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ABSTRACT

Linear quadratic control models were utilized to analyze problems of conjunctive use of surface and groundwater in two California settings: (1) Yolo County, where a finite element hydrologic model was developed to provide physical data for an economic model, and (2) Kern County where groundwater overdrafting has been a long standing issue.

The principal thrust of the Yolo study was to determine the economic efficiency of spatial surface and groundwater allocations and the efficiency of intertemporal groundwater decisions, given the common property problems arising from uncontrolled groundwater use.

The Kern study had two primary thrusts: (1) to model groundwater demands and supplies and determine the optimal steady state depths of water tables in various areas and the factors influencing the optimal steady state, and (2) to model water quality linkages with quantity in order to derive implications for efficient water allocation, management, and control.

Study results show clear evidence of significant resource misallocation of water both spatially and temporally. Severe impediments to efficient water mobility exist in legal and administrative allocation processes. Some control over groundwater use is shown to be needed and some state policy governing groundwater use is recommended. Implementation is required, however, only in a limited number of critical groundwater basins in the near future.

JUSTIFICATION OF WORK PERFORMED

On the one hand, with restrictions in new supplies, and increasing demand for agricultural, municipal, and industrial water in California, the scarcity values of water is expected to increase sharply in the future. On the other hand, currently the prices, however, paid by agricultural users of water are based on rules only vaguely related to the costs of delivering water to the ultimate users under riparian and prior-appropriation legal doctrines. Often long term contracts are utilized, and under inflationary conditions the fixed prices do not change with movements in general price levels. This basis of water pricing leads to wide variations in the effective price of water, both spatially and temporally, leading to inefficient allocation of the water resource among users and among time periods. These pricing methods also impede the mobility of water by reducing the trading of water rights among water districts and even the renting of water within a given year. Lack of controls on groundwater pumping produces a situation where the scarcity value of the groundwater stocks is understated and water is pumped if the value of water is greater than the variable pumping costs. The results can be over-utilization of groundwater reserves and excessive investment in wells, pumps, pipes, and distribution and drainage systems.

These conditions, leading to inefficient water development and allocation, require a search for policy measures that might mitigate the economic misallocation of water. We need to know empirically how severe this misallocation is and what improvements can be achieved by policies that are designed to alleviate the water mobility problem and the groundwater common pool problem described above. Of course, simultaneous consideration of surface and groundwater use issues leads us to a conjunctive use problem that has both spatial and temporal dimensions. The foregoing justification statement is a sufficient rationale for a description of study methodology and research results which follows.

METHODOLOGY, STUDY RESULTS, AND PRINCIPAL FINDINGS

It will be convenient to report the overall study results by discussing each component separately.

Yolo County Conjunctive Use Study

The objectives of the Yolo County Conjunctive Use study were to:

(1) Formulate a mathematical model of a groundwater system such that the physical changes resulting from conjunctive use of surface and groundwater can be forecast and used as a basis for an economic analysis

(2) Analyze the expected future demand and supply interrelationships between rural-urban environments and economies with respect to conjunctive use of ground and surface water, land, and energy.

(3) Determine the optimal intertemporal allocation of the water supply as an integrated whole and determine the optimal allocation among classes of users for each future time period.

(4) Analyze the institutional setting surrounding the current allocation of water supplies, and note policy options available to change the institutions so as to move toward an efficient allocation between users.

The first objective was met by the construction of a regional, two-dimensional hydrologic flow model which utilized finite element techniques. The advantage of using finite element analysis in monitoring and analyzing aquifer flows became evident when attempting to model irregular geographic boundaries and variables such as natural recharge, various pumping rates, and heterogeneous aquifer properties.

A general algorithm was developed to handle both confined and unconfined aquifer flows. The model was verified by comparing simulated model results with known hydrologic data from the area.

Unconfined and confined groundwater flow analysis was employed to simulate the hydrodynamic response of the Yolo County aquifer systems. The Galerkin time step scheme formulation was found applicable for small time steps. Based on minimization of differences between recorded and computed groundwater levels, the confined analysis using reliable constant transmissivity values is regarded as the most appropriate model for the aquifer systems.

To achieve objectives 2, 3, and 4, the hydrologic model described above was utilized by the economists on the project to construct a hydrologic-economic model that could answer questions relating to efficient resource allocation. The Yolo County aquifer was divided into six basins, each hydrologically connected to the others by the hydrologic model. It so happens that the hydrologic boundaries of the Yolo County aquifer are almost identical to the political boundaries and, thus, the aquifer could be considered as a closed hydrologic system. This greatly facilitated the articulation of economic and physical data.

The economic framework utilized was a linear quadratic control model (LQCM) from which optimal trajectories of spatial and temporal water allocations and aquifer stock values are obtained. The LQCM contained hydrologic and economic components.

