A Modeling Framework for Sustainable Water Resources Management

by

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Approved by
Dissertation Committee:

In memory of my grandfather

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Publication No._____________

Ximing Cai, Ph.D.
The University of Texas at Austin, 1999

Supervisor: Daene C. McKinney

A prototype modeling framework for quantitative analysis of sustainable water resources management at the river basin scale is developed and applied to the Syr Darya River basin in Central Asia to analyze long-term water resource system sustainability. The research problem is specified as long-term, sustainable water resources management in river basins that are characterized by (semi)-arid climate, a heavy dependence on irrigated agriculture, and possibly severe environmental degradation in the form of water and soil salinity. Sustainable water management is defined here as ensuring a long-term, stable and flexible water supply capacity to meet crop water demands, as well as growing municipal and industrial water demands, at the same time as keeping a stable relationship between irrigation practices and their associated environmental consequences. For this research, an innovative systems approach has been developed to model and analyze sustainability issues related to water resources management.

The core of this modeling framework consists of an intra-year, short-term optimization model and an inter-year, long-term, dynamic model that combines simulation and optimization. In the intra-year model, essential hydrologic, agronomic, economic, and institutional relationships are integrated into a coherent analytical framework at the river basin scale to reflect the interdisciplinary nature of water resources problems. The inter-year model includes long-term changes and uncertainties in both water supply and demand, and incorporates prescribed sustainability principles for river basin system performance control. Relations between short-term irrigation practices and their long-term economic and environmental consequences are modeled and controlled in the inter-year modeling framework.

The intra-year, or short-term, model is applied to the Syr Darya River basin to explore case-specific, in-depth hydrologic-agronomic-economic-institutional relationships. This application shows the power of this type of integrated optimization model. Moreover, the application of the long-term modeling framework to the case study area shows the effectiveness of this tool for sustainability analysis in this region.

Three approaches based on decomposition analysis and newly developed genetic algorithms for solving highly complex water resources management models that are large, nonconvex, and nonlinear are presented and applied. The short-term model, which is a large and nonlinear model, is solved by a “piece-by-piece” approach based on model decomposition. A new genetic algorithm – linear programming approach is used to solve the long-term model.

Throughout the study, both the feasibility and the effectiveness of incorporating the philosophy of sustainability into traditional water resources management modeling are addressed. It is argued that system modeling techniques, if well supported by relevant empirical studies, and if sufficient data

are available, can promote the understanding of sustainability in water resources research, a concept of utmost importance that will strongly influence future research in water resources management.

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Chapter 1

Introduction

1.1 MOTIVATION

Water scarcity, water pollution and other water related environmental and ecological problems in many areas have brought a water crisis to the world. The future water crisis seems to be more serious than that at present. *"The real crisis in water is a 'creeping crisis'- it comes on slowly but it demands a response right now"* (Grigg, 1996). What kind of response should we have right now? This question needs to be answered with information on both current and future water demand and supply. The concepts of sustainable development, a popular concept in planning since the Brundtland Commission report (WCED, 1987), brings some hope for water researchers and policy makers. Sustainable development was defined as:

Development that meets the needs of the present without compromising the ability of the future generations to meet their own needs.

In light of this philosophy, sustainable water resources development has become an important topic in many national and international agencies such as the United Nations (UN), the World Bank, the American Society of Civil Engineers, etc. (detailed work of these agencies will be discussed in the background review). The definition of sustainable water resource systems is given by ASCE (1997) as:

> *Sustainable water resource systems are those designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental and hydrological integrity.*

We have already received many guidelines for water resources management in light of sustainable development; unfortunately, we still do not know how to achieve this goal even though we know something about what to do. Biswas (1994) commented that:

> *Operationally it (sustainable development) has not been possible to identify a development process which can be planned and then implemented, and which would be inherently sustainable*.

In the water resources literature, there are many studies that argue the importance of sustainability for water resources development, and that describe principles needed to direct water resources management in view of sustainability. But only a few studies (e.g., Simonovic, 1996a, b) can provide a systematic approach to incorporate sustainability principles in an analytic framework of water resources management. This is why Simonovic (1996a, b) suggested finding a way to put principles into practices.

Often hydrologists and water resources engineers focus on the operation of hydrologic systems (reservoir systems or aquifers) without considering economic principles, which are essential to sustainable development. On the other hand, natural resource economists have made significant contributions to modeling of sustainable development, but their work generally ignores the physical complexity which affects decisions placed on any natural resource system. To develop an analytical framework for sustainable water resources management, it is necessary to bring the work of hydrologists and economists together.

The following comments given by The World Engineering partnership for Sustainable Development (WEPSD) may be appropriate to express the motivation of this research:

> *Engineers need to translate the dreams of humanity, traditional knowledge, and the concepts of science into action through creative application of technology to achieve sustainable development.*

1.2 BACKGROUND AND THE CASE STUDY AREA

1.2.1 Background

The background of this research is a research project on water allocation and environment protection in the Aral Sea basin of Central Asia (McKinney, et al., 1997). The Aral Sea, a land-locked lake (i.e. without surface outflow), is located among the deserts of Central Asia (Figure 1.1). Its level is determined by the inflow of two feeding rivers, the Amudarya River and the Syr Darya River. In the1960's, this inland lake was the world's fourth largest such lake, but now it is dying due to intensive irrigation water withdrawal from the two rivers of the basin. The average inflow from the Amudarya River and the Syr Darya River once was 72 and 37 km^3 per year, respectively, and now has decreased to a mere trickle. Compared to the status in 1960, the Sea is now half the size, 16 meters lower and three times as salty (Micklin, 1993). Figure 1.2 shows surface area of the Aral Sea over years, as well as the irrigated area in the basin.

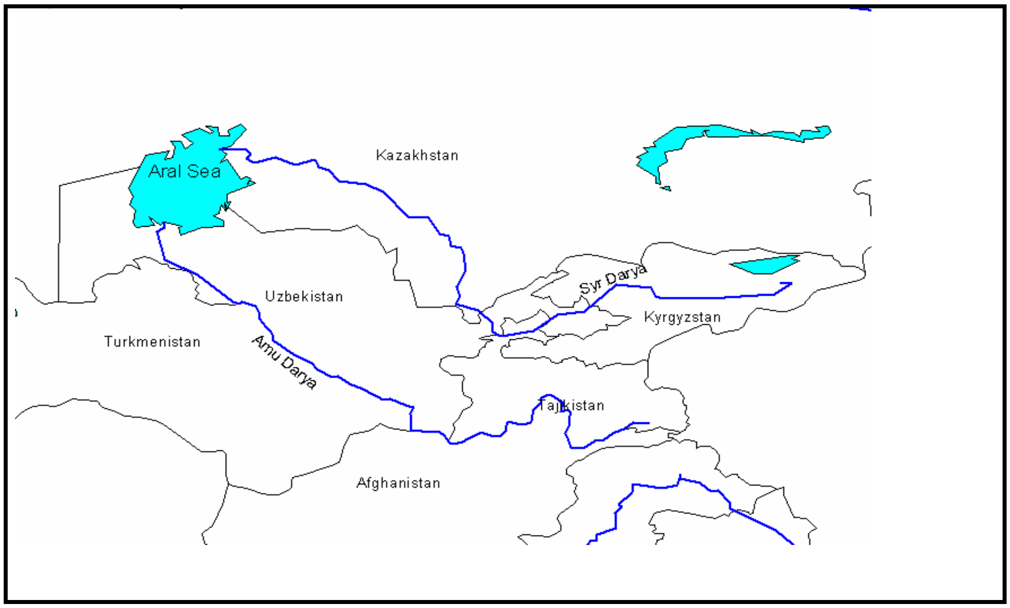


Figure 1. 1. The Aral Sea basin in Central Asia.

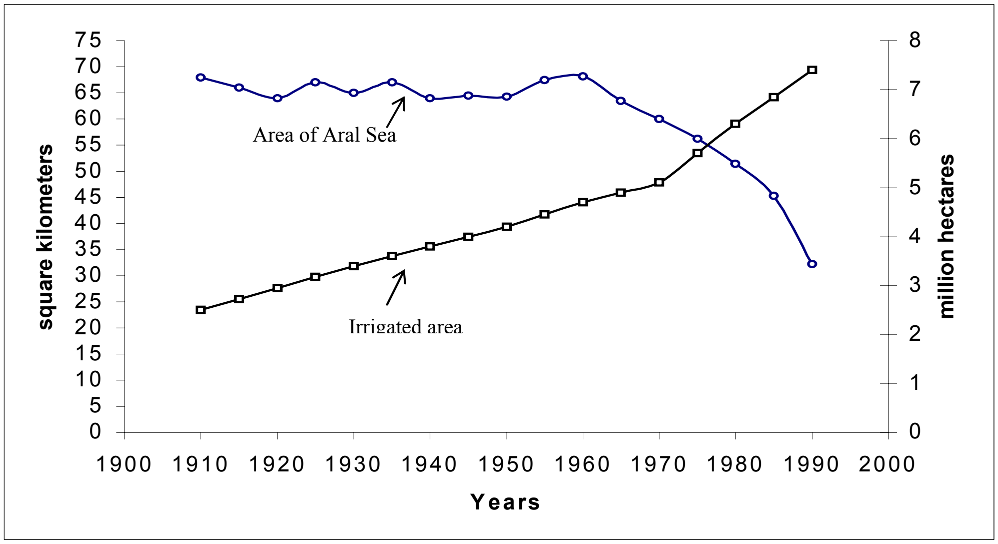


Figure 1. 2. Irrigated area (million ha) in the Aral Sea Basin and surface area (sq. km.) of the Aral Sea (after Micklin, 1993).

The impacts of unsustainable water management in the Aral Sea basin extend far beyond the fate of the Sea. Thirty-five million people have been losing access to the use of the lake for its water, fish, reed beds and transport, and more extensive environmental and ecological problems, such as dust storms, erosion, soil waterlogging and salinity, and poor water quality for drinking and other purposes, are endangering the human health and economy in this region. The Aral Sea disaster presents a very serious lesson for unsustainable water development.

The huge hydrogeological changes which Soviet engineers have unwittingly triggered in the Aral Sea basin will take decades to reverse (Micklin, 1993). To stop the catastrophe, reduction in the use of irrigation water will be unavoidable. However, more sadly, the Aral Sea basin countries have become dependent on a specialized, but unsustainable, pattern of agriculture, and the room for maneuver is limited. "*Any rapid reduction in the use of irrigation water will reduce living standards further unless these economies receive assistance to help them diversify away from irrigated agriculture*" (World Bank, 1992). The price to completely reverse the catastrophe caused by unsustainable water development in the Aral Sea basin may be too high to be paid by the new independent developing states in Central Asia.

The environmental and ecological problems in the Aral Sea basin have attracted attentions from all round the world, and financial aid for research on water resources management in this region have been provided by many international/national agencies including the U.S. Agency for International Development (USAID), the World Bank, and the European Union. Among the research work, USAID supported the Center for Research in Water Resources (CRWR) of The University of Texas at Austin, and the local partner, Tashkent Institute of Engineers of Irrigation and Mechanization of Agriculture (IEI) to develop a new computer modeling system for regional water allocation and salinity control (McKinney et al.,1997). This system is a geographic information system (GIS) based decision support system (DSS), which includes two major models: multiple objective optimization model for the Amudarya River basin water management (McKinney and Cai, 1996), and an optimization model for negotiation between upstream hydropower generation and downstream irrigation in the Syr Darya River basin (McKinney and Cai, 1997). These models were also extended to incorporate irrigation management, agronomic production functions and economic incentives by researchers in CRWR and International Food Policy Research Institute (IFPRI). The extended model was applied to the Maipo River basin in Chile (Rosegrant et al., 1999). All these works form a basis for this research, which focuses on the development of a modeling framework for sustainable water resources management in irrigation-dominated regions like the Aral Sea basin.

1.2.2 Case study area

The case study area of this research is the Syr Darya River basin. The Syr Darya River is one of the two major feeding rivers of the Aral Sea. The river begins at the Pamir and Tienshan plateaus, crosses the territories of several Central Asia republics, Kirgizstan, Tajikistan, Uzebekistan, and Kazakhstan, and terminates in the Aral Sea. About 70% of the flow is generated in the upper parts of the basin. In the middle and lower reaches, considerable anthropogenic influence is found in the forms of water diversions from the river and the discharges of return flows. The total water resource of the basin is assessed at 37.14 km^3 of natural runoff in a normal hydrologic year, plus 15 to 17 km^3 of return flow from irrigated fields (EC, 1995, Vol. II). Groundwater is an integral part of the basin water resources. Installed pumping capacity is about 8.3 km^3 per year, which covers about 30% of the natural recharge (EC, 1995, Vol. II).

The water quality of the natural flows meets all typical international water quality standards, but it is seriously affected by anthropogenic activities. Agricultural drainage is the major factor affecting water quality in middle and lower sections. The mineralisation 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 (EC, 1995, Vol. II).

Raskin et al. (1992) estimated the 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 in the basin was 57 km^3 in 1987 (Raskin et al., 1992). The flow to the Aral Sea has varied from 1.8 to 9.0 km^3 annually since 1990.

The Syr Darya basin's water supply system is one of the most complicated human water development systems in the world. There are 9 major tributaries, 11 reservoirs, 6 major water distribution systems and numerous distributing canals. Figure 1.3 shows a modeling network of the Syr Darya River basin, which follows the sketch of Raskin et al. (1992).

Records show that just downstream of the Fergana Valley, a major irrigation district 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. Salinity conditions vary significantly along the river from upstream to downstream, as shown in Table 1.1.

Table 1. 1. Salinity in the Syr Darya River basin (source: EC, 1995).

Items	Upstream	Midstream	Downstream
Salinity of water supplied to irrigation (g/l)	0.56	0.89	1.16
Salinity of drainage disposed from irrigation (g/l)	2.10	3.00	3.40
Ratio of salinity of driange disposal to water supplied	3.7	3.4	2.9

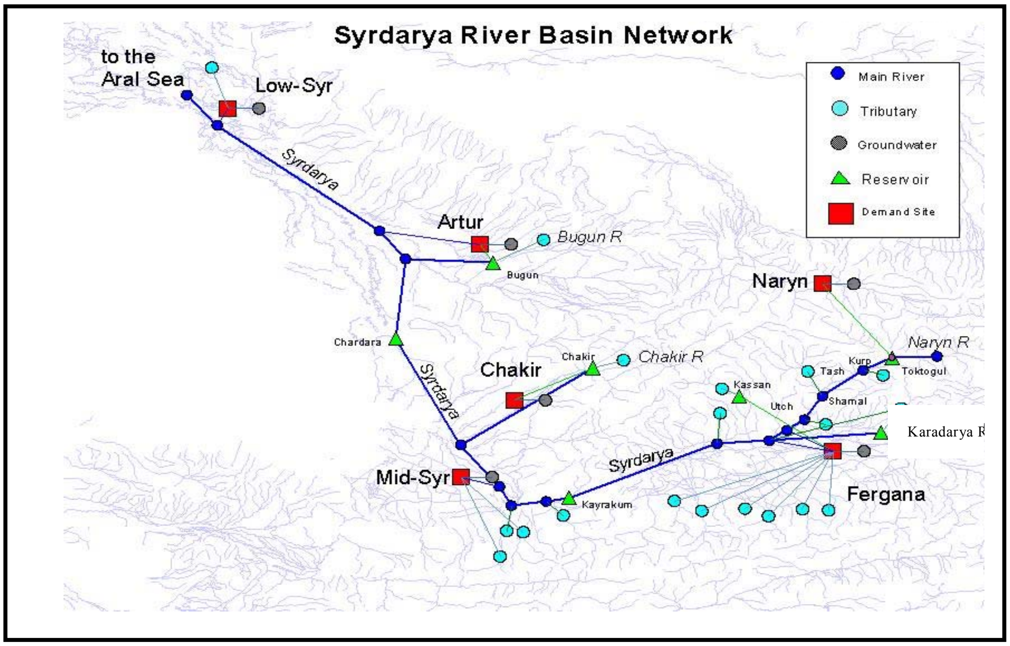


Figure 1. 3. The Syr Darya River basin network

In the last 30 years, with the increase of irrigated area, the river diversion for irrigation has increased and through the return of saline drainage water into the rivers, the salinity of the water in the rivers has increased. The effects are most pronounced in the downstream reaches of the river basin. Figure 1.4 plots salinity at selected points in the Syr Darya River from 1950 to 1990. The stability and even improvement of water quality over the last 10 years at all points has resulted from improved water distribution and irrigation and drainage facilities.

Soil salinity in the Syr Darya River basin has increased with irrigation practices too. Currently only 50% of the land in the basin is classified as non-saline. The soil salinity problem varies along the river just like river water salinity does. In the upper reaches, less than 10% of the land has moderate to strong salinity, while in downstream areas over 50% of the irrigated lands are classified as moderately to strongly saline. Salinisation is rapidly increasing in the midstream areas that are irrigated with water from the Srydarya river. For example, the percentage of moderately to strongly saline lands in the midstream area increased from approximately 26% in 1970 to 54% in 1995 (EC, 1995).

Intensive irrigation practices in the river basin have affected groundwater levels by recharging aquifers through deep percolation, as well as by pumping from aquifers. Table 1.2 shows the percentage of irrigated land with a number of water table ranges. During the period from 1970 to 1989, there was a relative decrease in the proportion of land with water table shallower than 1 meter, but the percentage of irrigated land with water table less 2, and 5 meters has increased. The decrease shows the benefit of new drainage schemes installed during this time. However, the large relative increases in the proportion of land with water table between 2 and 5 still show a threat of waterlogging at some areas in the basin.

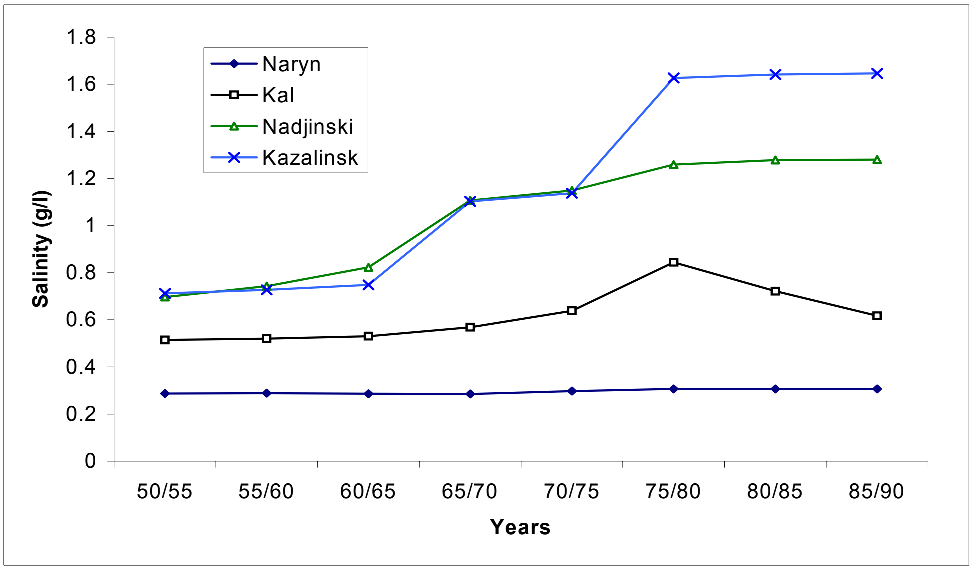


Figure 1. 4. Salinity at selected points in the Syr Darya River from 1950 to 1990 (Source: EC, 1995).

Table 1. 2. Change of percentage of irrigated land with various groundwater table from 1970 to 1989 (source: EC, 1995).

Locations	Depth of water table in meter			
	<1	1-2	2-3	3-5
Upper Reaches	0	0	-61	0
Fergana	-44	18	88	-59
Middle region	-91	16	37	41
Chakir	-62	16	-22	139
Artur	0	0	20	460
Lower reaches	0	-65	1180	2088
Average	-78	1	40	67

Facing these environmental impacts, the questions to be studied for this basin include: (1) whether the environmental problems related to water management in the basin, including contamination of water in the lower reaches, soil degradation due to intoxication, salinization, erosion and compaction and climatic consequences from the desiccation of the Aral Sea, will worsen. (2) whether the current irrigation system will be deteriorated in the future due to consecutive droughts, waterlogging, and high salinity in irrigation water and soil salinity accumulation. This is a serious question for people living in the basin, since a large portion of the national economies are derived from irrigated agriculture. Actually these two aspects, irrigation system and the environment in the basin are closely interconnected. More water withdrawal for irrigation will lead to less inflow to the Aral Sea, and probably, more salt and other pollutants being discharged to the river system, which will increase pollutant concentration in the river downstream, and finally this will affect irrigation water quality. Consdiering these two questions together, we want to know whether such a high level of irrigated agriculture can be sustained while preventing or minimizing adverse environmental and ecological impacts. The answer to this question is at the heart of what sustainable water resources management means for the basin, and it presents an important research topic for life and development in the basin.

After the collapse of the former Soviet Union, the management of the basin, which crosses four independent republics, has become an international issue, and it has attracted extensive attention around the world. Many research projects, supported by both international and national funds, have been searching for solutions to this well-known environmental problem. About ten years ago, the first systematic study on water management in the Aral Sea region which has been reported in the non-Soviet literature, began in the Stockholm Environment Institute (Raskin, et al., 1992). A detailed water demand and supply simulation was performed for 1987-2020 period, assuming that the current agricultural practices continue. Water demand and supply were treated in an integral fashion using the Water Evaluation and Planning System (WEAP), a simulation modeling system. Water balance scenarios were studied considering alternative development patterns and supply dynamics.

More recently, the Water Resources Management & Agricultural Production (WARMAP) in the Central Asian Republics, supported by the European Union Technical Assistance to Common Wealth of Independent States Program, was reported (EC, 1995). This project (Phase 1) includes a comprehensive land and water resources survey and an evaluation of irrigated crop production systems, as well as legal and institutional aspects. Data reported in this project provide a basis for analysis of land and water resources management strategies.

The World Bank, cooperating with other international agencies like EU and UNDP, has been developing strategies for attaining a sustainable management and development of water resources with regard to environmental requirements. Their work includes the development of management information systems, and economic-hydrologic modeling analysis (World Bank 1996). Unfortunately, even after five years, this effort is still in the planning and preparation phase and no concrete results have been reported.

USAID has supported the Environmental Policy and Technology (EPT) Project (1994-1998) and the Environmental Policies and Institutions for Central Asia (EPIC) Program (1998-2001) Under these programs, a series of regional water, energy, and environmental management projects have been carried out, including the new modeling system developed in the Center for Research in Water Resources (CRWR) of the University of Texas of Austin, as described before, which has served as the basis for this research.

These projects, especially the WARMAP project, provide an adequate base of data for further water resources management studies in this region.

The countries in the Syr Darya basin have expressed a great need for water policy analysis tools of the type to be developed in this research. In fact, an early version of the Syr Darya basin model has been developed and distributed to water and energy officials in the region (McKinney and Cai, 1997) and the current version of the short-term model described in Chapter 3 below has been adopted by the countries for planning purposes in the Syr Darya basin. Ongoing work will continue this development and dissemination of the results of this research.

1.3 OBJECTIVES AND SCOPE

Sustainable water resources management entails a fundamental shift from looking to construction as a means for solving water needs to looking to improved management (non-structural) as a means for solving such problems. Structural solutions are often necessary, however, the traditional emphasis on structural solutions is more expensive and often can result in greater environmental damage than nonstructural solutions. Increased consideration of non-structural measures may lead to reduced financial pressure and environmental damage (Zilberman, 1998).

The goal of a sustainable water resources management approach is to achieve substantive improvements in water use efficiency and preservation of the environment and ecology associated with the water use. This goal presupposes detailed information about current conditions of water supply, accurate and timely forecasts of meteorological events, how water is presently used, and what the needs of individual water users are. Through both qualitative and quantitative analysis, the management approach proposes (1) operational rules for storage and delivery system operations, as well as operations of terminal water use systems; (2) institutional directives and economic incentives that might encourage water users to use water more efficiently; (3) mechanisms for supporting decision making, including “what-if” scenario analysis and alternatives for evaluation; and (4) evaluation of the potential possibility, necessity and effectiveness of structural measures.

The viewpoint of this research is formed by such a management approach that combines the structural solutions and the non-structural measures to achieve sustainability in real world practices. The modeling framework developed here is built on an integral river basin system with arid or semi-arid climates and irrigation-dominated water supply, and where salinity control is a major water quality and environmental problem. The integrated hydrologic-agronomic-economic-institutional modeling framework includes the following considerations: (1) integrated regulation among hydrologic systems, irrigation systems and environment systems; (2) representation of spatial externalities resulting from spatially distributed water supply and demand; (3) representation of temporal externalities resulting from intergenerational water allocation tradeoffs, and (4) consideration of uncertainty and risk on both water supply and demand sides. The major relationships in the modeling are hydrologic continuity, crop production as a function of both water application and water and soil salinity, and economic incentives for salinity control, water conservation and irrigation system improvement.

The core of the modeling framework is an intra-year, short-term optimization model and an inter-year, long-term, dynamic control model. The short-term model is an extended irrigation management model, including essential hydrologic, agronomic, economic and institutional relationships, and the inter-year control model includes long-term changes and uncertainties, and incorporates prescribed sustainability principles for river basin system performance control. The intra-year model and the inter-year model are integrated into a long-term modeling framework, so that the tradeoff between short-term and long-term benefits can be analyzed based on sustainability principles. The short-term model is also run separately to study the in-depth hydrologic-agronomic-economic relationships.

Three approaches based on decomposition techniques and genetic algorithms (GAs) respectively, are developed to solve the large complex models developed in this research. Three approaches can be generally used for solving other complex models with appropriate conditions.

The major questions answered through this research include:

- For a sufficiently complex case study, such as the Syr Darya River basin in Central Asia, what are the important inter-connections among water management, agricultural production and environment for sustainable water management? To what extent is policy making in each sphere (water management, agriculture, and environment) influenced by policy making in the others?
- What is an effective expression of sustainability for the specific study area? That is to say, do the quantified criteria of sustainability used in the modeling effectively reflect reliability in water supply, equity in water allocation, environmental preservation and economic efficiency in water use?
- What potential conflicts are likely to arise between agriculture and other competing water uses, including environmental uses, industrial and municipal uses?
- How can we achieve sustainability in water resources management, specifically in river basins where irrigation water use dominates other uses and salinity is a potential problem? What implications for sustaining the water management system and the environmental system can be derived from the model results? More specifically, what kind of rules should be defined for hydrological system operations under various uncertainties?

What is the scope for applying water-conserving and water pollution prevention techniques and practices? How effective are economic incentives like penalty taxes on salt discharge?

- How can we solve the large, complex optimization models for sustainable water resources management under the currently available computer hardware and software capacity?

This research develops a general methodology for sustainability modeling in irrigation-dominated river basins. The methodology is applied to the case study area, the Syr Darya River basin of Central Asia, based on the data available. The problems in the case study area are specifically analyzed, and suggestions are presented based on modeling results. However, due to the limited data and time during this research, the solutions found in this research may not be taken as the practical solutions for the basin before further verification.

The rest of the dissertation is organized as follows:

Chapter 2 presents principles and guidelines for sustainable water resources management, especially in irrigation dominated river basins with arid or semi-arid climate. A summary of previous research on sustainable water resources management is presented. Emphasis is put on what is an operation concept of sustainable development for water resources engineers, and why traditional models for various purposes in water resources management should be updated based on the principles of sustainability.

Chapter 3 discusses basic components and structure of an integrated hydrologic-agronomic-economic-institutional model at the river basin scale. The Chapter begins with a review of the background for integrated hydrologic-agronomic-economic-institutional modeling at the river basin scale, and then describes the essential hydrologic, agronomic, and economic components and the inter-connections between these components.

Chapter 4 presents a short-term analysis based on the output from the short-term model applied to the case study area. This chapter demonstrates the performance of the complex, integrated hydrologic-agronomic-economic model by showing useful modeling output for sustainability analysis and decision-making. The outcomes of water uses under various scenarios are examined in terms of economic efficiency, equity, environmental impact, as well as the risk from hydrologic uncertainties. Since the model is applied for short-term analysis, and results also show why the short-term model is not efficient for sustainability analysis.

Chapter 5 develops three approaches for solving difficult water resources management models that are large, nonlinear and nonconvex: (1) the GBD (General Bender's Decomposition) based approach that can be used to search approximate global optimal solution for large nonconvex nonlinear models, (2) the GA-LP approach (genetic algorithm – linear programming) that can be used to find approximate global solutions or feasible solutions for large models with high nonlinearity and nonconvexity, and (3) the "piece-by-piece" approach that can be applied to solve large nonlinear models with multiple compartments. Each approach is applied to an example that shows its effectiveness and limitations.

Chapter 6 develops a long-term, dynamic modeling framework for sustainability analysis. The critical issue for this modeling is to trace and control long-term consequences resulting from short-term "wait-and-see" actions, with predicted changes and uncertainties on both water demand and supply in the future. Sustainability criteria with respect to risk, equity, environmental impacts and social-economic acceptability are quantified and incorporated into the long-term modeling framework. The GA-LP approach is used to solve the long-term dynamic modeling.

Chapter 7 applies the long-term model for sustainability analysis in water resources management. The issues of sustainability are discussed based on the long-term modeling results under various scenarios for the case study area. Through this analysis, we demonstrate the use of the analytical tool to evaluate sustainability with respect to the specific water management problems in the case study area, and also explore some policy implications for sustaining both the water resource and the environment of the basin.

Chapter 8 presents summaries, conclusions and recommendations for future work.

Chapter 2

Sustainability - A Systems Approach for Water Resources Management

2.1 INTRODUCTION

For water resources management, sustainability implies a notion of equilibrium that simultaneously satisfies the needs of water uses and the preservation of the water resources system. The question of sustainable water resources management then becomes: by what development strategies, management policies, or operational rules, can water uses still maintain long-term stable relationships with the water resources system and not deteriorate the recycling nature and potential sources of the system? On the other hand, facing uncertainties and fluctuations in the future, can the water resources system supply water with required quantity and quality at required times to satisfy various water demands? Sustainable water resources management should deal with these two inter-connected questions in an integrated framework.

Based on some general concepts and principles of sustainability, this chapter focuses on the operational aspects of sustainable water resources management within a specific scope, and presents a systems approach for implementing sustainability analysis of water resources management in irrigation dominated river basins.

We start this chapter by introducing the previous studies, which have focused on two aspects: (1) what are the guidelines for water resources management in light of sustainability? And (2) what should we do according to the guidelines?

Many guidelines for sustainable water resources management have been identified by various agencies. Bruce and Shrubsole (1994) presented "stewardship" for Canadian water management. Stewardship directs attention not only to the necessity to manage water to meet basic needs for a variety of interests, but also to ensure that water is protected and conserved, and its uses and values are sustained. Some activities were proposed to realize stewardship, which included maintaining ecological integrity and diversity, merging environment and economics in decision making, building comprehensive water resources information systems, and conducting public education.

The World Bank (Serageldin, 1995) has adopted a new policy for water resources management that takes a comprehensive approach, emphasizing economic behavior, the overcoming of market and policy failures, more efficient use of water, and greater protection of the environment. This approach moves attention away from the past approaches that tended to center on developing new sources of water - a "supply" focus, and puts emphasis on a "demand" focus, which implies so called "demand management". Demand management is an approach that leads to water conservation, water protection and efficient use of water through pricing mechanisms, regulatory measures, and technology updating. To implement these objectives, the Bank, working actively with its partner countries, has supported capacity building, promoted the creation of hydrologic, hydrogeologic, water quality, and environmental data bases, and financed many waste treatment and water conservation projects.

The United Nations Conference on the Environmental and Development (UNECD) in Rio de Janeiro in 1992 made a very impressive contribution to sustainable water resources management. In that conference, a number of countries came to a common perception that water should be taken as an integral part of the ecosystem, "*a natural resource and social and economic good*" (Chapter 18, Report of the UNCED, 1992). The major issues of water management were addressed, including drinking water supply, water and urban development, water and food production, and impacts of climate changes on water resources. A comprehensive analytical framework was suggested and encouraged (1) to take into account interdependencies among sectors; (2) to create incentives for financial accountability and improved performance through greater use of pricing, and decentralization of administration; (3) to realize consistent regulations and coordination among agencies on different levels; (4) to use new technical measures in waste treatment, water recycling and polluted groundwater remediation; (5) to promote water use efficiency, optimal water allocation, extreme event (flood and drought) control; and (6) to build comprehensive data bases.

Institutional weakness is thought to be one of the major obstacles to implementing sustainable water management. Therefore "capacity building", as an institutional activity for water management, has been encouraged (Alaerts et al., 1991). Three elements are involved in improving institutions: (1) creating an enabling environment with appropriate policy and legal frameworks; (2) institutional development, including community participation; and (3) human resources development and strengthening of managerial systems. Biswas (1996) argued that for effective capacity building, the first and the most essential requirement is having a good cadre of capable senior managers, and the appropriate institutions, policies or laws.

More recently, the American Society of Civil Engineers (ASCE), associated with United Nation’s International Hydrologic Program (UN/IHP), organized a special committee on sustainable water resources development and management. The committee conducted a comprehensive study of the definitions, guidelines, applications, and research potentials of sustainability in water resources development and management, and published a monograph of their findings (ASCE and UN/IHP, 1998). The authors outlined some approaches for measuring and modeling sustainability and illustrated ways in which these measures and models might be used when evaluating alternative designs and operating policies.

Of all water use sectors, agriculture uses the largest amount of water in the world. Globally, 70 percent of freshwater diverted for human purposes goes to agriculture. On the other hand, low efficiency in agricultural water use causes more stress of water shortage, and non-point pollution carried in irrigation return flow often threatens the environment more seriously than other water uses. Therefore, sustainable water resources management in agriculture has been identified as very important by scientists and engineers. Very recently, the Organization for Economic Co-Operation and Development (OECD) hosted a workshop on issues and policies related to the sustainable management of water in agriculture (OCED, 1998). The workshop helped to illustrate what needs to be done to manage water sustainably in agriculture, in particular through reviewing the experience in OECD countries. The main conclusions include improving the transparency of water management policies, taking into account environmental considerations and implementing economic incentives.

As a summary, documents resulting from various national and international conferences, working grouping or committees have identified some broad guidelines and principles for sustainable water resources management. These guidelines may be briefly summarized as follows:

Successful accomplishment of beneficial objectives

This is the first and the most important principle for water resources management. The successful services of water resources systems should meet multiple objectives in domestic and municipal water supply, economic development, and environmental maintenance. Adequate water quantity and quality should be considered for various water demands. We should not only provide successful services for the current generation, but also leave options for the future generations.

Minimization of negative impacts

Potential negative impacts to health, environmental systems should be carefully studied in every step of water resources system planning, design and operation. The long-term cumulative negative impacts should be forecast and be mitigated to the lowest possible level.

Stability and flexibility

Any system failure including system structural failure and operational error should be controlled to the lowest possible frequency, in order to maintain stable services. On the other hand, the system should be resilient enough to recover to normal status in case of system failure. Water resources systems should also be flexible enough to deal with various extreme events such as flooding, drought, excessive waste discharge, and other anticipated stochastic events.

Realization of equity

Water available in a basin may unevenly distribute. People in the upstream of a river may hold back too much water, or they discharge an excessive amount of pollutants into the river, which hinders people in the basin from sharing water rights. Both structural and non-structural measures should be implemented to make equitable water rights possible.

Optimal system operations

Under the physical constraints and policy limits, optimization of social, environmental and economical objectives should be sought through optimal system operations. Conjunctive use of surface and groundwater, and integral water quantity and quality management are often efficient methods for optimal system operations. Carefully planned structural measures like reservoirs may make up the integrity of the physical system, while non-structural measures through current facilities may bring additional benefit and avoid environmental damage.

Financial feasibility and economic efficiency

To increase water availability and maintain water quality, construction is often necessary. One problem is whether there is sufficient investment capital; another problem is that whether the investment is economically efficient. The investment limit and the requirement of economic efficiency form some external constraints to water resources planning and development.

Another aspect of economic efficiency is related to water allocation. In some regions, water is limited, and appropriate strategies of water allocation among various water users are necessary to lead to high level of economic efficiency.

Adaptation to new technology

"... *sustainable development is an effort to use technology to help clean up the mess it helped make, and engineers will be central players in its success or failures*." (Prendergast, 1993). Engineers make new technology and apply it to solve problems in the real world so that better service can be provided, and greater economic efficiency can be achieved. New technology in water resources is expected to find more efficient methods of water conservation, sea water desalination, greater water reuse and recycling, waste minimization, more comprehensive economic/environmental assessments, and more effective operation of water resources systems.

These principles and guidelines reflect some of the important aspects of sustainability in water resources management. There is no doubt that they would provide some assistance and guidance to those who are actually involved in planning and decision making in specific regions. However, we still need to translate these broad guidelines into operational concepts that can be applied to the designing, operating and maintaining of water resources systems in specific regions. Another observation about these guidelines is that all of them mainly address the qualitative aspects of sustainable water resources management. How can we translate those qualitative descriptions into quantitative analysis that can provide more exact information for specific decisions in water management? An analytical framework that combines water resource systems modeling with newly defined sustainability criteria is a meaningful research topic.

In this research, we examine sustainable water resources management specifically for river basins like the Syr Darya, the study area introduced in Chapter 1. In those basins, the weather is arid or semi-arid, and water quantity is at a critical level especially in dry years. Irrigation is currently the major water use, however, instream and ecological water requirements are competing with irrigation water use, and the necessity for transferring water from irrigation to other off-stream water uses such as industrial and municipal water uses also emerges. Current irrigation practices already bring adverse environmental impacts such as waterlogging, soil salinization, and water quality reduction, which may finally destroy current irrigation effectiveness.

For the study area, we translate the broad sustainability guidelines into operational concepts for water management. In the rest of this chapter, we first discuss sustainability issues of water management in agriculture. Following that, we define some criteria that can be applied to measure sustainability in quantitative forms. Finally, a systems approach based on the concepts and principles of sustainability is described, which forms the backbone of this research.

2.2 SUSTAINABILITY IN IRRIGATION-DOMINATED WATER MANAGEMENT

2.2.1 Irrigation and crop production

Over the last 30 years, irrigation has contributed a great deal to the increases in food production that have made it possible to feed the world's growing population. There has been a continuos upward trend in the irrigated area for most countries, and the ratio of the irrigated to total cultivated area has also risen (Bonnis and Steenblik, 1998). Clearly, irrigation has played a major role in boosting agricultural yields and output.

However, because of high losses through evaporation and transpiration, irrigation uses the largest fraction of water in almost all countries, and globally, irrigation water demand is still increasing due to the expanding of irrigated area. In some countries, the expansion of surface water use appears to be approaching the physical limits, and groundwater abstractions are increasingly exceeding rates of replenishment. Crop production has had a major impact on water uses. In many countries or regions, conflicts have already appeared in transferring irrigation water to other uses.

2.2.2 Irrigation and environment

Although the achievements of irrigation in ensuring food security and improving rural welfare have been impressive, past experience also indicates problems and failures of irrigated agriculture mostly related to environmental issues.

Water depletion

Water depletion is the most immediate effect of irrigation. Hydrological records over a long period (more than 50 years) have shown a marked reduction in the annual discharge on some of the world's major rivers (OECD, 1998). Excessive diversion of river water has brought environmental and ecological disasters in downstream areas, like the Aral Sea. Pumping groundwater at unsustainable rates has contributed to the lowering of groundwater tables and to saltwater intrusion in some coastal areas. For example, excessive and inefficient irrigation has substantially reduced storage of the Ogallala Aquifer situated in the mid-western USA, and the water table has dropped more than 15m over 25 percent of the area since 1940 (ASCE, 1998).

In arid or semi-arid geographic regions, depletion is more serious when irrigation is concentrated in a few months of the year when river water levels are low. Peak irrigation diversion usually exceeds naturally low water volumes, which leads to a deficit of minimum required flow for ecological uses.

Water quality reduction

Many water quality problems have also been created or aggravated by changes in stream flows associated with agriculture's consumptive uses. Generally return flow and deep percolation from irrigated fields lead to concentrated pollutants such as pesticides and nutrients, and raise the average temperature of water bodies. Key water quality issues related to irrigation include eutrophication, contamination, turbidity, deoxygenation, acidification and salinisation.

Waterlogging and salinisation

Inappropriate irrigation practices, accompanied by inadequate drainage, have often damaged soils through over-saturation and salt build-up. In arid and semi-arid regions, less leaching water is often the main cause for soil salinity accumulation. The United Nations Food and Agriculture Organization (FAO) estimates that over 20 million irrigated hectares are seriously affected, and that 60 to 80 million hectares are affected to varying degrees by water waterlogging and salinity (FAO, 1996).

