Integrated Hydrologic-Agronomic-Economic Model for River Basin Management

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Abstract: The interdisciplinary nature of water resources problems requires the integration of technical, economic, environmental, social, and legal aspects into a coherent analytical framework. This paper presents the development of a new integrated hydrologic-agronomic-economic model in the context of a river basin in which irrigation is the dominant water use and irrigation-induced salinity presents a major environmental problem. The model's main advantage is its ability to reflect the interrelationships between essential hydrologic, agronomic, and economic components and to explore both economic and environmental consequences of various policy choices. All model components are incorporated into a single consistent model, which is solved in its entirety by a simple but effective decomposition approach. The model is applied to a case study of water management in the Syr Darya River basin in Central Asia.

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Integrated Hydrologic-Agronomic-Economic Modeling

The interdisciplinary nature of water resources problems requires the integration of technical, economic, environmental, social, and legal aspects into a coherent analytical framework (Serageldin 1995). A river basin is a natural unit for integrated water resources planning and management, since water interacts with and to a large degree controls the extent of other natural components such as soil, vegetation, and wildlife. Human activities, too, so dependent on water availability, might best be organized and coordinated within the river basin unit. Water resources management needs to focus on an integrated basin system, including water supply, water demand, and intermediate components. Accordingly, policy instruments designed to make more rational economic use of water resources are likely to be applied at this level. To provide an analytical framework at the basin scale, modeling techniques for integrated models have been studied and found to present opportunities for the advance of water resources management (McKinney et al. 1999).

Irrigation is the dominant water use in many arid and semiarid river basins, and irrigation management plays a critical role in water management in these basins. An integrated hydrologic-agronomic-economic model combines the management of surface and subsurface reservoir (supply) systems with irrigation and farming, evaluates irrigated crop yields, and derives reservoir operating policies. Some recent studies of such systems include Vedula and Mujumdar (1992), Dudley and Scott (1993), and Vedula and Kumar (1996), in which reservoir release and field-water allocation decisions are integrated in a modeling framework, taking into account soil moisture dynamics and crop growth at the field level. Reservoir inflow and precipitation can be considered stochastic, and water allocation among multiple crops is included (Vedula and Kumar 1997). Models in all these studies are applied to a single farm and a single reservoir, and result analysis is limited to reservoir operation and irrigation scheduling.

Moreover, due to increasing water scarcity and worsening water quality, irrigation planning should take both irrigation purposes and water quality control into account. Models integrating irrigation water application and salinity control have been extensively studied since the 1970s [for example, Yaron et al. (1980); Bras and Seo (1987); Musharrafieh et al. (1995)].

Important economic issues in integrated economic-hydrologic river basin modeling include transaction costs, agricultural productivity effects of allocation mechanisms, intersectoral water allocation, environmental impacts of allocations, and property rights in water for different allocation mechanisms (Rosegrant and Meinzen-Dick 1996). A notable effort in integrating economic and hydrologic modeling into a multibasin conjunctive use model was reported by Noel and Howitt (1982). A number of auxiliary economic and hydrologic models were used to derive sets of linear first-order difference equations. These were incorporated into a linear-quadratic control model that was used to determine the optimal spatial and temporal allocation of a complex water resource system and to examine the relative performance of various policies (social optimum, pumping tax, and laissez-faire).

Lefkoff and Gorelick (1990b) combined distributed parameter simulations of stream-aquifer interactions, salinity changes, and agronomic functions into a long-term optimization model to determine annual groundwater pumping, surface-water applications, and planting acreage. This model was further extended to incor-

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porate a rental market mechanism (Lefkoff and Gorelick 1990a) considering annual water trading among farmers.

Instead of fixed-quantity proposals (prescribed water-use rights), endogenous demand functions for individual demand sites have been included in the integrated hydrologic-economic models. Booker and Young (1994) provided a remarkable example using this type of analysis. Their model includes complex relationships on both water supply and demand sides. For supply, flow and salt balances were written for a river basin network (the Colorado River); on the demand side, marginal benefit functions were defined for offstream uses (irrigation, municipal, and thermal energy) and instream uses (hydropower and water quality). The model was used to estimate impacts of alternative institutional scenarios, river flows, and demand levels.

In terms of model formulation and solution approaches, integrated hydrologic-economic models can be classified into models with a compartment modeling approach and models with a holistic approach (Braat and Lierop 1987). Under the compartment approach there is a loose connection between the economic and hydrologic components, and only output data is usually transferred between the components [for example, Lefkoff and Gorelick (1990a,b)]. Under the holistic approach, there is one single unit with both components embedded in a consistent model. Information transfer between hydrologic, agronomic, and economic components remains a technical obstacle in ''compartment modeling,'' while in ''holistic modeling,'' information transfer is conducted endogenously. However, the hydrologic side is often considerably simplified due to model-solving complexities [for example, Booker and Young (1994)].

Under the compartment modeling approach, combined simulation and optimization techniques can be used, while under the holistic approach, the model must be solved in its entirety. Stochastic dynamic programming (SDP) has often been used to solve those complex holistic models [for example, Vedula and Mujumdar (1992); Dudley and Scott (1993)]. However, SDP is often computationally impractical due to dimensionality problems. Other solution approaches include linear programming (Booker and Young 1994), and quadratic programming (Bras and Seo 1987).

This paper extends integration of the management of a water supply system and irrigation farming system to a spatially much larger and more complex system than previous studies, such as Vedula and Mujumdar (1992) and Dudley and Scott (1993). The model is developed based on a river basin network, including multiple-source nodes (reservoirs, aquifers, river reaches, etc.) and multiple demand sites, with a number of crops considered in each demand site. This paper also extends the connections between hydrologic, agronomic, and economic modeling components, which have not been presented in detail before. In order to model water allocation mechanisms and policies, agroclimatic variability, and multiple water uses and users, we consistently account for a large number of physical, economic, and behavioral relationships.

Our modeling framework includes the following components: (1) flow and pollutant (salt) transport and balance in the river basin network, including the crop root zone; (2) irrigation and drainage processes; (3) crop production functions, including effects of both water stress and soil salinity; (4) benefit functions for both instream-water and offstream uses, accounting for economic incentives for salinity control and water conservation; (5) tax and subsidy systems to induce efficient water allocation, improvement of irrigation-related capacities, and protection of the environment; (6) infrastructure improvement with consideration of investment; and (7) institutional rules and policies that govern water allocation.

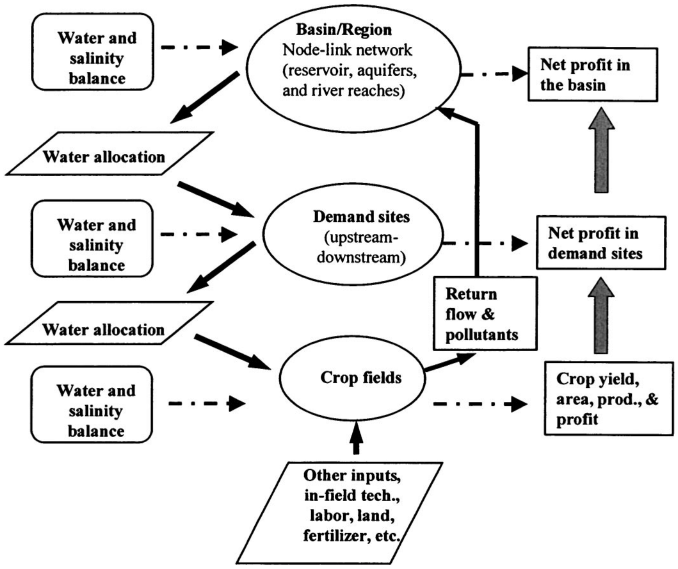

Fig. 1. Spatial scales for hydrologic and economic modeling

All these components are integrated into a consistent system whose core is a multiperiod network model of the river basin, ranging from crop root zones to the river system, whose objective is to maximize total water use benefit from irrigation, hydropower generation, and ecological water use. The model, which is large and contains many nonlinearities, is solved by a decomposition approach. It is applied to water management analysis of the Syr Darya River in the Aral Sea basin of Central Asia.

Model Description

Referring to Fig. 1, we start with the river basin as a *region*, identify each agricultural demand site within the region as a *farm*, and subdivide each farm into several *areas* with specific soil types. A *soil area* can have several *fields*, corresponding to specific crop patterns. Decisions at the regional level include hydrologic systems operation and water allocation among demand sites (cities and farms). At the farm level, water is allocated to areas with specific soil types, and the efficiency of water distribution and drainage in each farm is determined. Crop acreage and water allocation among crops are determined at the soil area level. Finally, water mixing for irrigation, irrigation scheduling among growing stages, and the type of irrigation technology are determined at the crop field level. The following subsections provide mathematical descriptions of the modeled physical, agronomic, and economic components.

Physical Processes

Water and Salinity Balances in Rivers, Reservoirs, and Groundwater Sources

Water balances at nodes, n, representing rivers, reservoirs, and aquifers can be written as

$$\sum_{n1\in(n1,n)} Q^t(n1,n)-\sum_{n2\in(n,n2)} Q^t(n,n2) = S^t(n)-S^{t-1}(n) \quad \forall \;\; n,t \tag{1}$$

where $Q^t(n1,n)$ = flow from node $n1$ to node n during time period t, and $S^t(n)$ = storage at the end of time period t at node n. Node types include river reaches and tributaries, reservoirs, aquifers, and demand sites. The set $(n1,n)$ represents all links from $n1$ to n while $(n,n2)$ represents all links from n to $n2$.

