ASSURING SUSTAINED GROUNDWATER AVAILABILITY AND ACHIEVING CONJUNCTIVE WATER MANAGEMENT BY TARGET APPROACHES

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INTRODUCTION

Assuring the sustained availability of water of adequate quality and quantity in a stream-aquifer hydrologic system frequently requires coordinating the use of groundwater and surface water. Since, without the use of reservoirs, it is difficult to assure that available river water will be adequate at a particular time and place, providing an assured supply requires reliance on groundwater.

Regional sustained yield groundwater withdrawal strategies can be calculated using specialized computer programs. Each such strategy consists of a set of volumes that can be withdrawn from different portions of an aquifer system, year after year, without causing undesirable changes in groundwater levels (the potentiometric or piezometric surface). In fact, pumping in compliance with such a 'safe yield' strategy will eventually cause the evolution of a particular, unique, steady-state potentiometric surface. The first objective of this report is to provide a brief overview of methods for designing desirable or optimal regional steady-state potentiometric surfaces. Examples are presented of how a stable potentiometric surface can be modified to: (1) assure adequate groundwater availability for time of drought and (2) prevent the unacceptable spread of groundwater contamination.

Conjunctive water management refers to coordinating the use of groundwater and surface water resources that may or may not be in hydraulic connection. Causing the evolution and maintenance of a desirable potentiometric surface by systematic water use is an appropriate planning approach for either situation.The second objective of this paper is to describe applications for each case. The first application develops sustained yield strategies that maintain legal in-stream water requirements by controlling the potentiometric surface elevations and hydraulic gradient in the vicinity of the streams. This example also illustrates the usefulness of the approach in maintaining necessary groundwater flow across legal or institutional boundaries. The second application determines the time-varying requirement for diverted river water to supplement sustainable groundwater use. It illustrates how sustained yield strategies can be used in planning the diversion of water to nonriparian lands.

Assessment of the chances of implementing a sustained yield-conjunctive use strategy in Arkansas requires consideration of existing water laws. The legal feasibility of maintaining a 'target' potentiometric surface in Arkansas, without considering conjunctive use or stream-aquifer interaction, has been previously analyzed in detail as a Special Report in the Arkansas State Water Plan (Peralta and Peralta, 1984b). The third objective is to present the salient features of that analysis and to discuss possible steps toward utilization of the target level approach for conjunctive water management.

Implementation of a sustained yield-conjunctive use strategy, in an area in which groundwater problems are arising because of intensive use, will require some change in practice by individual water users. The final objective is to demonstrate how an individual water user may use water or change water use following implementation of a district-wide sustained yield strategy.

LITERATURE REVIEW OF REGIONAL STEADY-STATE POTENTIOMETRIC SURFACE DESIGN

It should be mentioned that there are many theoretical models for using optimization in groundwater management, although actual applications to large systems are scarce. Gorelick (1983) provides an excellent review of reported efforts. One of these methods, the embedding approach, consists of using optimization with embedded steady or unsteady-sate flow equations. Aguado et al, (1974) pioneered this approach in demonstrating how to minimize the cost methods are discussed in more detail below. Also, application of the Surrogate Worth Trade-off Method (Haimes and Hall, 1974) for aiding a group of decision makers to select a 'compromise' strategy from a pareto optimum in a multiobjective situation has been demonstrated (Datta and Peralta, 1986). In summary, a fairly comprehensive group of techniques are available for designing desirable regional potentiometric surfaces and sustained yield groundwater withdrawal strategies. They are applicable for conjunctive water management in stream-aquifer systems.

It should be noted that most of the procedures mentioned above utilize steady-state flow equations to derive annual groundwater withdrawal rates. As a result they do not consider the additional capture of water that may be caused by time-varying pumping. Thus, actually sustainable time varying groundwater withdrawals along recharge sources may be somewhat greater than sustainable groundwater pumping calculated by steady-state approaches. The same innacuracy exists for the applications mentioned below.