Threats to natural life systems

Changes in flow rates and seasonal variations may lead to wetland loss and alter the biological cycles of aquatic and riparian plants and animals. Contamination of surface water from agricultural pollutant runoff causes death and deformities in fish and other life forms, and destroys possible sources of drinking water.

Crop production depends on water and soil quality, as well as water quantity. For example, when the salt concentration in irrigation water, or soil salinity in the crop root zone, exceeds crop salinity tolerance thresholds, crop production is affected, and to a serious extent, crop growth will stop. Therefore, the environmental impacts resulting from inappropriate irrigation practices can deteriorate crop production.

Certain effects of irrigation are indirectly beneficial to the environment. These include recharge of groundwater, regulation of runoff, and reuse of wastewater. However, today's irrigation practices seem to impose more negative impacts on the environment as discussed above.

2.2.3 Sustainable water management for irrigation – an operational definition

Now, people realize that irrigation, crop production and environment are parts of an integrated system. The purpose of irrigation is to increase crop production, however, its by-products may be environmental problems which reduce the quality of irrigation water sources, reduce the soil quality in the crop field, and may finally decrease crop production. Sustainable water management in irrigated agriculture has to employ appropriate irrigation practices that simultaneously satisfy the needs of crop water demands and environmental preservation, both now and in the future. Actually, humans have kept a stable relationship between these two conflicting aspects and formed the foundation of civilization for millennia. Only recently, over the last 30-50 years, the resonant relationship has been destroyed in some regions due to inappropriate irrigation practices such as excessive river and groundwater depletion, poor drainage, reuse of untreated field drainage, and use of polluted water from industrialization and urbanization.

Further, some environment problems such as groundwater quality reduction, and soil salinity accumulation have resulted from inappropriate, long-term irrigation practices. In some regions, these inappropriate practices may not impose immediate problems today, however, they may contribute to long-term environmental disasters, which will be suffered for generations.

A two-part objective is defined for sustainable water resources management within the scope of this research. One is to sustain the environment including water and soil systems, and this part implies "*preservation*" or "*conservation*". The other aspect is to sustain crop production systems, on which people are assumed to depend. This is true in the Aral Sea basin since millions of people in the basin depend on irrigated agriculture for their economic livelihood, and desiccation of the Aral Sea, due to the extensive irrigation system, has caused tremendous social, environmental and economic impacts. This aspect implies "*development*".

Protecting environment is critical to the "*preservation*" side, and it is also important to the "*development*" side, since environmental damage, such as polluted water and soil, diminishes opportunities for development of the crop production system. For the "*development*" side, however, actions needed are more than "*defensive*". For planned crop water demands, is there sufficient and timely water supply? This question relates to water storage capacity (reservoirs, groundwater storage) facility, water delivery facilities (water distribution system), and field water application facilities (irrigation systems). Adequate capacity and efficiency of these facilities are necessary to maintain the development of irrigated agriculture.

Another question is that under some extreme conditions like consecutive years of drought, how will water supply and crop production be affected? Sustainable water resources management requires a stable water supply with enough flexibility to deal with various extreme conditions.

Based on the discussion above, we give a definition to sustainable water resources management, which is applied to the specific scope of this research:

In river basins where irrigation is the major water use, sustainable water management should ensure a stable and flexible water supply capacity for crop water demands, and at the same time keep a stable relationship between irrigation practices and the associated environment.

This definition raises questions about water supply and water demand, as well as management policy to achieve the two-side objective of sustainability. These questions require decisions such as:

Decisions for water supply and water use:

- Long-term reservoir and groundwater storage capacity and operations;
- Water distribution facility capacity and efficiency;
- Level of irrigation system (water use efficiency);
- Level of drainage system;
- Level of drainage disposal and treatment; and
- Level of drainage reuse.

Decisions for water demands

- Irrigated area;
- Crop pattern;
- Water allocation among demand sites;
- Water allocation among crops; and
- Non-irrigation water supply for industrial, municipal, and ecological uses.

Decisions on management policy

- Water prices;
- Tax on pollutant discharge;
- Water rights and water markets (water right exchange), and
- Management institutions.

Based on the above definition, a modeling framework which includes both engineering and economic measures becomes both necessary and possible to integrate all these decisions, and search for sustainability through quantitative analysis.

2.2.4 Modeling sustainability – interconnected relationships

Within the scope of this research, modeling sustainability presupposes essential hydrologic, agronomic, economic and institutional relationships, and the integration of these relationships. Hydrologic flow and contaminant balance and distribution from crop field to river network, from short term to long term, provides a physical basis to evaluate water availability and water quality conditions. Appropriate estimation of deep percolation, return flow and their contaminant concentrations, as well as groundwater levels, are essential to evaluate the environmental impacts of irrigation. Long-term simulations of these processes are necessary to trace the dynamic consequences such as waterlogging, soil salinisation, and groundwater water quality reduction.

A crop production function that includes water and soil variables is an appropriate connection between water, soil quality and crop production. Based on this function, appropriate water supply capacity and soil quality to sustain the crop production can be determined.

Economic relationships, i.e., water use benefits or profit and water pricing and taxing systems, provide incentives for making various decisions so as to achieve more efficient water development and use. An assessment of the environmental damage from the depletion of water over time is critical to evaluating the environmental impacts of irrigation. Institutional relationships present directives aimed at achieving equity in water resources management.

Modeling sustainability also presupposes a decision process that will include decision-maker's preference. Through modeling the integrated hydrologic, agronomic, economic and institutional relationships, we can compute the benefit of water uses and the environmental damage associated with them, and we can also compute the benefit and damage of both current and future water uses. Tradeoffs between benefit and damage, and between the current and the future should be considered in the modeling.

How do we know the modeling outputs reflect sustainability or not? For this we need a measure of sustainability, which will be set up as the objective of the modeling. This is further elaborated through the sustainability criteria discussed in the following.

2.3 SUSTAINABILITY CRITERIA

Sustainable water resources management criteria reflect the principles and guidelines of sustainability. In this context, we assume that the objectives for achieving sustainability are (1) water supply system reliability, reversibility and vulnerability; (2) environmental system integrity, (3) equity in water allocation and (4) socio-economic acceptability. Other objectives are possible and may be more appropriate in some situations. However, for the purposes of this research, this limited and quantifiable set has been selected. In this section, we review the definitions of these items, followed by a brief introduction to the current research.

2.3.1 Reliability, reversibility and vulnerability of water supply system

Water supply systems, in a long-term view, are subject to substantial risk due to inherent stochastic variability and a fundamental lack of knowledge. Risk is identified as one of the key sustainability issues in water resources management (Simonovic, 1997). The traditional measures of system performance (mean value or variance of some variables) are insufficient to capture risk behavior, and additional criteria must be used to quantify recurrence, duration, severity and other consequences of the non-satisfactory system performance. These criteria include *reliability, reversibility and vulnerability* (Kundzewicz and Kindler, 1995).

Reliability represents the probability of a system success state, and it is a complimentary item to ***risk***, which represents the frequency of system failure. The definitions of reliability used in water resources management include:

- *Occurrence reliability*, calculated as the ratio of the number of periods of system success to the number of periods of operation;
- *Temporal reliability*, determined as the ratio of time the system is in a success state to the total time of operation; and
- *Volumetric reliability*, often defined as the ratio of the volume of supplied water to the total demanded volume.

Reversibility, also called ***resilience,*** is the probability of recovery of the system from failure to some acceptable state within a specified time interval. Fiering (1982) proposed several alternative indices of resilience, including the duration of the system's residence in the satisfactory state, steady state probability of the system being in the satisfactory state, and some other indices. Hashimoto et al. (1982a, b) developed a mathematical definition of resilience, suggesting that resilience could be a measure of the probability of being in a period of no failure in the current period when there was a failure in the last period. Moy et al. (1986) incorporated a formulation of resilience into mathematical programming for reservoir operation where resilience was measured as the maximum number of consecutive periods of shortages that occur prior to recovery.

Vulnerability represents the severity or magnitude of a system failure. Hashimoto et al. (1982a, b) developed a metric for overall system vulnerability as the expected maximum severity of a sojourn into the set of unsatisfactory states. Emphasis was placed on the maximum severity (how bad things are) for each unsatisfactory state, and the probability that the failure with the maximum severity would occur. Moy et al. (1986) defined a vulnerability criterion as the magnitude of the largest water supply deficit during the period of operation. Kundzewicz and Kindler (1995) used a reciprocal of vulnerability measured by the mean maximum deficit.

Reliability, resilience and vulnerability of a system are not independent, and Moy et al. (1986), Hashimoto et al. (1982a, b), and Kundzewicz and Kindler (1995) considered tradeoffs among them. These criteria may be insufficient for non-stationary and uncertain conditions due to changing economic and social contexts, and therefore, the appropriate treatment of the uncertain and the unknown is imperative (Kundzewicz and Kindler, 1995).

In this research, in order to include these criteria in the measurement of sustainability, reliability, resilience and vulnerability are quantified with respect to water supply for irrigation and for environmental use. This is described in Chapter 6, Section 6.2.1 after we elaborate more details about this research.

2.3.2 Environmental system integrity

As discussed in section 2.2.2, environmental impacts often put the sustainability of water resources systems at risk. A guiding criterion for sustainable water resources management is to make a water resource system interfere as little as possible with the integrity of the associated environmental system. To meet this criterion, we must at least ensure the following:

(1) Sufficient water regimes to maintain and restore, if applicable, the health of aquatic and floodplain ecosystems;

(2) No long-term irreversible or cumulative adverse effects on the environment and ecosystems;

(3) Water quality that meets certain minimum standards that may vary over time and space; and

(4) Integrated consideration of water quality and quantity when designing and operating water resource systems.

To reflect the environmental system integrity in a modeling framework, first the environmental impacts, especially the long-term environmental consequences resulting from water uses, must be simulated and expressed in some quantitative forms, for example, salt concentration in groundwater, soil salinity in the crop field. Second, those environmental impacts need to be assessed in some forms that can be comparable with other criteria. One of the common direct forms is economic damage from environmental degradation, which, is often difficult to evaluate. Generally, indirect forms are used to calculate these effects, including normative forms related to water quality standards or institutional environment water supply quantum. The specific form of environmental system integrity for the purposes of this research is discussed in Chapter 6, Section 6.2.2.

2.3.3 Equity criteria

Equity is one of the basic concepts within the primary definition of sustainable development (WCED, 1987). In view of equity, sustainable water resources systems must allow people, "now and then" and "here and there" to share the water use right (both benefit and cost) in such a way that no one should be disadvantaged or inadequately compensated (ASCE, 1998). Factors that affect either temporal equity or spatial equity in water resources development can be either anthropogenic or natural, or both. Temporal equity is associated with long-term cumulative consequences, which may lead to damages or even disasters in the future. One typical case related to spatial equity is the conflict between upstream and downstream areas in a river basin. Conflict may arise when people in the upstream area want to use water during different periods than people in downstream reaches. This is the case in the Syr Darya basin where upstream power generation demands in winter are in conflict with downstream irrigation demands in summer. Conflict may also arise when upstream users release excessive pollutants into the river, and downstream users suffer damage due to the poor water quality. This is the case in the Syr Darya basin, where return flows from the Fergana valley in Uzbekistan impact water quality downstream in Kazakstan.

Since equity in water resources management involves complex natural, political and socio-economical factors, there is no general expression for this term. In this research we describe equity as an even distribution of beneficial water use related benefits in both spatial and temporal domains. Some statistical forms to represent both temporal and spatial distribution of water use benefit are described in Chapter 6, Section 6.2.3.

2.3.4 Socio-economic acceptability

To determine the optimal scale of a sustainable economy, economists suggest the metric ***natural capital*** (Daly and Cobb, 1989), and the growth of the economy should proceed to the point at which the marginal costs associated with natural capital depletion just equal the marginal benefits. In the field of water resources planning and management, we propose a similar concept called ***socio-economic acceptability.*** When the marginal cost associated with water resources development and management is greater than the marginal benefit, the water resources development activities lose their socio-economic acceptability, and the water resources system enters an unsustainable state at this point.

An example would be the water resources management problem in the Aral Sea basin in Central Asia. The withdrawal of water for irrigation has created great profits for that region, but at the same time the environmental disaster due to excessive water withdrawal has caused huge damage. The environmental costs due to the excessive irrigation are so high that they go beyond the economic capacity of the newly independent republics in Central Asia (World Bank, 1992). The marginal cost from the irrigation activities is much higher than the marginal benefit. This might be an economic explanation of the unsustainable state of water management in the basin.

2.4 A SYSTEMS APPROACH FOR SUSTAINABILITY MODELING

For water resources management, the concept of sustainability needs to be addressed with an innovative systems approach. In this research we develop such an approach to model and analyze sustainability in irrigation-dominated river basins. The major issues of this approach are described in the following.

Multidisciplinary data requirement

Modeling sustainability requires multidisciplinary data. Within the scope of this research, the modeling framework includes hydrologic, agronomic, economic and institutional relationships, and data related to each of these components are needed. For long-term modeling, required data include changes from year to year in both water demand and water supply. This research uses data from previous research projects, as well as data from related literatures. However, comprehensive data collection and verification are beyond the scope of this research.

Integrating hydrologic-agronomic-economic-institutional modeling at a river basin scale

Representations of hydrologic processes at scales ranging from single reservoir to multiple reservoir systems, from separate surface and groundwater systems to conjunctive systems, and from the soil profile to the cropped field, are important precursors to understanding and describing the mass balances at the river basin scale. Sustainability needs an integrated basin system to reflect the integrality of the real world. It is at the basin level that 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. This research develops an integrated hydrologic-agronomic-economic-institutional model at the basin scale, which has the following characteristics: (1) representation of an integral river basin network which includes the water supply system (surface and groundwater), the delivery system (canal network), the water users system (agricultural and non-agricultural), the drainage collection system (surface and subsurface drainage), and a waste water disposal and treatment system, as well as the connections between these sub-systems; (2) representation of the spatial distribution of water flow and pollution, and water demand; (3) integrated water quantity and quality management, including flow and pollutant (salinity in this research) transport and mass balance, and regulation between required quantity and quality standards; and (4) integration of hydrologic, agronomic, economic and institutional relationships in an endogenous system that will adapt to environmental, ecological, and socio-economic status related to the river basin domain.

Connecting short-run and long-run models

Short-term modeling and long-term modeling, apart from different time horizons, have different purposes. Short-term modeling is used to calculate immediate profits and operations, ignoring temporal externalities, while long-term modeling is applied to search social benefits, considering both spatial and temporal externalities. For long-term modeling, two issues have to be taken into account: first, the conditions for future years can only be predicted with potential errors; and second, if something in the short-term is done inappropriately, then long-term benefits might be affected. Taking these factors into account, in a combined short-term and long-term model, the short-term decisions are directed by both short-term desires and long-term adjustments, and the long-term decisions try to reach a long-term optimality: satisfying the immediate demands and desires without compromising those of future years, which reflects the spirit of sustainability.

System performance control

System performance control is based on the sustainable water resources management criteria described qualitatively in section 2.4 and described quantitatively below. The risk criteria describe how often system failures occur, how long periods of unsatisfactory performance are likely to last and how severe a failure might be. Additional criteria for system performance are needed for control of negative environmental impacts, the consideration of equity, and socio-economic acceptability. These criteria are incorporated into the modeling so that system performance can be forecast, evaluated, analyzed and controlled based on these criteria. Combining sustainability criteria with water resources systems modeling is one of the major efforts of this research.

Solution techniques for large complex systems

A complex system model is necessary for sustainability analysis. In this research, a basin-wide model that integrates hydrologic, agronomic, economic and institutional components is applied for long-term sustainability analysis. Such large-scale complex modeling can not be solved by currently available algorithms and computing capacity. New algorithms are developed in this research to solve the complex large-scale system modeling.

Chapter 3

Integrated Hydrologic-Agronomic-Economic-Institutional Modeling

3.1 INTRODUCTION

Integrated water resources management arises as a new direction in sustainable water resources management. The interdisciplinary nature of water resources problems requires new attitudes towards integrating the technical, economic, environmental, social and legal aspects into a coherent analytical framework. Water resources development and management should incorporate environmental, economic and social considerations based on the principles of sustainability. They should include the requirements of all users as well as those relating to the prevention and mitigation of water-related hazards, and constitute an integral part of the socio-economic development planning process (Booker and Young, 1994). Comprehensive discussions of this topic are provided in UNECD (1992) and Serageldin (1994) and these issues have been reviewed in Chapter 2.

To bring the concept of integrated water resources management into an analytical framework, modeling techniques for integrating hydrologic, agronomic, economic and institutional components were studied and found to present opportunities for the advance of water resources management in this new direction. In this chapter we first review the related background for the integrated hydrologic-agronomic-economic-institutional modeling, and then describe the basic components and structure of a prototype model that is able to provide capability for determining rational and effective water management strategies at river basin scales.

3.2 BACKGROUND

Modeling methodologies in water resources management are reviewed in this section in order to find implications for modeling sustainability at the river basin scale. We focus on water management in irrigation-dominated river basins. Irrigation and drainage management is reviewed as part of integrated river basin modeling; empirical crop productions (crop yield vs. water use) are shown to provide a critical linkage between hydrologic, agronomic, and economic components; the economics of water management are illustrated as incentives for effective water use and salinity control in river basins where salinity presents a serious problem. Finally, with these basic approaches, previous integrated models are discussed, and the general modeling methodologies are addressed.

3.2.1 Water resources management modeling at the river-basin level

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 soils, 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. Figure 3.1 shows a schematic diagram of the components of a river basin system, which includes the water supply system (ground and surface water), the delivery system (canal network), the water use system (agricultural, municipal, and industrial), and the drainage collection system (surface and subsurface). The atmosphere forms the river basin's upper bound, and mass and energy exchange through this boundary determines the hydrologic characteristics within the basin. However, the state of the basin (for example reservoir and aquifer storage, and water quality), and the physical processes within the basin (for example stream flow, evapotranspiration, infiltration and percolation), are also characterized by human actions, including impoundment, diversion, irrigation, drainage, and discharges from urban areas. Therefore, water resources management modeling of a river basin system should not only include natural and physical processes, but it must also include artificial “hardware” (physical projects) and “software”(management policies). The essential relations within each component and the interrelations between these components in the river basin can be considered in an integrated modeling framework.

As an example, Figure 3.2 presents a framework for river basin management modeling, including relationships and decision items at various levels. Water can be used for instream purposes including hydropower generation, recreation, waste dilution, as well as offstream purposes that are differentiated into agri cultural water uses and municipal and industrial (M&I) water uses. Socio-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 control for the system is assumed to be the institutional directives like water rights, and economic incentives such as water price, crop price, and any penalty tax on waste discharge and irrigation drainage. The institutional directives and economic incentives constrain or induce hydrologic system operations and decisions within both M&I demand sites and agricultural demand sites. Water uses are

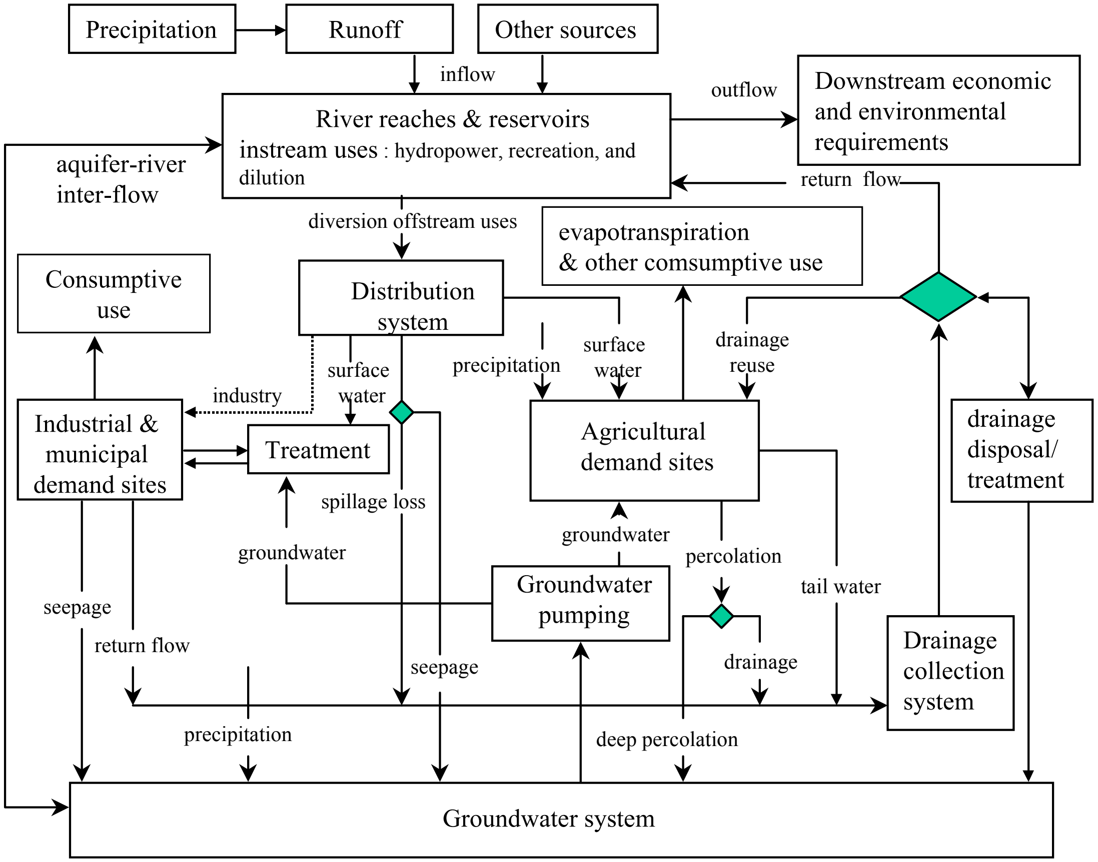


Figure 3. 1. Schematic representation of river basin processes (adapted Daza and Peralta, 1993)

competitive among various water users, under prescribed institutional rules and economic incentives.

The hydrologic system interacts with M&I water use system, irrigation and drainage system, and instream water use systems. The operation of hydrologic system is driven by these water use systems and on the other hand, the water use systems are constrained by the hydrologic system.

Combined Optimization and Simulation Models

Of particular importance to basin-scale analyses are models of two fundamental types: simulation models which *simulate* water resources behavior in accordance with a set of rules (actual or hypothetical) governing water allocations and infrastructure operations, and optimization models which *optimize* allocations based on an objective function (economic or other) and accompanying constraints. McKinney et al (1999) provided a comprehensive review of the simulation, optimization, and combined simulation-optimization models applied to integrated river basin management. Figure 3.3 presents a schematic view of the complementary application of basin-scale simulation and optimization models. Whereas the assessment of system performance can be best addressed with simulation models, optimization models serve best if improvement of the system outcomes is the main goal. Hydrologic interactions among principal water sources and their uses are often described in less detail than they would in models of the separate entities in order to capture the broader resource dynamics.

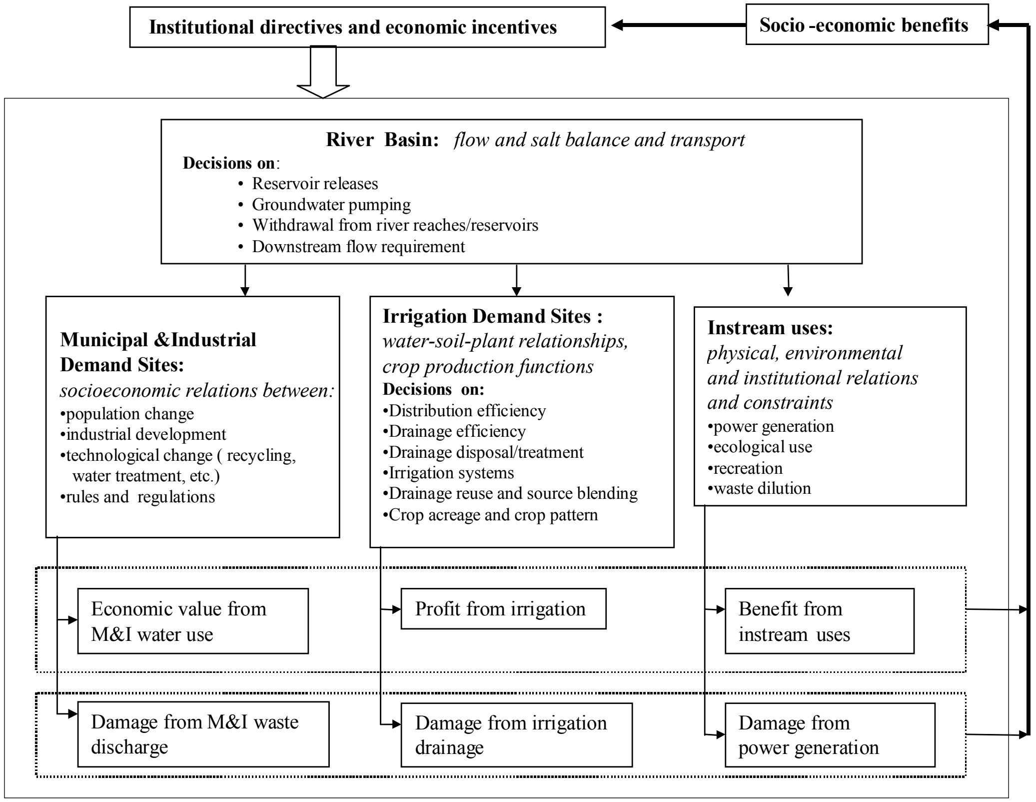


Figure 3. 2. A framework for river basin management modeling

Simulation and optimization models of river basin-scale water resource systems are complementary research tools to address problems related to the competition over water resources as well as to the design and assessment of alternative systems of water allocation. Models can often simultaneously include simulation and optimization capabilities. Applied optimization models must be able to characterize the hydrologic regime in order to calculate the objective function. Optimal water allocation must also be feasible, at a minimum from an infrastructure operations perspective, for policymakers and system managers to consider their adoption. In the following, several models that integrate simulation and economic optimization capabilities with the goal of policy analysis and recommendations are reviewed.

Louie et al. (1984) used a multi-objective simulation/optimization procedure to study unified basin-wide water resources management. Three major issues are simultaneously considered in the procedure: (1) water supply allocation; (2) water quality control; and (3) prevention of undesirable overdraft of groundwater. The optimization procedure is implemented by interactively solving several optimization and simulation models. Three optimization models, each corresponding to one of the three major simulation models, are solved separately. The optimization model for water quality control is solved combined with a groundwater quantity-and-quality model or a river flow-and-mass transport model through the influence coefficient method (Becker and Yeh, 1972). After the three optimization models are solved, payoff tables are created, and the original multiple objective problem is converted into a constrained problem involving the three objectives. Finally the multiobjective optimization problem is solved for noninferior solutions. This procedure was applied to a small test problem.

Labadie et al. (1994) extend MODSIM, a widely used simulation language for river basin network flow modeling to incorporate constraints on water quality loading and concentrations. The new model, MODSIMQ directly includes water quality regulations as constraints. The assessment of risks and uncertainties associated with water quality predictions and projections is included through an interactive linkage with the QUAL2E streamflow water quality model of the United States Environmental Protection Agency. QUAL2E is used to update water quality coefficients in MODSIMQ, and MODSIMQ calculates both network flows and concentrations, which are then fed into QUAL2E for further simulation. This approach is similar to that of Dandy and Crawley (1992) but removes some of the limitations in that work.

More recently, Lee and Howitt (1996) modeled water and salt balances in the Colorado River basin to determine salinity levels which maximize net returns to agricultural and municipal & industrial (M&I) water users at selected locations in the basin. Nonlinear crop production functions and M&I costs per unit of salinity are derived for inclusion in the objective function, which was solved using the GAMS/MINOS software. Three scenarios are considered: (a) economic optimality; (b) no change in cropping patterns with subsidies for salinity control measures; and (c) cropping changes with subsidies to maintain agricultural profits. The first-best, economically optimal scenario indicates major declines in cropped area with significant returns to M&I uses. Of the two scenarios with subsidies, the cropping changes subsidized to maintain profits indicate marginally lower total subsidies with a minor, but significant reduction in salinity. The authors note that optimal solutions were modeled without consideration of transaction costs or equity criteria.

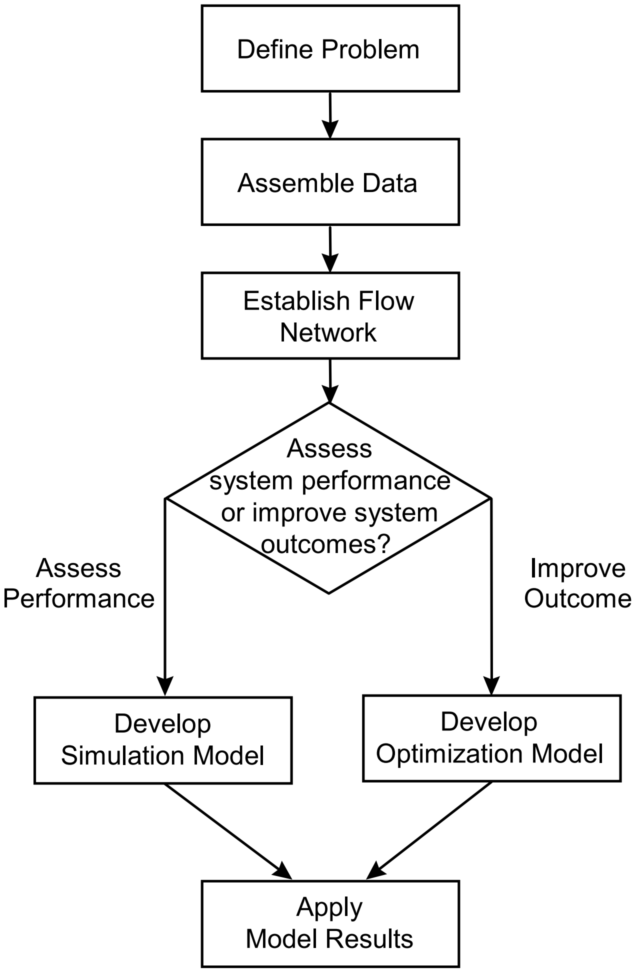


Figure 3. 3. Schematic view of the complementary application of basin-scale models (After McKinney et al., 1999).

A final example of integrated simulation-optimization modeling of water resource systems involves groundwater usage (Faisal et al., 1994). Faisal et al characterize the hydrologic flow regime using a linear response matrix, which allows the superposition of the effects of pumping at different aquifer locations on the particular location where drawdown is to be controlled. The location-to-location drawdown functions, however, are derived using the popular MODFLOW three-dimensional finite-difference groundwater model developed by the United States Geological Survey. The conjugate gradient method applied to solve the optimization of the nonlinear objective function produces results that are identical with a GAMS/MINOS solution. Two scenarios are modeled: (a) the social optimum for the basin, and (b) the common pool problem consisting of self-interested farmers. While discounted net benefits for the two scenarios are not markedly different, the common pool results in significantly reduced aquifer levels.

Decision Support Systems

Decision support systems are proactive tools for sustainable river basin planning and management, which provide interactive, graphics-based users interfaces, comprehensive data management techniques, complex modeling capabilities, and flexible strategy analysis functions. In the following, a few recent examples are discussed to show the application of DSSs in integrated water management at the river basin scale.

Fedra and Jamieson (1996) reported an on-going comprehensive decision-support system (DSS) for river basin planning, the 'WaterWare'. The analytical components comprise a geographic information system(GIS), geo-referenced database, groundwater pollution control, surface-water pollution control, hydrological processes, demand forecasting and water-resources planning. All these components were integrated into a common executive environment and an analytical framework. Other similar DSSs include the Tennessee Valley Authority's Environment and Water Resource Aid (TERRA) (Reitsma et al., 1994), the Interactive Mass-Balance Simulator of River-Aquifer Systems (IRAS) (Loucks et al., 1994), and RAISON (Lam and Swayne, 1990). In Europe, a major five-year program was initiated in 1992 to develop a sophisticated decision support system for integrated river basin management. The purpose for this DSS is to assist managers in coping with the complexities of multi-objective sustainable planning within imposed environmental, public acceptance and legal and administrative constraints (ASCE, 1998).

3.2.2 Irrigation and drainage management: short-term and long-term models

Due to the increasing water scarcity and worsening salinity condition, greater attention has been given to integrated water quantity and quality management in irrigated agriculture. Inappropriate irrigation is often responsible for highly saline drainage returning to surface river systems and groundwater systems, and for long-term salt accumulation in soil (Hanks and Anderson, 1979).

The physical basis for integrated water quantity and quality management includes the dynamics of soil moisture and salt movement in the root zone, which is generally described by the Richard's Equation. Apart from some detailed simulation models, e.g., DRAINMOD (Skaggs, 1980) and WATRCOM (Parsons et al., 1990). These physical relations, combined with management strategies and economic incentives have been extensively studied since 1970's. A distinction can be made among the models in terms of the range of time that they cover: short-term models, long-term models, and extended long-term models (Yaron et al, 1980).

Short-term models

A short-term model is confined to one year or a single irrigation season. The model deals with the initial salinity of the soil profile; it analyzes the optimal combination of water quality and quantity for each initial state but does not take into account the effects of accumulation of salt over time. For example, Bresler and Yaron's (1972) model is a short-run model developed to obtain the optimal quantity-quality combination of irrigation water in a single irrigation season via linear programming. Yaron et al. (1980) presented a dynamic programming model for scheduling of irrigation with soil salinity parameters explicitly considered. Two discrete state variables, soil moisture and salinity level of the soil were used to characterize the modeling system. Gini (1984) developed a short-run model which simulates the dynamics of water allocation and salt movement in a two-layered soil column. Nonlinear differential equations performing water and salt balance in the unsaturated and saturated zones were included in the model. The critical salinity approach (Mass and Hoffman, 1977) was used to estimate yield reduction from excessiveive salinity in the root zone.

Long-term models

A long-run model accounts for the effects of salt accumulation in the soil profile over time. The model comprises a succession of short-run processes, the initial conditions of which are affected by salt accumulation in previous periods. The irrigation decision over a single season takes into account the resulting terminal conditions and the effects on succeeding periods. Yaron and Olian (1973) studied a long-run model for the analysis of a winter leaching policy on a perennial crop in a Mediterranean climate. In their model a stage was defined as a year consisting of a rainy season (winter) and a dry season (summer). The state variable was the mean chloride concentration in the soil profile at the end of a rainy season, and the decision variable was the quantity of water used to leach the soil profile at the end of a rainy season. Matanga and Marino (1979) modified this model taking into account seasonal irrigation depth as another decision variable; they also extended this model from considering a single crop to multiple, and then optimal area-allocation among crops was considered. Bras and Seo (1987) developed a conceptual model to describe the dynamics of water allocation and salt movement in the root zone of a crop. Moisture stress and osmotic stress were combined to obtain the integrated inhibitory effect of salinity on transpiration. The long-term prevention of salt accumulation was handled via probabilistic state constraints with impose desired salinity and moisture levels with a particular confidence level. Bresler et al. (1983) considered soil variability and uncertainty via stochastic modeling in a long-run mixed integer linear programming model. In their study, soil properties were regarded as random variables that were characterized by their probability density function.

Extended long-term models

There has been considerable interest in evaluating long-term trends of groundwater quality within irrigated stream-aquifer systems by studying the relationship between agricultural practices and water quality variations in the irrigated stream-aquifer systems. The extended long-term models, which take in account both salt accumulation into the soil profile and its accumulation in the underground water reservoirs, have been developed for this purpose. These models include soil water flow and solute transport, groundwater flow and solute transport, stream aquifer interflow, water use decisions, and agronomic relationships between crop production and the depth of applied irrigation water.

Latif and James (1991) presented a conjunctive-use model used to maximize a water user's return under limited and dynamic water supply for long-term considerations. Salt distribution and transport in the crop root zone were modeled using the physical soil properties and mass balance, and a daily crop water stress index was used to quantify crop yield reduction due to water stress over the growing stages. The model was used to explore optimal groundwater extraction corresponding to the agronomic behavior.

Daza and Peralta (1993) developed a conjunctive water management model for an irrigated area. The model utilized a transient multilayer groundwater hydraulic simulation/ optimization model, incorporating the irrigation technology explicitly. Irrigation inflow was taken as a decision variable, and deep percolation and runoff losses from irrigation were state variables. Similar studies include Peralta et al, (1988), Lefkoff and Gorelick, (1990a), Peralta et al. (1990), and Musharrafieh et al. (1995), all of which applied simulation/optimization models to determine an optimal irrigation strategy that would maximize crop yield while preventing groundwater contamination.

Finally, an example of integrated short-term and long-term model was developed by Feinerman and Yaron (1983) who used a linear programming model, deterministic in the short run and stochastic (random rainfall) in the long run. The short-run model, limited to a single year, incorporated the physical, biological, and economic relationships involved in one endogenous system. The long-run model considered the effects of short-run decisions on the stream of future profits and rainfall uncertainty, with several relationships incorporated exogenously. These relationships, including irrigation water mixing, soil salinity ranges, crop yields, and net profits, were pre-determined based on the short-run model's results. The hydrologic aspects were meaningful but highly simplified in this study. This study was limited to a single farm, and no externalities were considered.

3.2.3 Crop production functions: yield - water use relationships

Existing modeling approaches to crop-water relationships (for example, surveys by Hanks (1983) and Vaux and Pruitt (1983) address economic, engineering, and biological aspects of the production process. These surveys conclude that crop-water relationships are very complicated and that not all management issues have been fully addressed in one comprehensive model. An ideal crop-water production model should allow the assessment of policy-related problems, and results should be transferable between locations. In addition, the model should be simple to operate, requiring a small data set; easily adjustable to various farming conditions; and sufficiently comprehensive to allow the estimation of externality effects. In addition, the interaction between water quantity and quality and the water input/production output should be clearly defined (Dinar and Letey 1996).

Four broad approaches to production functions can be identified, evapotranspiration models, simulation models, estimated models, and hybrid models (McKinney, et al., 1999). Among these model types, the simulation models either simulate in detail the production process of one crop, or focus on one production input or the subsystems associated with a particular production input, and the hybrid models combine aspects of the other three types. In the following we do not go further with the simulation models and the hybrid models, but focus on the empirical evapotranspiration models and estimated models that are more related to this research.

Evapotranspiration Models

Evapotranspiration models predict the relationship between crop yield and crop evapotranspiration under varying conditions of salinity levels, soil moisture conditions, and irrigation strategies. De Wit (1958) found a linear relationship between dry matter yield and cumulative transpiration by the crop. Hanks (1974) improved this relationship and derived the following crop yield function:

$$YA^{st} = YM^{st}\left(\frac{TP}{TPM}\right)_{st} \tag{3-1}$$

where

YA = actual yield

YM = maximum yield,

TP = cumulative transpiration by the crop, and

TPM = potential value of TP.

and *st* represents a growth stage in the season. The total dry matter in a season is obtained by the following additive relation:

$$YA = \sum_{st=1}^{ST} YA^{st} = \sum_{st=1}^{ST} YM^{st} \left(\frac{TP}{TPM} \right)_{st} \tag{3-2}$$

Jensen (1968) proposed the following multiplicative relation for estimating grain yield of crops:

$$YA = YM \prod_{st=1}^{ST} \left(\frac{ETA}{ETM} \right)_{st}^{w_{st}} \tag{3-3}$$

where

ETA = actual evapotranspiration,

ETM = maximum crop evapotranspiration (eq. 3-5), and

w_{st} = a weighting factor for stage *st*.

Hill et al. (1982), Dariane and Hughes (1991) used both relations with different crops. In most cases, equation (3-2) has performed better than equation (3-3).

FAO (1979) recommended a relationship between relative yield decrease and relative evapotranspiration deficit given by the empirically-derived yield response factor (*ky*), or:

$$1 - YA / YM = ky \cdot (1 - ETA / ETM) \tag{3-4}$$

The value of *ky* for different crops is based on experimental evidence, which covers a wide range of growing conditions. The relationship is given for the total growing period and the individual growth periods of the crops. The maximum evapotranspiration is calculated as (also see Chow et al., 1987):

$$ETM = kc \cdot ET_0 \tag{3-5}$$

where ET_0 is the reference evapotranspiration, which represents the rate of evapotranspiration of an extended surface of an 8 to 15cm tall green grass cover, actively growing, completely shading the ground and not short of water. The Penman method is widely used to calculate ET_0. k_c is the empirically-determined crop coefficient relating ET_0 to *ETM*. The value of *kc* varies with crop, development stage of the crop, and to some extent with wind speed and humidity. For most crops, the *kc* value increases from a low value at time of crop emergence to a maximum value during the period when the crop reaches full development, and declines as the crop matures.