For many river reaches with a time period of one month, the storage effect can be neglected, that is, $S^t - S^{t-1} = 0$. Inflow to a river reach includes (1) flow from upstream river reaches or reservoirs; (2) return flow from demand sites; (3) discharge from aquifers; and (4) natural drainage. The outflow includes (1) flow diversion to demand sites; (2) flow to downstream river reaches or reservoirs; and (3) evaporation loss. For reservoirs, inflows are from (1) upstream reservoirs or river reaches; and (2) natural drainage. The outflow goes to (1) demand sites; (2) downstream rivers or reservoirs; (3) evaporation loss; and (4) seepage to groundwater. For groundwater sources, given the overall complexity of this model, we use a simple single-tank model (Bear 1977) to simulate flow and salt balance in shallow groundwater, which maintains flow exchanges with irrigated areas. Assuming that each demand site has one groundwater "tank," the inflow to the tank includes natural recharge (R), surface water leakage (L), and deep percolation (*DP*) from irrigation fields. The outflow includes pumping (P), groundwater extraction to root zones (G), and discharge to surface water systems (*DS*). The resulting flow balance at a groundwater node n is

$$\begin{aligned}\Delta t[R^t(n)+L^t(n)+DP^t(n)-G^t(n)-P^t(n)-DS^t(n)]\\ =AA(n)\cdot s(n)\cdot[h^{t+1}(n)-h^t(n)]\quad\forall\quad n,t\end{aligned}\tag{2}$$

where AA = horizontal area of the aquifer; s = storativity; and h = average water table elevation. A linear relationship is assumed between the discharge *DS* and the water table head *h*. To avoid waterlogging, it is important that the groundwater table, *h*, does not rise above a critical threshold. This critical depth depends on the root depth of the crop, the efficiency of irrigation water use, and the hydraulic characteristics of the soil. This drives the need for sufficient field drainage to prevent waterlogging of fields.

Salinity balances at nodes, *n*, representing river reaches, reservoirs, and aquifers can be expressed as

$$\begin{aligned}\sum_{n1\in(n1,n)} Q^t(n1,n)\cdot C^t(n1)-\sum_{n2\in(n,n2)} Q^t(n,n2)\cdot C^t(n)\\ =S^t(n)\cdot C^t(n)-S^{t-1}(n)\cdot C^{t-1}(n)\quad\forall\quad n,t\end{aligned}\tag{3}$$

where $C^t(j)$ = salt concentration at node j at the end of period t.

Water Allocation within Demand Site

Within a demand site, water delivered from reservoirs, rivers, and local sources is mixed and then allocated to areas with different soil types. Within each area, *a*, surface water is allocated to fields, *f*, according to the following constraints

$$\sum_{n1\in(n1,d)} Q^t(n1,d)\cdot\varepsilon 1(d)=\mathrm{WDA}^t(d)\quad\forall\quad d,t\tag{4a}$$

$$\mathrm{WDA}^t(d)=\sum_a\sum_f \mathrm{WFLD}^t(d,a,f)\quad\forall\quad d,t\tag{4b}$$

where $Q^t(n1,d)$ = water withdrawn from node $n1$ to demand site d during time period t; $\mathrm{WDA}^t(d)$ = water arriving at demand site d; and $\mathrm{WFLD}^t(d,a,f)$ = surface water allocated to field f in area a at demand site d in period t. The variable $\varepsilon 1$ = water distribution efficiency, defined as the ratio of the water arriving at the demand site to the total water diverted to that site. Distribution efficiency depends on the condition of irrigation canals, and it is assumed to be uniform within a demand site, but variable among demand sites.

Water Available to Crops

The total water available to a crop field (*WA*) includes irrigation water (WAI), effective rainfall (*ER*, a data item), and groundwater extraction (*G*):

$$\begin{aligned}WA^t(d,a,f)=\mathrm{WAI}^t(d,a,f)+ER^t(d,a)\cdot A(d,a,f)\\ +G(d,a,f)\quad\forall\quad d,a,f,t\end{aligned}\tag{5}$$

WAI = the total irrigation water applied to a crop field (WAF, including surface water, WFLD, drainage reuse, REUSE, and groundwater, *P*) multiplied by irrigation efficiency ($\varepsilon 2$):

$$\begin{aligned}\mathrm{WAI}^t(d,a,f)&=\mathrm{WAF}^t(d,a,f)\cdot\varepsilon^2(d,a,f)\\ &=[\mathrm{WFLD}^t(d,a,f)+\mathrm{REUSE}^t(d,a,f)\\ &\quad+P^t(d,a,f)]\cdot\varepsilon 2(d,a,f)\quad\forall\quad d,a,f,t\end{aligned}\tag{6}$$

Assuming (1) no surface runoff from the field, and (2) constant efficiency over all crop growth stages, *irrigation efficiency* ($\varepsilon 2$) can be defined as the ratio of irrigation water available for use by crops to the total water applied to fields [$\mathrm{WAF}^t(d,a,f)$ in Eq. (6)].

Since different crops have different salt tolerances, the model allows crops with high salt tolerance to use water with high salt concentration by Eq. (6). For each crop, diversions and local sources may be blended with local groundwater and reused drainage. A highly salt-tolerant crop may reuse a larger amount of field drainage.

ER is a function of total precipitation, crop evapotranspiration, and soil characteristics (USDA 1967). As for groundwater extraction (*G*), assuming only small changes in the water table, the monthly upward movement of water from the water table (*G*) can be estimated from water table depth and soil characteristics (Eagleson 1978).

Flow and Salt Balance in Root Zone

Soil water balance in the root zone is expressed as

$$RD^t\cdot(Z^t-Z^{t-1})+\mathrm{ETA}^t=\frac{WA^t}{A}\tag{7}$$

$$DP^t=\left(\frac{\mathrm{WAF}^t}{A}\right)\cdot[1-\varepsilon 2]\tag{8}$$

where *RD* = root zone depth; *Z* = percentage soil moisture content in the root zone; ETA = actual evapotranspiration; and *DP* = deep percolation. Note Eq. (8) is based on the assumption that there is no surface runoff due to irrigation. All variables in Eqs. (7) and (8) are indexed over a *crop field* (f) in a *soil area* (a) at a *demand site* (d), as are all variables in the following equations except for specified exceptions.

The root zone salt balance equation is based on the following equation, by which the salinity in deep percolation and the root zone are determined, assuming no lateral flow in the root zone. Following Abdel-buyem and Skaggs (1993), the root zone salt balance is

$$DP^t\cdot SP^t=\frac{\mathrm{WAF}^t}{A}\cdot SW^t+G^t\cdot SG^t-Zs\cdot RD^t\cdot(SE^t-SE^{t-1})\tag{9}$$

where *SP*, *SW*, *and SG* = salinity in the percolation, applied water, and groundwater, respectively, and *SE* = salinity of the soil moisture when the soil is saturated.

Return Flow to River System

Return flow (*RF*) from a demand site to the river system is calculated in the model as

$$RF^t(d) = \left[\sum_a \sum_f DP^t(d,a,f) \cdot \varepsilon 3(d) \cdot \eta(d) - DD^t(d) \right]$$

$$+ \sum_{(n,d)} DS^t(n) \quad \forall \quad d,t \tag{10}$$

where RF = sum of surface drainage from all fields, plus subsurface drainage [discharge from the groundwater tank (*n*) associated with the demand site (*d*)] minus drainage disposal (*DD*) by evaporation; $\varepsilon 3$ = drainage efficiency, defined as the ratio of drainage to field percolation; and η specifies the evaporation and seepage loss during the path of the surface drainage back to the river system.

Salt concentration in the return flow is computed by a salt balance equation, including the salt mass carried with each item in Eq. (10).

Agronomic Relationships

Crop Production as Function of Soil Moisture and Soil Salinity

The actual evapotranspiration (ETA) is a function of both soil moisture (*Z*) and soil salinity (*SS*). Soil salinity here is the salinity in the soil moisture, which is a function of the salt content of both the soil and the salinity of the available water. Based on the work of Jensen et al. (1971) and Hanks (1985), we may write an expression for the actual evapotranspiration as

$$\mathrm{ETA}^t = ET0^t \cdot (1 - ks) \cdot \mathrm{kat}^t \cdot \mathrm{kct}^t + \mathrm{kap}^t \cdot (kc^t - \mathrm{kct}^t) \tag{11}$$

where ks = coefficient of the soil salinity effect; kat = coefficient of the soil water stress effect for transpiration; kct = crop transpiration coefficient [kct = 0 before crop emergence, and after that, kct = $0.9 \cdot kc$; Hanks (1985)]; kap = coefficient of the soil water stress effect for soil evaporation; and kc = crop evapotranspiration coefficient (Doorenbos and Pruitt 1978).

The soil salinity effect coefficient (*ks*) is estimated based on the yield-seasonal root zone salinity relationship given by Maas and Hoffman (1977), which expresses crop tolerance to salinity in terms of relative yield (YR), threshold salinity (S'), and percent yield decrement per unit increase in salinity in excess of the threshold (*B*).

$$ks = \begin{cases} 0 & \text{if } \overline{SE} < S' \\ B \cdot [\overline{SE} - S'] & \text{otherwise} \end{cases} \tag{12}$$

where $\overline{SE}$ = average seasonal root zone salinity. (This nonsmooth equation is treated in the model by the following nonlinear equations: Define another variable ks'; we have (1) $ks \cdot ks' \geqslant 0$; (2) $ks^2 \leqslant ks'^2$; (3) $ks' = B \cdot (\overline{SE} - S')$; and $ks \geqslant B \cdot (\overline{SE} - S')$. Note that $ks \geqslant 0$. By these equations, when $ks' \geqslant 0$, $ks = ks'$, while $ks' < 0$ implies $ks = 0$.

The factor kat is estimated by the following equation, given by Jensen et al. (1971)

$$\mathrm{kat}^t = \ln\left[100 \cdot \left(\frac{Z^t - Zw}{Zs - Zw}\right) + 1\right] \Big/ \ln(101) \tag{13}$$

Zs = saturated soil moisture, and Zw = soil moisture at the wilting point.