SPECIAL APPLICATIONS OF TARGET SURFACE APPROACHES TO GROUNDWATER MANAGEMENT

One study was performed to determine the minimum springtime saturated thickness needed in a particular cell in order to assure that existing wells would be able to function even during a droughty growing season (Peralta et al., 1986). (The wells in this particular cell are shown in Figure 1.) To accomplish this, fairly accurate information was compiled concerning the elevations of the base of the aquifer. A survey of well-owners was conducted to determine the rice acreages supported by groundwater (Table I). Irrigation schedules were developed for these acreages for the climatic conditions of four representative years. Then, an iterative simulation procedure was used to determine the springtime saturated thickness that would be necessary in order

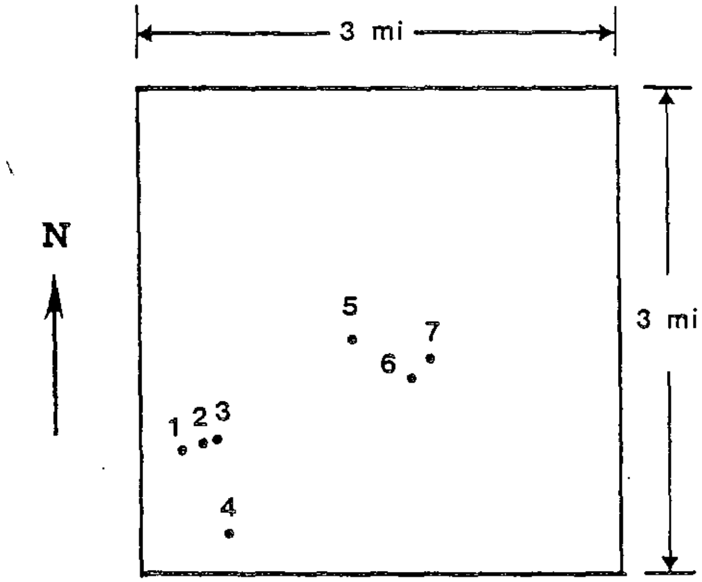

Fig. 1. Well locations in cell.

TABLE I. Well Owners' Questionnaire Results

Well #	Yield (GPM)	Diameter (in.)	Acres Normally Irrigated	Acres Irrigated in Drought
1	600	8	*	65
2	900	8	*	95
3	900	24	*	160
4	700	24	80	80
5	500	8	50	50
6	350	10	30	30
7	400	12	40	40

* Used only as supplementary irrigation wells in normal seasons.

TABLE II. Necessary Initial Saturated Thickness

	Saturated Thickness (ft)	
	Well 7	Center of Critical Cell
Minimum (1975)	15	9
Mean (1973)	15	9
Maximum (1978)	16	10
Drought (1980)	19	13

that each well have adequate saturated thickness throughout each pumping season. Table II shows the resulting minimum acceptable saturated thickness for well 7 (near the center of the cell) and for the cell center. It can be seen that a year with minimum irrigation requirements (1975) requires less initial saturated thickness than an extremely dry year (1980). The results of this study were then used to tailor a regional sustained yield strategy in order to cause the evolution of a springtime water table that would provide water users with some protection from drought.

Another study was performed in order to determine how to modify a stable water table at a cell so that future salt concentrations in the groundwater at that cell would not exceed a certain value (Datta and Peralta, 1987). The study was performed on the hypothetical area shown in Figure 2. Assume that the water table elevations in the area are as shown and that they represent an economically optimal steady-state potentiometric surface for the region. The groundwater use strategy that maintains that surface was developed without considering water quality as a constraint. Assume that a water management agency is considering construction of a canal along the right edge of the area. The canal will convey water containing 1000 ppm (parts per million) of salt and will be in hydraulic connection with the aquifer.

The water table contours of Figure 2 indicate that contaminated water will move from the right edge toward the center of the area. Using a water quality simulation model, it was determined that after 200 years, the groundwater concentrations shown in Figure 3 would result. Assume that 235 ppm is the maximum acceptable future concentration for the shaded cell. This is less than the 262 ppm that is predicted. The use of an innovative procedure determined that appropriate changes in pumping at three cells would cause a 0.3 m decrease in water table elevation at that cell and would reduce the future concentration to 233 ppm. Thus the water quality constraint could be

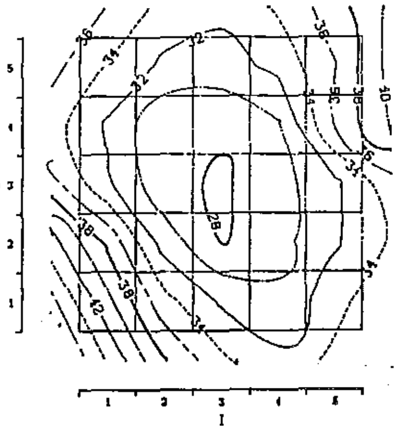

Fig. 2. Optimal potentiometric surface elevations (m above sea level)

