Ground Water Quantity and Quality Management: Agricultural Production and Aquifer Salinization over Long Time Scales

Keith C. Knapp and Kenneth A. Baerenklau

An economic model of ground water salinization is developed. Starting from a full, high-quality aquifer, there is an initial extraction period, an intermediate waste disposal period, and a final drainage period. Drainage management is initially source control and reuse, but eventually culminates in evaporation basins and a system steady-state. This process occurs over long time scales but is consistent with historical observation. Efficiency is qualitatively similar to common property though quantitative magnitudes differ substantially. Regulatory pricing instruments are developed to support the efficient allocation. The system is not sustainable in that net returns generally decline through time until the steady-state.

Key words: common property, dynamic programming, efficiency, ground water, irrigation, salinity, sustainability

Introduction

Soil and ground water salinity have contributed to the decline and fall of several societies. Examples include ancient Mesopotamia (Jacobsen and Adams, 1958), the Viru Valley in Peru (Tanji, 1990), and the indigenous Hohokam people of the Salt River region in Arizona (Tanji). Currently, 10%–37% of arable lands worldwide are saline/sodic (Tanji), including some 39% of the agriculturally productive land of California's San Joaquin Valley (Backlund and Hoppes, 1984). Other regions such as Israel, the Indus Plain, Australia, and Pakistan also suffer from salinity degradation (Wichelns, 1999).

Although soil salinity has a substantially developed literature in economics [Dinar, Aillery, and Moore (1993), and Knapp (1999) provide reviews], *ground water* salinization has received relatively scant attention by economists. Cummings (1971) and Cummings and McFarland (1974) propose conceptual frameworks with interpretations of efficiency conditions. Dinar (1994) and Dinar and Xepapadeas (1998) simulate energy costs, surface water limits, and exogenous pump taxes for farms overlying a common property aquifer and for time horizons of two decades or less. Zeitouni and Dinar (1997) consider a two-aquifer system where subsurface flows from a high-salinity aquifer degrade a low-salinity

aquifer, while Reinelt (2005) develops a computational model of seawater intrusion due to irrigated agriculture. Several studies consider ground water degradation from other pollutants (e.g., Conrad and Olson, 1992; Kim et al., 1997; Zeitouni, 1991; Fleming, Adams, and Ervin, 1998); however, this literature typically considers only waste emissions and water quality, and not extractions and water table dynamics.[1] Roseta-Palma (2002) develops an insightful theoretical analysis of ground water quantity and quality, but unlike the analysis here assumes a natural regenerative capacity for the pollutant and focuses on the steady-state.[2]

This paper develops a long-term economic-hydrologic model of agriculturally induced ground water salinization. The agricultural production model includes choice variables for land allocation, crop type, applied water depth, and irrigation source. This model is coupled to an aquifer model with endogenous water table height and salt mass. In contrast to the vast majority of previous work, biophysical relations in the model are specified so that a complete mass balance accounting of water and salt flows in the basin is maintained. The model is quite general and can be used to understand a wide variety of natural resource and environmental quality issues faced by irrigated agriculture. Here we concentrate specifically on the problems of salinization over long time scales, efficient management in the presence of both pumping cost and salt externalities, and development of supporting policy instruments with an application to Kern County, a major agricultural region in the San Joaquin Valley of California.[3]

The results demonstrate that the ground water system can evolve rather slowly in the quality dimension and rather quickly in the quantity dimension, and that it exhibits interesting transition dynamics which would be omitted from a steady-state analysis. We also find benefits from ground water management that are considerably larger than previous studies for both this basin (Dixon, 1989; Knapp and Olson, 1995) as well as most other basins (Koundouri, 2004). Some sensitivity analysis is reported to further understand the determinants of these benefits. State-dependent price instruments are also developed to induce efficient ground water use. These are quite nonlinear due to the combined effects of water table dynamics, soil-plant-water relationships, and hydrologic balance constraints. Overall, the analysis suggests greater efforts to manage ground water than recommended by earlier economic studies.

Agriculture and Aquifer Salinization

Aquifers in irrigated agricultural regions can be salinized by a variety of mechanisms, including naturally occurring salts in the parent aquifer material, surface water importation, lateral flows from an adjacent saline aquifer, salt water intrusion, and lack of sufficient drainage. Here we consider salinization due to both imports of surface water (which naturally contain at least some salts), and restricted drainage. These are the predominant mechanisms in the study area here, but they also are relevant to understanding historical salinity problems as well as preventing and/or mitigating current problems in most irrigated agricultural environments.

---

[1] Empirical studies by Bernardo et al. (1993) and Taghavi, Howitt, and Marino (1994) consider water table elevation and water quality for nitrates and pesticides.

[2] Salts can precipitate out of solution, thus moderating salt concentrations, but they remain in the system and would reappear in solution if aqueous salt concentrations decline.

[3] Throughout the paper, "efficient management" refers to maximizing the present value of net benefits.

Figure 1 illustrates the conceptual problem. An irrigated agricultural region overlies a ground water aquifer of initially high quality (low salinity) and with a relatively small amount of natural recharge. Water for irrigation is obtained either by pumping ground water or by importing surface water, some of which is lost to the aquifer via leakage from the canal system. The total amount of arable land is fixed and subject to crop rotation and marketing constraints, but land allocation is endogenous. Land areas may be used for crop production with either surface or ground water, left fallow, or used for disposal of saline ground water via evaporation ponds.[4] Such ponds have been and continue to be used in the San Joaquin Valley and in other naturally drainage-limited agricultural regions. The quantities of surface and ground water applied to each crop are also endogenous.

Although the imported surface water is high quality (low salinity), it does contain some salts, as does all irrigation water. Crop evapotranspiration (ET) removes large quantities of applied water from the rootzone with negligible salt uptake, thus concentrating salts in the rootzone. Some irrigation water is not used by the crop and percolates to the aquifer, thereby removing salts from the rootzone. These deep percolation flows arise partly from salt leaching requirements for crop growth but mostly from non-uniform irrigation.[5] In addition, both water and salt flows must satisfy regional mass balance restrictions governed by physical processes that are calibrated for Kern County. These include the evaporation rate for pond water disposal, the aquifer-specific yield, and pressure-induced drawdown at ground water wells. Finally, the water table must be maintained at a level conducive to crop growth, as high water tables can inhibit plant growth via poor aeration and/or increased soil salinity.

Economic-Hydrologic Model of a Saline Aquifer

Annual net benefits from crop production in year t are given by:

$$(1) \qquad \pi_t = \sum_{i \in \{s,g\}} \sum_{j=1}^{n} \pi_{ijt} x_{ijt} - \gamma_{st} - \gamma_{gt} - \gamma_p x_{pt},$$

where π_{ijt} is per acre net returns, x_{ijt} are cropped areas, x_{pt} is evaporation pond area, γ_{st} is total surface water cost, γ_{gt} is total ground water cost, γ_p is the unit (area) cost for evaporation ponds, $i \in \{s,g\}$ denotes irrigation water source, and $j \in \{1, ..., n\}$ denotes crop type. Here both cotton (relatively salt-tolerant) and tomatoes (relatively salt-sensitive) are considered due to their predominance in the region and profitability. The irrigation system is furrow with ¼-mile runs representing the standard system in Kern County and elsewhere. All monetary values are in 2000 dollars, and the interest rate $r = 4\%$.

---

[4] Another possibility would be to blend surface and ground water sources to irrigate a single crop but, consistent with field observations, Kan, Schwabe, and Knapp (2002, p. 34) find that "blending two heterogeneous sources of irrigation water is an unlikely solution from an efficiency perspective." Knapp and Dinar (1984) and Dinar, Letey, and Vaux (1986) derive similar results. Despite their finding that surface water scarcity can lead to blending, Kan, Schwabe, and Knapp conclude such constraints are "likely to lead to profit-maximizing solutions consisting of corner solutions" (p. 34). Therefore, we delineate land use by both crop type and irrigation water source.

[5] All irrigation water contains salts. Salt leaching refers to the downward movement of salts in deep percolation flows away from the crop rootzone. Without leaching, salts accumulate in the rootzone, and eventually crop production is no longer possible.
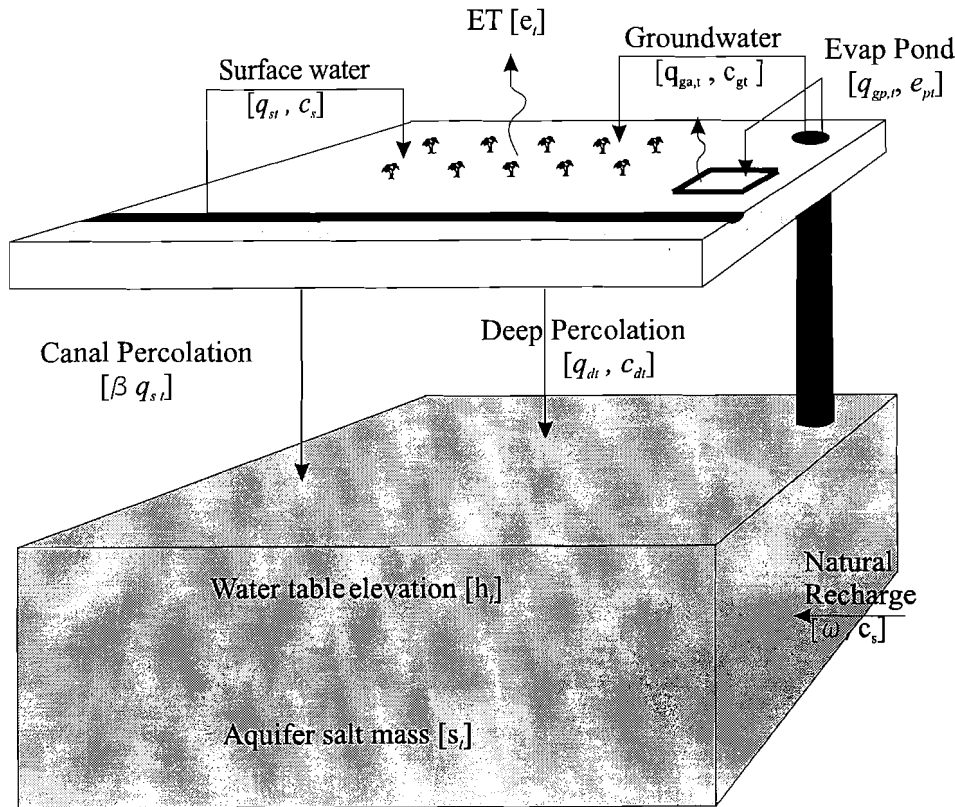
Figure 1. Regional agricultural production with surface water supply and overlying an aquifer system with salinity (q = water quantity, c = salt concentration, e = evaporation/transpiration, h = hydraulic head, and s = aquifer salt mass)

