INTEGRATED WATER RESOURCES MANAGEMENT MODEL FOR THE SYR DARYA BASIN

Prepared by:
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August 1999

Prepared for:
Central Asia Mission
U. S. Agency for International Development

Environmental Policy and Institutional Strengthening Indefinite Quantity Contract (EPIQ)
Partners: International Resources Group, Winrock International, and Harvard Institute for International Development

Subcontractors: PADCO; Management Systems International; and Development Alternatives, Inc.

Collaborating Institutions: Center for Naval Analysis Corporation; Conservation International;
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1. Introduction

1.1 BACKGROUND

The interdisciplinary nature of water resources problems requires new attitudes towards integrating the technical, economic, environmental, social and legal aspects of these problems into a coherent analytical framework. Water resources development and management should constitute an integral part of the socio-economic development planning process (Booker and Young, 1994). To bring the concept of integrated water resources management into an analytical framework, modeling techniques for integrating hydrologic, agronomic, economic and institutional components have been studied and found to present opportunities for the advance of water resources management (McKinney, et al., 1999). This paper describes the basic components and structure of a prototype model that is able to provide capability for determining rational and effective water management strategies at the river basin scale. The model is applied to the Syr Darya river basin in Central Asia. The model results show how the essential hydrologic, agronomic and economic components can be integrated into an endogenous modeling system at the river basin scale. This paper also presents a solution approach to solve the integrated model with multiple components, and demonstrates the analytical capacities of the model through a complex case study.

A river basin is a natural unit for water resources planning and management, in which water interacts with and to a large degree controls the extent of other natural components in the landscape 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. Thus, water planners often utilize the river basin as the basic planning area. A river basin system is made up of three components: (1) source components such as rivers, canals, reservoirs, and aquifers; (2) demand components such as irrigation fields, industrial plants, and cities; and (3) intermediate components such as treatment plants and water reuse and recycling facilities. Sustainable water resources management needs an integrated basin system to reflect the integrality of the real world. At the basin level, essential hydrologic, agronomic and economic relationships can be integrated into a comprehensive modeling framework, and as a result, policy instruments designed to make more rational economic use of water resources are likely to be applied at this level. As an example, Figure 1 presents a framework for river basin management modeling. Water can be used for instream purposes including hydropower generation, recreation, waste dilution, as well as offstream purposes that are differentiated into agricultural water uses and municipal and industrial (M&I) water uses. Socio-economic benefits of the river basin area are an important component of a water management strategy of the basin. These include the positive contribution from the economic value of municipal and industrial (M&I) water use, profit from irrigation water use, and benefits from instream water uses, as well as environmental damage due to such things as M&I waste discharge and irrigation drainage. The top level of control for the system is assumed to be a system of institutional directives such as water rights, and economic incentives such as water price, crop price, and any tax on pollution discharge. The institutional directives and economic incentives constrain or induce hydrologic system operations and decisions within both M&I planning zones and agricultural planning zones. Water uses are competitive among various water users, under prescribed institutional rules and economic incentives.

1.1. PREVIOUS WORK

In river basin planning and management, operation of hydrologic systems is often driven by multiple objectives including socio-economic and environmental objectives, while economic incentives are applied subject to physical relationships. A notable research effort in integrating economic modeling and complex hydrologic modeling was reported by Noel and Howitt (1982), who incorporated a quadratic economic welfare function (Takayama and Judge, 1964) in a multibasin conjunctive use model. A number of economic (derived demand, opportunity cost, and urban demand) and hydrologic (groundwater, and surface water potentially) auxiliary models were applied to derive linear sets of first-order difference equations which formed a so-called linear quadratic control model (LQCM). This model was then used to determine the optimal spatial and temporal allocation of a complex water resource system, and examine relative performances of social optimal policy, pumping tax policy, and laissez-faire policy.

Lefkoff and Gorelick (1990a) reported using the "compartment modeling" approach (Braat and Lierop, 1987). Distributed parameter simulation of stream-aquifer interactions, salinity changes, and agronomic functions were combined into a long-term optimization model to determine annual groundwater pumping, surface water applications and planting acreage. Microeconomic theory of the firm, associated with agronomic functions related to water quantity and quality, was applied for each farm during each season for farmers to choose a level of production where marginal revenue equals marginal cost. This model was further extended to incorporate a rental market mechanism (Lefkoff and Gorelick, 1990b), considering annual water trading among farmers.

Information transfer between hydrologic, agronomic and economic components remains a technical obstacle in the "compartment modeling" approach, while in the "holistic modeling" approach (Braat and Lierop, 1987), information transfer is conducted endogenously. Booker and Young (1994) presented a nonlinear optimization model for investigating the performance of alternative market institutions for water resources allocation at the river basin scale. This model includes complex relationships on both water supply and demand side. On the supply side, flow balance and transfer, and salt balance were considered in a river (the Colorado River) basin network including river nodes, reservoir nodes, hydropower station nodes and planning zone nodes; on the planning zone, both offstream (irrigation, municipal, and thermal energy) and instream (hydropower and water quality) uses were represented by marginal benefit functions. The model was used to estimate impacts of alternative institutional scenarios, river flows, and demand levels. In a related work, Faisal et al. (1997) studied a problem of groundwater basin management in which economic objectives were combined with realistic aquifer responses through the use of discrete kernels.

A comprehensive discussion about the technical aspects of economic-ecological modeling was given by Braat and Lierop (1987). The "compartment modeling" approach is more widely used for large complex systems, since it is relatively easy to solve each compartment instead of the whole system. However, the loose connection between compartments may not be effective for information transformation between the components. In "holistic modeling", model components are tightly connected in one consistent model, instead of being put together separately, thus eliminating the information transformation problem , but less complexity may be enclosed, however, it is often very difficult to solve such models.

1.3. TASK OF THIS PAPER

In order to trace the complex relationships across water allocation mechanisms and policies, agroclimatic variability, and the different water uses and users, it is necessary to consistently account for a large number of physical, economic, and behavioral relationships. This paper develops an analytical modeling framework including several elements: (1) physical and technical management of water resources due to new developments; (2) growing competition for water among agricultural, industrial, urban, and instream uses that can be traced along the entire basin; (3) increased attention to environmental impacts of anthropogenic interventions, and (4) tracing the complex relationships and implications of water allocation mechanisms and policies on economic efficiency. The components of the prototype model include:

- hydrological components, which account for flow and pollutant transport in the river basin network including the crop root zone;
- crop production functions including effects of both water stress and soil salinity;
- benefit functions for instream-water uses;
- irrigation and drainage management;
- institutional rules and policies that govern water allocation; and
- economic incentives for salinity control, and water conservation.

The crop production function presented in this paper is a critical connection between these components. In this function, crop yield is a function of both soil moisture and soil salinity, which result from soil water and salinity balances, and these are further related to the water and salinity balance in the entire basin. That is to say, through the crop production function, crop yield is related to the performance of the entire hydrologic system. Furthermore, crop production determines the irrigation benefit in the economic relationships of the model. Therefore, the crop production function connects the hydrologic, agronomic and economic components together into an endogenous system that adapts to environmental, ecological, and socio-economic status of the basin. The modeling framework is built upon a river basin network with multi-level spatial domains from river system to crop root zone in water planning zones.

The modeling framework is applied to the Syr Darya River in the Aral Sea basin of Central Asia. In this basin, irrigation is the dominant water use (about 90% of all off-stream uses), and soil and water salinization are major environmental problems. Through the model application to the model to the case study, we argue that this kind of integrated model is critical in sustainable water management analysis.

2. Model Description

2.1. INTRODUCTION

The main water use categories considered in the model described here are agricultural, industrial, and municipal. In this paper, agricultural planning zones are modeled in more detail, since the study area, the Syr Darya basin, is dominated by agricultural water use. We start with the river basin as a *region*, identify each agricultural planning zone within the region as a *planning zone* and within each planning zone, several *areas* with specific soil types are identified. A soil area can have several *fields*, corresponding to specific crop patterns. Figure 1 illustrates this hierarchical structure. The regional level is used for hydrologic systems operation and water allocation among planning zones (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 planning zone 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. Figure 2 shows the decisions and benefits associated with various levels within the river basin.

2.2. INSTITUTIONAL ASSUMPTIONS

Optimal water management must be consistent with the existing institutions. Brown et al. (1982) recognized four objectives of concern to water management institutions: economic improvement, environmental preservation, maintenance of agricultural lifestyle, and equitable access to water. Young (1996) argued that if water management institutions are inadequate, optimal farm level resource use will be suboptimal when considered from the societal perspective. Gardner et al. (1990) encouraged the collective management of ‘common pool resources’ like water, which have many users. Each individual user may only reach suboptimal outcomes, while a collective institution is more likely to attain global optimality.

In this research, we assume that a central authority exists in the river basin which can make decisions based on the overall socio-economic and environmental benefits in the river basin. This is the case in the Syr Darya basin where the riparian countries have agreed to an allocation of water use rights between the countries and an interstate coordinating water commission (ICWC) has been established to approve annual allotments according to these shares and the predicted runoff or water availability in any given year. Thus, each country must consider its allotment as an upper bound in its water use planning. In addition, the Central Asia Energy Pool (CAEP) is operated so as to respect the river basin operation constraints.

2.3. MODELED PROCESSES

2.3.1. Definitions and Sets

The processes considered in this model include those associated with the flow and salt balance in reservoirs, river reaches, aquifers, and root zones, and flow and salt transport between these entities. Some of the processes specifically related to irrigation and drainage activities are described in this section.

2.3.1.1. Index Sets

The equations presented below that describe the modeled processes use several index sets which are described here:

t: time periods (months);
y: years;
st: crop growth stages, $st \subset t$;
n: Nodes in the river basin network;
  $n =\{river\ reaches, reservoirs, aquifers, planning\ zones\}$;
  $n1$ represents a from-node, $n2$ represents a to-node;
  set ($n1$, n) represents all links from $n1$ to n; and
  set (n, $n2$) represents all links from n to $n2$;
  set *pws* representd all nodes with hydropower stations
d: planning zones (or Planning Zone), $d \subset n$;
a: areas with specific soil types, $a \subset n$;
f: fields; and
cp: crops

Several items relate anthropogenic controls to hydrologic processes include the various water distribution, irrigation, drainage efficiency, and drainage disposal ratio. These are defined and discussed below. These are all determined endogenously in the model, by the objective of maximizing irrigation benefit, as well as by management policies for equity and environmental protection. They are also constrained by their current conditions, their potential for improvement, and the economic efficiency of investment in these improvements.

2.3.1.2. Water Distribution Efficiency

Water distribution efficiency ($e1$) is the ratio of the water arriving at a planning zone to the total water diverted

$$e1(d) = \frac{WDA^t(d)}{WD^t(d)} \tag{1}$$

where $WDA^t(d)$ is the amount of diverted water which is available for use at planning zone d in period t, and $WD^t(d)$ is the total water diverted to the planning zone (including local sources). $e1$ depends on the condition of canals and it is constant over time and uniform within a planning zone, but it can vary among planning zones.

2.3.1.3. Irrigation Efficiency

Irrigation efficiency ($e2$) is defined as (Clemmens and Dedrick, 1994)

$$e2 = \frac{\text{average depth of water stored in the root zone}}{\text{average depth of water applied}} \tag{2}$$

The numerator refers to water which is available for consumptive use by plants, and is eventually used for that purpose. To use this definition in the model, we make two assumptions: (1) no surface runoff from the field, and (2) $e2$ is the same over all crop growth stages. The first assumption may only be reasonable for large crop fields in arid or semi-arid areas, and the second applies for the average condition of large crop fields. With these assumptions, $e2$ is calculated as

$$e2(d,a,f)=\frac{\sum_{t\in st} WAU^{t}(d,a,f)}{\sum_{t\in st} WAF^{t}(d,a,f)} \tag{3}$$

where $WAU^{t}(d,a,f)$ is the applied water that is available for use by crops, and $WAF^{t}(d,a,f)$ is the total water applied to fields, including diversion, local surface sources, groundwater pumping, and drainage reuse.