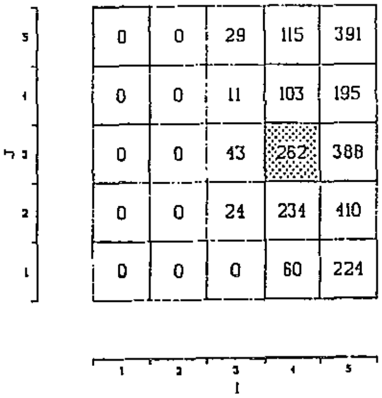

Fig. 3. Predicted salt concentrations (ppm) after 200 years

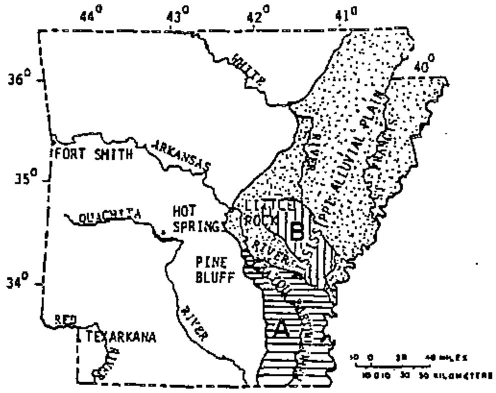

Fig. 4. Mississippi Plain Alluvial Aquifer underlies all shaded areas. Strategies have been developed for Area A (Bayou Bartholomew Basin) & Area B (Grand Prairie Region).

Table III. Maximum Sustainable Annual Groundwater Pumping in the Bayou Bartholomew Basin. (cubic decameters/yr)

Upper Limit on Aquifer Recharge from Streams Flowing to Louisiana. (cubic decameters/yr) #	Upper Limit on Groundwater Flow from Louisiana (cubic decameters/yr)	Lower Limit on Groundwater flow to Louisiana (cubic decameters/yr)
	5,800	3,700
95,800	192,300	181,500
15,400	109,600	107,100

\# These streams include the Bayou Bartholomew, Boeuf Tensas River and Bayou Macon. Recharge from the Arkansas River and Mississippi River is not included.

satisfied by modifying the sustained yield pumping strategy and the steady-state water table. The adverse consequence of those changes would be an increase in regional cost of $ 3,800 per year. This is an example of how an optimal regional strategy and steady-state surface can be refined to better consider matters not initially considered explicitly within the optimization model.

APPLICATIONS OF TARGET SURFACE APPROACHES TO CONJUNCTIVE WATER MANAGEMENT

Maintaining appropriate streamflow in a stream-aquifer system is an important capability of any conjunctive water management methodology. For example, streams in the 8285 sq. km. (3200 sq. mi.) Bayou Bartholomew Basin (Area A in Fig. 4) flow from Arkansas into Louisiana. Water management strategies developed for that area must assure that reasonable streamflow will continue. Strategies developed using an optimization model can be formed to comply with such a requirement. When developing a strategy for the Bayou Bartholomew Basin using the SSTAR model (Peralta et al., 1985), a limit on recharge to the aquifer from each stream is imposed. Assuming average inflow to the stream and average diversion by riparian users, implementation of a sustained yield strategy that causes no more than average recharge to the aquifer will assure at least average streamflow.

Table III shows maximum sustainable groundwater pumping for four scenarios. These differ in a) how much annual recharge to the aquifer from the streams is acceptable, and b) the direction and volume of annual groundwater movement between Arkansas and Louisiana. Clearly, as one permits less recharge and more streamflow from streams, sustainable groundwater pumping decreases. Similarly, a hypothetical interstate agreement to maintain at least 3700 cubic decameters (3000 ac-ft) of annual groundwater flow to Louisiana would reduce sustainable groundwater pumping from that achievable if up to 6800 cubic decameters (5500 ac-ft) could enter from Louisiana .

The ability to evaluate the temporally and spatially varying need for water from different sources is also important for conjunctive water planning. In one project, an agency needed to know when, where and how much river water would need to be diverted to supplement available groundwater if irrigated crop production were maximized for the 4660 sq. km. (1800 sq. mi.) Arkansas Grand Prairie (Figure 4) (Yar et al., 1985). It was assumed that a sustained yield pumping strategy would be implemented which would assure at least 6 m (20 ft) of saturated thickness in all cells while approximately maintaining current groundwater levels. The resulting conjunctive use strategy is summarized in Table IV.