The economic component was composed of a derived demand model for water in various agricultural uses, a stock opportunity cost model that allowed valuation of groundwater stocks, and an urban demand model that estimated projected urban water needs. The derived demands for water applied to agricultural crops were obtained from a linear programming model. The stock values were derived from the linear quadratic control model.

The LQCM also maximized the values of the economic component of the model subject to the constraints imposed by the hydrologic component. The welfare function maximized was the sum of regional consumer and producer surplus associated with water use through time. The optimal control model estimated the marginal values of the water held in the aquifer for various time periods under varying rates of pumping. These values, of course, are opportunity costs; i.e., they must reflect the present value of the highest future use that is foregone if water is used in the present. Economists call these values, user costs. Of course, if user costs exceed marginal water values in current use, it indicates that the aquifer is being utilized too intensively, exactly the situation that will result if groundwater is a common property resource and there are no pumping restrictions.

The empirical results are very significant. Marginal values of water in agriculture uses in the base period (1977) vary significantly among the six basins (from \$2.44 per acre foot to \$61.13 per acre foot) indicating significant potential for efficient spatial reallocation. The problem is the restrictions on water mobility imposed by the legal and administrative structure which prevents water transfers. The user costs (1977) vary from \$12.23 to over \$100 per acre foot, indicating both spatial and temporal misallocation (the latter because user costs are higher than marginal values). Obviously, significantly higher economic returns could be captured by water users if pumping from the aquifer were limited to the socially optimal quantity where the welfare functions were maximized.

The results also clearly show that the degree of aquifer overuse is not the same for all six basins. In fact, two of the six basins in the County were actually using less groundwater than was optimal. Another important study finding is that as assumed energy prices increase, the model reveals how much the quantity of water pumped from the aquifer should decline if use is optimal.

Given that uncontrolled pumping leads to suboptimal utilization of groundwater aquifers, two control mechanisms were studied to determine which would be most efficient. The pro-rata quota method attacks the common pool problem by adjudicating annual groundwater quotas to overlying landowners. A severance pump tax can also be used to overcome the common pool problem by forcing the water users to pay for the damage inflicted on other pumpers, thus, internalizing external common property costs. Quota-setting imposes a tighter constraint on the resource than does taxation and transfers the decision on how much to pump from the private user to some central agency. In any case, the study shows that the tax is a more economically efficient way of restricting pumping to the optimal level than is a quota since the objective function has a higher value.

The implications of the Yolo County study are pervasive and far-reaching. If differences in the value of water in a single county and for only agricultural uses are very large as the study clearly shows, one can only imagine how large they might be across a large state like California and for a multitude of industrial, recreational, and domestic as well as agricultural uses.

Kern County Study--Empirical Assessment of Water Pricing Policies

The objectives of this part of the study were to:

(1) Empirically calculate the derived demands for surface and groundwater for 14 homogeneous agricultural production regions in California.

(2) Use the empirical derived demand elasticities for ground and surface water to show the feasibility of using demand pricing systems to allocate state water resources.

(3) Empiricise an economic intertemporal model of ground and surface water use in a region of several water districts.

(4) Use the intertemporal regional model to investigate empirically the value of pricing systems in allocating water under shortrun drought-induced supply constraints.

A mathematical optimization model of California agriculture developed at the University of California, Davis, was modified to yield the derived demand functions for ground and surface water. Significant improvements in previous models are: a quadratic objective function that accounts for demand effects of crop changes; disaggregation of the state into 14 homogeneous production regions with two alternative soil types per region; specific recognition of both ground and surface water availability in each region; and conjunctive demands for ground and surface water.

The model required elaborate cost data. Almost 1,200 cost budgets have been developed for Kern County crops. This has been a huge task and was greatly facilitated by the use of Cooperative Extension's Budget Generator, a computerized method of estimating costs. The model was designed to handle 42 crops for each of 21 water districts on two soil types.

Once again, the empirical results are very revealing and are sometimes contrary to prevailing views. Five principal conclusions can be drawn from the empirical analysis:

(1) Overdrafting groundwater in many cases is socially beneficial in that benefits exceed costs, but sooner or later will reach a point where the long-term costs of overdraft will exceed the short-term benefits in present value terms.

(2) The critical stocks of groundwater at which overdrafting changes from a process that yields economic net benefits to one that produces net costs is sensitive to the relative prices of pumping power and agricultural products. The trends over the past seven years and next foreseeable ten years have added greatly to the user cost of groundwater stocks.

(3) Groundwater levels and pumping costs in the San Joaquin Valley have reached the point where it is essential that workable management basins be defined and analysis undertaken to determine whether or not further overdraft of aquifers will be costly to water users.

(4) Groundwater management plans should not require that basins, which are shown by competent analysis to be many years away from reaching the socially optimal steady state depths, be prevented from overdrafting or spend large sums of money on elaborate regulation programs.