2.3.1.4. Drainage Efficiency

Drainage efficiency ($e3$) is the ratio of drained crop area to total irrigated crop area

$$e3(d)=\frac{\sum_{a}\sum_{f} AD(d,a,f)}{\sum_{a}\sum_{f} A(d,a,f)} \tag{4}$$

where *A(d,a,f)* is the irrigated crop area within planning zone *d*, and *AD(d,a,f)*is the drained irrigated crop area.

2.3.1.5. Drainage Disposal Ratio

Drainage disposal ratio ($e4$) is the ratio of the amount of drainage disposal through evaporation (*WDD*) to the total amount of field drainage (*WDN*)

$$e4(d)=\frac{\sum_{t} WDD^{t}(d)}{\sum_{t}\sum_{a}\sum_{f} WDN^{t}(d,a,f)} \tag{5}$$

2.3.2. Water and Salt Balances in Rivers, Reservoirs and Aquifers

The balance of water and salt is computed in each of the major flow and storage elements of the river basin, including river reaches, reservoirs, and aquifers.

2.3.2.1. *Water Balances in Rivers and Reservoirs*

Water balances in river reaches and reservoirs can be written as

$$\sum_{n1\in(n1,n)} Q^t(n1,n) - \sum_{n2\in(n,n2)} Q^t(n,n2) = S^t(n) - S^{t-1}(n) \qquad (6)$$

where $Q^t(i,j)$ is the flow from node *i* to node *j* during time period *t*, and $S^t(n)$ is the storage at the end of time period *t* at node *n*. For many river reaches the storage effect in Equation 6 can be neglected, i.e., $S^t - S^{t-1} = 0$. The inflow to a river reach or reservoir includes: flow from upstream river reaches or reservoirs; drainage from planning zones; discharge from aquifers; and natural drainage. The outflow includes: flow diversion to planning zones; flow to downstream river reaches or reservoirs; evaporation losses, and seepage to groundwater.

2.3.2.2. *Hydropower Generation*

The hydroelectric energy generated at any power station (*pst*) is proportional to the flow through the turbine times the difference between average surface elevation and tail water elevation *tw(n).* The maximum energy generation in a period cannot exceed the energy generation capacity of a station (*PC*).

$$P^t(n) = k(n) * \{\frac{1}{2}[H^t(n) + H^{t-1}(n)] - tw(n)\} * \sum_{n_1\in(n,n_1)} Q^t(n,n_1) \qquad n \in pws \qquad (7)$$

$$P^t(n) \le PC(n) \qquad n \in pws \qquad (8)$$

2.3.2.2. Water Balance in Aquifers

A simple single-tank model (Bear, 1977) is used to simulate water balances in aquifers. Each planning zone is assumed to have one groundwater "tank" associated with it, the inflow to the tank includes: natural recharge (*R*), surface water leakage (*L*), and deep percolation (*DP*) from irrigation fields. Outflow from the tank includes pumping (*P*), groundwater extraction to root zones (*G*) and discharge to surface water systems (*DS*). The water balance in any tank can be represented as

$$\Delta t\left[R^{t}(n)+L^{t}(n)+DP^{t}(n)-G^{t}(n)-P^{t}(n)-DS^{t}(n)\right]=AA(n)\cdot s(n)\cdot[h^{t+1}(n)-h^{t}(n)] \quad (9)$$

in which *AA* is the horizontal area of the aquifer, *s* is the aquifer storativity, and *h* is the average water table elevation in the tank. A linear relationship is assumed between the discharge *DS,* and *h* (Smedema and Rycroft, 1983),

$$DS^{t}(n)=h\cdot h^{t}(n) \quad (10)$$

where h is a coefficient calibrated by local observations. To avoid waterlogging of crops, it is important that the groundwater table not rise above a critical threshold. This critical depth depends on the root depth of the crop, the efficiency of irrigation water use and on the hydraulic characteristics of the soil. This affects the extent of field drainage required to prevent waterlogging of fields.

2.3.2.3. Salt Balances in River Reaches, Reservoirs, and Aquifers

The salt balances in river reaches, reservoirs, and aquifers are based on the water balances in each of these entities, and can be expressed as

$$\sum_{n1\in(n1,n)} Q^{t}(n1,n)\cdot C^{t}(n1)-\sum_{n2\in(n,n2)} Q^{t}(n,n2)\cdot C^{t}(n)=S^{t}(n)\cdot C^{t}(n)-S^{t-1}(n)\cdot C^{t-1}(n) \quad (11)$$

where $C^{t}(j)$ is the salt concentration at node *j* at the end of period *t*.

2.3.3. Water Allocation Within a Planning Zone

Within a planning zone, water delivered from reservoirs, rivers, and local sources are mixed, and then allocated to areas with different soil types. Within each area, water is allocated to fields (Figure 3)

$$\sum_{n1 \in (n1,d)} Q^t(n1,d)[1-e1(d)] = WDA^t(d) \tag{12a}$$

$$WDA^t(d) = \sum_a \sum_f WFLD^t(d,a,f) \tag{12b}$$

where $Q^t(i,d)$ is the flow from node i to planning zone d during time period t, $WFLD^t(d,a,f)$ is the surface water allocated to field f, in area a, at planning zone d in period t.

2.3.4. Water Available to Crops

2.3.4.1. Water Available to a Crop

The total water available to a crop includes applied irrigation water and effective rainfall. For each crop, sources may be blended with local groundwater and reused drainage (Figure 3)

$$WA^t(d,a,f) = WAU^t(d,a,f) + ER^t(d,a) \cdot A(d,a,f) \tag{13}$$

$$WAU^t(d,a,f) = \left[WFLD^t(d,a,f) + REUSE^t(d,a,f) + P^t(d,a,f)\right] \cdot e2(d,a,f) \tag{14}$$

in which, *WA* is the water available to crops, *REUSE* is the drainage water reused in the planning zone, and *ER* is the effective rainfall. Effective rainfall (*ER)*, the rainfall infiltrated into the root zone and available for crop use, can be estimated by the evapotranspiration/precipitation ratio method (USDA, 1969).

2.3.4.2. Root Zone Water Balance

The root zone water balance is expressed as (see Figure 4)

$$RD^t(a) \cdot \left[Z^t(d,a,f) - Z^{t\text{-}1}(d,a,f)\right] = \frac{WAF^{\,t}(d,a,f)}{A^t(d,a,f)} + IR^t(d,a,f) + G^t(d,a,f) - ETA^t(d,a,f) - PN^t(d,a,f) \tag{15}$$

in which, *RD* is the root zone depth, *Z* is the soil moisture content in root zone, *G* is the groundwater extracted from the aquifer by absorption and available in the root zone, *ETA* is the actual evapotranspiration, and *IR* is the infiltrated precipitation.

By the definitions of $e2$ and *ER*, we can split Equation 15 into

$$RD^t(a) \cdot \left[Z^t(d,a,f) - Z^{t-1}(d,a,f)\right] + ETA^t(d,a,f) = \frac{WA^t(d,a,f)}{A(d,a,f)} + ER^t(d,a,f) + G^t(d,a,f) \tag{16}$$

and

$$PN^t(d,a,f) = \left(\frac{WAF^{\,t}(d,a,f)}{A(d,a,f)}\right) \cdot \left[1 - e2(d,a,f)\right] + IR - ER^t(d,a,f) \tag{17}$$

where Equation 16 shows the sum of water for crop evapotranspiration in the current period and water stored in the root zone for that purpose in a later period is the sum of applied irrigation water, effective precipitation, and groundwater extraction. Percolation (*PN*) is defined as the movement of water to a depth that is inaccessible to plant roots. Equation 17 shows that percolation from the crop field includes excess applied irrigation water and excess water from infiltrated precipitation.

Assuming only small changes in the water table, the monthly upward movement of water from the water table (*G*) can be estimated based on the depth of water table and soil characteristics (Eagleson, 1978)

$$G^t(d,a,f) = \mathrm{K}(d,a)\left[1+\frac{1.5}{\mathrm{m}(d,a)\cdot \mathrm{c(d,a)}-1}\right]\cdot\left[\frac{\Phi s(d,a)}{\mathrm{GD}^t(d,a,f)}\right]^{\mathrm{m}(d,a)\cdot \mathrm{c}(d,a)} \Delta t \qquad (18)$$

where K is the soil saturated hydraulic conductivity, c is the soil's pore connectivity index, m is a parameter related to the soil connectivity and tortuosity, Φs is the saturated soil matric potential. All of these items are known parameters for a specific soil type. *GD* is the depth of water table, and *Dt* is the time duration of one period.

2.3.4.3. Root Zone Salt Balance

Assuming no lateral flow in the root zone, Abdel_buyem and Skaggs (1993) propose the following root zone salt balance expression

$$PN^t(d,a,f)\cdot SP^t(d,a,f) = \frac{WAF^t(d,a,f)}{A(d,a,f)}\cdot SW^t(d,a,f) + G^t(d,a,f)\cdot SG^t(d,a,f)$$
$$- Zs(a)\cdot RD^t(f)\cdot\left[SE^t(d,a,f) - SE^{t-1}(d,a,f)\right] \qquad (19)$$

where *SP, SW,* and *SG* are the salinity in the percolation, applied water, and groundwater, respectively; *SE* is the salinity of the soil moisture. Sharply and Williams (1990) proposed the following salt transport equation

$$PN^t(d,a,f)\cdot SP^t(d,a,f) = Zs(a)\cdot RD^t(f)\cdot\left[SE^t(d,a,f) + SE^{t-1}(d,a,f)\right]\cdot$$
$$\left\{1-\exp\left[\frac{-PN^t(d,a,f)}{\left[Zs(a)-Zw(a)\right]\cdot RD^t(f)}\right]\right\} \qquad (20)$$

where the left side of the equation represents the salt mass leaving the root zone with the water flow and the right side represents the salt mass in the root zone multiplied by a discounting factor determined by the amount of outflow.

2.3.4. Drainage Produced in a Planning Zone

Control of drainage from irrigated fields is necessary to maintain water quality and ecological conditions in a river basin. Generally, drainage flow is of lower quality and contains more salt than the water applied for irrigation, but the quantity is less than the primary diversion. Therefore, the drainage brings higher salinity water back to the river system. Drainage flow is related to anthropogenic controls including distribution efficiency, drainage system, and drainage reuse and disposal capacity. The amount of drainage (*RF*) leaving a planning zone is

$$RF^{t}(d) = \sum_{a}\sum_{f} WDN^{t}(d,a,f) + DS^{t}(d) - WDD^{t}(d) - \sum_{a}\sum_{d} RUSE^{t}(d,a,f) \tag{21}$$

Salt concentration in the drainage is computed by a salt balance equation including salt mass carried with each item in Equation 21.

