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MANAGING ARTIFICIAL GROUNDWATER RECHARGE

by

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SUMMARY: Increase in maximum groundwater mining resulting from recharge basin usage in the Grand Prairie is reported. Management model incorporates new influence coefficients that describe effect on groundwater levels of simultaneously occurring basin/aquifer interflow and groundwater extraction.

KEYWORDS: Groundwater, Operations Research, Management, Modeling

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INTRODUCTION

In the Arkansas Grand Prairie (Fig. 1), wells are becoming inoperable and the threat of litigation is increasing because of decreasing groundwater availability. Groundwater provides over half of the irrigation water currently used in this important rice and irrigated soybean producing area. Most groundwater is obtained from a relatively shallow Quaternary aquifer, part of the Mississippi Plain alluvial aquifer. The aquifer underlying the Grand Prairie is recharged primarily from the larger aquifer system which completely surrounds it. No doubt, rivers peripheral to the study area contribute recharge, but their effect is considered to be lumped with that of the surrounding aquifer. Very little vertical recharge occurs within the Grand Prairie because of a relatively impermeable clay cap. As a result, groundwater levels have been declining in the unconfined central portion of the Grand Prairie and saturated thickness has decreased alarmingly in some locations.

The Grand Prairie is a likely candidate to be the first region designated as a critical groundwater area in Arkansas. Recent legislation has given the Arkansas Soil and Water Conservation Commission responsibility for identifying such regions. Selected areas may experience more intensive state control and management than is the norm in Arkansas.

Large-scale diversion of water from the Arkansas and White Rivers is the most likely means of reducing reliance on groundwater. Enhancing aquifer recharge is a complementary, though partial, solution. State and federal agencies have cooperated in evaluating the feasibility of diverting river water. However, at least 10 years would be required to bring proposed diversion systems into operation and reduce reliance on Quaternary groundwater. In the meantime, enhanced recharge of the aquifer may help alleviate the adverse impact of continued groundwater use.

Previous studies determined that recharge via injection was impractical for the central Grand Prairie (Sniegocki, 1963; Sniegocki et al, 1965; Griffis, 1976). An alternative is the use of recharge basins near peripheral streams where aquifer material outcrops. The primary purpose of this paper is to quantify the increase in optimal groundwater extraction that would occur were two such basins installed. The increase is determined using a computer model that calculates maximum extraction volume for a specific planning period, subject to constraints. For efficiency, the linear model utilizes the discrete kernel (algebraic influence coefficient) concept.

The second objective of this paper is to discuss development of new influence coefficients which permit calculation of aquifer response to simultaneous groundwater pumping and interflow between recharge basin and aquifer. This is not trivial since interflow is a function of water levels which are in turn functions of pumping. Use of these coefficients in simulation or optimization models eliminates the need of somewhat inaccurately computing interflow in a time step using groundwater levels of the end of the previous time step.

