AN ANALYTICAL SYSTEM FOR THE EVALUATION OF LAND USE AND WATER QUALITY POLICY IMPACTS UPON IRRIGATED AGRICULTURE

by

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ABSTRACT

The economic and environmental impacts of nonpoint pollution control policies being developed under the Federal Water Pollution Control Act Amendments of 1972 are required to be estimated by that law. A methodology is developed that specifies the relationships between land use and quality, irrigation practices, water quality and the benefits and costs of alternative policies. The methodology involves systematically collecting and organizing data, specifying physical and economic relationships and estimating environmental and economic changes that result from these policies. The analytical system is comprised of four subsystems which are interrelated through the supply and demand of agricultural commodities and resources. The demand for regional commodity production is projected from estimates of changes in population, income and U.S. trade policies. From these demand projections, regional commodity supply response and the marginal values of resources are estimated from a regional linear programming model. An optimal control model predicts the changes in land use over time in response to changes in commodity demands, technological change, resource supply and policies. The estimates of regional commodity and resource supplies are used by a location specific linear programming model that is sequentially linked to a mass balance hydrology model to project the amounts and quality of return flows.


INTRODUCTION

Resource economists and planners have concluded that water quality regulations must be coordinated with water resource development and land use planning to achieve a better allocation of our natural resources. Smith and Krutilla (1979) have stated the need for identifying the interdependence between the economic and physical systems in order to determine the effect of public policy decisions on natural resource use and environmental quality (p. 406). The opportunity to integrate resource development and environmental protection policies currently exists in the U.S. Water and related land use planning is required under the Water Resources Planning Act (PL 89-80), the Watershed and Flood Prevention Act (PL 83-566), the Colorado River Basin Salinity Control Act (PL 93-320) and the Federal Water Pollution Control Act Amendments of 1972 (PL 92-500). PL 92-500 requires water quality management planning on two major levels: (1) river basin water quality management planning conducted by the States and (2) areawide waste treatment management planning (Section 208) to be conducted by either regional agencies or States.

Specifically, Section 209 requires that Level B basin plans that integrate all aspects of past and current resource planning efforts be prepared. This requirement will be accomplished within the structure of Section 208 that requires each state to formulate an areawide waste treatment management plan. Each plan will include; (1) the identification of agriculturally related nonpoint sources of pollution and (2) the specification of procedures and methods to control, to the extent feasible, such sources. These control procedures are termed, "Best Management Practices" (BMP). Under Section 305, each state is required to develop estimates of the environmental impact and the economic and social costs and benefits associated with attainment of the objectives of Public Law 92-500. In addition, each state must maintain a continuing planning process consistent with the provisions of the Act to insure that the initial plan formulated under Section 208 remains effective under changing environmental conditions.

Subsequent amendments to PL 92-500 authorizes the Administrator of EPA to enter into agreements with other Federal agencies to utilize their authorities and programs to support the development and implementation of water quality management plans. Traditionally, most agricultural programs have been conservation or production oriented. The extent that past conservation and production practices will become "best management practices" is a subject of current debate.

At the present time, a clear set of alternative "best management practices," implementation procedures and evaluation criteria do not exist. The U.S. General Accounting Office (1978, p. 30) concluded that:

"Planning is not being done comprehensively under Section 208 of Public Law 92-500 as envisioned by the Congress. Water quality management planning needs to be comprehensive if the Nation's water quality problems are to be solved in the most cost-effective manner."

This criticism is indicative of a lack of a planning structure and the
need for an analytical methodology for developing and evaluating resource use and environmental plans.

The objectives of this paper are to: (1) suggest a set of evaluation criteria; (2) derive a theoretical basis for an integrated resource use and water quality analytical system and (3) present a methodology to evaluate resource use and water quality policies in an irrigated agricultural region.

EVALUATION CRITERIA

The approval of the Section 208 plan and the related BMP will depend on several criteria. The approval mechanism provides organized groups and individuals with the opportunity to participate in the final review of the plan. That review process is expected to require diverse sets of information. The following criteria were suggested by Bower, et al., (1977) specifically for evaluating alternative environmental management strategies.

Environmental or Physical Effects

The degree to which an environmental strategy can improve the overall quality of resources is the ultimate criteria. The quality of resources will affect other physical conditions such as improved wildlife habitats, outdoor recreation opportunities or the opportunities for alternative uses. Measuring the quality and quantity of return flows and their spatial distribution prior to being incorporated with the receiving waters would be an appropriate measure of control method effectiveness but it would not determine the degree of improvement in water quality. The relationship between changes in irrigated agricultural practices and the quantity and quality of irrigation return flows is not completely known for a very broad set of physical conditions. Therefore, there is uncertainty in determining the effectiveness of BMP's. Even less is known about the relationship between quantities and qualities of return flows, overall water quality, and damages to fisheries, wildlife or persons using those receiving waters. These relationships need to be measured before control strategies can be correctly evaluated.

Economic Effects

Direct benefits from improved water quality can be measured in reduced water treatment costs, increased value of a fishery, reduced medical costs, and reduced damages to property. Direct costs are those incurred by farmers as a result of control methods. These include the costs of capital, labor, land, management, water and reduced production should it result from control methods. Other direct costs include the cost to the public agency of providing facilities to reduce return flows or to improve the assimilative capacity of the environment.

The modern industrial economy is highly interdependent. Reductions or expansions in a given industry will result in changes in the amount of resources purchased from other industries and supplied to other industries. Depending on the degree of interdependence, the indirect effects can exceed direct costs and benefits to a single industry in terms of income, employment and resource use.
Persons or firms benefiting or bearing the costs of a pollution program should be identified by geographical area or socioeconomic group. Horner and Dudek (1977) concluded that increasing the cost of irrigation water to reduce irrigation return flows reduced the income to small farmers proportionately more than large farmers. Bower, et al., (1977) characterize the distribution of benefits and costs as the most important physical and economic effect of pollution control. However, measurement of the distributional effects of public policies is difficult due to the confidential nature of personal income and asset data.

Institutional Effects

Implementing control strategies usually requires additional accounting, monitoring, reporting, supervision, enforcement and management. These additional costs vary substantially according to the type of control method selected and they are usually borne by public agencies and irrigators alike. The importance of administrative costs is usually not considered in deciding on a course of public action. In some cases, the public and private administrative costs of a program may exceed the public benefits derived from the program.

An effective control strategy must also be flexible enough to accommodate changing economic and physical conditions. Included in this criteria is the ability of the method to self adjust to changing conditions. The ability of one control method to be applied to various pollution parameters and activities is a desirable characteristic. The procedural ease of adjustment and application is also important. For example, a permit system applied to irrigation return flows requires the considerable effort of filing applications and establishing monitoring positions.

The 208 plans require approval from a diverse set of interest groups. Each interest group representative will probably weigh the effects of each BMP on the goals of the interest group. This approval process suggests that compromise BMP's will probably result. The politics of governments may also be important. The responsibility for Sacramento - San Joaquin River Delta water quality is a case in point. Although the Bureau of Reclamation and the State Water Project use the Delta to transport water to the San Joaquin Valley and Southern California, the Bureau does not accept responsibility for maintaining the level of quality as the State does. In addition, the institutional arrangement and legal framework may not exist to allow some control strategies to operate. The establishment of new institutional structures represents an important political decision requiring general support of the public. The last, but certainly not the least, political consideration is the acceptance of the program by the general public.