2.3.5. Crop Production as a Function of Soil Moisture and Soil Salinity

2.3.5.1. Crop Evapotranspiration

Actual evapotranspiration (*ETA)* is a function of both soil moisture (*Z*) and the salinity in the soil moisture (*SE*) which is a function of the salt content of both the soil (that is, sorbed to the soil) and the salinity of the available water. The presence of excessive soil salinity leads to a high level of soil osmotic potential which inhibits the "passive" entry of water into the roots in the same manner as does the soil matric potential. We assume that: (1) the soil matric potential affects both the bare soil evaporation and plant transpiration; (2) the soil osmotic potential only reduces the plant transpiration; and (3) the soil water content and the soil salinity have independent effects on crop yield. Based on these assumptions and combining the work of Jensen et al. (1971) and Hanks (1985) we may write an expression for *ETA*

$$\begin{aligned} ETA^{\mathrm{t}}(d,a,f) = \mathrm{ET0}^{\mathrm{t}}(d) \cdot \Big\{ \big[1 - ks(d,a,f)\big] \cdot kat^{t}(d,a,f) \cdot \mathrm{kct}^{t}(a,f) \\ + kap^{t}(d,a,f) \cdot \big[\mathrm{kc}^{t}(a,f) - \mathrm{kct}^{t}(a,f)\big] \Big\} \end{aligned} \tag{22}$$

where *ks*, *kat*, *kct*, and *kap* are coefficients of soil salinity effect, soil water stress effect on transpiration, crop transpiration effect, soil water stress effect on soil evaporation, and crop evapotranspiration effect, respectively. The soil salinity effect coefficient (*ks*) is estimated from the yield - seasonal root zone salinity relationship given by Maas and Hoffman (1977)

$$YR(d,a,f,cp) = 1 - ks(d,a,cp) \tag{23}$$

and

$$ks(d,a,cp) = \begin{cases} 0 & \text{if } \overline{SE}(d,a,f) < S'(cp), \\ B(cp)\cdot\left[\overline{SE}(d,a,f) - S'(cp)\right] & \text{otherwise} \end{cases} \tag{24}$$

where, $\overline{SE}$ is the average seasonal root zone salinity, *S'* is a threshold salinity, and *B* is the percent yield decrement per increase in salinity in excess of the threshold. *kat* is estimated by the following equation given by Jensen et al. (1971)

$$kat^{t}(d,a,f) = \ln[100\cdot(\frac{Z^{t}(d,a,f) - \mathrm{Zw}(a)}{\mathrm{Zs}(a) - \mathrm{Zw}(a)}) + 1]/\ln(101) \tag{25}$$

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

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

$$kap^{t}(d,a,f) = \left[\frac{Z^{t}(d,a,f) - 0.5\cdot Zw(a)}{Zs(a) - 0.5\cdot Zw(a)}\right]^{0.5} \tag{26}$$

2.3.5.2. Crop Production

FAO (1979) recommends a relationship between relative yield decrease and relative evapotranspiration deficit

$$YR = 1 - \mathrm{ky}\cdot\left(1 - \frac{ETA}{ETM}\right) \tag{27}$$

where ky is the yield response factor. The value of ky for different crops is based on experimental evidence, which covers a wide range of growing conditions. *ETA* is calculated from Equation 22. The maximum evapotranspiration (ETM) can be calculated as

$$\mathrm{ETM} = \mathrm{kc} \cdot \mathrm{ET0} \tag{28}$$

where ET0 is the reference evapotranspiration (FAO, 1979), and kc is the crop coefficient (FAO, 1979). Critical crop stage is the crop growth stage in which the relative yield (*YR*) is minimum among all stages. To account for water stress and salinity effects in individual crop growth stages, *YR* is calculated as

$$YR = \min\left\{ \min_{st}\left[1 - ky^{st} \cdot \left(1 - \frac{CETA^{st}}{CETM^{st}}\right)\right], 1 - ky^{season} \cdot \left(\frac{ETA^{season}}{ETM^{season}}\right) \right\} \tag{29}$$

where $CETA^{st} = \sum_{t=1}^{st} ETA^{t}$ and $CETM^{st} = \sum_{t=1}^{st} ETM^{t}$ are *cumulative* actual and maximum evapotranspiration up to stage *st*, respectively. Thus, the crop production function includes the effects of soil water moisture and soil salinity over all crop growth stages.

2.5. ECONOMIC INCENTIVES

2.5.1. Introduction

One of the important purposes in this paper is to study the effects of economic incentives on hydrologic system operations and determine principles of effective and rational water management. The economic incentives should enable 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 “dilution bank”. The economic components included in the modeling framework are:

- Agricultural production as a function of the volume of water beneficially transpired, soil salinity level resulting from current irrigation and previous salt accumulation, and area of irrigated land;
- Infrastructure improvements as functions of investment on an annualized basis;
- Instream water use value from hydropower generation and ecological maintenance;
- Tax on excess salt discharge to both surface and ground water systems, and subsidy for infrastructure improvements; and
- Externalities from excess water diversion and salt discharge by upstream planning zones, producing negative effects on crop production at downstream planning zones.

With these incentives included in the model, the objective is to maximize the net benefit from use of basin resources. Instead of fixed-quantity proposals (prescribed water use rights), in this paper, endogenous demand functions for individual planning zones and an institutional framework are used to direct the search for optimal inter-planning zone and inter-crop water allocations.

Tax and subsidy systems are popular incentives for resource allocation and pollution control (Baumol and Oates,1992). Specific discussions of tax/subsidy effects on agricultural nonpoint pollution include Howe and Orr (1974), Griffin and Bromley (1982), and Dinar and Letey (1996). We assume that excess salt discharge is penalized by a Pigouvian tax (Baumol and Oates,1992) and that it can be mitigated by improvements in water distribution, drainage collection and disposal, and irrigation system efficiency. A tax/subsidy system is implemented in the model so that excess salt discharge is taxed and infrastructure improvements are subsided.

Using this system, a subsidy is available for investments in all measures that conserve water or reduce drainage directly or indirectly, including improvement of canal lining, drainage facilities, and irrigation systems. All planning zones in the river basin share the subsidy, but the allocation of the subsidy among planning zones, and among the facilities is determined by the model. Often, returns from irrigated agriculture can not finance infrastructure development and improvement, the government must provide this financing. In this model, we assume the total subsidy is equal to the total tax plus an additional input provided by the central authority, generally funded by the government.

2.5.2. Benefit Functions

Net benefit from irrigated agriculture in planning zone *d* is

$$IB(d) = \sum_{a}\sum_{f} \left\{ \sum_{cp} \left[\mathrm{p}(cp) \cdot YA(d,a,f,cp) - \mathrm{fc}(d,a,f,cp) \right] \cdot A(d,a,f,cp) \right.$$

$$- \sum_{t} \left[\mathrm{cg}(d) \cdot P^{t}(d,a,f) + \mathrm{cs}(d) \cdot WD^{t}(d) + \mathrm{cr}(d) \cdot RUSE^{t}(d,a,f) \right.$$

$$\left. \left. + \mathrm{cdn}(d) \cdot WDN^{t}(d) + \mathrm{cdd}(d) \cdot WDD^{t}(d) \right] \right\} - tax(d) \cdot MES^{t}(d) \tag{30}$$

where *p* is the price of crop, *fc* is the fixed cost per unit area of crop, *cg, cs, cr, cdn*, and *cdd* are the costs of groundwater pumping, water diversion, drainage collection, drainage reuse, and drainage disposal, respectively, *tax* is the tax imposed on excess salt discharge, and *MES* is the salt mass in return flow in excess of what was present in the original diversion.

The instream water use benefit from hydropower generation (*HB*) at hydropower stations (*st)* is

$$HB = \sum_{t}\sum_{st} \left[ppw(st) - cpw(st) \right] \cdot PW^{t}(st) \tag{31}$$

where *PW* is the power generated at station *st* in month *t*, *ppw* is the selling price of power, and *cpw* is the power generation cost. The value of ecological water use (*EB*) is

$$EB = \sum_{t} weco \cdot WECO^{t} \tag{32}$$

where *WECO* is the water for ecological use, and *weco* is the socio-economic net benefit per unit of ecological water use. Combining these three basin water uses into a single benefit function we have the total water use benefit (*TB*)

$$TB = IB + HB + EB \tag{33}$$

2.5.3. Investments for System Improvement

Annual investments for water distribution, irrigation and drainage, and drainage disposal in the river basin are represented as

$$IDS(d) = ids(d) \cdot \Delta e1(d) \cdot \sum_{t} WD^{t}(d) \tag{34}$$

$$IIR(d, a, f) = iir(d) \cdot \sum_{a} \sum_{f} \Delta e2(d,a,f) \cdot \sum_{t} WFLD^{t}(d, a, f) \tag{35}$$

$$IDN(d) = idn(d) \cdot \Delta e3(d) \cdot \sum_{a} \sum_{f} A(d, a, f) \tag{36}$$

$$IDD(d) = idd(d) \cdot \Delta e4(d) \cdot \sum_{t} \sum_{a} \sum_{f} WDN^{t}(d, a, f) \tag{37}$$

in which *IDS, IIR, IDN,* and *IDD* are annual investments in water distribution, irrigation, drainage collection, and drainage disposal systems, respectively, *ids, iir, idn,* and *idd* are investments per unit of water savings from water distribution, irrigation, drainage collection, and drainage disposal systems, respectively. The investment within the river basin is limited by total tax income and additional government payments, or

$$INV \le \sum_{d} tax(d) \cdot MES(d) \cdot (1 + rgp) \tag{38}$$

where

$$INV = \sum_{d} \left[IDS(d) + IIR(d) + IDN(d) + IDD(d) \right]$$

where *rgp* is the ratio of government to local financing.

2.6. MODEL IMPLEMENTATION

The model is formed from the objective function, Equation 33 and the constraints which are represented in Equations 6 - 29. The model is implemented in the GAMS (General

Algebraic Modeling System) language (Brooke et al., 1988). This leads to a model with 9874 equations and 13713 variables.

The nonlinear items include bilinear items, exponential items, and logarithmic items. Obviously, this is a large and complex model. The two widely used GAMS NLP solvers, MINOS5 (Murtagh and Saunders, 1987) and CONOPT (Drud, 1994), were unable to find feasible solutions, even with very relaxed tolerances. Since the model could not be solved directly using the available solvers, a "piece-by-piece" approach is applied to solve the model.

We notice that all calculus-based NLP solvers (e.g., MINOS5, and CONOPT2) depend on "initial values" of the model variables. Inappropriate initial values can cause a solver to take a long time to find a feasible solution or even stop at an "infeasible solution", which often happens for large and complex NLP models. The idea of the "piece-by-piece" approach is to provide the model with better initial values step by step. Often, large models can be decomposed into several pieces, and the model solved step by step with one piece added at each step. At each step, the solution of the current partial model begins from the solution found in the previous step, and the solution from the current step is saved as a basis for the next step. At the final step, the model contains all pieces and the whole model is then solved. The model is divided into the following sub-models:

Model-1: flow balance

crop production functions

Model-2: **Model-1** + salinity balance

Model-3: **model-2** + effect of soil salinity on crop evapotranspiration

Model-4: **Model-3**+

tax-salt discharge relationships, and

investment constraint on infrastructure improvement

In **Model-1,** we assume that crop production is related only to soil water stress, neglecting the effect of soil salinity. Salt balances are added to **model-2**. The purpose of **Model-2** is to find feasible values for all salinity variables, as well as flow, but the interrelationships between soil salinity and crop evapotranspiration are not included**.** These interrelationships complicate the water and salinity relations in the crop root zone, and they further affect the flow and salinity balances in the river and aquifer system. Before feasible values for the salinity variables are found, these complications make the model difficult to solve. This is why the inter-relationships between salinity and crop evapotranspiration are not included in **Model-2**, but they are included in **Model-3**, in which feasible initial values for both flow and salinity are available.

Economic relationships such as the tax-salt discharge relationships, and the investment constraint on infrastructure facilities are not included in **Model-1**, **Model-2** or **Model-3**, but they are added to **Model-4**, which is equivalent to the original model. The solution of **Model-3** provides feasible initial values for flow and salinity, which satisfy all constraints in the original model, except the added economic relationships. Therefore, solving **Model-4** with the values found from **Model-3** is possible, while solving the original model directly is not.

The approach takes advantage of the "restart" facility of GAMS to solve the series of models step by step. The solution variables of the model in one step are taken as initial values for the model in the next step. At the final step, the model includes all pieces, which is equivalent to the original model with appropriate initial values for all variables. The solve statements are:

GAMS Model-1 *s* Solution-1

(solve Model-1 and save the solution to Solution-1)

GAMS Model-2 *r* Solution-1 *s* Solution-3

(solve Model-2 starting from Solution-1 and save the solution to Solution-2)

GAMS Model-3 *r* Solution-2 *s* Solution-3

(solve Model-3 starting from Solution-2 and save the solution to Solution-3)

GAMS Model-4 *r* Solution-3 *s* Solution-4

(solve Model-4 starting from Solution-3 and save the solution to Solution-4)

3. Model Data

3.1. SYR DARYA BASIN

The model described above was applied to the problem of water and salt management in the Syr Darya River basin. The Syr Darya River is one of the two major rivers feeding the Aral Sea. The river begins at the Pamir and Tien Shan plateaus, crosses the territories of several Central Asian republics, Kyrgyzstan, Tajikistan, Uzebekistan, and Kazakhstan, and terminates in the Aral Sea. The Syr Darya basin covers 484.5 thousand km^2 and it is 2,337 km in length. The Syr Darya basin's water supply system is comprised of 9 major tributaries, 11 reservoirs, numerous irrigation distribution systems (23 in all, but they are aggregated to 6 in this paper) and numerous distributing canals. Figure 4 shows a modeling network of the Syr Darya River basin, which follows the sketch of Raskin et al. (1992).

