Conjunctive Water Use/Sustained Ground-Water Yield Planning : Case History*

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Abstract : A methodology for computing perennial ground-water yield and conjunctive water use strategies is presented, using the Arkansas Grand Prairie as a case study. This includes development and use of an optimization model for computing sustainable ground-water pumping strategies and a post-processor for allocating ground-water and surface water supplies in time and space. The optimization model utilizes embedded finite difference flow equations as constraints and bounds on pumping, recharge and potentiometric head. Computed conjunctive use strategies will maintain, as much as possible, the existing stressed potentiometric surface. They will also assure at least 6 meters of saturated thickness in all locations to provide protection from drought.

Résumé : A partir de l'étude de cas Grande Prairie d'Arkansas, l'article présente une méthodologie destinée à calculer les rendements en eau souterraine et formuler des stratégies d'utilisation cohérente des eaux. Cette méthodologie comprend le développement et l'usage d'un modèle d'optimisation qui calcule les stratégies de pompage d'eau souterraine et d'un modèle affectant l'eau souterraine et l'eau de surface dans le temps et dans l'espace. Le modèle d'optimisation utilise des équations aux différences finies d'écoulement comme contraintes et limites pour le pompage, la recharge et la charge potentiométrique. Les stratégies d'utilisation calculées maintiendront, autant que possible, l'organisation des écoulements existante. Elles assureront également une épaisseur saturée d'au moins 6 mètres à tout endroit, afin de procurer une protection contre la sécheresse.

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* **Utilisation cohérente des eaux/Planification du rendement de l'eau souterraine : Etude de cas**

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Reviewed manuscript for publication received 5 September 1990

Introduction

In the Arkansas Grand Prairie (Figure 1), ground water has long been used to irrigate rice and soybeans. Ground-water levels in the initially confined, but currently unconfined aquifer have declined with time and are now significantly depressed (Figure 2). Probably more than 50 years without pumping would be required for the potentiometric surface to appear unstressed. In some locations saturated thickness is so small that wells become inoperable in time of drought. Peralta et. al. (3) predict decreasing saturated thickness in some portions of the area. Obvious results, if current water management is not improved, will be economic hardship and a lack of water in time of drought. The potential for litigation, invoked to halt declining water levels, will increase.

A goal of local state and federal agencies is to prevent further decline in the potentiometric surface. To achieve this, and maximum agricultural production, the conjunctive use of water is necessary. Planners desire estimates of how much river water could potentially be required for diversion to the area. This paper describes part of a feasibility study conducted to determine a conjunctive water use strategy for the area. The strategy is a pattern of spatially and temporally varying ground-water and surface water use.

The main objective of this paper is to describe a method for computing a conjunctive water use and sustained ground-water yield strategy that can satisfy maximum potential irrigation water demand in the study area, for climatically average growing seasons, while maintaining the existing potentiometric surface as much as possible. It includes use of a model for optimizing sustained yield ground-water withdrawal rates and a post processor for allocating time-varying water use in compliance with the sustained yield strategy.

The process includes determining, on a monthly and seasonal basis, the potential irrigation demand in each of the 5 km x 5 km cells for average climatic conditions. It is assumed that the potential demand will be satisfied using a combination of sustainable ground-water withdrawals and surface water diversions. Thus, a sustained ground-water withdrawal strategy that will approximately maintain current ground-water levels is presented. This strategy consists of a set of sustainable annual ground-water withdrawal volumes which will maintain at least 6 m of saturated thickness in all cells.

After computing the sustained yield ground-water withdrawals, the annual diverted volume of surface water required for each cell is computed. Finally, the potentially required annual volumes of ground water and diverted river water are appropriately apportioned for each month of the irrigation season. This is accomplished in such a way as to minimize river water requirements during months of low flow. The resulting set of monthly cell-by-cell ground-water and river water use volumes is a conjunctive water use strategy.