An empirical equation used by Prajamwong et al. (1997) is applied here to estimate kap:

$$\mathrm{kap}^t = \left(\frac{Z^t - 0.5 \cdot Zw}{Zs - 0.5 \cdot Zw}\right)^{0.5} \tag{14}$$

Doorenbos and Kassam (1979) recommended a relationship between relative yield, *YR*, and relative evapotranspiration given by an empirically derived yield response factor (ky), or

$$YR = 1 - ky \cdot \left(1 - \frac{\mathrm{ETA}}{\mathrm{ETM}}\right) \tag{15}$$

The value of *ky* for different crops is based on experimental evidence that covers a wide range of growing conditions. The relationship is given for the total growing period and the individual growth periods of a crop. The maximum evapotranspiration (ETM) is equal to $ET0$, the reference evapotranspiration multiplied by the crop coefficient, *kc*. Through Eq. (15), ETA, the actual crop evapotranspiration, brings soil moisture and soil salinity into the crop production function. The relationships between relative crop yield and soil moisture and salinity are plotted in Fig. 2.

Critical Crop Stage

The critical crop stage is the growth stage where the relative crop yield (*YR*) attains its minimum over all stages. To account for water stress and salinity effects in individual crop growth stages (*st*), *YR* at the critical stage (YRC) is calculated as

$$\mathrm{YRC} = \min\left\{ \min_{st}\left[1 - ky^{st} \cdot \left(1 - \frac{\mathrm{CETA}^{st}}{\mathrm{CETM}^{st}}\right)\right], \right.$$

$$\left. 1 - ky^{\mathrm{season}} \cdot \left(1 - \frac{\mathrm{ETA}^{\mathrm{season}}}{\mathrm{ETM}^{\mathrm{season}}}\right) \right\} \tag{16}$$

where $\mathrm{CETA}^{st} = \Sigma_{t=1}^{st} \mathrm{ETA}^t$ and $\mathrm{CETM}^{st} = \Sigma_{t=1}^{st} \mathrm{ETM}^t$ are cumulative actual and maximum evapotranspiration up to stage *st*, respectively. The actual crop yield is equal to the maximum crop yield (*YM*) multiplied by YRC.

Thus, the crop production function includes the effects of soil water moisture and soil salinity over all crop growth stages. This makes it possible to connect crop production to hydrologic system operation by using the same time interval for crop growth and hydrologic system operation. For a discussion of the match of crop growth stages, time intervals for irrigation scheduling, and time intervals for reservoir system operation, see Vedula and Mujumdar (1992), who suggested a time interval of 2 weeks or less in order to provide a useful guide for operating the reservoir system, based on information on crop growth and harvested yield.

Economic Incentives

Instead of prescribed water use rights, we use endogenous demand functions for individual demand sites and a central authority-based decision-making framework to direct the search for optimal water allocations to demand sites and crops (Booker and Young 1994).

Tax and subsidy systems have been popular incentives for resource allocation and pollution control (Dinar and Letey 1996). These measures can motivate farms to invest in improved distribution facilities and irrigation technology, pay for the safe disposal of drainage, or divert less water and leave more water in the

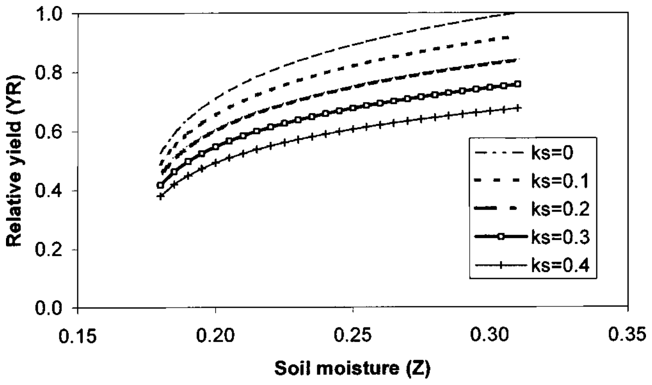

Fig. 2. Crop yield versus soil moisture under various soil salinities

"dilution bank." On the other hand, resource and pollution problems can also be mitigated by improvements in water distribution, drainage collection and disposal, and irrigation system efficiency. A tax/subsidy system consistent with this assumption is implemented in this model so that salt discharge is taxed and infrastructure improvements are subsidized. We assume the government can fund the total subsidy required for infrastructure improvement.

Profit from irrigation (*IP*) at a demand site *d* is

$$\begin{aligned} IP(d)=&\sum_a \sum_f \sum_{cp} [pc(cp)\cdot YA(d,a,f,cp)\\ &-fc(d,a,f,cp)]\cdot A(d,a,f)\\ &-\sum_a \sum_f \sum_t [cg(d)\cdot P^t(d,a,f)]\\ &-cs(d)\cdot \mathrm{WWD}^t(d)-\mathrm{cdn}(d)\cdot DN^t(d)-\mathrm{cdd}(d)\cdot DD^t(d)\\ &-\sum_a \sum_f \mathrm{IIR}(d,a,f)-\mathrm{IDS}(d)-\mathrm{IDN}(d)-\mathrm{IDD}(d) \end{aligned} \tag{17}$$

where fc = fixed cost per unit area of crop; pc = price of the crop; and *cs*, *cg*, *cr*, cdn, and cdd = costs of surface water withdrawal (WWD), groundwater pumping (*P*), drainage collection (WDN), and drainage disposal (*DD*), respectively. The annual investments in water distribution (IDS), irrigation (IIR), drainage (IDN), and drainage disposal (IDD) are

$$\mathrm{IDS}(d)=\mathrm{ids}(d)\cdot \Delta\varepsilon 1(d)\cdot \sum_t \mathrm{WWD}^t(d) \tag{18}$$

$$\mathrm{IIR}(d,a,f)=\mathrm{iir}(d)\cdot \sum_a \sum_f \Delta\varepsilon 2(d,a,f)\cdot \sum_t \mathrm{WFLD}^t(d,a,f) \tag{19}$$

$$\mathrm{IDN}(d)=\mathrm{idn}(d)\cdot \Delta\varepsilon 3(d)\cdot \sum_a \sum_f A(d,a,f) \tag{20}$$

$$\mathrm{IDD}(d)=\mathrm{idd}(d)\cdot DD(d) \tag{21}$$

in which ids and iir = annualized investments per unit of water savings from distribution systems and irrigation systems, respectively; idn = annualized investment per hectare of new drained area; and idd = annualized investment per unit of drainage disposal.

Including a tax on salt discharge, we define irrigation benefit (*IB*) for demand site *d* as

$$IB(d)=IP(d)-\mathrm{rtax}(d)\cdot \sum_t \mathrm{SALT}^t(d) \tag{22}$$

where rtax = tax rate imposed on salt discharge, and SALT = salt mass in return flow.

In addition to irrigation benefits, our objective function also includes benefits from hydropower and from water used to preserve the downstream ecological system. Energy generated from hydropower stations is computed from a nonlinear function with monthly average flow release through turbines and net reservoir head as variables, as described in Loucks et al. (1981), and profit from hydropower is estimated based on the total energy generated and an exogenously supplied price for electric power. Ecological benefits (*EB*) depend on ecological water requirements and data availability for valuing ecological water use in different basins (Loomis 2000). The method used for the case study in this paper is described in the next section.

The objective function is to maximize the sum of irrigation benefit (*IB*), hydropower profit (*HP*), and ecological benefit (*EB*).

$$\mathrm{Max(Objective)}=\sum_d IB(d)+HP+EB \tag{23}$$

Model Application to Syr Darya Basin

Case Study Area and Assumptions

The model described above was applied to the problems of water and salt management in the Syr Darya River basin. The river is one of the two major rivers feeding the Aral Sea. The basin's water supply system has 9 major tributaries, 11 reservoirs, numerous irrigation distribution systems (23 in all, aggregated to 6 in this model), and numerous distribution canals. Each demand site is assumed to have a single groundwater tank associated with it. Fig. 3 shows a network model of the basin. Reservoirs located on both the main river and its tributaries can control most of the basin's inflow in normal years. Previous modeling studies have shown that the combined use of these reservoirs can, with some trade-offs, achieve multiple purposes such as irrigation and hydropower generation (McKinney and Cai 1997).

A complete listing of all data in hydrology, infrastructure, agronomy, economy, and water demand used in the model is available in Cai (1999). Six demand sites are delineated along the river basin, following Raskin et al. (1992). Three soil types—sandy clay (scl), loam (*l*), and sandy loam (*sl*)—are classified for each demand site from information in the WARMAP report (EC 1995). Five major crops of the Syr Darya basin are considered in the model: cotton, wheat, forage, maize, and alfalfa. All others are grouped into a single crop. These crops are further grouped into four types of crop combinations with their respective growing periods: cotton and forage (cot-foa), wheat and maize (wht-maz), alfalfa (alf-alf), and other crops (oth-oth), which are indexed by crop fields defined in this section.