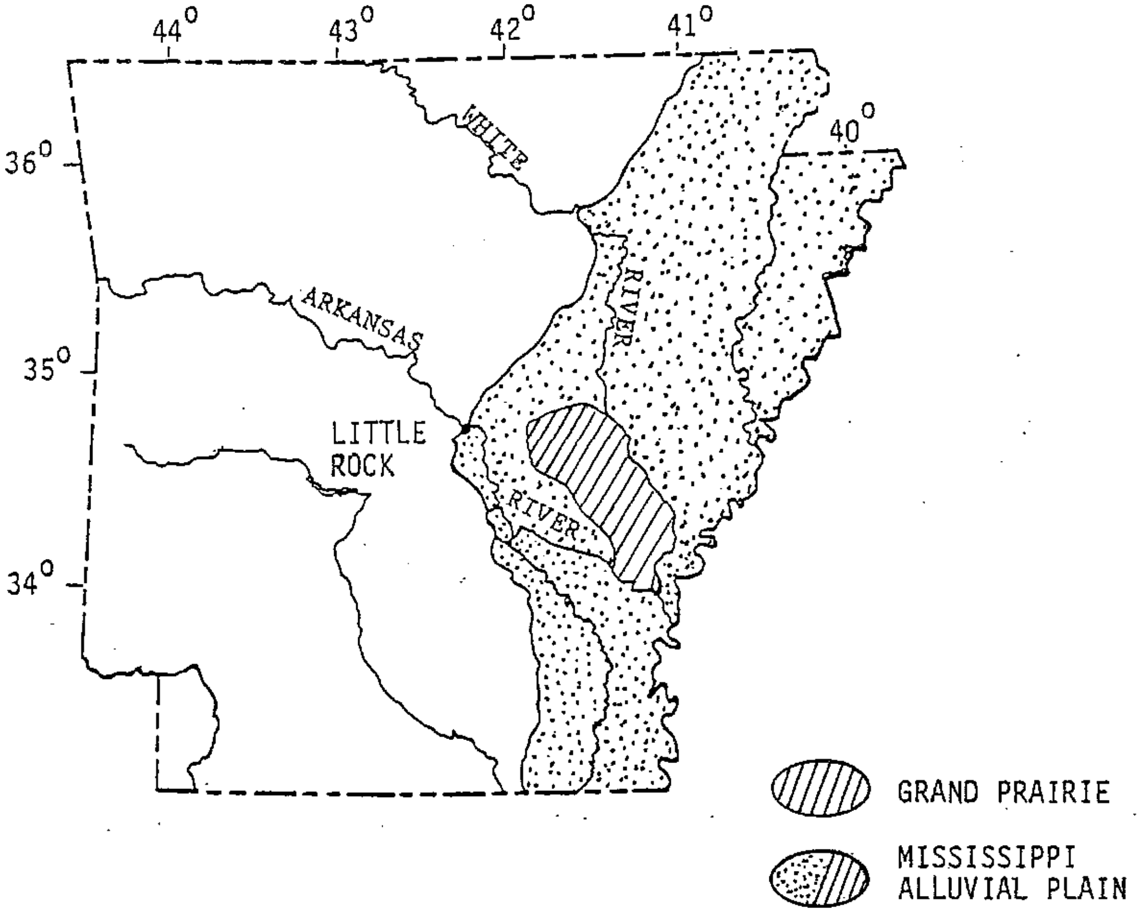

Figure 1. Arkansas, the Mississippi Alluvial Plain and the Grand Prairie

RELATION TO PREVIOUS WORK

The linear influence coefficient approach has long been used in groundwater simulation or management optimization (Maddock, 1972; Morel-Seytoux et al, 1973; Maddock and Haimes, 1975; Morel-Seytoux, 1975a,b,c,d; Morel-Seytoux and Daly, 1975; Haimes and Dreizin, 1977; Morel-Seytoux et al, 1981; Heidari, 1982; Illangasekare and Morel-Seytoux, 1984; Illangasekare et al, 1984; Colarullo et al, 1984; Danskin and Gorelick, 1985; Morel-Seytoux, 1985; Peralta et al, 1985; Peralta and Kowalski, 1986b). Gorelick (1982) provides an excellent review of early papers on that subject.

Peralta and Kowalski (1986a) used discrete kernels to determine optimal groundwater extraction strategies for the Grand Prairie. By appropriate recharge constraints, they assured that the developed strategies would not disrupt the surrounding regional groundwater flow patterns. They developed strategies maximizing groundwater extraction and maximizing the present value of net economic return resulting from extraction. Four different sets of constraints affecting acceptable drawdown and change in pumping with time were used .

They found that both objective functions yielded essentially the same total pumping and net return. This probably results from the facts that all net return is assumed to be generated from groundwater and there are no foregone costs of unsatisfied demand for water. The major difference in results was that maximum return strategies extracted more groundwater in the early part of the planning period, while the maximum pumping strategies pumped more in the latter part.

Based on the findings of Peralta and Kowalski (1986a), only strategies maximizing extraction are analyzed in this paper. We use the same objective function, but selectively add recharge basins to demonstrate the effect of those basins on maximum extractable groundwater. The same sets of constraints are used in this paper as were used in the pervious work.