The actual evapotranspiration (*ETA*) is a function of both soil water content and soil salinity. FAO (1979) provided an approach to estimate *ETA* based on only soil water content. Bras and Seo (1987) presented an example of determining *ETA* based on both soil water stress and salinity. Prajamwong et al. (1997) implemented a more empirical method to include soil salinity in calculation of *ETA*.

Equation 3-4 is probably the most complete summary of available data, and has been widely used for planning, designing and operating irrigation supply system taking account of the effect of the different water regimes on crop production (Perry and Narayanamurthy, 1998).

As a summary, although evapotranspiration and transpiration models capture important aspects of crop-water relationships, they have limited ability to capture the impacts of non-water inputs. The relationships refer to high producing variety, well-adapted to the growing environment, growing in fields where optimum agronomic and irrigation practices, except for water, are provided.

Estimated Production Functions

Estimated production functions are more flexible than other types of models. Polynomial or quadratic functions are most widely used. Moore et al. (1993) used farm-level, census data from the western United States to estimate crop water production functions for 13 crops in Cobb-Douglas and quadratic forms. Van Liebig response functions for nutrients and water have been estimated using experimental data, and likely outperform polynomial functional forms (Paris and Knapp 1986). However, they are rarely applied as they require detailed field-level data. Berck and Helfand (1990) found that crop yields were better approximated by a smooth concave function.

However, Dinar and Letey (1996) argued that the specification and estimation procedures of an estimated model must comply with plant-water relationships: (1) plant yield increases as water quantity increases beyond some minimum value; (2) yield possibly decreases in a zone of excessiveive water applications; (3) yields decrease as the initial level of soil salinity in the root zone or the salt concentration in the applied irrigation water increase beyond some minimum value; and (4) the final level of root zone soil salinity decreases with increasing irrigation quantities, except for possible increases, where relatively insufficient water quantities have been applied.

In order to meet these requirements, polynomial functions have been applied in many production functions. Dinar and Letey (1996) applied the following quadratic polynomial form in the case of 3 production inputs:

$$YA/YM = a_0 + a_1 w + a_2 s + a_3 u + a_4 w \cdot s + a_5 w \cdot u + a_6 s \cdot u \\ a_7 w^2 + a_8 s^2 + a_9 u^2 \qquad (3\text{-}6)$$

where:

w = relative irrigation water (water application to potential evapotranspiration,

s = salinity of the irrigation water,

u = irrigation uniformity, and

a_i (i=1,..9) = estimated coefficients.

The function can be estimated through regression method based on a number of simulations on the inputs.

Salinity effect on crop production

The salinity effect on crop production can be explained by the increase in the energy required by the plant to acquire water from the soil and to take make the biochemical adjustment necessary for crop growth under stress (Yaron and Frenkel, 1994). Maas and Hoffman (1977) expressed crop tolerance to salinity in terms of relative yield (*YR*), threshold (*S'*), and percentage decrement value per unit increase of salinity in excessive of the threshold (*B*), as follows:

$$YR = \frac{YA}{YM} = 100 - B \cdot \left(Se - S'\right) \qquad (3\text{-}7)$$

where, *Se* is the average seasonal root zone salinity, expressed in electrical conductivity of saturated soil extract (in dS/m). Figure 3.4 from Mass and Hoffman shows a representative yield-salinity curve.

The tolerance to salinity varies from species to species, and among crop development stages. During emergence and the early stages of growth, the tolerance limits are more restrictive. The tolerance is also affected by climatic conditions and soil fertility.

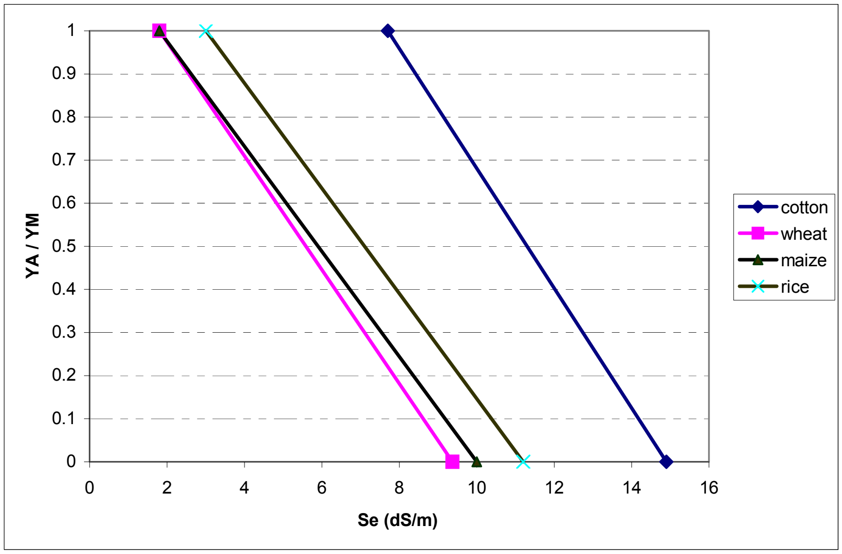


Figure 3. 4. Representative crop yield – salinity relations
(after Maas and Hoffman, 1977)

3.2.4 Economics of water management

Economists consider *prices*, *permits*, *rights*, and *markets* as a means to improve water allocation and water quality in an economically efficient way (Easter et. al., 1997). A given allocation of resources is said to be *economically efficient* if and only if no individual could be made better off without making someone else worse off (Pareto optimality). Apart from prices, permits and rights are alternatives for efficient water allocation and pollution control. Permits are used to control pollution, and substantial interest has arisen in the concept of transferable, marketable pollution permits. Water rights can be defined in terms of a share of an uncertain streamflow, or a share of an aquifer or reservoir, and these rights can be granted as either the actual water right (ownership) or as a use right (the case in the western United States).

In an irrigation-dominated river basin, the non-point pollution produced from irrigated fields has been the focus of several studies. Griffin and Bromley (1982) identified four types of policies that could be used to regulate nonpoint-source pollution. These are nonpoint incentives, nonpoint standards, management practice incentives, and management practice standards. Nonpoint incentives place a tax on estimated emissions from individual firms, whereas nonpoint standards limit the total emissions from each firm. Management practice incentives impose a system of taxes and subsidies on inputs to the production process, while management practice standards specify the actual input levels to be used. Examples for applying these policies include: Howe and Orr (1974), putting penalty cost to tons of salt load; Scherer (1977), placing an offer for leaving water in a diluting bank; and Dinar and Letey (1996), imposing a tax on the volume of drainage.

Based on the development of a water rights system, water can be allocated through trading water rights among users in markets. The market approach may offer a number of potential advantages, including flexibility in responding to change in water value; empowerment of water users by requiring consent to any reallocation of water and compensation for any water transferred; security of water rights tenure, which improves incentives for investment in water-saving technology; establishment of incentives for water users to consider the full opportunity cost of water, including its value in alternative uses; and reducing the pressure to degrade resources (Howe et al., 1986; Rosegrant and Binswanger, 1994). However, a number of possible problems are also identified (Howe et al., 1986): the "third-party" effects from externalities, obstacles to communication among potential buyers and sellers that result from wide geographic separation; and understating the value of instream flows. To strengthen these weaknesses of water markets, Howe et al. (1986) argued that a complete water right should be defined, which not only covered water quantity aspects (quantity diverted and consumed, timing, and places of diversion and application), but also included a description of the water quality. In this way, a water right entitles the owner to a certain quantity of water of a quality at a standard, and at specified periods. Integrated hydrologic-economic modeling will be helpful to define this complete water right for water markets.

Rosegrant and Meinzen-Dick (1996) identify some economic concepts and issues that need to be examined through integrated economic-hydrologic river basin modeling, including *Transaction Costs, Agricultural Productivity Effects, Intersectoral Water Allocation, Environmental Impacts, and Property Rights in Water.* For transaction costs, institutional mechanisms that are most effective in minimizing the associated costs should be studied. Impacts of alternative water allocation mechanisms should be evaluated with concerns on farmer water use, choice of inputs, investments, productivity of water, agricultural production and income in different agroeconomic and scarcity environments. Tradeoff between agriculture and non-agriculture water use should analyze for intersectoral water allocation, and allocative mechanisms and associated institutions are important to eliminate the conflicts in water use between sectors. To develop the relationship between allocation mechanisms and environmental externalities caused by water uses is an urgent task to capture environmental impacts, and so is to design appropriate economic incentives and institutional directives to prevent environment reduction caused by water uses. Finally, setting up appropriate property rights in water is important in the actual implementation of allocation mechanisms, especially for the purpose of equity.

3.2.5 Integrated hydrologic -economic models

Integrated hydrologic-economic models combine hydrologic components and economic incentives either in one consistent model or through a connection between these two components. There are two approaches to combine these two components. One is referred to as the "compartment modeling" approach, and the main question is which mathematical formats are available to transform information between the hydrologic model and the economic model. The other approach is often called "holistic modeling", in which the models are typically built as one consistent model, instead of being put together from separate, mono-disciplinary sub-models. To use the holistic approach, the modelers have to use one single technique (simulation, dynamic programming etc.) and use a single denominator for the variable quantities.

In integrated hydrologic-economic models, the operation of hydrologic systems is driven by a socio-economic objective (or multiple objectives including socio-economic and environmental objectives), while economic incentives are conducted on the physical system which is simulated by hydrologic components. 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.

More recently, Lefkoff and Gorelick (1990a) reported another research using the "compartment modeling" approach. Distributed parameter simulation of stream-aquifer interactions, water salinity changes, and empirical 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 and economic components remains a technical obstacle in the "compartment modeling" approach, while in the "holistic modeling" approach, 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 was built on the optimization model of market transfer exemplified by Vaux and Howitt (1984), and extensions were made on both 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 demand site nodes; on the demand site, both offstream (irrigation, municipal, and thermal energy) and instream (hydropower and water quality) uses were represented by empirical marginal benefit functions. This 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.

3.2.6 Technical aspect of integrated hydrologic-economic modeling

A comprehensive discussion about the technical aspects of economic-ecological modeling was given by Braat and Lierop (1987). The following discussion heavily depends on their work.

The modeled relationships in the integrated hydrologic-economic model should not only reflect the structure or function of the real-world relationships but also allow for effective transfer of information from one component to the other. Hydrologic models are mostly built for simulation experiments, while a majority of the economic ones use optimization techniques. These two kinds of models may be conducted in different spatial scales and temporal scales, and their requirements of data may be different too. These differences often bring difficulties in transferring information between the hydrologic and the economic component.

In spatial aspects, the boundaries of the economic system considered in a resources problem analysis may not a priori be the same as those of the hydrologic system. In economic models we generally have to consider the political and administrative boundaries, and in hydrologic models we generally consider watershed boundaries. Another kind of problem is that the two models may have different spatial development horizons, which refer to the area (or volume) over which impacts and development extend, as well as the area (or volume) over which the model can be validated.

The temporal aspects relate to two problems: different time intervals and different time horizon used in hydrologic models and economic models. Economic models generally use larger time intervals (seasonal or annual) and longer time horizon (e.g. in long-term forecast), while, in hydrologic models, the time interval should be small enough to reflect the real-world processes, and the time horizon often can not be too long due to the computation capacity and data availability.

Data requirements relate to type of data and level of aggregation. Mixed types of data, including experiment data, statistical data, and empirically estimated data, are used in multidisciplinary models, and data desired and available may differ as to their temporal and spatial resolution.

For the two approaches to develop an integrated river basin model, 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 transform between the components. For the "holistic modeling", modeling components are tightly connected in one consistent model, instead of being put together from separate, and thus no problem with information transform, but less complexity should be enclosed, otherwise, it will be very different, if not possible, to solve the model.

3.3 DEVELOPING MODELS FOR SUSTAINABILITY ANALYSIS - RESEARCH NEEDS

White (1969) argued water resources management strategies could be addressed according the following questions: who makes what choices (how decisions are made)? What is the effect upon the public welfare and what is the effect upon the natural environment (consequences of the choice)? For sustainable water resources management, we may need to ask two more questions: what is the interrelation between the effect upon the public welfare the effect upon the natural environment? How does this interrelation evolve with time, subject to the changes and uncertainties in the future? Integrated hydrologic-agronomic-economic-institutional models will provide a comprehensive framework to analyze these questions for river basins where irrigation dominates the water use.

In an integrated model built at a river-basin level, water management and policy solutions must be tailored to specific regions or districts, because of differences in institutional capabilities, irrigation and urban water supply infrastructure, the structure of agriculture, and the degree of water scarcity. Moreover, because of the increasing competition for water resources, water use will include not only offstream consumption of water in agricultural, municipal and industrial production, but also instream non-consumptive water use such as hydropower, ecological maintenance, and recreational purpose.

The outcomes of water use will be examined in terms of efficiency, equity, and environmental impact. Over time, these outcomes may change with climate and hydrologic fluctuations, man-made events such as flow regulation and pollutant discharges, technological change, institutional change, and other social and economic uncertainties and changes. The water policy research should seek to address these issues in ways that are directly relevant to water management authorities and policymakers in choosing appropriate water policies and establishing priorities for reform of institutions and incentives that affect water uses.

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. To accomplish this, it is possible to develop an analytical modeling framework based on several elements as below: (1) a necessary unit for the 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 only be traced along the entire basin; (3) increased attention on environmental impacts of anthropogenic interventions that can only be managed at a basin scale, and (4) a necessary unit to trace the complex relationships and implications of water allocation mechanisms and policies on economic efficiency.

Such as a modeling framework can be applied to river basins with arid or semi-arid climates and irrigation-dominated water supply, and where salinity control is a major water quality and environmental problem. The components of an prototype model will include (1) the hydrological components, which account for flow and pollutant transport and balance in the river basin network which is extended to include crop root zone, (2) crop production functions of both water stress and soil salinity, and benefit functions for instream-water uses (3) irrigation and drainage management, (4) institutional rules and policies that govern water allocation; and (5) economic incentives for salinity control, water conservation and irrigation system improvement. The analytical issues based on the output of the model will then concentrate on searching management policies and rules to sustain growth in irrigated agricultural production, to satisfy growing municipal and industrial water demands, and to reverse the ongoing degradation of the water and soil resources systems.

3.4 A PROTOTYPE MODEL

3.4.1 Introduction

Referring to the schematic diagram of an integral river basin system shown in Figure 3.1, the essential relations within each component and the interrelations between these components are included in a prototype model developed in this research.

The water users system is differentiated into agricultural demand sites and industrial and municipal demand sites. However, the emphasis in this research will be put on agricultural demand sites. We model each agricultural demand site as a *farm*, and within each farm, a number of *areas with specific soil types* will be identified. An area can have several *crop fields*, corresponding to specific crop patterns. Therefore, the modeling framework has a hierarchical structure of combined macro and micro levels including the *region, farm, area with a specific soil type,* and the *crop field* (Figure 3.5 and Figure 3.6). The regional level is used for hydrologic systems operation and water allocation among demand sites (cities and farms) possibly under conditions of maximizing social benefit in the whole region of a river basin. At the farm level, water is allocated to areas with specific soil types, and the efficiency of water distribution and drainage in each farm is to be planned. Crop acreage and water allocations among crops are determined at the soil area level. Finally, water mixing for irrigation, irrigation scheduling among growing stages and the type of irrigation technology are determined at the crop field level. The relations of these decisions with institutional regulations and economic incentives are referred to Figure 3.2.

Three components are included in the modeling framework: (1) hydrologic components, including water and salt balance in reservoirs, river reaches, aquifers, and root zones. Deep percolation, stream-aquifer interaction, surface drainage and subsurface drainage, soil salt accumulation, and return flow will be calculated explicitly; (2) agronomic components, including crop yield response with both irrigation water quantity and salinity in soil and in irrigation water, and crop acreage allocation; (3) economic components, including benefit and cost calculation and tax/subsidy systems. A short-term model (also called yearly model in the long-term framework) includes all these components in a one-year time horizon with 12 modeling periods (months). The long-term model extends the yearly model to multiple years, and includes changes and uncertainties in both water supply and demand.

In the rest of this chapter, the essential hydrologic, agronomic and economic relationships, as well as the formulation of the objective function of the model are first described, and generic analysis of the river basin network based water allocation system is presented.

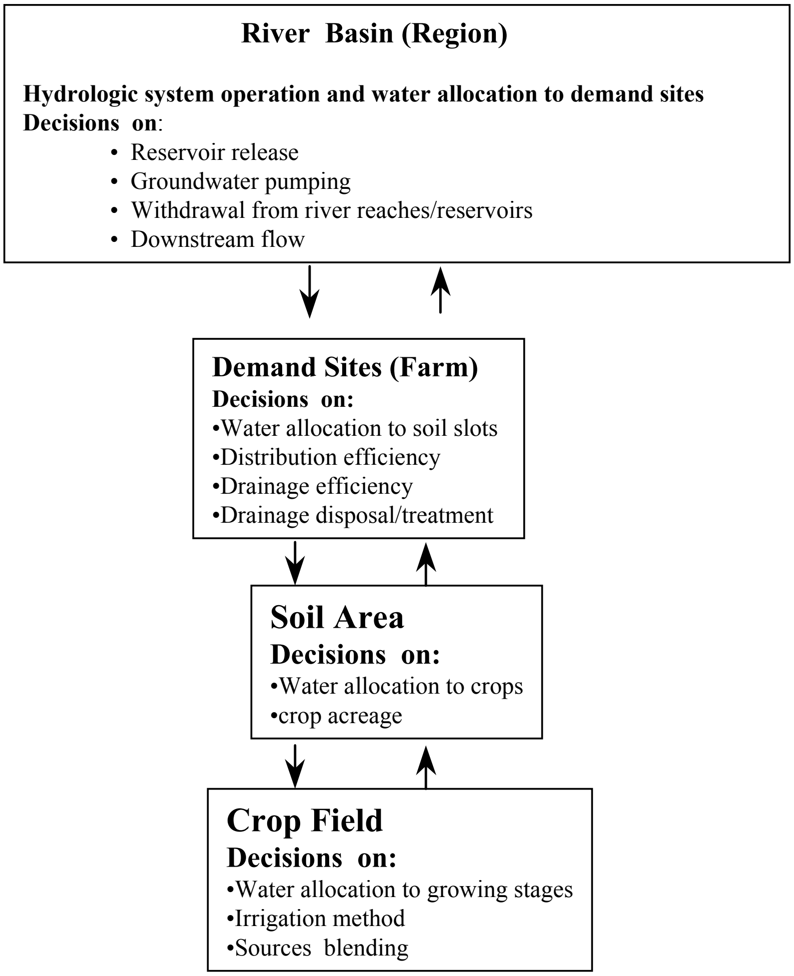


Figure 3. 5. Hierarchical structure of a multi-level irrigation management model.

3.4.2 Institutional assumptions

Optimal water management must be consistent with specified institutions. Brown et al (1982) recognized four social values embodied in water institutions: economic improvement, environmental preservation, maintenance of agricultural lifestyle, and equitable access to water. Young (1996) pointed out that the individually rational resource use might not be optimal when considered from the perspective of society, if institutions are inadequate in the water use framework. Gardner et al. (1990) encouraged a collective management of a 'common pool resource' like water, which has many appropriators or users. Each individual user may only reach sub-optimal outcomes, while a collective institution is needed to catch a global optimality. In this research, we assume that there is such a central authority in the river basin who can make decisions for the operation of the river basin system, standing on the overall socio-economic and environmental benefits in the region of the river basin. Some economic incentives that are active within the proposed institution will be discussed later in the section on economic considerations.

3.4.3 Hydrologic processes

Hydrologic processes include flow and salt balance in reservoirs, river reaches, aquifers, and root zones, and flow and salt transport between these entities. The general mass balance equations are referred to Mays and Tung (1992) and Loucks (1996). Some of the processes specifically related to irrigation and drainage activities are described in this section, as well as the associated assumptions. Before that we define some items that build connections between hydrologic processes and anthropogenic controls, including irrigation and drainage technologies. Some indices commonly used in the following equations are:

t: time periods (months),

y: years,

st: crop growth stages, $st \subset t$,

dm: demand sites,

riv: river reaches,

rev: reservoirs,

gw: aquifers,

n : water supply or demand nodes in the river basin network, *n* ={*riv, rev, gw, dm*}, Further, *n1* represents a from-node, and *n2* represents a to-node. (*n1, n*) represents all links from *n1* to n, and (*n, n2*) represents all links from n to *n2*.

sa: areas with specific soil types,

fd: crop fields, and

cp: crop patterns. It is assumed that each crop field has a single crop pattern, and *fd* and *cp* has the one-to-one relation. For example, in a field, spring wheat (growth stages from Jan. to Jun.) is planted, and then late maize (growth stages from Aug. to Nov.) may be planted in the same field.

Delivery and distribution efficiency (*EDS*), which is defined as the ratio of the water arriving at the crops fields to the total water diverted:

$$EDS_{dm} = \frac{WDA_{dm}^{t}}{WD_{dm}^{t}} \tag{3-8}$$

where,

WDA : diverted water available for use in demand site (eq. 3-17), and

WD : total water diversion from rivers and reservoirs, including local sources.

EDS depends on the condition of the canal lining. Here we assume even *EDS* within a demand site, but it can vary among demand sites.

Irrigation Efficiency *(EIR)*, which is often referred to as application efficiency, is defined as (Clemmens and Dedrick, 1994):

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

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 crop field, and (2) *EIR* is the same over all growth stages. The first assumption may be only reasonable for large crop fields in arid or semi-arid area, and the second applies for the average condition of large crop fields. With these assumptions, *EIR* is calculated as:

$$EIR_{dm,sa,fd} = \frac{\sum_{t \in growth\ stages} WEU^{t}_{dm,sa,fd}}{\sum_{t \in growth\ stages} WAF^{t}_{dm,sa,fd}} \tag{3-9}$$

where,

WEU : water effectively used by crops (equation 3-19), and

WAF : total water applied to crop fields.

WAF includes diversion, local surface source, groundwater pumping, and drainage reuse (eq. 3-19). It should be noted that *EIR* is a measure of the performance of the conventional irrigation systems, and it is not related to runoff irrigation by rainfall. Therefore, neither *WEU* nor *WAF* includes rainfall.

Drainage efficiency (*EDN*) is defined as the ratio of drainage over percolation from the root zone,

$$EDN_{dm} = \frac{\sum_{t}\sum_{sa}\sum_{fd} DN^{t}_{dm,sa,fd}}{\sum_{t}\sum_{sa}\sum_{fd} PN^{t}_{dm,sa,fd}} \tag{3-10}$$

where,

DN : drainage from a crop field, including surface drainage and subsurface drainage, and

PN : percolation in a crop field, the amount of water leaving root zones to downward soil layers.

Part of the percolation is drained, and the rest, which is called *deep percolation (DP),* enters the groundwater.

$$PN^{t}_{dm,sa,fd} = DN^{t}_{dm,sa,fd} + DP^{t}_{dm,sa,fd} \tag{3-11}$$

An even *EDN* is assumed for one demand site and over all time periods.

Drainage disposal/treatment ratio (*EDP*) is the ratio the magnitude of drainage disposal and treatment to drainage at each demand site,

$$EDP_{dm} = \frac{\sum_{t} DT^{t}_{dm}}{\sum_{t}\sum_{sl}\sum_{fd} DN^{t}_{dm,sa,fd}} \tag{3-12}$$

where *DT* is the amount of drainage disposed (in an evaporation pond) or treated at a demand site.

The four items defined above relate anthropogenic controls to hydrologic processes. Delivery and distribution efficiency (*EDS*), irrigation efficiency (*EIR*), and the drainage disposal and treatment ratio (*EDN*) are all determined in the model. The decisions on these variables are induced by irrigation profit, as well as management policies for equity and environment protection. They are also constrained by their current conditions, potential improving capacities, and economic efficiency of investment.

3.4.3.1 Water and salinity balances in rivers, reservoirs and aquifers

Water balances in rivers, reservoirs, and aquifers can be simply represented as:

$$\sum_{n1\in(n1,n)} Q_{in}^{t}(n1,n) - \sum_{n2\in(n,n2)} Q_{out}^{t}(n,n2) = ST^{t} - ST^{t-1} \qquad (3\text{-}13)$$

where

Q_{in}: inflow during time period t,

Q_{out}: outflow during time period t,

ST: storage at the end of a time period,

$(n1, n)$: inflow links to node n from node $n1$,

$(n, n2)$: outflow links from node n to node $n2$.

For river reaches, since the time period is one month, the storage effect can be neglected (Loucks, 1996), i. e., $ST^{t} - ST^{t-1} = 0$. The inflow includes (1) flow from upstream river reaches or reservoirs; (2) return flow (eq. 3-31) from demand sites; (3) discharge from aquifers (eq. 3-15); and (4) natural drainage. The outflow includes (1) flow diversion to demand sites; and (2) flow to downstream river reaches or reservoirs; and (3) evaporation loss.

For reservoirs, the inflow comes from (1) upstream reservoirs or river reaches, and (2) natural drainage. The outflow goes to (1) demand sites; (2) downstream rivers or reservoirs; (3) evaporation loss; and (4) seepage to groundwater.

For aquifers, given the inherent complexity of the hydrologic-economic models considered here, we simply use a single-tank model (Bear, 1977) to simulate flow and salt balance in aquifers. Assuming each demand site has one groundwater "tank", the inflow to the tank includes natural recharge (*NR*), artificial recharge (*AR*), surface water leakage (*SL*) and deep percolation (*DP*) (related to drainage efficiency) from irrigation fields, and the outflow includes pumping (*PM*), groundwater extraction to root zones (*GE*) and discharge to surface water systems (*DS*), namely,

$$\Delta t\left[NR + AR + SL + DP - GE - PM - DS\right] = AA \cdot s \cdot \left(\overline{hg}\big|_{t+\Delta t} - \overline{hg}\big|_{t}\right) \qquad (3\text{-}14)$$

in which *AA* is the horizontal area of the aquifer, *s* is the aquifer storativity, and *hg* is the average water table elevation in the cell.

A linear relationship is assumed between the discharge *DS,* and the water table head *hg* (Smedema and Rycroft, 1983),

$$DS = \eta \cdot hg \qquad (3\text{-}15)$$

where the water table (*hg*) is a state variable in the model, and η is a coefficient to be calibrated by local experiments.

It is assumed that the groundwater table should not be above a critical threshold. The critical groundwater table mostly depends on the rooting depth of the crop, the efficiency of irrigation water use and on the hydraulic characteristics of the soil. This assumption drives sufficient field drainage so as to prevent waterlogging in crop fields.

The salinity balances in river reaches, reservoirs, and aquifers are based on the flow balances in each of these entities, which can be simply expressed as:

$$\sum_{n1\in(n1,n)} Q_{in}^{t}(n1,n)\cdot C^{t}(n1) - \sum_{n2\in(n,n2)} Q_{out}^{t}(n,n2)\cdot C^{t}(n) = S^{t}\cdot C^{t} - S^{t-1}\cdot C^{t-1} \qquad (3\text{-}16)$$

where C is the salt concentration with various flows.

For long-term assessment of groundwater salinity change, solute transport simulation is necessary. Ahlfeld et al. (1988) and other researchers directly incorporated distributed parameter numerical simulations of solute transport into a nonlinear optimization problem. Alley (1986) and Lefkoff and Gorelick (1990a) developed regression equations to predict changes in groundwater salinity as a function of hydrologic conditions and water use decisions, by using Monte Carlo techniques. However, we simply use equation 3-18 for groundwater salinity computation, which still makes sense for the basin-wide integrated model developed in this research.

3.4.3.2 Water allocation within a demand site

Within a demand site, water delivered from reservoirs, diverted from rivers, and local sources are mixed, and then allocated to areas with different soil types. Within each area, water is allocated to crop fields (Figure 3.6)

$$\left(\sum_{rev} D\_REV_{rev,dm}^{t} + \sum_{riv} D\_RIV_{riv,dm}^{t} + LS_{dm}^{t}\right)\cdot\left(1 - EDS_{dm}\right) = WDA_{dm}^{t} \qquad (3\text{-}17a)$$

$$WDA_{dm}^{t} = \sum_{sa}\sum_{fd} WFLD_{dm,sa,fd}^{t} \qquad (3\text{-}17b)$$

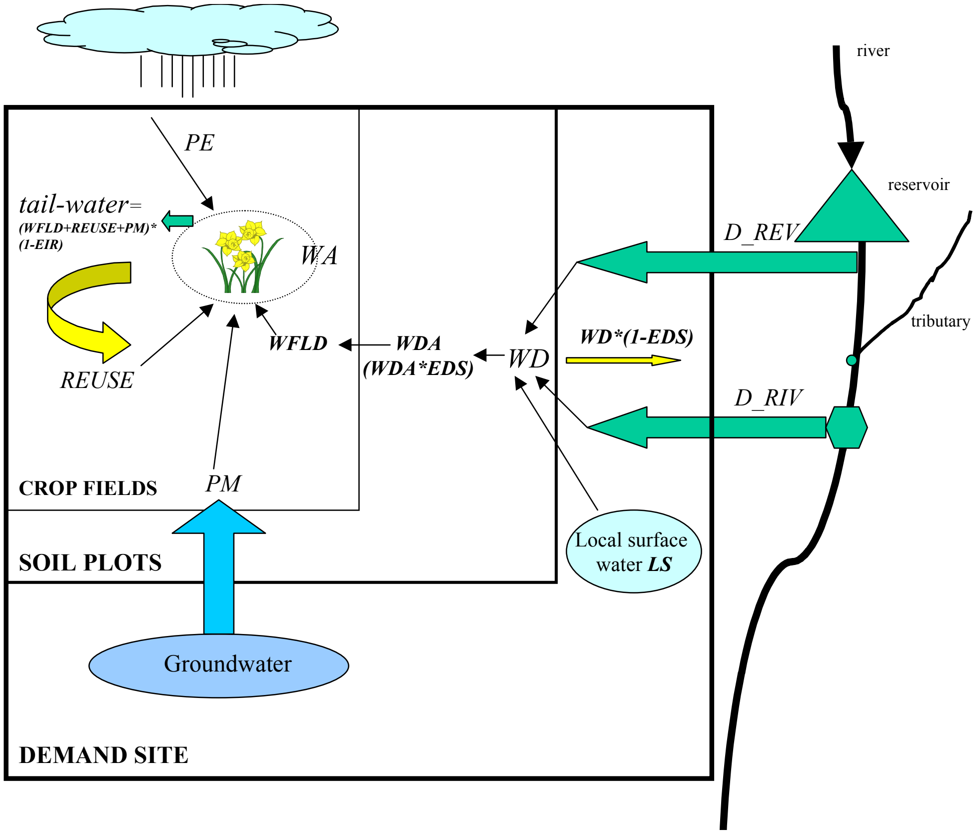


Figure 3. 6. Diagram of water balances in multiple levels

in which,

D_REV : delivery from reservoirs to a demand site [L^3],

D_RIV : diversion from rivers to a demand site [L^3],

LS : local surface water source [L^3],

$WFLD$: surface water allocated to crop fields [L^3].

3.4.3.3 Water available to crops

The total water available to a crop includes irrigation water application and effective rainfall. Since different crops have different salt tolerances, the model allows a crop with a high salt tolerance to use water with high salt concentration. For each crop, we assume that the normal sources, including diversions and local sources, may be blended with local groundwater and reused drainage (Figure 3.6). A highly tolerant crop may reuse a larger amount of drainage.

$$WA^t_{dm,sa,fd} = WEU^t_{dm,sa,fd} + ER^t_{dm,sa} \cdot IA_{dm,sa,fd} \tag{3-18}$$

$$WEU^t_{dm,sa,fd} = (WFLD^t_{dm,sa,fd} + REUSE^t_{dm,sa,fd} + PM^t_{dm,sa,fd}) \cdot EIR_{dm,sa,fd} \tag{3-19}$$

in which,

WA : water available to a crop [L^3],

$REUSE$: drainage reuse [L^3],

PM : groundwater pumped [L^3],

ER : effective rainfall [L], and

IA : irrigated area [L^2].

Effective rainfall *ER* is the rainfall infiltrated into the root zone and available for crop use. *ER* depends on total rainfall (*TR*), soil moisture content (*Z*), reference crop evapotranspiration (ET_0), and soil characteristics (hydraulic conductivity K, moisture content at field capacity Z_s , etc). ER can be estimated by the evapotranspiration/precipitation ratio method (USDA, 1969). Given total rainfall (TR), ET_0 and soil characteristics, an empirical relationship between ER and Z can be developed as:

$$ER^{t}_{dm,sa,fd} = f(Z^{t}_{dm,sa,fd} \mid TR^{t}_{dm}, ET^{\ t}_{0dm}, K_{dm,sa}, Zs_{dm,sa} ...) \tag{3-20}$$

3.4.3.4 Flow and salt balance in the root zone

Soil water balance in the root zone is expressed as (see Figure 3.7):

$$\begin{aligned} RD^{t}_{sa} \cdot (Z^{t}_{dm,sa,fd} - Z^{t-1}_{dm,sa,fd}) = {} & WAF^{t}_{dm,sa,fd} / AF_{dm,sa,fd} + IR^{t}_{dm,sa,fd} \\ & + GE^{t}_{dm,sa,fd} - ETA^{t}_{dm,sa,fd} - PN^{t}_{dm,sa,fd} \end{aligned} \tag{3-21}$$

in which,

RD : root zone depth [L],

Z : soil moisture content in root zone in percentage,

GE : groundwater extraction by absorption [L] (eq. 3-11),

ETA : actual evapotranspiration [L] (eq. 3-25),

IR : infiltrated precipitation [L].

and all other items have been defined before.

By the definitions of EIR and ER, we can split equation 3-21 into the following two equations:

$$RD^{t}_{sa} \cdot (Z^{t}_{dm,sa,fd} - Z^{t-1}_{dm,sa,fd}) + ETA^{t}_{dm,sa,fd} = \\ WA^{t}_{dm,sa,fd} / AF_{dm,sa,fd} + ER^{t}_{dm,sa,fd} + GE^{t}_{dm,sa,fd} \tag{3-22}$$

$$PN^{t}_{dm,sa,fd} = \left(WAF^{t}_{dm,sa,fd} / AF_{dm,sa,fd}\right) \cdot (1 - EIR_{dm,sa,fd}) \\ + IR^{t}_{dm,sa,fd} - ER^{t}_{dm,sa,fd} \tag{3-23}$$

where equation 3-22 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 equal to the sum of irrigation water application, precipitation, and groundwater extraction that are effectively used for crop growth. Percolation is defined as the movement of water to a depth that is inaccessible to plant roots. Equation 3-23 shows percolation from the crop field includes excessive irrigation water and excessive water from infiltrated precipitation. If we assume the infiltrated precipitation (*IR*) can all be effectively used by crops, then the last two items in equation 3-23 can be dropped.

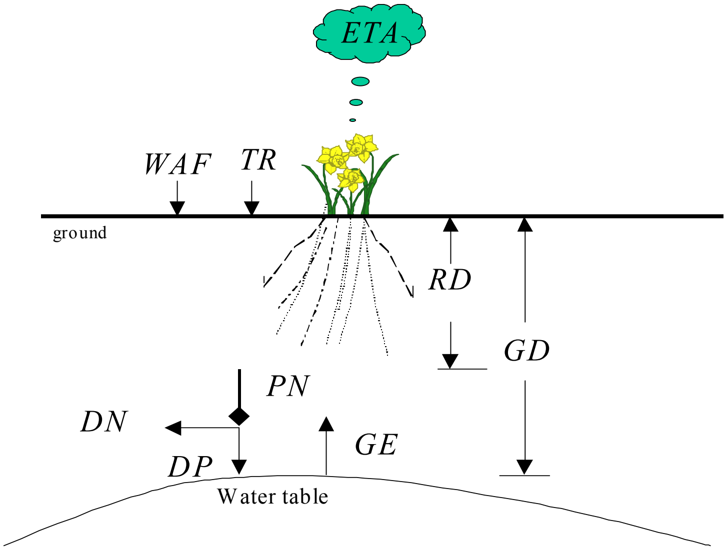


Figure 3. 7. Diagram of water balance in root zones.

Assuming no large change in the water table, the monthly upward movement of water from the water table (*GE*) can be calculated based on the equation given by Eagleson (1978):

$$GE^{t}_{dm,sa,fd} = K_{dm,sa}\left[1+\frac{1.5}{m_{dm,sa}\cdot c_{dm,sa}-1}\right]\cdot\left[\frac{\Phi s_{dm,sa}}{GD^{t}_{dm,sa,fd}}\right]^{m_{dm,sa}\cdot c_{dm,sa}}\cdot\Delta t \qquad (3\text{-}24)$$

where K is the saturated hydraulic conductivity, c is a coefficient taken as 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 Δt is the time duration of one period.

The actual evapotranspiration (*ETA)* is a function of both soil water content (*Z*) and soil salinity (*SS*). The presence of excessive soil salinity leads to a high level of soil osmotic potential (ψ_0, potential due to the presence of solved salts, $\psi_0 = 0$ for pure water). Osmotic potential inhibits the "passive" entry of water into the roots in the same manner as does the soil matric potential (ψ_m, resulting exclusively from the soil matrix, varying with soil water content). We assume that the soil matric potential affects both the bare soil evaporation and plant transpiration, while the soil osmotic potential only reduces the plant transpiration. Another assumption is that the soil water content and the soil salinity have independent effects on crop yield. Based on these assumptions, combining the work of Jensen et al. (1971), Hanks (1985), and Prajamwong et al. (1997), we may write an expression of the actual evapotranspiration as:

$$\begin{aligned} ETA^t_{dm,sa,fd} = {} & ET0^t_{dm} \cdot [(1 - ks^t_{dm,sa,fd}) \cdot kat^t_{dm,sa,fd} \cdot kct^t_{sa,fd} \\ & + kap^t_{dm,sa,fd} \cdot (kc^t_{sa,fd} - kct^t_{sa,fd})] \end{aligned} \tag{3-25}$$

where,

ks : coefficient of soil salinity effect (eq. 3-26),

k_{at} : coefficient of soil water stress effect for transpiration (eq. 3-27),

k_{ct}: crop transpiration coefficient. According to Hanks (1985), $kct=0$ before crop emergence, and after that, $kct = 0.9 \cdot kc$,

k_{ap} : coefficient of soil water stress effect for soil evaporation (eq. 3-28),

k_c : crop evapotranspiration coefficient (Chow, et. al., 1988).

k_s is estimated based on the yield - seasonal root zone salinity relationship in equation 3-4 as:

$$ks^{t}_{dm,sa,cp} = \begin{cases} 0 \quad if\ Se < S', \\ 1 - \dfrac{YA}{YM} = B_{cp} \cdot \left(Se^{t}_{dm,sa,cp} - S'_{cp}\right)/100 \quad \text{otherwise} \end{cases} \tag{3-26}$$

k_{at} is estimated by the following equation given by Jensen et al. (1971)

$$kat^{t}_{dm,sa,fd} = \ln[100 \cdot (\frac{Z^{t}_{dm,sa,fd} - Zw_{sa}}{Zs_{sa} - Zw_{sa}}) + 1] / \ln(101) \tag{3-27}$$

The following empirical equation (Prajamwong et al., 1997) is used to estimate *kap*:

$$kap^{t}_{dm,sa,fd} = \left[\frac{Z^{t}_{dm,sa,fd} - 0.5 \cdot Zw_{sa}}{Zs_{sa} - 0.5 \cdot Zw_{sa}}\right]^{0.5} \tag{3-28}$$

where,

Zs : saturated soil moisture, and

Zw: soil moisture at the wilting point.

The root zone salt balance equation is based on the following two equations. Assuming no lateral flow in the root zone, Abdel_buyem and Skaggs (1993) gave an equation as:

$$\begin{aligned} PN^{t}_{dm,sa,fd} \cdot ECp^{t}_{dm,sa,fd} &= WAF^{t}_{dm,sa,fd} / AF_{dm,sa,fd} \cdot ECw^{t}_{dm,sa,fd} \\ &+ GE^{t}_{dm,sa,fd} \cdot ECg^{t}_{dm,sa,fd} \\ &- Zs_{sa} \cdot RD^{t}_{fd} \cdot (ECe^{t}_{dm,sa,fd} - ECe^{t-1}_{dm,sa,fd}) \end{aligned} \tag{3-29}$$

where *ECp, ECw, and ECg* are the salinity in the percolation, water application, and groundwater extraction, respectively, expressed as electric conductivity [dS/m = mmhos/cm, $1\, dS/m \approx 700\, mg/l$]; *ECe* represents a salt extract of soil solution made when the soil is at saturation point, expressed as electric conductivity [dS/m].