The Syr Darya water resources in an average year amount to 40.6 km^3, with 37.12 km^3 is surface inflow, 2.18 km^3 underground inflow, and atmospheric precipitation runoff is 1.30 km^3 (Khamidov, 1999). Water quality in the Syr Darya basin is seriously affected by anthropogenic activities in the basin. Agricultural drainage is the major factor affecting water quality in middle and lower sections. Records show that just downstream of the Fergana Valley, a major irrigated area in the basin, the average salinity of the river water has increased to 1.2 g/l from a concentration of less than 0.5 g/l entering the valley (Raskin et al., 1992), illustrating that return flow has a considerable impact on water quality in the river. The average mineralisation in irrigation drainage is 0.2 - 0.7 g/l in the upstream area, 0.7 - 2.3 g/l in the midstream area, and 9.0 -10.0 g/l in the downstream area (WARMAP, 1995).

Raskin et al. (1992) estimated the total water demand in the Syr Darya River basin in 1987 as 43.77 km^3 per year, which was dominated by the agriculture sector, accounting for 82% of the total demand. The total irrigated area was 3.3 million hectares in 1987, and the major crops were cotton, wheat, maize and alfalfa; rice was also a major crop in the downstream area. The annual withdrawal of water (including return flow reuse) in the basin was 57 km^3 in 1987 (Raskin et al., 1992). The flow to the Aral Sea from the Syr Darya River has varied from 1.8 to 9.0 km^3 annually since 1990 (P. Micklin, personal communication, 1997).

In the last 40 years, intensive irrigation practices in the river basin have significantly increased water management and soil salinity problems in the basin, especially in the downstream area. The salinity of the water in the river in the downstream reaches has increased from 0.7g/l in 1950’s to1.8g/l in 1980’s and the percentage of moderately to strongly saline lands in the midstream area increased from approximately 26% in 1970 to 54% in 1995. Recharging to aquifers through deep percolation in irrigated fields also put a threat of waterlogging in middle and down stream area of the basin (WARMAP, 1995).

It is urgent to study the tradeoff relationships between irrigation and its associated economic benefits and environmental effects. Irrigation is important to the economic development of the area, because a large portion of the national economies (40-50% of GPD) is derived from irrigated agriculture (World Bank, 1996). However, withdrawal of water for irrigation leads to decreased inflow to the Aral Sea, increased salt and other pollutant discharge to the river system, and an increase in pollutant concentration in downstream river reaches. Facing these environmental impacts, one can ask the question whether such a high level of irrigated agriculture can be sustained while preventing or minimizing adverse environmental and ecological impacts.

The model described in this paper is applied to the Syr Darya River basin for water management analysis within a one-year time horizon. We describe the model for this purpose as a *short-term model*, which is used to study the performance of the complex, integrated hydrologic-agronomic-economic river basin system to provide useful information for sustainability analysis and decision-making in water resources management of irrigation-dominated river basins. This model is a large-scale, nonlinear optimization model, which includes all essential hydrologic, agronomic, economic and institutional relationships in one endogenous system. The major state variables of the model include monthly reservoir storage, soil moisture content, aquifer water table, soil salinity level, and salt concentrations in rivers, reservoirs and aquifers. The major flow process variables include flow in the surface water system, evapotranspiration, deep percolation, drainage and return flow from irrigation fields, groundwater discharge, and salt concentration associated with all these processes. Economic parameters, such as crop prices, water supply price, and tax on salt discharge, and subsidies for infrastructure improvement are all taken as external data. The model is used to study the performance of the complex, integrated hydrologic-agronomic-economic river basin system.

3.2. MODEL DATA AND ASSUMPTIONS

3.2.1. Hydrologic data

The basin model network includes 11 river reaches, 11 reservoirs, 6 aquifers, 5 hydropower stations, and 6 planning zones, and return-flow linkages between these entities. The model is built on this network and the planning zone – soil plot – crop field concept described in the previous section.

The long-term average inflow to rivers and reservoirs is presented in Table A.1 of Annex A to this report. The long-term average local source from runoff collection is given in Table A.2. Table A.3 shows the characteristics of the major reservoirs in the Syr Darya basin. Five major reservoirs are used to control the water in the basin: Toktogul, Kayrakum, and Chardara on the main stem at the upstream, mid-stream, and down-stream, respectively, and Andijan and Charvak reservoirs on the major tributaries, Karadarya and Chirchik Rivers, respectively. Toktogul reservoir (14.5 km3 active capacity) is the major multi-year regulation reservoir in the syste; the remaining reservoirs are used for seasonal reregulation of water.

Major hydropower generatiing stations are associated with five upstream reservoirs, Toktogul, Utchkurgan, Kurpskaya, Tashkumur, and Shamdalsai. The characteristics of these stations are presented in Table A.4. Currently the Toktogul hydropower station Toktogul is the largest one. The water head for the four reservoirs downstream of Toktogul is kept constant throughout each year, and hydropower generation for the stations only depends on the inflow to these reservoirs (McKinney and Cai, 1997).

Few data related to the aquifers in the study area were available for this research. Assuming each planning zone has a single aquifer, all water distribution losses and deep percolation occurring in a planning zone are assumed to go to the aquifer associated with the planning zone. Pumping from an aquifer is limited by the pumping capacity. Table A.5 gives, for each planning zone, the pumping capacity in 1987 (Raskin, et al., 1992), water table depth (WARMAP, 1995), estimated surface area and yield coefficient, and estimated ratio of aquifer discharge to water table (h). As discussed previously, h is a coefficient to be calibrated by local experiments, which is not available for this case study. This value was estimated by trial-and-error, in which the calculated aquifer discharge is compared to the value provided by another study (WARMAP, 1995).

Table A.6 shows the monthly average reference evapotranspiration (ET0); Table A.7 presents the monthly average precipitation (WARMAP, 1995).

Three soil types, sandy clay (*scl*), loam (*l*), and sandy loam (*sl*) are classified for each Planning zone. The available irrigated area with the soil types in each Planning zone is shown in Table A.8, which is based on soil distribution study by WARMAP (1995), and the physical characteristics of the three soil types are shown in Table A.9, which are estimated based on Eagleson (1978).

3.2.2. Agronomic Data

Five crops are considered here: cotton, wheat, forage, maize, and alfalfa, which are the major crops in this area. All other crops are grouped into one single crop (other). The growth periods of these crops are: cotton (April - Sept.), forage (Oct. – Mar.), wheat (Nov. – May), maize (June - Sept.), alfalfa (perennial), and other (Mar. – Nov). Considering the rotation relationships, these crops are grouped into four types of crop combinations: cotton and forage (*cot-foa),* wheat and maize (*wht-maz),* alfalfa (*alf_alf)*, and other crops (*oth_oth)*. In one soil area, four types of crop *fields* corresponding to the four crop combinations are defined. Soil water and salinity balance are modeled in each field.

Crop coefficients of evapotranspiration (k_c) (FAO, 1977) are presented in Table A.10. The empirical salinity coefficients (Mass and Hoffman, 1979) are shown in Table A.11. Crop yield response coefficients (k_y) (FAO, 1977) are shown in Table A.12, and maximum crop productions (dry matter) are shown in Table A.13. The maximum crop production is calculated by methods described in FAO (1979), in which the maximum crop production depends on solar radiation, temperature, and crop characteristics.

3.2.3. Economic and Infrastructure Improvement Data

Table A.14 shows the estimated average water delivery and distribution efficiency ($e1$) and drainage ratio ($e4$) for each Planning zone. Table A.15 shows the estimated irrigation application efficiency ($e3$) over all Planning zones, soil types, and crop fields. All these efficiencies are based on WARMAP (1995).

The cost of surface water supply (*cs*), and groundwater pumping (*cg*) are shown in Table A.16 and they were estimated from WARMAP (1995). Crop fixed cost (*fc: 160 – 390*

$/ha) and crop values (*vc: 110 – 770 $/ton*) for different crops were estimated from the World Bank (1996) report, which are shown in Table A.17.

Data for infrastructure investment are estimated based on WARMAP (1995) information. Table A.18 shows the annual investment ($/m^3) for improving canal lining and on-farm drainage system. The annual investment ($/m^3) of improved on-farm irrigation methods, for different crop fields, is given in Table A.19.

The cost of drainage water reused for irrigation purposes is in the range of $54 - 73 per 1000 m^3. The cost of drainage disposal to the desert is about $100 per 1000 m^3 (WARMAP, 1995). Average hydropower power generation cost is estimated as 0.05 $/kWh, and the economic value of power is about 0.08 $/kWh (World Bank, 1996).

Maintaining a required volume of inflow from the Syr Darya River to the Northern Aral Sea is a main ecological concern in the basin. In order to consider the Aral Sea as a separate "user" of water in the model, the historic record of flows in the Syr Darya River at Kazalinsk, in the far downstream reach of the river, is used as a measure of the required flows to the sea. The annual inflow to the sea was about 7.0 km^3 in a normal hydrologic year and 10.0 km^3 in a wet year, during the period 1965-75. An ecological benefit (or damage) function for the flow to the sea is

$$eben = ev \cdot (inflow\text{-}inflow0) \tag{39}$$

where

inflow:	model computed annual inflow to the Aral Sea;
inflow0:	required annual inflow to the sea;
ev:	economic benefit (*inflow – inflow0 >0*) or damage (*inflow – inflow0 <0*), per unit of inflow to the Aral Sea. *ev* has been estimated as 0.1 $/m^3 (Anderson, 1997)

The ecological benefit calculated from Equation 39 does not directly represent the real ecological benefit. Formulating the ecological benefit in this way maintains downstream flow for ecological purposes to the extent normally required, while presenting a measure of the tradeoff between the benefit from ecological water uses and that from other uses. However, the fact that some threshold value of flow may be necessary to trigger such benefit or damage accrual has not been investigated..

M&I water use benefit is not explicitly considered in the case study. Irrigation water demand covers more than 80% of the total water demand in the Syr Darya basin. Municipal and industrial water demand has the first water supply priority, and it is satisfied in all scenarios reported here. Table A.20 shows the M&I water demand (Raskin, et al., 1992).

The penalty tax on excess salt discharge is assumed to be 10$/ton. The model is run using various values of this item to search for an appropriate value.

4. Model Results

4.1. SENSITIVITY ANALYSIS

Sensitivity analysis was performed to determine the factors have the most impact on the model results. Several sensitivity analysis scenarios are defined for basin inflow, effective rainfall (*ER*), and reference evapotranspiration (*ET0*) and the results are shown in Table B.1. All numbers in these tables are relative values.

The irrigation benefit (*IB*) is very sensitive to inflow and *ET0*, especially when inflow decreases and *ET0* increases, but *IB* is less sensitive to *ER*. Since *ER* accounts for a small amount of the total irrigation water in the basin, increasing or decreasing *ER* does not have much effect on *IB*. The effect on irrigated area is similar that on *IB*. When *ET0* decreases, irrigated area increases; however, when *ET0* increases, irrigated area decreases slightly. As expected, hydropower profit (*HP*) is very sensitive to inflow, but it is not sensitive to *ET0* or *ER*.

Flow to the Aral Sea increases when *ET0* increases and it also increases when *ET0* decreases. When *ET0* increases, crop water demand increases, and irrigation water supply becomes less profitable, more flow stays in the river and goes to the Aral Sea; while, when *ET0* decreases, crop water demand decreases, and water going to irrigation or ecological use depends on the marginal value of water for irrigation and ecological use. When water supply for irrigation reaches a certain level, additional water supply to irrigation becomes less profitable or unnecessary, and then more water goes to ecological use.

Total water use benefit (*TWB*) is not sensitive to *ET0* increases. The increase of *ET0* causes a decrease in *IB*; however, since more water goes to ecological use, benefit from this use increases. Finally the decrease of *IB* is offset by the increase in the ecological benefit. The same explanation can be given to the non-sensitivity of the total benefit to *ER*.

Increased inflow results in lower salt concentration in the surface water of the basin, less salt mass entering groundwater, and lower soil salinity. Higher *ET0* causes lower salt concentration in surface water of the basin, more salt mass entering the groundwater, and higher soil salinity. High *ER* use results in higher salt concentration in surface water outflow of basin, higher salt mass entering groundwater, and higher soil salinity.