The value of ecological water use (*EB*) in the basin is estimated based on a previous study for the Syr Darya basin (Anderson 1997):

$$EB=\sum_t \mathrm{weco}\cdot \mathrm{WECO}^t \tag{24}$$

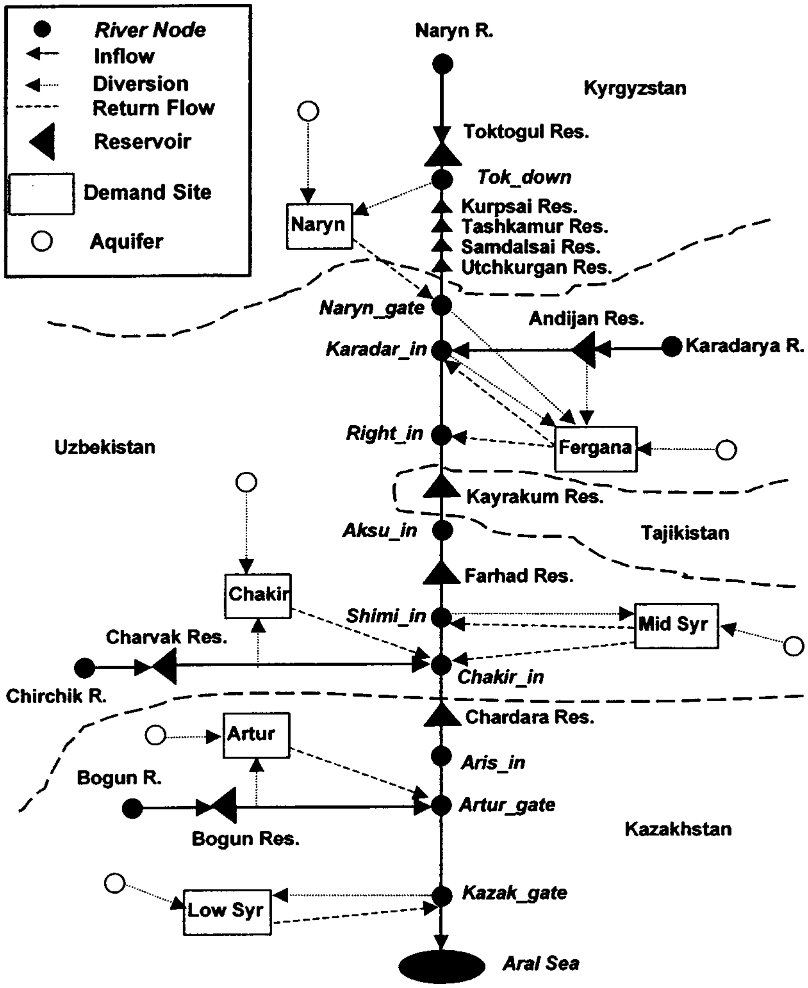

Fig. 3. Syr Darya River basin network

where WECO is the water for ecological use, and weco is the socioeconomic net benefit per unit of ecological water use.

The model is applied to a 1-year time horizon, including 12 monthly time intervals. The monthly time interval is appropriate for this model because its purpose is for overall economic, hydrologic, and environmental analysis in the context of the basin rather than for real-time reservoir system operation and irrigation scheduling. The model is formulated as a deterministic optimization model based on long-term average precipitation, crop evaportranspiration and inflows.

Solving Model

A typical instance of the model of this system has 9,874 constraints, 13,713 variables, and 57,200 nonzero Jacobian elements, 31,099 (54.4%) of them nonconstant. Due to its size and complexity, currently available nonlinear optimization solvers were unable to solve such instances from the best a priori initial points available. This motivated us to solve the model by a domain decomposition approach. The large nonlinear optimization model is composed of pieces—hydrologic, agronomic, and economic components—which form the subsets of decision variables and constraints in the entire model. Each piece represents an additional aspect of the situation being modeled, such as

- mod1 = *flow balance and crop production functions*, with *fixed* soil salinity in the crop production function;
- mod2 = mod1 plus *salinity balance*, but still with *fixed* soil salinity in the crop production functions;
- mod3 = mod2 plus relationships defining the effect of soil *salinity on crop yield*, with soil salinity as a new variable in the crop production functions; and
- mod4 = mod3 plus *tax-salt discharge relationships*, with *salt discharge* from each demand site as new variables.

This opens the possibility of solving the simplest piece, mod1, first; then solving mod2, given the initial value of flows from the solution of mod1; solving mod3, given initial values of flows and salt concentrations from the solution of mod2; and finally solving mod4, given initial values of all state and decision variables from the solution of mod3. Actually, mod4, including all variables and constraints of the primary model, is the equivalent of the entire model. For example, for one case solving with mod1, there are 2,614 initial infeasibilities; with mod2, 706; mod3, 2; and mod4, 0. Thus, this "piece-by-piece" approach provides each submodel with a good starting point, which greatly increases the probability that a good nonlinear solver will find an optimal solution.

In addition to its ability to solve the final model, this approach yields insight into the effects of adding each piece, obtained by comparing optimal solutions to successive submodels. This provides insight into the relative importance of the hydrologic, agronomic, economic, and institutional components of the model. For details about this approach, see Cai et al. (2001).

Table 1. Comparison of Scenario Results

Scenario	Total benefit ($\$10^9$)	Irrigation profit ($\$10^9$)	Power profit ($\$10^6$)	Irrigated area (1,000 ha)	Average relative yield	Water withdrawal (km^3)	Winter Toktogul release (km^3)	Summer Toktogul release (km^3)	Flow to Aral Sea (km^3)	Total power (10^6 kWh)	Summer power (10^6 kWh)	Investment ($\$10^6$)	Salt discharge (10^6 Mt)
Baseline	2.86	2.50	337	3,570	0.74	51.8	6.33	6.46	7.3	11,230	5410	—	32.7
Full-optimize	3.76	3.26	358	3,260	0.89	45.6	5.68	7.35	8.4	11,950	6480	366	25.1

Policy Analysis

Two scenarios are defined for related policy analysis in the case study application. One is a baseline scenario (BAS), which is specified with monthly releases of the Toktogul reservoir, the major multiyear regulation reservoir in the system, according to the existing intergovernmental agreement; infrastructure of the early 1990s; crop patterns and irrigated areas of the early 1990s; and zero tax on salt discharge. Since this is a normative model, we did not expect the results from the model to match the observed records exactly. However, we did adjust various parameters listed in the model description and made the outcomes of the hydrologic, agronomic, and economic components comparable to some observed values, including flow through river reaches; reservoir storage and release, water withdrawals; crop harvested area and yield, and farmer's income.

The other scenario is a full optimization scenario (FOP), which relaxes all those specifications and determines the reservoir release, infrastructure, crop patterns, and irrigated area endogenously in the model. The results from these two scenarios are summarized in Table 1.

The FOP results in a total benefit increase of $900 million over the BAS, with $760 million of that due to increases in irrigation profit and $21 million to an increase in hydropower profits. The average relative yield for all crops in the basin increases by 0.15; water withdrawal decreases by 6.2 km^3; and the flow to the Aral Sea increases 1.1 km^3. Profit with winter hydropower generation decreases by $11 million, and profit with summer hydropower generation increases by $32 million.

Another significant improvement of the FOP scenario is the tremendous decrease of salt discharge from 32.7 to 25.1 million tons, a 24% reduction. The significant increase in irrigation profit and decrease in salt discharge is due to a combination of the factors discussed above. The infrastructure improvements, primarily in water delivery efficiency ($\varepsilon1$, from 0.5–0.6 to 0.70–0.8, with different increases by demand sites) and in irrigation efficiency ($\varepsilon2$, from 0.5–0.65 to 0.80–0.85), require an investment of $366 million, most of which is used in the Mid_syd ($140 million), Fergana ($90 million), and Low_syd ($60 million) demand sites. The tax collected in this scenario is $251 million, which is 68% of the investment and 32% of the increase in irrigation profit. These figures show that the investments could be financed through taxation on the increased profits resulting from the infrastructure improvements.

The FOP scenario has increases of 10 to 30% in the irrigated area for cotton at all demand sites, compared to the areas in the early 1990s. Although cotton requires more water, the average economic value per unit of water for cotton is much higher than that of other crops (Table 2). To determine realistic crop patterns, food production requirements should be verified. Moreover, planting of cotton, a crop with high salt tolerance, may lead to excessive salt accumulation in the soil in the long term if salt leaching is not sufficient. Therefore, the long-term environmental consequence of crop pattern and acreage should also be considered.

Reservoir Operations

Results show that the combined use of these reservoirs can, with some trade-offs, achieve multiple purposes such as irrigation water supply, hydropower generation, flow release for downstream ecological use, and salinity control. Among the reservoirs, Toktogul, Kayrakum, and Chardara—located upstream, midstream, and downstream on the main river, respectively—provide the major flow regulation. The Toktogul Reservoir and the four downstream constant-volume reservoirs provide over 80% of the installed generating capacity in the Kyrgyz Republic, where the peak demand for domestic power occurs in the winter (Burns and Roe 1998; McKinney and Kenshimov 2000).