The first step in strategy development was to determine for each cell, the maximum potential annual and monthly irrigation water requirement based on soil type, suitable crops, irrigation scheduling, and average climatic conditions. These annual water requirements were considered to be upper bounds on acceptable annual ground-water withdrawal in the cells. They were used in SSTAR to calculate the desired annual sustained yield pumping strategy. Simple subtraction of annual groundwater availability from annual water need provides annual need for diverted river water in each cell.

The second step involved consideration of the monthly variation in water use from the two sources. This was accomplished by assuming that one would want to minimize surface water use during periods of low river flow. Since streamflow diminishes between April and August, and crop water needs are greatest and most critical during August, it was reasonable to plan to use as much groundwater as possible during August. The monthly potential need for diverted river water was estimated by assuming that as much of the annual allotment of groundwater as possible would be used in August. If annual

Table IV. Monthly Percentages of Potential Crop Water Needs and the Need for Groundwater and Diverted River Water in the Grand Prairie

Month	Monthly Percentage of Potential Seasonal Water Needs	Percentage of Potential Needs Which Can Be Met By Groundwater	Percentage of Potential Needs Which Will Require Surface Water
April	5	1	99
May	7	1	99
June	29	2	98
July	25	4	96
August	32	36	64
September	2	1	99
Entire Season	----	14	86

Table V. Anticipated Annual Reasonable Use, Necessary Reduction in Use, and Additional Available Water Resulting from Implementation of a Sustained Yield Strategy in a Developed Aquifer. (Quantities refer to those for an individual water user.)

	TN <= GA	SA > Ø	S$ > G$	TN >= GA + SA	GU	SU	DIF	XG	XS
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
a.	yes	yes	yes	no	TN	Ø	Ø	GA - TN	SA
b.	yes	no	----	no	TN	Ø	Ø	GA - TN	Ø
c.	y/n	yes	no	no	TN - SA	SA (limit SU <= TN)	Ø	GA - TN + SA	Ø
d.	no	yes	yes	no	GA	TN - GA	Ø	Ø	SA - TN + GA
e.	no	yes	y/n	yes	GA	SA	TN - GA - SA	Ø	Ø
f.	no	no	----	yes	GA	Ø	TN - GA	Ø	Ø

NOTE:

TN = Total annual Need for water (pumped from the aquifer or diverted from a river), (volume);
GA = Ground water Availability, sustainable, (volume);
SA = Surface water Availability, current year, (volume);
$G = unit cost of Groundwater, ($/unit volume);
$S = unit cost of Surface water, ($/unit volume);
GU = Ground water Use, (volume);
SU = Surface water Use, (volume);
DIF = DIFference between water need, TN, and utilized water (GU + SU), (vol.);
XG = eXtra Groundwater available for use, (volume);
XS = eXtra Surface water available for use, (volume).

groundwater availability exceeded the August water requirements of a cell, the remaining available groundwater was utilized consecutively in July, June, May, April and lastly in September.

Clearly, river water would need to be the dominant source of supply. Available groundwater is inadequate to support potential irrigated acreages over the long-term. This analysis does not address the potential availability of surface water. If surface water availability is insufficient, then the assumed potential irrigated acreages are not sustainable.

LEGAL FEASIBILITY AND NEEDED LEGAL CHANGES FOR IMPLEMENTING A SUSTAINED YIELD/CONJUNCTIVE WATER USE STRATEGY IN ARKANSAS, A REASONABLE USE STATE.

Conjunctive use, for the purposes of this discussion, includes both stream/aquifer interaction and the coordination of surface and groundwater use to meet water requirements. The examples presented have outlined the utility of some of the technical tools available for achieving conjunctive use. The question, then, is whether the legal means to apply these tools is available in the state of Arkansas. Minimum legal requirements for achieving conjunctive use goals must include: (1) a single legal system governing both ground and surface water use; (2) legislative and judicial willingness to adapt the basic riparian rights doctrine to accomodate changing needs; (3) the ability of riparians and non-riparians to use surplus surface water transfered from other basins; and (4) coordinated state agency oversight. A brief overview of pertinent Arkansas water law and analysis follow.

Arkansas, like most of her eastern neighbors, is a riparian rights state. The riparian rights doctrine, based on the old English common law, has long been recognized as the governing doctrine for the legal use of water in Arkansas.(a) Under the riparian rights doctrine, the right to use surface water is incident to ownership of "riparian" land -- land abutting surface water. The right to use groundwater is incident to the ownership of land overlying groundwater.