OPTIMAL NATURAL RESOURCE ALLOCATION IN IRRIGATED AGRICULTURE

While the philosophical underpinnings of the concern for natural resources has been highly developed, little effort had been devoted to the development of a quantitative economic theory of conservation. However, Burt and Cummings (1970) set out a general theory for the intertemporal allocation of natural resources from which preceding individual resource studies could be derived as special cases. In particular, both production
from and investment in natural resources are simultaneously optimized over a social planning horizon. However, the particular agricultural resource problems of salinity, drainage, irrigation return flows and the conversion of land to nonagricultural uses are more appropriately analyzed from a narrower resource characterization. Two additional works (Cummings (1969) and Cummings and McFarland (1974)) provided helpful insight to the specification of the current model. The current model approaches the set of land and water resource problems with the aid of the economic theory of exhaustible resources while the physical problems of salinity and drainage are characterized as problems of conjunctive management. Finally, a recent contribution by Fisher, Krutilla, and Cichetti (1972) further characterized the resource conversion or development problem.

Characterization of Land Resource Use-Stocks

The land resources of the study area may be categorized according to numerous criteria, but the distinctions of use and productivity differences are most germane to a consideration of long-run agricultural productivity. In particular, the land resources have been grossly partitioned into four use classes: idle, nonperennial, perennial and urban. Idle lands in general include those lands devoted to wildlife habitat, grazing of the natural grassland biome, and other extensive uses which do not require substantial transformations of the natural landscape. Nonperennial and perennial agricultural lands are those irrigated areas producing crops. Urban lands include residential, commercial, industrial, and other intensive uses involving substantial capital investment. Productivity differences among the land resources have been denoted by two categories: prime and nonprime. The basic assumption underlying the general dichotomization of land resources is that prime and nonprime stocks are distinguished on the basis of natural physical criteria which cannot be abrogated through management or investment.

The basic dynamic relationships among land uses in the regional model are contained in the equations of motion - first order difference equations which explicitly describe how the system changes over time. The general equation of motion describing the intertemporal flows between land resource use-stocks is then:

\[ X_{it+1} = X_{it} + f_i(X_{jt}, U_{kt}) \quad \forall \quad i=1, \ldots, m \]
\[ j=1, \ldots, m \]
\[ k=1, \ldots, n \]
\[ t=0, \ldots, T-1 \]

The state variables \( X_{it} \) represent the quantity of the \( i^{th} \) land resource use-stock at time \( t \) and as such describe the state of the system at that time. The function \( f_i(X_{jt}, U_{kt}) \) gives the net rate of conversion to the \( i^{th} \) use-stock from the \( m \) use-stocks during period \( t \). The variables \( U_{kt} \) are control variables - elements of the system which are subject to manipulation by decision-makers and affect conversions between states. Such controls may be explicit policy variables such as sign-ups under the California Land Conservation Act or the quantities of irrigation water delivered. Land resources are also subject to the usual capacity constraint:
\[
\sum_{i=1}^{m} x_{i t+1} = \sum_{i=1}^{m} x_{i t} = L \\
t=0, \ldots, T
\]  

(2)

where \( L \) is the fixed quantity of land in the study area of this productivity type. In addition, the initial distribution of land resources among the use-stocks at time \( t=0 \) is given as:

\[
x_{i0} = \bar{x}_{i0} \\
i=1, \ldots, m
\]  

(3)

States and of course nonnegatively defined.

**Irreversibility and Conversions**

An important feature of the characterization of use-stock flows is the concept of irreversibility which, while not explicitly articulated, underlay Krutilla's (1967) consideration of unique attributes of nature. The concept was first developed by Arrow and Kurz (1970) in application to the problem of optimal capital accumulation. They defined irreversibility as "a nonnegativity constraint on the rate of decumulation of capital" (p. 331). Fisher and Krutilla (1975) in a consideration of the economics of natural environments, significantly expand the application of the concept, aggressively exploiting its implications for resource development. The crucial aspects are the length of lag in adjustment to changes in demand, the existence of substitutes and/or technology for the production of substitutes for the transformed resource and the magnitude of the adjustment costs. In this model, the concept of irreversibility is applied to the case of the conversion of land resources from idle or agricultural uses to urban uses. Irreversibility stems from the magnitude of the required reversion costs and uncertainty as to the efficacy of the outcome. The irreversibility condition is then written as:

\[
f_{m}(x_{jt}, u_{kt}) \geq 0 \\
t=0, \ldots, T-1
\]  

(4)

where the \( m \)th state variable is urban use. Expression (4) is the simple requirement that the urban area either grow or remain the same.

Control variables are also subject to intraperiod constraints which define the vector of admissible values:

\[
h_{k}(u_{kt}) \leq b_{kt} \\
k=1, \ldots, n \\
t=0, \ldots, T-1
\]  

(5)

Expression (5) represents either institutional constraints on the possible levels of control action imposed by enabling legislation or it may define the physical maximum limit at which the policy or program could be potentially applied. For example, in the case of the use-value assessment program enacted in the California Land Conservation Act for prime agricultural land, the program's upper limit is the physical quantity of prime land. Controls are also required to be nonnegative.

**Salinity**

In differentiating land resources between the prime and non-prime categories, it was noted that specific resource problems remediable
at a cost could be included in the model. As has been previously discussed, the most severe resource problems affecting the long-run productivity of the agricultural economy of the San Joaquin Valley Basin are salinity and drainage, two interrelated phenomena. Following Cummings and McFarland, the process of salinization is represented as:

$$S_{it+1} = S_{it} + F_{it}(W_{lt}, Y_{lt}, Z_{lt}, K_t) + n_{it}$$  \[i=1,...,m \]

$$l=1,2$$

$$t=0,...,T-1$$

Equation (6) states that the salt accumulation in land class i in the t+1th period, S_{it+1}, is equal to the salt accumulated as of the tth period, S_{it}, minus the change in salt accumulation associated with water use (W_{lt}), water applied for leaching (Y_{lt}), the salt content of the water applied (Z_{lt}), and capital investments in salinity control (K_t). The function F_{it} while specific for each of the agricultural land classes in the study area, has as its arguments only water-related parameters. n_{it} represents the natural additions of salts. For each parameter, the l index describes the source of irrigation water, i.e., l=1 is surface water while l=2 represents groundwater.

Capital invested for the control of drainage, e.g., on-farm tile drainage installation, district-wide collection systems, master drains, etc., is given by:

$$K_t = c_k(U_k)$$  \[k=1,...,n \]

$$t=0,...,T-1$$

where c_k is the drainage cost function.

### Drainage

The change in the depth to groundwater between periods is given in the expression:

$$d_{it+1} = d_{it} + E_{it}(W_{lt}, Y_{lt}, C_{it}, \delta_{lt}, K_t)$$  \[i=1,...,m \]

$$l=1,2$$

$$t=0,...,T-1$$

the function E_{it} describes the net change in water table depth. The variable C_{it} represents the water-transmission properties of land class i at time t. The quantity of subsurface drainage flows, \delta_{lt}, enters the function E_{it} as a negative externality. In particular given the unique geology of the San Joaquin Valley Basin, i.e., the underlying impervious clay layer, increases in subsurface flows, ceteris paribus, result in rises in the water table.