Prices for outputs and non-water inputs are constant over the horizon. Clearly this will not be the case in the long run, but incorporating general equilibrium effects and/or time trends for these variables is not necessary to establish the main results and would complicate the model significantly. Per acre net returns are $\pi_{ijt} = (p_j + p_{oj} - \gamma_{hy,j})y_{ijt} - \gamma_{hr,j}p_j y_{ijt} - \gamma_{hj} - \gamma_j$, where y_{ijt} is crop yield, p_j is crop price, p_{oj} is other sources of revenue (i.e., seed credit for cotton), $\gamma_{hy,j}$, $\gamma_{hr,j}$, and γ_{hj} are yield, revenue (i.e., Cotton Board assessment), and harvest costs, respectively, and γ_j is production costs other than water and evaporation pond costs. Production costs γ_j include capital recovery costs; irrigation system purchase and operating and maintenance costs (O&M), including taxes, insurance, and estimated repair costs; and planting, cultivation, fertilization, and pesticide application costs. Output prices and values for these cost parameters are summarized in table 1.

Crop-water production relationships are specified using functional forms and the data-generating model in Kan, Schwabe, and Knapp (2002):

$$(2) \qquad y_{ijt} = \sum_{k=1}^{2} \phi_{kj}^{y}\left(e_{ijt} - \underline{e}_j\right)^k,$$

Table 1. Agricultural Production Parameter Values

Parameter	Description	Units	Cotton	Tomatoes
p	Output price	[$ ton^{-1}]	1,661.09	57.61
p_0	Other income	[$ acre^{-1} yr^{-1}]	75.19	0
γ_h	Harvest costs (area)	[$ acre^{-1} yr^{-1}]	63.70	54.86
γ_{hy}	Harvest costs (yield)	[$ ton^{-1}]	12.53	13.25
γ_{hr}	Harvest costs (revenue)	[$ $^{-1}$]	0.005	0
γ	Production costs	[$ acre^{-1} yr^{-1}]	584	692.54
h_{rz}	Rootzone depth	[ft.]	5	5

Notes: Monetary values are in 2000 dollars. Economic data are from Kan, Schwabe, and Knapp (2002) and sources therein, with adjustment for inflation as necessary.

$$(3) \qquad e_{ijt} = \frac{\bar{e}_j}{1 + \phi_{0j}^e \left(c_{it} + \phi_{1j}^e w_{ijt}^{\phi_{2j}^e}\right)^{\phi_{3j}^e}},$$

where y_{ijt} is crop yield, e_{ijt} is evapotranspiration (with lower and upper bounds given by the parameters $\underline{e}_j$ and $\bar{e}_j$), c_{it} and w_{ijt} are the salt concentration [deciSiemens per meter (dS/m)] and depth of applied irrigation water (ft/yr), and each ϕ is a parameter. Mass balance restrictions give definitions for deep percolation flows (ft/yr) and salt concentrations for each land use: $d_{ijt} \equiv w_{ijt} - e_{ijt}$ and $c_{ijt}^d \equiv c_{it} w_{ijt}/d_{ijt}$ assuming steady-state conditions in the rootzone.[6] Parameter estimates are reported in table 2, while cotton yields and deep percolation flows are illustrated in figure 2 for several salt concentrations and applied water depths. The qualitative properties of this figure will help explain some of the empirical results as discussed later.

Evaporation ponds provide drainage disposal to maintain the water table at an acceptable level for crop production. Pond construction costs are annualized and denoted on a per unit area basis by γ_p; however, pond area displaces crop area, implying an additional opportunity cost that is endogenous to the model. This opportunity cost reflects land use for productive crops and can greatly outweigh explicit pond costs in regions with high-value agricultural production. With the above definitions, total land use is constrained by

$$\sum_{i \in [s,g]} \sum_{j=1}^{n} x_{ijt} + x_{pt} \le \bar{x},$$

where $\bar{x} = 0.9$ million acres is the total land available for agricultural production in the study region. An additional rotation and marketing constraint is imposed that requires total tomato acreage to be no more than one-half of total cotton acreage.

---

[6] Several studies in the soil salinity economics literature find convergence to a steady-state in approximately 4–7 years (Dinar and Knapp, 1986; Dinar, Aillery, and Moore, 1993; Letey and Knapp, 1995). Because this is one to two orders of magnitude faster than the time required to investigate ground water salinity issues, it is reasonable to assume steady-state soil salinity. This implies the useful result that the salt mass in applied irrigation water equals the salt mass in deep percolation flows during each time period.

Table 2. Crop-Water Production Function Parameter Values [equations (2) and (3)]

Parameter	Description	Units	Cotton	Tomatoes
ϕ_1^y	Yield slope	[ton acre ft^{-1}]	0.651	19.527
ϕ_2^y	Yield quadratic	[ton acre ft^{-2} yr]	-0.152	6.415
$\bar{e}$	ET maximum	[ft yr^{-1}]	2.39	2.003
$\underline{e}$	ET minimum	[ft yr^{-1}]	0.502	0.334
ϕ_0^e	ET potential weight	[dS^{-1} m]	2.38×10^{-4}	2.38×10^{-9}
ϕ_1^e	ET matric weight	[dS m^{-1} ft^{-1}]	48.15	40.38
ϕ_2^e	ET matric power	[dimensionless]	-1.578	0.504
ϕ_3^e	ET potential power	[dimensionless]	2.54	5.45

Source: Estimated by the authors using the data-generating model in Kan, Schwabe, and Knapp (2002).

Surface water in Kern County is relatively high quality (low salinity) and comes from three major sources: the California State Water Project, the federal Central Valley Project, and the Kern River. Total surface water imports are:

$$q_{st} \equiv \frac{1}{1 - \beta_s} \sum_{j=1}^{n} w_{sjt} x_{sjt},$$

where $\beta_s = 0.3$ accounts for percolation losses from the canal system to the aquifer. Surface water has a constant salt concentration $c_{st} = \bar{c}_s$ consistent with the study area, although inflow salt concentrations can increase over time in some regions (Characklis, Griffin, and Bedient, 2005). Surface water costs are estimated from data in Vaux (1986) and Kern County Water Agency (1998) with inflation adjustment, and reflect differential costs of alternate sources within the region. These costs are:

$$(4) \qquad \gamma_{st} = \begin{cases} 15.47 q_{st} + 1.365 q_{st}^2 + 6.239 q_{st}^3, & 0 \le q_{st} \le 0.86, \\ -22.03 + 84.89 q_{st} - 70.69 q_{st}^2 + 30.79 q_{st}^3, & 0.86 < q_{st} \le \bar{q}_{st}, \end{cases}$$

where diversions are subject to an upper bound $\bar{q}_{st} = 1.8$ million acre-feet (maf) per year, reflecting water deliveries in a normal year (Kern County Water Agency, 1998).

Ground water extractions are

$$q_{gt} \equiv \sum_{j=1}^{n} w_{gjt} x_{gjt} + q_{gp,t},$$

where drainage flows $(q_{gp,t})$ equal the Kern County atmospheric evaporation rate times pond area $q_{gp,t} \equiv e_p x_{pt}$. Pumping costs are:

$$(5) \qquad \gamma_{gt} = \left(\gamma_{gk} + \gamma_e \left(\bar{h} - h_t + h_d \right) \right) q_{gt} + \frac{\gamma_e}{2As^y} q_{gt}^2,$$

where γ_{gk} denotes well and pump capital costs calculated on a per unit basis, γ_e are energy costs for lifting water, $\bar{h}$ is land surface elevation relative to mean sea level (MSL), h_t denotes water table elevation (hydraulic head), h_d denotes drawdown (the
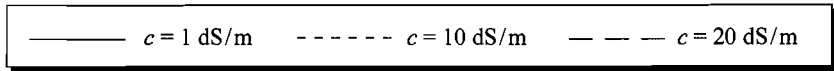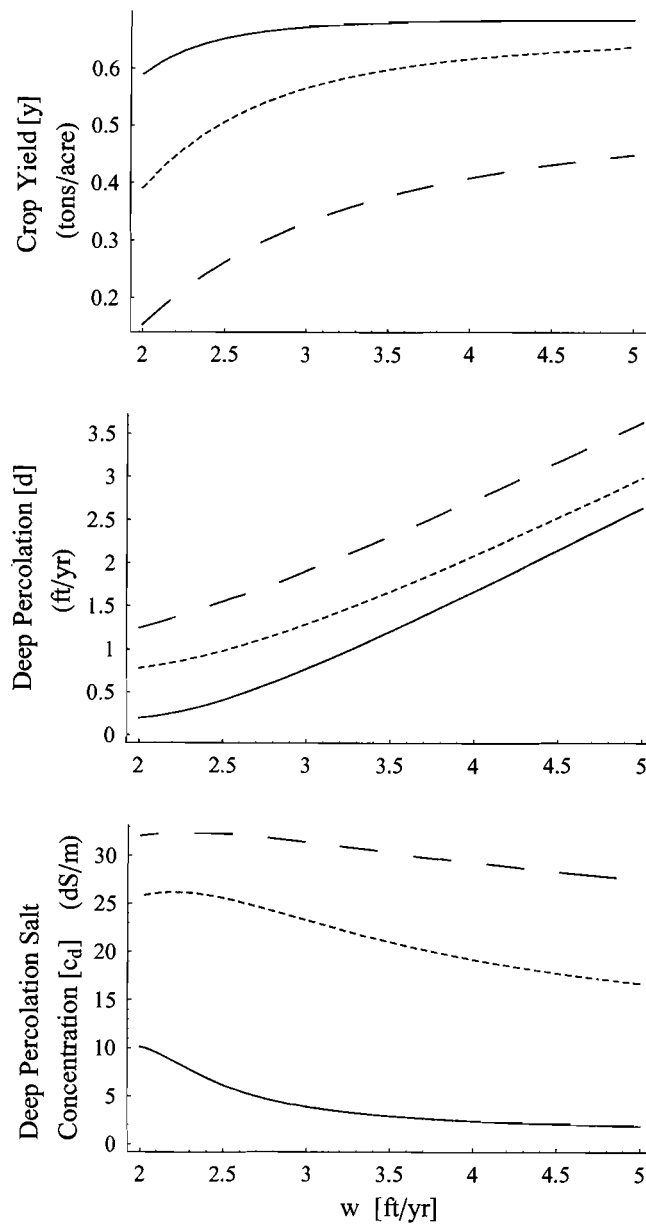
Figure 2. Cotton crop-water production function: yield (*y*), and deep percolation depth (*d*) and salt concentration (c_d) as functions of applied water depth (*w*) and salt concentration (*c*)