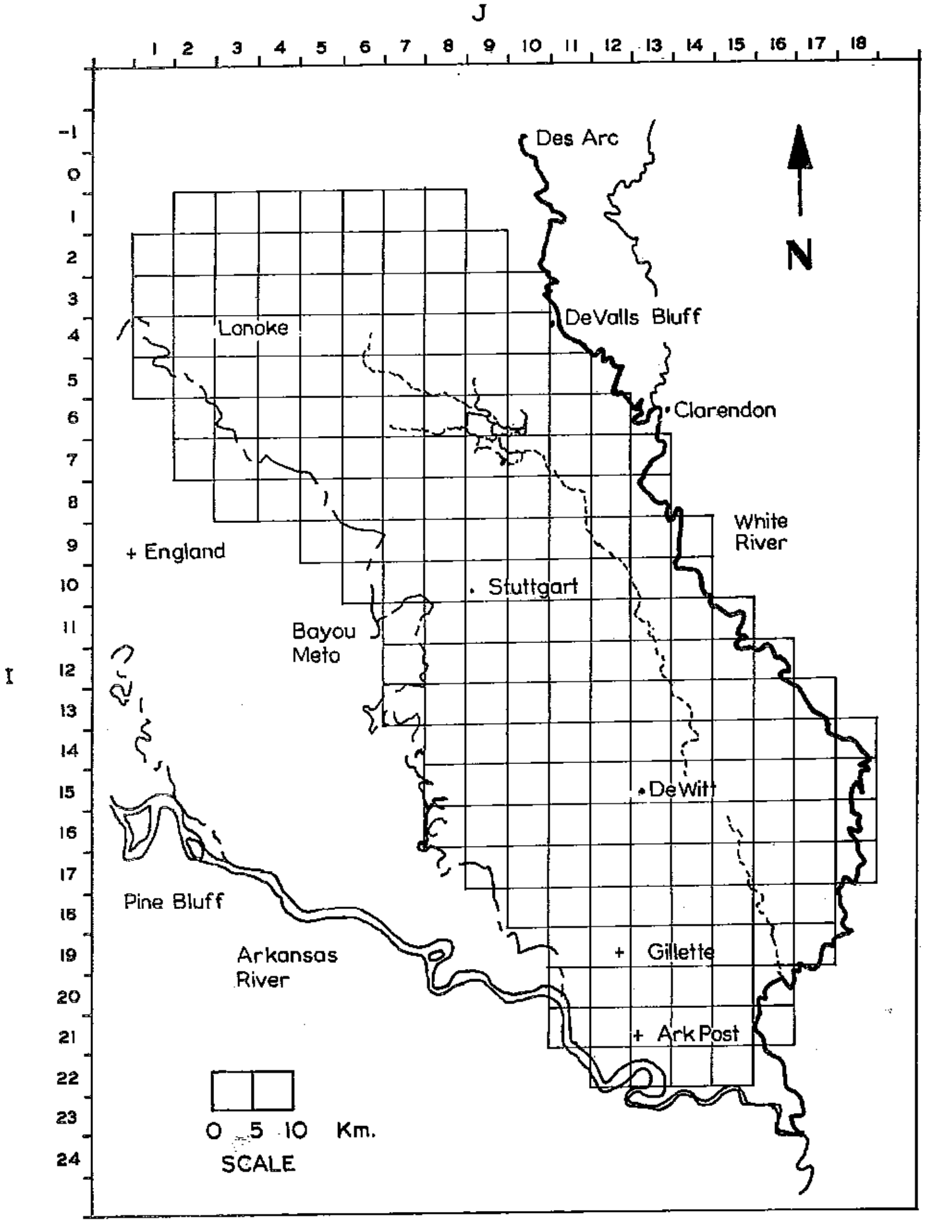

Figure 1. The Arkansas Grand Prairie and finite difference discretization

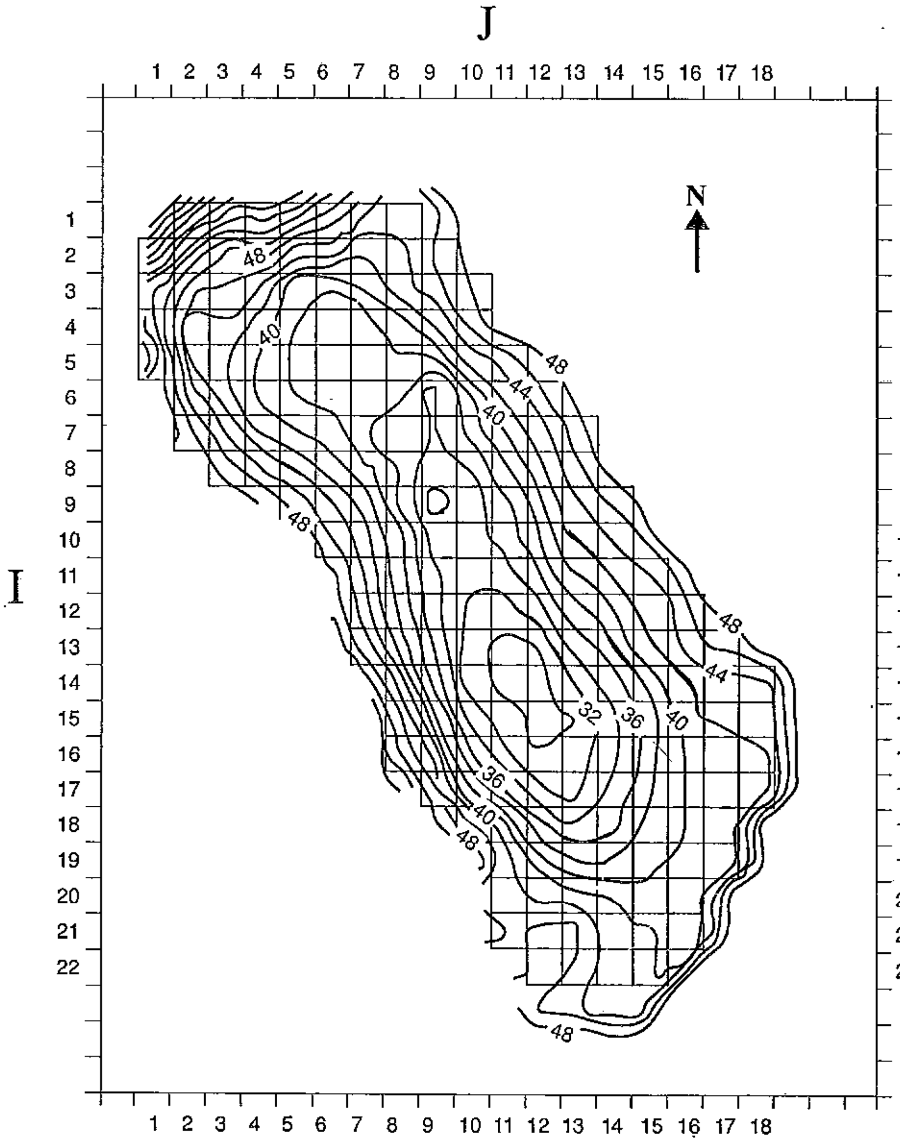

Figure 2. Current potentiometric surface elevation contours in the Grand Prairie, in meters above sea level

Methodology

Data Development

The Grand Prairie study area is underlain by an alluvial sand and gravel Quarternary aquifer. The aquifer is overlain by 8 to 15 m of silt and clay and is underlain by a thick confining bed in the Jackson Group. The average thickness and hydraulic conductivity of the aquifer are respectively 27 m and 82 m per day

A permeability of 81 to 82 m per day was reported by Sniegocki (8), Griffis (2), and Peralta et. al. (3). They concluded that deep percolation from the ground surface into the aquifer was negligible because of the clay cap overlying the aquifer.

Both Griffis (2) and Peralta et. al. (3) calibrated two-dimensional finite difference ground-water flow simulation models of the Grand Prairie. The latter used the same discretization, 204 (5 km x 5 km) cells, as this study (Figure 1). Here, all peripheral cells were treated as constant-head restrained flux cells Ground-water flow through these constant-head cells was constrained so as not to exceed prespecified values. In the 152 internal cells, heads are permitted to vary in response to pumping.

Crops considered to require irrigation water in the internal cells are soybeans, rice, and wheat. The maximum potential acreage of each crop in each cell was estimated using Soil Conservation Service crop recommendations for the existing predominant soils (9). This had already been accomplished for some parts of the region (5,6,7).

The first step involved identifying soil texture. In the second step a crop or land use was assigned to each soil texture. Based on the county soil surveys (9), out of the three most water intensive crops (soybeans, rice and wheat) the one that was appropriate for a particular soil texture was assigned to that texture. Land that is only appropriate for or was already assigned to pastures, woodlands, urban use, water (bayou, reservoir, stream, etc.), levees, mines, quarries, borrow pits or wildlife habitat was not considered available for agricultural production. Nor were non usable lands (unmapped, intermittent, rocky, or cobbly) considered appropriate for agriculture.

Finally, the potential acreage appropriate for each crop in each cell was computed for all the cells. The total areas of land judged to be appropriate for three crops are; soybeans (50,484 ha), rice (219,871 ha), and wheat (11,606 ha).