### Surface Water Quantity

Given the institutional nature of the allocative mechanism for water and the operation of the California State Water Plan, the transition and
constraint equations are written specifically for the study area. Thus, for the quantity of surface water available for irrigation, we have:

\[ W_{1t+1} + Y_{1t+1} = W_{1t} + Y_{1t} + \alpha_{1t} \quad t=0,\ldots,T-1 \]  

which states that the amount of surface water available in period \( t+1 \) is the quantity available in period \( t \) plus any augmentations \( \alpha_t \), resulting from planned increments as a part of the State Water Project. Essentially, surface water supplies for irrigation are considered to be relatively constant with the possibility of discrete variations. The effective supply of surface water, however, can be adjusted by improvements in the efficiency of distribution and application systems, i.e.,

\[ W_{1t} + Y_{1t} \leq G_{1t}(K_{1t}) \quad t=0,\ldots,T-1 \]  

**Groundwater Quantity**

The secondary source of irrigation water is the pumping of groundwater from the confined and unconfined aquifers underlying the study area. The confined aquifer is the dominant source of supply providing about 75 percent of the total groundwater pumped. The intertemporal change in the stock of groundwater \( A_t \), is defined as:

\[ A_{t+1} = A_t - W_{2t} - Y_{2t} + R_t(e_t, W_{k_t}, Y_{k_t}, K_{k_t}) \quad t=0,\ldots,T-1 \]  

The function \( R_t \) measures the recharge of the aquifer. Increases in natural recharge from river and stream flows \( (e_t) \) and the aggregate applications of irrigation waters, \( W_{k_t} \) and \( Y_{k_t} \), are both assumed to have positive effects upon recharge for the aquifer. Capital invested in the efficiency of irrigation and application systems, however, may have a negative effect if the increments to effective water supply are committed to additional irrigated acres and not to an explicit groundwater recharge program. It should be noted that \( W_{2t} + Y_{2t} \) may be considered to be policy variables for the management of the aquifer. As with surface water, there is a constraint on effective supply:

\[ W_{2t} + Y_{2t} \leq G_{2t}(K_{2t}, A_{t+1} - A_t) \quad t=0,\ldots,T-1 \]  

with a synonymous interpretation. Expression (12) with the explicit inclusion of the change in groundwater stocks over time \( (A_{t+1} - A_t) \), however, recognized the possibility of a periodic necessity to deepen wells if the aquifer is in an overdraft condition. Further there is the possibility of increasing pumping capacity and thus the quantity available for irrigation and leaching in any one period. Lastly, as with the land resources, there is a total water constraint:

\[ \sum_{\ell=1}^{2} (W_{\ell t} + Y_{\ell t}) \leq G_{\ell t}(K_{\ell t}) + G_{2t}(A_{t+1} - A_t, K_{2t}) \quad t=0,\ldots,T-1 \]
Water Quality

The quality dimension of the water resources available to irrigated agriculture also requires specification. Quality is relevant because of its direct impact on the productivity of crops, its relation to the salinization process as evidenced in equation (6) and because it is the object of public policy (in particular, Public Law 92-500). Again following Cummings and McFarland, the change in water quality (measured by salt concentration) in the aquifer is given by:

\[ Z_{2t+1} = Z_{2t} + N_{2t} [R_t (e_{t, W_{lt}, Y_{lt}, K_{lt}}, S_{it})] \]

where the function \( N_{2t} \) measures the change in groundwater quality as a result of natural recharge, irrigation return flows, investments in distribution and application systems efficiency and salt accumulation. Since irrigation water supplies originating from surface sources are assumed to be constant importations into the basin, changes in the quality of water are the result of phenomena external to the study area. Thus we have:

\[ Z_{lt} = Z_{lt} \]

as a point estimate of surface water quality specified exogenously for each year. The specification of expressions (14) and (15) recognizes neither the intraperiod degradation of water quality faced by downstream users nor the possibility of blending waters from surface and ground sources to attain a prespecified water quality target.

The Objective Functional

Following numerous preceding resource studies (Burt and Cummings (1970); Cummings and McFarland (1974)), the intermediate function is specified as net social returns resulting from resource use at time \( t \), i.e.,

\[ I_t = B_t (X_t, S_t, \lambda_t, \omega_t, Y_{lt}, A_t, Z_{lt}, U_{kt}, K_t, K_t) \]

where \( I \) demonstrates the explicit dependence on the time-paths of the state and control variables in the pertinent time frame and where the vector arguments of the function \( B_t \) are as previously defined. It is assumed that the benefit function is appropriately concave, continuous and differentiable and that the necessary underlying production relationships exist. The objective functional \( J \) is then the sum of the present value net social benefits throughout the planning horizon:

\[ J \equiv \sum_{t=0}^{T} \beta^t I_t \]

where \( \beta \) is defined as \( 1/(1+\rho) \) where \( \rho \) is the social rate of discount. The problem facing society is the maximization of (17) subject to expressions (1) through (15).
The Optimal Control Problem

Given the mathematical statement of the problem and its explicit dynamic character, the problem of allocating scarce resources throughout a planning horizon is one of optimal control. The optimal control problem is the selection of time-paths for those admissible values of the control variables specified by the control set which when combined with the equations of motion yield the time-paths of the state variables describing the modeled system. All time-paths are selected according to the criteria specified in the objective functional. The resource planning problem under consideration will be described from this perspective.

For ease in exposition, the preceding set of constraints (1) through (15) is partitioned into aggregate constraint subsets and designated with a general notation. The first order difference equations describing changes in the state variables \(X_{it}, S_{it}, d_{it}, W_{lt}, Y_{lt}, A_{t}, W_{2t}, Y_{2t}, \text{ and } Z_{2t}\) over time will be represented by the following general form:

\[
X_{t+1} - X_{t} = f(X_{t}, U_{t}) = 0 \quad t=1,\ldots,T-1
\]

where \(X_{t+1}\) and \(X_{t}\) are \((p \times 1)\) column vectors and \(f(X_{t}, U_{t})\) is a column vector containing the scalar-valued functions which describe the changes in states over time as a function of the current states and the controls. The inequalities which explicitly define the feasible set of states for each time period \(t\) are in general:

\[
g(X_{t}) \leq a_{t} \quad t=0,\ldots,T-1
\]

in which \(g(X_{t})\) is a \((p \times 1)\) column vector of scalar-valued functions of state variables and \(a_{t}\) is a column vector of boundary points correspondingly dimensioned. In analogous terms, the admissible control set \(\{U_{t}\}\) is written as:

\[
h(U_{t}) \leq b_{t} \quad t=0,\ldots,T-1
\]

where \(h(U_{t})\) is a column vector containing scalar-valued functions of the \(r\) possible control variables and \(b_{t}\) is an \((r \times 1)\) vector of institutional constraints in period \(t\). The nonnegativity constraints on states are:

\[
X_{t} \geq 0 \quad t=0,\ldots,T
\]

The irreversibility condition is stated in expression (4). Finally, there are the initial conditions which may be generally represented as:

\[
X_{0} = \bar{X}_{0}
\]

where \(X_{0}\) and \(\bar{X}_{0}\) are \((p \times 1)\) vectors.
The Maximum Principle

Employing the compacted constraint definitions presented in expressions (18) – (22), and following Benavie (1972), the Lagrangian functional for the constrained optimization of (17) is:

\[
L = \sum_{t=0}^{T-1} \left[ I^n + \lambda_t f(X_t, U_t) - \lambda_t (X_{t+1} - X_t) + \mu_t [a_t - g(X_t)] \right]
\]

\[
+ \gamma_t [b_t - h(U_t)]
\]

where \( \lambda_t \) is a \((1 \times p)\) vector of costate variables and \( \mu_t \) and \( \gamma_t \) are appropriately dimensioned row vectors of Lagrange multipliers. The costate \( \lambda_t \) gives the marginal value of an additional unit of \( X_t \) over the remainder of the planning horizon while the Lagrange multiplier gives the marginal value of a one unit constraint relaxation for that period. In problems of this general form, terminal conditions are also usually specified. When omitted, the terminal values are taken to be identically equal to zero and the control problem is termed the Problem of Lagrange (Intriligator, 1971).