To demonstrate the effect of recharge basins on groundwater extraction, we must consider how best to linearly model interflow between basin and aquifer. In general, influence coefficients utilized by other researchers have been designed to describe groundwater level response to specific extraction or injection stimuli. This is not entirely satisfactory when stimuli are themselves functions of existing groundwater levels, for example in a connected surface water/aquifer system. Interflow between a reservoir and aquifer is affected by the difference in head between the surface water and the groundwater (Morel-Seytoux et al, 1973; Morel-Seytoux and Daly, 1975). In such a situation, common practice is to estimate interflow based on levels existing in a preceding time step, or to estimate and then recalculate until heads and interflow are in harmony. Clearly, a need exists for discrete kernels that can express groundwater level response to both pumping and interflow based on simultaneously existing groundwater and surface water heads. The presented discrete kernels accomplish this.

THEORY AND MODEL FORMULATION

The simple model used in this study maximizes groundwater extraction subject to constraints and bounds (Heidari, 1982).

$$\max Z = \sum_{k=1}^{K} \sum_{i=1}^{J} g_{i,k} \qquad \ldots[1]$$

where

K is the number of time steps in the planning period;

J is the number of variable-head cells in the study area;

$g_{i,k}$ is groundwater extraction in cell i, time step k, (L^3).

Subject to

$$0 \leq g_{i,k} \leq w_i \qquad \text{for } i = 1 \ldots J,\ k = 1 \ldots K \qquad \ldots[2]$$

$$s_{i,k} \leq s^U_{i,k} \qquad \text{for } i = 1 \ldots J,\ k = 1 \ldots K \qquad \ldots[3]$$

$$e^L_{l,k} \leq e_{l,k} \leq e^U_{l,k} \qquad \text{for } l = 1 \ldots L,\ k = 1 \ldots K \qquad \ldots[4]$$

and, if it is desirable that the annual pumping volume in a cell not increase after it has decreased from current pumping (unidirectional change):

$$g_{i,k+1} \leq g_{i,k} \qquad \text{for } i= 1 \ldots J,\ k = 1 \ldots K-1 \qquad \ldots[5]$$

where

w_i is the volume of groundwater required for irrigation to support current (1982) acreages in cell i under average climatic conditions in a single time step (L^3);

$s_{i,k}$ is the mean drawdown that has occurred in cell i by the end of time step k, (L);

$s^U_{i,k}$ is the upper bound on acceptable drawdown in cell i by the end of period k, (L);

$e_{l,k}$ is the volume of groundwater that will enter the study area aquifer in peripheral cell l and time step k from extensions of the aquifer outside the study area, (L^3);

$e^L_{i,k}$ and $e^U_{i,k}$ are lower and upper bounds on the volume of groundwater flowing between the aquifer underlying cell 1 and extensions of the aquifer outside the study area in time step k, (L^3);

L is the number of peripheral cells surrounding the variable-head cells of the study area. In this study the peripheral cells are all constant-head/restrained flux cells.

In actuality, neither $s_{i,k}$ nor $e_{i,k}$ are explicitly used as variables within the models. Since groundwater movement is a function of water levels, e is represented as a function of s (Peralta and Kowalski, 1986a). s is a function of pumping developed in the following way. First, adopting the convolution equation described by Morel-Seytoux et al (1981) and Illangasekare et al (1984), the drawdown in water level since initial time in cell i by the end of time period N is:

$$s_{i,N} = \sum_{k=1}^{N} \sum_{j=1}^{J} \delta_{i,j,N-k+1} \left(q_{j,k} - q^{ass}_{j}\right) \qquad ..[6]$$

where

$\delta_{i,j,N-k+1}$ is a nonnegative-valued discrete kernel (linear influence coefficient) that describes the contribution to the hydraulic head at cell i in time step N caused by a unit ($q_{j,k}-q^{ass}_{j}$). The temporal subscript N-k+1 is used merely to insure that the proper @ is preventing recharge from ($1/L^2$) ;

$q_{j,k}$ is the net vertical hydraulic stimulus in cell j in time step k. It is the sum of all discharges (+) from the aquifer and recharges (-) to the aquifer from the ground surface, (L^3);

q^{ass}_{j} is the net vertical (possibly artificial) hydraulic stimulus that must occur in each time step in cell j for that cell to maintain its initial head. It is calculable using the linearized Boussinesq equation for steady-state two-dimensional flow through porous media, (L^3).