The monthly releases from the Toktogul Reservoir under the BAS and FOP scenarios are plotted in Fig. 4. As mentioned above, the baseline scenario follows the intergovernmental agreement on Toktogul release. Releases under the FOP are quite different, increasing annual hydropower generation by 6%, while decreasing hydropower generation in the winter months by 5%. Considering the large increase in irrigation benefit (+30%) and decrease of salt discharge (−24%) in the FOP, the intergovernmental agreement is not optimal from an economic standpoint

Table 2. Marginal Value of Water by Demand Site and Average Value by Crop Patterns

			Average Economic Value by Crop Patterns ($\$/m^3$)			
Demand site	Average relative yield	Marginal value of water ($\$/m^3$)	*cot_foa*	*wht_maz*	*alf_alf*	*oth_oth*
Naryn	0.94	0.008	0.148	0.126	N/A	0.068
Fergana	0.94	0.009	0.152	0.074	N/A	0.048
Mid_syd	0.86	0.014	0.137	0.099	N/A	0.068
Chakir	0.95	0.009	0.156	0.111	0.048	0.081
Artur	0.87	0.032	0.104	0.073	0.062	0.049
Low_syd	0.74	0.043	0.156	0.112	0.051	0.083
Whole basin			0.14	0.094	0.051	0.068

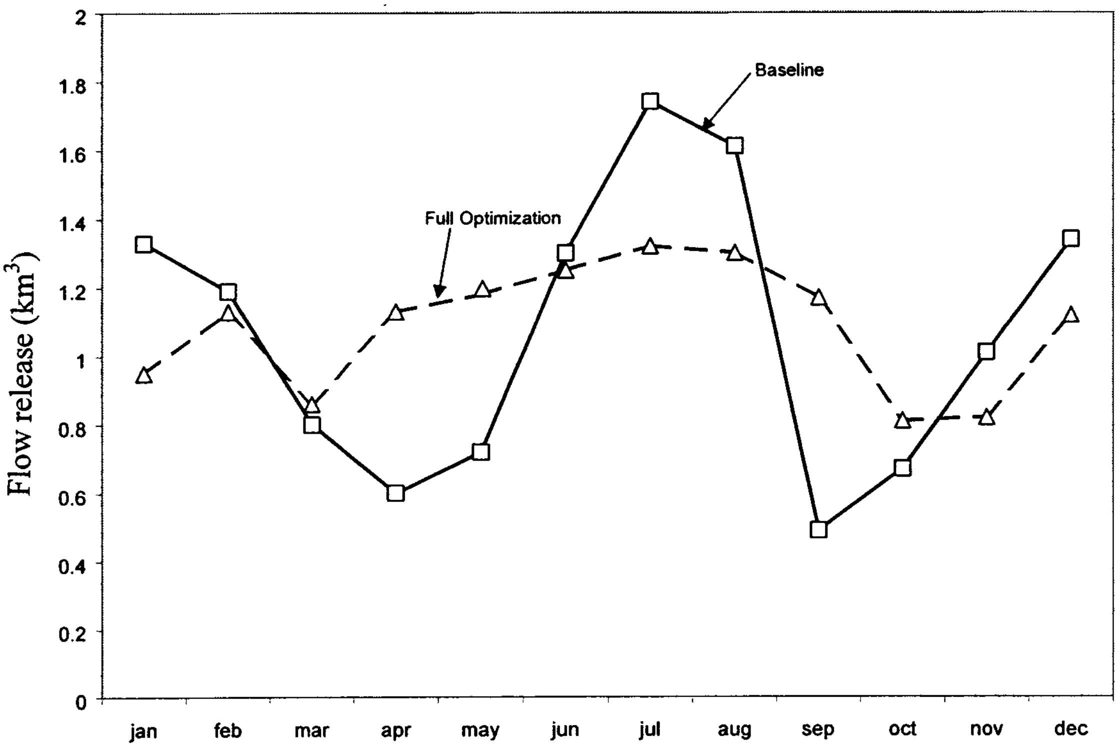

Fig. 4. Monthly release of Toktogul Reservoir under *baseline* and *full optimization* scenarios

when combined with the infrastructure improvements, crop pattern changes, and salt penalty tax of the FOP.

The Toktogul Reservoir summer release helps meet downstream irrigation needs. However, to make releases in this period, it is preferable for this reservoir to store water in the winter, when there is little runoff. Therefore, from the perspective of achieving a balance between hydropower and irrigation uses, the preferred release during the summer is generally less than the downstream irrigation requirement, except in a wet year. Combined with Toktogul, the other two major reservoirs, Kayrakum and Chardara, can be used to alleviate the conflict between upstream and downstream areas. The complementary functions of these reservoirs are shown in Fig. 5 (releases) and Fig. 6 (storages). Note that there is a constant high release from the Chardara Reservoir through all months, in order to supply water for irrigation at downstream demand sites in the vegetation period, and to supply flow to the

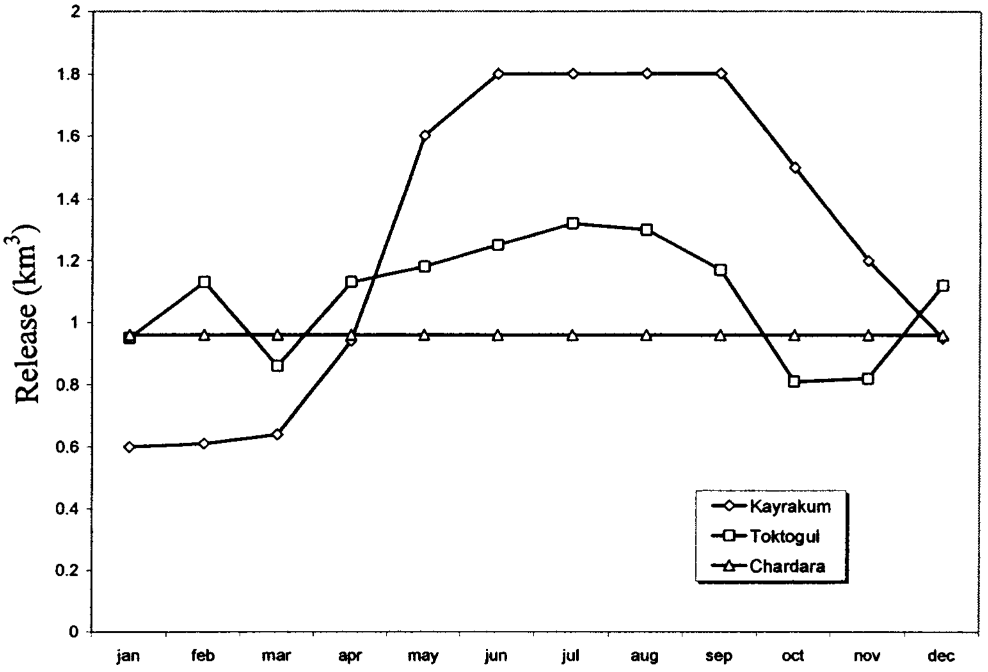

Fig. 5. Releases of three major reservoirs under full optimization scenario

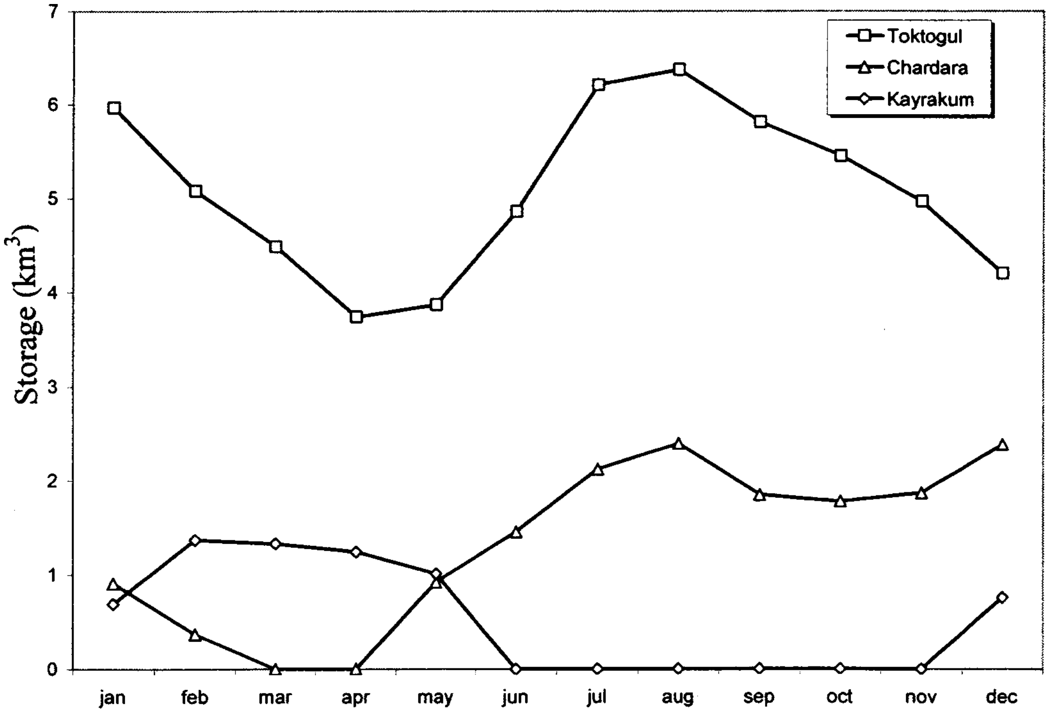

Fig. 6. Storage of three major reservoirs (*full optimization* scenario)

Aral Sea in the nonvegetation period. Chardara acts as the main control facility for downstream ecological release requirements in each month.