In estimating the potential water needs for each cell, the potential rice land is assumed to be planted half in rice and half in soybeans and wheat in a given season. The potential soybeans land is assumed double cropped with wheat, and the potential wheat land is planted to wheat only. This results in assuming actual areas of 109,936 ha for rice, 160,420 ha for soybeans and 172,026 ha for wheat in the tested cropping pattern. Potential water requirements for a particular crop were estimated using irrigation scheduling models by Peralta and Dutram (7). These programs compute daily water balances by considering precipitation, irrigation, evapotranspiration, runoff, seepage and either flood level (for rice) or soil moisture (for soybean and wheat). Using 15 years of climatic data and representative system efficiencies, average irrigation water need for each crop was computed (rice, 60.5 cm; soybeans, 17.8 cm; wheat, 7.4 cm). These values correspond well with those commonly assumed for the Grand Prairie (7). Finally the potential irrigation water needs for each cell were calculated for a climatically average season(Figure 3).

Maximum annual recharge or minimum annual discharge rates that occurred across the study area boundaries during ten recent years were computed. This was done by: assuming ground-water levels measured in wells by the U.S. Geological Survey, using kriging to estimate head values that exist in the center of cells, and solving a system of steady-state two-dimensional finite difference flow equations to compute the boundary fluxes (recharge at constant-head cells) needed to maintain those heads. The steady-state flow equations used the same aquifer parameters and grid system as a calibrated simulation model.

This recharge comes either from surface water resources in connection with the aquifer, or from extensions of the aquifer system outside the study area. The historic recharge values were subsequently used as limits on acceptable recharge rates in the optimization model.

Ground-water Model Development and Sustained Yield Computations

A sustained ground-water withdrawal strategy was developed for the study area using one of the approaches suggested by Yazdanian and Peralta (10). Based on their comparisons and recommendations, a quadratic goal programming model was selected. It minimizes the sum of the squares of the deviations between the target (current) water levels and the optimized ground-water levels, while determining the spatially distributed ground-water withdrawal strategy that will maintain the optimized levels. In developing the strategy, the kriged top and bottom elevations of the aquifer, current saturated thicknesses and a hydraulic conductivity of 82 m/day were assumed. As mentioned previously, upper limits were placed on the volume of ground water that could enter the study area in any constant-head cell. No limit was placed on the volume of ground water that could leave the study area. In addition, heads were bounded so as to leave at least 6 m of saturated thickness in each cell. (This thickness is considered adequate for representative wells and drought conditions)