Assume that $q_{j,k}$ equals groundwater pumping ($g_{j,k}$) minus recharge basin/aquifer interflow ($o_{j,k}$)), where we assume movement of water from surface to aquifer. Saturated basin/aquifer interflow at cell j in time step k equals the reach transmissivity, Γ, times the difference in heads between the reservoir and the underlying water table. Thus,

$$o_{j,k} = \Gamma_j (\sigma_{j,k} - h^{o}_{j} + s_{j,k}) \qquad \ldots[7]$$

where

Γ_j is reach transmissivity, (L^2). It is zero for all cells without surface water resources in hydraulic connection with the aquifer;

$\sigma_{j,k}$ is the elevation of the free water surface in the reservoir, (L);

h^{o}_{j} is the initial water groundwater table elevation, (L);

Combining equations [6] and [7] yields

$$s_{i,N} = \sum_{k=1}^{N} \sum_{j=1}^{J} \delta_{i,j,N-k+1} (g_{j,k} - \Gamma_j (\sigma_{j,k} - h^{o}_{j} + s_{j,k}) - q^{ass}_{j}) \qquad \ldots[8]$$

Rearranging to move all s values to the left side yields

$$s_{i,N} + \sum_{k=1}^{N} \sum_{j=1}^{J} \delta_{i,j,N-k+1} \Gamma_j s_{j,k} =$$

$$\sum_{k=1}^{N} \sum_{j=1}^{J} \delta_{i,j,N-k+1} (g_{j,k} - \Gamma_j (\sigma_{j,k} - h^{o}_{j}) - q^{ass}_{j}) \qquad \ldots[9]$$

$$= Q_{\text{vertical}} = kia = \frac{L}{T}\left(\frac{\Delta L}{\Delta L}\right)\left(L^2\right) = \frac{L^3}{T}$$

$$= k\left(\frac{\Delta h}{\text{sat thick}}\right)(\text{area}) = \overset{\text{hydraulic}}{\frac{L}{T}}\Bigg(\frac{\Delta h}{\underset{\text{saturated thickness}}{L}}\Bigg)\Bigg(\underset{\text{area}}{L^2}\Bigg) = \frac{L^2}{T}\Delta h = \Gamma \Delta h$$

Solving equation [9] for a system of N times J linear equations yields

$$s_{i,N} = \sum_{k=1}^{N} \sum_{j=1}^{J} B_{i,j,N-k+1} (g_{j,k} - q_{j}^{ass}) - v_{i,j,N-k+1} (\sigma_{j,k} - h_{j}^{o}) \quad ..[10]$$

where

$B_{i,j,k}$ is a resolvent influence coefficient, (L^2);

$v_{i,j,k}$ is a dimensionless coefficient which equals $\Gamma_j B_{i,j,k}$.

In summary, the model consists of one objective function, equation [1]; JxK variable pumping values bounded via equation [2]; JxK drawdown variables bounded by combining equations [3] and [10]; L constraints on recharge, equation [4]; and either none or Jx(K-1) of equation [5], depending on whether the change in pumping is to be unidirectional.

METHODOLOGY

Data Development

As previously mentioned, the Grand Prairie is only a portion of an extensive aquifer system. Since it is economically impractical to develop optimial groundwater extraction strategies for the entire system, some boundaries assumed in this study are not hydrologic in nature. Justification of the use of constant-head/restrained flux boundary conditions is provided by Peralta and Kowalski (1986a). They also discuss bounds on flux across peripheral cells, e^L and e^U in equation [4], necessary to prevent disruption of regional flow.