The control problem may be approached by either the calculus of variations, dynamic programming or the maximum principle. However, the inclusion of inequalities of the type in expressions (19) and (20) vitiates the use of the classical calculus of variations since variable parameters cannot satisfy such inequalities when the possibility of satisfaction as an equality is also presented (Pontryagin, et al., 1962). The maximum principle overcomes this difficulty and "by contrast to dynamic programming, it usually suggests the nature of the solution" (Intriligator, p. 344). Consequently, the characterization of a solution to the optimal control problem will be pursued via the maximum principle.

The first step in such a characterization is the specification of the Hamiltonian function. The Hamiltonian is defined as the sum of the intermediate function of the objective functional plus the inner product of the vector of costate variables and the vector of functions defining the rate of change of the state variables. The Hamiltonian, then, is formed by the first two terms within the bracket on the righthand side of equation (23), i.e.,:

\[
H(X_t, U_t, \lambda_t) = I^n + \lambda_t f(X_t, U_t)
\]

where \( I^n \) is the intermediate function previously defined, \( \lambda_t \), the vector of costate variables, is user cost and \( \lambda_t f(X_t, U_t) \) is the opportunity cost of changes in the states or the total user cost. As such, the Hamiltonian summarizes the present value of net social benefits directly resulting from resource use at time \( t \) as well as the opportunity cost of such use for each time period. Following Intriligator, the Lagrangian functional can then be rewritten as:
Consequently, the constrained maximization of the Lagrangian stated in (25) implies the maximization of the Hamiltonian in (24) for each period for admissible $U_t$ and for feasible $X_t$ which is the essence of the maximum principle (Benavie, 1970).

Cummings has expressed the view that the "extension of the classical calculus of variations by Optimal Control Theory is... analogous to the extension of the classical calculus by Kuhn-Tucker theory" (Cummings, p. 203). Then applying the Kuhn-Tucker theorem, the necessary conditions for a local maximum which the optimal trajectories $\{X^*_t\}, \{U^*_t\}, \{A^*_t\}$ must satisfy are:

\[
\frac{\partial L}{\partial U_t} = \frac{\partial H}{\partial U_t} - \gamma_t \frac{\partial h}{\partial U_t} = 0 \quad t=0,\ldots,T-1 \tag{26}
\]

\[
\frac{\partial L}{\partial X_t} = \frac{\partial H}{\partial X_t} + \lambda_t - \lambda_{t-1} - \mu_t \frac{\partial g}{\partial X_t} = 0 \quad t=1,\ldots,T-1 \tag{27}
\]

\[
\frac{\partial L}{\partial \lambda_t} = \frac{\partial H}{\partial \lambda_t} - (X_{t+1} - X_t) = 0 \quad t=0,\ldots,T-1 \tag{28}
\]

\[
\frac{\partial L}{\partial \mu_t} = a_t - g(X_t) \geq 0 \quad t=0,\ldots,T-1 \tag{29}
\]

\[
\mu_t \frac{\partial L}{\partial \mu_t} = 0, \quad \mu_t \geq 0 \tag{29}
\]

\[
\frac{\partial L}{\partial \gamma_t} = b_t - h(U_t) \geq 0 \quad t=0,\ldots,T-1 \tag{30}
\]

\[
\gamma_t \frac{\partial L}{\partial \gamma_t} = 0, \quad \gamma_t \geq 0
\]

The characterization of the solution to the control problem by the necessary conditions (26) - (30) is elucidated by consideration of the economic interpretation of these conditions. Inequalities (29) and (30) are the usual complementary slackness conditions. The p conditions in (28) state that the rate of change of the Hamiltonian with respect to a particular costate variable $\lambda_{it}$ with all other variables constant is the equation of motion $f_i(X_{jt}, U_{kt})$ which specified the change in the system between time periods measured in terms of the state variables as a function of the state and control variables. Since the costate variables are the dynamic analog of the Lagrange multipliers of static problems and since "to any dynamic economizing problem of allocation over time there corresponds a dual problem of valuation over time" (Intriligator, p. 352), the costate $\lambda_{it}$ is the
shadow price of the time path of state variable $X_t$ from $t+1$ to $T$, i.e., $(X_{it+1}, X_{it+2}, \ldots, X_{iT})$ which given the time path of controls $\{U_t\}$ and the value of the state at $t$ is determined by the equation of motion $f_i(X_{it}, U_{kt})$. Alternatively, following Benavie (1970), $\lambda_{it}$ may be thought of as the change in net social benefits associated with $(X_{it+1}, X_{it+2}, \ldots, X_{iT})$. Similarly, $\lambda_{it-1}$ is the marginal net social benefit associated with $(X_{it}, X_{it+1}, \ldots, X_{iT})$. Then an incremental exogenous change in $X_{it}$ may be decomposed into the sum of the changes in the Hamiltonian from period $t$ to $T-1$:

$$
\lambda_{it-1} = \frac{\partial H(X_{ti}, U_{ti}, \lambda_{t})}{\partial X_{it}} + \frac{\partial H(X_{ti+1}, U_{ti+1}, \lambda_{t+1})}{\partial X_{it+1}} + \ldots + \frac{\partial H(X_{T-1}, U_{T-1}, \lambda_{T-1})}{\partial X_{iT-1}}
$$

$$
\lambda_{it} = \frac{\partial H(X_{t+1}, U_{t+1}, \lambda_{t+1})}{\partial X_{it+1}} + \frac{\partial H(X_{t+2}, U_{t+2}, \lambda_{t+2})}{\partial X_{it+2}} + \ldots + \frac{\partial H(X_{T-1}, U_{T-1}, \lambda_{T-1})}{\partial X_{iT-1}}
$$

Subtracting (32) from (31) yields exactly condition (27), i.e., the rate of change of the Hamiltonian with respect to a change in the state variable $X_{it}$. This condition may be interpreted as a resource development rule. For example, convert land in period $t$ until the marginal net social benefit of conversion is just equal to the marginal cost of conversion over the remainder of the planning horizon. Condition (26) may be rewritten as:

$$
\frac{\partial L}{\partial U_t} - \gamma_t \frac{\partial h}{\partial U_t} = - \lambda_t \frac{\partial f}{\partial U_t}
$$

by substituting for $\frac{\partial H}{\partial U_t}$ and rearranging. Tile drainage should be installed until the marginal net social benefit of draining land is just equal to the marginal cost of drainage over the remainder of the planning horizon.

AN INTEGRATED PHYSICAL-ECONOMIC SYSTEMS ANALYSIS OF LAND AND WATER USE IN IRRIGATED AGRICULTURE

Although the theoretical framework is conceptualized as a dynamic optimization process characterized as a problem in optimal control, data requirements prevent the construction of such an analytical system to study all aspects of land use, water development and water quality policies. With respect to the San Joaquin Valley Basin, the number of states described in the theoretical model would number in the thousands. The application of the control approach to the complete problem would suffer from an obvious problem of dimensionality. Therefore, other static models with appropriate sequential and recursive techniques have been included in the methodology.

The economic information required for resource planning and evaluation can be discussed under the four interrelated headings of commodity demand, commodity supply, resource demand and resource supply. Given the planning setting, the necessary set of information and the analytical models to be employed, it is useful to see how the basic economic concepts of commodity demand and supply and resource demand and supply will be operationalized.
These concepts can readily be identified as flows of information between different components of the analytical system as indicated in Figure 1.