Table 3. Evaporation Pond, Surface Water, and Aquifer Parameter Values

Parameter	Description	Units	Value
e_p	Pond evaporation rate	[ft yr^{-1}]	5.32
γ_p	Evaporation pond costs	[$ acre^{-1} yr^{-1}]	122.59
β_s	Surface water infiltration coefficient	N/A	0.3
$\bar{q}_{st}$	Maximum surface water flow	[maf yr^{-1}]	1.8
c_s	Surface water salt concentration	[dS m^{-1}]	0.7
γ_{gk}	Well and pump O&M costs	[$ af^{-1}]	7.28
γ_e	Energy cost	[$ af^{-1} ft^{-1}]	0.23
h_d	Pump drawdown (cone of depression)	[ft]	60
A	Aquifer area	[10^6 acres]	1.29
$\bar{h}$	Land surface elevation	[ft above MSL]	385
$\underline{h}$	Minimum hydraulic head (aquifer bottom)	[ft above MSL]	-233
s_y	Aquifer-specific yield	[maf/maf]	0.13
ω	Natural recharge	[maf yr^{-1}]	0.052

Notes: Monetary values are in 2000 dollars. Data sources, with adjustment for inflation as necessary, are as follows: pond data are from Kan, Schwabe, and Knapp (2002) and sources therein; energy cost of ground water pumping is calculated from the California Public Utility Commission rate schedule (March 4, 2002); well and pump costs, drawdown, and aquifer geophysical data are from Knapp et al. (2003).

depth of the cone of depression) at the well, A is the regional aquifer area, and s^y is the aquifer-specific yield. The first term on the right-hand side of equation (5) accounts for capital costs and pumping costs associated with lifting water from the initial water table height at the beginning of year t. The second term accounts for increasing pumping costs due to the declining water table height during year t. Other surface water and aquifer parameter values and data sources are given in table 3.

The ground water system evolves through time in both quantity and quality dimensions. In the quantity dimension, the water table height evolves according to:

$$(6) \qquad h_{t+1} = h_t + \frac{1}{As^y}\left(\omega + \beta_s q_{st} + \sum_{i\in\{s,g\}} \sum_{j=1}^{n} d_{ijt}x_{ijt} - q_{gt} \right),$$

where ω = natural recharge, and all other terms are as defined previously. Equation (6) states that natural recharge plus percolation from both canal losses and irrigation cause the water table to rise, while extractions for irrigation and drainage cause it to fall. Letting h_{rz} = rootzone depth, the water table must lie within the interval $\underline{h} \le h_t \le \bar{h} - h_{rz}$ representing the lower aquifer boundary and the maximum elevation for feasible crop production, respectively. The lower aquifer bound limits ground water extractions to the available supply, while the upper bound limits net deep percolation flows to available storage capacity.[7]

---

[7] This constraint follows from the observation that, with high water tables and sufficiently low hydraulic conductivities, deep percolation generated by a farm can damage that farm for some time, even if neighboring farms are not also doing the same. This assumption is quite realistic for Kern County, but it may not be if lateral transmissivities are high enough and farming units are small enough such that the damage caused by deep percolation at a farm is largely borne by other farms.

At the beginning of each time period, ground water salt concentration is calculated as $c_{gt} \equiv s_t / (As^y(h_t - \underline{h}))$, assuming uniform salt mixing in the aquifer as befits the long time scales considered here. In the quality dimension, assuming steady-state conditions in the rootzone, and letting c_ω denote salt concentration of natural recharge, aquifer salt mass evolves according to:

$$(7) \qquad\qquad\qquad s_{t+1} = s_t + c_s q_{st} + c_\omega \omega - c_{gt} e_p x_{pt}.$$

Here, surface flows and natural recharge bring salts into the system, while disposal via evaporation ponds removes salts from the system. Salt flows due to irrigation with ground water and deep percolation exactly cancel under steady-state rootzone conditions, and therefore do not appear in the mass balance described by equation (7).

Decision Rules and Transition Dynamics: Common Property

Given the model and empirical specification defined above, we now consider evolution of the aquifer system as an unregulated common property resource. With many relatively small users, the effect of an individual user's current decisions on future aquifer characteristics is borne almost entirely by others. Therefore it is reasonable to assume that under such conditions each user acts to maximize profits in each period without regard for future values of the state variables, rather than maximizing the present value of profits over multiple time periods (which we consider next). This is consistent with the Gisser and Sanchez (1980) pumping cost model.[8]

The common property optimization problem is solved using MINOS (Murtagh and Saunders, 1998). During each time period there are nine decision variables: four cropped areas (cotton/tomatoes irrigated with surface/ground water), four applied water depths (one for each cropped area), and the evaporation pond area; and two state variables: the water table height and the aquifer salt mass (or concentration). Consistent with the above reasoning, the decision variables are chosen to maximize annual net benefits in each year given the current values of the state variables and subject to the land and rotation constraints presented in the previous section. This is then simulated forward in time to generate time-series values.

Figure 3 shows the optimal decision rules for applied surface water $[(1 - \beta_s) q_{st}]$, applied ground water

$$\left[q_{ga,t} = \sum_{j=1}^n w_{gjt} x_{gjt} \right],$$

and evaporation pond area as functions of the two aquifer state variables. Applied surface water is at the maximum level over a quadrilateral representing low ground water quantity (low hydraulic head), low quality (high salt concentration), or both. Beyond this region, surface water is decreasing in both ground water quantity and quality. Ground

---

[8] Game theory models of non-saline ground water use include Negri (1989) and Provencher and Burt (1993). Dixon (1989) and Gardner, Moore, and Walker (1997) suggest the game-theoretic solution is essentially identical to the Gisser and Sanchez (1980) competitive model when there are more than a half-dozen or so users. The Census Bureau reports that in 1997 there were almost 2,000 farms in Kern County overlying a common aquifer, with two-thirds of them each covering less than 500 acres.

Applied Surface Water $[(1-\beta_s)\ q_{st}]$ *(maf/yr)*
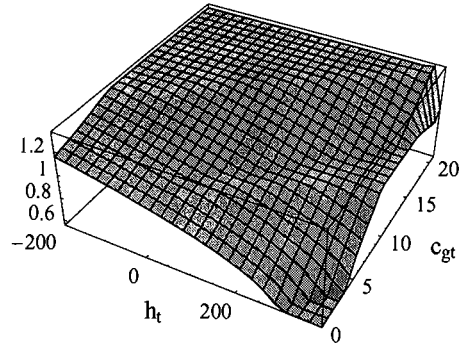
Applied Ground Water $[q_{ga,t}]$ *(maf/yr)*
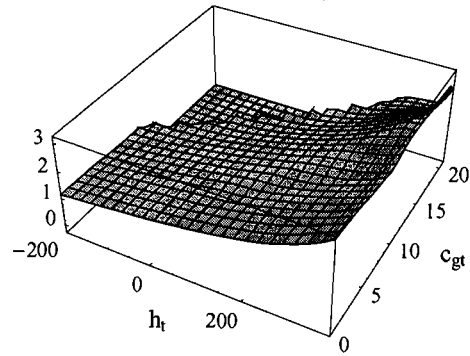
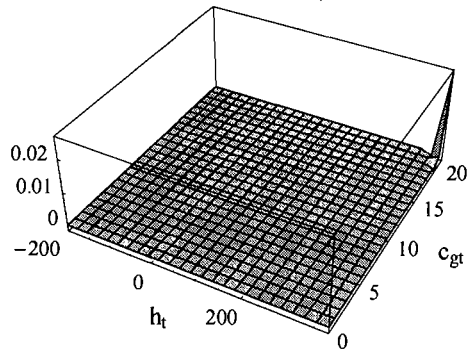*Evaporation Pond Area* $[x_{pt}]$ $(10^6$ *acres)*

Figure 3. Common property decision rules: Applied surface water, ground water, and pond area as functions of h_t = hydraulic head (feet above MSL), and c_{gt} = aquifer salt concentration (dS/m)

water extractions for agriculture are zero for low water tables and/or high salt concentrations. Extractions are generally increasing in hydraulic head; however, the relation to salt concentration is more complicated. Increased salt concentration typically leads to increased extractions, but in some circumstances the opposite can occur. The explanation can be seen from the production functions in figure 2. Increased salt concentration for a given water application level typically increases the marginal product of water (due to additional rootzone leaching and dilution), and hence induces increased water application rates. However, at a low water application rate and a high salt concentration, increasing the salt concentration can lower the marginal product of water, thereby inducing decreased application rates. Finally, figure 3 shows that only a small amount of land is allocated to evaporation ponds for any combination of aquifer state variables, reflecting the high cost of ponds for disposal relative to source control (i.e., limiting deep percolation flows) and reuse (i.e., using saline ground water to irrigate relatively salt-tolerant crops).