In Arkansas, the riparian rights doctrine has been modified to allow "reasonable use" of the ground and surface waters of the state by overlying and riparian land owners.(b) In Harris v. Brooks, the landmark case for reasonable use case in Arkansas, the Arkansas Supreme Court ruled that:

> "the purpose of the law is to secure to each riparian owner equality in the use of water as near as may be by requiring each to excercise his right reasonably and with due regard to the rights of others similarly situated."(c)

In Jones v. OZ-ARK-VAL Poultry Co., the court stated that the reasonable use rule applied to all underground waters, in addition to surface waters, whether a "true subterranean stream" or "subterranean percolating waters."(d) The Arkansas high court further favorably recognized the California correlative rights doctrine as set forth in Hudson v. Dailey.(e) Under correlative rights, the reasonable use rule is modified in times of scarcity to allow each overlying land owner a proportionate or prorated share of the supply. The court ruled that an overlying groundwater user 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."(f)

What constitutes "unreasonable use" has been ruled "largely a matter of the discretion of the court after an evaluation of the conflicting interests of each of the contestants before the court."(g) The court considers such factors as the purpose, extent, duration, necessity of use, the nature and

and size of the water supply, the extent of injury versus the benefit accrued from pumping and any other factors that come to the attention of the court.(h) The court has recognized two alternatives for dealing with "unreasonable users", depending upon "all the facts and circumstances of a particular case": (1) declaring the interfering use "unreasonable and, as such, enjoined"; or (2) making a "reasonable and equitable adjustment."(i) (For example, in a groundwater case, ordering payment to extend affected wells to greater depths or limiting the number of hours per day that the interferring well(s) may legally be used).(j)

Both case and statutory law have consistently given domestic use precedence over other uses of surface water.(k) In harmony with the laws governing surface water use, the court has ruled industrial use of groundwater which interferes with domestic use to be "unreasonable."(l) In such cases, the legal utility of an activity which produces harm is weighed against the legal gravity of the harm on a case by case basis by the court.

The court's policy of weighing "the extent of injury versus the benefit accrued" from the pumping" lends itself well to the designation of appropriate target groundwater levels by the governing water management agency. Target levels are established to protect existing rights by: reducing the incidence of injury and by assuring the long-term availability of the resource for beneficial use. Indeed, the Arkansas Supreme Court has previously used a sort of "target level" approach to settle water disputes.(m) For example, in <u>Harris</u> v.<u>Brooks</u>, the court ruled that the appellees should be enjoined from pumping water out of Horseshoe Lake when the water level reached 189.67 feet, and stated: "We make it clear that that this conclusion is not based on the

> fact that 189.67 is the normal level and that appellees would have no right to reduce such level. Our conclusion is based on

the fact that we think the evidence shows this level happens to be the level below which appellants would be unreasonably interfered with."(n)

In a groundwater case, Lingo v. City of Jacksonville, the court restricted pumping by the City of Jacksonville "to the extent that it would damage the plaintiffs." Saying that "It is difficult at this time to find with any confidence the exact amount of water that may be removed without damage to the landowners," the court concluded that "the pumps individually may not be operated during any one twenty-four hour period for more than eight hours."(o) An optimization method like the Target Objective Approach may well be used in future cases to increase the degree of certainty with which the court can predict the permissible pumping rates to protect existing legal usages. Peralta,et al. (1986) demonstrate how a target level can be designed to provide a degree of protection from depletion for individual well users in a critical cell.

The court has openly stated that "the benefits accruing to society in general from a maximum utilization of our water resources should not be denied merely because of the difficulties that may arise in its application."(p) The Arkansas high court has declared that it is "not necessarily adopting all the interpretations given it by the decisions of other states."(q) The Arkansas Supreme Court has consistently based its decisions on the best available hydrologic data, and has not refused to modify the riparian rights doctrine to accomodate beneficial uses of water in the state.

Several proposed water codes have been considered (and rejected) by the Arkansas legislature. The rejections have not apparently been because of a lack of committment, but because of an apparent lack of general public support for sweeping changes in the existing water rights system. The Arkansas General

Assembly has modified the riparian rights doctrine a number of times. In Act 81 of 1957, the legislature made provisions for the lead state water agency (Arkansas Soil and Water Conservation Commission) to allocate surface water in times of shortage. In Act 180 of 1968, the ASWCC was given authority over registration of legal diversions from streams. Finally, in 1985, the legislature passed Act Act 1051, providing for interbasin transport of waters under the jurisdiction of the ASWCC. Regulations governing such transfers are currently being drafted.