The combined utilization of these three reservoirs, as well as others on the tributaries, can also help control salinity in the downstream area. Fig. 7 shows the salt concentration in flows along the Syr Darya River from June to September under the FOP scenario, with return flow inlets shown along the horizontal axis (the locations of these inlets are shown in Fig. 3). Drainage from the *Naryn* and *Fergana* upstream demand sites causes the salt concentrations to increase in river reaches from *Naryn_gate* to *Right_in*. Fergana has the largest irrigated area (about 1.3 million

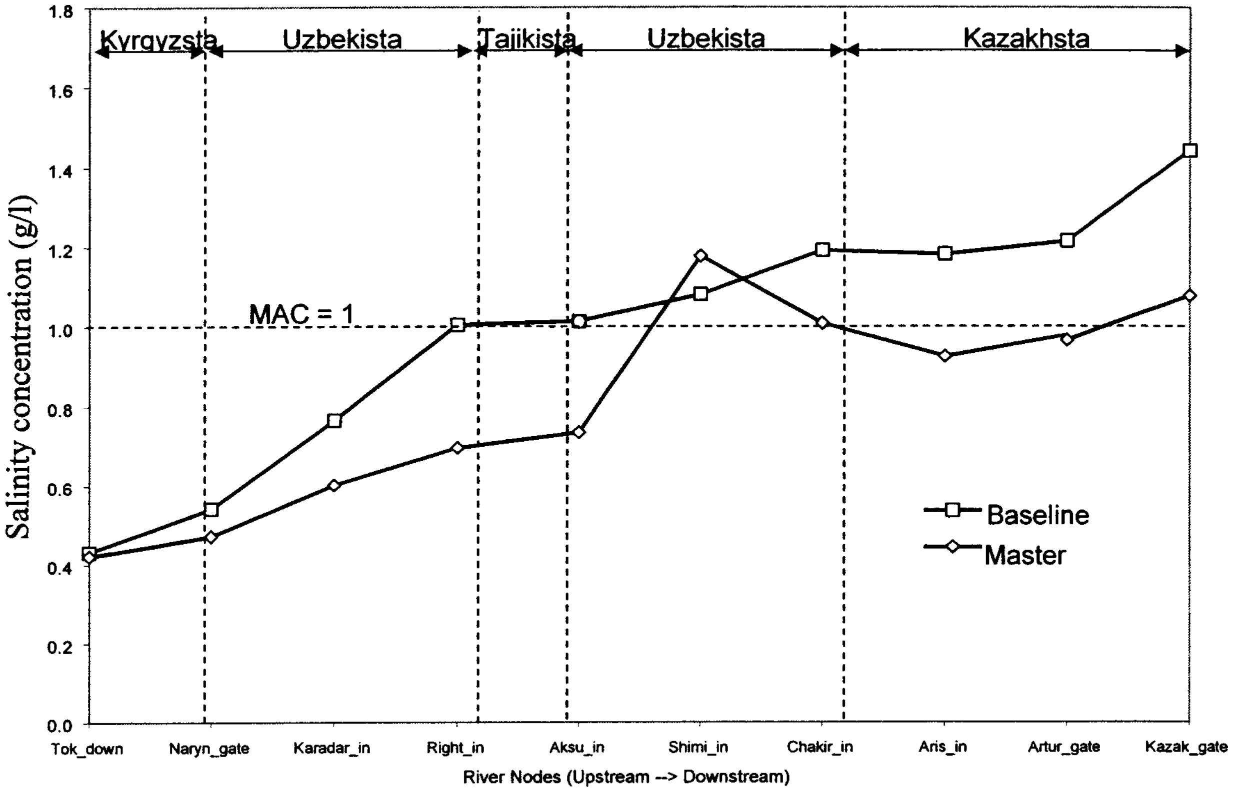

Fig. 7. Average salt concentration for July to September along Syr Darya River (*full optimization* scenario)

Table 3. Analysis of Irrigation Efficiency ($\varepsilon 2$)

	Economic Benefit[a]			Environmental Problem[b]		
$\Delta\varepsilon 2$	Irrigation profit (\$$10^9$)	Infrastructure investment (\$$10^9$)	$\frac{\Delta\text{Irrigation profit}}{\Delta\text{Investment}}$	Percolation (cm)	Soil salinity (dS/m)	Water use (m^3/ha)
0.0 (baseline)	2.5	0	—	46.9	1.643	12,346
0.1	+0.05	0.049	1.02	44.1	1.727	11,334
0.2	+0.10	0.095	1.05	34.7	1.924	10,557
0.3	+0.14	0.142	0.98	29.4	2.000	8,603

[a] Basin average.

[b] Demand site: Fergana; soil type: loam; crop: cotton forage.

ha) among all demand sites, and the average yearly return flow from this demand site is 6.1 km^3, 40% of the total drainage in the basin, and 39% of the total water withdrawal to Fergana. From the Kayrakum Reservoir onward, salinity increases only slightly until river reach *Asku_in*, due to salt dilution caused by the Kayrakum Reservoir. Between *Asku_in* and *Shimi_in*, drainage from demand site *Mid_syr* causes an abrupt salinity increase. Demand site *Mid_syr* withdraws 11.0 km^3 of the river flow and returns 3.1 km^3 to the river, with salt concentrations up to 2.5 g/L in later vegetation periods. A significant result of this scenario is that after the Chardara Reservoir, the salt concentration remains below 1.0 g/L until after the last demand site in the system, which shows that the storage of the Chardara Reservoir dilutes the drainage.

Economic and Environmental Evaluation of Infrastructure Improvement

Improving irrigation and drainage infrastructure is critical to satisfying crop water demands while conserving limited water resources and minimizing environmental problems. It should be noted that these improvements require large capital investments and significant implementation times. We are not suggesting that these improvements could occur over a 1-year period or instantaneously, but rather we wish to know what their effect would be if they were implemented.

We now consider irrigation efficiency as an example for economic and environmental evaluation of infrastructure improvements. As defined before, irrigation efficiency ($\varepsilon 2$) is the ratio of water effectively used by crops to the total water applied in the crop season. Advanced irrigation systems have higher efficiency, which is important for saving water. However, high efficiency means less percolation and insufficient salt leaching, which may cause soil salinity accumulation if irrigation water salinity is high. Table 3 shows the effects of increasing $\varepsilon 2$ incrementally from 1.0 (*baseline*) to 1.3 times its current value. As $\varepsilon 2$ increases, irrigation profit also increases. However, water use per hectare and field percolation also decrease and soil salinity increases, which causes salinity to build up in the crop root zone over the long term.

Results show that investment in irrigation systems is economically efficient in all cases for efficiencies up to 30% above the baseline; further investment is not attractive. The incremental benefit to irrigation and total water use provides a measure of the amount of funding that might be used to finance irrigation system improvements.

Economic Incentives—Penalty Tax on Salt Discharge

To further illustrate the economic incentive of the salt discharge tax, the tax rate was parametrically varied from \$0 to \$200 per ton of salt mass in the FOP scenario. Figs. 8 and 9 show irrigation water withdrawal and salt discharge versus tax rate on salt discharge. All these items decrease with the tax rate, with water withdrawals and agricultural profits exhibiting a nearly linear decline. The trade-offs (slopes) between water withdrawal and agricultural profit and tax rate are 0.06 km^3 and \$1.3 million per dollar/ton tax, respectively. That is, a \$1 increase in the tax rate will decrease water withdrawals by 60 million m^3 and agricultural profits by \$1.3 million, respectively. Up to \$50/ton, a small increase in the tax rate reduces irrigation water withdrawal and salt discharge significantly, while only slightly reducing irrigation profit and total water use benefit. This indicates that a tax on salt discharge may help solve environmental problems, while having only a small effect on irrigation profit.

In reality it is difficult to measure return flow from irrigated fields. This model can be used to estimate return flow from irrigated fields at specific demand sites, and it provides a framework for analyzing tax incentives for salinity control.

Economic Value of Water Use for Crops and Demand Sites

The model outputs can also be used to derive average or marginal economic value of water use for crops and demand sites. The economic value of water in producing a particular crop (dollars/cubic meters) is defined as the net revenue from that crop divided by the water applied to the crop. This is shown in Table 3 for a normal flow year and under the baseline scenario. These values strongly influence model decisions on crop acreage, within limits specified by lower and upper bounds. Table 3 also shows the marginal values of water for several demand sites at the baseline scenario. Higher marginal values of water occur in demand sites having lower crop yield. *Cot-foa* has the highest average economic value of water (0.12–0.15 \$/m^3) while *alf-alf* has the lowest.

Sensitivity Analysis

The following four important parameters in the model have been selected for sensitivity analysis based on the BAS: (1) natural inflow to rivers and reservoirs; (2) salinity in natural drainage; (3) reference crop evapotranspiration (ET_0); and (4) water price. The effects on key aggregate outputs of changing each of these parameters individually are shown in Table 4, expressed as percentages of the output resulting from the scenario with base casevalues. A 20% reduction in natural inflow reduces flow to the Aral Sea by 44%, hydropower generation in the winter by 12.5%, irrigation profit by 6.6%, and total water use benefit by 19.4%. The benefits of a wet year are far less than the harm caused by a dry one, with hydropower receiving the largest benefit. The only adverse affect of wet conditions is higher salt discharge.

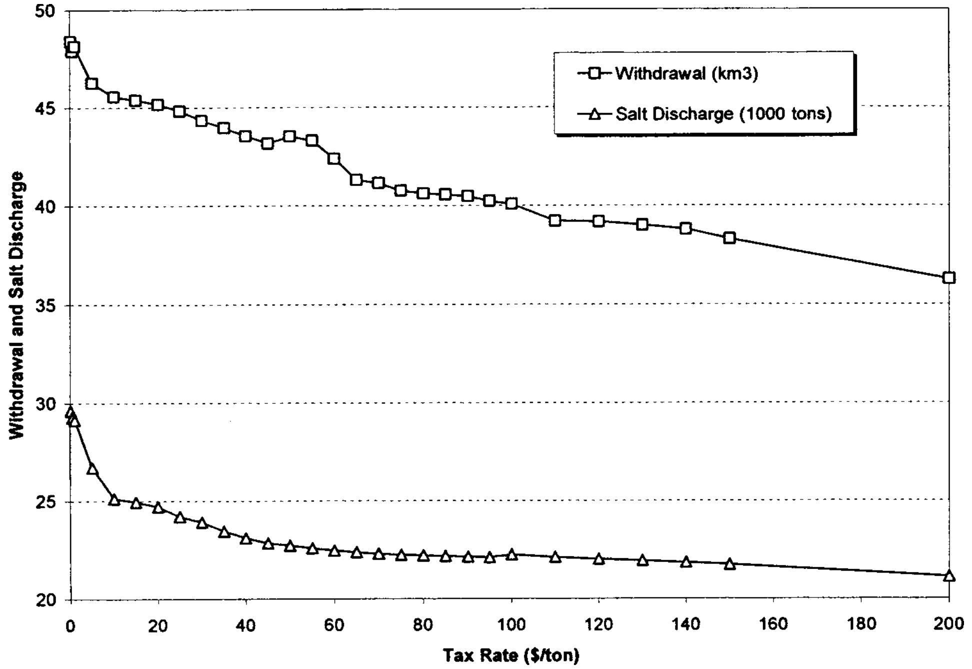

Fig. 8. Irrigation water withdrawal and salt discharge versus tax charge on salt discharge

Increasing the salt concentration in natural runoff by 25% leads to a 1.4% decrease in average crop yield, a 1.6% decrease in irrigation profit, and a 3.2% increase in salt discharge, while a 25% decrease leads to a 2.2% decrease in salt discharge and smaller effects on all other outputs. Actually salt concentration in the natural runoff, mainly originating from the upstream mountain area, is less than 0.5 g/L, and thus a change of ±25% of the salt concentration in natural runoff does not have large impacts. Agricultural drainage is the major factor affecting water quality in the middle and lower sections. Records show that just downstream of the Fergana Valley, a major irrigation district in the basin, the average salinity of the river water increases to 1.2 g/L from a concentration of less than 0.5 g/L entering the valley (Raskin et al. 1992).