Figures 4 and 5 display simulated time-series results for the control and state variables and annual net benefits under common property (CP). (Efficiency results in the figures are discussed later.) Initial conditions for these simulations include a completely full aquifer (h_0 = 360 feet above MSL) and an initial salt concentration of c_{g0} = 1 dS/m. Figure 4a depicts hydraulic head and suggests there are three distinct regimes for ground water use. The first is labeled the Resource Extraction era. Here ground water is relatively abundant and high-quality, so extractions exceed deep percolation flows and the water table falls. As the water table falls, pumping costs increase and the salt concentration rises (figure 4b) due to increasing salt mass from water imports and the concentrating effect of reduced volume. These effects tend to reduce ground water extractions over time (figure 5). Eventually, deep percolation flows exceed ground water extractions (around year 200) and the water table begins to rise. This new regime is called the Waste Disposal era: although beneficial extractions still occur, these extractions are outweighed by deep percolation flows. Figure 4b shows that ground water salt concentration continues to rise during this second era, as well.

In the third and final stage (Drainage era), the water table is at its maximum height. For irrigation to continue, hydrologic balance must be maintained by balancing deep percolation flows with ground water extractions. Initially this is accomplished via source control and reuse (figure 5): at approximately year 1,150, there is a discrete drop in surface water acreage and applied depth and a discrete increase in ground water acreage. During this period, however, aquifer salt concentration is still rising, making reuse increasingly less attractive as a solution. Consequently, a point is reached where evaporation ponds are the desired disposal option: at approximately year 1,750, surface water area increases while ground water area decreases. At this point the system is stabilized, all variables remain constant thereafter, and the economic value of the aquifer to the production system is exhausted.

Figure 4c depicts aggregate annual net benefits for common property use. Annual net benefits initially decline through time as the water table falls, pumping costs increase, and ground water quality decreases. This occurs until the water table turning point at about year 200, after which annual net benefits then slightly increase through time due to the rising water table. Although ground water quality is substantially degraded at this point, the benefits of reduced pumping costs outweigh the costs of reduced ground water quality, and thus annual net benefits increase. Once the Drainage era is reached,
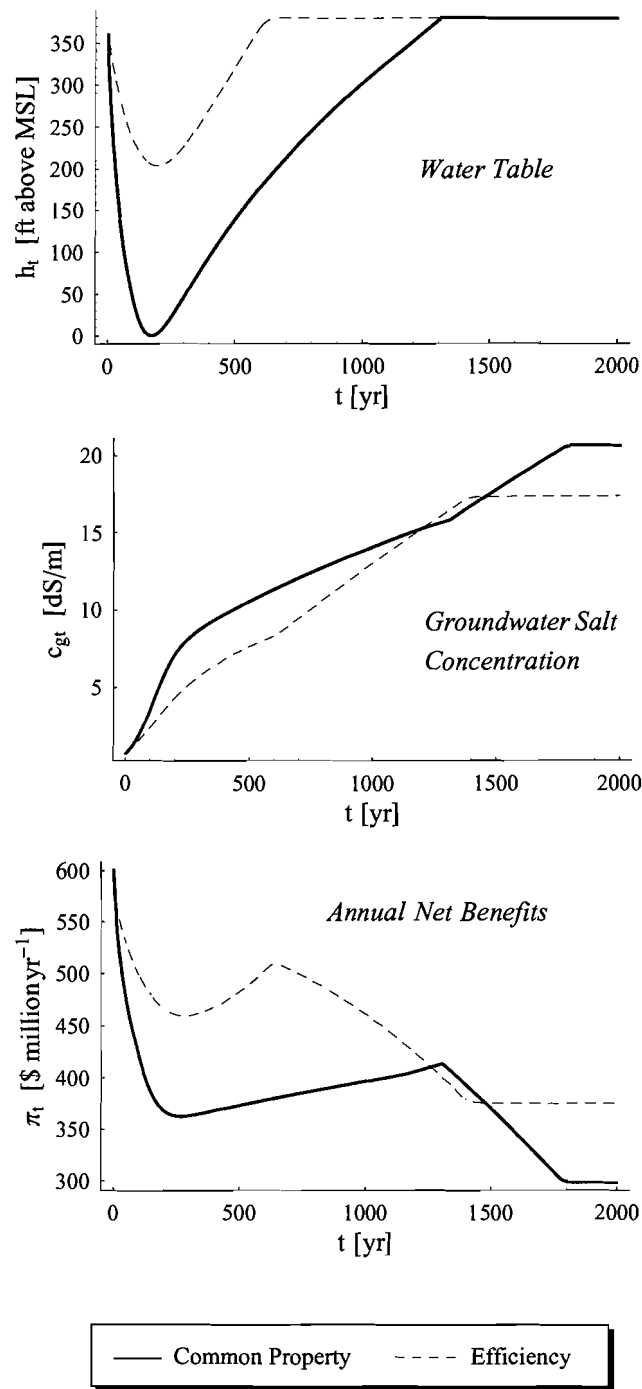
Figure 4. Time paths for water table elevation, ground water salt concentration, and annual net benefits under common property and efficient management
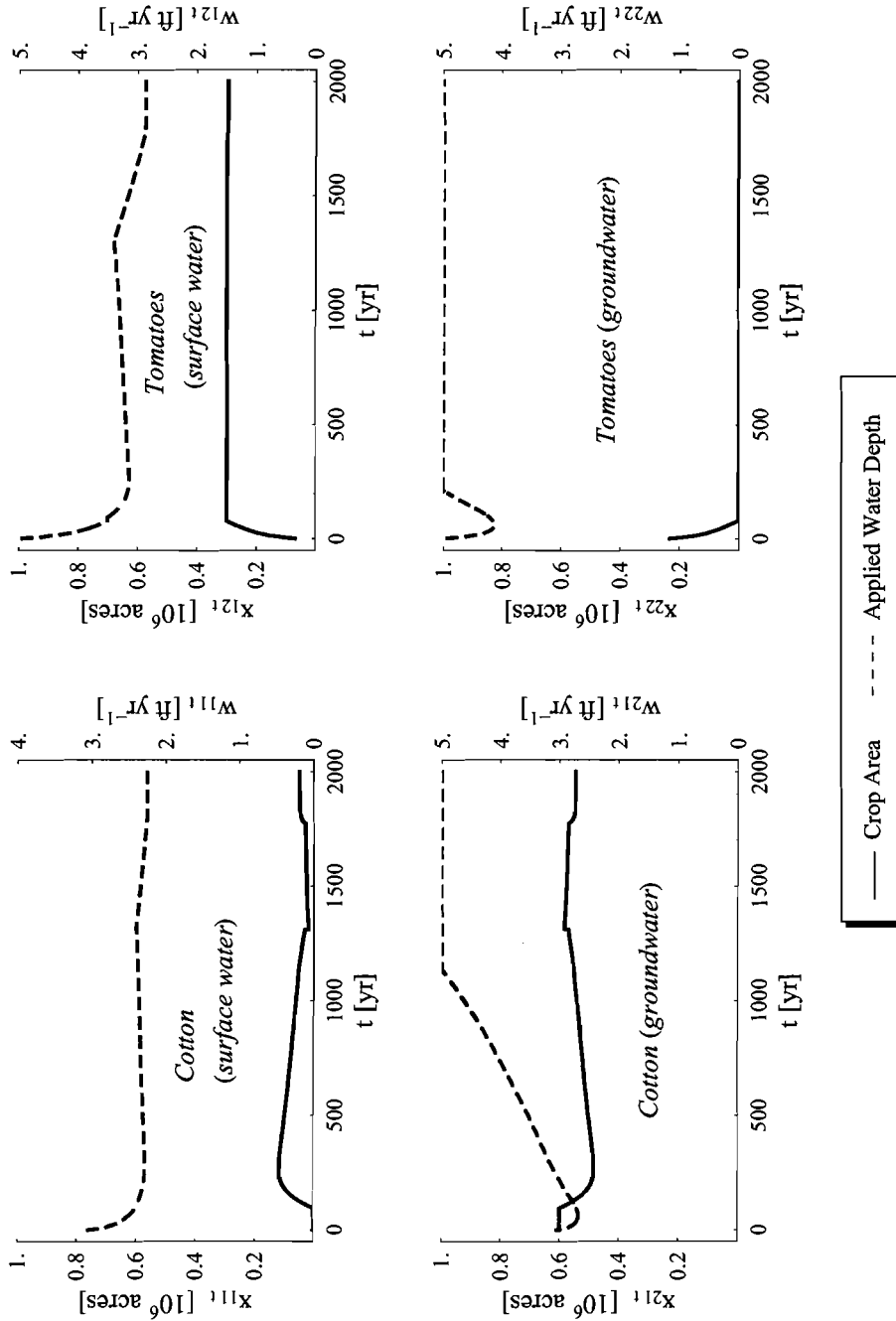
Figure 5. Crop area and applied water depths in the Kern County aquifer system under common property usage

annual net benefits fall as aquifer salt concentration increases until a steady-state is reached with the onset of evaporation ponds. The common property system therefore is not sustainable in the sense of maintaining or improving incomes over time. Note also that net benefits are expected to drop by over 50% during the simulation.

Our interest is in providing a relatively complete analysis of the production/aquifer system starting from an originally full, high-quality aquifer and sufficiently long to achieve a steady-state. For the particular empirical setting here, this is a long time frame; however, it is consistent with the historical salinity problems noted at the outset—for example, irrigation initiated approximately 6,000 BC in Mesopotamia with development of city-states during the ensuing three millenia (Scarre, 1993). Jacobsen and Adams (1958) note the decline in agricultural productivity due to salinity in southern Mesopotamia during the period 2400 BC–1700 BC.[9] In the Viru Valley of Peru, irrigation systems were developed during the period 400 BC–0 BC; population peaked in 800 AD, with a precipitous decline after 1200 AD attributed at least in part to rising soil salinity and water tables (Tanji, 1990). Tanji also cites the Hohokam Indians in the Salt River region of Arizona during the period 300 BC–1450 AD. Records reveal crop damages caused by water logging and salinization on the valley floor, with no record of habitation after this period.