4.2. RESERVOIR OPERATION

Eleven reservoirs are considered in the river basin network. Among them, Toktogul, Kayrakum, and Chardara Reservoirs, located at upstream, middle-stream, and downstream, respectively, provide the major flow regulation in this basin. Five upstream reservoirs, Toktogul, Utchkurgan, Kurpskaya, Tashkumur, and Shamdalsai have hydropower stations. It should be noted that two other large reservoirs exist in the basin but they are on the tributaries to the main stem of the Syr Darya river; Andijan reservoir on the Karadarya River and Charvak reservoir on the Chirchik River, respectively. This section discusses the combined operation of the three major reservoirs under three cases: (1) irrigation water supply only; (2) irrigation and hydropower generation; and (3) irrigation, hydropower generation, and soil and water quality maintenance. In Case 1, the objective function of the model does not include profit from hydropower generation (*HP*), and the constraints do not include salt balance or transport at any levels, i.e., there are no constraints on salt concentrations in any river, reservoir or aquifer, and there are no limits on soil salinity, and the effect of soil salinity to crop production is not considered. Case 2 is Case 1 with the inclusion of the hydropower generation profits. Case 3 is Case 2 with the inclusion of the salinity balance and salinity effect to crop production. In each of the three cases the model is run with average inflow and agricultural and economic data described above.

We define reservoir utilization efficiency (*RUE*) as the ratio of actual storage to the total available storage. For a system including multiple reservoirs, we define this ratio using the sum of the storage of all reservoirs. *RUE* shows how much of available storage capacity is used within a time period, and a high value of *RUE* shows more flow is controlled by reservoirs. Figure 7 shows the *RUE* in each month under the three cases. The average *RUE* is 0.288, 0.324, and 0.329 for Cases 1, 2, and 3, respectively. *RUE* increases from Case 1 to Case 2 due to additional reservoir storage used for hydropower generation, and it increases from Case 2 to Case 3 due to additional reservoir storage used for salinity control. The time horizon of the this model is one year, this is why the *RUEs* under these cases are low. *RUE* also depends on the initial reservoir storage, which were one-third full for this calculation, and the ending storage is equal to the initial storage for all these reservoirs.

One of the major sources of the Syr Darya River is the Naryn River in the mountainous Kyrgyz Republic. This source is controlled by the cascade of Toktogul reservoir plus the four downstream constant volume reservoirs. The Toktogul Reservoir controls more than 30% of the total inflow to the basin, and has the largest hydropower station in the area. The other four hydroelectric power stations have relatively small and constant storage, and minor drainage inflow, and they depend on the release from the Toktogul Reservoir for hydropower generation. These five hydropower stations provide over 80% of the installed generating capacity in the Kyrgyz Republic, where the peak demand for domestic power occurs in winter.

However, the downstream countries (mainly Uzbekistan and Kazakstan), which do not have much local water source, but do have large irrigated lands, must rely on the water releases of the upstream reservoirs, and their peak demand for irrigation water occurs in the summer. Since the major runoff period occurs in the summer, the Kyrgyz Republic would like to release some water in the summer period, which helps to meet the downstream irrigation needs; but at the same time, they would like to store water for power generation in the winter when there is little runoff. The Kyrgyz Republic’s preferred release during April to September is generally expected to be less than the downstream irrigation requirement, except in a wet year.

Combined with Toktogul Reservoir, the other two major reservoirs, Kayrakum and Chardara, have been utilized to solve this upstream and downstream conflict. The two reservoirs, located at midstream and downstream of the basin respectively, are designed for seasonal regulation of Toktogul release and flooding control. The results from the model developed in this research show that the combined utilization of the three reservoirs can also provide facilities for salinity control, as well as solving the timing problem between upstream hydropower generation and downstream irrigation. In winter periods, Toktogul releases water for power generation, and the released water can be stored in Kayrakum and Chardara Reservoirs for later irrigation and salt dilution releases in the vegetation period.

Figures 8-10 show reservoir active storage volumes and Figures 11-13 show reservoir releases for these three major reservoirs under the three Cases. In Case 1, reservoir operation is only driven by irrigation water supply. The releases of all reservoirs follow irrigation water demands, which increase in March, remain high from June to August, and decrease in non-vegetation period. In Cases 2 and 3, the releases from Toktogul Reservoir are higher in winter and other periods. The releases of the other two reservoirs are not very different from those in Case 1, because they are only driven by irrigation demand (an upper bound constraint is set for flooding control downstream of Chardara Reservoir). However, the storage in these two reservoirs are different for various purposes. The Kayrakum Reservoir stores water in non-vegetation period and almost dries up in the vegetation period. From Case 1 to Case 3, the non-vegetation period storage is increased, due to (1) in Cases 2 and 3 Toktogul releases more in non-vegetation period; (2) in Case 3 more storage is needed for salt dilution. For the downstream region, salt concentration in drainage and groundwater is higher, and Chardara Reservoir keeps more water in storage in most periods in Case 3 than Cases 1 and 2 in order to avoid higher salinity.

Figure 14 shows the salinity along the Syr Darya River from June to September. The return flow inlets along the river are shown in the figure. The drainage from upstream planning zones *Naryn* and *Fergana* causes salinity to increase in river reaches from *Naryn_gate* to *Right_in*. The natural inflow to *Karadar_in* and *Right_in* may dilute the drainage, therefore the increasing magnitude of salinity is not very significant here. From *Right_in* to the Kayrakum Reservoir, salinity decreases slightly. Through the Kayrakum Reservoir the salinity stays constant until *Shimi_in*, where drainage from planning zone *Mid_syr* causes an abrupt salinity increase. Inflow to *Chakir_in*, and the storage of the Chardara Reservoir dilute the drainage, and after the Chardara Reservoir, the salinity shows less fluctuation.

4.3. BASIN-WIDE SALINITY DISTRIBUTION ANALYSIS

As discussed above, Figure 14 shows the salt concentration along the Syr Darya River. Neglecting other factors that may affect salinity distribution in the basin, the our model results show that the salinity change in the river is due to drainage from planning zones distributed along the river. The peak salt concentration happens in river reach *Shimi_in*, which is caused by drainage from planning zone *Mid_Syr*. From the Farhad Reservoir to river reach *Chakir_in*, more than 80% of the river flow is diverted to *Mid_Syr*, the site of the major Uzkeb diversion for the “hungry” steppe region, in the irrigation months (June, July, and August), and about 45% of the water withdrawn returns back to the river, with higher salinity (about 1.5 – 2.5 times of the salinity in water withdrawn, depending on the month). Even with the dilution from natural inflow and reservoir storage, the salinity is higher for the downstream planning zones than for those upstream.

Figure 15 shows the average monthly salt concentration in water withdrawal for irrigation water supply in each Planning zone. The downstream Planning zones *Low_Syr* and *Artur* have the highest salt concentration. Planning zone *Chakir* is supplied by a local tributary, where the salt concentration is relatively low and constant.

Salinity variation over the year depends on irrigation scheduling, as well as the temporal distribution of natural water sources. The salinity at the end of September is higher than that of June (Figure 15), indicating that drainage has a significant effect on salinity just after the major irrigation period. Soil salinity increases through irrigation months, and reaches its peak at the end of the season. Therefore, salinity in drainage water is highest just after the peak irrigation period.

After the peak irrigation period, if there is considerable rainfall, drainage may have a high salinty since crops consume less water during this period. This process is called salt leaching, which may result in better soil salinity conditions, but may also result in worse surface and ground water salinity if drainage is properly treated or disposed of. Figure 16 shows soil salinity, salt mass entering the root zone and salt mass leaving the root zone. Obviously, the salt leaching in this case is not enough, since the soil salinity increases. This figure also shows that if drainage is not adequate, then irrigation may produce poor soil salinity conditions.

Salinity in the three major reservoirs is presented in Figure 17. Toktogul Reservoir is not affected by drainage and the salinity in this reservoir varies only with the salinity in natural inflow. The salinity in Kayrakum and Chardara reservoirs reaches a peak in the late irrigation season when the amount of drainage from crop fields is high.

Noking te that the salinity in reservoir storage and the soil salinity are significantly higher at the ending time period (Dec.) than those in the starting period (Jan.). This end effect means the water use (mainly irrigation) has imposed negative impacts to the environment, which is obviously not desirable. This effect can be managed in the long-term taking account of salt accumulation. The results also shows that groundwater salinity does not change significantly in a one-year time horizon. This is expected since generally only a long-term percolation process may affect groundwater salinity significantly.

4.4. IRRIGATION AND DRAINAGE MANAGEMENT

4.4.1. Blending Irrigation Water Supplies

Four kinds of water sources for irrigation are considered in the model: surface water; groundwater; drainage reuse; and effective rainfall. Table B.2 shows the ratios of these sources for cotton and wheat under a normal hydrologic conditions, and Table B.3 presents the seasonal average salt concentrations of these sources. Blending these sources for a specific crop depends on the soil and water salinity and crop salinity tolerance. Cotton has much higher salt tolerance than wheat so sources with higher salinity (groundwater and field drainage) can be used for cotton than for wheat in all planning zones. No drainage reuse is applied to cotton and wheat in planning zone *Mid_Syd*, due to the high salinity of the drainage there. Downstream planning zone *Low_Syd* reuses a significant amount of drainage for cotton. Low effective rainfall from planning zone *Mid_Syd* results in a high salinity in the drainage from that planning zone.

4.4.2. Irrigation Efficiency

Irrigation efficiency ($e2$) is the ratio of water effectively used by crops to the total water application. Advanced irrigation systems have higher irrigation efficiency. Therefore, high irrigation efficiency can result in increased water conservation. On the other hand, irrigation systems with high efficiency produce less percolation, which is necessary for salt leaching in areas where soil salinity is a serious problem. Soil salinity accumulation may result from long-term irrigation actions without sufficient leaching.

Tables B.4 - B.5 show four modeling scenarios of $e2$ in a dry year. With the increase of $e2$, both irrigation benefit (*IB)* and total water benefit (*TB)* increase. However, as shown in Table B.5, with the increase in $e2$, field percolation decreases, and soil salinity increases. The determination of irrigation efficiency needs to be studied in a long-term framework, considering both economic benefit and environment consequence.

4.4.3. Water Distribution and Delivery Efficiency

Water distribution and delivery efficiency ($e1$) for each Planning zone is shown in Table A.14. The results of a scenario with improved $e1$, in which $e1$ is increased to 0.8 for all planning zones (about 15% increase of the current value), are shown in Table B.6. The results show that decreased water diversion produces increased irrigation benefit and total benefit. The increase of total benefit (0.601) is larger than that of irrigation benefit (0.423), which shows that less withdrawal for irrigation can increase hydropower or/and ecological benefit, as well as irrigation benefit. That is, a 5% decrease in total water diversion produces a 26% increase in total net benefits.

4.4.4. Drainage Reuse and Disposal

Drainage effluent makes up a large amount of water available for use in the basin. However, reuse of this water can cause problems. Drainage disposal and treatment can sometimes be used to limit the problems caused by using drainage with high salinity. The results of a scenario in which the amount of drainage reuse is increased are shown in Table B.7. These results show a positive contribution to irrigation benefit and total benefit. Under this scenario, drainage reuse in fields is increased and less drainage is retuned to the river system, the salinity in downstream flow decreases. These contributions may be short-term and the soil salinity problem may ultimately decrease the positive contributions when accumulated soil salinity exceeds the crop tolerance, and groundwater salinity exceeds its standard.

4.4.5. Salt Leaching

Salt leaching is often necessary to sustain crop production over time. The required amount of leaching depends upon crop type, irrigation water salinity, soil characteristics, and management. Leaching fraction (*LF*) is defined as the ratio of water that drains below the root zone to the volume of water applied.

Tables 4.40 and 4.41, show that (1) the *LF* for crop field *wht-maz* is larger than that for *cot-foa*, since *wheat* and *maize* have lower salinity tolerances than *cotton* and *forage*; (2) the *LF* values in winter are largest, because of less crop consumptive use in winter periods; and (3) in both cases of crop field, soil salinity in the last period is significantly higher than that in the first period, which may not be realistic. Higher *LF* may be needed to reduce soil salinity. A long-term model can deal with this problem.