Aquifer parameters assumed for computation of q^{ass}, δ, B, and v are an effective porosity of 0.3 and finite difference transmissivities. Transmissivities are calculated from kriged saturated thicknesses and a hydraulic conductivity of 82.3 m/day (270 ft/day) (Engler et al, 1945; Griffis, 1972; Peralta et al, 1985). δ influence coefficients are computed using an algorithm of Verdin et al (1981). B and v are computed from the δ. Changes in saturated thickness resulting from the optimal extraction strategies do not exceed the standard error of the estimate of the initially estimated saturated thickness. Therefore, initially computed influence coefficients are valid throughout the optimization period.

Values of w used as upper bounds on pumping in equation [2] are the volumes of groundwater currently being withdrawn from the aquifer under average climatic conditions. It is assumed that water currently provided from other sources will continue to come from those sources, and that no expansion of irrigated acreages is likely.

Upper bounds on drawdown in equation [3] are those values that will leave a minimum acceptable saturated thickness remaining at the end of each time step. Optimizations were performed using either 3 m or 6 m (10 or 20 ft) as the minimum acceptable terminal saturated thickness.

The initial heads used in equation [10] are those existing in spring 1982. Heads in the basin are at ground level and are assumed constant with time.

An identical recharge basin is assumed for each of two cells near the Bayou Meto on the western edge of the Grand Prairie (Figure 2). These are cells: 1) at which aquifer material outcrops, based on records of water well construction, 2) proximal to a surface water resource, and 3) adjacent to cells at which groundwater recharge to the area limits achievable groundwater extraction. Cells satisfying the third criterion are not identified until after optimizations are performed without considering recharge basins.

Rectangular basins 70 m x 35 m (200 ft x 100 ft) respectively, are assumed. The conservatively estimated aquifer saturated thickness beneath the basins is 4.6 m (15 ft). The result of these values and an aquifer hydraulic conductivity of 82.3 m/day is a reach transmissivity of 880 sq. m (9500 sq. ft) per day, computed using the procedure of Peters and Morel-Seytoux (1980).

Results and Discussion

Eight optimizations maximizing groundwater extraction are presented, Table 1). Four utilize recharge basins and four do not. Optimization was performed using the QPTHOR code (Liefsson et al, 1981). Each group of four optimizations consists of possible combinations of: 1) constraining saturated thickness to be at least 6 m or at least 3 m, and 2) either forcing pumping to be unidirectional in change with time or letting it change freely within initial bounds.

The optimization problems become less constrained and maximum pumping increases from top to bottom of Table 1. As is expected, maximum pumping that is directionally constrained is less than the maximum pumping obtainable for freely varying pumping. Similarly, pumping that can reduce saturated thickness only to 6 m is less than pumping that can reduce saturated thickness to 3 m.

In all cases, recharge basin utilization increases maximum regional pumping by at least 5 percent. This is probably greater than it would be if the recharge basins were located in other cells, although the difference is not quantified in this paper. It is important that the recharge basins be located where they can do the most good. In design practice an interactive procedure for refining recharge system design is desirable, because constraints that are tight based on one set of assumptions may no longer be tight if assumptions are changed slightly. An example computer graphics-based program for rapidly modifying optimal strategies is presented by Killian and Peralta (1985).