In other settings the time frame involved could be considerably less. For example, regions with a smaller aquifer depth and/or higher salt concentration of imported surface water could experience more rapid salt build-up. Another major determinant is initial aquifer conditions, a prominent example being the west side of the San Joaquin Valley where the parent material for soils and the aquifer material was marine in origin and contained considerable salts when production began. Consequently, that portion of the valley is subject to severe salinity/drainage problems despite agriculture of the same or less duration than Kern County. Nevertheless, both the model and results are still of interest, as that problem corresponds to the time-series results with a high water table and salt concentration.[10]

Efficient Use

Economic efficiency for the aquifer maximizes the present value of net benefits

$$\sum_{t=1}^{\infty} \alpha^t \pi_t$$

subject to the definitions, constraints, and equations of motion as before, and where $\alpha = 1/(1 + r)$ is the discount factor and $r = 4\%$. Again there are nine control variables (four water application rates and five land areas) and two state variables (hydraulic

---

[9] Archival records indicate the visible presence of salinity in fields previously known to be salt-free, there was a discernible shift in crops from less salt-tolerant wheat to more salt-tolerant barley, and wheat yields declined by some 65%. Salt build-up is attributed to seepage and over-irrigation contributing to high water tables in the presence of low permeability soils, eventually leading to land abandonment (Jacobsen and Adams, 1958; Gelburd, 1985).

[10] Technology can clearly change over the time horizons reported here; however, there are inherent limits to crop salt tolerance and irrigation system efficiencies, implying that all the processes evaluated here will still be relevant. In addition, population and income growth can imply increased food demand matching or exceeding technological development. Consequently, we feel it is of interest to analyze the time-autonomous problem as a baseline case. We also point out that the constant parameter assumption analyzed here is completely consistent with other infinite horizon studies in economic dynamics as well as previous literature on ground water quantity and quality (e.g., Roseta-Palma, 2002).

head and aquifer salt concentration). This problem is solved using dynamic programming. The value function (optimized objective function) is defined by

$$V(h_1, s_1) \equiv \max_{\{w_t, x_t\}} \left[\sum_{t=1}^{\infty} \alpha^t \pi_t \right],$$

where h_1 and s_1 are the initial aquifer height and salt mass, $\mathbf{w}_t$ and $\mathbf{x}_t$ are the decision vectors for applied water and land areas, respectively, and the optimization is subject to relations (1)–(7) and associated definitions and bounds. The value function V must satisfy Bellman's form:

$$(8) \qquad\qquad V(h, s) \equiv \max_{\mathbf{w}, \mathbf{x}} \left[\pi(h, s, \mathbf{w}, \mathbf{x}) + \alpha V \left[\mathbf{g}(h, s, \mathbf{w}, \mathbf{x}) \right] \right],$$

where π is annual net benefits as (implicitly) defined by equations (1)–(5) and associated definitions, and $\mathbf{g}$ is a vector function which gives hydraulic head and aquifer salt mass in the next period as functions of the state and control variables. The vector function $\mathbf{g}$ is defined by the equations of motion (6) and (7).

Equation (8) is a functional equation in the unknown value function and follows from standard arguments in the dynamic programming literature (Bertsekas, 1976; Judd, 1998). Also note that the optimal decision rules are the solution to the control optimization problem on the right-hand side of (8) and are functions of the state variables. This optimization problem differs from common property where users maximize current net benefits [the first term on the right-hand side of equation (8)] while ignoring future impacts on hydraulic head and aquifer salt concentration (accounted for by the second term), implying common property is inefficient.

Bellman's equation (8) is solved for the value function and associated optimal decision rules using a successive approximation algorithm (value function iteration) after discretizing the aquifer state space (Bertsekas, 1976; Judd, 1998). The overall structure of this algorithm is standard. The algorithm is first initialized by assuming an initial estimate of the value function which is identically zero. At the beginning of each iteration, a smooth estimate of the value function is created from the current estimate of the value function as described below. This smooth approximation is inserted into the right-hand side of Bellman's equation (8), and the control optimization problem indicated in (8) is solved for every point in state-space. This yields a new estimate of the value function for the next iteration. This procedure is repeated until the algorithm converges, after which it is straightforward to calculate the optimal decision rules and associated optimal time paths.

As in all dynamic programming problems, several implementation issues arise. The control optimization problems in (8) at each point in state-space are solved using MINOS (Murtagh and Saunders, 1998), which is an established and widely used general purpose solver. Consequently, a smooth approximation to the value function is needed, as MINOS uses gradient-based procedures. Standard polynomials such as quadratic or cubic are not necessarily shape-preserving and can distort the successive approximation process (Judd, 1998)—which has also been our experience on other problems. Accordingly, we use a bicubic spline (Press et al., 1992; Judd, 1998) to approximate the value function. A bicubic spline is a function consisting of piecewise polynomials where each polynomial holds over a region of the function domain (here, the state-space grid). The

polynomials are third order and are estimated so that they fit the estimated value function points exactly and have continuous derivatives everywhere, including the cell boundaries between each polynomial.

To further increase computational efficiency and preserve shape, the derivatives of the value function being estimated in each iteration are also computed at each point in the state-space along with the level values. These derivative estimates utilize the envelope theorem and shadow values from the control optimization problems. Both the computed level values and derivatives for the value function estimate at each point in state-space are used as inputs to create an exact-fit bicubic spline approximation. This serves as the smooth approximation for the value function to be used on the right-hand side of Bellman's equation (8).[11]

Figure 4 shows that the efficient time paths are qualitatively similar to the common property solution but exhibit significant quantitative differences. Hydraulic head under economic efficiency follows the U-shaped path to a steady-state as previously observed, but remains at significantly higher levels and reaches the steady-state maximum level sooner. Although the aquifer salt concentration increases through time, as in the common property solution, the rate of increase is somewhat less and the steady-state level is approximately 20% lower. Efficient annual net benefits are generally declining until the steady-state as in common property, but they are generally higher than previously observed. The difference can be quite substantial, amounting to $67 acre^{-1} yr^{-1} in the steady-state, for example. Basin-wide annualized net benefits are $552 and $530 million/year under efficiency and common property, respectively.

Efficient time paths for the decision variables are not illustrated, as they have the same qualitative properties as common property in terms of shape. However, the time-series paths do differ quantitatively. To briefly summarize the differences, after approximately year 200, land areas irrigated with surface water are more stable under efficiency than common property: they are lower during the intermediate time periods but slightly higher during the steady-state. Surface water applied depths generally exceed those under common property by up to 1 ft/yr. Land areas irrigated with ground water are significantly less than common property in the initial years, but roughly comparable afterward. Applied ground water depths are initially comparable to those under common property, but during the intermediate periods they can exceed the common property solution by up to 0.5 ft/yr or more. This is presumably due to the higher water table and lower aquifer salt concentration during the intermediate periods. Another significant quantitative difference is that evaporation ponds are initiated earlier under efficiency. This is the primary mechanism for maintaining the lower aquifer salt concentration under efficiency.

As implied by the preceding results, efficient management restricts ground water withdrawals in the early periods in order to achieve a higher water table than would otherwise occur. This reduces pumping costs and also dilutes the aquifer salt concentration. Later, evaporation ponds stabilize the aquifer salt concentration at lower levels than otherwise would occur. These actions contribute to a higher level of annual net

---

[11] The bicubic spline results in an algebraic system of the unknown coefficients given the finite set of level values and associated derivatives for the function to be approximated (here, the value function) and given the requirements for continuous derivatives along the boundaries of the individual polynomials. This system can be solved by efficient algorithms as discussed by Press et al. (1992) and Judd (1998). These references provide excellent discussions of bicubic splines and general approximation theory.

benefits in the basin over the majority of the time horizon (CP net benefits exceed those under efficiency for the first seven years). Ultimately, the differences occur because efficient ground water withdrawals are chosen to reflect both current net benefits and future impacts, while common property considers only the former. Thus, efficient use can be viewed as an investment whereby growers forego early returns in exchange for higher returns later, with the net effect being positive.

Aquifer Management Benefits

Common property is theoretically inefficient because it ignores future impacts of current decisions, and the above results demonstrate potentially large empirical disparities. However, whether or not the resource should be actively managed depends in part on management benefits defined as the difference between the present values of common property and efficiency. Starting with Gisser and Sanchez (1980), a substantial literature has found that management benefits are typically modest but, as noted previously, this literature has focused on pumping cost externalities without consideration of water quality.[12] For the region here, annualized management benefits are $25.62 acre^{-1} yr^{-1}. Compared with the results summarized in table 4 (which consider only water quantity), this is significantly larger than previous estimates for both this basin and other western U.S. ground water basins (save one which is almost identical).

Although the model developed here differs from previous studies in both the study area and parameter values, sensitivity analysis in the previous studies typically does not find large changes in management benefits either across regions or due to reasonable changes in parameter values (Koundouri, 2004). Consequently, the question arises as to whether the larger benefits reported here are due to water quality (salinity). This was investigated with an equivalent non-saline model, where ground water salt concentration is maintained at a constant value equal to surface water salt concentration over the horizon. Management benefits with no salinity are $24.58 acre^{-1} yr^{-1}, or almost the same as reported with salinity. This finding is understandable given that salinization occurs over a relatively long time scale, and discounting reduces the importance of the far future, as emphasized in the sustainability literature (Portney and Weyant, 1999).

Table 5 further explores management benefits as influenced by initial conditions. Here various points along the CP time path are selected as starting points for both CP and efficiency to estimate management benefits under different initial conditions. While management benefits are influenced by the starting point, in no case do they exceed the values reported above by any substantial amount. While salinity does not dramatically affect management benefits, it does seem crucial for an overall understanding of the ground water problem. As an example, in the non-saline case, hydraulic head converges to a steady-state near the bottom of the aquifer (-230 ft MSL), while in the saline model, hydraulic head never falls below 10 ft MSL and eventually converges to a steady-state at the *upper* aquifer bound. Thus it would not be possible to understand the long-run aquifer dynamics without accounting for aquifer salinization.