4.5. ECONOMIC ANALYSIS

In the model presented here, hydrologic system operation and irrigation and drainage management are integrated by economic objectives to maximize the total benefit from irrigation (*IB*), hydropower generation (*HP*), and ecological water use (*EB*). Economic incentives such as water supply prices, crop prices, and a tax on excess salt discharge are used to search for more economic and ecological gains, and to avoid serious environmental damages.

The economic value of water can be evaluated with respect to water application to crops and water withdrawal to Planning zones, respectively. In the model, decisions on crop irrigation acreage, water application to crops, and water allocation among planning zones are based on the water value with crops or with planning zones, as well as physical water availability constraints and institutional directives.

4.5.1. Economic Value of Water With Crops

The economic value of water with a crop (V_c, \$/m^3) is defined as:

$$V_c = \frac{\textit{profit from crop harvest - water supply } \cos t \textit{ - other } \cos t}{\textit{total amount of water applied to the crop field}} \tag{40}$$

The numerator does not include infrastructure investment, and the denominator refers to water arriving at the field. Tables B.8 and B. 9 show V_c and irrigated area for various crop combinations in a normal hydrologic year. Irrigated area for crops is determined by the model according to V_c, as well as other factors.

Figure 4.17 shows the average V_c for the four crop combinations in the whole basin, under three hydrologic levels (dry, normal, and wet). *Cot_foa* has the highest value (0.12 – 0.15 \$), while *alf_alf* has the lowest (0.038 – 0.042 \$). For all crop combinations *cot_foa* and *wht_maz*, the value in a dry year is the highest, while that in a wet year is the lowest. For *alf_alf* and *oth_oth*, the normal year has a highest water value. In a dry year, if the amount of water applied to a crop is too small then either crop yield (production per unit of planted area) or planted area will be sharply reduced due to water stress. Thus, crop profit, which is assumed to be linearly related to crop production, divided by the water applied will still be low. It seems that water application to *alf_alf* and *oth_oth* falls in this condition, and for all other crop combinations, reduction of water application in a dry year will not cause sharp reduction of crop yield or planted area.

However, the result shown here is based on a given set of crop prices, and the changes of crop prices will significantly affect the water value with crops, which will be discussed later.

4.5.2. Economic Values of Water with Planning Zones

Economic value of water in a planning zone (V_d, \$/m^3) can be defined as

$$V_d = \frac{revenue\ from\ \ crops\ \text{-}\ water\ supply\ \cos t\ \text{-}\ other\ \cos t - infrastructure\ invest.}{total\ amount\ of\ water\ withdrawn\ ,\ pumped\ ,and\ reused.} \quad (41)$$

Figure 19 shows V_d for each planning zones in a dry, normal or wet year. *Fergana* planning zone has the highest value, while the *Low_syd* has the lowest one. Decreased available and quality makes water less valuable in the downstream planning zones. Relatively high crop evapotranspiration downstream also makes water less valuable in the downstream planning zones. However, factors other than water, such as soil capacity and farmer’s inputs of labor and fertilizer affect crop yield and the economic value of water in planning zones. In the results shown here, those conditions are the same for all planning zones.

Hydrologic levels affect V_d in downstream and upstream planning zones in different ways. At upstream Planning zones, in *Naryn* and *Fergana*, where there is more water of better quality available, V_d decreases with inflow availability; while downstream, where there is less water of lower qulity available, V_d increases with inflow availability.

Water value with planning zone, as well as physical water availability and institutional constraints, could be used to determine water allocation among planning zones. However, existing, agreed allocations of water among the nations of the river basin take precedence over economic allocation of water in the basin. The allocation of water among the basin states has not been considered in this model, but could be easily incorporated as these allocations represent an upper limit of the water that may be used in any planning zone, since the planning zones, for the most part, are determined on national boundaries.

Table B.10 shows the ratios of calculated irrigated area to total available irrigated area for each planning zone in a dry, normal or wet year. At the downstream planning zone (*low_syd*) this ration is 0.21. The model results point out the need to reduce irrigated area under drought conditions and this reduction is on the order of 8-17% of irrigated lands in the basin.

4.5.3. Crop Prices

Table B.11 shows results of three model scenarios for crop prices: (1) primary crop prices reduced by 25%; (2) primary prices for all crops; and (3) primary crop prices increased by 25%. Irrigation profits at all planning zones, especially at the downstream planning zones are very sensitive to crop prices. From these scenarios, the model results show that increasing crop prices by 25% will increase irrigated area by 13.4%, while decreasing crop prices by 25% will decrease irrigated area by 4.6%. For the downstream planning zone, *Low_syd*, when the crop prices increase by 25%, the irrigation benefit (*IB*) increases by 7.26 times. Detailed results show that irrigated area is reduced by 75% with the primary crop prices, while, with a 25% price increase, there is no reduction in irrigated area. Clearly, crop price is a strong incentive for water allocation and agricultural production in the basin.

The value of each crop price affects the mixture of crops planted at each planning zone. Table B.12 shows that an increase in wheat-maize prices by 25% increases the irrigated area of wheat-maize and that a 50% increase will make wheat-maize dominate the irrigated area. Table B.13 shows that higher prices increase the irrigated area in planning zone *Low_syd*. Table B.14 shows the economic values of water with planning zones (V_d) for the three scenarios.

4.5.4. Water Supply Price

The model was run under four scenarios of water supply prices (*cs*): original surface and ground water supply prices (Table A.16) and 2, 4, and 8 times of the original prices. Model results are shown in Tables B.15 - B.17. The results show that irrigation and total benefits decrease, instream benefits (hydropower and ecological benefits) increase as water supply price increases. Total water withdrawal and irrigated area decrease with increasing water price. Table B.16 shows that water values decrease with increasing water price for all crops and for all planning zones. When *cs* is increased to 8 times of the original value, alfalfa and “other crops” have negative profit in some planning zones, and negative water value in *low_syd*. Water values for each crop in each Planning zone with high *WP* is presented in Table B.17.

4.5.5. Salt Discharge Tax

As discussed in Section 3.4.5, a tax on excess salt discharge (*tax*) is another economic incentive considered in the model. We consider a range of *tax* of \$10 – \$400 per ton of excess salt mass discharge. Figures 4.19 – 4.22 show the total benefit (*TB*) vs. *tax*, irrigation benefit (*IB*) vs. *tax*, total instream water use benefit *INB* (= hydropower profit (*HP*) + ecological water use benefit (*EB*)). vs. *tax*, and total excess salt mass discharged (*SM*) vs. *tax*, respectively. From these results, we see that total benefit, irrigation benefit, and instream benefits increase as the tax increases up to \$50/ton and they decrease beyond that point. Salt mass discharged decreases for all tax levels. Thus, from these results, a *tax* of \$50 per ton of salt mass discharged may be optimal and that taxes above \$50 do not improve benefits. In fact it is difficult to measure return flow from irrigated fields, which is generally non-point flow. Therefore implementing the tax on salt discharge with drainage may not be realistic.

4.5.6. Economic Efficiency of Infrastructure Investment

4.5.6.1. Water Distribution and Delivery Systems

Scenarios were run with the water distribution and delivery efficiency ($e1$) increased from the base value to 0.8 in all planning zones. The ratio of total and irrigation benefits (*TB*) to invested amount for various hydrologic scenarios *D(TB)/D(INV)* and *D(IB)/D(INV)* between the base scenario and the improved scenario are shown in Table B.18. In these scenarios, irrigation and drainage efficiencies ($e2$) do not change. At all hydrologic levels, the investment on water distribution and delivery systems appears to be economically efficient.

4.5.6.2. Irrigation System Efficiency

Four scenarios of irrigation efficiency ($e2$) are considered: $e2$ at the base value (Table A.15) and irrigation efficiency at 1.15, 1.30 and 1.40 times the base value. Values of *D(TB)/D(INV)* and *D(IB)/D(INV)* for the different scenarios are shown in Table B.19. The table shows that investment in irrigation systems is economically efficient in all cases and at all hydrologic levels. The investment is most efficient in a dry year and less efficient in a wet year. The incremental benefit to irrigation provides a measure of the amount of funding that might be used to finance irrigation system improvements. Results from the model show investment on drainage systems is not economically attractive.

5. Summary

A new integrated hydrologic-agronomic-economic model has been developed and applied to the Syr Darya River basin. The main advantage of this model comes from system integration which provides an analytical framework to consider both economic and environmental consequences of policy choices. Alternative solutions are compared based on hydrologic, agronomic, economic and institutional conditions within the integrated system.

The limitations of using a short-term model for river basin analysis are presented in this paper. The problems arise from the fact that long-term environmental impacts are not wholly connected to the utility of water uses. More specifically, groundwater quality degradation can not be captured in this short-term model; soil salinity worsens, economic efficiency of drainage system improvements may be under-evaluated. Therefore, the results from this model do not wholly reflect conditions of sustainability of water management in irrigation-dominated river basins.

As additional work on this model, we can consider the following:

- Update data sets and modeling grid to reflect real situation in basin and current data.
- Short-term model may be extended to a long-term model, providing a tool to analyze sustainability in water resources management at the river basin scale.
- Uncertainty analysis

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Appendix A.

Model Data

Table A.1

Average Monthly Inflow (km^3) to the Syr Darya Basin (Raskin, et al., 1992)

Source	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Right_in	0.012	0.012	0.019	0.074	0.184	0.192	0.141	0.124	0.079	0.036	0.032	0.027
Shimi_in	0.003	0.003	0.003	0.003	0.003	0.003	0.005	0.005	0.004	0.003	0.003	0.003
Aksu_in	0.015	0.015	0.013	0.015	0.018	0.030	0.044	0.026	0.017	0.021	0.016	0.014
Tokgul_rev	0.371	0.336	0.415	0.652	1.518	2.374	2.135	1.442	0.779	0.563	0.457	0.399
Kurp_rev	0.015	0.012	0.011	0.016	0.043	0.057	0.070	0.057	0.041	0.035	0.026	0.022
Sham_rev	0.043	0.052	0.062	0.233	0.369	0.292	0.180	0.100	0.070	0.066	0.064	0.054
Utch_rev	0.002	0.002	0.006	0.015	0.020	0.014	0.011	0.009	0.004	0.004	0.005	0.004
Andjan_rev	0.183	0.206	0.476	1.206	1.856	1.910	1.534	0.846	0.411	0.387	0.440	0.393
Chakir_rev	0.254	0.249	0.383	0.999	1.922	2.283	1.955	1.341	0.691	0.450	0.358	0.339
Bugun_rev	0.164	0.131	0.179	0.409	0.348	0.315	0.261	0.171	0.106	0.093	0.081	0.086

Table A.2

Average Monthly Local Sources in the Syr Darya Basin (km3) (Raskin, et al., 1992)

Planning Zone	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Fergana	0.091	0.075	0.067	0.099	0.295	0.521	0.763	0.670	0.291	0.168	0.133	0.125
Mid_syd	0.003	0.002	0.005	0.016	0.015	0.007	0.005	0.003	0.002	0.003	0.005	0.005
Low_syd	0.055	0.043	0.085	0.145	0.059	0.018	0.015	0.010	0.007	0.009	0.006	0.008

Table A.3

Major Water Storage Facilities of the Syr Darya Basin

Reservoir	*Active Storage Capacity (km^3)*	*Dead Storage Capacity (km^3)*
Toktogul	14	5.5
Chardara	4.7	1
Kayrakum	2.55	1.48
Charvak	2.08	0.35
Andjan	1.64	0.15
Bugun	0.37	0.007
Kassan	0.25	0.02
Kurpskaya	0.0288	0.341
Utchkurgan	0.012	0.04
Tashkumur	0.006	0.134
Shamdalsai	0.005	0.039

Table A.4

Hydropower Station Data for the Syrdarya River Basin

Station	Production Capacity (MW)	Efficiency (%)	Maximum Pool Elevation (m)	Tailwater Elevation (m)	Average Head on Turbine (m)
Toktogul	864	0.85	900	700	200
Kurpskaya	576	0.85	724	618	106
Tashkumur	162	0.85	628	568	60
Shamdalsai	69.12	0.85	572	540	32
Utchkurgan	129.6	0.85	540	504	36