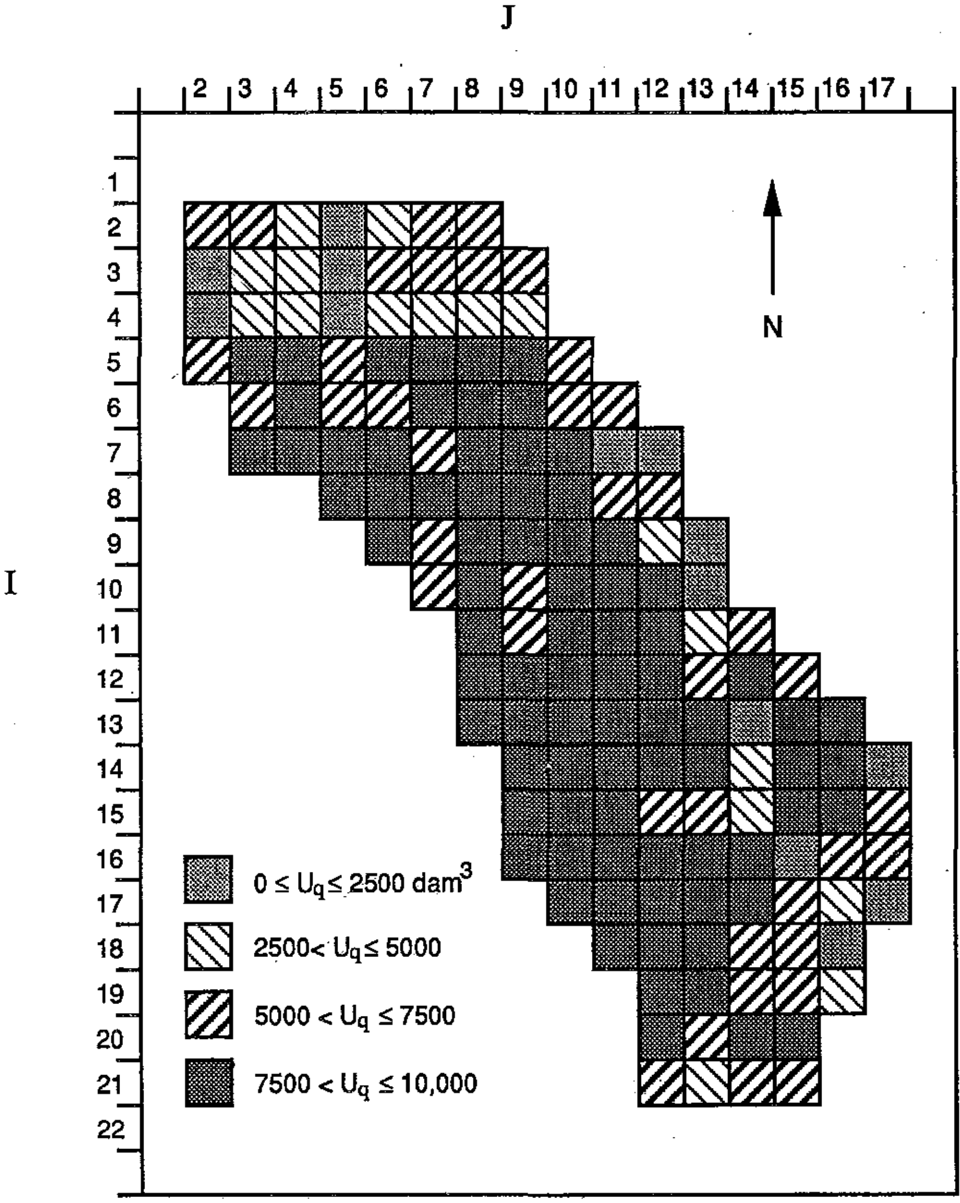

Figure 3. Annual potential irrigation water needs (Uq) for an average season in each 5 km x 5 km cell in the Grand Prairie region

The aquifer system is represented by a square finite-difference grid of n cells. These include the m cells located inside the area (internal cells), and n-m cells located on the periphery of the system (boundary cells). In the boundary cells, reacharge from outside the system is treated as a variable.

The objective function value is minimized subject to constraints on pumping and recharge and bounds on heads in each finite difference grid square. Expressed in quadratic programming matrix notation, the problem is represented as:

$$\text{minimize } Z = -2(H_{tw})\{H_*\} + (1/2)(H_*)^T [W]\{H_*\} + (H_{tw})\{H_t\} \qquad (1)$$

subject to:

$$\{L_q\} \leqslant \{Q\} = [T]\{H_*\} \leqslant \{U_q\} \qquad (2)$$

$$\{L_h\} \leqslant \{H_*\} \leqslant \{U_h\} \qquad (3)$$

where:

Z = the objective function value, L^2

(H_{tw}) = a 1 X m row vector whose elements are the product of the known target heads in the internal cells and the weighting factors, L

$\{H_*\}$ = the m X 1 column vector of initially unknown heads in the internal cells that are optimized, L

$(H_*)^T$ = transpose of column vector $\{H_*\}$, L

$[W]$ = the m X m diagonal matrix whose diagonal elements are two times the weighting factors, dimensionless

$\{H_t\}$ = the m X 1 column vector of the known target heads in the internal cells, L

$\{L_q\}$, $\{L_h\}$ = n X 1 and m X 1 column vectors whose elements are the lower bounds on pumping (or recharge) in all the cells in the system, L^3/T and on optimal steady-state heads in the internal cells, L, respectively

$\{U_q\}$, $\{U_h\}$ = n X 1 and m X 1 column vectors whose elements are the upper bounds on pumping (or recharge) in all the cells in the sytem, L^3/T, and on optimal steady-state heads in the internal cells, L, respectively

$\{Q\}$ = an n x 1 column vector of net steady-state pumping (or recharge) rates for all the cells, L^3/T and

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

The first and second terms on the right hand side of equation [1] are linear and quadratic, respectively, in terms of the unknown heads. The third term consists of constants.

Problem formulation and optimization was performed using the SSTAR model (4). This algorithm accepts simple cell and system data, formulates all bound and constraint equations, performs optimization (for a selected objective function) and prints output in a map format. The objective function used here is useful for other areas having a greatly stressed potentiometric surface, but is not usually appropriate for less developed aquifers.