A salt transport equation is given by Sharply and Williams (1990) as:

$$PN^{t}_{dm,sa,fd} \cdot ECp^{t}_{dm,sa,fd} = Zs_{sa} \cdot RD^{t}_{fd} \cdot (ECe^{t}_{dm,sa,fd} + ECe^{t-1}_{dm,sa,fd}) \cdot \left\{ 1 - \exp[\frac{-PN^{t}_{dm,sa,fd}}{(Zs_{sa} - Zw_{sa}) \cdot RD^{t}_{fd}}] \right\} \tag{3-30}$$

where the left side of the equation represents the salt mass leaving the root zone with the water flow, which should include the surface runoff and the vertical percolation, but it is assumed that no surface runoff in the crop field. The right side represents the salt mass in the root zone multiplied by a discounting factor determined by the amount of the total outflow.

3.4.3.5 Salt transport in irrigated areas

Four phenomena of salt transport in an irrigated area are considered. The first one is the salt accumulation in the root zone due to consumptive crop evapotranspiration; the second phenomenon that may occur in some irrigated areas is the leaching or mining of indigenous salts from the soil. The third process, which is called 'groundwater displacement effect', may occur if an irrigated area is underlain by an aquifer whose chemical composition permits very high leaching by salt pickup (Skogerboe and Walker, 1973). In this case the root zone water percolates through the aquifers, displacing water of salinity perhaps 3 or 4 times that of the root zone drainage. A final consideration that is important in some irrigated areas is the leaking of delivery canals. Some or all of the loss may leave the basin , or it may eventually return to the source river. At one extreme, this loss may percolate into an aquifer and emerge as the same salinity as that of the diversion canal. At the other extreme, it may enter the type of highly saline aquifer described above and displace very salty water to the river. In any event, lining the canal can essentially eliminate the effect of the leakage.

3.4.3.6 Return flow

Control of irrigation return flow is necessary for maintaining water quality in a river system. Estimation of return flow is critical to the economic evaluation of externalities from irrigation water use. Generally, the irrigation return flow contains more salt than the water diverted from a river system, but the quantity is less than the primary diversion. Therefore, the return flow can bring high salt concentrations to the water in the river system. The irrigation return flow is related to anthropogenic controls including improved distribution efficiency and drainage facility, and enlarged disposal and treatment capacity. Drainage reuse reduces return flow. Return flow from a demand site (*dm*) is the sum of calculated in the model as:

$$\begin{aligned} RF_{dm}^{t} = [\ & NIW_{da}^{t} \cdot \left(1 - cmp_{da}^{t}\right) + \sum_{sa}\sum_{fd} DN_{dm,sa,fd}^{t} + DS_{dm}^{t} \\ & - DT_{dm}^{t} - \sum_{sa}\sum_{fd} RUSE_{dm,sa,fd}^{t}\ ] \cdot \left(1 - rfe_{dm}^{t}\right) \end{aligned} \tag{3-31}$$

where

NIW: non-irrigation water supply,

cmp: consumptive use rate of the non-irrigation water supply,

DS: discharge from the aquifer associated with the demand site (eq. 3-15), *RUSE*: drainge reuse,

rfe: evaporation loss rate of the return flow, and all other items have been defined before.

Salt concentration in the return flow is computed by a salt balance equations including salt mass carried with each item in equation 3-23.

3.4.4 Agronomic relationships

3.4.4.1 Crop production as a function of soil moisture and soil salinity

The yield evapotranspiration relation (equation 3-4) and the yield-salinity relation (equation 3-7) are used to derive a yield - soil moisture - soil salinity relation. Equation 3-4 shows crop yield is a function of actual crop evapotranspiration (ETA), and in equation 3-21 to 3-24, ETA is explicitly expressed as a function of soil moisture and soil salinity. The yield – soil moisture - soil salinity relation can be described by the following generic equations:

$$YA = f_1(ETA) \qquad (= \text{Equation 3-4})$$

$$ETA = f_2(ks, kap, kat) \qquad (= \text{Equation 3-25})$$

$$kap = f_3(z) \qquad (= \text{equation 3-28})$$

$$ks = f_4(s\ ) \qquad (= \text{Equation 3-26})$$

$$kat = f_5(z) \qquad (= \text{Equation 3-27})$$

Equations 3-4 and 3-7 show a linear relation between crop yield and evapotranspiration and soil salinity, respectively. However, the new relation based on these two linear relations is not a simple linear one. For example, Figure 3.8

presents the relative yield of cotton vs. soil moisture under various soil salinity conditions (represented by salinity effecting coefficient, *ks*).

3.4.4.2 Critical crop stage

Critical crop stage is the stage in which the relative crop yield (*YR*) is the minimum among all crop growth stages. To account for water stress and salinity effect in individual crop growth stages (*st*), *YR* is calculated as:

$$YR = \min\left\{ \begin{array}{l} \min\limits_{st}\left[1 - ky^{st} \cdot (1 - CETA^{st} / CETM^{st})\right] \\ 1 - ky^{season} \cdot (ETA^{season} / ETM^{season}) \end{array} \right\} \tag{3-34}$$

where $CETA^{st}$ and $CETM^{st}$ are *cumulative* actual and maximum evapotranspiration in each growth stage, respectively. $CETA^{st} = \sum_{st'}^{st} ETA^{st'}$, and $CETM^{st} = \sum_{st'}^{st} ETM^{st'}$. Finally,

$$YA = YM \cdot YR \tag{3-35}$$

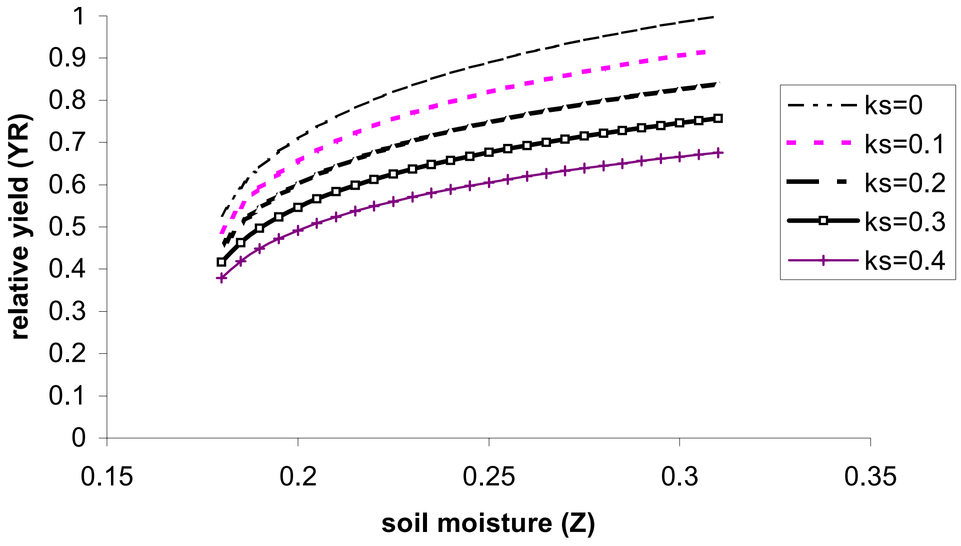


Figure 3. 8. Crop yield vs. soil moisture under various soil salinity

Thus, the crop production function includes the effects of soil water moisture and soil salinity over all crop growth stages, which makes possible to connect the crop production to hydrologic system operation by setting the same manipulating period for crop growth and hydrologic system operation. In the case study of this research, we use month, which is normal for both hydrologic and agronomic system management modeling.

3.4.5 Economic incentives

One of the important purposes in this research is to apply economic incentives to influence hydrologic system operations and water use so as to reach optimal and rational water management. These incentives can enable farms to invest in improved distribution facilities and irrigation technology, pay for the safe disposal of drainage produced on their fields, or divert less water and leave more water in the “dilution bank”. The institutions that allow these incentives to be realized have been discussed before (Section 3.4.2) and they are further stated here: (1) individual demand sites (like firms) obey a central regulatory authority; (2) each of them is assumed to maximize profits subject to regulations and charges imposed by the authority, and (3) the authority owns the right let demand sites to withdraw water or to keep water for instream use.

The economic components included in the modeling framework represent:

- agricultural production as a function of the volume of water beneficially transpired, the soil salinity level that is contributed by both current irrigation and previous salt accumulation in the root zone, and the acreage of irrigated land (eq. 3-25, 3-26, 3-35);
- Municipal and industrial water demand function, and a crop price function (Rosegrant,1997, personal communication) (eq. 3-38 and 3-39);
- infrastructure improvements, as functions of investment on an annualized basis (eq. 3-41 – 44);
- instream water use value from hydropower generation and ecological maintenance (eq. 3-40);
- a tax applied to the excessive salt discharge load to both the surface and ground water system, and a subsidy applied to the improvements of infrastructure. (eq. 3-36, and 3-44); and
- representation of externalities resulted from excessive water diversion and salt discharge by upstream demand sites, producing negative effects to crop production at downstream demand sites. Flow and salt balances through the river basin network with the extension to crop fields provide a basis to analyze the effects (Appendix C).

With these components integrated in the model, the objective of this research is limited to search for optimal management of the river basin, i.e. the objective function is to maximize the overall returns to land and management from all subregions. The maximization of private profit will not be analyzed specifically in this research, however, the equity among the subregions under the overall optimum will be analyzed in the long-term model. Howe and Orr (1974) had similar considerations of economic incentives as those proposed here, but they did not consider any sort of river basin or hydrologic network. This research also builds an analytic framework that represents potential communication among demand sites through an integral river basin network, includes both in-stream and off-stream water uses, and embeds externalities of water allocation at the river basin scale.

Instead of fixed-quantity proposals (prescribed water use rights), in this research, empirical demand functions for individual demand sites are specified, and a hypothetical water market mechanism is used to identify optimal inter-demand site and inter-crop water allocations. Brooke and Young (1994) provided a remarkable example along this line of analysis. This research seeks to extend the work of Brooke and Young (1994) with more detailed hydrologic, agronomic and economic relationships, so that (1) an integral river basin network including surface water, root zone soil water, and groundwater systems, is represented; (2) a production function which considers both water stress and soil salinity explicitly is developed; (3) a more exact expression of externalities is represented through simulating return flow from crop fields and introducing agronomic water-salinity-production functions; (4) irrigation management and planning decisions (water distribution efficiency, drainage facilities, and irrigation technology) are connected to both shot-term and long-term water allocation, (5) tax and subsidy systems are used to induce efficient water allocation, improvement of irrigation-related capacities, and protection of the environment, and (6) sustainability principles are used to account for tradeoffs between short-term and long-term benefits and costs. These sustainability principles have never been included in a model like this before.

Tax and subsidy systems have been popular incentives for resource reservation 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). In this research, we assume that efficient water use is affected by excessive salt discharge; on the other hand, the negative effect might be mitigated by improvements in water distribution capacity, drainage collection and disposal capacity, and irrigation systems. A tax/subsidy system, consistent with this assumption, is implemented in the model so that excessive salt discharge is taxed, and the infrastructure improvements are subsided. The tax on the net salt discharge is the so-called Pigouvian tax. The principle of the Pigouvian tax is that for an optimal policy, the tax on pollution should be equal to the marginal damage due to the pollution (Baumol and Oates, 1992). For simplicity, the tax on salt discharge is set as a parameter in the model, and scenario analysis of this parameter is made for optimal policy analysis. However, for further research, it can be determined endogenously in the model.

A subsidy is imposed on all factors that conserve water and/or reduce production of drainage directly and indirectly, including canal lining, improvement of drainage facilities, and use of advanced irrigation systems. The demand sites in the whole river basin share the subsidy, but the allocation of the subsidy among demand sites, and among these improved facilities is determined by the model so that an efficient allocation of the subsidy will be selected so as to approximate a socially optimal management. Because returns from irrigated agriculture can rarely finance infrastructure development and improvement, generally, the government has to provide the finance source. In this research, we assume the total subsidy is equal to the total tax plus input provided by the central authority, generally funded by the government (see eq. 3-32).

The function of irrigation profit in an individual irrigation demand site is formulated as:

IP (dm) = income from all crops
- *fixed crop cost*
- *groundwater pumping cost*
- *surface water diversion and distribution cost*
- *cost on drainage reuse (not including fixed investment)*
- *cost on drainage pumping (not including fixed investment)*
- *cost on drainage disposal (not including fixed investment)*

$$\begin{aligned} IP_{dm} = & \sum_{sa}\sum_{fd} pcp_{cp\in fd} \cdot YLD_{dm,sa,cp\in fd} \cdot AF_{dm,sa,fd} \\ & -\sum_{sa}\sum_{fd} fc_{dm,sa,fd} \cdot AF_{dm,sa,fd} - \sum_{sp}\sum_{fd}\sum_{t} cg_{dm} \cdot PM^{t}_{dm,sa,fd} \\ & -\sum_{t} cs_{dm} \cdot WD^{t}_{dm} - \sum_{t}\sum_{sa}\sum_{fd} cr_{dm} \cdot RUSE^{t}_{dm,sa,fd} \\ & -\sum_{t} cdn_{dm} \cdot WDN^{t}_{dm} - \sum_{t} cdt_{dm} \cdot WDT^{t}_{dm} \end{aligned} \tag{3-36}$$

where, fc : fixed crop input cost per unit area,

pcp : crop selling price,

cg : groundwater pumping cost,

cr : cost per unit of drainage reuse,

cdt : cost per unit of drainage disposal (not including fixed investments),

cdn : cost per unit of drainage collection (not including fixed investments).

The net revenue (*NREV*) from irrigation at a demand site is equal to the irrigation profit minus the tax on excessive salt discharge:

$$NREV_{dm} = IP_{dm} - tax_{dm} \cdot \sum_{t} MES_{dm}^{t} \qquad (3\text{-}37)$$

where,

tax : tax imposed on excessive salt discharge,

MES : salt mass in return flow in excessive of what was presented in the original diversion, and all other items have been defined before.

Crop prices can be determined through an inverse demand function (or price function, Rosegrant, personal communication, 1997)

$$\ln(pcp_{cp}) = \alpha + \beta \cdot (1/\varepsilon) \cdot \ln(TYLD_{cp}) \qquad (3\text{-}38)$$

where α is the *intercept* calibrated to "normal" production, β is the market share of the commodity, and ε is the price elasticity of demand. The term $1/\varepsilon$ is called the price flexibility coefficient. *TYLD* is the total yield of crop *cp* from all fields at all demand sites in the river basin.

The profit function of municipal and industrial water use (*PTMI*) in one demand site is given as (Rosegrant, personal communication, 1997):

$$PMI_{dm}^{t} = mv_{dm} \cdot \left(1 + \frac{1}{\varepsilon'_{dm}}\right) \cdot NMWD_{dm}^{t} \cdot \left(\frac{WSMI_{dm}^{t}}{NMWD_{dm}^{t}}\right)^{(1+1/\varepsilon'_{dm})} \qquad (3\text{-}39)$$

where, mv : marginal value of water,

ε' : elasticity of demand of water,

$NMWD$: normal demand, which is a function of population and industrial production,

$WSMI$: water supply for municipal and industrial use.

The total water use benefit (*TWB*) in the river basin includes off-stream benefits from irrigation, municipal & industrial water use, and in-stream benefits from power generation (HP) and ecological water use value (*EB*), which is expressed as:

$$\begin{aligned} TWB = &\sum_{dm}\left(PI_{dm} + \sum_{t} PMI_{dm}^{t}\right) \\ &+ \sum_{t}\sum_{st}\left(ppw_{st} - cpw_{st}\right)\cdot PW_{st}^{t} + \sum_{t} veco \cdot WECO^{t} \end{aligned} \tag{3-40}$$

where,

PW : power generation from hydropower station *st* in month *m*,

ppw : power selling price,

cpw : power generation cost,

$WECO$: water for ecological use, and

$veco$: socio-economic value from per unit of ecological water use under the condition of water scarcity.

The annual fixed investments on water delivery, irrigation and drainage, and drainage disposal are calculated as:

$$AINV\_DS_{dm} = inv\_ds_{dm} \cdot \Delta EDS_{dm} \cdot \sum_{t} WD_{dm}^{t} \tag{3-41}$$

$$AINV\_DN_{dm} = inv\_dn_{dm} \cdot \Delta EDN_{dm} \cdot \sum_{t}\sum_{sa}\sum_{fd} PN^{t}_{dm,sa,fd} \tag{3-42}$$

$$AINV\_DP_{dm} = inv\_dp_{dm} \cdot \Delta EDP_{dm} \cdot \sum_{t}\sum_{sa}\sum_{fd} DN^{t}_{dm,sa,fd} \tag{3-43}$$

$$AINV\_IR_{dm,sa,fd} = inv\_ir_{dm} \cdot \sum_{sa}\sum_{fd} \Delta\, EIR^{t}_{dm,sa,fd} \cdot \sum_{t} WFLD^{t}_{dm,sa,fd} \tag{3-44}$$

where,

AINV_DS : annual investment for improving water delivery & distribution systems,

AINV_DN : annual investment for improving drainage collection systems,

AINV_DP : annual investment for improving drainage disposal/treatment systems,

AINV_IR : annual investment for improving irrigation system,

inv_ds : annual investment for per unit of water saving from delivery & distribution systems,

inv_dn : annual investment for increasing one unit of artificial drainage from the drainage collection system,

inv_dp : annual investment for increasing one unit of drainage disposal in the drainage disposal systems,

inv_ir : annual investment for per unit of water saving from irrigation systems.

The total investment within the river basin is limited by total tax income and additional government payment, which is expressed as:

$$\sum_{dm}(AINV\_DS_{dm} + AINV\_DN_{dm} + AINV\_DP_{dm} + AINV\_IR_{dm}) \leq \sum_{dm} TAX_{dm} \cdot MES \cdot (1 + rgp) \tag{3-45}$$

where *rgp* is the ratio of government input to the local input, and all other items are defined as before.

3.5 SUMMARY

The basic components and structure of an integrated hydrologic-agronomic-economic-institutional model at the river basin scale are discussed in this chapter. Beginning with a review of the background for integrated hydrologic-agronomic-economic-institutional modeling at the river basin scale, the essential hydrologic, agronomic, and economic components and the inter-connections between these components are described. The next chapter is to apply this integrated model to the case study area for a one-year short-term analysis in water resources management.

Chapter 4

The Model Applied for Short-Term Analysis

The integrated hydrologic-agronomic-economic-institutional model described in Chapter 3 is applied to the study area, the Syr Darya River basin of Central Asia, for water management analysis within a one-year time horizon. We define the model for this purpose as a *short-term* model. The short-term 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 short-term 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. The decision variables are composed of the following four classes:

- ***Reservoir/aquifer operations,*** including reservoir release and groundwater pumping;
- ***Water uses,*** on-farm water allocation to specific crop fields, drainage reuse, and source blending for various crops;
- ***Infrastructure improvements,*** including improvements to water delivery and distribution efficiency, irrigation efficiency, drainage collection efficiency, and drainage disposal facilities; and
- ***Irrigated area,*** irrigated area for the major crops planted in the study area.

Economic parameters, such as crop prices, water supply price, and tax on salt discharge, and subsidies for infrastructure improvement are all taken in the model as external data. However, scenario analysis on each of these items is conducted to provide information for examining various policies for water resources management at the river basin scale. Further, and tax on salt discharge is used as a decision variable in the long-term model discussed later.

The short-term model is used to study the performance of the complex, integrated hydrologic-agronomic-economic river basin system, and then determine whether this type of model can provide useful information for sustainability analysis and decision-making in water resources management of irrigation-dominated river basins.

In this chapter, data and assumptions are first described, then, in order to verify that the results from the model are reasonable, the results are compared to some published studies. Finally, the analytical issues are discussed to determine the capacity of the model for examining sustainable water resources management at the river basin scale.

4.1 DATA AND ASSUMPTIONS FOR THE CASE STUDY

4.1.1 Hydrologic data and assumptions

As shown in Figure 1.3, the basin-wide node-link network of the study area includes 11 river reaches, 11 reservoirs, 6 aquifers, 5 hydropower stations, and 6 water demand sites, and return-flow linkages between these entities. The model is built on this network and the farm (demand site) – soil plot – crop field concept described in Chapter 3.

The long-term average inflow to rivers and reservoirs is presented in Table 4.1, and the standard deviation of these flows is shown in Table 4.2. Analysis of a long flow record for the primary basin tributaries shows that a log-normal distribution fits the inflow to the basin. Figure 4.1 shows the relative frequency function of the log-inflow to Toktogul Reservoir (the largest reservoir in the basin), calculated from samples and the fitted distribution, respectively. A χ^2 test (Haan, 1977) shows that distribution can not be rejected at the 95% confidence level. Calculation of the relative frequencies is based on 84-year records of the inflow to the Toktogul Reservoir (Gidroproekt, 1976).

The long-term average local source from runoff collection is given in Table 4.3.

Table 4. 1. Long-term average monthly inflow (km^3) to the Syr Darya River basin (Raskin, et al., 1992).

River/ Reserv.	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	***Total***
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	0.932
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	0.041
Aksu_in	0.015	0.015	0.013	0.015	0.018	0.03	0.044	0.026	0.017	0.021	0.016	0.014	0.244
Tok_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	11.441
Kurp_rev	0.015	0.012	0.011	0.016	0.043	0.057	0.07	0.057	0.041	0.035	0.026	0.022	0.405
Sham_rev	0.043	0.052	0.062	0.233	0.369	0.292	0.18	0.1	0.07	0.066	0.064	0.054	1.585
Utch_rev	0.002	0.002	0.006	0.015	0.02	0.014	0.011	0.009	0.004	0.004	0.005	0.004	0.096
Andj_rev	0.183	0.206	0.476	1.206	1.856	1.91	1.534	0.846	0.411	0.387	0.44	0.393	9.848
Chakir_rev	0.254	0.249	0.383	0.999	1.922	2.283	1.955	1.341	0.691	0.45	0.358	0.339	11.224
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	2.344
Total	1.062	1.018	1.567	3.622	6.281	7.47	6.336	4.121	2.202	1.658	1.482	1.341	38.16

Table 4. 2. Standard deviation (km^3) of the monthly inflow to the Syr Darya River basin.

River/Resv.	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Right_in	0.001	0.001	0.003	0.009	0.033	0.037	0.029	0.028	0.014	0.005	0.005	0.003
Shimi_in	0.000	0.000	0.001	0.000	0.000	0.001	0.001	0.001	0.001	0.000	0.001	0.000
Aksu_in	0.001	0.001	0.002	0.002	0.003	0.006	0.009	0.006	0.003	0.003	0.003	0.001
Tokgul_rev	0.059	0.046	0.053	0.231	0.418	0.796	0.682	0.372	0.167	0.091	0.075	0.068
Kurp_rev	0.001	0.001	0.002	0.002	0.008	0.011	0.014	0.013	0.007	0.005	0.004	0.002
Sham_rev	0.002	0.004	0.010	0.030	0.066	0.056	0.037	0.023	0.012	0.009	0.010	0.005
Utch_rev	0.000	0.000	0.001	0.002	0.003	0.003	0.002	0.002	0.001	0.001	0.001	0.000
Andjan_rev	0.009	0.014	0.077	0.154	0.330	0.368	0.313	0.192	0.071	0.051	0.069	0.038
Chakir_rev	0.013	0.017	0.062	0.128	0.341	0.440	0.399	0.304	0.119	0.059	0.056	0.033
Bugun_rev	0.008	0.009	0.029	0.052	0.062	0.061	0.053	0.039	0.018	0.012	0.013	0.008

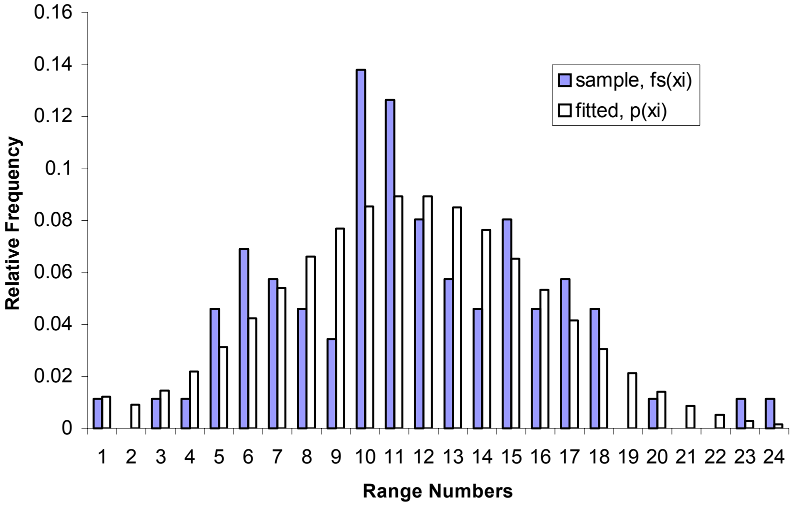


Figure 4. 1 Relative frequency function of the monthly inflow to the Toktogul Reservoir.

Table 4. 3. Average monthly local sources (km^3) (Raskin, et al., 1992).

Demand sites	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Total*
Fergana	0.091	0.075	0.067	0.099	0.295	0.521	0.763	0.67	0.291	0.168	0.133	0.125	3.298
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	0.071
Low_syd	0.055	0.043	0.085	0.145	0.059	0.018	0.015	0.01	0.007	0.009	0.006	0.008	0.46
Total	0.149	0.12	0.157	0.26	0.369	0.546	0.783	0.683	0.3	0.18	0.144	0.138	3.829

Table 4.4 shows the characteristics of the major reservoirs in the Syr Darya basin. The three reservoirs, Toktogul, Kayrakum, and Chardara, located at upstream, middle-stream, and downstream respectively, are the major reservoirs in this basin.

Table 4. 4. Major water storage facilities of the Syr Darya basin.

Reservoir	*Active storage capacity (km^3)*	*Dead storage capacity (km^3)*
Toktogul	14.0	5.5
Chardara	4.7	1.0
Kayrakum	2.55	1.48
Chakir	2.08	0.35
Andjan	1.64	0.15
Bugun	0.37	0.007
Farhad	0.30	0.15
Kassan	0.25	0.02
Kurpskaya	0.029	0.341
Utchkurgan	0.012	0.04
Tashkumur	0.006	0.134
Shamdalsai	0.005	0.039

Hydropower stations are associated with five upstream reservoirs, Toktogul, Utchkurgan, Kurpskaya, Tashkumur, and Shamdalsai. The characteristics of these stations are presented in Table 4.5. Currently the Toktogul hydropower station is the largest one. The water head for the four reservoirs downstream of Toktogul is kept constant throughout each year, and hydropower generation for these stations only depends on the inflow to these reservoirs (McKinney and Cai, 1997).

Table 4. 5. Hydropower Station Data for the Syr Darya River Basin.

Station	Production capacity (MW)	Efficiency (%)	Maximum pool elevation (m)	Tailwater elevation (m)	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

Few data related to the aquifers in the study area were available for this research. Assuming each demand site has a single aquifer, all water distribution losses and deep percolation occurring at a demand site are assumed to go to the aquifer associated with the demand site. Pumping from an aquifer is limited by the pumping capacity. Table 4.6 gives, for each demand site, the pumping capacity in 1987 (Raskin, et al., 1992), water table depth (EC, 1995), estimated surface area and yield coefficient, and estimated ratio of aquifer discharge to water table ($\eta = q/h$, eq. 3-28).

As discussed in Section 3.4.3.6, η 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 (EC, 1995).

Table 4. 6. Aquifer characteristics.

Aquifers with demand sites	Pumping capacity (10^9 m^3)	Water table depth (m)	Surface area (1000 ha)	Yield coefficient	Initial salt conc. (g/l)	$\eta = q / h$ (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

Following Raskin, et al. (1992), 6 demand sites are located according to the geographic, climatic and political conditions. Table 4.7 shows the monthly average reference evapotranspiration (ET_0); Table 4.8 gives the monthly average precipitation (estimated according to EC, 1995), and Table 4.9 presents the standard deviation of the monthly average precipitation. Analysis of long precipitation records in the study area shows that a normal distribution fits the monthly average precipitation . Figure 4.2 shows the fitted relative frequency vs. relative frequency calculated from samples of precipitation data. Calculation of the relative frequencies is based on 92-year records of the precipitation observed at station Lenin at the middle stream of the Syr Darya River basin.

Table 4. 7. Monthly average reference evapotranspiration (ET_0, in mm) (EC, 1995).

Demand sites	*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 4. 8. Long-term monthly average precipitation (TR in mm) (World Bank, 1996).

Demand sites	*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 4. 9. Standard deviation of monthly average precipitation (mm) (World Bank, 1996).

Demand site	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Fergana	3.7	3.9	6.2	4.6	4.9	4.8	4	2	1	4.6	5.3	3.4
Low_syd	3.8	4.7	7.1	8.5	6.2	2.3	2	1.2	2	5.1	5.4	5.8
Mid_syd	6.8	6.4	11	10	7.1	2.2	4	0.5	1.3	8.4	7.7	6.7
Artur	3.4	4.3	5.8	7.1	5.5	2.1	2	1	1.7	4.4	4.7	4.7
Chakir	3.2	4.5	4.8	4.4	3.8	2.7	2	1.2	1.2	4	5.8	4.6
Naryn	3.9	3.7	5.4	5.5	3.9	3.5	3	6.6	2.8	4.2	4.8	4.3

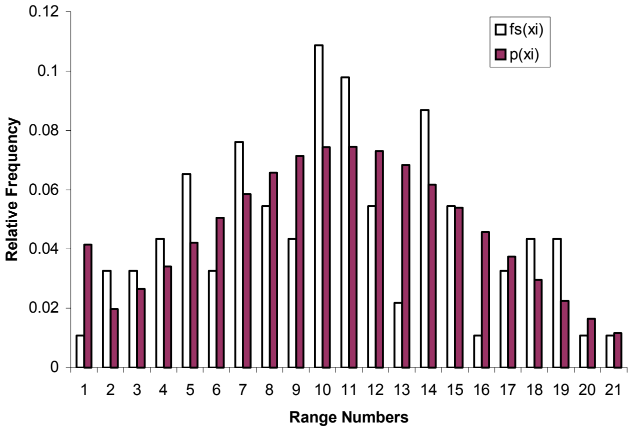


Figure 4. 2. Relative frequency function of the monthly precipitation at middle stream of the Syr Darya River basin.

Three soil types, sandy clay (*scl*), loam (*l*), and sandy loam (*sl*) are classified for each demand site. The available irrigated area with the soil types in each demand site is shown in Table 4.10, which is based on a soil distribution study by EC (1995). The physical characteristics of the three soil types are shown in Table 4.11, which are estimated based on Eagleson (1978).

Table 4. 10. Available irrigated area (1000 ha.) with soil types.

Demand sites	*Sand clay(scl)*	*Loam (l)*	*Sand loam(sl)*	**Total**
Fergana	190.0	855.0	255.0	1300.0
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
Total	428	1939	895	3262

Table 4. 11. Soil characteristics.

Demand sites	*Pore connectivity index (c)*			*Connectivity and Tortuosity (m)*			*Saturat. matric potential (Φs)*		
	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
Demand sites	*Hydr. conductivity (K in cm/day)*			*Satur. field capacity (Zs)*			*Permanent wilting point (Zw)*		
	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

Salinity in the Syr Darya River increases from upstream to downstream. The ranges in 1987 are upstream: 0.36-0.6 S/dm, mid-stream: 1.40 – 3.01 dS/m, and downstream 2.16 – 2.81 dS/m (EC, 1995).

Soil salinity in the basin demand sites has the similar spatial tendency as salinity in the Syr Darya River. In the upstream demand sites (Naryn and Fergana), the degree of soil salinity is low. At middle stream, the percent of land with moderate salinity (Sodium content, 3-6 me Na in100g soil) is about 30%, and the percent with severe salinity (Sodium content, 6-12 Me Na in100g soil) is about 11%. Downstream, over 50% of the land is has moderate salinity, and over 8% has severe salinity.

4.1.2 Agronomic data and assumptions

Cotton dominates irrigated cropping throughout the basin, with more than 40% of irrigated land planted to cotton. Alfalfa and other forages are second in importance to cotton. The reason for this is the established rotation between cotton and forages, which maintains soil fertility and provides winter-feed for livestock due to food security concerns. Cereal crops have increasingly replaced cotton in the area since the independence of the Central Asian republics in 1991. Of the cereals, the small grains like wheat have shown the greatest increase. In the middle stream and upstream of the basin, the percentage of irrigated land in small grains is over 20%. Maize is one of the crops most likely to be grown from midsummer following winter wheat. Cotton, grains and forages account more than 85% of irrigated cropping except in downstream, where rice occupies more than 15% - 22% of irrigated land. The remainder is a wide variety of fruits and vegetables grown largely for local consumption.

Five crops are considered in the research here: cotton, forage, wheat, maize, alfalfa (perennial forage), and all other crops are grouped into one single crop. 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, namely, *cot-foa* representing cotton and forage, *wht-maz*, representing wheat and maize, *alf_alf*, representing perennial alfalfa, and *oth_oth* representing all other crops. In a soil plot, four types of crop *fields* corresponding to the four crop combinations are defined. Soil water and salinity balance, and crop water application are modeled in each field.

Crop coefficients of evapotranspiration ,k_c, (FAO, 1977) are presented in Table 4.12. The empirical salinity coefficients (Mass and Hoffman, 1979) are shown in Table 4.13. Crop yield response coefficients (FAO, 1977) are shown in Table 4.14, and maximum crop productions (dry matter) are shown in Table 4.15. 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.

Table 4. 12. Crop coefficient of evapotranspiration (k_c).

Crop Fields	*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 4. 13. Empirical salinity coefficients, slope and threshold (Mass and Hoffman, 1979).

Salinity coefficient.	*Cotton*	*Forage*	*Wheat*	*Maize*	*Alfalfa*	*Other*
Slope (*B*)	0.139	0.08	0.132	0.083	0.14	0.095
Threshold (*S'*)	7.7	3	1.8	1.8	2	2.5

Table 4. 14. Crop yield response coefficients (k_y).

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 4. 15. Maximum crop productions (*YM*, dry matter in ton/ha).

Demand sites	*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

4.1.3 Data and assumption about on-farm irrigation and drainage infrastructure

According to the investigation of EC (1995), the average length of canal per hectare of irrigated land in the basin is 33m, which is rather high in view of the large size farms. Three quarters of the canals in the area are unlined; the majority of irrigated land, 56% overall, is served by furrow irrigation, and only 8% of land is under more sophisticated methods such as drip and sprinkler irrigation. Some 70% of irrigated land is artificially drained, about 62% is drained by gravity, with little or no sub-surface drainage. Table 4.16 shows the estimated average water delivery and distribution efficiency and drainage ratio (drained area to total irrigated area) for each demand site. Table 4.17 shows the estimated irrigation application efficiency over all demand sites, soil types, and crop fields. All these efficiencies are based on EC (1995).

Table 4. 16. Estimated Water distribution & delivery efficiency and drainage fraction (base value).

Demand sites	*Water distribution and delivery efficiency (EDS)*	*Drainage efficiency (EDN)*
Low_syd	0.64	0.67
Artur	0.65	0.66
Chakir	0.61	0.72
Mid_syd	0.57	0.5
Naryn	0.59	0.47
Fergana	0.56	0.8
Average	0.60	0.64

Table 4. 17. Estimated irrigation application efficiency (EIR, base value).

Demand site &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
Average	0.53	0.47	0.50	0.58

4.1.4 Economic data and assumptions

The cost of surface water supply (*cs*) is 3-6 $ per 1000 m^3, and groundwater pumping cost (*cg*) is 5-8 $ per 1000 m^3 (EC, 1995), the estimated surface and groundwater prices are presented in table 4.18. Crop fixed cost (*fc*) and crop values (*vc*) are estimated based on the World Bank's Aral Sea Basin study report (World Bank, 1996), which are shown in Table 4.19

Table 4. 18. Surface and groundwater supply cost (*cs* and *cg* in US$/$m^3$).

Items	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 4. 19. Crop prices (*pcp*) and fixed crop planting cost (*fc*).

Items	*cotton*	*Wheat*	*Maize*	*forage*	*alfalfa*	*Other*
Prices (vc in $/ton)	767.5	181.4	140.1	134.6	110.5	240.0
Fixed cost (fc in $ /ha.)	393.3	200.3	287.8	165.1	156.2	350.0

Data for infrastructure investment are estimated based on the EC's report (Annex 4.5, Vol. II, EC, 1995). Table 4.20 shows the annual investment (*ainv_ds*, $/$m^3$) necessary for improving canal lining, which is represented by annual investment for one cubic meter of water saved through the improved system. The annual investment (*ainv_dn*, $/ha) necessary for improving the on-farm drainage system is shown in Table 4.20 too, which is represented by annual investment for one hectare of irrigated land. The annual investment (*ainv_ir*, $/$m^3$) necessary for improving on-farm irrigation methods, for different crop fields, is given in Table

4.21. This item represents the annual investment for one cubic meter of water saved through the improved irrigation system.

Table 4. 20. Annual investment necessary for improved water distribution system and drainage collection system.

Demand Sites	*Water distribution System (ainv_ds, \$/m³)*	*Drainage collection System (ainv_dn, \$/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 4. 21. Annual investment (*ainv_ir*, US\$/m^3) for improved on-farm irrigation systems.

Demand sites	*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

The cost of drainage water reused (*cr*) for irrigation purposes lies within the range of \$54 - 73 per 1000m^3, about ten times of the cost of supplying irrigation water from the river system. Drainage disposal to the desert is a popular method in the study area. The cost for this purpose (*cdt*) is about \$0.1/m^3 (EC, 1995). Average hydropower power generation cost (*cpw*) is estimated as 0.05 \$/kWh, and the economic value of power (*ppw*) is about 0.08 \$/kWh (World Bank, 1996).

Maintaining a required volume of inflow to the Aral Sea, the destination of the Syr Darya River is a main ecological concern in water resources management in the study area. In order to consider the Aral Sea as a separate "user" of water, 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 flows to the sea. The annual inflow to the sea is about 7.0 km^3 in a normal hydrologic year and 10.0 km^3 in a wet year. Anderson (personal contact, 1996) gave an estimation of the economic value of $\$0.1/m^3$ water flowing into the Aral Sea. In this research, we assume an ecological benefit (or damage) expression as:

$$eben = ev \cdot (inflow\text{-}inflow0) \tag{4-1}$$

where

$inflow$: computed annual inflow to the Aral Sea,
$inflow0$: normal annual inflow to the sea by historic records,
ev: economic benefit ($inflow - inflow0 > 0$), or damage ($inflow - inflow0 < 0$), per unit of inflow.

The ecological benefit calculated from equation 4-1 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, this policy-based approach should be verified before it is applied for policy analysis in water resources management in any area.

Municipal and industrial (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 will be satisfied in any analytical cases.

Therefore, the benefit of M&I water supply is assumed to be constant, and it is not included in the objective function of the optimization model. Table 4.22 shows the M&I water demand in 1987(Raskin, et al., 1992).

The penalty tax on excessive salt discharge is initially assumed to be 10$/ton. The model is run under various values of this item so as to search for an appropriate value.

Table 4. 22. Monthly industrial and municipal water demands in 1987 (km^3).

Demand Sites	*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

4.1.5 Data availability and reliability

As stated above, multi-disciplinary data are required for model. The data availability is a critical factor in successfully applying the model. The data for the case study were directly found or estimated from some previous studies (e.g., EC, 1995; World Bank, 1996, Raskin, et al., 1992, etc.), and other related literatures, or calculated based on some intermediate data. However, it is beyond the effort of this research to verify all the data. Therefore, the results presented in this research are limited to demonstrating the kind of information can be derived from the model for decision support in sustainable water resources management. However, the results should not be taken as real solutions to the case study area without further data verification.

For future application of this model in any real study, data reliability will be a great challenge even it is possible to obtain all required data. Hydrologic data should be studied based on extensive historic climatic records (e.g., precipitation, flow, temperature) and appropriate hydrologic modeling (e.g., runoff and inflow, evaporation /evapotranspiration, effective rainfall). Agronomic data such as maximum crop yield, crop evapotranspiration coefficients, crop response coefficients to water stress and soil salinity are mostly based on empirical studies and should be verified for the study area. Economic data such as water value, crop cost and price, infrastructure investment, penalty tax, are related to external economic analysis. Therefore, beyond the model developed in this research, far more work is needed, and without those supporting works, the results from this model may not be applied usefully.