Table A.5

Aquifer Characteristics

Aquifers	Pumping Capacity (10^9 m^3)	Water Table Depth (m)	Surface Area (1000 ha)	Yield Coeffi-cient	Initial Salt Conc. (g/l)	$h = q / h$ (10^{-5})
Naryn_gw	1.00	10.0	163	0.35	0.9	1.4
Ferga_gw	4.80	2.0	1300	0.36	1.2	1.6
Midsyd_gw	1.00	3.5	690	0.32	1.3	1.7
Chakir_gw	1.00	5.5	400	0.30	1.2	1.8
Artur_gw	0.25	3.0	162	0.30	1.3	1.7
Lowsyd_gw	0.25	7.5	530	0.32	1.4	2.0

Table A.6

Monthly Average Reference Evapotranspiration (ET0, mm) (WARMAP, 1995)

Planning Zone	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Fergana	12	24	51	99	141	174	180	150	99	51	21	12
Artur	20	30	36	40	158	188	226	220	138	75	45	40
Chakir	18	30	54	96	141	180	186	159	108	57	27	15
Mid_syd	21	30	51	99	168	243	285	252	177	102	45	24
Low_syd	25	35	50	73	192	344	347	290	150	87	60	40
Naryn	12	24	49	90	130	154	170	140	85	47	19	12

Table A.7

Monthly Average Effective Precipitation (ER, mm) (World Bank, 1996)

Planning Zone	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Fergana	23.0	21.0	30.0	21.0	20.0	11.0	6.0	3.0	2.0	13.0	22.0	20.0
Artur	17.1	17.5	22.6	25.5	18.0	3.4	2.8	1.2	2.8	10.3	16.5	26.4
Chakir	35.5	36.4	57.2	49.6	26.9	6.1	3.5	0.7	2.6	22.1	27.0	32.2
Mid_syd	22.2	23.6	26.0	29.9	23.0	4.4	3.2	1.5	3.1	11.8	22.4	31.7
Low_syd	42.8	41.1	48.4	46.6	28.8	11.5	6.5	4.9	7.6	24.9	43.0	41.8
Naryn	24.0	20.0	26.0	25.0	16.0	8.0	5.0	10.0	6.0	12.0	20.0	25.0

Table A.8

Available Irrigated Area (1000 ha.) with Soil Types

Planning Zone	*Sand Clay (scl)*	*Loam (l)*	*Sand Loam (sl)*	**Total**
Fergana	190	855	255	1300
Artur	15.6	106.4	40.0	162.0
Chakir	52.0	208.0	140.0	400.0
Mid_syd	71.5	398.5	220.0	690.0
Low_syd	82.0	260.0	188.0	530.0
Naryn	16.9	111.1	52.0	180.0

Table A.9

Soil Characteristics

Planning Zone	*Pore connectivity index*			*Connectivity and tortuosity*			*Saturated matric Potential (m)*		
	scl	*l*	*sl*	*scl*	*l*	*sl*	*scl*	*l*	*sl*
Fergana	9.4	9.0	8.2	0.457	0.546	0.686	55.4	83.6	86.4
Artur	8.8	8.6	8.2	0.457	0.546	0.686	55.4	83.6	86.4
Chakir	9.4	9.0	8.0	0.502	0.546	0.730	69.5	83.6	86.5
Mid_syd	9.0	8.5	8.0	0.457	0.508	0.686	55.4	83.9	86.4
Low_syd	8.8	8.6	8.0	0.464	0.546	0.730	54.8	83.6	86.5
Naryn	9.3	9.0	8.2	0.502	0.546	0.686	69.5	83.6	86.4
	Hydraulic conductivity (cm/day)			*Saturated field capacity*			*Permanent wilting point*		
	scl	*l*	*sl*	*scl*	*l*	*sl*	*scl*	*l*	*sl*
Fergana	5.06	5.39	6.13	0.355	0.342	0.322	0.225	0.186	0.186
Artur	5.06	5.39	6.13	0.355	0.342	0.322	0.225	0.186	0.186
Chakir	4.90	5.39	6.58	0.348	0.342	0.315	0.212	0.186	0.182
mid_syd	4.87	5.40	6.13	0.355	0.342	0.322	0.225	0.186	0.186
Low_syd	5.06	5.39	6.58	0.347	0.342	0.315	0.218	0.186	0.182
Naryn	5.06	5.39	6.13	0.348	0.342	0.322	0.212	0.186	0.186

Table A.10

Crop coefficient of evapotranspiration (kc)

Crop Pattern	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
cot_foa	0.80	0.80	0.90	0.50	0.80	1.10	1.20	0.90	0.70	0.50	0.50	0.50
wht_maz	0.50	0.85	1.20	0.95	0.60	0.85	1.20	0.95	0.60	0.50	0.40	0.30
alf_alf	1.00	1.00	0.40	0.45	0.80	1.05	1.10	1.05	1.10	1.10	1.10	1.00
oth_oth	1.00	1.00	0.60	0.70	0.80	1.08	1.15	1.10	1.05	0.90	0.70	1.00

Table A.11

Empirical salinity coefficients, slope and threshold, (Mass and Hoffman, 1979)

Salinity Coefficient	*Cotton*	*Forage*	*Wheat*	*Maize*	*Alfalfa*	*Other*
Slope	0.139	0.08	0.132	0.083	0.14	0.095
Threshold (dS/M)	7.7	3	1.8	1.8	2	2.5

Table A.12

Crop yield response coefficients (ky)

Crops	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Cotton	0.00	0.00	0.00	0.20	0.30	0.75	0.60	0.30	0.25	0.00	0.00	0.00
Wheat	0.40	0.90	1.10	0.70	0.50	0.00	0.00	0.00	0.00	0.20	0.10	0.10
Maize	0.00	0.00	0.00	0.00	0.00	0.90	1.20	0.70	0.20	0.00	0.00	0.00
Alfalfa	0.00	0.00	0.70	0.73	0.92	1.00	1.00	0.90	0.80	0.75	0.70	0.00
Forage	0.70	0.80	0.80	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.20	0.20
Other	0.00	0.00	0.30	0.40	0.45	0.60	0.75	0.70	0.60	0.40	0.30	0.00

Table A.13

Maximum crop productions (dry matter) (ton/ha)

Planning Zone	*Cotton*	*Wheat*	*Maize*	*Alfalfa*	*Forage*	*Other*
Fergana	1.63	4.10	7.10	5.70	7.00	5.00
Artur	1.60	4.09	7.05	5.70	7.00	5.00
Chakir	1.60	4.10	7.03	5.70	7.00	5.00
mid_syd	1.62	4.12	7.00	5.70	7.00	5.00
Low_syd	1.61	4.10	7.03	5.70	7.00	5.00
Naryn	1.60	4.05	7.00	5.70	7.00	5.00

Table A.14

Estimated Water Distribution efficiency and drainage fraction

Planning Zone	*Water distribution and delivery efficiency* ($e1$)	*Drained area /Total available area* ($e4$)
Low_syd	0.64	0.67
Artur	0.65	0.66
Chakir	0.61	0.72
Mid_syd	0.57	0.50
Naryn	0.59	0.47
Fergana	0.56	0.80

Table A.15

Estimated irrigation application efficiency

Planning Zone & Soil type	*cot_foa*	*wht_maz*	*alf_alf*	*oth_oth*
Fergana.scl	0.57	0.5	0.63	0.64
Artur.scl	0.6	0.52	0.53	0.62
Chakir.scl	0.55	0.5	0.55	0.65
Mid_syd.scl	0.54	0.52	0.54	0.65
Low_syd.scl	0.61	0.54	0.53	0.62
Naryn.scl	0.54	0.48	0.5	0.55
Fergana.l	0.52	0.46	0.58	0.58
Artur.l	0.55	0.47	0.48	0.56
Chakir.l	0.5	0.46	0.5	0.59
Mid_syd.l	0.49	0.47	0.49	0.59
Low_syd.l	0.56	0.49	0.48	0.56
Naryn.l	0.49	0.44	0.46	0.5
Fergana.sl	0.6	0.42	0.53	0.62
Artur.sl	0.5	0.43	0.44	0.59
Chakir.sl	0.46	0.42	0.46	0.56
Mid_syd.sl	0.45	0.43	0.45	0.56
Low_syd.sl	0.51	0.45	0.44	0.6
Naryn.sl	0.45	0.4	0.42	0.46

Table A.16.

Surface and groundwater supply cost (cs and cg in US$/m3)

Prices	*low_syd*	*Artur*	*chakir*	*mid_syd*	*naryn*	*fergana*
Surface water price (*cs*)	0.004	0.004	0.006	0.006	0.005	0.005
Groundwater price (*cg*)	0.006	0.006	0.006	0.006	0.005	0.006

Table A.17

Crop prices and fixed crop planting cost

Items	*Cotton*	*Wheat*	*Maize*	*Forage*	*Alfalfa*	*Other*
Prices ($/ton)	767.54	181.35	140.11	134.56	110.50	240.00
Fixed cost ($ /ha.)	393.3	200.3	287.8	165.1	156.2	350.0

Table A.18

Annual investment for improved water distribution and drainage collection systems

Planning Zone	*Water Distribution System ($/m^3)*	*Drainage Collection System ($/ha.)*
Low_syd	0.02	700
Artur	0.02	700
Chakir	0.016	750
Mid_syd	0.017	700
Naryn	0.012	650
Fergana	0.014	800

Table A.19

Annual investment ($/m3) for improved on-farm irrigation systems

Planning Zone	*cot_foa*	*Wht_maz*	*alf_alf*	*oth_oth*
Fergana	0.03	0.03	0.03	0.02
Artur	0.03	0.03	0.03	0.023
Chakir	0.035	0.035	0.035	0.022
Mid_syd	0.04	0.04	0.04	0.02
Low_syd	0.045	0.045	0.045	0.022
Naryn	0.025	0.025	0.025	0.023

Table A.20

Monthly industrial and municipal water demands (km3)

Planning Zone	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Naryn	0.018	0.018	0.033	0.024	0.054	0.066	0.085	0.074	0.026	0.016	0.013	0.018
Fergana	0.112	0.113	0.211	0.151	0.342	0.424	0.542	0.473	0.169	0.104	0.080	0.114
Mid_syd	0.079	0.080	0.149	0.107	0.242	0.300	0.384	0.335	0.119	0.074	0.057	0.081
Chakir	0.071	0.072	0.133	0.096	0.217	0.269	0.344	0.300	0.107	0.066	0.051	0.072
Artur	0.020	0.021	0.038	0.028	0.063	0.078	0.099	0.086	0.031	0.019	0.015	0.021
Low_syd	0.046	0.046	0.086	0.062	0.139	0.173	0.221	0.192	0.069	0.042	0.033	0.046

Appendix B.

Model Results

Table B.1

Sensitivity to basin inflow, reference ET0, and effective rainfall (ER)

(all relative values)

Inflow	*Irrigation benefit (IB)*	*Hydropower profit (HP)*	*Flow to Aral*	*Total benefit (TB)*	*Downstr. Salinity (Ss)*	*Percol. Salinity (Sp)*	*Root zone Salinity (Sf)*	*Irrigated Area (A)*
Dry (0.80)	0.85	0.68	1.00	0.86	1.00	1.04	1.00	0.93
Normal (1.00)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wet (1.17)	1.06	1.29	1.07	1.07	0.98	0.93	0.93	1.02
ET0								
High (1.15)	0.87	1.01	1.10	0.99	0.95	1.02	1.02	0.97
Normal (1.00)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Low (0.85)	1.17	1.00	1.06	1.11	1.05	0.90	0.93	1.14
ER								
High (1.25)	1.08	1.00	0.94	1.01	1.02	1.01	1.02	1.01
Normal (1.00)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Low (0.75)	0.95	1.00	1.05	0.99	0.97	0.98	0.96	0.99

Flow-to-aral = annual downstream flow to Aral Sea

Conc. in downstr. = annual average salt concentration in downstream flow

Salt in percol. = salt mass in deep percolation to groundwater, result from planning zone mid_syd; soil type *loam*; field *cot-foa*

Salinity in root zone = result from planning zone: *mid_syd*, soil type: *loam*; field: *cot-foa*.