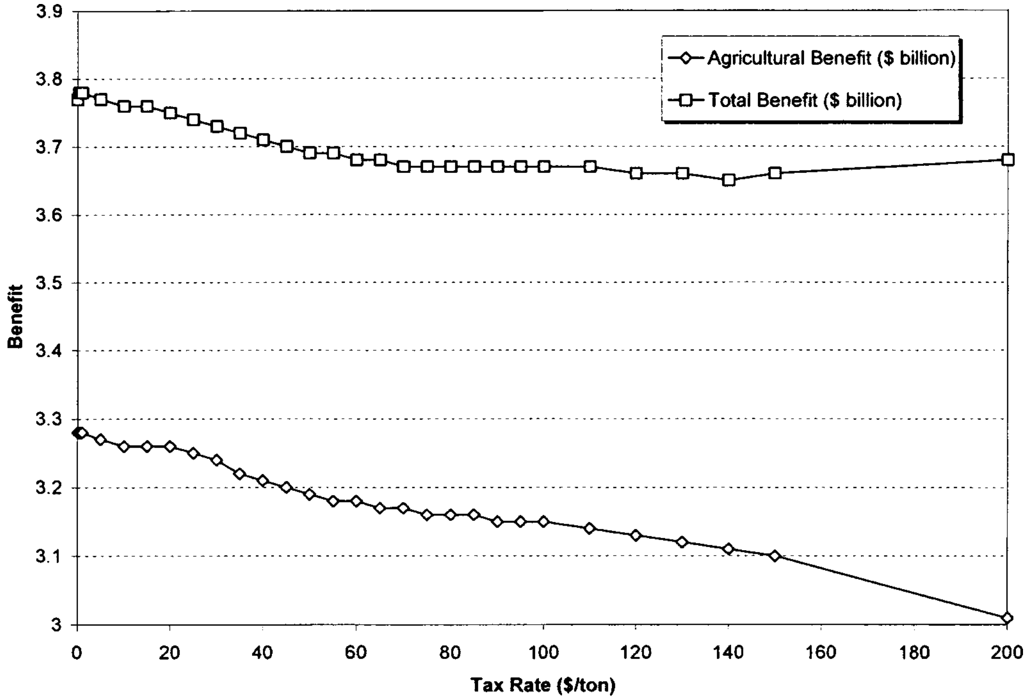

Fig. 9. Irrigation profit and total water use benefit versus tax on salt discharge

Table 4. Sensitivity Analysis for Selected Parameters (Percent)

Parameters	Cases	Total profit	Irrigation profit	Average yield	Hydropower in winter	Flow to Aral Sea	Water withdrawal	Salt discharge
Natural inflow	*Dry (−20%)*	81.8	94.0	95.9	71.6	55.1	87.5	96.1
	Wet (+17%)	102.8	102.0	101.4	101.0	101.8	107.0	103.2
Salinity in source	*High (+25%)*	100.0	98.4	98.6	100.0	100.3	100.0	102.3
	Low (−25%)	100.0	100.8	100.3	100.3	99.7	100.0	97.7
Crop ET0	*High (+25%)*	87.1	84.8	91.9	101.3	98.6	100.6	102.9
	Low (−25%)	103.8	104.0	101.4	100.0	100.8	99.8	99.4
Water price	*High (+50%)*	96.5	95.2	100.0	100.0	101.1	99.7	99.8
	Low (−50%)	103.8	104.8	100.0	99.9	98.5	100.3	100.2

Changing crop reference evapotranspiration (ET_0) by ±25% has striking effects on all model outputs. A 25% increase leads to a 15.6% decrease in irrigation profit and a slight increase in irrigation water withdrawal. High ET_0 leads to high consumptive water use by crops and a decrease in return flow (field drainage), which causes the decrease in total water flow. This is why flow released to the Aral Sea also decreases by 4%, although irrigation water withdrawal increases slightly. In this case, the marginal value of water used for irrigation decreases, so less water is withdrawn for irrigation upstream and more water is used for hydropower generation, which increases by 1.2%. A 25% ET_0 decrease implies low crop water demand, so irrigation profit increases by 19.3% while irrigation water withdrawal decreases by 2.5% and flow to the Aral Sea increases by 3.4%. Therefore model outputs are very sensitive to ET_0, and errors in estimating this parameter will significantly affect model results.

A 50% higher price for irrigation water results in slightly lower water withdrawals and a 4.5% decrease in agricultural profit, while a 50% decrease leads to a similar profit increase. The small effects of these large changes are probably due to the fact that the current water price (0.003–0.006 \$/m^3) is much lower than the marginal value of water for irrigation (Table 3).

Conclusions and Discussions

This paper describes the development and application of a new integrated hydrologic-agronomic-economic model to irrigation-dominated river basins. Its main contribution lies in the integration of hydrologic, agronomic, and economic relationships in the context of a river basin to form a consistent model. The model's main advantage is its ability to reflect the interrelationships between these components and to explore both economic and environmental consequences of policy choices.

All model components are incorporated into a single consistent model. This large and highly nonlinear model is solved by a simple but effective domain decomposition approach. The model is applied to problems of water management in the Syr Darya River basin in Central Asia, providing environmental and economic information regarding reservoir operations, infrastructure improvement, economic incentives, and economic evaluation of irrigation water use.

The holistic model with multiple components is confronted with some challenges. One challenge is to integrate different temporal and spatial scales inherent to the disciplines into the model. The boundaries of the economic system of a specific resources problem may not a priori be the same as those of the hydrologic system, and an appropriate combination or matching of spatial resolutions and aggregation is required. That is to say, the spatial resolution of water resources modeling needs to allow or facilitate economic analysis and vice versa. An ideal matching would allow for effective information transfer between the two components, while economizing on the complexity of the holistic modeling framework so as to maintain an appropriate model size.

In the model presented in this paper, as shown in Fig. 1, water and salt balance is simulated at the spatial scales from crop fields, demand sites, source nodes (reservoirs, river reaches, and groundwater sources), and the entire basin. Agricultural water use profit is calculated at the crop field scale and aggregated to the demand site and the entire basin scale. Both time intervals and time horizons applied need to be compatible with regard to modeling components and the specific modeling purpose.

Time scales for water and salinity balance, crop growth, and crop profit assessment are involved in the model used in this paper. The model then determines the optimal reservoir operating policy of the river basin systems and at the same time determines the intraseasonal irrigation requirement of all crops in all demand sites to enable release/diversion/pumping decisions to be made such that the right amount of water with right water quality is provided at the right time to the right place (demand sites/soil areas/crop fields). As mentioned above, the month time interval used in this model may not be appropriate for real-time reservoir operation and irrigation scheduling that needs a shorter interval (1 to 2 weeks).

In this spatial and temporal scale setting, the model generates reasonable results compared to the actual records and observations in water resources and regional economy, including instream water flows, water withdrawals, water consumption and return flows, irrigated crop area, yield and production, and water use profits (Cai 1999).

The model presented in this paper is mainly used for short-term analysis. Difficulties arise from the fact that long-term environmental impacts often run counter to the short-term utility of water uses. More specifically, groundwater quality degradation cannot be captured in a short-term model; soil salinity worsens; short-term crop patterns yield short-term economic profits but neglect long-term environmental consequences; and the economic efficiency of drainage system improvements may be undervalued. Although these problems can be handled to some degree by adding additional constraints on these conditions to the short-term model (for example, the groundwater table is constrained below a level; no additional salt accumulation is allowed by the end of the time horizon; and soon), a long-term dynamic framework will be of greater value. This extension has been presented in Cai et al. (2002).

Appendix

Terminology

Indices

t = time intervals (months);
st = crop growth stages;
n = nodes in the river basin network,
n = {river reaches and tributaries, reservoirs, aquifers, demand sites };
d = demand sites, $d \subset n$;
a = areas with specific soil types, $a \subset n$;
f = fields that may have multiple crops over one year period;
cp = crops; and
hpst = hydropower stations.