4.2 MODEL VERIFICATION: COMPARE MODEL RESULTS TO OTHER STUDIES

It is beyond the effort of this research to calibrate and verify the model to the study area due to limitations of time and resource (i.e., data) availability. However, in order to check if results from the model are reasonable, we can compare the modeling results to those published in other papers and reports. Raskin et al. (1992) applied a simulation model (Water Evaluation and Planning System, WEAP) to the study area, which presented outputs on water balance in the river basin network and water allocation among the demand sites. (EC, 1995, Vol. II and III) provided some data on flow and salinity balance, crop production, and economic outputs in the study area. Most of WARMAP's data are from field observation, survey, and empirical estimation. Based on these two sources, we can check the results of the model developed in this research.

The base year is selected as 1987, since this is also the base year used in the simulation model of Raskin et al. The WARMAP's outcomes are also around this year. Raskin et al defined 1987 as a wet year for the Syr Darya River basin, and they provided the surface water sources and groundwater availability, as well as agricultural and non-agricultural water demands. The same data was used in the short-term model, and the following tables (Tables 4.23 – 4.30) present the comparisons between the results of this model and those of WEAP and WAR-MAP.

Table 4. 23. Comparison of flow diversions from rivers and reservoirs (km^3).

River & Resv.	*WEAP*	*This model*
Toktogul Resv.	1.83	1.39
Farhad Resv.	12.09	13.60
Kazah gate	7.00	8.10
Andjan Resv.	0.00	6.84
Karadar_in	9.57	1.20
Karadarya total	9.57	8.04
Chakir Resv.	10.76	9.83
Naryn gate	2.56	4.80
Artur gate	1.00	3.34
Bugun Resv.	2.13	0.09
TOTAL	47.00	49.70

Table 4. 24. Comparison of water diversion to demand sites (km^3).

Demand sites	*WEAP*	*This Model*
Naryn	1.83	1.39
Fergana	12.13	13.24
Mid_syd	12.10	13.68
Chakir	10.76	9.83
Artur	3.13	3.45
Low_syd	7.01	8.11
Total	46.95	49.71

The total water application (river diversion, pumping and local surface water) is 57.8 and 60.0 km^3 from WEAP and this model, respectively, and the flow to the Aral Sea is 2.51 and 3.36 km^3, respectively, in the two models. The total drainage is 18.6 km^3 from this model in a normal year, and WARMAP's estimation is 17-19 km^3.

Table 4. 25. Annual salt discharge (million tons).

Ranges	*WARMAP*[1]	*This Model*[2]
Upstream of Kayrakum Reservoir	14	12
Kayrakum to Chardara Reservoirs	10	11
Lower part of Syr Darya	1	1.5
Total	25	24.5

[1] 1983-1990 average;
[2] with tax on salt discharge of 100 US$/ton

Table 4. 26. Comparison of salt concentration (g/l) in drainage (annual average)[*]

Demand sites	*WARMAP1*	*This model*
Naryn	0.35-1.5	1.28
Fergana	1-2.7	1.84
Mid_syd	1.9-5.6	2.78
Chakir	0.35-5.7	1.89
Artur	1.6-4.6	1.49
Low_syd	1.6-4.6	2.55

[*] Toryanikova (1998) showed the salt concentration in drainage as: in upstream river reaches, 1 – 2.68 g/l; in midstream river reaches, 2.0 – 5.6 g/l, and in downstream river reaches, 1.2 – 5.2 g/l.

Table 4. 27. Comparison of salt concentration (g/l) in the Syr Darya River.

Ranges	*WARMAP*	*This model*
upstream	0.3 – 0.5	0.36-0.57
middle	0.9-2.0	0.76-2.14
low	1.4 -1.9	0.89-2.01

Table 4. 28. Comparison of irrigated area (1000 ha).

Demand sites	*WEAP*	*This model*
Naryn	173.1	165.6
Low_syd	445.1	340.8
Artur	173.0	145.5
Chakir	462.0	462.0
Mid_syd	680.0	553.0
Fergana	1365.6	1238.5
TOTAL	3298.8	2905.4

Table 4. 29. Comparison of water use rate (m^3/ha) for selected crops.

Demand Sites	*Cotton and forage*		*Wheat and maize*	
	WEAP[1]	This model[2]	WEAP[1]	This model[2]
Naryn	7542	8550	7008	7700
Low_syd	8653	8150	6960	7400
Artur	7347	8400	5536	7200
Chakir	9443	9850	7756	7700
Mid_syd	10901	9750	11802	8100
Fergana	9485	9850	9040	7700
Average	8895	9092	8017	7633

[1] Estimated from the data used in the WEAP model (Raskin et al., 1992)
[2] and the soil type is *loam*.

From the above comparisons, the results from this model, including flow, salinity distribution, and water use for irrigation are close to those from the other studies. However, from Table 4.23, we see this model results in quite different reservoir operation. For example, this model shows demand site *Fergana* withdraws 6.84 km^3 water from the *Andijan* Reservoir, but the withdrawal was 0 in 1987 from *WEAP* model. This model also shows too much water was applied at the midstream demand site in 1987. Furthermore, the model implicates that perhaps the irrigated area in 1987 should have been reduced by 12% in the basin based on the optimal objective and other all considerations in the model.

The verification of the crop production function is addressed in the following. Based on FAO crop yield-water relationship (see eq. 3-4), crop yield has a linear relation with actual crop evapotranspiration (*ETA*). Running the model under various hydrologic levels, we get a set of values of (*Yield, ETA*). This set of values and those calculated directed from equation (3-4), are plotted in Figure 4.3. The results from the modeling experiments are well fitted with the FAO empirical equation.

However, currently little information is available to check the economic outputs from the model. The feasibility of the economic incentives are need to be verified based on further study.

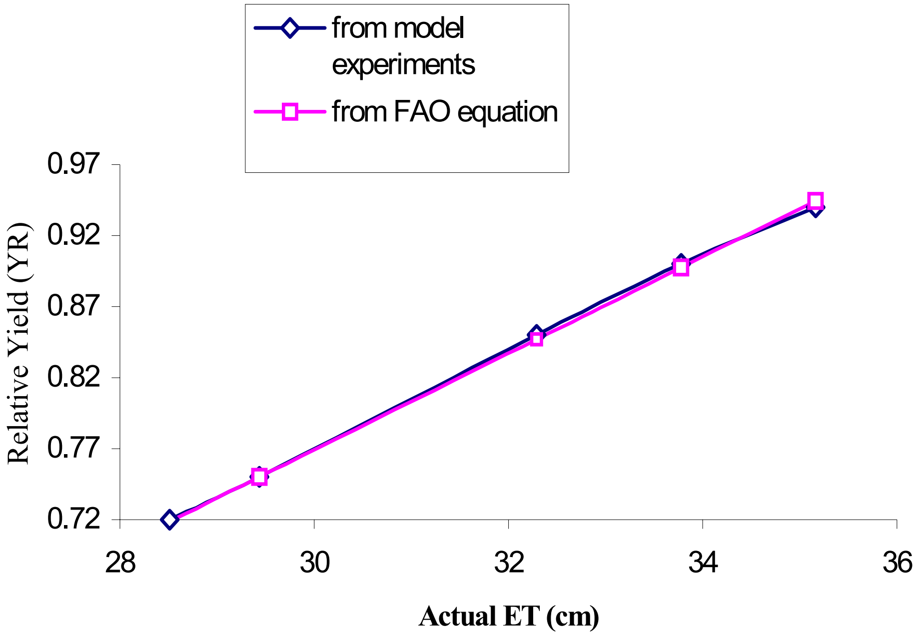


Figure 4. 3. Actual ET vs. relative crop (*wheat*) yield (in demand site *Mid_Syd*, and the soil type is *loam*).

4.3 ANALYTICAL ISSUES OF THE INTEGRATED MODEL

The model output includes values for all state variables, process variables, and decision variables described at the beginning of this chapter, with spatial dimensions (demand sites, soil plots, crop fields) and time dimensions (month and year). The model results are analyzed in this section in order to show the analytical functions of the model. Based on the results, the major research questions include: what policy implications does this model point out for sustainable water management in irrigation-dominated river basins? Why is the integration of hydrologic, agronomic and economic components at the river basin scale necessary for sustainability analysis? Finally, what are the limitations of the short-term model presented here?

4.3.1 Implications for hydrologic system operations

In the integrated hydrologic-agronomic-economic-institutional modeling framework, hydrologic system operations are connected to (1) infrastructure facilities (e.g., water distribution and delivery systems, irrigation and drainage systems, drainage reuse, and drainage disposal and treatment facilities), (2) climatic conditions (e.g., precipitation and all factors related to crop evapotranspiration), (3) soil type and salinity condition, and (4) crop patterns. Since the model has multiple time periods, decision on hydrologic system operations will also be affected by the timely requirements of irrigation for various crops.

At the river basin scale, spatial heterogeneity of water sources and water demands, and externalities due to upstream water diversion and return flow are considered for optimal social benefit of the river basin area through economic incentives, as well as institutional directives (water rights).

4.3.1.2 Sensitivity analysis on major hydrologic parameters

Various scenarios are defined for inflow, effective rainfall (*ER*), and reference evapotranspiration (ET_0) for sensitivity analysis, and the results are shown in Table 4.30-32, respectively. All numbers in these tables are relative values. Under the scenarios of effective rainfall, we assume that the total rainfall does not change from what shown in Table 4.8, and the increase or decrease of *ER* is due to the status of runoff collection for irrigation. Runoff irrigation is an effective management measure for irrigation in arid and semi-arid areas (Ben-Ashir and Berliner, 1994). For simplicity in this case, we do not consider investment or O&M costs of runoff irrigation.

The profit from irrigation (*IP*) is very sensitive to the inflow and the ET_0, especially when the inflow decreases (15% decrease in *IP* in a dry year) and the ET_0 increases, but the profit is less sensitive to the *ER* (lossing inly 5% when ER decreases by 25%). Since *ER* accounts for less than 15% of the total irrigation water in the basin, increasing or decreasing the *ER* by 25% does not have much effect on irrigation profit. Irrigated area has a similar sensitivity to these parameters with irrigation profit. When ET_0 decreases by 15%, irrigation area increases by 14%. However, when ET_0 increases by 15%, irrigation area decreases only by 3%.

As expected, hydropower profit (*HP*) is very sensitive to inflow, but it is not sensitive to ET_0 or *ER*.

Flow to the Aral Sea increases by 10% when ET_0 increases by 15%, and it increases by 6% when ET_0 decreases by 15%. When ET_0 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 ET_0 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 the ecological use.

Total water use benefit (*TWB*), including profits from irrigation (*IP*), power generation (*HP*) and benefits from ecological uses (*EB*), is not sensitive when ET_0 increases. The increase of ET_0 makes water for irrigation less profitable, and irrigation profit decreases; however, since more water goes to the ecological use (1.1 times of the normal value), benefit from this use increases. Finally the decrease of irrigation profit 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*.

From these tables we can also make some observations about salinity. Increased inflow results in a lower salt concentration in the surface water outflow of the basin, less salt mass entering the groundwater, and lower soil salinity. Higher ET_0 causes lower salt concentration in the surface water outflow of the basin, and more salt mass entering the groundwater, and higher soil salinity. High *ER* use results in higher salt concentration in the surface water outflow of the basin, higher salt mass entering the groundwater, and higher soil salinity, which shows that a high level of runoff irrigation may produce negative environmental effects, as well as a positive contribution to irrigation profit in a short-term analysis.

Table 4. 30. Sensitivity analysis of inflow to the basin (relative values).

Inflow (relative Inflow)	*Irrigation profit (IP)*	*Hydro-power profit (HP)*	*Flow-to-aral*	*Total-benefit (TBEN)*	*Salt conc. In downstr. (Ss)*	*Salt. In percol. (Sp)*	*Salinity in root zone (Sf)*	*Irrigation Area (AF)*
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

Table 4. 31. Sensitivity analysis of reference ET_0 (relative values).

ET_0 (relat. Value)	*Irrigation profit (IP)*	*Hydro-power profit (HP)*	*Flow-to-aral*	*Total-benefit (TBEN)*	*Salt conc. In downstr. (Ss)*	*Salt. In percol. (Sp)*	*Salinity in root zone (Sf)*	*Irrigation Area (AF)*
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

Table 4. 32. Sensitivity analysis on effective rainfall (relative values).

Eff. Rainf. (relat. Value)	*Irrigation profit (IP)*	*Hydro-power profit (HP)*	*Flow-to-aral*	*Total-benefit (TWB)*	*Salt conc. In downstr. (Ss)*	*Salt. In percol. (Sp)*	*Salinity in root zone (Sf)*	*Irrigation Area (AF)*
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

Notation

Flow-to-aral = annual downstream flow to the Aral Sea;
Conc. in downstr. = annual average salt concentration in downstream flow;
Salt in percol. = salt mass in deep percolation to groundwater, result from demand site mid_syd; the soil type is *loam*; the crop field is *cot-foa*; and
Salinity in root zone = result from demand site: *mid_syd*, soil type: *loam*; crop field: *cot-foa*.

4.3.1.2 Reservoir operation

Eleven reservoirs are considered in the river basin network (See Figure 1.3). 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. This section discusses the combined operation of the three major reservoirs under three cases: (1) for irrigation water supply only; (2) for irrigation and hydropower generation; and (3) for irrigation, hydropower generation, and soil and water quality maintenance. It should be noted that two other large reservoirs exist in the basin but they are on the main tributaries to the main stem of the Syr Darya river; Andijan reservoir on the Karadarya River and Charvak reservoir on the Chirchik River, respectively. 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 multi-year average inflow (Table 4-1) and current agricultural and economic data described in Section 4.1.

We define reservoir utilization efficiency (*RUE*) as the ratio of actual utilized 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 for flow control within a time period, and the high value of *RUE* shows more flow is effectively controlled by reservoirs. Figure 4.4 shows the *RUE* in each month under the three cases. The average annual *RUE* is 0.288 for case 1, 0.324 for case 2, and 0.329 for case 3. The *RUE* is increased from case 1 to case 2 due to additional reservoir storage used for hydropower generation, and the *RUE* is increased from case 2 to case 3 due to additional reservoir storage used for salinity control. The major reservoirs on the Syr Darya River were designed for multiple-year flow regulation, however, the time horizon of the short-term model is just one year, this is why the *RUEs* under various cases are low. The values of *RUE* also depend on the initial storage of reservoirs in this one-year model. We assume the initial storage for the major reservoirs is one-third of the full storage of those reservoirs, and the ending storage is equal to the initial storage for all these reservoirs. The long-term operation will be discussed in Chapter 7.

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.

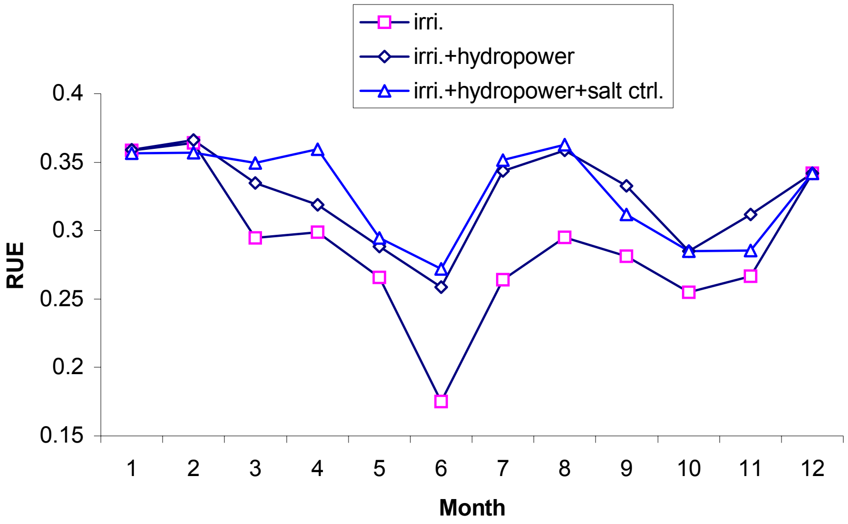


Figure 4. 4. Reservoir utilization efficiency.

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.

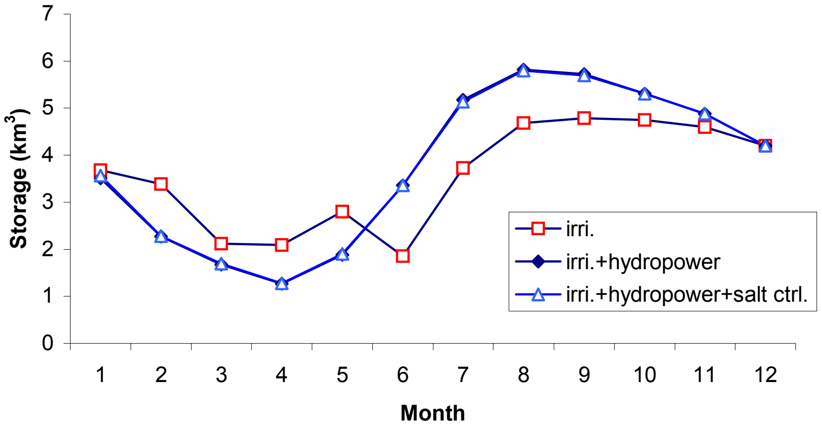


Figure 4. 5. Storage of the Toktogul Reservoir under the three operational cases.

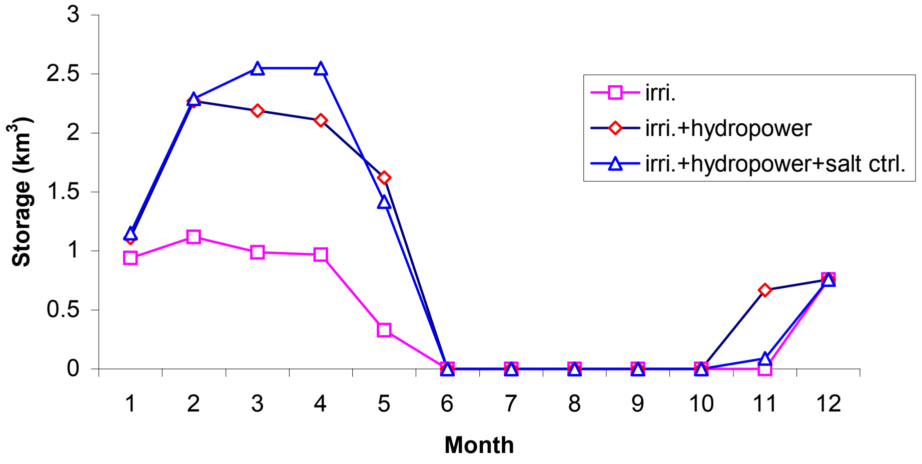


Figure 4. 6. Storage of the Kayrakum Reservoir under the three operational cases.

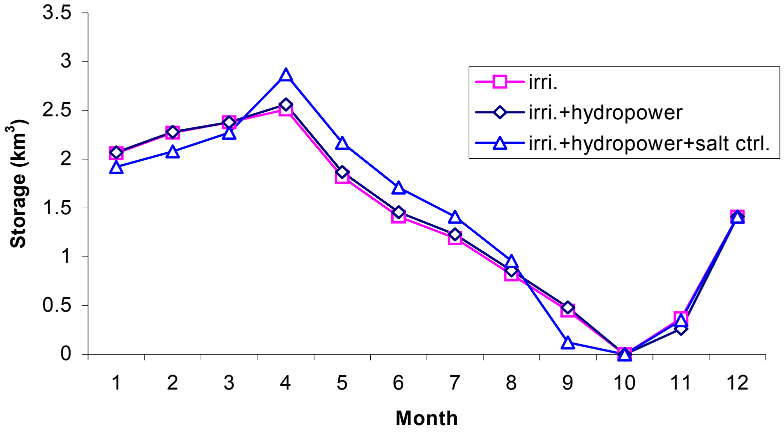


Figure 4. 7. Storage of the Chardara Reservoir under three operational cases.

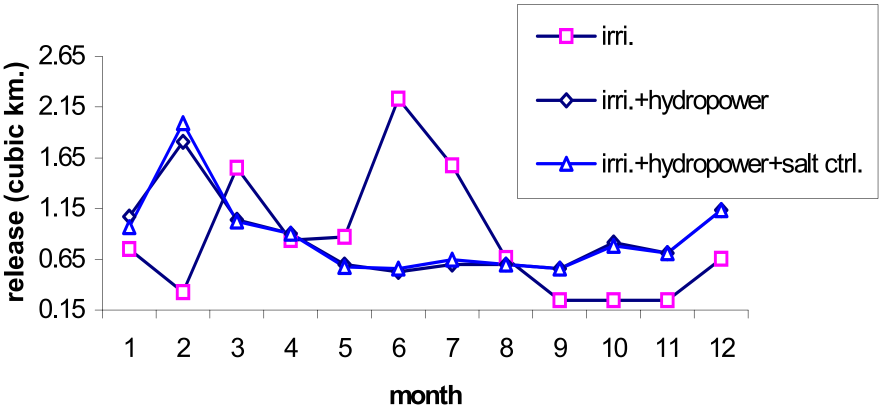


Figure 4. 8. Releases of the Toktogul Reservoirs under three operational cases.

Release in the vegetation period (Apr. – Oct.) is 6.43, 3.77, 3.87 km^3 in the three cases, respectively. The total release in one year is 10.23, 10.34, 10.48 km^3, respectively.

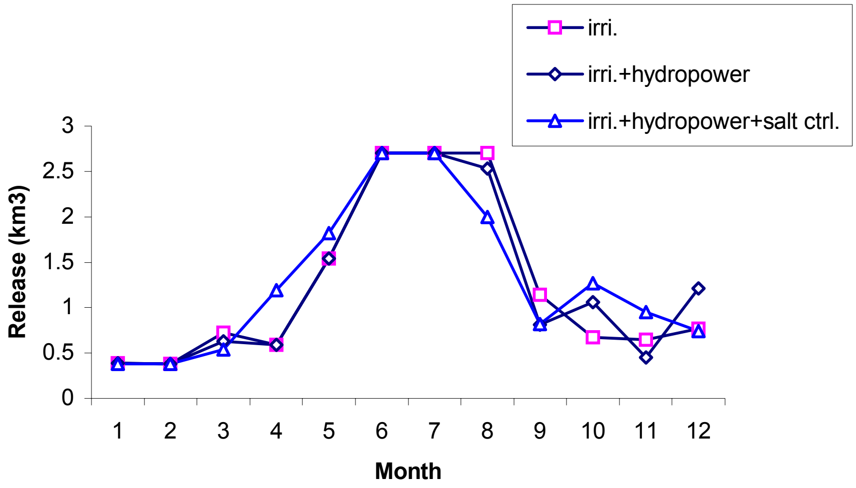


Figure 4. 9. Releases of the Kayrakum Reservoirs under three operational cases.

Release in the vegetation period (Apr. – Oct.) is 11.37, 10.67, 11.23 km^3 in the three cases, respectively. The total release in one year is 14.95, 14.99, 15.94 km^3, respectively.

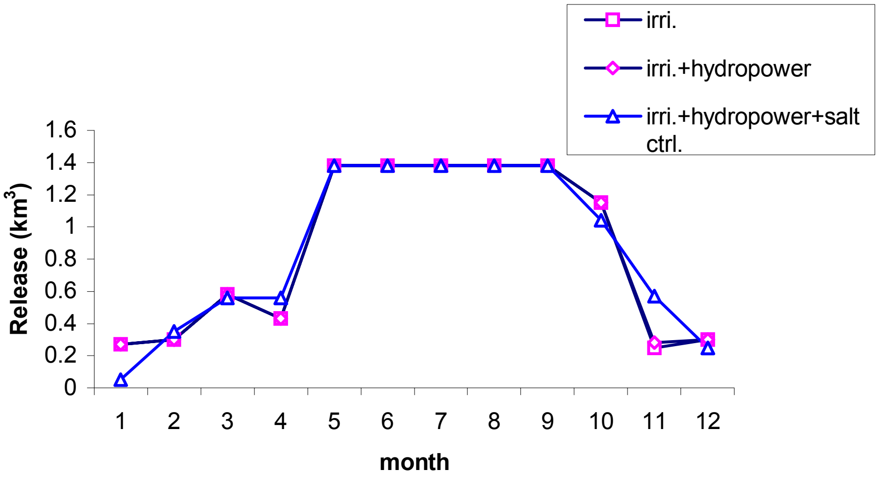


Figure 4. 10. Releases of the Chardara Reservoirs under three operational cases.

Release in the vegetation period (Apr. – Oct.) is 7.33, 7.33, 7.47 km^3 in the three cases, respectively. The total release in one year is 10.18, 10.21, 10.28 km^3, respectively.

Combined with Toktogul Reservoir, the other two major reservoirs, Kayrakum and Chardara, have been utilized to solve the 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 water supply to irrigation and salt dilution in summer periods.

Figures 4.5-4.7 show the reservoir active storages vs. months, and Figures 4.8-4.10 show reservoir releases vs. months, of the three major reservoirs under three cases. In Case 1, reservoir operation is only driven by water supply, which is mainly for irrigation. The releases of all reservoirs follow irrigation water demands, which increase in March, remain high from June to August, and decrease in non-irrigation periods (Oct. – Mar.). In Cases2 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). However, the storage behaviors of these two reservoirs are different for various purposes. The Kayrakum Reservoir stores water in non-irrigation periods and almost dries up in irrigation periods. From Case 1 to Case 3, the storage in the non-irrigation period is increased, due to (1) in Cases 2 and 3 Toktogul reservoir releases more in non-irrigation periods; (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 4.11 shows the salt concentration (at the end of a month) in flows along the Syr Darya River in months from June to September. The return flow inlets along the river are shown in the Figure. The drainage from upstream demand sites *Naryn* and *Fergana* causes the salt concentrations 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. From *Right_in* to the Kayrakum Reservoir, the salt concentrations decrease slightly in all the months except increasing lightly in August. Through the Kayrakum Reservoir the salt concentrations in all the months stay constant until river reach *Shimi_in*, where drainage from demand site *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 salt concentrations show less fluctuation.

In June and July, the Kayrakum and Chardara Reservoirs have more capacity for salt dilution than in August and September. Salinity at the end of a month affects crop production in the next month, i.e., salinity at the end of June, July and August affect crop production in July, August and September, respectively. Since peak withdrawal for irrigation occurs in June, July and August, reservoir operation has a stronger influence on salt dilution in June and July than in August and September, in the peak irrigation demand periods the water withdrawal has lower salinity helping increase crop production.

Unlike Kayrakum Reservoir located at the mid-stream, Chardara Reservoir has to keep enough water in storage for downstream ecological release requirements in each month, and therefore no consecutive dry periods occur with this reservoir.

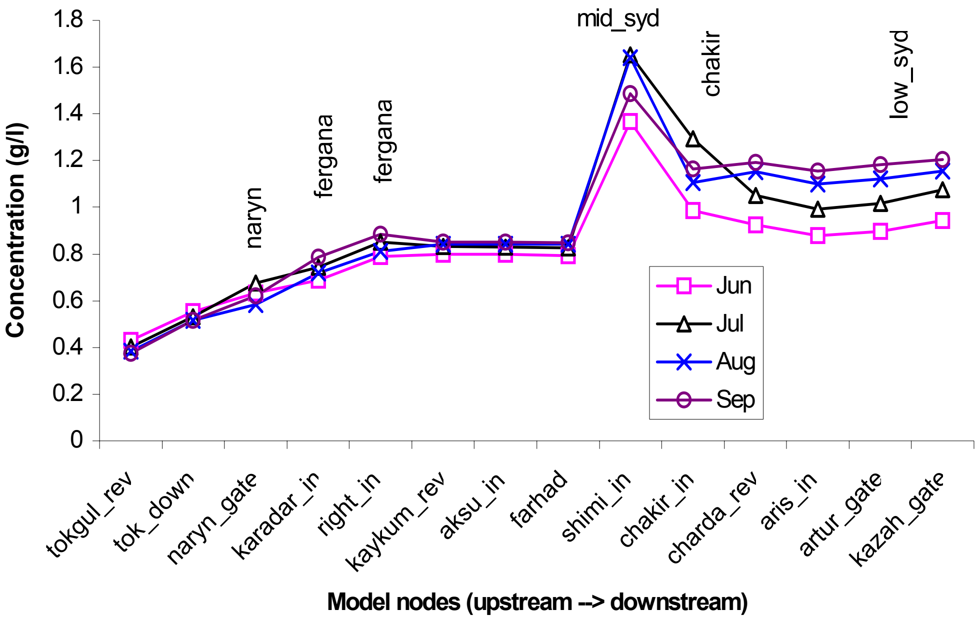


Figure 4. 11. Salt concentration along the Syr Darya River (in a normal year).

4.3.1.3 Basin-wide salinity distribution analysis

Beside water shortage, salinity is another serious problem in the study area. In this section, we discuss both the spatial and the temporal distribution of salinity at a basin-wide scale. The "third-party" effect of irrigation drainage is demonstrated through the modeling results.

As discussed above, Figure 4.11 shows the salt concentration along the Syr Darya River. Neglecting other factors that may affect salinity distribution in the study area, our modeling results show that the salinity change in the river is due to drainage from irrigation fields distributed along the river. The peak salt concentration happens in river reach *Shimi_in*, which is caused by drainage from demand site *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 with the water withdrawal is higher for the downstream demand sites than for the upstream demand sites. As described in Appendix D, the return flow from upstream demand sites is responsible for the salinity increase at downstream river reaches.

Figure 4.12 shows the average monthly salt concentration in water withdrawal for irrigation water supply in each demand site. The downstream demand sites *Low_Syr* and *Artur* have the highest salt concentration. Demand site *Chakir* is supplied by a local tributary, where the salt concentration is relatively low and constant.

Figure 4.13 shows the salinity affecting coefficient (*ks*, eq. 3.22) for the same crop with the same soil type, at each demand site. Note that the salinity affecting coefficient in a period is a function of soil salinity, which is affected by soil salinity accumulation in the previous periods, and salinity in irrigation water in the current period.

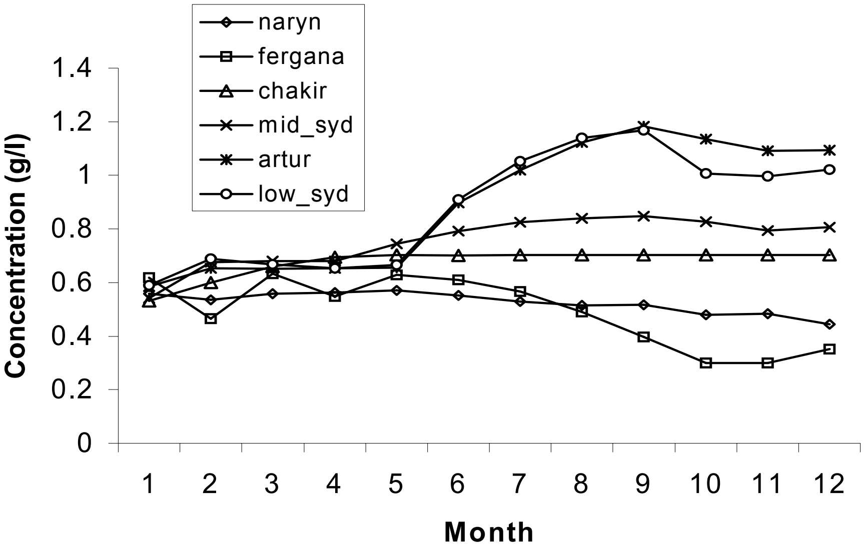


Figure 4. 12. Average monthly salt concentration in mixed water supply.

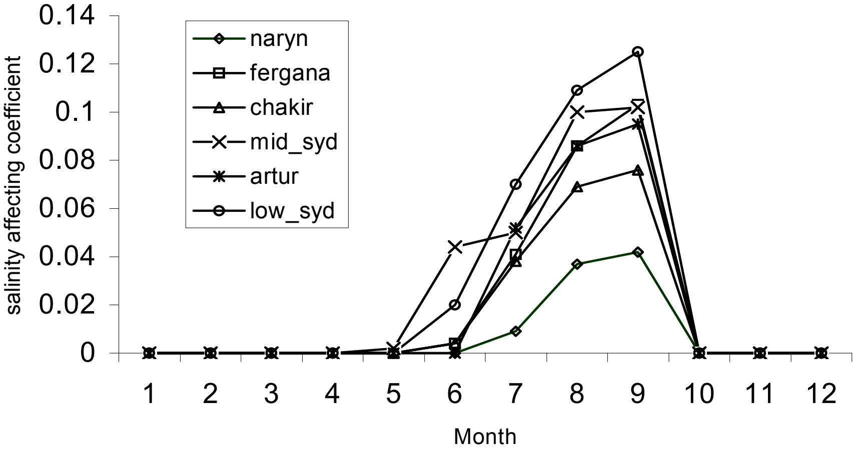


Figure 4. 13. Average monthly salinity affecting coefficients (*ks*) (soil: loam; crop pattern: wheat-maize).

Salinity variation with time periods (months) depends on irrigation period scheduling, as well as the temporal distribution of natural sources. From Figure 4.13, we notice that the salinity at the end of September is higher than that of June, showing that the drainage effect is most significant just after the major irrigation months. Soil salinity increases through the major irrigation months, and reaches its peak at the end of the season. Therefore, the salt concentration in drainage water is highest in September, a period just after the peak irrigation months.

After the peak irrigation period, if there is considerable rainfall, the drainage amount may have a high salt concentration since crops consume less water during this period. This process is called salt leaching, which can create better soil salinity conditions, but may also result in worse surface and ground water salinity if drainage is not well treated. Figure 4.14 shows soil salinity (saturated extraction), 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 appropriate, then irrigation motivated by a short-term objective may produce poor soil salinity conditions. Additional issues about salt leaching will be discussed later in this chapter.

Salt concentrations in the three major reservoirs vs. months are presented in Figure 4.15. In this model, the Toktogul Reservoir is not affected by drainage from crop fields, 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 (around Sept.), when the amount of drainage from crop fields is high.

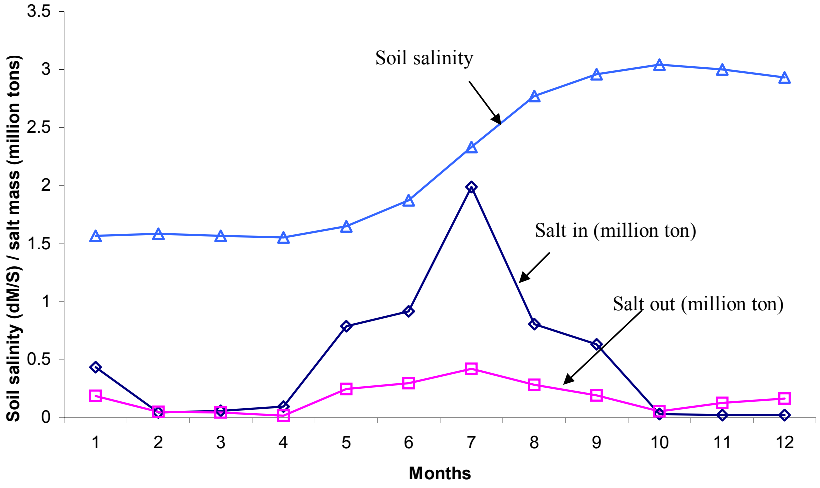


Figure 4. 14. Soil salinity change through irrigation periods (demand site: Fergana, soil type: loam; crop field: cot_foa).

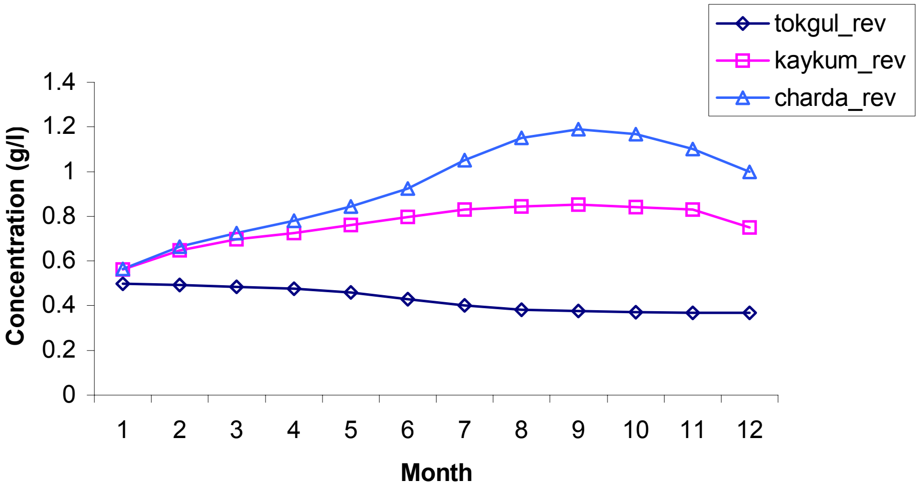


Figure 4. 15. Average monthly salt concentration in reservoirs.

Note that the salinity in reservoir storage (Figure 4.15) and the soil salinity (Figure 4.14) are significantly higher at the ending time period (Dec.) than those in the starting period (Jan.). This ending 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 modeling that takes account of salinity accumulation. Another problem that the short-term model can not deal with is the groundwater salinity. The model shows that the groundwater salinity does not change significantly in a one-year time horizon. This is normal since generally only a long-term percolation process may affect groundwater salinity significantly.

4.3.2 Irrigation and drainage management

Irrigation and drainage management is a conjunctive part of basin-wide sustainable water resources management, especially in irrigation-dominated basins. Once water withdrawn from surface water systems or pumped from groundwater sources are determined, irrigation and drainage management measures will be necessary to satisfy crop water demands, while conserving limited water resources and not producing any environmental problems. The main practical aspects of irrigation are the determination of how much water to apply to a given crop and when to apply the water. The ideal situation would be avoidance of water stress throughout the growing season, yet having no losses. Basically, drainage systems are installed for (1) trafficability so that field operations such as seedbed preparation, planting and harvesting can be conducted in timely manner; (2) for protection of the crop from excessiveive soil water condition; and (3) for salinity control (Skaggs and Murugaboopathi, 1994). In this section we analyze some issues including irrigation water application and infrastructure improvements.

4.3.2.1 Blending irrigation water supplies

Four kinds of sources for on-field irrigation water sources are considered in the model, including surface water (river and major canal diversion and local surface source), groundwater, drainage reuse, and effective rainfall. Table 4.33 shows the ratios of these sources for cotton and wheat under a normal hydrologic level, and Table 4.34 presents the seasonal average salt concentrations of these sources. The blending of these sources to a specific crop depends on the salinity of these sources, previous soil salinity, as well as crop salinity tolerance. The accessibility of sources to a specific crop field is not yet considered in the model, but the total availability is limited.

Cotton has much higher salinity tolerance than wheat so that more sources with higher salinity (groundwater and field drainage) can be used for cotton than for wheat in all demand sites. No drainage reuse is applied to cotton and wheat in demand site *Mid_Syd*, due to the high salt concentration in drainage. Downstream demand site *Low_Syd* reuses more field drainage for cotton.

Demand site *Mid_Syd* has the lowest effective rainfall. This is another reason for the high salinity in the drainage from the demand site.

Table 4. 33. Ratios of sources to total irrigation water application (Under a normal hydrologic level).

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

Table 4. 34. Annual average salt concentration (g/L) in different sources (Under normal hydrologic level).

Demand Sites	*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	-	-	-	-	-	-

4.3.2.2 Irrigation efficiency

As defined in section 3.4.3, irrigation efficiency (*EIR*) used in the model is the ratio of water effectively used by crops to the total water application. The advanced irrigation systems have higher irrigation efficiency. Therefore, high irrigation efficiency means more water conservation, which is very important for competitive water uses, and water storage for long-term risk aversion. On the other hand, irrigation systems with high irrigation efficiency produce less percolation, which is necessary for salt leaching in farms where soil salinity is a serious problem. Soil salinity accumulation may result from long-term irrigation actions without sufficient leaching.

Tables 4.35 and 4.36 show four modeling scenarios of *EIR* in a dry year. With the increase of *EIR*, both irrigation profit and total benefit increase. However, as shown in Table 4.36, with the increase of irrigation efficiency, field percolation decreases, and soil salinity increases. The determination of irrigation efficiency should be studied in a long-term framework, considering both economic benefit and environment consequence.

Table 4. 35. Analysis on irrigation efficiency (*EIR*): Economic benefit.