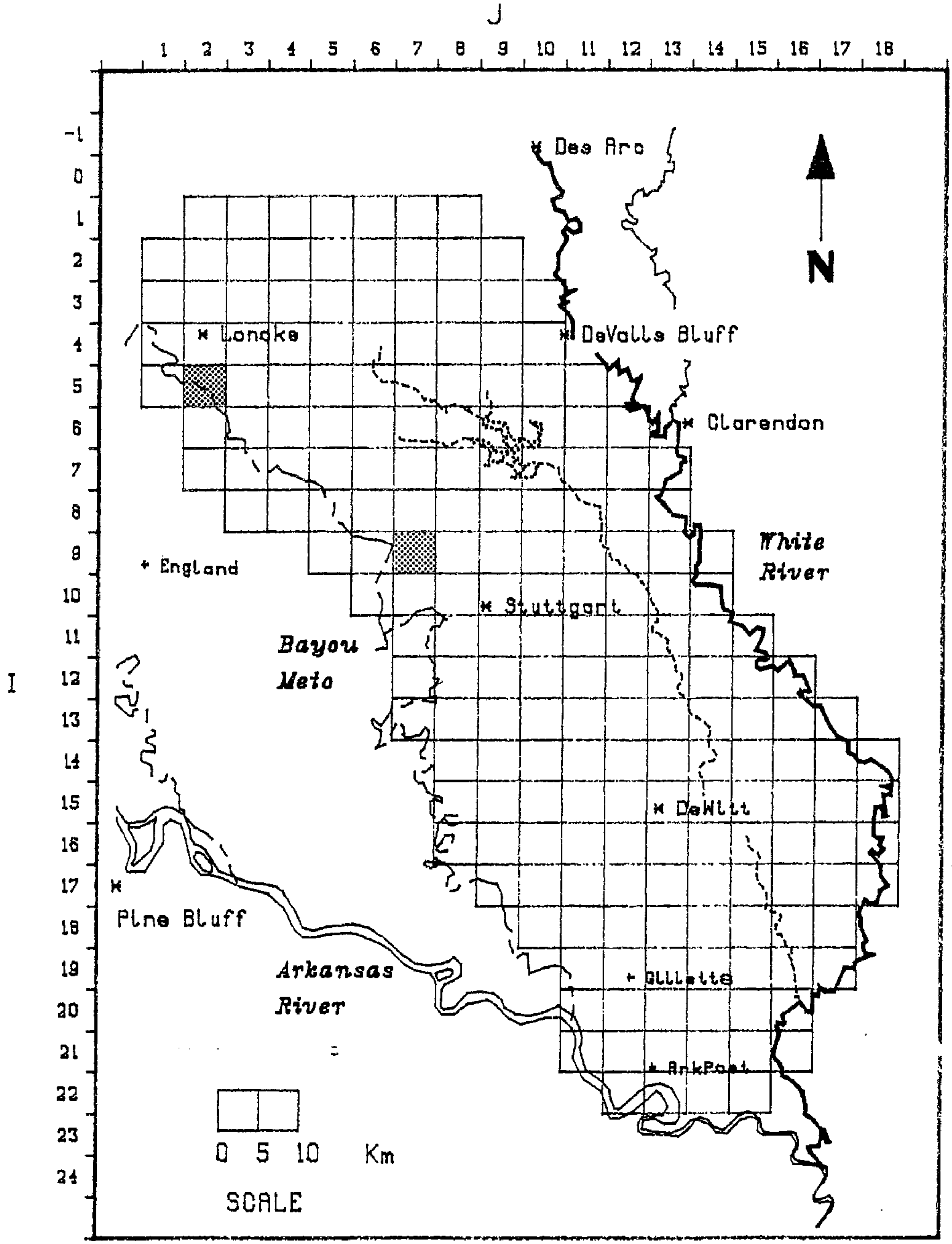

Figure 2. Recharge Basin Sites in the Arkansas Grand Prairie.

Table 1. Increase in maximum feasible 10-year groundwater extraction resulting from recharge basin usage

Strategy	Total Groundwater Extraction (million cubic meters)		Percent Increase
	Without Recharge Basins	With Recharge Basins	
Unidirectional Pumping[a]			
MST[b] = 6 m	2026	2150	6.1
MST = 3 m	2144	2266	5.7
Free Pumping			
MST = 6 m	2155	2306	7.0
MST = 3 m	2300	2449	6.5

[a] In 'unidirectional' strategies pumping cannot increase from one time step to the next.

[b] 'MST' is the minimum saturated thickness acceptable in any cell in a given strategy.

Note: to convert from cubic meters to acre-feet divide by 1233.5

CONCLUSIONS

Appropriately located recharge basins can contribute significantly to groundwater available for pumping. Hydraulically desirable sites can be identified by considering the constrained derivatives (shadow prices) that describe the effect of recharge constraints on attainment of the objective of an optimizing water management model.

To develop optimal strategies for such recharge systems, it is desirable to utilize discrete kernels that describe the effect on water levels of pumping and interflow based on simultaneously existing groundwater and surface water heads. This assures that saturated interflow between reservoir and aquifer is modeled efficiently. Discrete kernels that accomplish this are presented.

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