The demand for regional commodity production is projected from estimates of changes in population, income and U.S. trade policies. The production model determines the amount of land and productive inputs to achieve the projected level of commodity demand which in turn is effected by land use policy decisions. The specific location of commodity production and resource use is determined in the water quality model from which projections of the amount and quality of irrigation return flows result. Alternative water quality policies can be simulated within this analytical system to determine environmental and economic effects.

Land Use

The land use analytical system has three primary component models; a projections model, a regional linear programming model and a linear quadratic control model (see Figure 1). The rationale for this interactive amalgamation is two pronged. A very basic design criterion is a careful assessment of the system's attributes and processes that are being modeled. Agricultural firms are presumed to optimize their intertemporal wealth positions given the resources at their behest and the values of policy variables exogenously dictated to them. The regional model, on the other hand, presumes the existence of some rational central planning authority concerned with the level of social welfare generated by particular patterns of resource allocation. The role of this authority is to optimally set the levels of policy instruments available to it given the valuation of resources. Clearly, then, there is a process of bi-level decision-making in operation. The central authority optimally sets policies predicated upon the resource values established by firms. Firms perceiving these policy levels adjust their use and valuation of resources. The new resource valuation causes the central authority to re-examine its policy set and levels and make the necessary adjustments. Aggregate firm behavior is represented by the regional linear programming model while the analogue for the central authority is the linear quadratic control model.

Projections Model

In order to accurately portray changes in the irrigated crop economy of the subbasin between periods, projections of the rate of resource deterioration, differences in the availability of land resources (due primarily to urbanization), alterations of the effective supply of irrigation water, changes in technological coefficients, yields and the demands for crop commodities facing the region are needed.

Particularly crucial to the determination of resource problem effects is the projection of commodity demands. While there is a wide variety of projection approaches varying with the quantitative techniques employed, the area of interest and their ultimate application, the basic approach employed is that reported by King, Carter and Dudek (1977).

This approach consists of an interactive, man-computer, data based synthetic method of analysis whose elements are arithmetic, statistical and judgmental and which may be technically classified as a deterministic simulation. Essentially, projections of national demand are disaggregated
Figure 1. Integrated Land Use, Water Resource and Water Quality Analytical System
to the State or regional level through the projection of shares of national production as in Dean, et al. (1970). The principal shifters of the domestic component of national demand are population and per capita income (Dean and King, 1970), but trends in per capita consumption, presumed to capture changes in tastes and preferences, may also be included. The addition of projected export-import balances produces estimates of national demand requirements, i.e., given favorable economic conditions, no radical changes in price-cost relationships and the assumption of perfectly elastic supply, these are the commodity quantities which would have to be produced in order to satisfy the domestic and international components of national demands. Thus, these projections are conditioned upon the levels specified for key projection parameters -- population, per capita consumption, per capita income, exports and imports.

These national projections are then the points of departure in making State and/or regional projections. It is recognized that the translation of the complex interplay of forces comprising the national agricultural economy to a State level is fraught with difficulties. Ideally, to adequately portray these relationships would require a multiproduct, multi-region, multisector, intertemporal general equilibrium formulation of the economy. In lieu of this, the projection techniques employed attempt to capture the direction of economic forces that have favored regional shifts in the location of production and the effect of counterforces such as changing resource prices which tend to stabilize the system over time. The projection of shares of national production are based upon the region's historical share. The projected regional share of national demand requirements is then the projected regional demand requirements which are transformed, into price terms through price forecasting equations (see Figure 1).

One of the shortcomings of the presently constituted linear programming analysis is the reliance upon constant commodity prices. This equilibrium assumption is particularly limiting in analyzing resource productivity impairment in a region producing specialty crops and/or supplying a proportion of output significant enough to affect price. Quadratic programming as employed by Adams (1975) or separable programming as in Huang and Hogg (1976) overcome this liability. Another alternative, however, which did not require a restructuring of the existing model is to update the crop commodity prices in the objective function via regional price forecasting equations. McKusick (1973) postulated a general price forecasting model as:

\[ P_i = f(Q_i, Q_{iUS}, Q_{iIM}, Y, T) \]  

(34)

where:

\( P_i \) is the regional price of the \( i^{th} \) commodity

\( Q_i \) is the regional production of the \( i^{th} \) commodity

\( Q_{iUS} \) is the national production of the \( i^{th} \) commodity net of regional production

\( Q_{iIM} \) is the total imports of the \( i^{th} \) commodity
Y is an index of national total personal disposal income and 
T is a trend variable.

Various alternative combinations of these variables have been estimated using ordinary least squares regression and the results analyzed for significance and fit.

**Regional Linear Programming Model**

Commodity supply response is estimated by the Regional Production Model using the San Joaquin Valley Basin regional linear programming model (Figure 2). This model has been developed by the USDA California River Basin Planning Staff as part of an ongoing analysis of the water and related land resource problems of the area (McKusick, et al., 1973 and McKusick, 1974). The linear programming model was developed to analyze the impact of deteriorating drainage conditions on production patterns in the study area and the evaluation of program, policy or project measures designed to remedy the problem.

For the purpose of introducing some location specificity, the basin is divided into its component subbasins each of which is modeled by a separate linear program. Each subbasin is then further subdivided into an east and west side. For 30 principal crops, production activities were established for 18 soil groups, three drainage conditions and the four locations. Technological coefficients on an annual per acre basis are specified as yields, applied water requirements (which include estimates of the leaching requirement and embody an implied irrigation efficiency), harvest and nonharvest labor, nitrogen fertilizer and gas and diesel fuels. The objective function maximizes net agricultural crop returns to land management and risk subject to the availability of land resources by soil group, drainage condition and location, the availability of surface and groundwater for irrigation, labor, cropping pattern restrictions and the underlying production technology. In this particular form, the model optimizes crop production, resource use and investment in resources. Specifically, land drainage, land development and groundwater development activities are included.