Ratio of Assumed to primary efficiency (R)	*Irrigation profit (IP) (billion $)*	*Δ(IP)* [1]*/ Δ(R)* [2]	*Total benefit(TWB) (billion $)*	*Δ(TWB)* [3]*/ Δ(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

[1] *Δ(IP)* change of irrigation profit
[2] *Δ(R)* change of ratio of assumed to primary efficiency
[3] *Δ(TWB)* change of total water use benefit.

Table 4. 36. Analysis on irrigation efficiency (*EIR*): Environmental problem (Result from demand site Fergana, soil type is loam).

Ratio of Assumed to primary efficiency (R)	***Cotton-forage***			***Wheat-maize***		
	Percolation (cm)	*Soil salinity (dm/s)*	*Water use per ha. (m^3)*	*Percolation (cm)*	*Soil salinity (dm/s)*	*Water use per ha. (m^3)*
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

4.3.2.3 Water distribution and delivery efficiency

The current average water distribution and delivery efficiency (*EDS*) for each demand site is shown in Table 4.16. A model scenario with improved *EDS* is defined, in which *EDS* is increased to 0.8 for all demand sites (about 15% increase of the current value), and Table 4.37 compares this scenario to the scenario with the current *EDS* in a dry year. In the improved scenario, less total water diversion produces more irrigation profit and total benefit. The increase of total benefit (0.601) is larger than that of irrigation profit (0.423), which shows that less withdrawal for irrigation produces more hydropower or/and ecological benefit, as well as irrigation profit. That is, a 5% decrease in total water diversion produces a 26% increase in total net benefits.

Table 4. 37. Analysis on water distribution and delivery efficiency (based on a "dry" hydrologic level).

EDS	Total Benfit (*TWB*) (billion $)	Irri. Profit (*IP*) (billion $)	Irrigated Area (10^3ha.) (*AF*)	Water Diversion (*WD*, km^3)						
				Naryn	Ferg-ana	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
Ratio	1.26	1.27	1.00	1.14	1.11	0.76	0.98	0.83	0.82	0.95

4.3.2.4 Drainage reuse and disposal

Drainage effluent currently accounts for about 35% of water available for use within the study area, and it is an important source in the area. However, its on-field reuse can be problematic, and is a contributory factor to soil and groundwater salinisation. Drainage disposal/treatment is thus necessary when drainage with high salinity seriously pollutes soil and water systems. Tables 4.38 and 4.39 show scenario analysis on drainage reuse. Table 4.38 shows positive contributions to irrigation profit and total benefit when the amount of drainage reuse is increased. However, these contributions are short-term values, the soil salinity problem shown in Table 4.39 may ultimately decrease the positive contributions when accumulated soil salinity exceeds the crop salinity tolerance, and groundwater salinity exceeds its standard. Since more drainage is reused in fields, less drainage is disposed to the river system, the salt concentration in downstream flow decreases for the scenario of larger reuse amount, but this is also a short-term result.

Modeling results show that drainage disposal to the desert can increase irrigation profit only in a wet year. For example, the model result shows 0.784 km^3

drainage disposal can increase irrigation profit \$10 million, and total benefit \$13 billion \$. Again the short-term model is not able to deal well with the drainage disposal issue since it does not consider long-term environmental benefits.

Table 4. 38. Drainage reuse scenario analysis: Short-term benefit (based on a "dry" hydrologic level).

Scenarios (reuse amount) (km^3)	*Irrigation profit (IP) (billion \$)*	*Total benefit (TWB) (billion \$)*
0	1.563	2.094
0.71	1.579	2.170
1.42	1.593	2.242
2.06	1.604	2.289

Table 4. 39. Drainage reuse scenario analysis: Environmental problems (based on a "dry" hydrologic level).

Scenarios (reuse amount) (km^3)	*Conc. in drainage[1] (g/l)*	*Soil salinity[2] (dS/m)*	*Conc. in downstr.[3] flow (g/l)*
0.00	*1.33*	*1.58*	*1.07*
2.06	*1.75*	*2.38*	*1.02*

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

[3] Annual average salt concentration.

4.3.2.5 Salt leaching

Salt leaching is often necessary to sustain crop production over time. The amount of leaching required depends upon the crop, the salinity of the irrigation water, soil characteristics, and management. The 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.

Table 4. 40.[1] Analysis on salt leaching: Wheat - maize.

Items	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dev*	**Annual**
Applied water (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
Drained water (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
LF	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
ECw (dS/m)	0.81	n/a	N/a	0.81	0.90	0.87	0.84	1.79	1.78	n/a	n/a	n/a	
ECe (dS/m)	1.09	1.11	1.19	1.19	1.18	1.27	1.40	1.67	2.06	2.12	2.06	1.99	

Table 4. 41[2] Analysis on salt leaching: Cotton - forage.

Items	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	**Annual**
Applied water (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
Drained water (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
LF	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]*ECw(dS/m)*	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]*ECe (dS/m)*	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] ECw: salinity of irrigation water in dS/m;

[4] ECe: soil saturated extraction in dS/m.

4.3.3 Agronomic analysis

Through the operation of hydrologic systems and irrigation and drainage management, the quantity and quality of water to be applied to specific crop fields in scheduled periods can be determined. The agronomic relationships included in the model determine the crop production. This section demonstrates crop yield as a function of both soil moisture and soil salinity.

Figure 4.16 shows the crop yield (*YR*) vs. soil moisture (*z*) with the effect of soil salinity. Basically the relation of yield and soil moisture is nonlinear, and the non-linearity is affected by soil salinity. Define *dy* as the change of crop yield, *ks* as the salinity affecting coefficient, *d(ks)* as the change of *ks*, and *dz* as the change of the soil moisture. We have the following observations from Figure 4.16: (1) *d(YR)/dz* decreases as *d(ks)* increases; and (2) when *ks* is larger, *d(ks)* has larger effect on *d(YR)/dz*.

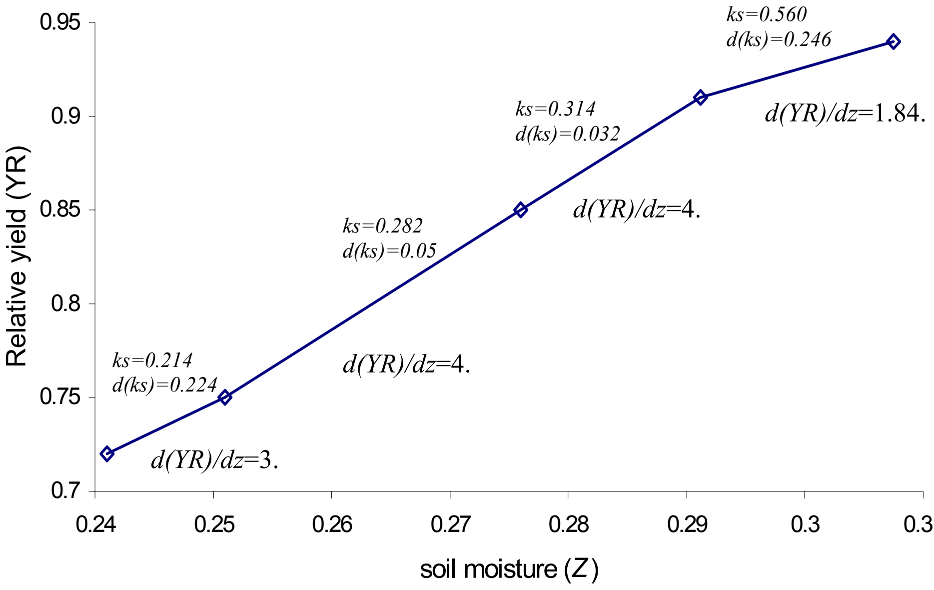


Figure 4. 16. Actual ET vs. relative crop(wheat) yield (in Mid_Syd, the soil type is loam).

4.3.4 Economic Analysis

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

The economic value of water is evaluated with respect to water application to crops and water withdrawal to demand sites, respectively. Decisions on crop irrigation acreage, water application to crops, and water allocation among demand sites are based on the water values with crops or with demand sites, as well as physical water availability constraints and institutional directives.

4.3.4.1 Economic values of water with crops

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

$$V_c = \frac{profit\ from\ crop\ harvest\ \text{-}\ water\ supply\ \cos t\ \text{-}\ other\ \cos t}{total\ amount\ of\ water\ applied\ to\ the\ crop\ field} \tag{4-5}$$

The numerator does not include infrastructure investment, and the denominator refers to water arriving to the crop field. Table 4.42 shows the values of V_c in a normal year. Irrigation area for crops is determined according to the water values with crops, as well as some other factors formulated by lower and upper bounds to the irrigation area of a crop in the model. Table 4.43 shows the irrigated area for each crop combination at each demand site.

Table 4. 42. Economic value of water with crops (V_c, \$/m^3) (in a normal year).

Crop-patterns	*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
Whole basin	0.141	0.103	0.041	0.081

Table 4. 43. Irrigated area (1000 ha.).

Crop-patterns	*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

Figure 4.17 shows the average economic values 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.

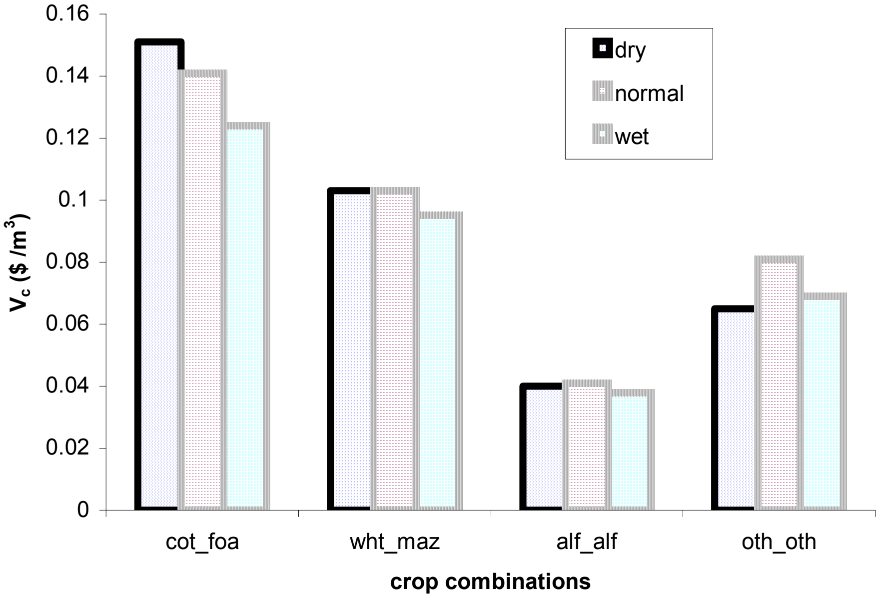


Figure 4. 17. Water values with crops.

4.3.4.2 Economic values of water with demand sites

Economic value of water with a demand site (V_d, \$/m^3) is defined as:

$$V_d = \frac{revenue\ from\ \ crops\ \text{-}\ water\ supply\ \cos t\ \text{-}\ other\ \cos t - infrastructure\ invest.}{total\ amount\ of\ water\ withdrawn\ ,\ pumped, and\ reused.} \qquad (4\text{-}6)$$

Figure 4.18 shows economic values with demand sites in a dry, normal or wet year. The upstream demand site *Fergana* has the highest value, while the most downstream demand site *Low_syd* has the lowest one. Water quantity and quality are the two factors explicitly considered in the model, less quantity available and worse water quality makes water less valuable downstream. Relatively high crop evapotranspiration downstream (see Table 4.8), resulting in higher consumptive water use, may make water less valuable at downstream demand sites. However, factors other than water, such as various soil capacity and farmer's inputs of labor and fertilizer also affect the crop yield, and the economic value of water with demand sites. In this case study, we simply assume that those conditions are the same for all demand sites.

Hydrologic levels seem to affect downstream and upstream demand sites in different ways. At upstream demand sites, like Naryn and Fergana, where there is more water of better quality available, water value decreases with inflow availability; while at downstream demand sites, where there is less water available and it has worse water quality, water value increases with inflow availability.

Water value with demand site, as well as physical water availability and institutional constraints, could be used to determine water allocation among demand sites. 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 demand site, since the demand sites, for the most part, are determined on national boundaries. Table 4.44 shows the ratios of calculated irrigated area to total available irrigated area for each demand site in a dry, normal or wet year. The ratio at the downstream demand site (*low_syd*) is only 0.21. The difference between demand sites will be addressed in the following sections. Clearly, 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.

Table 4. 44. 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

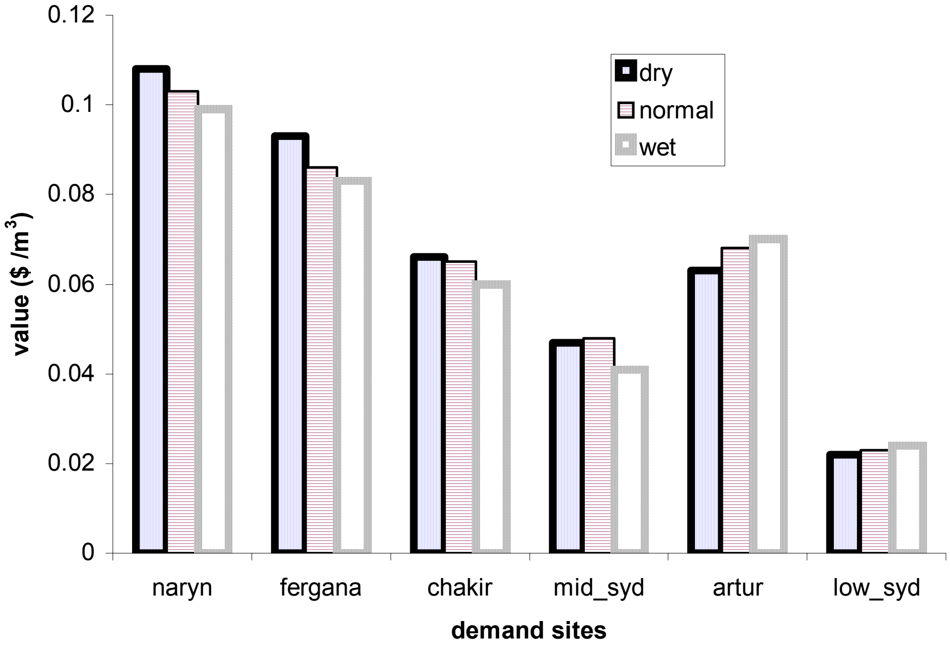


Figure 4. 18. Economic values (V_d) with demand sites.

4.3.4.3 Crop prices

Crop price is one of the economic incentives considered in the model. Table 4.45 shows results of three model scenarios: the first one used 75% of the primary crop prices (see Table 4.18 for the primary crop prices), the second used the primary prices for all crops, and the third used 125% of the primary prices for all crops. Irrigation profits at all demand sites, especially at the downstream demand sites are very sensitive to crop prices. The relative values of the total irrigated areas are 0.956, 1.000, and 1.134, resulted from these scenarios, respectively. That is to say, 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 demand site, *Low_syd*, when the crop prices increase by 25%, the irrigation profit (*IP*) increases by 7.26 times. Detailed result shows under this case, no irrigated area reduction at *Low_syd*, while the irrigated area is reduced by 75% with the normal crop prices. Therefore, crop price may be a strong incentive for water allocation and agricultural production in the basin.

Wheat – maize is a potential crop combination replacement for cotton-forage in the study area (EC, 1995). However, results from the model, clearly show that cotton-forage still dominates the crop pattern (Table 4.43). A potential solution to increase the irrigated area of wheat-maize is to increase the prices for wheat-maize. Table 4.46 shows that increasing wheat-maize prices by 25% will significantly increase the irrigated area of wheat-maize. Table 4.47 shows that increasing wheat-maize prices by 50% will make wheat-maize dominate the irrigated area and significantly increase the irrigated area in demand site *Low_syd*, as well as the total irrigated area in the study area. Table 4.48 shows the economic values of water with demand sites (V_d) for the three scenarios.

Table 4. 45. Irrigation profit vs. crop prices (relative values).

Crop price changes	*Naryn*	*Low_syd*	*Artur*	*Chakir*	*Mid_syd*	*Fergana*	**Total**
25% decr.	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% incr.	1.369	7.260	1.617	1.372	1.409	1.355	1.571

Table 4. 46. 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% incr.	0.16	0.58	0.07	0.09	1.00	0.85
50% incr.	0.11	0.73	0.07	0.01	1.00	0.94

Table 4. 47. Ratios of calculated irrigated area to total available irrigated area with various 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% incr.	1.00	0.21	0.92	1.00	0.92	1.00
50% incr.	1.00	0.79	0.92	1.00	0.91	1.00

Table 4. 48. Economic values of water ($\$/m^3$) with demand sites with various 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% incr.	0.123	0.035	0.083	0.079	0.062	0.098
50% incr.	0.135	0.084	0.103	0.096	0.077	0.118

4.3.4.4 Water prices

The model was run under four scenarios of water prices (*WP*), and some results are shown in Tables 4.49, 4.50 and 4.51. The first scenario uses the original surface and ground water supply prices (Table 4.18), and the other three apply 2, 4, and 8 times of the original prices. From Table 4.49, we find that $d(IB)/d(WP) <0$, $d(HP)/d(WP)>0$, $d(EB)/d(WP)>0$, and $d(TWB)/d(WP)<0$, where *IB*, *HP*, and *EB* are the net profits to irrigation and power production, and benefit to environment, respectively and, *TWB* is the total net benefit. Total water withdrawal and irrigated area decrease with *WP*.

Table 4.50 shows $d(V_c)/d(WP)<0$ for all crops, and $d(V_d)/d(WP)<0$ for all demand sites. When *WP* is increased to 8 times of the original value, alfalfa and "other crops" have negative profit in some demand sites, and negative water value happens in *low_syd*.

Water values for each crop in each demand site with high *WP* is presented in Table 4.51.

Table 4. 49. Analysis on water supply prices[1].

Water prices	*Irri. Profit, IP (billion $)*	*Hydro-Power Profit, HP (billion $)*	*Ecological Benefit, EB (billion $)*	*Total Benefit, TWB (billion $)*	*Withdrawal (km^3)*	*Irr. Area (1000 ha.)*
Original	2.755	0.187	1.160	4.102	31.70	2753.5
2* original	2.507	0.194	1.162	3.863	31.64	2703.5
4* original	2.002	0.200	1.238	3.439	30.75	2665.4
8* original	1.235	0.205	1.446	2.886	27.81	2600.0

Table 4. 50. Water values for crops and demand sites under various water supply prices[2].

Water supply prices	Water values for crops				Water values for demand sites					
	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 4. 51. Water values for crops in each demand site with high water supply prices[3].

Demand sites	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.

4.3.4.5 Tax on excess salt discharge

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 (*TWB*) vs. *tax*, irrigation profit (*IP*) 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 have the following observations:

1) $d(TWB)/d(tax) > 0$, and $d(IP)/d(tax) > 0$, when $tax \leq \$50.0$ *per ton*,
   $d(TWB)/d(tax) < 0$, and $d(IP)/d(tax) < 0$, otherwise;
2) $d(INB)/d(tax) > 0$, when $tax \leq \$60.0$ *per ton*,
   $d(INB)/d(tax) < 0$, otherwise; and
3) $d(SM)/d(tax) < 0$ for the whole range.

From Figures 4.19 and 4.20, it is seen that a *tax* of \$50 per ton of salt mass discharged appears to be optimal and that taxes above \$50 do not improve benefits. However, this must be offset by the fact that the instream benefits increase with the tax, as shown in Figure 4.21. Figure 4.22 indicates that a tax in excess of $100 per ton provides negligible decreases in salt mass discharge.

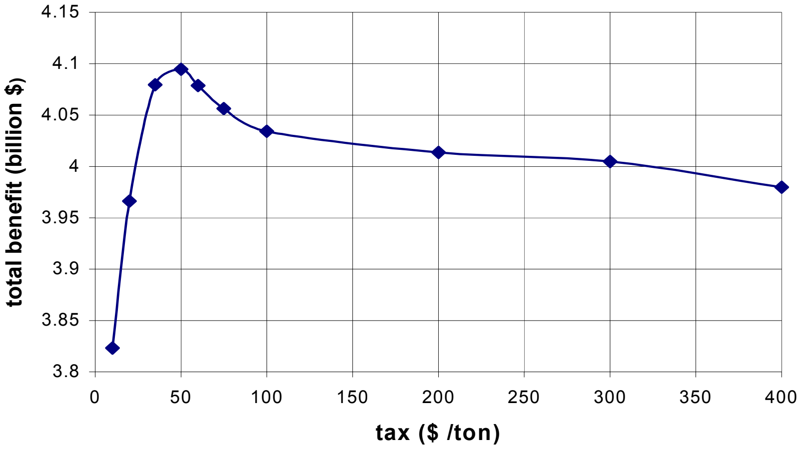


Figure 4. 19. Total-benefit vs. tax on salt discharge.

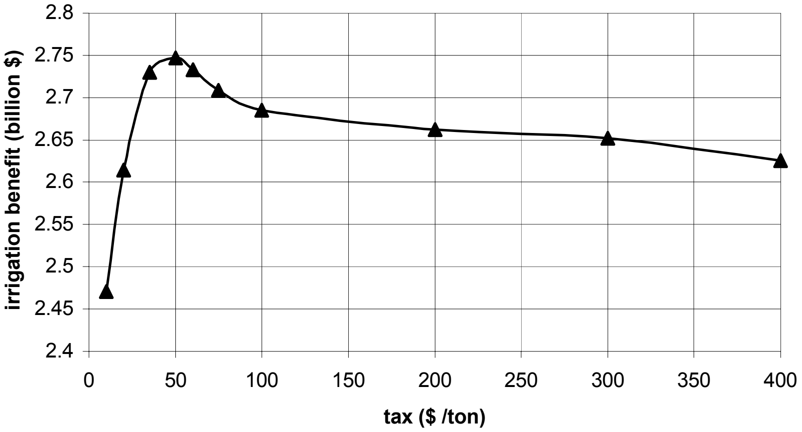


Figure 4. 20. Irrigation profit vs. tax on salt discharge.

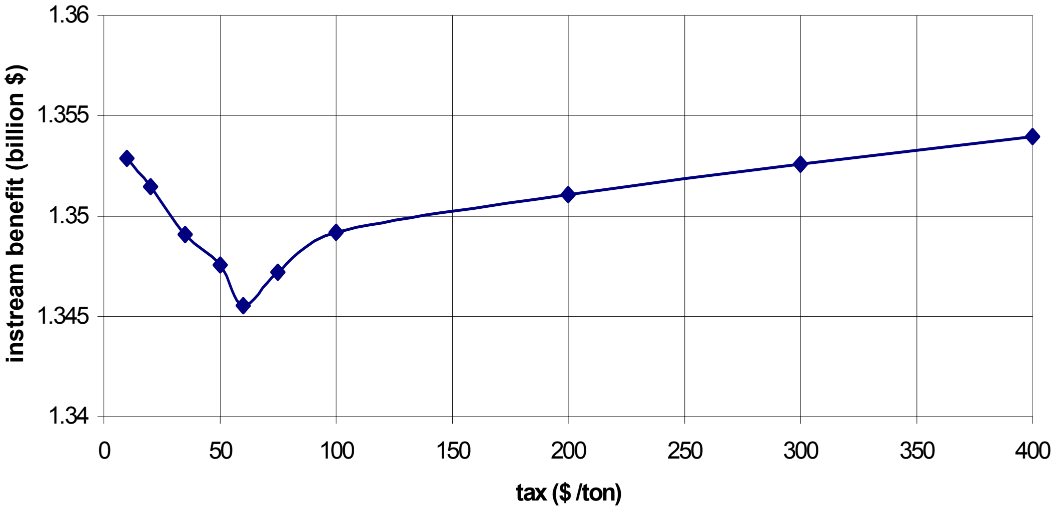


Figure 4. 21. Instream water use benefit vs. tax on salt discharge.

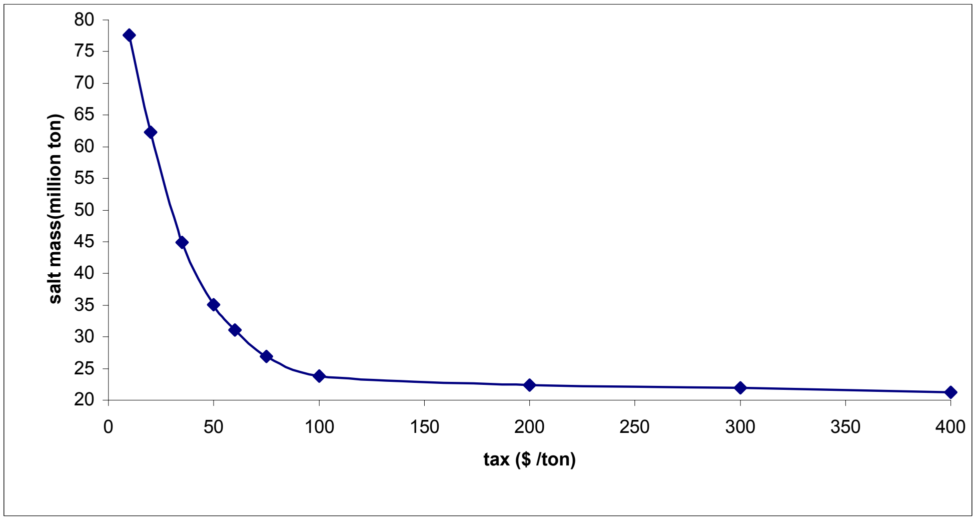


Figure 4. 22. Excess discharged salt mass vs. tax on salt discharge.

In reality it is difficult to measure return flow from irrigated fields, which is generally non-point flow. Therefore implementing the tax on salt discharge with the return flow may not be realistic. The model developed here can be used as an inexpensive tool to estimate return flow from irrigated fields at specific demand sites, and then provide a framework to analyze tax potentially applied for salinity control, as well as other management policies.

4.3.4.6 Irrigation vs. Hydropower generation

There exists a tradeoff relationship between the water use for upstream hydropower generation and downstream irrigation. The hydropower sale price (*ppw*) was varied in a range from \$0.08 (base value) to \$0.32 per kWh, about 4 times the base value. The hydropower profit (*HP*) vs. *ppw* in a normal year is shown in Figure 4.23. From this we see that that *d(HP)/d(ppw)* >0, and *ppw* = \$0.15 kWh is a critical point, *d(HP)/d(ppw)* is much larger before this point than that after this point.

When *ppw* is increased from \$0.08 to \$0.32 kWh, in a normal year, irrigation profit decreases from $\$2.755\text{x}10^9$ to $\$2.735\text{x}10^9$. It seems that changing the price has small effect on irrigation profit. Figure 4.24 shows a "tradeoff" relation between hydropower generation and irrigation profit.

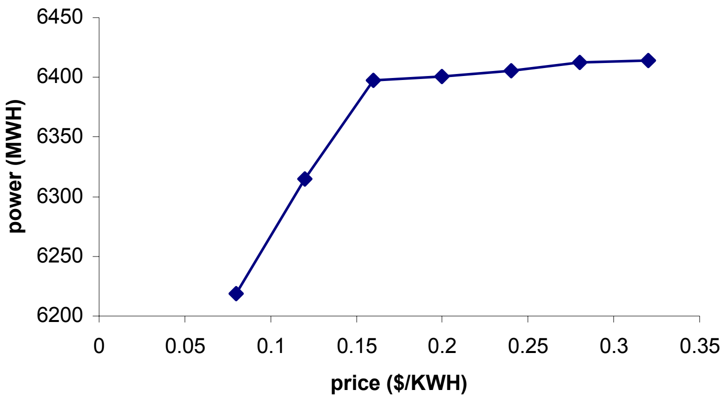


Figure 4. 23. Hydropower generation vs. power price.

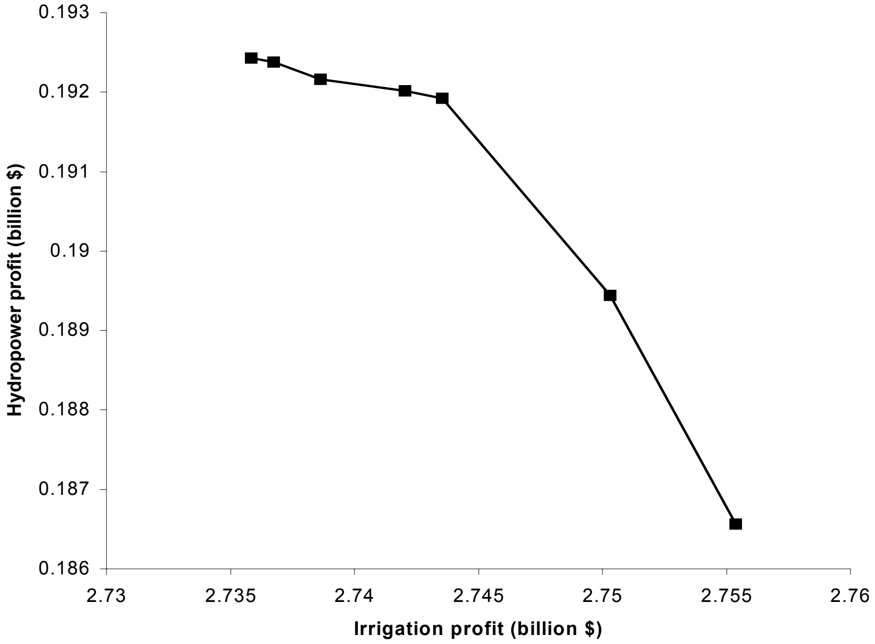


Figure 4. 24. Hydropower profit vs. Irrigation profit.

4.3.4.7 Economic efficiency of infrastructure investment

The effect of infrastructure improvements have been discussed in Section 4.3.2.2–4. In this section, we analyze the economic efficiency of the investments (*INV*) on water distribution and delivery systems, irrigation and drainage systems, and drainage disposal systems, respectively.

Water distribution and delivery systems

Assume that the water distribution and delivery efficiency is increased from the base value (Table 4.16) to 0.8 in all demand sites. The ratio of total benefits (*TWB*) to invested amount for various hydrologic scenarios $\Delta(TWB)/\Delta(INV)$ and $\Delta(IB)/\Delta(INV)$ between the base scenario and the improved scenario are shown in Table 4.52. In both scenarios, irrigation and drainage efficiencies do not change. At all hydrologic levels, the investment on water distribution and delivery systems is economically efficient.

Table 4. 52. Economic efficiency of investment for water distribution and delivery systems.

$\Delta(TWB)^1/\Delta(INV)^2$			$\Delta(IP)^3/\Delta(INV)$		
Dry	Normal	Wet	Dry	Normal	Wet
6.0	2.0	2.3	3.1	3.7	3.6

[1] $\Delta(TWB)$: change of total water use benefit (*TWB*),
[2] $\Delta(INV)$: change of infrastructure investment (*INV*),
[3] $\Delta(IP)$: change of irrigation profit (*IP*).

Irrigation systems

Four scenarios of irrigation efficiency were considered. In the base scenario, irrigation efficiency takes the base value shown in Table 4.17. In the other three scenarios, the irrigation efficiency was 1.15, 1.30 and 1.40 times the base value, respectively. Values of *Δ(TWB)/Δ(INV)* and *Δ(IB)/Δ(INV)* for the different scenarios are shown in Table 4.53. For example, if irrigation efficiency is increased from the base value to 1.15 times the base value, *Δ(TWB)/Δ(INV)* is 7.0, 4.0, 3.5 in a dry, normal, or wet year, respectively. The table shows that investment in irrigation systems is economically efficient in all cases and at all hydrologic levels. The investment is most efficient with a "dry" hydrologic level and less efficient with a wet level. In a wet year, in view of the irrigation profit, the investment is not attractive. In view of the total benefit, since saved water from irrigation can always be used for instream purposes, the investment is less sensitive to hydrologic levels. The incremental benefit to irrigation provides a measure of the amount of funding that might be used to finance irrigation system improvements.

Table 4. 53. Economic efficiency of investment for irrigation systems.

Irrigation System Efficiency Change	Δ(*TWB*)/Δ(*INV*)			Δ(*IB*)/Δ(*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

Results from the model show investment on drainage systems is not economically attractive.

4.3.4.8 Effect of municipal and industrial (M&I) water demand

Municipal and industrial water demand accounts for less than 20% of the total water demand in the study area. In the model we assume the M&I water demand must be satisfied. However, with the increase of the M&I water demand in the study area, conflict will arise between the M&I water supply and water supply for other purposes such as irrigation and ecological use. To find the effect of the M&I water demand, four scenarios were considered in which the M&I water demand is 1.0, 1.25, 1.50, and 2.0 the base value (shown in Table 4.21), respectively. The hydrologic level considered is normal, and all other conditions are the same as the base model. Table 4.54 shows the results of these scenarios. Irrigation profit and ecological benefit will be affected, and no change of hydropower profit, when the M&I water demand increases.

Table 4. 54. Effect of M&I water demand.

Scenarios of M&I water demand (* base value)	Irrigation profit *IP* (billion $)	Ecological benefit *EB* (billion $)	Power profit *HP* (billion $)	Total benefit *TWB* (billion $)
1.00	2.7554	1.3466	0.1866	4.2886
1.25	2.6774	1.3164	0.1866	4.1804
1.50	2.5782	1.2904	0.1866	4.0551
2.00	2.3516	1.2248	0.1866	3.7629

4.3.5 Uncertainty Analysis

In the integrated model presented here, uncertainties exist in hydrologic, agronomic, economic and institutional components. Considering the risks associated with these uncertainties is necessary for appropriate decision-making. The integrated model provides a framework to analyze risks based on the inter-relationships between the components considered in the model. In this section we mainly discuss the risks from hydrologic uncertainties, and the effects of hydrologic uncertainties on agronomic and economic outputs are demonstrated. Due to data incompleteness, risks from agronomic and economic factors will only be addressed normatively.

4.3.5.1 Risk from hydrologic uncertainty-chance-constrained models

A large body of studies on stochastic water resources management has appeared in the literature. The models used in those studies include stochastic dynamic programming models (Louck et al., 1981), chance-constrained models (Mays and Tung 1992), and recourse models (Watkins, 1997). Among these models, chance-constrained models have the simplest structure. A chance-constrain model can be expressed as:

$$\begin{aligned} &\min\ \mathbf{cx} \\ &s.t.\ \mathbf{P}(\tilde{\mathbf{A}}\mathbf{x} \le \tilde{\mathbf{b}}) \ge \mathbf{a} \end{aligned} \tag{4-6}$$

where both right hand side coefficient $\tilde{\mathbf{b}}$ and technological coefficients $\tilde{\mathbf{A}}$ can be random. **a** is a vector of specified reliability of compliance (or confidence). This kind of models accepts infeasibility, but only with ‘small’ probability. One of the advantages for the chance-constraint is that the model is not driven by the ‘worst’ scenario; and another advantage, maybe most advantageous to realistic application, is that the size of equivalent deterministic model is almost as large as the stochastic model. One of the disadvantages is that magnitude of violation is not captured. This disadvantage can be cleared by using a recourse model, in which infeasibility is corrected at a cost represented by a recourse function. The recourse models have been proved to be proactive methods for stochastic programming (Mulvey et al., 1994, Watkins, 1997). However, to use a recourse model, the equivalent deterministic model has to incorporate a number of scenarios, and the model size is often proportional to the number of the scenarios, which will make the model very large. As described in Chapter 3, the deterministic short-term model is already a large model, and it is necessary to keep the model at an appropriate size so that it can be solved efficiently. Based on this consideration, in this research, we only use the chance-constrained models to treat hydrologic uncertainties, including those of monthly inflow and precipitation.

Equation (4-6) represents a linear model and the derivation of its deterministic form is given in Mays and Tung (1992). The integrated model described in Chapter 3 is a highly nonlinear model, and we treat the monthly inflow and precipitation as the right hand side coefficient $\tilde{\mathbf{b}}$ in water balance equations of reservoirs, river reaches, and crop root zones. The reservoir and river reaches water balance equations are linear, but the soil water balance equations are nonlinear. However, as shown in Appendix I, if only the right hand side coefficient $\tilde{\mathbf{b}}$ is random, a general stochastic model, linear or nonlinear has the same deterministic form with a linear model.

As described in section 4.1.1, a log-normal distribution fits the monthly inflow of the study area, and a normal distribution fits the monthly precipitation. The statistics of both inflow and precipitation are included in the chance-constrained model. We assume the monthly inflow and the monthly precipitation have the same reliability, i.e., the same vector of reliability ($\boldsymbol{a}$) of compliance is applied in the right side of equations including the item of inflow or precipitation. For simplicity, the same reliability is applied in each month. We defined six scenarios, corresponding to the values of reliability 1.00, 0.95, 0.85, 0.75, 0.65 and 0.50 respectively. Based on the above assumptions, a scenario with reliability 1.00 means the reliability of both the monthly inflow and the monthly precipitation in all months is 1.00. The standard variates of the random item corresponding to above reliabilities are presented in Table 4.55.

Table 4. 55. Reducing slope with reliability in the chance-constrained model (Mays and Tung, 1992).

Reliability	*50%*	*65%*	*75%*	*85%*	*95%*	*100%*
Reducing slope	0	-0.385	-0.675	-1.037	-1.645	-3.492

In Figure 4.25, we show the results from the six scenarios total benefit (*TWB*) vs. reliability and the irrigation profit (*IP*) vs. reliability are plotted. The range of *TWB* is \$3.00-4.04 billion, and the range of *IP* is \$1.91-2.68 billion.

Water value for each demand site under the six hydrologic-reliability scenarios is shown in Table 4.56. Water values for demand sites at downstream (*Low_syd* and *Artur*) and at tributaries (*Chakir* and *Artur*) are less sensitive to the hydrologic reliability; while for demand sites upstream, the values decrease when the reliability is reduced.

Water value for each crop combination is shown in Table 4.57. The values for the major crops decrease when the hydrologic reliability is reduced.

Table 4. 56. Water values (US\$/m^3) for demand sites under hydrologic reliability scenarios.

Hydro. Reliability	Naryn	Low_syd	Chakir	Artur	Mid_syd	Fergana	Average
100%	0.110	0.022	0.063	0.065	0.015	0.098	0.062
95%	0.110	0.022	0.063	0.066	0.042	0.095	0.066
85%	0.107	0.022	0.063	0.065	0.047	0.092	0.066
75%	0.105	0.022	0.063	0.065	0.048	0.09	0.066
65%	0.104	0.022	0.063	0.065	0.048	0.086	0.065
50%	0.103	0.023	0.068	0.065	0.048	0.086	0.066

Table 4. 57. Water values (US$/m^3) for crops under hydrologic reliability scenarios.

Hydro. Reliability	Cot_foa	wht_maz	alf_alf	oth_oth
100%	0.179	0.103	0.041	0.058
95%	0.158	0.103	0.041	0.063
85%	0.149	0.103	0.041	0.065
75%	0.146	0.102	0.041	0.075
65%	0.144	0.102	0.040	0.078
50%	0.141	0.101	0.040	0.081

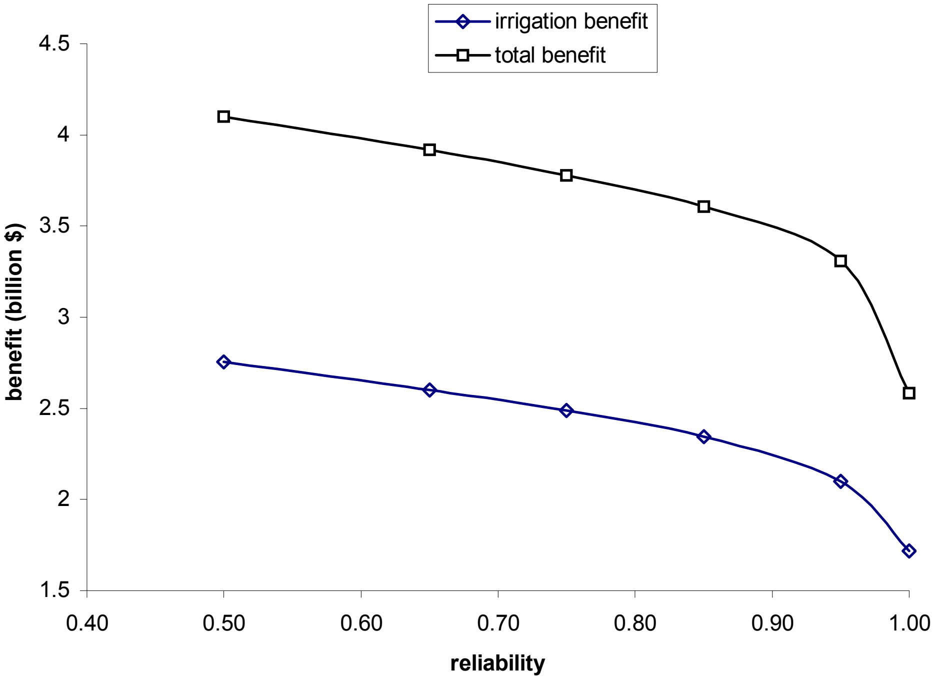


Figure 4. 25. Irrigation profit & socio-benefit vs. Hydrologic reliability.