(5) Many areas in the San Joaquin Valley appear to be rapidly approaching the critical steady state point, and for their own long-term economic and social benefit should swiftly implement effective and equitable regional groundwater management.

A significant extension of the Kern County study involved water quality considerations. Where the supply of irrigation water is either solely groundwater or conjunctive use of surface and groundwater, the optimal allocation of water quantity is inextricably linked over time with attempts to minimize the net damages produced by quality degradations via salinity build-up. Thus, the linkage between quantity and quality management strategies is implicit. In the conjunctive use situation, the removal or regulation of salinity in the root zone can usually only be achieved by deep percolated leaching or by export from the basin into drains and sinks. If substantial surface runoff is employed, the stocks of groundwater will be depleted more rapidly. However, the alternative and more common approach of leaching and deep percolation does not deplete the stock of groundwater but does increase the salinity of the groundwater stocks. If the irrigation system is closed without significant water export, depletion of the groundwater reserves also results in an increase in their salinity.

Thus, an optimal analysis of a region prone to salinity problems should consider the trajectory of optimal groundwater pumping policies, the value of additional imports of low salinity surface water to the region, the cost of salinity in the root zone of soils, the cost of various levels of salinity in groundwater stocks, and the conflicting costs of surface runoff (positive from improvement of quality, and negative from the reduction in quantity available for plants).

An optimal control model was developed that incorporated these considerations. The objective function assumed social benefits would be a maximum when the stream of discounted net benefits to the overlying urban and rural water users was maximized. A linear quadratic control problem was formulated and solved as a quadratic program. The model was applied to 214,000 acres in Kern County at the Southern end of the San Joaquin Valley.

Runs of the model varied discount rates, supplies of surface water to the region, energy prices, and rates of pumping from the aquifer. The time period chosen was 80 years. Significant findings are as follows:

(1) When confronting a lower discount rate, the model yields a social decision that sacrifices actual crop production in the present in order to secure a better quality groundwater resource for use in the future.

(2) Increasing surface water imports into the region reduced the pumping quantities from the aquifer over the entire time horizon, consequently leading to an increase in groundwater stocks. Soil salinity levels are also lower over the horizon, but the leaching process is accelerated and the groundwater salinity level increases.

(3) Increasing energy prices shows the largest effect among all the alternatives analyzed on the volume of groundwater pumping, resulting also in the largest groundwater stock accumulation. Clearly, as energy prices increase, current production should be sacrificed in order to reduce pumping costs and increase the water table. In terms of salinity, the optimal strategy consists in keeping lower soil salinity levels over the horizon, while the groundwater salinity accumulation is slightly larger.

As in the Yolo County study, the costs of operating a groundwater aquifer without controls on pumping were estimated, and a pump tax was computed that would reduce pumping to the socially optimal level. These taxes ranged from $2.55 per acre foot to $5.95 depending on the scenario assumed in the variables discussed above.

The model also yielded an estimate of the value of recharging one unit of salt free water into the aquifer, purely in terms of quality; $1.21 per acre foot. How much would society be willing to pay to reduce soil salinity on one acre by 10 percent? The answer is $6.12 under current irrigation technology and $10.41 for a more efficient irrigation system.

Finally, what would be the net benefits from a tile drainage system removing high salinity water? Given that soil salinity would be reduced, the salt load reaching the aquifer would be reduced, but the future stock of groundwater would also be reduced. The net gain is $13.23 per acre foot of annual drainage capacity in the system.

RECOMMENDATIONS

Recommendations growing out of this project are of two kinds: (1) recommendations for further research, and (2) recommendations for policy and institutional change.

Further Research Needs

1. Using conceptual and empirical techniques developed in this study, analysis is needed in either geographic areas to determine:

(a) marginal values of water in various uses in order to determine how efficient water allocations are.

(b) user costs of groundwater stocks.

(c) steady state optimal depth for groundwater tables.

(d) marginal cost functions for new water supplies including groundwater pumping.

(e) the taxes on groundwater use that will induce optimal quantities of water pumped and optimal groundwater quality.

Institutional Change and Policy

1. Determine optimal boundaries for water management districts, especially those responsible for managing groundwater aquifer.

2. Ways must be sought to permit greater mobility of water. Riparian rights and pre-1914 rights should be quantified in the same manner as appropriative rights giving greater impetus to water transfers. Giving surface water ownership rights to individual users rather than to water districts would improve incentives for water exchanges and transfers.

3. Invoke a system of water levies or taxes on groundwater pumped from common property aquifers. This will provide incentives for water users to pump optimal quantities and maintain optimal groundwater quality.

4. Perfect property rights in groundwater to facilitate efficient use, security of tenure, and possible transfers where efficient. Taxes could be utilized on each unit pumped for export to compensate other basin users for externalities created by transfers.

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