The Arkansas Soil and Water Conservation Commission can provide oversight for conjunctive use in the state. Both ground and surface water matters fall under the jurisdiction of this single state agency.

EFFECTS OF STRATEGY IMPLEMENTATION ON INDIVIDUAL WATER USERS

If a sustained yield/conjunctive use strategy, as discussed above, is implemented at some time in the future in Arkansas, what is the impact of such implementation on individual water users? Table V is a logic table approach to estimating the possible changes in groundwater and diverted river water use in a cell following strategy implementation. It should be mentioned that although the table describes annual water use, the approach is adaptable to smaller time steps as well. Variables (defined, with acronyms, beneath the table) which are considered include: water need, sustainable groundwater withdrawal volume and unit cost, and the volume of divertable surface water and cost. The impact on water users within a cell for each of the six situations covered by Table V are as follow.

a. Total need is less than sustained groundwater availability (as calculated by a sustained yield planning strategy), and since available surface water costs more than groundwater, the district would expect the user to meet total needs with groundwater. If it does not matter to the district whether someone uses less groundwater than is available (GA), then there will be no charge or rebate for not pumping at least that amount.

b. Total need is less than groundwater availability, and since no surface water is available, total needs will be met by groundwater.

c. Total need is less than the combined availability of groundwater and surface water. Available surface water does not cost more than groundwater. If the district does not care whether someone pumps less than GA, then as much surface water as is available will be used, as long as it does not exceed total need.

d. Total need is greater than groundwater availability, but less than the sum of gw and surface water availability. The cost of available surface water is greater than cost of groundwater. The maximum sustained availability of gw will be pumped and the rest of the need will be provided by sw.

e. Total need exceeds total availability, even though both groundwater and surface water are available. All available groundwater and surface water will be used. There is a necessary reduction in use of water from these two sources by the amount of shortfall.

f. Total need exceeds availability of groundwater. No surface water is available. There is a necessary reduction in water use.

Table V represents one possible set of outcomes of strategy implementation. Other outcomes are possible. To some extent however, Table V is generally applicable. It assumes that, when offered a choice, users will prefer to use the most inexpensive source of water. Since water management districts commonly have some control over water prices, taxes and rebates, a district can influence the use of one source of water in lieu of another (Peralta, A., et al, 1985).

SUMMARY

Groundwater and surface water regional models can be created to develop water use strategies that maximize achievement of predetermined regional objectives. In addition, the water use strategies developed by such planning models can:

- assure the sustained availability of groundwater;
- make best use of surface water resources while they are available for recharge to an aquifer or for diversion to riparian or nonriparian lands; and
- successfully coordinate the use of groundwater and surface water resources that hydrologically interact with each other.

Implementing a sustained yield groundwater management strategy that can sustain approximately the same amount of pumping year after year at each pumping location will ultimately result in the development of a 'steady-state' water table, piezometric or potentiometric surface. Let 'potentiometric surface' refer to the water table or piezometric surface. This optimal steady-state potentiometric surface is a 'target' surface that, when properly designed, assures:

- adequate saturated thicknesses for existing or planned wells;
- adequate saturated thickness to permit additional groundwater pumping in time of drought;
- hydraulic gradients which will appropriately restrict groundwater contaminant movement;
- hydraulic gradients which will cause appropriate water movement between the aquifer and connected aquifers or streams; and
- hydraulic gradients which will cause appropriate water movement across legal or institutional boundaries.

The bad news is that some water users adhering to a particular water management strategy may expect to have to change their water use habits. If adequate supplies exist, they may still have the same total annual volume of water available for use. In lieu of groundwater however, users may need to utilize diverted river water when it is available. A water management agency may affect the decision of the water users through economic incentives and disincentives.

In summary, water users adhering to an appropriate sustained yield groundwater management strategy should enjoy some degree of protection from successful litigation charging 'unreasonable use'. Furthermore, the use of diverted surface water can be coordinated with the sustainable use of groundwater to maximize the total use of available water. Fortunately, there is not now any major legal impediment to conjunctive ground and surface water use in Arkansas. It is hoped that future acts of the legislature, courts and administrative agencies will continue the present trends.

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