4.3.5.2 Risk from other uncertainties

Because of the data incompleteness, risk analysis of agronomic and economic factors could not be performed for this case study. However, risks from the uncertainties of these factors should have the same important impact to the outcomes of water uses, as hydrologic uncertainties do. Among the agronomic parameters, the one with the largest uncertainty may be the maximum crop production (Table 4.15), which is the crop production under perfect conditions, water, soil, fertilizers, labor input, etc. Many factors may bring uncertainty to the estimation of this parameter. In economic parameters, crop prices and water supply prices, which are affected by many socio-economic factors, are most uncertain.

Although no systematic risk analysis is presented for these parameters, results under various scenarios of these parameters are already shown above, which may help to understand the effect of the uncertainties associated with these parameters. If a probability distribution is available for any of these parameters, the chance-constrained model applied to handle hydrologic uncertainties could be effectively used for analyzing agronomic and economic uncertainties.

4.4 CONCLUSIONS

The major purpose of this chapter is to answer the following two questions: Why is the integrated hydrologic-agronomic-economic model recommended for sustainability analysis? Why is the short-term model not enough for sustainability analysis? Through the results from various scenarios of the short-term model, the performance of the integrated hydrologic-agronomic-economic model applied in irrigation dominated river basins has been demonstrated. We show that hydrologic system operations are derived by agricultural productivity and instream water use (hydropower and ecological use). Irrigation and drainage management, as a conjunctive part for basin-wide sustainable water resources management, has important contributions to the outcomes of water uses. Economic analysis explores the economic values of water uses under various scenarios of hydrologic conditions and infrastructure status of irrigation and drainage management. Economic incentives, including water supply prices, crop prices and tax on excess salt discharge, are shown to have profound influences on the performance of integrated hydrologic-agronomic-economic systems. Finally, the effects from hydrologic uncertainties on agronomic and economic outputs are demonstrated.

The outcomes of water uses are examined in terms of economic efficiency, equity, environmental impact, as well as the risk from hydrologic uncertainties. Hydrologic system operation rules, irrigation and drainage infrastructure improvements, and economic incentives are searched within an optimization framework to maximize the total benefit from irrigation, hydropower generation, and ecological water use. The main advantages from using the model for sustainability analysis at a river basin scale include: (1) system integration instead of fragmentation provides an analytical framework to find both economic and environmental consequences from policy choices. This process represents a tradeoff between gains and losses and it is necessary to trace sustainability in water resources management; and (2) alternative solutions can be searched based on hydrologic, agronomic, economic and institutional conditions within the integrated system. As we will show later, by extending this short-term model to a long-term model, we can have an inexpensive tool to analyze sustainability in water resources management at the river basin. This short-term model includes the basic components and relationships of the modeling tool.

Through the analytical issues discussed in this chapter, we also clearly demonstrate the limitations of using the short-term model for sustainability analysis. The problems are due to the fact that environmental impacts are not wholly connected to the utility of water uses. More specifically, groundwater quality degradation could not be reflected in the short-term model; soil salinity ends with worse status, economic efficiency for drainage is under-evaluated. Therefore, the results from the model do not wholly reflect sustainability of water management in irrigation-dominated river basins. To solve these problems, a long-term model is a necessity.

Finally, it should be noted that some technical difficulties exist in developing and applying the large-scale model formulated in this research. The major difficulty comes from data requirements and data processing. The model needs hydrologic, agronomic, economic and institutional data, which may be available from experiments, statistics, and empirically estimation. Optimistically, assuming the availability of all the data, one should be careful when mixing data of different themes, different types, and different spatial and temporal scales. The difficulties on data preparation for integrated hydrologic-economic models are discussed in Chapter 3.

Another technical difficulty is to solve the model. The short-term model is a large-scale, nonconvex, nonlinear optimization model written in the GAMS high level language (Brooke et al., 1988, 1996). The model statistics are as below:

Number of equations: 9874
Number of variables: 13713
Number of non-zero elements: 57200
Number of nonlinear non-zero elements: 31099

Due to the size and complexity of the model, it is very difficult, to use any currently available solvers to solve the model. In this research, a piece-by-piece procedure was developed and applied to solve the model efficiently.

Chapter 5

Solving Large-Scale NLP Water Resources Management Models

5.1 BACKGROUND

5.1.1 Nonlinear water resources management models

For many water resources management models, nonlinear programming (NLP) offers a general mathematical formulation for handling non-separable objective functions and nonlinear constraints. Often, these models contain at most bilinear or quadratic objectives and constrains. Some of these models with bilinear items are summarized in Table 5.1.

Yeh (1985) reviewed some traditional nonlinear programming (NLP) algorithms in surface water resources management, including the quasi-Newton method, the gradient projection method, the reduced gradient method and the Lagrangian dual procedure. However, these calculus-based NLP algorithms are generally suitable for convex problems, and they very often do not lead to the global solution of the nonconvex problems (Floudas et al.,1989). In addition, the computational speed of these algorithms tends to be slow. Yeh argued that NLP gained its practical importance only in some cases, such as the following: (1) when inequality constraints can be dealt with by using an interior point barrier function and equality constraints can be dealt with using an exterior penalty function; (2) when nonlinear constraints can be linearized; and (3) when nonlinear problems can be decomposed into separable sub-problems, assuming the problems are convex. Obviously these conditions can often limit the application of NLP in water resources management modeling.

Table 5. 1. Water resources management models with bilinear relations

Model types	**Nonlinear items**	**References**
Reservoir operation with hydropower Generation	*release*head*, and storage and surface area may be nonlinear function of head.	Loucks et al., (1981) and this research
Water distribution model with contaminant constituent balance	*flow * concentration*	McKinney and Cai (1997), and this research
Irrigation cropping model	*Irrigated area * depth of water applied*	Kumar et al. (1998), and this research
Groundwater quantity management model (unconfined aquifers)	*head * head*	Willis and Yeh (1987)
Integrated Groundwater quantity and quality management model	*velocity * concentration*	Willis and Yeh (1987), and Gorelick (1983)

For groundwater management models, Gorelick (1983) found much work had been done for solving water quality management models with known groundwater velocity fields, while, for some cases, groundwater velocity fields might be unknown and should be considered explicitly within the management model. In these cases, the contaminant transport equation and the groundwater flow equation must be solved simultaneously, and nonlinearities arise as a result of products of unknown concentrations and unknown velocity components which occur in advective and dispersive transport terms. The tightest connection of water quantity and quality aspects exists in these nonlinear models.

In many cases the NLPs in water resources management models are nonconvex, but local solvers are applied. Methods for obtaining global solutions to nonconvex mathematical programming problems have appeared rarely in the water resources literature, even though these problems are the rule more than the exception.

5.1.2 Genetic algorithms

In recent years, genetic algorithms (GAs) have been proposed as a promising method to solve nonconvex NLP problems in water resources systems planning. Genetics algorithms (GAs) are a subclass of general artificial-evolution search methods based on natural selection and the mechanisms of population genetics (Michalewicz, 1992). In this form of search the solution vector evolves throughout generations, improving the features of potential solutions by means of biologically inspired operations. GAs belong to a family of optimization techniques in which the solution space is searched by generating candidate solutions with the help of a pseudorandom number generator. As the run proceeds, the probability distribution by which new candidate solutions are generated may change, based on results of trials earlier in the run. The theory behind GAs was proposed by Holland (1975) and further developed by Goldberg (1989) and others in the 1980s. These algorithms rely on the collective learning process within a population of individual candidate solutions, each of which represents a search point in the space of potential solutions. The theoretical principle of implicit parallelism (Holland, 1975) enables highly fit solution structures (schemata) to receive increased numbers of offspring in successive generations and thus lead to better solutions.

There are many variations of GAs but the important features are general. The analogy with nature is established by the creation within a computer of a set of candidate solutions called a population. Each individual in a population is represented by a set of parameters that completely describe a solution. These are encoded into chromosomes, which are, in essence, sets of character strings analogous to the chromosomes found in DNA. Standard GAs use a binary alphabet (characters may be 0's or 1's) to form chromosomes. But not all GAs restrict representation to the binary alphabet, which makes them more flexible and applicable to variety of decision-making problems.

The initial population of solutions is usually chosen at random, and then it is allowed to evolve over a number of generations. For each generation, a measure of how good each chromosome (or candidate solution) is with respect to an objective function is calculated. This measure is called the *fitness* for each individual in a population. For each individual, its binary alphabet is decoded into parameter values, and then these values are substituted into a program that is used to calculate the value of the objective function, i.e., its fitness. Next, individuals are selected for "mating" to produce offspring, and this process is called *reproduction*. The reproduction is based on probabilities calculated from the individual's fitness value, which means that strings with a higher value have a higher probability of participating in reproduction and contributing one or more offspring in the next generation. Two important processes continue after the reproduction phase, namely *crossover* and *mutation.* In the process of crossover, genetic material crosses over from one chromosome to another. Reproduction and crossover combine to test and exchange high-performance notions in the search for potentially new ideas, which is the process of *innovation.* However, in the processes of reproduction and crossover, some potentially useful genetic materials may be lost. The process of mutation, which is the occasional random alternation of the value of a string position, protects against such an irrecoverable loss. Crossover plays a primary role in GAs, and the probability of crossover is generally set high, while mutation plays a secondary role, and the probability mutation is set low. Using GAs for a particular problem, these probabilities need to be selected by trial-and-error, which is a drawback of using GAs.

GAs have clearly demonstrated their capability to yield robust and good approximate solutions even in cases of complicated multimodal, discontinuous, nondifferentiable functions (Savic and Walters, 1994). Because of their stochastic nature, there is no guarantee that the global optimum solution will be found, but a variety of applications have shown a high-level of performance across the spectrum of the problems. Recently, there has been a significant growth of interest in using GAs for water resources planning and design. McKinney and Lin (1994) and Huang and Myer (1997) applied a binary-coded GA to the pump-and-treat groundwater remediation, Savic and Walters (1996) applied GAs for least-cost design of water distribution networks, and Halhal et al (1997) studied water network rehabilitation, replacement, and expansion by using a structured messy genetic algorithm. Oliveira and Loucks (1997) developed a GA-based approach to search effective operating policies for multipurpose multireservoir systems. All problems dealt with in these studies are basically nonlinear. Huang and Myer (1997), and Oliveira and Loucks (1997) included state transformation between discrete time periods. All others were static models. The advantage of GAs for a nonlinear problem comes from its stochastic search strategy: the optimal solution is searched for by testing solutions of the problem which are first created randomly within the solution space, and then induced by the "fitness" of the modeling output. The modeling method for each solution testing is generally simulation, which handles nonlinear relationships and large models easily.

The major obstacle for using standard GAs in water resources designing, planning and management is the long computation time due to the global random search. For large-scale water resources models, a study on computation time with GAs has not yet appeared in the literature.

5.1.3 Decomposition techniques in water resources modeling

If the size of NLP models (i.e. the number of variables and the number of equations) is large, solving them becomes difficult. Decomposition techniques are extensively used to handle large and complex models in water resources management modeling. The most important factor encouraging the decomposition of a large water resource system into small systems, namely subsystems, is the difficulties faced in designing a large system as a single system. The difficulties come from two aspects: one is that, typically, the computing time required to solve a large model is not acceptable, given current computing capacity; the other is that for some large and complex systems, the traditional algorithms are not able to find satisfactory solutions (Yeh, 1985; Gorelick, 1983). Decomposition is generally applied for cases such as those described below:

(1) Spatial decomposition, decomposing a hydrologic system into a number of subsystems. This method is most often used in conjunctive surface water and groundwater use and multi-reservoir operation. River systems and aquifers are simulated separately, but both are regulated through the physical interactions between them (seepage, river depletion, groundwater discharge etc). For some multiple reservoir operation problems, reservoirs are first modeled individually, and then an inter-reservoir control program is used to regulate the relations between reservoirs, arriving at an approximate global solution (Turgeon, 1981).

(2) Temporal decomposition, decomposing a long-time horizon into a number of stages. Discrete-time modeling is based on this decomposition. The previous, current, and next stage are connected through physical transformation relations, respectively. Among these approaches, dynamic programming (DP) is popular in use (Augustine, 1989).

(3) Thematic decomposition, decomposing an integral problem into some sub-problems according to thematic characteristics. For example, separating water quantity and quality modeling.

For all decomposition approaches, the critical step is to implement the interaction between the subsystems. Theoretical work on the decomposition techniques was introduced by Lasdon (1970). The most popular decomposition techniques include Dantzig-Wolfe Decomposition (1960), Bender's Decomposition (1962), and Generalized Bender's Decomposition (Geoffrion, 1972). Although these techniques are different in implementation, and are suitable for different problem structures, they are all based on the same idea: the initial problem is decomposed into smaller sub-problems, whose coordination is controlled by what is called the master problem. The master problem and the sub-problems are solved interactively: the master problem creates a proposal and sends it to the sub-problems, and the proposal is tested and information is sent back to the master problem. The master problem then creates a new proposal according to the "feedback", and so on.

On the practical side of water resources planning and management, development of general methods for decomposition does not seem to be feasible, due to the specific purposes and conditions of the problems studied. However, evidence of this kind of development can be found in the literature. Haimes (1977) developed a multilevel decomposition technique for large water resources systems, in which the basic idea is the same as in the theoretical decomposition methods in the sense that the top level acts as a master problem. More recently, work to incorporate general theoretical decomposition methods (e.g., Bender's Decomposition) into procedures to solve large-scale complex water resources management problems has been done. Watkins and McKinney (1997) used Generalized Bender's Decomposition (GBD) and Outer Approximation (OA) to solve a mixed-integer nonlinear (MINLP) water resources optimization model with fixed costs. Cai et al. (1999) presented a global search approach to solve large-scale nonlinear nonconvex problems in water resources management. The approach was proved effective in solving two large water resources management models: a multi-reservoir operation model with nonlinear hydropower generation functions and a regional water allocation model with linear flow balance equations and nonlinear salt balance equations.

5.1.4 New approaches: extensions of GA and decomposition techniques

This chapter presents three approaches to solve large NLP water resources management models. The first approach is based on Generalized Benders Decomposition (GBD) algorithm, using an approximation to the GBD cuts proposed by Floudas et. al.(1989) and Floudas (1995). To insure feasibility of the GBD subproblem, we relax its constraints by introducing elastic slack variables, penalizing these slacks in the objective function. This approach leads to solutions with excellent objective values in run times much faster than the GAMS NLP solvers MINOS (Murtagh and Saunders, 1987), and CONOPT (Drud, 1994). This approach is especially useful for nonconvex NLP problems, and we apply it to a large nonconvex water allocation model involving flow and salinity balance at the river basin scale.

The second approach presented in this chapter is based on the combination of a genetic algorithm (GA) and a linear programming (LP), and it is applied to solve a nonlinear reservoir operation model with nonlinear hydropower generation relationships. As shown in Table 5.1, bilinear items (reservoir surface elevation multiplying release) appear in the hydropower generation expression. The original model is reformulated as a linear program by fixing the reservoir surface elevation, which is treated as a variable vector in the genetic algorithm. The genetic algorithm determines the values of the surface elevation, and these values are taken as parameters and substituted into the LP model. The solution from the LP model is used to calculate the fitness, which is fed back to the genetic algorithm for creating a new generation (a set of new values for reservoir elevations), and so on. The process of improved solution generating and evaluating is repeated until no further improvement in performance is obtained.

The third approach is called the "piece-by-piece" approach. It is assumed that a large model can be decomposed into several pieces, and the model is solved step by step with one more piece added in each step. At each step, solving the partial model is based on the solution found in the last step, and the solution from the current step is saved as a basis for the next step. At the final step, all pieces are added together, and the whole model is then solved. For a large model including nonlinear relationships, available solvers may not directly solve the model. This is the case for the short-term model described in Chapter 3. However, the model was successfully solved by the "piece-by-piece" approach.

Details about these approaches and their applications are described in the rest of this chapter.

5.2 A GBD -BASED APPROACH

A more theoretical description of this approach should is given in Floudas et. al. (1989), and Cai et al. (1998). Here we put more emphasis on the implementation and application of this approach to nonconvex nonlinear water resources management models. As an example, the approach is applied to solve a river basin water allocation and salinity control model developed by McKinney and Cai (1997). Through the example, we demonstrate some advantages of this approach in (1) dealing with nonconvexity; (2) solving large models; and (3) searching for an approximate global optimal solution.

5.2.1 Generalized Benders Decomposition

In the Benders' Decomposition method (*BD*) (Benders, 1962), the key procedure is to select *complicating variables* in the original problem, so that the original problem becomes a much easier problem to solve when the complicating variables are fixed. The procedure leads to the decomposition of an original problem into a sub-problem (*SP*) and a master problem (*MP*), and the final solution of the original problem is reached through iterating between these problems. One limitation for *BD* is that the parameterized *SP* needs to be linear. Geoffrion (1972) generalized *BD* (*GBD*) to a broader class of problems in which the *SP* needs no longer be linear. The mathematical programming problem that Geoffrion defined is:

Original problem (OP):

$$\begin{aligned} &Max \quad f(x,y) \\ &\text{subject to:} \\ &g(x,y) \geq 0 \\ &x \in X, y \in Y \end{aligned} \tag{5-1}$$

If $\boldsymbol{y}$ is chosen as a class of complicating variables, then a *SP* is formulized as:

Sub-problem (SP):

$$\begin{aligned} &\underset{x}{Max}\, f(x,y^*) \\ &\text{subject to:} \\ &g(x,y^*) \geq 0 \\ &x \in X \end{aligned} \tag{5-2}$$

The *SP* has an optimal *multiplier vector* ***u*** for each $\boldsymbol{y}^{*} \subseteq \boldsymbol{Y} \cap \boldsymbol{V}$, if **X** is convex, ***g*** and ***f*** are both concave on **X** for each $\boldsymbol{y}^{*}$, and

$$V = \left\{ y | y \in Y, \exists x \in X, g(x,y) \geq 0 \right\} \neq \Theta \tag{5-3}$$

The derivation of the master problem begins with a partitioning of the original problem into an equivalent formulation featuring an inner and outer optimization problem:

Equivalent problem to the original problem:

$$\begin{aligned} &\boldsymbol{Max}\ \ \boldsymbol{v(y)} \\ &\text{subject to} \\ &v(y) = \{\max \ \ f(x,y) | g(x,y) > 0, \ \ x \in X\} \\ &y \subseteq Y \cap V \end{aligned} \tag{5-4}$$

The inner optimization problem over $\boldsymbol{x} \in \boldsymbol{X}$ is simply the SP. The outer optimization problem seeks to maximize ***v(y)*** over all $\boldsymbol{y} \subseteq \boldsymbol{Y} \cap \boldsymbol{V}$**,** defined as the set of all *y* that provides a feasible solution to the constraint set *g(x, y)*. ***v(y)*** and ***V*** can be represented explicitly by dualizing the inner problem:

$$v(y) = \underset{u \geq 0}{Min} \ \underset{x \in X}{Max} \left\{ f(x,y) + u^{T} g(x,y) \right\} \tag{5-5}$$

$$V = \left\{ y | \underset{x \in X}{Max}\, \lambda^T g(x,y) \geq 0, \forall \lambda \in \Lambda \right\} \tag{5-6}$$

where,

$$\Lambda = \left\{ \lambda \in R^m : \lambda \geq 0 and \sum_{i=1}^{i=m} \lambda_i = 1 \right\} \tag{5-7}$$

If we define

$$L^*(y,u) = \underset{x \in X}{Max} \left\{ f(x,y) + u^T g(x,y) \right\} \tag{5-8}$$

$$L_*(y,\lambda) = \underset{x \in X}{Max}\, \lambda^T g(x,y) \tag{5-9}$$

Then, the master problem (MP) can be written as:

Master problem (MP):

$$\begin{aligned} & Max\ y_0 \\ & \text{subject to:} \\ & y_0 \leq L^*(y,u) \quad \forall u \geq 0 \\ & L_*(y,\lambda^j) \geq 0 \\ & y \subseteq Y \end{aligned} \tag{5-10}$$

The master problem can be difficult to solve in its above form since it has an infinite number of constraints. This difficulty can be overcome by relaxing the formulation to form the following relaxed master program (*RMP*):

Relaxed master problem (RMP):

$$Max\, y_0$$

$$\text{Subject to:} \qquad (5\text{-}11)$$

$$y_0 \le L^*(y, u^i) \quad i = 1,2 \ldots r$$

$$L_*(y, \lambda^j) \ge 0 \quad j = 1,2 \ldots p$$

$$y \subseteq Y$$

Testing the solution of the relaxed problem requires solving the *SP*. If this problem is feasible, then a new constraint (L^*) based on the optimal multiplier vector **u** is generated for the *RMP* to make it closer to the original problem. If the *SP* is infeasible, then a constraint of the form $L_*(y, \lambda^j) \ge 0$ is violated for some λ. For that λ, the L_* constraint is added to the *RMP* to keep it in the feasible range of the original problem.

As the *RMP* contains fewer constraints than the equivalent of the original problem, its optimal value must be greater or equal to the optimal value of the original problem. Thus the *RMP* provides an upper bound on the final solution. Conversely, as the complicating variables are fixed in the *SP*, it contains more constraints than the equivalent of original problem, and thus the *SP* provides a lower bound to the final solution.

5.2.2 GBD based approach for solving nonlinear nonconvex models

The approach was primarily proposed by Floudas et. al. (1989), who suggested a 4-stage approach:

stage 1 - Identification of sources of nonconvexities.

stage 2 - Transformations and partitioning of variable set and the nonconvex constraint set.

stage 3 - Decomposition of the original nonconvex problem into two subproblems whose global solutions are attainable.

stage4 - Iterations between the two subproblems to identify the optimal solution, using GBD.

They claimed that *"the key idea in the partitioning and decomposition stages is to select the complicating variables and decompose the problem in such a manner that both the primary and the master problem can be solved for their respective global solutions at each iteration." "The complicating variables are defined as those variables which are responsible for nonconvexities and which when fixed at particular values, allow the resulting subproblem to be solved for its global solution".* If nonconvexities are bilinear in form, then fixing one variable (i.e. the complicating variable) will make the bilinear terms linear, making both the *SP* and the *RMP* linear programs (LPs), which can always attain their global solution if feasible solutions exist. If nonconvexities are in the form other than bilinear, then those items can be transformed into equivalent bilinear forms. Terms that do not have equivalent bilinear forms may be replaced by their "linear underestimating functions" (Floudas et al., 1989). As noted by Floudas et. al., even though the *SP* and the *RMP* can attain their global solution in each iteration, there is no theoretical guarantee that the proposed approach will always identify the global solution. Despite this limitation, Floudas et. al. found that the approach identified the global solution for several nonconvex nonlinear problems (NLP) and mixed-integer nonlinear problems (MINLP).

During the iterations between the *SP* and the *RMP*, if *SP* is feasible, then an optimal multiplier vector ***u*** is generated, and an $\boldsymbol{L}^*$ type constraint is added to the *RMP*. While, if for some y^k, the *SP* is infeasible, Floudas et. al suggested solving a relaxed sub-problem (*RSP*) to obtain the required Lagrangian multipliers $\boldsymbol{\lambda}$**.** The RSP was defined as:

Relaxed *Sub-problem (SP):*

$$\begin{aligned}
&Min \quad \alpha \\
&\text{subject to:} \\
&g(x, y^k) \qquad \geq 0 \\
&h(x, y^k) + \alpha \geq 0 \\
&-h(x, y^k) + \alpha \geq 0 \\
&x \in X
\end{aligned} \tag{5-12}$$

in which the function set ***h*** represents the equality constraints, and α is a positive slack variable vector.

It should be noted that all the examples which Floudas et al (1989) used in their paper are small NLP problems (at most 7 variables, and 10 constraint equations). Although the approach was successfully applied to those examples, we may find it difficult to implement the approach to some large-scale NLP problems that have a large number of complicating variables, and constraints involving the complicating variables. We may need a method to simplify the model structure that includes the $\boldsymbol{L}^*$ and $\boldsymbol{L}_*$ constraints, and includes both the primary ***SP*** and the relaxed *SP*. In our research, we introduce an alternative form of the *RSP*. For each of the tight constraints (generally equality constraints), a slack variable is added, and all slack variables are also penalized in the objective function. This *RSP* is formulated as:

Alternative Relaxed Sub-problem (RSP):

$$\begin{aligned} & \max\ f(x, y^*) - w \cdot (s_1 + s_2) \\ & \text{subject to:} \\ & g_1(x, y^*) \geq 0 \\ & g_2(x, y^*) + s_1 - s_2 = 0 \\ & x \in X \end{aligned} \tag{5-13}$$

where g_1 represents all inequality constraints, and g_2 represents all equality constraints in the primary sub-problem, $\mathbf{s}_1$ and $\mathbf{s}_2$ are positive slack variables, and w is a weight assigned to the penalty item, which depends on the magnitude of the real objective value and the value of the penalty item. This new relaxed sub-problem (*RSP*) is then "feasible" for any values of the complicating variable y^*. Therefore, the *RMP* will have one more L^* function in each iteration, and the L_* function is not needed since all proposals from the master problem will be feasible. The primary *SP* (eq. 5-2) and the relaxed *SP* (eq. 5-12) are replaced by the single relaxed *SP* defined in (5-13).This alternative form makes the application of the approach to large models much easier than with the primary form.

The iterations between the *RMP* and the *RSP* first drive all the slack variables to zero, i.e. a feasible solution to the original problem, and further lead to the optimum solution. Since we put the slack variable in the *RSP* objective function as a penalty, a straight conclusion is that if the original problem is feasible, the slack variable should decrease to zero when the solution is reaching its optimum status, otherwise the non-zero slack will always penalize the objective. But this is not always the case. Assuming we add the slack variables to a reservoir storage balance equation, the model can consider the slack item (a_1 - a_2) as extra water in the reservoir, which may increase the objective value somehow, while simultaneously the nonzero slack variables penalize the objective value. Therefore the slack variable may bring an apparent, but fictitious, tradeoff into the model. Generally, we can give the penalty item a larger weight, so that the slack variable always penalizes the objective more than it improves the objective.

Finally, to apply the GBD based approach proposed by Floudas et. al. for large water resources management problems, we recommend using the relaxed sub-problem (*RSP*) defined in equation (5-13). The steps of the GBD-based approach are:

1. Initialize: $r = 0 =$ iteration number, $y_0 \in Y =$ user supplied initial values for *y*, *lbd* (lower bound) $= -\infty$, *ubd* (upper bound) $= +\infty$, $\in =$ convergence tolerance.
2. Solve $RSP(y_r)$, obtaining an optimal solution x_r objective value $v(y_r)$, and an optimal multiplier vector u_r. If $v(\mathrm{y_r}) > lbd$, set $lbd = v(\mathrm{y_r})$.
3. Generate a closed form expression for $L^*(y, u_r)$ and add the constraint $y_0 \le L^*(y, u_r)$ to *RMP(r-1),* creating *RMP(r).*
4. Solve *RMP(r).* The optimal solution is (y_0^r, y_r). Set $ubd = y_0^r$.
5. If $(ubd - lbd)/abs(lbd) < \in$, stop. (x_r, y_r) is an $\in -optimal$ solution to the original problem.
6. Replace *r* by *r+1* and go to step 2.

5.2.3 Implementation of the GBD based approach

This algorithm has been implemented using the algebraic modeling language GAMS (Brooke et. al., 1988), version 2.50. Both subproblem and relaxed master program (RMP) models are defined, and a loop statement is used to drive the GBD algorithm. This loop contains SOLVE statements for the master and the subproblem, respectively, both using the OSL simplex LP solver. The GBD cut is created by a GAMS statement which includes the optimal values of the primal and dual variables from the previous subproblem solution, and the new cut is indexed by the loop index. The GBD termination criterion is that of Step 5 of Section 5.2.2, with *tol* = 1.0E-3.

The GAMS program exploits the fact that the GBD subproblem structure remains the same at each iteration, but with different parameters (values of *y*), and that only one equation is added to the relaxed master program (*RMP*) in each iteration. All solutions of these linear programs after the first take advantage of GAMS' automatic warm start capabilities. The optimal basis from each LP is saved and used as a starting basis for the next SOLVE. This restarting facility saves significant computing time (Brooke et. al., 1996).

Theoretically, any initial values for *y* should work, since the solution is independent of the initial values. However, better initial values should save computing time. If the number of complicating variables is not large, it is easy to estimate the initial values, $y_0 \in Y$. However, for cases with a large number of complicating variables, initial values for y are best chosen by first solving the relaxed master program with no GBD cuts, i.e., finding $y_0 \in Y$.

5.2.4 An example: solving a river basin water allocation model

5.2.4.1 Model formulation

As an example, we show how to use the GBD-based approach to solve a river basin water allocation model, which was developed by McKinney et al. (1997) for the Karshi region of the Amudarya River basin of Central Asia. It is used to support water allocation decisions with multiple goals including satisfying water demand, maintaining river flow for ecological protection, balancing water use rights among demand sites, and controlling salinity. The network used to model this basin includes 6 reservoirs, 6 aquifers, 8 river reaches, 2 canals, 7 agricultural drainage water collectors, and 10 demand sites (irrigation, municipal and industrial water demands). There are 12 monthly time periods. When salt concentrations are included in the objective, this model instance has 1567 constraints, 2039 structural variables (not including the artificial variables), and 9129 nonzero Jacobian elements, of which 4773 (about 52%) are nonconstant. Hence this model is highly nonlinear, due to the presence of 540 nonlinear salt balance constraints. For a detailed description of the mathematical structure, the reader should refer to McKinney et al. (1997), and Cai et al. (1999). The generic form of the model can be expressed as:

$$
\begin{aligned}
&\max \quad \boldsymbol{\alpha}_0\mathbf{q} + \boldsymbol{\beta}_0\mathbf{c} + \boldsymbol{\sigma}_0\mathbf{o} \\
&\text{Subject to:} \\
&\boldsymbol{\alpha}_1\mathbf{q} = 0 \\
&\boldsymbol{\alpha}_2\mathbf{q} + \boldsymbol{\sigma}_2\mathbf{o} = 0 \\
&\boldsymbol{\alpha}_3(\mathbf{q}\cdot\mathbf{c}) = 0 \\
&\mathbf{q}^l \le \mathbf{q} \le \mathbf{q}^u \\
&\mathbf{c}^l \le \mathbf{c} \le \mathbf{c}^u \\
&\mathbf{o}^l \le \mathbf{o} \le \mathbf{o}^u
\end{aligned}
\qquad (5\text{-}14)
$$

in which variable vector **q** represents flow and storage (volume) variables, including flow in a river reach, release from a reservoir, storage in a reservoir, pumping from an aquifer, the water table of an aquifer, the inflow and outflow from a treatment plant, diversions from sources to demand sites, and return flows from demand sites to water sources; vector **c** represents salt concentrations associated with the corresponding flows or storages; and vector **o** represents intermediate variables that are only related to flow and storage variables. $\boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\sigma}$ are all constant coefficients. *l* denotes lower bound, and *u* denotes upper bound. The objective function is to maximize the benefit from water supply to irrigation, municipal and industrial, environmental, and recreational water uses. The first constraint set represents the system flow balance; the second represents the relations between the intermediate variables and the flow variables; and the third represents the system salt mass balance in river and canal reaches, reservoirs, aquifers, and irrigation fields.

It is natural to choose the salt concentrations **c** as the complicating variables *y*, since there are fewer of them. Surprisingly, this is not the best choice. In fact, for this model, when we chose the salt concentrations **c** as the complicating variables, the GBD-based approach converged very slowly to a good solution. Computational results show that when choosing **q** and **o** as the complicating variables, the computing time with the GBD-based approach is much shorter than with two popular NLP solvers MINOS5 and CONOPT2 (Cai et al., 1999).

This choice may be explained by examining the structures of the *RMP* and *RSP*. If we take the salt concentrations **c** as complicating variables, then initially no constraints except the variable bounds exists in the *RMP*, and all primary constraints remain in the *RSP*. In this way, the *RSP* has the same number of constraints as the primary model, and if the primary model is large, then the *RSP* is large although it is linear. Solving a large *RSP* will take more time, and it has to be solved repeatedly with the proposed GBD-based approach. On the other hand, in this structure, the number of constraints in *RMP* starts from 1 and increases by 1 in each iteration, so the *RMP* has less constraints in early iterations, and the number of the constraints is far less than that of variables, if the number of variables is large. Under this condition, in early iterations, it is difficult for the *RMP* to provide good "proposal" to the *RSP*.

However, if we choose **q** and **o** as the complicating variables, the above problems can be avoided. The constraints in the primary model are split into two parts. The first two sets of constraints are included in the *RMP*, and the third remains in the *RSP*. In this structure, we can avoid solving a large model if the primary model is large. Further, the *RMP* is initially constrained by the flow balance equations and other equations relating flow variables to the objective variable. Such a tight *RMP* provides better proposals (i.e., close to the feasible solution of the primary problem) from the very beginning. Although the size of the *RMP* in this structure is increased by including the additional constraint set, the effect is not significant since the size of the *RMP* is mainly determined by the number of the iterations conducted in the approach.

Introducing two vectors of slack variable ($\mathbf{s_1}$ and $\mathbf{s_2}$, both positive) into the salt mass balance constraints, the *RSP* and the *RMP* of the water allocation model are as follows:

The RSP for the river basin water allocation model

$$\max \ \boldsymbol{\alpha}_0\mathbf{q}^* + \boldsymbol{\beta}_0\mathbf{c} + \boldsymbol{\sigma}_0\mathbf{o}^* - w\cdot(\mathbf{s_1}+\mathbf{s_2})$$

Subject to: (5-15)

$$\boldsymbol{\alpha}_3\left(\mathbf{q}^*\cdot\mathbf{c}\right) + \mathbf{s_1} - \mathbf{s_2} = 0$$

$$\mathbf{c}^l \le \mathbf{c} \le \mathbf{c}^u$$

where ($\mathbf{q}^*$, $\mathbf{o}^*$) is the "proposal" provided by the *RMP*, and *w* is the weight for the penalty item.

The RMP for the river basin water allocation model

$$
\begin{aligned}
&Max \quad y_0 \\
&\text{Subject to:} \\
&\boldsymbol{\alpha}_1\mathbf{q} = 0 \\
&\boldsymbol{\alpha}_2\mathbf{q} + \boldsymbol{\sigma}_2\mathbf{o} = 0 \\
&y_0 \le \boldsymbol{\alpha}_0\mathbf{q} + \boldsymbol{\beta}_0\mathbf{c}^* + \boldsymbol{\sigma}_0\mathbf{o} - \omega\cdot(\mathbf{s}_1{}^* + \mathbf{s}_1{}^*) + \mathbf{u}^{\mathbf{T}}\cdot\left\{\boldsymbol{\alpha}_3\left(\mathbf{q}\cdot\mathbf{c}^*\right) + \mathbf{s}_1{}^* - \mathbf{s}_2{}^*\right\} \\
&\mathbf{q}^l \le \mathbf{q} \le \mathbf{q}^u \\
&\mathbf{o}^l \le \mathbf{o} \le \mathbf{o}^u
\end{aligned}
\qquad (5\text{-}16)
$$

where $\mathbf{c}^*$ is the salt concentration solved from the *RSP*, **u** is a vector of Lagrange multipliers for the constraints expressed in equation set (5-15).

5.2.4.2 Computational results

In the structure described above, the river basin water allocation model has 1499 complicating variables *y*, and 540 coupling constraints. As mentioned, the most effective way to choose initial y's is to solve the relaxed master program with no GBD cuts. Figure 5.1 shows the behavior of the lower bound, and upper bound versus iteration count for the model when the initial *y* is chosen in this way. This model, with 1499 complicating variables, converges in only 13 iterations.

We believe that this faster convergence is due to the "tighter" relaxed master program of the water allocation models.

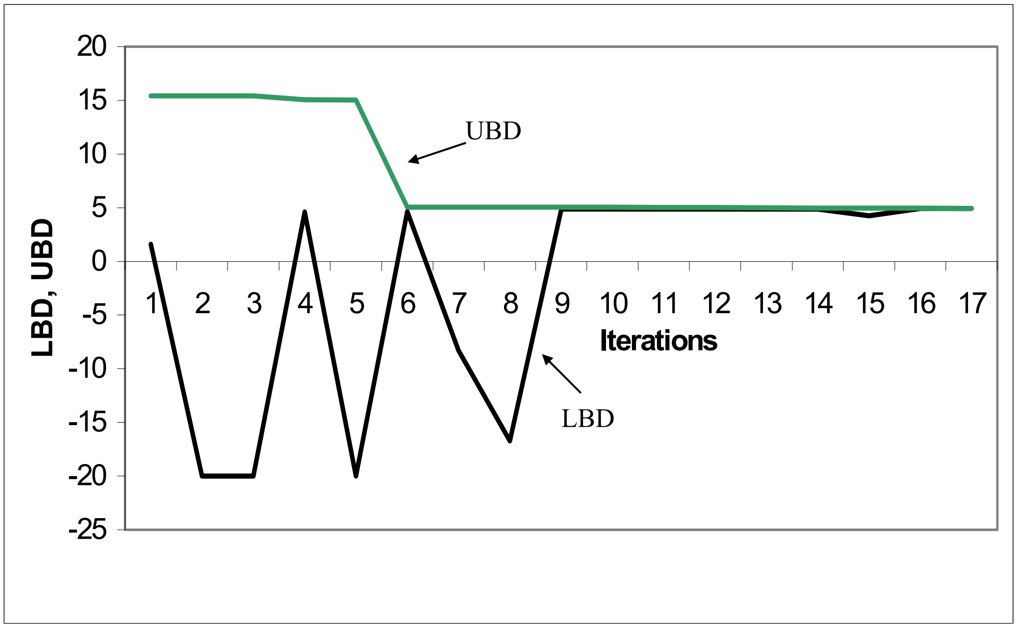


Figure 5. 1. GBD Lower bound (LBD) and upper bound (UBD)

Several cases are defined to test the GDB-based approach based on various initial values for the complicating variables as shown in Table 5.2. We first solved the problem using the GBD-based approach and then, using the final GBD solution as an initial point, solve it using MINOS and CONOPT2, separately. The objective value from the GBD-based approach is 4.9744, and the objective value from MINOS5 and CONOPT2 with the GBD solution as an initial point is 4.9809 and 4.9812, respectively. Despite the excellent initial points, MINOS and CONOPT2 were unable to improve on the first three significant figures of the final GBD values in cases 1 and 2, so this value is at least locally optimal to within the rather tight default tolerances of CONOPT2. Cai et al. (1999) discuss why the solution is not a real global solution but just an approximate one.

Table 5.2 shows the final objective values, GBD iterations, and run times of GBD, MINOS and CONOPT2 when they use the same initial point. MINOS and CONOPT2 use all default tolerances and options. Run times shown are the "resource usage" times reported on the GAMS listing file for the solution phase. The computer used is a Pentium II 300 mHz PC. Four different initial points are used. The best initial point, Case 1, chooses initial *y's* as the "optimal flow" solution described above, and initial *x's* by solving the GBD subproblem. The other three cases use different "ballpark" initial y values, assigning identical "ballpark" values to each variable within a set of related variables, e.g., flows into and out of river nodes, from rivers to canals, etc.

GBD produces objective values slightly worse than the other 2 solvers in all cases, but the largest difference, in Case 3, is only 0.74%. GBD is much faster than the other two solvers, often by more than a factor of 20 over MINOS, and by factors of 3 to 9 over CONOPT2. GBD time is affected very little by the starting point. In the column "MINOS, Third Run", we show the final objective value resulting from 3 successive applications of MINOS, using 3 consecutive GAMS SOLVE statements. SOLVE 1 uses the same initial solution as GBD, and SOLVES 2 and 3 use the result of the previous SOLVE as starting points. This easy-to-implement strategy improves the MINOS objective value achieved with one SOLVE by 1.56% in case 3. Using a single SOLVE, CONOPT2 achieves slightly better objective values than the other solvers in two of the four cases, but fails to find a feasible solution in case 2. However, CONOPT2 achieves the best objective value of all using three successive SOLVES in this case.

Table 5. 2. Performance of GBD, MINOS, and CONOPT using 4 different initial points.