Constraints (1) through (8) (Figure 2) differentiate land resources by soil group and drainage condition that are suitable and available for irrigated agricultural operations by their use in the base period. The first constraint set established by soil group and drainage condition exactly which land resources were developed and in production in 1972. All other lands have been inventoried and assessed for their development potential. These irrigable but unirrigated lands limit the extent of potential future irrigation development. Columns (4) and (5) in the tableau represent activities that allow for the installation of subsurface tile drainage in currently irrigated acreage. The land development activities are illustrated in columns (6) – (8). Rows (7) and (8) in the tableau provide the correspondence between the activities of the linear programming model and the agricultural state variables of the control model (see Figure 1). There is one such constraint for each of the state variables. It's these constraints which are parameterically varied to estimate the marginal values of land resources. The cropping pattern constraints (11) require that the mix of crop output in the optimal solution replicate the base period condition. These constraints
<table>
<thead>
<tr>
<th>ACTIVITIES</th>
<th>CROP ALTERNATIVES BY SOIL GROUP AND DRAINAGE CONDITION</th>
<th>LAND DRAINAGE</th>
<th>LAND DEVELOPMENT</th>
<th>CROPPING PATTERN</th>
<th>COMMODITY SELLING</th>
<th>GROUND-WATER DEVELOPMENT</th>
<th>WATER SUPPLY</th>
<th>INPUT SUPPLY</th>
</tr>
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<tr>
<td></td>
<td>Adequately Drained</td>
<td>Partially Drained</td>
<td>Poorly Drained</td>
<td>Adequately Drained</td>
<td>Partially Drained</td>
<td>Poorly Drained</td>
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<td>Price per unit of yield</td>
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<tr>
<td>Row Name</td>
<td>RBL Type</td>
<td>(1.)</td>
<td>(2.)</td>
<td>(3.)</td>
<td>(4.)</td>
<td>(5.)</td>
<td>(6.)</td>
<td>(7.)</td>
</tr>
<tr>
<td>LAND</td>
<td></td>
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</tr>
<tr>
<td>(1.)</td>
<td>Adequately Drained</td>
<td>≥</td>
<td>1</td>
<td>−1</td>
<td>−1</td>
<td>−1</td>
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<td>(2.)</td>
<td>Partially Drained</td>
<td>≥</td>
<td>1</td>
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<td>(3.)</td>
<td>Poorly Drained</td>
<td>≥</td>
<td>1</td>
<td>1</td>
<td>−1</td>
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<td>(4.)</td>
<td>Adequately Drained</td>
<td>≥</td>
<td>1</td>
<td></td>
<td>1</td>
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<td>(5.)</td>
<td>Partially Drained</td>
<td>≥</td>
<td>1</td>
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<td>(6.)</td>
<td>Poorly Drained</td>
<td>≥</td>
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<td>(8.)</td>
<td>Crop Yields</td>
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<td>y</td>
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<td>Average Crop Yields</td>
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<td>(11.)</td>
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<td>(12.)</td>
<td>Total Seasonal Water Use</td>
<td>≥</td>
<td>w</td>
<td>w</td>
<td>w</td>
<td>−1</td>
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<td>(13.)</td>
<td>Surface Water Sources</td>
<td>≥</td>
<td></td>
<td></td>
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<td></td>
<td>1</td>
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<td>(14.)</td>
<td>Groundwater Sources</td>
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<td></td>
<td></td>
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<td>(15.)</td>
<td>Groundwater Development</td>
<td>≥</td>
<td></td>
<td></td>
<td></td>
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<td>INPUTS</td>
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</tr>
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<td>(16.)</td>
<td>Labor</td>
<td>≥</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>−1</td>
<td></td>
<td></td>
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<tr>
<td>(17.)</td>
<td>Fertilizer</td>
<td>≥</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>−1</td>
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<td></td>
</tr>
<tr>
<td>(18.)</td>
<td>Gas</td>
<td>≥</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>−1</td>
<td></td>
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<tr>
<td>(19.)</td>
<td>Diesel</td>
<td>≥</td>
<td>d</td>
<td>d</td>
<td>d</td>
<td>−1</td>
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</tbody>
</table>

**FIGURE 2.** San Joaquin Valley Basin Regional Linear Programming Model
eliminate the necessity to impose individual crop acreage or production restrictions. These constraints are termed the average yield reality restraints. Given the myopic maximization criteria employed in linear programming, the differential productivities of soil groups and the varying net returns of the individual crops, it is necessary to require that the linear combination of cropping activities in the optimal solution produce a pattern of production and resource use consistent with that observed in the aggregate. In the absence of such a constraint, the most productive soils would be exclusively devoted to the highest value crops with resulting average crops yields significantly above those that actually occurred. Excluding the locational distinctions, there are three basic sources of water supply available for irrigation. These are surface water deliveries, groundwater pumping and the development of new wells. The possibility of groundwater development has been added to complement the potential to expand existing irrigated acreage. These constraints are represented as rows (13) to (15).

Optimal Control Model of Land Use

The regional linear program will be used to generate the marginal values for land resources. These marginal values are the basis of land use valuations within the control model. The optimal control model will be used to predict the dynamic changes in land use for the valley in reaction to changes in agricultural commodity demands, population, resource productivity and availability and environmental and land use policies. The control model generates optimal land uses over time, the social values resulting from these allocations and the opportunity costs of changing those resource uses.

Specifically the control model predicts the availability of land resources for agricultural production which are required in the regional linear programming model. Projections of commodity demands from the system previously described are introduced into the LP and a new cycle of model interactions is initiated. In this manner, the process is repeated over the planning horizon with the result being a close approximation of the optimal patterns of land uses over time in the Valley (see Figure 1).

The objective function of the control model is of a familiar quadratic form:

\[ J = \sum_{t=0}^{T-1} \left( q'y_t + \frac{1}{2}y_tQy_t + r'u_t + u'_tRu_t \right) \beta^t + \left( q'y_T + \frac{1}{2}y_TQy_T \right) \beta^T \]  

where:

\[ q \] is an \((m \times 1)\) vector of land resource use-stock marginal value product intercept terms for \(t=0,\ldots,T-1\)

\[ Q \] is an \((m \times m)\) diagonal matrix of land resource use-stock marginal value product slope terms for \(t=0,\ldots,T-1\)  

\[ / \] Note that in the final term of the objective function, the \(q\) and \(Q\) terms are subscripted for the end of the planning horizon \(T\). These are the components of the terminal value functions.
$y_t$ is an $(m \times 1)$ vector of land resource use-stocks

$r$ is an $(n \times 1)$ vector of policy cost intercept terms

$R$ is an $(n \times n)$ diagonal matrix of policy cost slope coefficients

$u_t$ is an $(n \times 1)$ vector of policy levels

$\beta^t$ is the discount factor

The objective function measures the net social value of land resource use over time evaluated as the discounted sum of the total imputed values of the land resource use-stocks plus their economic rents minus the costs of policy actions over the planning horizon. For this subset of variables of the economic system being modeled, it is argued that this formulation of the objective function is a reasonable measure of social welfare.

Only those linear constraints known as the equations of motion need to be added to complete the structure of the model. The objective function is optimized subject to:

$$y_{t+1} = Ay_t + Bu_t + Cx_t + d$$

where:

$A$ is an $(m \times m)$ matrix of coefficients on lagged state variables

$B$ is an $(m \times n)$ matrix of coefficients on control variables

$x_t$ is a $(p \times 1)$ vector of uncontrollable exogenous variables

$C$ is an $(m \times p)$ matrix of exogenous variable coefficients

$d$ is an $(m \times 1)$ vector of constant terms

The addition of (35) completes the linear quadratic control model (LQCM).

Prior to defining the expected relationships between state variables over time, it is necessary to digress and consider the precise form of the land use data. Each of the entries in Table 1 represent the inter-temporal flow conversions between land resource use-stocks. The hypothesized relationships between state variables in stock form are presented

2/ This is the $q'y_t + \frac{1}{2}y_t^TQy_t$ component of the objective function. By geometric argument it is easy to show that this quantity is the sum of the areas under the marginal value product relationships to the left of any nonnegative $y_t$ values.
<table>
<thead>
<tr>
<th>Time $t$</th>
<th>Prime Idle Adequate</th>
<th>Prime Nonperennial Adequate</th>
<th>Prime Perennial Adequate</th>
<th>Prime Urban</th>
<th>Nonprime Idle Adequate</th>
<th>Nonprime Nonperennial Adequate</th>
<th>Nonprime Perennial Adequate</th>
<th>Nonprime Urban</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
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<tr>
<td>Prime Nonperennial Adequate</td>
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<td>Prime Nonperennial Poor</td>
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<tr>
<td>Prime Urban</td>
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<td>Nonprime Idle Adequate</td>
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<td>Nonprime Idle Poor</td>
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</table>

**TABLE 1. State Variable Intertemporal Relationships**
in Tables 2 and 3. There is a substantial and increasing drainage problem in the San Joaquin subbasin that poses real limitations upon the productivity of land resources in agricultural uses. Therefore, in considering a productivity typology of land resources it is insufficient to dichotomize soils into just a prime or nonprime delineation. In order to accommodate this particular resource problem in the characterization of land resources, two additional productivity categories are added—namely adequately drained and poorly drained. Thus there are four basic land uses, two qualitative representations of differing soil quality and now two discrete categories to describe the drainage condition. The union of these three basic sets of characteristics yields fourteen different variables which can be used to describe the state of land resources within the subbasin.