The optimal strategy thus computed approximately maintains the target (current ground-water levels (Figure 2) while insuring at least 6 m of saturated thickness in all cells (if boundary conditions and other assumptions remain valid). Ground-water levels computed by the model are the same as those that would be computed by a standard simulation model if the optimal pumping values were used as input in a steady-state simulation. The difference in transmissivity between that assumed in equation [2] and that compatible with computed heads is insignificant, when one considers the accurary of estimated water table and aquifer base elevations.

Figure 4 depicts the annual sustained yield ground-water withdrawals as a percentage of the annual crop water needs in each cell. Total optimal ground-water use is 150,220 dam^3 (cubic decameter) per year. This value is almost 100 percent of the total pumping that is computed for this region when using a maximum sustainable pumping objective function (although the spatial distribution of pumping is different). This similarity occurs because the bounds on recharge across the area boundaries are the most restricting conditions. In this study, the goal of maintaining existing water levels is achieved, and available ground water is well-utilized.

Computation of Surface Water Requirements

The potential annual surface (river) water required for diversion to a given cell was estimated by subtracting the optimal annual ground-water withdrawals of that cell from its total crop water needs. To estimate potential monthly surface (river) water requirements, it was assumed that as much of the annual allotment of ground water as possible would be used in August. If annual ground-water availability exceeded the August water requirements of a cell, the remaining available ground water was utilized consecutively in July, June, May, April, and lastly in September. The process was followed backwards in time to minimize the need for surface water during periods of low flow. For average climatic conditions, total annual potential crop water requirements for the study area were 1,064,690 dam^3 with surface water requirements of 914,470 dam^3 and ground-water pumpage of 150,220 dam^3 (Table 1). Also displayed are monthly