Table B.2

Ratios of sources to total irrigation water application (Under a normal hydrologic level)

Crops	Cotton					Wheat				
Planning Zone	*Surface water*	*Groundwater*	*Drainage re-use*	*Rainfall*	**Total**	*Surface water*	*Ground water*	*Drainage re-use*	*Rainfall*	**Total**
Naryn	0.103	0.700	0.057	0.140	1.000	0.413	0.413	0.020	0.153	1.000
Fergana	0.478	0.399	0.014	0.109	1.000	0.525	0.364	0.005	0.106	1.000
Mid_syd	0.185	0.708	0.000	0.107	1.000	0.869	0.032	0.000	0.099	1.000
Chakir	0.570	0.250	0.044	0.136	1.000	0.608	0.181	0.041	0.170	1.000
Artur	0.588	0.237	0.083	0.137	1.000	0.748	0.029	0.038	0.143	1.000
Low_syd	0.175	0.492	0.112	0.220	1.000	0.776	0.000	0.028	0.196	1.000

Table B.3

Annual average salt concentration (g/L) in different sources.

Planning Zone	*Naryn*	*Fergana*	*Chakir*	*Mid_syd*	*Artur*	*Low_syd*
Surface water	0.541	0.572	0.692	0.793	0.945	0.917
Ground water	1.066	1.193	1.194	1.294	1.199	1.399
Drainage	1.159	1.871	1.146	2.15	1.99	2.12
Rainfall	-	-	-	-	-	-

Table B.4

Analysis of irrigation efficiency: Economic benefit.

Ratio of $e2$ to primary efficiency (R)	*Irrigation benefit (IB) (billion \$)*	*D(IB)/ D(R)*	*Total benefit(TB) (billion \$)*	*D(TB)/ D(R)*
1.00	1.604		2.289	
1.15	1.808	1.36	2.460	1.14
1.30	1.924	0.77	2.526	0.44
1.40	1.937	0.13	2.559	0.33

D(IB) change of irrigation benefit

D(R) change of ratio of assumed to primary efficiency

D(TB) change of total water use benefit.

Table B.5

Analysis of irrigation efficiency (Planning zone: Fergana, soil type: loam).

Ratio of $e2$ to primary efficiency (R)	***Cotton-forage***			***Wheat-maize***		
	Percolation (cm)	*Soil salinity (dm/s)*	*Water use (m^3/ ha)*	*Percolation (cm)*	*Soil salinity (dm/s)*	*Water use (m^3/ ha)*
1.00	47.2	1.657	12891	33.2	1.992	8612
1.15	43.1	1.777	11236	29.6	2.14	7286
1.30	34.1	1.989	10164	28.8	2.159	7310
1.40	29.2	2.033	8153	20.9	2.207	6846

Table B.6

Analysis of water distribution and delivery efficiency ($e1$)

Efficiency ($e1$)	*Total benefit (TB) (billion $)*	*Irri. Benefit (IB) (billion $)*	*Irrigated Area (1000 ha)*	*Water Diversion (km^3)*						
				Naryn	*Fergana*	*Mid-Syr*	*Chakir*	*Artur*	*Low-syr*	Total
Original	2.319	1.59	2105	0.92	9.87	5.69	5.02	2.48	3.23	27.21
Improved	2.919	2.01	2105	1.05	10.97	4.31	4.94	2.05	2.64	25.96
Change	1.26	1.27	1.00	1.14	1.11	0.76	0.98	0.83	0.82	0.95

Table B.7

Drainage reuse scenario analysis

Reuse amount (km^3)	*Irrigation benefit (IB) (billion $)*	*Total benefit(TB) (billion $)*	*Drainage Salinity[1] (g/L)*	*Soil Salinity[2] (dM/S)*	*Downstr. Salinity[3] (g/L)*
0	1.563	2.094	*1.33*	*1.58*	*1.07*
0.71	1.579	2.170	-	-	-
1.42	1.593	2.242	-	-	-
2.06	1.604	2.289	*1.75*	*2.38*	*1.02*

[1,2] Seasonal average salt concentration[1] or saturated extract[2] in planning zone: *fergana*; soil type: *loam*; field: *wht-maz*.

[3] Annual average salt concentration.

Table B.8

Analysis on salt leaching

wht-maz[1]	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dev*	**Annual**
Water Applied (cm)	1.62	1.34	2.08	8.58	10.82	13.97	20.48	12.00	0.20	0.83	0.84	0.36	73.12
Water Drained (cm)	0.68	0.64	0.38	2.24	3.14	3.65	5.45	3.09	0.04	0.15	0.36	0.17	20.44
Leaching Fraction	0.42	0.48	0.18	0.26	0.29	0.26	0.27	0.26	0.20	0.18	0.43	0.46	0.28
EC_w (dM/s)	0.81	n/a	N/a	0.81	0.90	0.87	0.84	1.79	1.78	n/a	n/a	n/a	
EC_e (dM/s)	1.09	1.11	1.19	1.19	1.18	1.27	1.40	1.67	2.06	2.12	2.06	1.99	
Cot-for[2]													
Water Applied (cm)	1.98	1.28	1.74	1.68	15.52	18.34	20.53	12.26	7.76	1.49	0.95	0.60	84.14
Water Drained (cm)	0.62	0.64	0.57	0.23	3.11	3.32	3.75	2.06	1.32	0.35	0.35	0.23	16.84
Leaching Fraction	0.31	0.50	0.33	0.14	0.20	0.18	0.18	0.17	0.17	0.23	0.37	0.38	0.20
[3]EC_w (dM/s)	0.81	n/a	n/a	n/a	0.90	0.93	1.75	1.25	1.52	0.45	n/a	n/a	
[4]EC_e (dM/s)	1.10	1.12	1.16	1.23	1.16	1.32	1.65	2.03	2.13	2.24	2.20	2.15	

[1] Result of demand site: Fergana; soil type: loam; crop field: wht-maz., in a normal hydrologic year;

[2] Result of demand site: Fergana; soil type: loam; crop field: cot-foa, in a normal hydrologic year;

[3] EC_w: salinity of irrigation water in dM/s;

[4] EC_e: soil saturated extraction in dM/s.

Table B.9

Economic value of water with crops (Vc) (in a normal year).

Planning Zone	*Cot_foa*	*Wht_maz*	*Alf_alf*	*oth_oth*
Naryn	0.171	0.138	-	0.089
Low_syd	0.113	0.074	-	0.039
Artur	0.146	0.097	-	0.059
Chakir	0.152	0.129	0.055	0.084
Mid_syd	0.108	0.075	0.045	0.047
Fergana	0.154	0.119	0.051	0.084
Average for whole basin	0.141	0.103	0.041	0.081

Table B.9

Irrigated area (1000 ha.).

Planning Zone	*Cot_foa*	*wht_maz*	*Alf_alf*	*oth_oth*
Naryn	130.5	32.6	-	16.9
Low_syd	48.6	48.6	-	12.3
Artur	117.1	15.4	-	2.3
Chakir	275.6	37.6	34.8	52.0
Mid_syd	490.4	66.3	61.9	10.7
Fergana	882.9	116.1	111.0	190.0
Total	1945.1	316.6	207.7	284.3

Table B.10

Ratios of calculated irrigated area to total available irrigated area.

Hydrologic level	*Naryn*	*Low_syd*	*Artur*	*Chakir*	*Mid_syd*	*Fergana*
Dry	0.92	0.21	0.83	0.89	0.91	0.88
Normal	1.00	0.21	0.83	1.00	0.91	1.00
Wet	1.00	0.21	0.83	1.00	1.00	1.00

Table B.11

Irrigation benefit (IB) vs. crop prices (relative values)

Crop price change	*Naryn*	*Low_syd*	*Artur*	*Chakir*	*Mid_syd*	*Fergana*	**Total**
25% decrease	0.613	0.521	0.120	0.626	0.602	0.640	0.556
Original	1.000	1.000	1.000	1.000	1.000	1.000	1.000
25% increase	1.369	7.260	1.617	1.372	1.409	1.355	1.571

Table B.12

Irrigated area allocation (fraction) vs. wheat-maize prices

Wht_maz price	*Cot_foa*	*Wht_maz*	*alf_alf*	*oth_oth*	*Total*	*total area/ available area*
Original	0.71	0.11	0.08	0.10	1.00	0.84
25% increase	0.16	0.58	0.07	0.09	1.00	0.85
50% increase	0.11	0.73	0.07	0.01	1.00	0.94

Table B.13

Irrigated area allocation (fraction) vs. wheat-maize prices

Wht_maz price	*Naryn*	*Low_syd*	*Artur*	*Chakir*	*Mid_syd*	*Fergana*
Original	1.00	0.21	0.83	1.00	0.91	1.00
25% increase	1.00	0.21	0.92	1.00	0.92	1.00
50% increase	1.00	0.79	0.92	1.00	0.91	1.00

Table B.14

Economic values of water (Vd, $/m3) vs. wheat-maize prices

Wht_maz price	*Naryn*	*Low_syd*	*Artur*	*Chakir*	*Mid_syd*	*Fergana*
Original	0.103	0.023	0.068	0.065	0.048	0.086
25% increase	0.123	0.035	0.083	0.079	0.062	0.098
50% increase	0.135	0.084	0.103	0.096	0.077	0.118

Table B.15

Analysis on water supply prices1

Water prices	*Irrigation Benefit, IB (billion $)*	*Power Benefit, PB (billion $)*	*Ecological Benefit, EB (billion $)*	*Total Benefit, TB (billion $)*	*Water Withdrawal (km^3)*	*Irrigated Area (1000 ha.)*
Original	2.755	0.187	1.160	4.102	31.70	2754
2* original	2.507	0.194	1.162	3.863	31.64	2704
4* original	2.002	0.200	1.238	3.439	30.75	2665
8* original	1.235	0.205	1.446	2.886	27.81	2600

Table B.16

Water values for crops and planning zone vs. water supply prices2

Water supply prices	Water values for crops (V_c)				Water values for Planning Zone (V_d)					
	Cot_foa	*wht_maz*	*alf_alf*	*oth_oth*	*Naryn*	*Low_syd*	*Artur*	*Chakir*	*Mid_syd*	*Fergana*
Original	0.141	0.103	0.041	0.081	0.103	0.023	0.068	0.065	0.048	0.086
2* original	0.133	0.095	0.033	0.073	0.096	0.017	0.06	0.059	0.042	0.08
4* original	0.119	0.081	0.02	0.058	0.084	0.008	0.049	0.047	0.03	0.071
8* original	0.097	0.054	-0.013	0.032	0.059	-0.009	0.026	0.025	0.008	0.054

Table B.17

Water values for crops in each planning zone with high water supply prices3

Planning Zone	4 * original water supply price				8*original water supply price			
	Cot_foa	*wht_maz*	*Alf_alf*	*oth_oth*	*Cot_foa*	*wht_maz*	*alf_alf*	*oth_oth*
Naryn	0.128	0.115	-	0.071	0.117	0.083	-	0.049
Low_syd	0.091	0.051	-	0.021	0.066	0.027	-	-0.004
Artur	0.126	0.074	-	0.014	0.1	0.048	-	0.006
Chakir	0.131	0.107	0.035	0.062	0.11	0.08	0.008	0.035
Mid_syd	0.085	0.053	0.004	0.025	0.062	0.025	-0.03	-0.004
Fergana	0.132	0.097	0.029	0.062	0.11	0.073	-0.005	0.035

[1,2,3] All scenarios are under the normal hydrologic year, all conditions except the water prices are the same for all scenarios.

Table B.18

Economic efficiency of investment in improved water distribution and delivery systems efficiency

Hydrologic Scenario	*Dry*	*Normal*	*Wet*
D(TB)/D(INV)	6.0	2.0	2.3
D(IB)/D(INV)	3.1	3.7	3.6

$\Delta(TB)$: change of total water use benefit (TWB),

$\Delta(INV)$: change of infrastructure investment (INV),

$\Delta(IB)$: change of irrigation benefit (IB).

Table B.19

Economic efficiency of investment for improved irrigation system efficiency ($e2$)

Irrigation System Efficiency Change ($\Delta e2$)	*D(TB)/D(INV)*			*D(IB)/D(INV)*		
	Dry	*Normal*	*Wet*	*Dry*	*Normal*	*Wet*
1.15* base value	7.0	4.0	3.5	5.9	2.8	0.9
1.30* base value	4.3	3.2	3.0	2.4	1.9	0.8
1.40* base value	1.4	1.2	1.2	1.9	0.9	0.6
Average	3.3	3.0	2.9	3.0	2.0	0.7