To simplify the portrayal of the conceptual basis of state variable relationships, suppose that there are only two basic land states—idle and developed. In examining the changes that may occur between time t-1 and t between these two states, there are four possible outcomes. Idle land in period t-1 may remain idle and be carried over as idle land in period t. Analogously, developed land at t-1 may remain in use into time t. Each of these outcomes represent carry-overs from t-1 to t, i.e., no use change occurs under either of these possibilities. In each case, the stock of land in a particular use would be expected to be related to the stock in that use in the previous period. Idle land at t-1 may, however, be developed in the interval between t-1 and t. Thus the stock of idle land at t will also be a function of the stock of developed land at t. Similarly land that is developed in t-1 could be abandoned and appear as idle land in t so that the stock of developed land at time t would be expected to be related to the stock of idle land in period t. From these two basic states and four outcomes, it is hypothesized that the level of a state variable in the current time period is related to its own level in the previous period and the current level of the other state. This explains the simultaneity exhibited in Tables 2 and 3.

The study area was divided into cells which are homogeneous by soil group. Each of these underlying soil groups was then classified according to the USDA Land Capability Classification system. Class I and II soils were designated prime, all others nonprime. Each cell was also placed into an adequately or poorly drained category based upon an assessment of the typical depth to groundwater in that cell. Aggregate land use data for each of the cells was collected. These observations were then employed in the estimation of the equations of motion.

3/ Since the prime/nonprime classification of soil resources is mutually exclusive, each of these sets will be treated as independent blocks of equations.

4/ In actuality, use changes would occur under either of these outcomes since the state variables are measured as stocks at discrete points in time. Since these intervals are approximately eight years long, it is conceivable that land could be measured as idle in t-1, be developed and then abandoned and be measured as idle again in period t.
<table>
<thead>
<tr>
<th>TABLE 2. Prime Land Resource Use-Stock Model</th>
</tr>
</thead>
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<tr>
<td><strong>State Variables</strong></td>
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<td>Prime Urban</td>
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<td>Prime Perennial Poor</td>
</tr>
<tr>
<td>Prime Nonperennial Adequate</td>
</tr>
<tr>
<td>Prime Nonperennial Poor</td>
</tr>
</tbody>
</table>

| Prime Idle Adequate                        |
| Prime Idle Poor                            |
| Prime Nonperennial Adequate                |
| Prime Nonperennial Poor                    |
| Prime Perennial Adequate                   |
| Prime Perennial Poor                        |
| Prime Urban                                |

| Control Variables                          |
| Set-aside                                  |
| Williamson Act                             |
| Tile Drain Installation                    |
| Ground Water                               |
| Surface Water                              |
| Property Tax Rate                          |
| Population Density                         |

<p>| Exogenous Variables                        |
| Exports                                    |
| Extent of Irrigation                       |
| Rainfall                                   |
| Depth to E-Clay Layer                      |
| Nonperennial Crop Prices                   |
| Perennial Crop Prices                      |
| Population                                 |
| Distance to Central Place                  |</p>
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<tr>
<th>Nonprime Idle Adequate</th>
<th>Nonprime Nonperennial Adequate</th>
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<th>Nonprime Perennial Poor</th>
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**Dependent Variables**

**State Variables**

**Control Variables**

**Exogenous Variables**

+ denotes endogenous variables
✓ denotes predetermined variables

**TABLE 3. Nonprime Land Resource Use-Stock Model**
Water Quality

Resource use—stocks and commodity prices are also utilized in the water quality analytical subsystem (see Figure 1). This subsystem consists of two specific models sequentially linked to simulate agricultural production and water quality changes that occur over time as a result of policy changes (Horner and English, 1976). Two location specific linear programming models derive an optimal cropping pattern, select water application technologies, specify water and fertilizer use and the resulting surface runoff for the San Joaquin and Tulare Subbasins. The production patterns derived in the linear programming model serve as data inputs to the physical model. The physical model estimates the subsurface vertical and horizontal water movements created by the irrigation activity. The costs for collection and disposal of return flows, the costs for installing tile drainage to relieve high water tables, and yield reductions from high water tables are also calculated by the physical model. The change in production costs are then adjusted in the linear programming model. Solutions from the models are derived annually and are iterated a sufficient number of times to estimate the amount and quality of irrigation return flows resulting from a change in water and land use produced by the implementation of alternative policies.

Location Specific Linear Programming Model

The model is location specific in that the subregions specified in the water quality model are those cells described as the units of observation for the land use model. The specification of alternative cultural practices for each cell allows the estimation of spatial and temporal changes in agricultural production and return flows as a result of changes in policies. The model is segmented into regional activities and cell specific (subregional) activities (Figure 3). Regional activities include crop production (columns 66 and 67) and commodity marketing (column 76). The current production costs and land related costs imposed by BMP's are estimated by a budget generator. These activities are aggregate since sufficient differences do not exist in either market prices or production costs (other than irrigation and land costs) among the cells of the study area. However, the cell specific activities are sufficiently disaggregated to analyze changes in the spatial distribution of return flows, crop production, agricultural incomes and water use caused by alternative land use and water quality policies.

Crop rotations for each individual cell (columns 1 and 3) are specified according to actual cropping pattern. The drainage cost reflected in the objective function value is determined by the physical model. Cropping patterns can be changed as a result of price changes or they could be mandated as a land use or water quality policy. Land conversions from idle to perennial or nonperennial crops (columns 11 and 13) can occur if sufficient water supplies are developed.

Crop evapotranspiration (ET) is specified in column 20 to isolate water requirements from water application efficiencies. Research is currently being conducted to determine the effects of reducing ET requirements by stressing plants during noncritical stages of growth. Alternative water application technologies specified in columns 30–(33) include furrow and sprinkler systems that are both scheduled and nonscheduled.
<table>
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<th>ACTIVITIES</th>
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<th>COMMODITY SELLING</th>
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<th>WATER</th>
<th>FERTILIZER</th>
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FIGURE 3. Location Specific Linear Programming Model
efficiency and surface runoff are specified for each technique to account for the total amount of water diverted for irrigation. The possibility of subsidizing more efficient water application techniques has been considered as a BMP to reduce irrigation return flows. Sources of water include surface diversions and wells pumping primarily from the confined aquifer (columns (36) and (41)). Levying a pump tax or increasing surface water prices to reduce water use is possible. Surface runoff or tailwater can either be captured and reused or be disposed of in surface watercourses (columns (51) and (53)). Effluent charges on surface disposal or the subsidization of tailwater recycle could be implemented to reduce return flows. Crop nitrogen requirements and alternative application techniques are included in column (56).

The land use model provides estimates of perennial and nonperennial crops for prime and nonprime land for the two hydrological subbasins in the study area. These land uses are estimated over a period of about 20 years as a result of a specified set of policies on resource use and the present institutional structure. These are entered as alternative right-hand side vectors on an annual basis (rows (1) and (3)).

Physical Model

The physical model is partitioned into two separate models since there are two hydrologic subbasins. Each model has three interdependent submodels to analyze the hydrology, salinity balances and nitrogen concentrations. These submodels estimate the effects of irrigation water and fertilizer use on the water table depths and the amount and quality of irrigation return flows. The model is structured according to the cells of the LP so that it can sequentially interact with the location specific LP model to predict return flows on an annual basis (see Figure 1).