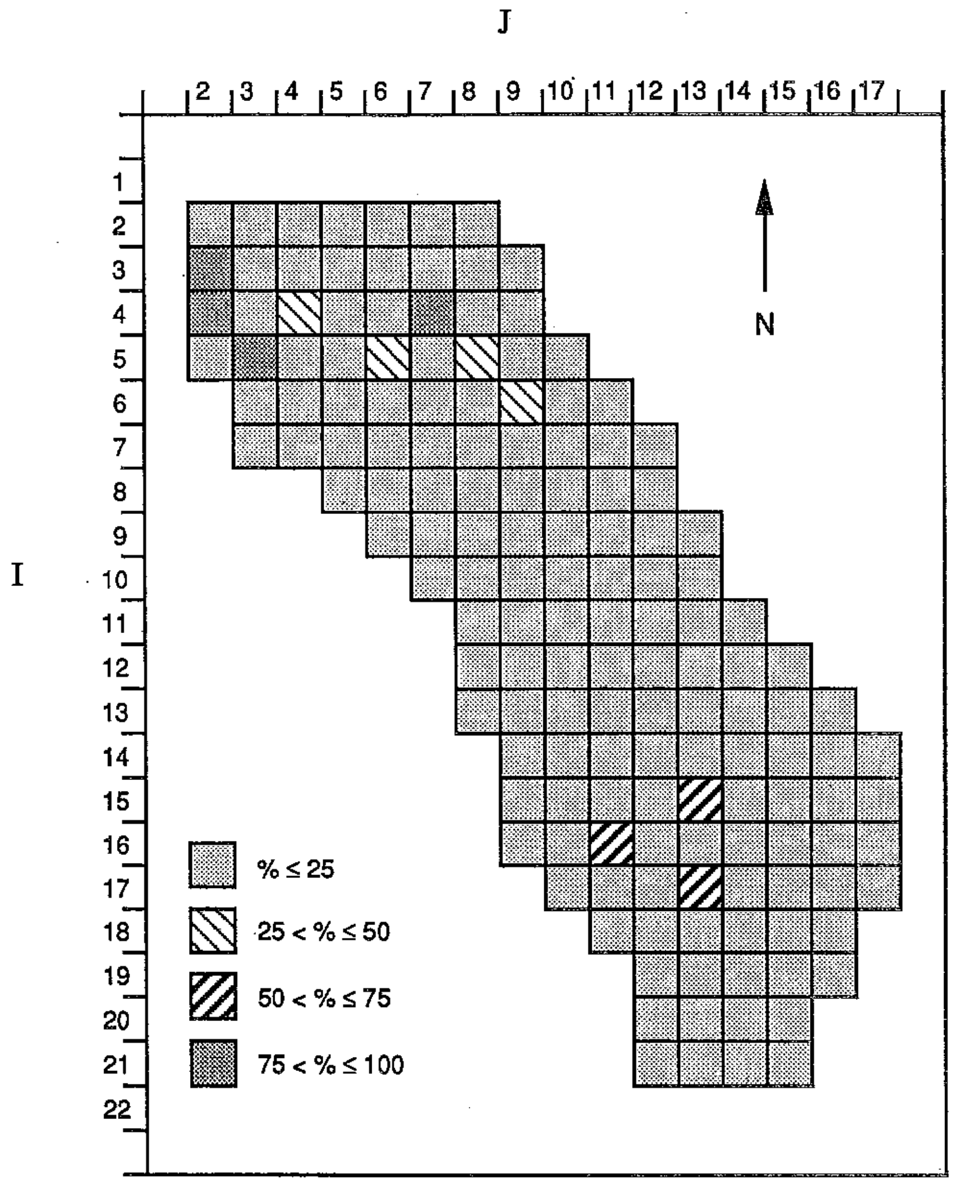

Figure 4. Annual withdrawals as a percentage of the total crop water needs based on the strategy that maintains at least 6 m saturated thickness and the current potentiometric surface

potential crop water requirements and surface and ground-water requirements based on the strategy presented above. Surface water and ground water satisfy 86 and 14 percent of the total crop water needs respectively, illustrating the crucial need for surface water to achieve production goals while maintaining the

Table 1. Monthly potential crop water needs and surface and ground-water use based on the strategy that maintains at least 6 m saturated thickness.

Month	Total water needs $(dam)^3$ (monthly % of annual water needs)	Surface water use $(dam)^3$ (monthly % of annual surface water)	Ground water use $(dam)^3$ (monthly % of annual ground water)	% of monthly water needs provided by	
				Surface water	Ground water
Aug.	345,018 (32.4)	219,808 (24.0)	125,210 (83.4)	63.7	36.3
July	263,840 (24.8)	247,160 (27.0)	16,680 (11.1)	93.7	6.3
June	307,963 (28.9)	301,434 (33.0)	6,529 (4.3)	97.9	2.1
May	78,361 (7.4)	77,415 (8.5)	946 (0.6)	98.8	1.2
April	48,110 (4.5)	47,531 (5.2)	579 (0.4)	98.8	1.2
Sept.	21,398 (2.0)	21,122 (2.3)	276 (0.2)	98.7	1.3
Total annual	1064,690	914,470	150,220		

Surface water will satisfy 85.9% of the total crop water needs.
Ground water will satisfy 14.1% of the total crop water needs.

existing stressed water levels. Eighty-three percent of the annual optimal pumpage would be utilized in August and 17 percent would be distributed over the other five months of the irrigation season.

Surface water diverted to the area would need to come from the White and Arkansas (via the Bayou Meto) Rivers. Generally, there is enough available water in these rivers to satisfy the computed need for surface water. Dixon and Peralta (1) analyzed flows in August (the low-flow month) and compared these with the flows necessary to maintain stream water quality standards, navigational requirements, and legal obligations. Under average climatic conditions and assuming a steady diversion rate, more than enough water is available. However, under dry conditions water need would increase, river flow would decrease and not enough surface water would be available.

As requested by the U.S. Army Corps of Engineers, this reconnaissance study used the most dense irrigated cropping pattern practicably conceivable for available soils. In reality, crop areas and average water need would probably be less than computed. In that case, the procedure could be performed anew, using revised data.

Summary

A reconnaissance level conjunctive (surface and ground) water resources management strategy was developed that can satisfy maximum potential irrigation water demand in the Grand Prairie region of Arkansas for climatically average growing seasons. It was assumed that the water demand will be satisfied using a combination of ground-water withdrawals and river water diversions. The developed strategy assures perennially sustainable ground-water withdrawals and adequate saturated thickness for the time of drought. It satisfies the socially important objective of maintaining the existing potentiometric surface, while making good use of available ground water. The presented methodology is applicable to other regions having a highly stressed potentiometric surface and the need to achieve high agricultural production levels.

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Acknowledgements

We appreciate the funding support of the U.S. Army Corps of Engineers and the Agricultural Experiment Stations of Utah and Arkansas.

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Dated : 23 October 1990

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