---

[12] Based on a survey of 15 studies, Koundouri (2004) reports management benefits range from 0.01% to 409.4% of common property welfare, with a median value of 3%.

Table 4. Estimated Management Benefits for Western U.S. Ground Water Basins

Location	Estimated Ground Water Management Benefits[a] ($ acre^{-1} yr^{-1})	References
Kern County (California)	[1.67, 8.34]	Dixon (1989); Feinerman and Knapp (1983); Knapp and Olson (1995); Knapp et al. (2003)
Madera County (California)	[0.55, 3.29]	Provencher (1993); Provencher and Burt (1994)
Yolo County (California)	25.52	Noel, Gardner, and Moore (1980)
Pecos Basin (New Mexico)	[0.00, 0.04]	Gisser and Sanchez (1980); Allen and Gisser (1984)
Ogallala (New Mexico)	[0.01, 7.03]	Brill and Burness (1994); Burness and Brill (2001)
Ogallala (Texas High Plains)	[0.02, 0.09]	Nieswiadomy (1985); Kim et al. (1989)

Note: All monetary values have been adjusted for inflation, and are in 2000 dollars.
[a] Values in brackets [ ] represent the range of estimated values from low to high when there are multiple studies for the region.

Table 5. Aquifer Management Benefits Under Alternate Initial Conditions

h_0 (ft MSL)	c_{g0} (dS/m)	Present Value of Net Benefits Common Property ($/acre)	Efficiency ($/acre)	Management Benefits ($ acre^{-1} yr^{-1})
360	1	586.0	612.3	26.3
0	5	422.3	434.7	12.4
130	10	417.9	433.7	15.8
280	13	442.8	466.1	24.7
380	14	481.6	490.0	8.4
380	20	343.0	363.0	20.0

Note: The variables h_0 and c_{g0} are defined as initial hydraulic head and aquifer salt concentration, respectively.

Aquifer salinization is also likely important for long-run sustainable resource management. As emphasized in the sustainability literature (Portney and Weyant, 1999), discounting reduces the importance of the far future. Under sustainability and reduced emphasis on discounting, then the differences between CP and efficiency in the physical variables and annual net benefits farther out in time are likely to become much more significant, and hence the importance of accounting for aquifer salinization may also increase. These observations are heightened by the historical evidence cited at the outset which implicates soil and aquifer salinization as contributors to the downfall of several civilizations.

Externalities and Policy Instruments

The preceding analysis demonstrates that there are significant benefits associated with managing the aquifer to achieve efficiency. But what is less obvious is specifically how efficiency might be attained through policy intervention. Any successful policy must address two externalities: ground water extractions and salt emissions. Salt emissions

to the aquifer generate an unambiguously negative externality. However, ground water withdrawals generate a negative externality in the classic case analyzed in the literature (declining water table leading to increased pumping costs), but they also can generate a positive externality in the saline aquifer case either by lowering a high water table and thereby mitigating drainage problems, or by reducing aquifer salt mass via pond disposal. In general, there are a variety of policy instruments for alleviating nonpoint pollution (Griffin and Bromley, 1982). Quantity regulation and/or market establishment policies are reasonably straightforward from the preceding results. The remainder of this section addresses the design of a pricing policy to manage the aquifer.

The model defined by equations (1)–(7) and associated definitions contains a potentially large number of decision variables for land area and applied water depths, and in general it would not be tractable to define price instruments for each of these micro-activities. Inspection of the equations of motion, however, indicates hydraulic head and aquifer salt concentration depend only on aggregate flows of water and salt; the specific micro-decisions that produce these aggregate flows affect current net returns, but not dynamics or future discounted returns. The model is therefore analogous to Baumol and Oates (1988) who show that a per unit emission charge, set equal to the marginal external cost of emissions at the efficient level of environmental quality, can achieve the efficient solution.

With two externalities, two such prices are required, one for salt emissions and one for ground water extractions. Furthermore, because the aquifer state variables depend only on aggregate flows, it follows that the efficient price instruments also depend on these flows. For policy analysis, therefore, it is convenient to specify a mathematically equivalent model formulated in terms of aggregate quantities, after which the micro-decisions can be derived. To this end, define $\mathbf{q}_t = \{q_{st}, q_{ga,t}, q_{gp,t}, q_{dt}\}$ as basin-wide quantities for surface water imports, ground water extractions for agricultural production, drainage (pond) water, and deep percolation flows in year t.

The agricultural production problem in aggregate quantities in year t is then written as:

$$(9) \qquad \begin{array}{c} \text{Max } \pi \\ {\scriptstyle w,x} \end{array}$$

$$\text{s.t.: } \sum_j w_{sj} x_{sj} = q_s, \ \sum_j w_{gj} x_{gj} = q_{ga}, \ x_p = q_{gp}/e_p, \ \sum_{i \in \{s,g\}} \sum_j d_{ij} x_{ij} = q_d,$$

$$\tilde{\mathbf{g}}(\mathbf{w}, \mathbf{x}) \le 0,$$

where π is defined by (1) and associated definitions, and $\tilde{\mathbf{g}}$ is a vector of model constraints including land and rotation constraints and variable bounds. The solution to this problem defines a conditional net benefit function $\tilde{\pi}(h, s, \mathbf{q})$ giving basin net benefits as a function of the aquifer states and the vector of aggregate quantities defined above. This optimization problem may not be feasible for all possible combinations of the aggregate flow variables; however, this can be handled by defining the conditional net benefit function as negative infinity in these instances.

With these definitions, the decision problem in year t for both common property and efficiency is to choose the vector of aggregate basin-wide flows to maximize

$$(10) \qquad\qquad\qquad \tilde{\pi}(h_t, s_t, \mathbf{q}_t) + \alpha J(h_{t+1}, s_{t+1}),$$

where $J(h_t, s_t) \equiv 0$ for common property, $J(h_t, s_t) \equiv V(h_t, s_t)$ for efficiency, and the future states are calculated from the original equations of motion. From the various definitions, it follows that the solution to this problem must be identical to that of the original problems investigated earlier, and the micro-decisions for applied water **w** and land areas **x** can be back-calculated from the conditional optimization problem (9) given the solution to (10).

With this reformulated structure, optimal regime-dependent quantity decisions are characterized by the first-order conditions:

$$(11) \qquad \frac{\partial \tilde{\pi}}{\partial q_s} + \frac{\alpha \beta_s}{As^y} \frac{\partial J}{\partial h} = -\alpha c_s \frac{\partial J}{\partial s}, \qquad\qquad \frac{\partial \tilde{\pi}}{\partial q_{ga}} = \frac{\alpha}{As^y} \frac{\partial J}{\partial h},$$

$$(12) \qquad \frac{\partial \tilde{\pi}}{\partial q_{gp}} - \frac{\alpha s_t}{As^y(h_t - \underline{h})} \frac{\partial J}{\partial s} = \frac{\alpha}{As^y} \frac{\partial J}{\partial h}, \qquad\qquad \frac{\partial \tilde{\pi}}{\partial q_d} + \frac{\alpha}{As^y} \frac{\partial J}{\partial h} = 0.$$

for surface water, ground water, drainage, and deep percolation, respectively (function arguments and time subscripts have been suppressed). These conditions have the usual interpretation and have been arranged whereby the terms on the left-hand side represent marginal benefit while those on the right represent marginal cost. Recalling $J \equiv 0$ for common property, it is apparent that the terms involving the partial derivatives of J are ignored by users under the common property regime, thus leading to inefficiency. These first-order conditions extend the usual analysis (e.g., Provencher and Burt, 1993) to include quality considerations, although see Roseta-Palma (2002) for a somewhat different formulation.

Under a decentralized common property management regime where prices can be charged for ground water extraction and salt disposal to the aquifer, producers maximize:

$$(13) \qquad \tilde{\pi}(h, s, \mathbf{q}) - p^{gw} * \left(q_{ga} + q_{gp} - \beta_s q_s - q_d \right) - p^{gs} * \left(c_s q_s - \frac{s}{As^y(h - \underline{h})} q_{gp} \right),$$

where p^{gw} and p^{gs} are the prices for ground water and salt quantities, respectively, and again time subscripts are suppressed. The associated first-order conditions are (after rearranging terms):

$$(14) \qquad \frac{\partial \tilde{\pi}}{\partial q_s} + p^{gw}\beta_s = p^{gs}c_s, \qquad\qquad \frac{\partial \tilde{\pi}}{\partial q_{ga}} = p^{gw},$$

$$(15) \qquad \frac{\partial \tilde{\pi}}{\partial q_{gp}} + \frac{p^{gs}s_t}{As^y(h_t - \underline{h})} = p^{gw}, \qquad\qquad \frac{\partial \tilde{\pi}}{\partial q_d} + p^{gw} = 0.$$

Comparing conditions (11)–(12) and conditions (14)–(15) reveals that prices

$$p^{gw} = \frac{\alpha}{As^y} \frac{\partial J}{\partial h} \quad \text{and} \quad p^{gs} = -\alpha \frac{\partial J}{\partial s}$$

will induce efficiency. Substituting the original value function V for J and converting from salt mass to salt concentration gives:

$$p_t^{gw} = \frac{\alpha}{As^y}\left[\frac{\partial V}{\partial h} - \frac{c_{gt}}{h_t - \underline{h}}\frac{\partial V}{\partial c_g}\right] \text{ and } p_t^{gs} = -\frac{\alpha}{As^y(h_t - \underline{h})}\frac{\partial V}{\partial c_g},$$

where time subscripts have been re-inserted to emphasize the optimal prices can vary through time. Note, although $\partial V/\partial c_g$ is invariably negative, $\partial V/\partial h > 0$ for low hydraulic head and $\partial V/\partial h < 0$ for drainage-limited conditions. Therefore, growers are charged for extractions and compensated for deep percolation during the Resource Extraction and Waste Disposal eras, while the reverse occurs during the Drainage era. Growers always are charged for salt emissions and compensated for pond disposal.

