determining what this best use may be. Datta and Peralta (1985) describe a methodology by which a group of decision makers can be assisted in achieving agreement in selecting a compromise strategy. Killian and Peralta (1985) present a procedure for refining a compromise regional strategy to better satisfy local (cell) objectives. Thus, the capability exists to tailor-make a regional conjunctive water use/sustained groundwater yield strategy for the Grand Prairie.

In conclusion, the predicted increasing unavailability of Quaternary groundwater (Peralta et al, 1985) is adequate justification for considering the feasibility of implementing a sustained yield strategy in the region. Among the tested strategies, only those that include both the implementation of conservation measures and diverted surface water can satisfy more than half of the water requirements. In fact, unless river water is diverted to the region, over one-quarter of the acreages currently supported by groundwater will need to switch to dryland agriculture, if a sustained (perennial) yield of groundwater is to be attained.

It must be reemphasized that this study was undertaken to provide a means of comparing the short-term economic impacts of alternative water policy scenarios. Prior to actually selecting a strategy, a more detailed evaluation of the maximum feasible recharge rates along boundaries at which rivers penetrate the aquifer should be performed. Relaxation of the limits on recharge imposed in this study could reduce unsatisfied demand and its attendant reduction in economic return. The resulting increase in groundwater availability is not expected to change the relative ranking of any of the strategies, since all may improve somewhat. Thus, the results of this study should be used as guides in the policy development process, rather than as alternative proposed strategies for implementation.

The additional detail work needed to actually select and implement a strategy will be merited only if the long-term maintenance of production at levels close to current levels is important enough to achieve (1) voluntary compliance by groundwater users with a sustained yield strategy, and (2) the diversion of adequate river water to the region. The reduction in water demand by simple water conservation measures is a desirable facet of an implementation program.

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