Hydrologic Model

The hydrologic model generates predictions of the rates of deep percolation through the soil, subsurface drainage, rates of groundwater flow among the cells and the movement of the water table in the unconfined aquifer. The soil type, depth of water table, ground surface elevation, and the depth to the impermeable layer are assumed homogeneous throughout each cell. In each cell, the annual rate of deep percolation in time t is computed as the sum of the components of water inputs and outputs at the surface. Therefore:

\[ DP_{kt} = g_k(I_{kt}, R_{kt}, ET_{kt}, RO_{kt}) \]  

where:

- \( DP_{kt} \) = Deep percolation in cell k
- \( g_k \) = Function relationships between deep percolation and hydrologic occurrences
- \( I_{kt} \) = Irrigation applications in cell k
- \( R_{kt} \) = Rainfall in cell k
ET<sub>kt</sub> = Evapotranspiration in cell k
RO<sub>kt</sub> = Surface runoff in cell k

In those cells in which the water table is within 5 feet of the surface, a drainage system is assumed to be installed only if it is determined in the LP model as economically feasible. In a cell where a drainage system has been installed, the rate of drainage is computed from the rate of deep percolation and the movement of the water table. The change in the water table depth between time periods is defined by:

\[ H_{kt+1} = H_{kt} + s_k (DP_{kt}, P_{kt}, \sum_j F_{jkt}) \]  

(38)

where:

- \( H_{kt} \) = Water table depth in cell k
- \( s_k \) = Specific yield of cell k
- \( P_{kt} \) = Water pumped from cell k
- \( F_{jkt} \) = Groundwater movement from (to) cell j to (from) cell k

The groundwater flow between cells is calculated according to Darcy's Law in which spatial and temporal averages of water table depths are used to arrive at an average hydraulic gradient between the two cells. A spatial average is used as a coefficient of permeability of the cells, and the area through which the flow moves is equal to the product of the length of the common boundary and the time-averaged depth of the saturated zones. One equation of the form of equation (37) is written for each cell resulting in n equations for n cells in n unknowns, i.e., the final water table depth for each cell. This system of equations is then solved by Gaussian elimination.

Salinity Model

One of the quality changes taking place in the soil moisture is increased total dissolved solids (TDS) concentrations due to evapotranspiration and chemical processes in the soil. Salt pickup in an irrigated soil is primarily a function of the chemical composition of the soil and of the applied water and the leaching fraction (Rhoades, et al., 1974). Analysis of the total annual salt load carried by subsurface drains in the area suggests that the total annual salt load per acre in tile drains is related to the total volume of water carried by the drain. It was therefore assumed that the annual rate of salt pickup for each cell can be approximated by the expression:

\[ SL_{kt+1} = SL_{kt} + c_k (DP_{kt}, Q_{kt}) \]  

(39)
where:

\[ SL_{kt} = \text{Amount of salt in the leaching water} \]
\[ c_k = \text{Functional relationship between water application and salt load} \]
\[ Q_{kt} = \text{Quality of irrigation water applied} \]

The functional relationship, \( c_k \), was estimated for various qualities of irrigation water using a model developed at the U.S. Salinity Laboratory at Riverside, California (Rhoades, et al., 1974).

A weighted average of the salinity concentration of groundwater within a cell is used to estimate the quality of water pumped from drainage sumps and wells within the cell, and the quality of water moving outward across the boundaries of the cell. This assumes, in effect, that all strata contribute proportionate shares to flows from the aquifer. Although wells will generally draw water from certain specific strata more than from others, it would have been impractical either to differentiate between the various strata in every cell or to determine the characteristics of every well in the study area. In addition, the gravel-pack wells used in the area result in some mixing between strata.

The quality of surface runoff was initially assumed to be the same as the quality of applied water. This approximation was supported by data observed for various locations in the Valley. Water entering subsurface drains was assumed to have the same quality as the percolation water, since water quality in groundwater is assumed to be stratified, with the water closest to the surface having the same characteristics as percolating water from the surface.

Nitrogen Model

The nitrogen concentration in the soil solution is based on a steady state mass balance model developed by Fried Tanji and Van De Pal (1975). They argue that many complex nitrogen reactions take place in the soil but that these do not need to be evaluated to predict changes in the nitrogen content of groundwater over time. The concept is based on the long-run effects of plant efficiency to utilize the nutrient. The steady state plant-soil system establishes a balance between nitrogen additions and losses. To predict the change in nitrogen concentration over time, the balance equation can be written as:

\[ N_{kt+1} = N_{kt} + b_r (NF_{kt}, NI_{kt}, NR_{kt}, W_{kt}, D_{kt}, NP_{kt}) \]  

(40)

where:

\[ N_{kt} = \text{Nitrogen concentration of the groundwater in cell } k \]
\[ b_r = \text{Functional relationship between nitrogen concentration and nitrogen additions and losses} \]
Nitrogen fertilizer applications in cell $k$

Nitrogen concentration of irrigation water applied in cell $k$

Nitrogen concentration of rainfall in cell $k$

Natural additions and losses of nitrogen in cell $k$

Denitrification in cell $k$

Nitrogen removed by crops grown in cell $k$

The analytical system presented here is sufficiently comprehensive to evaluate alternative resource use policies in terms of their economic and environmental impacts. It is structured so as to provide a spatial and temporal dimension for all parameters. Clearly the distribution of resource problems through time and space is a significant determinant of resource policy. In addition, the linkage of micro and macro characterizations of resource use among component models of the analytical system allows broader implications to be drawn about the nature of demands for land and water resources under diverse sets of policy options.

**POLICY IMPLICATIONS**

Why should a regional comprehensive analytical system be developed to evaluate nonpoint water quality policies affecting irrigated agriculture? As Bower, et al., (1977) point out, the degree to which an environmental strategy can improve overall environmental quality is the ultimate policy criteria. The physical, environmental and economic impacts of implementing these plans are not known but society has to anticipate these impacts in order to develop workable national resources policy.

At the present time, nonpoint policies are to be developed and implementation started. By 1983 the nation's waters are to be fishable and swimmable and by 1985 there is to be zero discharge of pollutants to these waters. The potential physical, environmental, and economic impacts (both on-site and off-site) of implementing nonpoint policies have generally been ignored by resource planners. Information on these impacts is needed to determine if regulations will be adopted in irrigable areas, the impact on the quality and quantity of irrigation return flows and the feasibility of the 1979, 1983, and 1985 goals.

An analytical system to quantify impacts of return flows for irrigated agriculture, on resource use and irrigation return flows has been presented. It recognizes that successful implementation of nonpoint regulations can not exclude other conservation and production practices. The scope of analysis involves not only the structure and operation of the individual farmer but the agricultural economy of the watershed and/or river basin where policies are implemented. Economic impacts of proposed environmental strategies should recognize the direct and indirect benefits and costs of improved water quality, program administration and other institutional costs, the distribution of costs and benefits, and the
implications of their distribution for cost-sharing and penalties.

Water quality policy should not be developed in isolation of land, air, conservation, production and other water policies. A model or mechanism to analyze all of these policies simultaneously does not exist and it is questionable if such a system will every exist. The comprehensive irrigated agriculture analytical system presented is a step in the right direction because the interaction of national commodity demands, regional production, land use and water quality are considered. The model does require a significant amount of data, both in quantity and detail. In the future the sensitivity of various environmental strategies to model specification and data aggregation will be tested. The sensitivity analysis will allow for a more generalizable model and data set that could be applied to other areas of the Western U.S.
References