Figure 6 plots state-dependent optimal ground water and salt emission prices. When drainage is not constraining and/or salt concentrations are low, the extraction price is generally increasing in water table elevation. It also increases with aquifer salt concentration up to a point, after which it decreases. The explanation for this pattern is largely driven by the corresponding state-dependent levels of efficient ground water extraction. To save space, these are not plotted, but they are qualitatively similar to the common property rules discussed earlier. In particular, the benefit from either a unit increase in water table elevation or a unit decrease in aquifer salt concentration increases with the extraction rate; therefore, the optimal price is higher. Figure 6 also shows that under drainage-limited conditions, the extraction price decreases in water table elevation and eventually becomes negative. This occurs because a high saline water table is a liability, and hence it is necessary to charge for deep percolation flows and subsidize extractions.

Salt emission prices decline with water table elevation at low salinity levels but increase at high salinity levels. They also increase with salt concentration up to an elevation-dependent point, after which they decline. As before, this pattern is largely explained by the corresponding levels of optimal ground water extraction. An additional consideration is the dilution effect which apparently overrides the quantity effect and produces the observed price decline with elevation at lower salinity levels. Figure 6 also reports price time-series evaluated along the efficient path. The extraction price initially falls during the Resource Extraction era, rises during the Waste Disposal era, and then declines to an eventual negative level during the Drainage era as the aquifer is increasingly salinized and elevated. Salt prices are generally increasing to a steady-state level following an initial transition period. The explanation for the time-series pattern follows from the considerations noted above for state-dependent prices.

It is important to note that increasing water prices and emission costs to growers can have adverse equity impacts. If ground water is managed by an external entity and the revenue from pricing instruments leaves the region, then growers can lose in the aggregate (Weitzman, 1974). If the basin is managed internally for the cooperative benefit of the region, revenues from water pricing and emission charges can be rebated to growers and others impacted by prices, or used to support other public projects. As long as rebates are not related to charges (e.g., per acre rebates), then efficiency will be maintained and the region benefits from management. This topic has received relatively little attention in the ground water literature (although see Feinerman and Knapp, 1983; Burness and Brill, 2001; and Provencher and Burt, 1994).
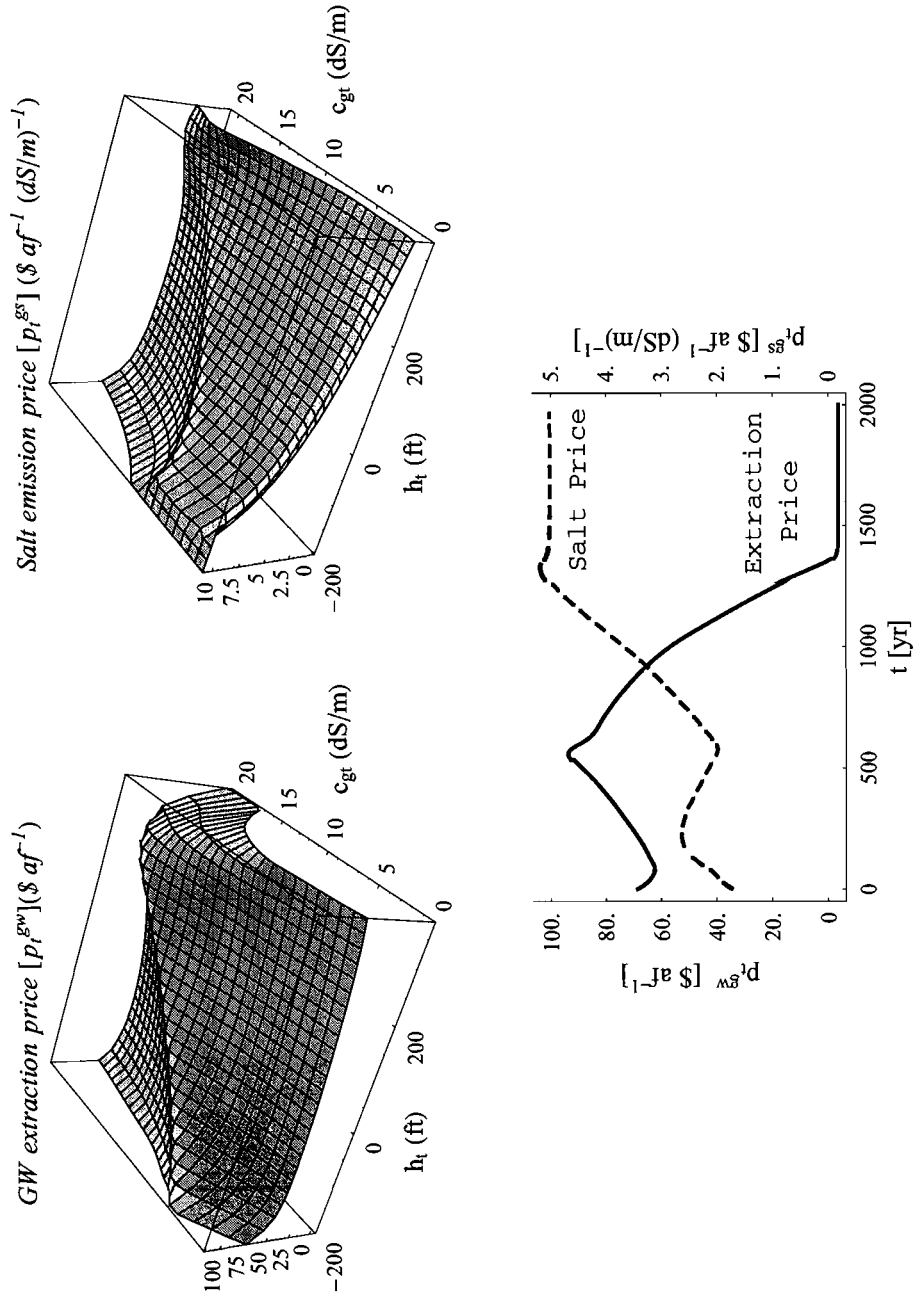
Figure 6. Regulatory prices for the agricultural production/saline aquifer system: (a) State-dependent ground water extraction prices, (b) state-dependent ground water salt emission prices, and (c) time series for extraction and salt emission prices

Conclusions

All economies are subject to conservation of mass and energy (Ayres and Kneese, 1969); however, the implications over long time and space scales are not often explored. Beginning with a plentiful, high-quality resource, the dynamics of the aquifer salinization problem initially are driven by resource extraction. The inevitable waste emissions back to the environment in conjunction with increasing extraction costs eventually result in waste disposal as the primary service role of the resource to the economy. Finally, a drainage regime stabilizes the system at which point the economic value of the aquifer is exhausted. The associated time scales are quite long, but they are order-of-magnitude consistent with historical evidence on salinity in agriculture. The primary reason for the long time scale is that salt quantities imported into the region in surface water are relatively small in comparison to the ultimate waste disposal capacity of the aquifer. The applied surface water depths in the study region are representative of many other regions, but aquifers of shallower depths would experience quicker build-ups.

Economically efficient use of the resource in this model is qualitatively very similar to common property use. Quantitatively, efficient use maintains the aquifer at a substantially higher elevation and lower salt concentration than under common property. This is accomplished at first by limiting ground water withdrawals, and later by initiating salt disposal earlier than under common property. Notably, efficient use is achieved through only modest changes in the decision variables and generates significantly higher future annual net benefits.

Previous studies find relatively small benefits from ground water management, defined as the difference in present values of efficient and common property usage. This may be due to limiting ground water pumping in many areas to overlying users, implying that ultimate resource use is based on marginal conditions, and hence average profit need not be—and typically is not—driven to zero as in a pure open-access resource. This literature has focused almost exclusively on pumping cost externalities; however, numerous other problems can develop, including water quality degradation.

Intuitively, accounting for these additional inefficiencies should increase the potential benefit of resource management. We did find significantly increased management benefits here; yet, somewhat surprisingly, the increase appears to be due less to salinization and more to other model features. This is due at least in part to discounting and the long time scales necessary for salinization to develop. Nevertheless, aquifer salinization does have dramatic implications for long-run aquifer use, so alternate discounting schemes and sustainability criteria which increase the visibility of the future could potentially increase the importance of salinization for overall management benefits.

The model integrates several disparate issues in ground water economics. The early literature focused on pumping cost externalities; later investigations considered prevention and mitigation of rising water tables (Knapp et al., 1990; Shah, Zilberman, and Lichtenberg, 1995); substantial effort has gone into managing agriculture in limited-drainage/high water table regions (Dinar and Zilberman, 1991); and still others have considered ground water quality. At a given point in time, a region may have one or more of these problems but not the others. For example, the west side of the San Joaquin Valley of California has severe salinity/drainage problems, while issues on the east side are excess pumping and falling water tables. Rather than being separate, seemingly unrelated problems, our analysis suggests these can be viewed instead as different stages of the same overall dynamic process.

Finally, the system considered is not sustainable under either common property or efficient use, in the sense that income is generally declining through time. While this finding seems somewhat inevitable given the initial conditions, it neglects the extent to which resource rents might be going into capital formation that could substitute (at least in part) for a declining resource. This is an inherent limitation of any partial equilibrium study of natural resource management for sustainability analysis. The fact that efficient use does not necessarily guarantee sustainability is consistent with the macro-environmental literature on economic growth (Toman, Pezzey, and Krautkraemer, 1995). This would be a fruitful area of future study for ground water and natural resource management in general.

[*Received July 2003; final revision received August 2006.*]

References

Allen, R. C., and M. Gisser. "Competition versus Optimal Control in Groundwater Pumping When Demand Is Nonlinear." *Water Resour. Res.* 20(July 1984):752–756.

Ayres, R. U., and A. V. Kneese. "Production, Consumption, and Externalities." *Amer. Econ. Rev.* 59(June 1969):282–297.

Backlund, V. L., and R. R. Hoppes. "Status of Soil Salinity in California." *California Agriculture* 38(October 1984):8–9.

Baumol, W. J., and W. E. Oates. *The Theory of Environmental Policy*, 2nd ed. London: Cambridge University Press, 1988.

Bernardo, D. J., H. P. Mapp, G. J. Sabbagh, S. Geleta, K. B. Watkins, R. L. Elliott, and J. F. Stone. "Economic and Environmental Impacts of Water Quality Protection Policies 1: Framework for Regional Analysis." *Water Resour. Res.* 29(1993):3069–3079.