Hydrologic and Water Application Terms

$Q^t(n,n1)$ = flow from node n to node $n1$ during time period t;
$S^t(n)$ = storage at end of time period t at node n;
R = groundwater recharge;
L = surface water leakage;
DP = deep percolation;
P = groundwater pumping;
G = groundwater extraction to root zones;
DS = groundwater discharge to surface water systems;
AA = horizontal area of groundwater tank;
s = soil storativity;
h = average water table elevation;
$C'(n)$ = salt concentration at node n at the end of period t;
WWD = water withdrawn to demand site d in period t;
WDA = water arriving at demand site d;
WFLD = surface water allocated to crop field;
WA = total water that can be effectively used by crops;
WAI = irrigation water that can be used by crops;
ER = effective rainfall;
WAF = total water application to crop fields;
RD = root zone depth;
Z = percentage soil moisture content in root zone;
DP = deep percolation;
RF = return flow from demand site to river system;
DD = drainage disposal by evaporation;
WECO = water for ecological use;
SS = soil salinity;
ks = coefficient of soil salinity effect;
kat = coefficient of soil water stress effect for transpiration;
kct = coefficient of crop transpiration;
kap = coefficient of soil water stress effect for soil evaporation;
$\overline{SE}$ = average seasonal root zone salinity;
SE = salinity of soil moisture when soil is saturated;
Zs = saturated soil moisture;
Zw = soil moisture at wilting point;
SP = salinity in percolation;
SW = salinity in applied water;
SG = salinity in groundwater;
SALT = salt mass in return flow;
$\varepsilon 1$ = water distribution efficiency;
$\varepsilon 2$ = irrigation efficiency (field application efficiency);
$\varepsilon 3$ = drainage efficiency; and
η = evaporation and seepage loss of return flow.

Agronomic Terms

ETA = actual crop evapotranspiration;
ETM = maximum crop evapotranspiration;
ET_0 = reference evapotranspiration;
kc = crop evapotranspiration coefficient;
CETA/CETM = cumulative actual/maximum evapotranspiration up to stage st;
S' = threshold salinity to crop growth;
B = percent yield decrement per unit increase in salinity in excess of salinity threshold;
ky = crop water-yield response factor;
YR = relative crop yield; and
YRC = relative crop yield calculated according to water availability at critical stage.

Economic Terms

IP = irrigation profit;
HP = hydropower profit;
EB = ecological benefit of water use;
fc = fixed cost per unit area of crop;
pc = price of crop;
cs = cost of surface water withdrawal;
cg = cost of groundwater pumping;
cr = cost of drainage reuse;
cdn = cost of drainage collection;
cdd = cost of drainage disposal;
IDS = annual investment for water distribution system;
IIR = annual investment for irrigation system;
IDN = annual investment for drainage system;
IDD = annual investment for drainage disposal system;
ids = annual investment per unit of water savings from water distribution system;
iir = annual investment per unit of water savings from irrigation system;
idn = annual investment per hectare of new drained area;
idd = annual investment for per unit of drainage disposal;
rtax = tax rate imposed on salt discharge; and
weco = socioeconomic net benefit per unit of ecological water use.

References

Abdel-buyem, M. S., and Skaggs, R. W. (1993). ‘‘Extension of DRAINMOD for simulation water management in arid regions.’’ *Transc. Am. Soc. Agri. Engr.*, 36(1), 210–220.

Anderson, R. C. (1997). ‘‘Environmental damage assessment of the Aral Sea disaster.’’ *Issue Paper No. 1*, Environmental Policies and Technology (EPT) Project, Almaty, Kazakhstan. U.S. Agency for International Development.

Bear, J. (1977). *Hydraulics of groundwater*, McGraw-Hill, New York.

Booker, J. E., and Young, R. A. (1994). ‘‘Modeling intrastate and interstate markets for Colorado River water resources.’’ *J. Envir. Econom. Manage.*, 26(1), 66–87.

Braat, L. C., and Lierop, W. F. J. (1987). ‘‘Integrated economic—Ecological modeling.’’ *Integrated economic ecological modeling*, L. C. Braat and W. F. J. Lierop, eds., 49–67.

Bras, R. L., and Seo, D. (1987). ‘‘Irrigation control in the presence of salinity: Extended linear quadratic approach.’’ *Water Resour. Res.*, 23(7), 1153–1161.

Burns and Roe Enterprises, Ltd. (1998). ‘‘Assessment of export markets for Kambarata electricity, step 2—Optimization of Naryn—Syr Darya River system operation.’’ *Final Rep.*, U.S. Agency for International Development, Almaty, Kazakhstan.

Cai, X. (1999). ‘‘Modeling framework for sustainable water resources management.’’ PhD dissertation, Univ. of Texas at Austin, Tex.

Cai, X., McKinney, D. C., and Lasdon, L. S. (2001). ‘‘Piece-by-piece approach for solving large nonlinear water resources management model.’’ *J. Water Resour. Plan. Manage.*, 127(6), 363–368.

Cai, X., McKinney, D. C., and Lasdon, L. (2002). ‘‘A framework for sustainability analysis in water resources management and application to the Syr Darya Basin.’’ *Water Resour. Res.*, 38(6).

Dinar, A., and Letey, J. (1996). *Modeling economic management and policy issues of water in irrigated agriculture*, Praeger, Westport, Conn.

Doorenbos, J., and Kassam, A. H. (1979). ‘‘Yield response to water.’’ *U. N. Food and Agriculture Organization (FAO) Irrigation and Drainage Paper 33*, Rome.

Doorenbos, J., and Pruitt, W. O. (1977). ‘‘Crop water requirements.’’ *U. N. Food and Agriculture Organization (FAO) Irrigation and Drainage Paper 24*, Rome.

Dudley, B. J., and Scott, B. W. (1993). ‘‘Integrating irrigation water demand, supply, and delivery management in a stochastic environment.’’ *Water Resour. Res.*, 29(9), 3093–3101.

Eagleson, P. S. (1978). ‘‘Climate soil and vegetation—A derived distribution of storm surface runoff.’’ *Water Resour. Res.*, 14(5), 740–748.

European Commission (EC). (1995). ‘‘WARMAP: Water Resources Management and Agricultural Production in the Central Asian Republics.’’ *Project Rep.*, Vols. 1–6, Brussels.

Hanks, R. J. (1985). ‘‘Crop coefficients for transpiration.’’ *Advances in evapotranspiration*, American Society of Agricultural Engineers, St. Joseph, Mich., 430–438.

Jensen, M. E., Wright, J. L., and Pratt, B. L. (1971). ‘‘Estimating soil moisture depletion from climatic, crop and soil data.’’ *Trans. ASAE,* 14(5), 954–959.

Lefkoff, L. J., and Gorelick, S. M. (1990a). ‘‘Benefits of an irrigation water rental market in a saline stream-aquifer system.’’ *Water Resour. Res.*, 26(7), 1371–1381.

Lefkoff, L. J., and Gorelick, S. M. (1990b). ‘‘Simulating physical processes and economic behavior in saline, irrigated agriculture: Model development.’’ *Water Resour. Res.*, 26(7), 1359–1369.

Loomis, J. B. (2000). ‘‘Environmental valuation techniques in water resource decision making.’’ *J. Water Resour. Plan. Manage.*, 126(6), 339–344.

Loucks, D. P., Stedinger, J. R., and Douglas, H. (1981). *Water resource systems planning and analysis*, Prentice-Hall, Englewood Cliffs, N.J.

Maas, E. V., and Hoffman, G. J. (1977). ‘‘Crop salt tolerance-current assessment.’’ *J. Irrig. Drain. Div.*, 103(2), 115–134.

McKinney, D. C., and Cai, X. (1997). ‘‘Multiobjective water resources allocation model for the Naryn-Syrdarya Cascade.’’ *Technical Rep.*, U.S. Agency for International Development, Environmental Policies and Technology (EPT) Project, Almaty, Kazakstan.

McKinney, C. D., Cai, X., Rosegrant, M., Ringler, C., and Scott, C. A. (1999). ‘‘Modeling water resources management at the basin level: Review and future directions.’’ *SWIM Paper No. 6*, International Water Management Institute, Colombo, Sri Lanka.

McKinney, D. C., and A. K. Kenshimov, eds., (2000). ‘‘Optimization of the use of water and energy resources in the Syrdarya Basin under current conditions.’’ *Technical Rep.*, U.S. Agency for International Development, Environmental Policies and Institutions for Central Asia (EPIC) Program, Almaty, Kazakstan.

Musharrafieh, G. R., Peralta, R. C., Dudley, L. M., and Hanks, R. J. (1995). ‘‘Optimization irrigation management for pollution control and sustainable crop yield.’’ *Water Resour. Res.*, 31(4), 1077–1086.

Noel, J. E., and Howitt, R. E. (1982). ‘‘Conjunctive multibasin management: An optimal control approach.’’ *Water Resour. Res.*, 18(4), 753–763.

Prajamwong, S., Merkley, G. P., and Allen, R. G. (1997). ‘‘Decision support model for irrigation water management.’’ *J. Irrig. Drain. Div.*, 123(2), 106–113.

Raskin, P., Hansen, E., Zhu, Z., and Stavisky, D. (1992). ‘‘Simulation of water supply and demand in the Aral Sea region.’’ *Water Int.*, 17, 55–67.

Rosegrant, M. W., and Meinzen-Dick, R. S. (1996). *Multi-country research program—Water resource allocation: Productivity and environmental impacts (MP-10). Program statement and methodology*. International Food Policy Research Institute, Washington, D.C.

Serageldin, I. (1995). ‘‘Water resources management: A new policy for a sustainable future.’’ *Water Int.*, 20, 15–21.

U.S. Department of Agriculture (USDA). (1967). ‘‘Irrigation water requirement,’’ *Technical release No. 21*, Engineering Div., Soil Conservation Service, Washington, D.C.

Vedula, S., and Kumar, D. N. (1996). ‘‘An integrated model for optimal reservoir operation for irrigation of multiple crops.’’ *Water Resour. Res.*, 32(4), 1101–1108.

Vedula, S., and Mujumdar, P. P. (1992). ‘‘Optimal reservoir operation for irrigation of multiple crops.’’ *Water Resour. Res.*, 28(1), 1–9.

Yaron, D., Bresler, E., Bielorai, H., and Haprinist, B. (1980). ‘‘A model for optimal irrigation scheduling with saline water.’’ *Water Resour. Res.*, 16(2), 257–262.