Bertsekas, D. P. *Dynamic Programming and Stochastic Control.* New York: Academic Press, 1976.

Brill, T. C., and H. S. Burness. "Planning versus Competitive Rates of Groundwater Pumping." *Water Resour. Res.* 30(June 1994):1873–1880.

Burness, H. S., and T. C. Brill. "The Role for Policy in Common Pool Groundwater Use." *Resour. and Energy Econ.* 23(2001):19–40.

Characklis, G. W., R. C. Griffin, and P. B. Bedient. "Measuring the Long-Term Regional Benefits of Salinity Reduction." *J. Agr. and Resour. Econ.* 30(April 2005):69–93.

Conrad, J. M., and L. J. Olson. "The Economics of a Stock Pollutant: Aldicarb on Long Island." *Environ. and Resour. Econ.* 2(1992):245–258.

Cummings, R. G. "Optimum Exploitation of Groundwater Reserves with Saltwater Intrusion." *Water Resour. Res.* 7(1971):1415–1424.

Cummings, R. G., and J. W. McFarland. "Groundwater Management and Salinity Control." *Water Resour. Res.* 10(1974):909–915.

Dinar, A. "Impact of Energy Cost and Water Resource Availability on Agriculture and Groundwater Quality in California." *Resour. and Energy Econ.* 16(1994):47–66.

Dinar, A., M. P. Aillery, and M. R. Moore. "A Dynamic Model of Soil Salinity and Drainage Generation in Irrigated Agriculture: A Framework for Policy Analysis." *Water Resour. Res.* 29(1993):1527–1537.

Dinar, A., and K. C. Knapp. "A Dynamic Analysis of Optimal Water Use Under Saline Conditions." *West. J. Agr. Econ.* 11(July 1986):58–66.

Dinar, A., J. Letey, and H. J. Vaux. "Optimal Ratios of Saline and Nonsaline Irrigation Waters for Crop Production." *Soil Sci. Society of Amer. J.* 50(1986):440–443.

Dinar, A., and A. Xepapadeas. "Regulating Water Quantity and Quality in Irrigated Agriculture." *J. Environ. Mgmt.* 54(1998):273–289.

Dinar, A., and D. Zilberman, eds. *The Economics and Management of Water and Drainage in Agriculture.* Boston: Kluwer Academic Publishers, 1991.

Dixon, L. S. "Models of Groundwater Extraction with an Examination of Agricultural Water Use in Kern County, California." Unpub. Ph.D. diss., Dept. of Agr. and Resour. Econ., University of California, Berkeley, May 1989.

Feinerman, E., and K. C. Knapp. "Benefits from Groundwater Management: Magnitude, Sensitivity, and Distribution." *Amer. J. Agr. Econ.* 65(November 1983):703–710.

Fleming, R. A., R. M. Adams, and D. E. Ervin. "The Role of Soil Test Information in Reducing Groundwater Pollution." *J. Agr. and Resour. Econ.* 23(July 1998):20–38.

Gardner, R., M. R. Moore, and J. M. Walker. "Governing a Groundwater Commons: A Strategic and Laboratory Analysis of Western Water Law." *Econ. Inquiry* 35(1997):218–234.

Gelburd, D. E. "Managing Salinity: Lessons from the Past." *J. Soil and Water Conserv.* 40(July-August 1985):329–331.

Gisser, M., and D. A. Sanchez. "Competition versus Optimal Control in Groundwater Pumping." *Water Resour. Res.* 16(1980):638–642.

Griffin, R. C., and D. W. Bromley. "Agricultural Runoff as a Nonpoint Externality: A Theoretical Development." *Amer. J. Agr. Econ.* 64(August 1982):547–552.

Jacobsen, T., and R. M. Adams. "Salt and Silt in Ancient Mesopotamian Agriculture." *Science* 128(1958): 1251–1258.

Judd, K. L. *Numerical Methods in Economics.* Cambridge, MA: The MIT Press, 1998.

Kan, I., K. A. Schwabe, and K. C. Knapp. "Microeconomics of Irrigation with Saline Water." *J. Agr. and Resour. Econ.* 27(July 2002):16–39.

Kern County Water Agency (KCWA). *Water Supply Report 1995.* Bakersfield, CA, 1998.

Kim, C. S., M. R. Moore, J. J. Hanchar, and M. Nieswiadomy. "A Dynamic Model of Adaptation to Resource Depletion: Theory and an Application to Groundwater Mining." *J. Environ. Econ. and Mgmt.* 17(1989):66–82.

Kim, C. S., C. Sandretto, R. A. Fleming, and R. A. Adams. "An Alternative Specification for Modeling Groundwater Dynamics." *Natural Resour. Modeling* 10(1997):173–183.

Knapp, K. C. "Economics of Salinity and Drainage Management in Irrigated Agriculture." In *Agricultural Drainage,* ASA Monograph 38, eds., R. W. Skaggs and J. van Schilfgaarde, pp. 1261–1284. Madison, WI: American Society of Agronomy, Inc., 1999.

Knapp, K. C., and A. Dinar. "Reuse of Agricultural Drainage Waters: An Economic Analysis." *Water Resour. Bull.* 20(1984):521–525.

Knapp, K. C., and L. J. Olson. "The Economics of Conjunctive Groundwater Management with Stochastic Surface Supplies." *J. Environ. Econ. and Mgmt.* 28(1995):340–356.

Knapp, K., B. Stevens, J. Letey, and J. D. Oster. "A Dynamic Optimization Model for Irrigation Investment and Management Under Limited Drainage Conditions." *Water Resour. Res.* 26(July 1990): 1335–1343.

Knapp, K. C., M. Weinberg, R. Howitt, and J. Posnikoff. "Water Transfers, Agriculture, and Groundwater Management: A Dynamic Economic Analysis." *J. Environ. Mgmt.* 67(2003):291–301.

Koundouri, P. "Potential for Groundwater Management: Gisser-Sanchez Effect Reconsidered." *Water Resour. Res.* 40(June 2004). Online journal.

Letey, J., and K. C. Knapp. "Simulating Saline Water Management Strategies with Application to Arid-Region Agroforestry." *J. Environ. Quality* 24(September-October 1995):934–940.

Murtagh, B. A., and M. A. Saunders. *MINOS 5.4 User's Guide.* Tech. Report No. SOL 83-20R, Systems Optimization Laboratory, Stanford University, 1998.

Negri, D. "The Common Property Aquifer as a Differential Game." *Water Resour. Res.* 25(1989):9–15.

Nieswiadomy, M. "The Demand for Irrigation Water in the High Plains of Texas, 1957–80." *Amer. J. Agr. Econ.* 67(August 1985):619–626.

Noel, J. E., B. D. Gardner, and C. V. Moore. "Optimal Regional Conjunctive Water Management." *Amer. J. Agr. Econ.* 62(August 1980):489–498.

Portney, P. R., and J. P. Weyant, eds. *Discounting and Intergenerational Equity.* Washington, DC: Resources for the Future, 1999.

Press, W. H., S. A. Taukolsky, W. T. Vetterling, and B. P. Flannery. *Numerical Recipes in FORTRAN: The Art of Scientific Computing,* 2nd ed. London: Cambridge University Press, 1992.

Provencher, B. "A Private Property Rights Regime to Replenish a Groundwater Aquifer." *Land Econ.* 69(November 1993):325–340.

Provencher, B., and O. R. Burt. "The Externalities Associated with the Common Property Exploitation of Groundwater." *J. Environ. Econ. and Mgmt.* 24(1993):139–158.

———. "A Private Property Rights Regime for the Commons: The Case for Groundwater." *Amer. J. Agr. Econ.* 76(November 1994):875–888.

Reinelt, P. "Seawater Intrusion Policy Analysis with a Numerical Spatially Heterogeneous Dynamic Optimization Model." *Water Resour. Res.* 41(2005). Online journal.

Roseta-Palma, C. "Groundwater Management When Water Quality Is Endogenous." *J. Environ. Econ. and Mgmt.* 44(2002):93–105.

Scarre, C. *Smithsonian Timelines of the Ancient World: A Visual Chronology from the Origins of Life to AD 1500.* Boston: Houghton Mifflin, 1993.

Shah, F., D. Zilberman, and E. Lichtenberg. "Optimal Combination of Pollution Prevention and Abatement Policies: The Case of Agricultural Drainage." *Environ. and Resour. Econ.* 5(1995):29–49.

Taghavi, S., R. Howitt, and M. Marino. "Optimal Control of Ground-Water Quality Management: Nonlinear Programming Approach." *J. Water Resour. Planning and Mgmt.* 120(1994):962–982.

Tanji, K. K. "Nature and Extent of Agricultural Salinity." In *Agricultural Salinity Assessment and Management,* ed., K. K. Tanji, pp. 1–17. New York: American Society of Civil Engineers, 1990.

Toman, M. A., J. Pezzey, and J. Krautkraemer. "Neoclassical Economic Growth Theory and Sustainability." In *The Handbook of Environmental Economics,* ed., D. W. Bromley, pp. 139–165. Cambridge, MA: Blackwell Publishers, 1995.

Vaux, H. J., Jr. "Water Scarcity and Gains from Trade in Kern County California." In *Scarce Water and Institutional Change,* ed., K. D. Frederick, pp. 67–101. Washington, DC: Resources for the Future, Inc., 1986.

Weitzman, M. L. "Free-Access vs. Private Ownership as Alternative Systems for Managing Common Property." *J. Econ. Theory* 8(1974):225–234.

Wichelns, D. "An Economic Model of Waterlogging and Salinization in Arid Regions." *Ecological Econ.* 30(1999):475–491.

Zeitouni, N. "Efficient Management of Groundwater Quality." *Natural Resour. Modeling* 5(1991): 293–320.

Zeitouni, N., and A. Dinar. "Mitigating Negative Water Quality and Quality Externalities by Joint Management of Adjacent Aquifers." *Environ. and Resour. Econ.* 9(1997):1–20.