CASES	GBD			MINOS[2]				CONOPT[3]			
	Obj	Iteration	Time	First Run		Third Run		First Run		Third Run	
				Obj	Time	Obj	Time[1]	obj	time	Obj	Time[1]
Case 1	4.9744	13	20.5	4.9809	68.71	4.9809	3.7	4.9812	24.0	4.9812	3.7
Case 2	4.9535	10	18.6	4.9837	738.2	4.9837	3.0	Failed	50.2	4.9838	172.8
Case 3	4.9426	15	23.9	4.8992	535.1	4.9760	3.0	4.9794	202.5	4.9794	0.44
Case 4	4.9653	12	19.8	4.9816	522.7	4.9816	2.3	4.9787	74.5	4.9787	0.54

Case 1: initial y values obtained by solving the GBD master program with no cuts.
Cases 2, 3, 4 use 3 sets of “ballpark” initial guesses for y.

All programs were run on the same PC-300, Pentium-II. The computational time here is defined as the “resource usage” in the GAMS output file.

[1] Additional time since the first run

[2] default feasibility and optimality tolerance

[3] default feasibility and optimality tolerance

5.2.5 Summary

Using a relaxed formulation of the GBD subproblems and a sufficiently large penalty weight, the GBD-based approach has performed well in solving the large, nonconvex, bilinear water management problem studied here. GBD solution quality is comparable to that of MINOS or CONOPT2, and GBD is considerably faster. Furthermore, GBD can be used advantageously in conjunction with these or any other local solvers, by using the final GBD solution as an initial point for the local solver. In our experiments, MINOS and CONOPT2 were able to improve this solution to a small degree. The GBD-based approach has been shown to handle roughly 1500 complicating variables in situations where the relaxed master program is tightly constrained by the constraints defining Y. Hence analysts considering using GBD to solve nonlinear problems should consider carefully which variables are designated as complicating, and consider reversing the "natural" assignment that tries to minimize the number of these variables. Although only one example is represented in this section, the proposed GBD-based approach should be suitable for all the water resources management models listed in Table 5.1. If well formulated, the approach can be used to solve large nonlinear nonconvex models in much less computing time compared to popularly available NLP solvers.

5.3 A COMBINED GA&LP APPROACH

5.3.1 Introduction

A standard genetic algorithm includes a program to calculate the "fitness" of each individual in a generation. In the GA literature, this program is generally an external simulation module that is integrated into the framework of the genetic algorithm. However, the approach proposed here, which is designed to solve nonlinear nonconvex optimization models, takes a linear programming (LP) model

model for the fitness calculation in a genetic algorithm. To illustrate this GA&LP approach, we start from a generic form of a type of nonlinear programming model, which is expressed as:

$$\begin{aligned} &\max z = \mathbf{c_1 x} + \mathbf{c_2 y} + \mathbf{c_3 xy} \\ &\mathbf{a_1 x} + \mathbf{a_2 y} + \mathbf{a_3} = 0 \\ &\mathbf{b_1 x} + \mathbf{b_2 y} + \mathbf{b_3 xy} + \mathbf{b}_4 = 0 \\ &\mathbf{x}^l \le \mathbf{x} \le \mathbf{x}^u \\ &\mathbf{y}^l \le \mathbf{y} \le \mathbf{y}^u \end{aligned} \tag{5-17}$$

in which **x** and **y** represent two variable vectors, respectively. z is the objective variable, and **a, b** and **c** are vectors for constant coefficients. Fixing **y** as $\mathbf{y}^*$, we have a LP model with **x**, which is:

$$\begin{aligned} &\max\ z^* = \mathbf{c_1 x} + \mathbf{c_2 y}^* + \mathbf{c_3 xy}^* \\ &\mathbf{a_1 x} + \mathbf{a_2 y}^* + \mathbf{a_3} = 0 \\ &\mathbf{b_1 x} + \mathbf{b_2 y}^* + \mathbf{b_3 xy}^* + \mathbf{b}_4 = 0 \\ &\mathbf{x}^l \le \mathbf{x} \le \mathbf{x}^u \end{aligned} \tag{5-18}$$

Solving the primary NLP model is equivalent to solving the LP model with $\mathbf{y}^* \in \mathbf{Y}$, and $\max\ z^* = \max\ z$. Applying the GA&LP approach to this problem, the GA is used to find a $\mathbf{y}^*$, and the LP model is used to calculate the "fitness" of $\mathbf{y}^*$, based on the value of the objective variable $\mathbf{z}^*$. The GA provides a number of $\mathbf{y}^*$ vectors, which are different from each other, to the LP. The LP is then solved under each of the provided $\mathbf{y}^*$s, and the fitness for each $\mathbf{y}^*$ is sent back to the GA, so that a new generation of $\mathbf{y}^*$s can be spawned, with more "genetic contribution" from the $\mathbf{y}^*$s with better fitness. The process is evaluated generation by generation, until y* converges to a final status in which the globally maximum value of *z* is found within a prescribed resolution.

An initial $\mathbf{y}^*$ is randomly selected within the range $\mathbf{y}^l \le \mathbf{y} \le \mathbf{y}^u$ by the GA in the first generation, and in the following generations, the better "genes" of $\mathbf{y}^*$ are kept for building better $\mathbf{y}^*$ in later generations. The GA&LP procedures for the NLP problem defined in (5-17) are shown in Figure 5.2.

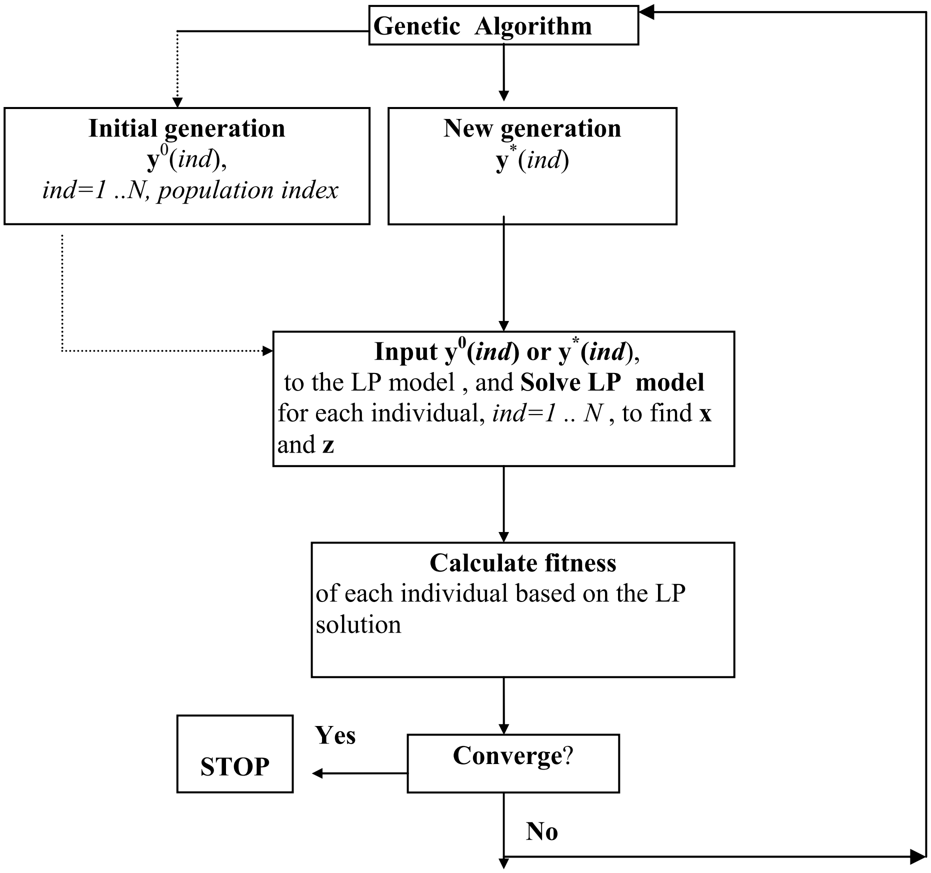


Figure 5. 2. Procedures of the GA-LP approach

5.3.2 A reservoir operation model with hydropower generation

We use a hypothetical multi-reservoir operation model shown in Figure 5.3. Five reservoirs are considered for hydropower generation, as well as water supply, flood control, and flow augmentation. An optimization model is developed to maximize the production of power, while satisfying the requirement of all other purposes. The formulation of the model is described in the following.

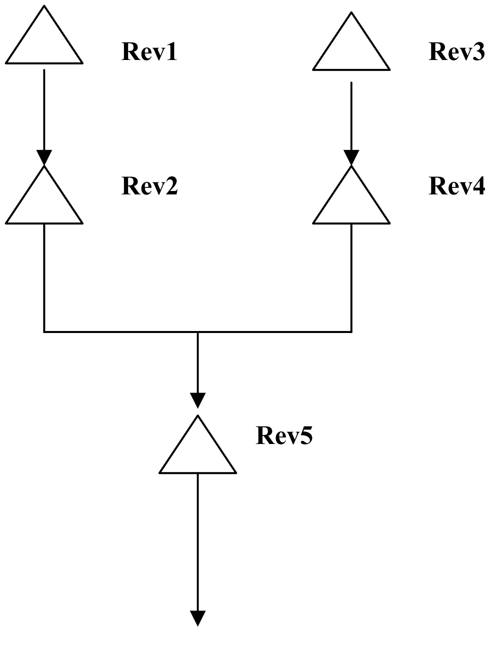


Figure 5. 3. A hypothetical multi-reservoir system

The objective is to

- Maximize the ratio of hydropower generation to power demand over all time periods

$$\max z = \sum_{t \in T} \left(\frac{\sum_{n \in pwst} PW(n,t)}{PDEM(t)} \right) \tag{5-20}$$

where *n* is the index of reservoir/hydropower stations, and *t* is the index of time periods. *PW(n, t)* is the power generated, *PDEM(t)* is the power demand of the study area in time period *t*.

The objective is constrained by:

- Reservoir head - volume relationship:

$$S(n,t) = \alpha_3(n) \cdot H(n,t)^3 + \alpha_2 \cdot H(n,t)^2 + \alpha_1 \cdot H(n,t) + \alpha_0 \qquad \forall n \in rev \tag{5-21}$$

- Reservoir head - area relationship:

$$A(n,t) = \beta_3(n) \cdot H(n,t)^3 + \beta_2 \cdot H(n,t)^2 + \beta_1 \cdot H(n,t) + \beta_0 \qquad \forall n \in rev \tag{5-22}$$

where

S = reservoir storage,

H = reservoir surface elevation,

A = reservoir surface area, and

a_i , β_i = constant coefficients, *i=0, 1,2,3.*

- Water balance at reservoirs

$$\begin{aligned} &S(n,t-1) + drn(n,t) + \sum_{un} RELS(un,n,t) \\ &= S(n,t) + \sum_{ln} RELS(n,ln,t) + withdw(n,t) + evap(n,t) \cdot A(n,t) \quad \forall n \in rev \end{aligned} \tag{5-23}$$

where

drn(n, t) = natural drainage to reservoirs, constant parameter in the model,

RELS(un,n,t) = flow from upstream reservoir(s),

RELS(n,ln,t) = flow to downstream reservoir(s).

withdw(n,t) = withdrawal to water demand sites, constant parameter, and

evap(n,t) = evaporation rate in length, constant parameter.

- Hydropower calculation

$$PW(n,t) \le k(n) \cdot \left\{ \frac{1}{2}\left[H(n,t) + H(n,t-1) \right] - tw(n) \right\} \left[\sum_{\ln} RELS(n,ln,t) + withdw(n,t) \right]$$

$$\forall n \in rev$$

(5-24)

where

PW(n,t) = hydropower power generation, and

tw(n) = average tail water level, constant parameter in the model.

Flood control and downstream flow augmentation are expressed as bounds of reservoir storage and release:

$$S(n,t)^{l} \le S(n,t) \le S(n,t)^{u} \qquad (5\text{-}25)$$

$$RELS(n,t)^{l} \le RELS(n,t) \le RELS(n,t)^{u} \qquad (5\text{-}26$$

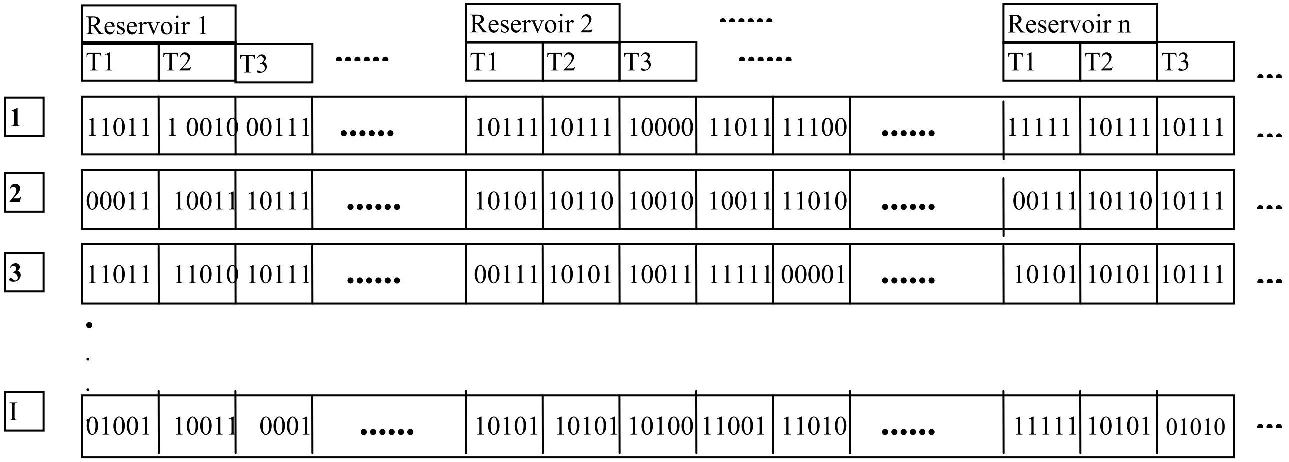


Figure 5. 4. Variable representation in the genetic algorithm. A 5-bit binary string is used to represent a single variable. An individual (1, 2, ... I) is represented by a string with a length of $5 \cdot N \cdot T$ bites, where *N* is the number of reservoirs, *T* is the number of the time periods. The whole population includes *I* individuals

5.3.3 Application of the GA-LP approach

In the model described above, if we treat the reservoir surface level *H(n, t)* as a constant parameter, then all the nonlinear equations including the reservoir head-volume, head-area relationships, and the power generation equation, will be linear. Therefore it is natural to choose *H(n, t)* as variables of the GA, and the original model with fixed *H(n,t)* is then a LP model. The number of variables of the GA is $N \times T$, *N* is the number of the reservoirs, and *T* is the number of the time periods. We use a binary string to represent these variables in the GA. Every variable *H(n, t)* (n=1,2, .. N, t=1, 2, ..T) is represented by a binary string of a number of bits (*B*=*5*). An individual (1, 2, ... *I*) is represented by a string with a length of $B \cdot N \cdot T$ bytes. The whole population (generation) includes a set of individuals, and we define the number of individuals as *I.* Figure 5.4 shows the representation of *H(n,t)*.

We use a standard GA program developed in the Center for Research in Water Research (CRWR) in the University of Texas at Austin, and use GAMS for solving the LP model.

As shown in Figure 5.2**,** for each generation, the LP problem has to be run for each individual, and the total LP running time T_{LP} in a generation can be expressed as

$$T_{LP} = \rho \cdot t \cdot I \tag{5-27}$$

where t is time to run the LP problem separately, and ρ is a discounting coefficient which is less than 1.0 because of the warm start capacity in GAMS. We formulate the LP problem in a loop structure in GAMS. In the loop, the model is run for each individual which provides different reservoir surface elevations to the model. Following the first runs, the LP solver can restart using the advanced basis from the former solution, and the computing time is reduced. The degree of the time reduction depends on the similarity of the individuals. The more similar, the greater the reduction. In each iteration of the loop, the values of $H(n, t)$ are updated based on the individuals created by the GA. The total number of variables in each individual is $N \times T$, and for more time periods and more reservoirs considered, there would be are more parameters to update in each LP run. Therefore for models with more reservoirs and larger time periods, the time savings based on the restarting facility of GAMS will be less effective in early generations of the GA.

So far, we assume an LP run should be conducted for each individual. However, some a number of individuals may be very similar. In the model considered here, the values of $H(n, t)$ may be so close for several individuals that there will not be a significant difference among the fitness of particular individuals. If we assume that they have the same fitness, then it is not necessary to run the LP model for each individual, but rather for a representative individual, and use the result from the representative case to calculate the fitness for all those individuals. This observation provides a strategy to reduce the LP running time.

To implement this strategy, first we need to group the similar individuals, and the question is how to measure the similarity among the individuals. For two individuals shown in Figure 5.5, the variables in the first individual are represented as F_1, F_2, .. F_v .., and the variables in the second individual are represented as S_1, S_2, .. S_v, .. We define the similarity (*sim*) between these two individuals as:

$$sim(ind\_f, ind\_s) = \sqrt{\sum_{v=1}^{N \cdot I} (F_v - S_v)^2} \tag{5-28}$$

IND_F	F_1	F_2	F_3	F_4	....	F_{n-1}	F_n	...	F_{N*I}
IND_S	S_1	S_2	S_3	S_4	....	S_{n-1}	S_n	...	S_{N*I}

Figure 5. 5. Two individuals used to evaluate the similarity between individuals

Another question is to how to define a threshold of the similarity. If the similarity between two individuals calculated by equation (5-28) is lower than the threshold, then the two individuals belong to one group. Setting a smaller threshold (corresponding to a high degree of similarity) will result in fewer individuals in one group. In this research, to determine the threshold, we calculate the similarity of the whole generation, defined as:

$$sim\_gen = \sqrt{\sum_{v=1}^{N \cdot I} {\sigma_v}^2} \tag{5-29}$$

where, σ_v is the standard deviation of the vth variable over all individuals in one generation. The threshold of the similarity (*sim*) can then be defined as a fraction of the similarity of the whole generation. The appropriate threshold should be determined by trial-and-error, and generally a relatively large value is recommended in the earlier generations, and a small value in the later generations. The reason for this is that, in the later generations, the individuals are more similar to each other

A Fortran program was written for this grouping strategy. Using this program, the individuals generated from the genetic algorithms are first classified into groups based on the similarity among individuals. Then, instead of running the LP model for each individual, the LP model is run for each group. Generally, in the later generations, the number of groups (G) is much less than that of the individuals since more individuals are grouped. Therefore, the grouping strategy can significantly reduce the computing time in later generations. The LP computing time is then expressed as:

$$T_{LP} = \eta \cdot t \cdot G \tag{5-30}$$

5.3.4 Results analysis

Our main concern in this section is whether the proposed GA-LP approach can solve a complex NLP model within reasonable computing time. To test the approach, we define several models by both spatial and temporal dimensions. The simplest model has nonlinear relationships (equation 5-21, 22, 23) for only one reservoir (reservoir 1 in Figure 5.3), and linear relationships for all other reservoirs, and the number of time periods is 12 (months). The most complex model has nonlinear relationships for all five reservoirs, and the number of time periods is 48 (months). Table 5.3 shows the definitions and statistics of all models, and Table 5.4 shows the parameters used in the genetic algorithm for all models.

The objective value vs generations for model_1 to model_6 is shown in Figure 5.6 to Figure 5.11, respectively. The solutions for all models, and the comparisons of the GA-LP approach with CONOPT2, are presented in Table 5.5. To demonstrate the convergence of the approach, the initial objective values (the objective values of the first generations), the “approximated” objective values, and the “improved” objective values are shown in Table 5.5.

From Figure 5.6 to 5.11, and Table 5.5, we find that for all models, the number of generations required to reach the “approximated” solution is much less than that required to move from the “approximated” solution to the improved solution. The convergence speed is affected by the parameters of the GA, especially the probability of crossover and the probability of mutation. The values for these terms in Table 5.5 are determined by trial-and-error.

For model_1, model_3, and model_5, which all have 12 modeling periods, the GA-LP approach found an objective value that is slight lower than the objective value resulting from CONOPT2 (3.5%, 1.5%, 16.4% for the three models, respectively). The GA-LP approach misses the real global solution, i.e., converging to an approximate solution, due to the stochastic nature of GAs, and potentially inappropriate values of the parameters used in the GA. For each of these three models, we tried both a real-time based seed and a fixed seed for random "gene" generation, ran the GA with the same parameters several times, and ran the GA for more generations. In all these efforts, however, we never found a solution within 1% of the CONOPT2 solution.

However, for model_2, model_4, and model_6, which have 24, 24, and 48 periods, respectively, the GA-LP approach found a solution that is better than that from CONOPT2, and the differences are significant. CONOPT2 (and MINOS5) is entrapped by local solutions to model_2, and model_4, and it is unable to find feasible solution to model_6, which is the largest model considered. For all these CONOPT2 runs, relaxed optimality and feasibility tolerances were tested, but no better result was found than the values presented in Table 5.5. The initial values for $H(n,t)$ in the CONOPT2 runs were estimated according to the variable bounds. However, taking the solution from the GA-LP as the initial value to CONOPT2 and MINOS5, the solvers find better solutions for all three models, which is also shown in Table 5.5.

In general, convergence speed depends on the model elements and structure, as well as the number of variables in the genetic algorithm. Comparing model_2 and model_3, they have the same number of variables (=24) in the genetic algorithm, but the total variables and nonzero elements in model_2 are more than in model_3. Model_2 takes about 200 generations to find the approximate solution, while model_3 takes only 95 generations. Model_3 also converges to the optimal solution faster than model_2 as well. The relative size and the convergence speed of all models are shown in Table 5.6 (taking model_1 as the base).

Table 5. 3. Model statistics of the six models for the test of the GA-LP approach.

Models	Number of reservoirs with nonlinear relationships	Time periods	Number of equations[*]	Number of variables[*]	Number of nonzero elements[*]	Number of nonzero nonlinear elements[*]
Model_1	1 (rev1)	12	97	349	655	59
Model_2	1 (rev1)	24	193	697	1315	119
Model_3	2 (rev1, rev2)	12	133	385	762	118
Model_4	2 (rev1, rev2)	24	265	769	1530	238
Model_5	5 (all reserv.)	12	241	445	1083	295
Model_6	5 (all reserv.)	48	1201	2221	4851	1495

[*] from model statistics in GAMS output file.

Table 5. 4. Parameters used in the genetic algorithm.

Models	Number of Variables in GA	Number of Individuals	Length of substring	Probability of crossover	Probability of mutation
Model_1	12	50	5	0.82	0.01
Model_2	24	50	5	0.83	0.01
Model_3	24	50	5	0.83	0.01
Model_4	48	50	5	0.90	0.01
Model_5	60	50	5	0.85	0.01
Model_6	240	50	5	0.93	0.01

Note: the fitness calculation for Model_4 and Model_6 is rank-based, and others are based on objective values. Time seed is used for random number generation.

Table 5. 5. Results from the GA-LP approach and the comparison with CONOPT2.

Models	**GA-LP**					**CONOPT2**		
	Objective value of 1-st generation[1]	*Approximated*		*Improved*		*Estimated Initial*		Starting *From GA-LP*[5]
		No. of Gen.s	*Obj. value*[2]	*No. of Gen.*	*Obj. value*[2]	*Obj. Value*	*Time*[4]	
Model_1	-94.392	17	1.976	60	2.289	2.381	0.34	2.381
Model_2	-165.976	201	3.315	330	4.205	2.577[3]	0.92	4.423
Model_3	-4.975	95	4.314	200	4.459	4.529	1.14	4.529
Model_4	-78.74	111	5.765	760	7.039	4.513[3]	3.34	11.642
Model_5	-203.462	428	9.725	610	12.538	14.994	5.11	14.995
Model_6	-423.345	445	34.215	1030	37.306	Failed[3]	9.56	52.225

[1] including non-zero slack variables,

[2] average value of three runs,

[3] same value was found for multiple runs, and the same result was found from solver MINOS5,

[4] all programs were run on the same PC-300, Pentium-II. The computational time here is defined as the "resource usage" in the GAMS output file.

[5] taking the solution from GA-LP as initial values

Table 5. 6. Comparison of convergence speed of models with various sizes and structures.

MODELS	***Number of equations***[*]	***Number of variables***[*]	***Number of nonzero nonlinear elements***[*]	***Number of nonzero nonlinear elements***[*]	***Number of Variables in GA***	***Number of generations for approximate solution***	***Number of generations for near-global solution***
model_1	100%	100%	100%	100%	100%	100%	100%
model_2	199%	200%	201%	202%	200%	1182%	550%
model_3	137%	110%	116%	200%	200%	559%	333%
model_4	273%	220%	234%	403%	400%	653%	1267%
model_5	248%	128%	165%	500%	500%	2518%	1017%
model_6	1238%	636%	741%	2534%	2000%	2618%	1717%

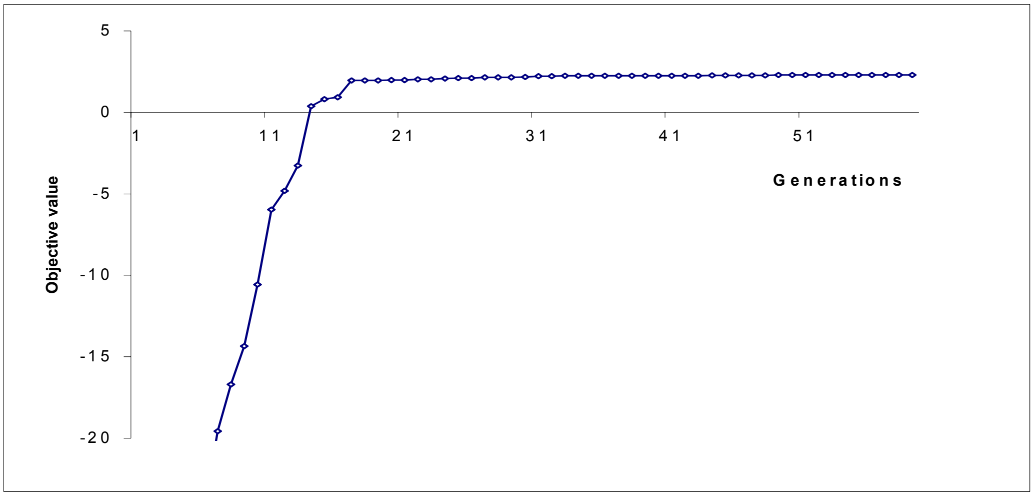


Figure 5. 6. Objective value vs generations, model_1, with 1 reservoir, 12 time periods.

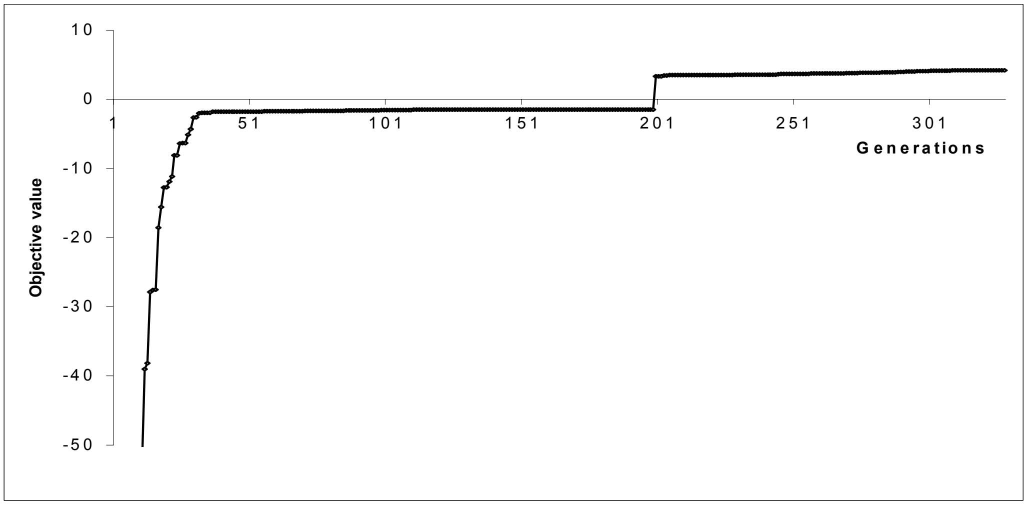


Figure 5. 7. Objective value vs generations, model_2, with 1 reservoir, 24 time periods.

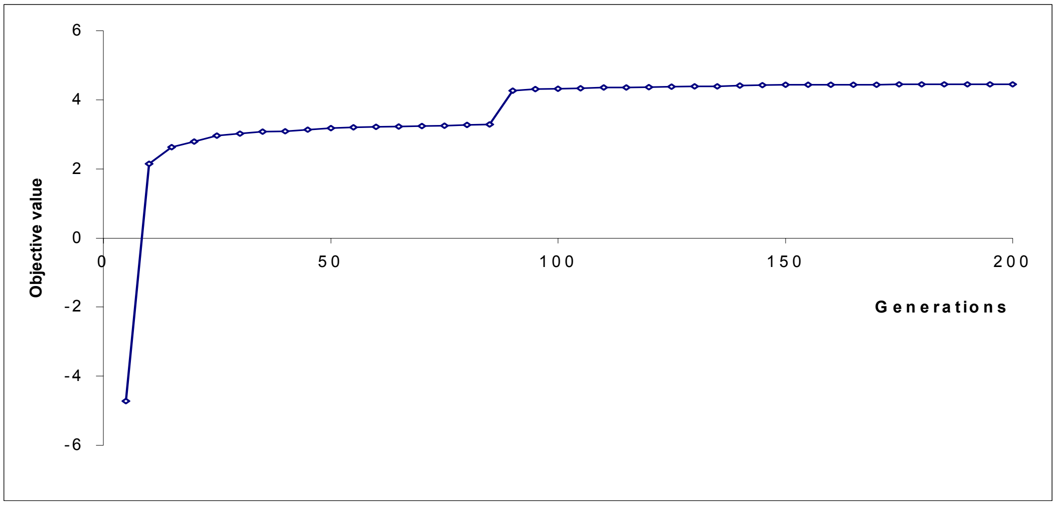


Figure 5. 8. Objective value vs generations, model_3, with 2 reservoirs, 12 time periods.

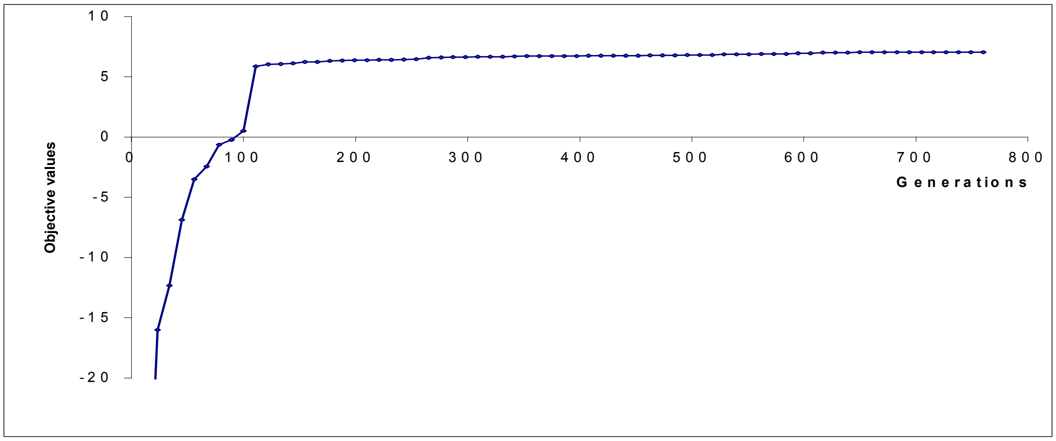


Figure 5. 9. Objective value vs generations, model_4, with 2 reservoirs, 24 time periods.

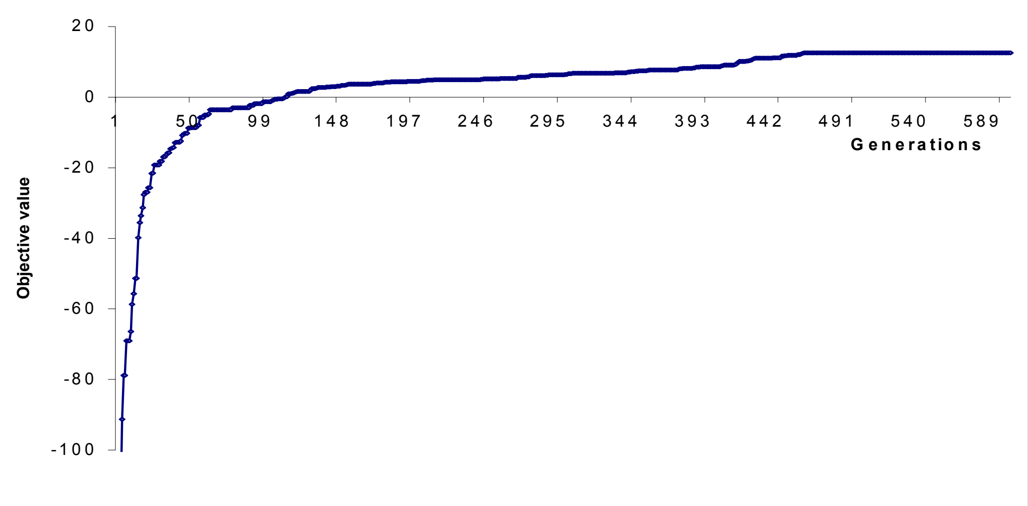


Figure 5. 10. Objective value vs generations, model_5, with 5 reservoirs, 12 time periods.

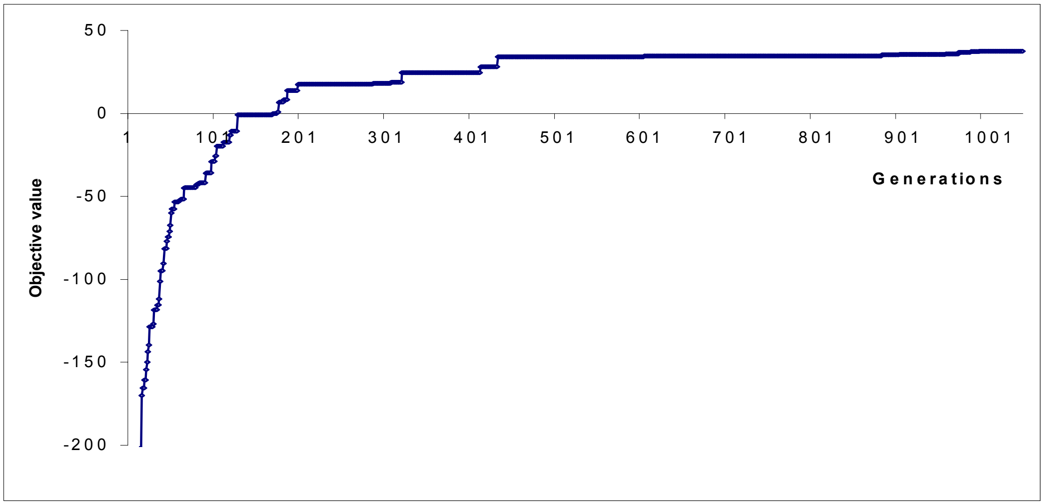


Figure 5. 11. Objective value vs generations, model_5, with 5 reservoirs, 48 time periods.

5.3.5 Discussion and conclusion

Through the computing experiments with the models considered in this study, the proposed GA-LP has the following potential advantages: (1) it is robust enough to find an approximate global solution or a feasible solution to complex NLP models. Even for the models in which NLP solvers CONOPT2 and MINOS5 are entrapped by local solutions that are far from the global solutions, or even unable to find a feasible solution, the proposed approach can still find better solutions; (2) the approach is more effective for larger models (e.g., model_2, model_4, and model_6) than smaller models (e.g., mode_1, model_3, and model_5); and (3) with the increase of the model size, the convergence time increases approximately linearly (i.e., there is no indication of a "curve of dimensionality").

However, with the models considered, the proposed approach converges to a near-global solution very slowly, or perhaps even misses the global solutions, and converges to a local solution. The convergence speed depends on setting appropriate parameter values in the genetic algorithm, which must be adjusted by trial-and-error. This is a very time consuming process. The probability of crossover and the probability of mutation are the two most sensitive parameters in the genetic algorithm. Other factors, such as the method of fitness calculation, and the selection of seed for random number generation, also affect the solution. We use a 5-digit substring and 50 individuals for all models, which may need to be improved. Experimenting with different substring lengths and different numbers of individuals in each generation has not been done in this study.

Even when the grouping strategy for reducing computing time is used, the proposed approach is still not comparable with the popular NLP solvers CONOPT2 and MINOS5. In the future the improvement of genetic algorithms should improve the proposed GL-LP approach.

5.4 THE "PIECE BY PIECE" APPROACH

5.4.1 Procedures of the "piece-by-piece" approach

This approach is based on the "restarting" facility of GAMS, and it is suitable to some large models, especially nonlinear programming (NLP) and mixed-integer nonlinear programming (MINLP) models, with the special structure described below. We consider a generic model as:

$$
\begin{aligned}
&\max \quad f(\mathbf{x},\mathbf{y},\mathbf{z}) \\
&\text{Subject to:} \\
&\mathbf{g}_1(\mathbf{x}) \le 0 \\
&\mathbf{g}_2(\mathbf{x},\mathbf{y}) \le 0 \\
&\mathbf{g}_3(\mathbf{x},\mathbf{y},\mathbf{z}) \le 0 \qquad \text{(5-30)} \\
&\mathbf{x}^l \le \mathbf{x} \le \mathbf{x}^u \\
&\mathbf{y}^l \le \mathbf{y} \le \mathbf{y}^u \\
&\mathbf{z}^l \le \mathbf{z} \le \mathbf{z}^u
\end{aligned}
$$

where **x**, **y** and **z** are vectors of variables, $\mathbf{g_1}$, $\mathbf{g_2}$, and $\mathbf{g_3}$ are sets of equations, which can be linear, nonlinear or mixed-integer linear or nonlinear relationships. This special structure allows the model to be solved by the proposed "piece-by-piece" approach.

We notice that all calculus-based NLP solvers (e.g. MINOS5, CONOPT, CONOPT2, etc.) depend on the "initial values" given to the variables. Inappropriate initial values may cause a solver to take longer to find a feasible solution or even stop at an "infeasible solution". These conditions are more critical 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. We use the model described above to illustrate the steps. In the following description, $\mathbf{x^0}$ represents a vector of fixed values for **x**, $\mathbf{x}^*$ represents a solution for **x**, and $\mathbf{x^i}$ represents an initial value for **x**. The same symbols are assigned for **y** and **z.**

Step 1: Solve the first "piece" of the model (**mod1**) with fixed **y** and **z**, defined as the following:

$$\max \ f(\mathbf{x},\mathbf{y}^0,\mathbf{z}^0)$$

Subject to:

$$\mathbf{g_1}(\mathbf{x}) \le 0$$

$$\mathbf{x}^l \le \mathbf{x} \le \mathbf{x}^u \qquad (5\text{-}31)$$

where

$$\mathbf{y}^l \le \mathbf{y}^0 \le \mathbf{y}^u$$
$$\mathbf{z}^l \le \mathbf{z}^0 \le \mathbf{z}^u$$

where $\mathbf{y^0}$and $\mathbf{z^0}$ represent a vector of fixed values for **y** and **z,** respectively.

This sub-model only includes variable **x** and equation set $\mathbf{g_1}$. It should be much easier to solve this model than the original one. Assuming this model can be solved, the solution is $\mathbf{x}= \mathbf{x}^*$.

Step 2: Add one more piece to **mod1**, set the initial value of **x** ($\mathbf{x^i}$) as the solution from **mod1** ($\mathbf{x}^*$), and set the initial value of **y** ($\mathbf{y^i}$) as $\mathbf{y^0}$, the fixed value used in **mod1**. Solve **mod2** defined as:

$$\begin{aligned}
&\mathbf{x}^i = \mathbf{x}^* \\
&\mathbf{y}^i = \mathbf{y}^0 \\
&\max \quad f(\mathbf{x},\mathbf{y},\mathbf{z}^0) \\
&\text{Subject to:} \\
&\mathbf{g}_1(\mathbf{x}) \le 0 \\
&\mathbf{g}_2(\mathbf{x},\mathbf{y}) \le 0 \qquad (5\text{-}32) \\
&\mathbf{x}^l \le \mathbf{x} \le \mathbf{x}^u \\
&\mathbf{y}^l \le \mathbf{y} \le \mathbf{y}^u
\end{aligned}$$

where

$$\mathbf{z}^l \le \mathbf{z}^0 \le \mathbf{z}^u$$

and $\mathbf{x}^i = \mathbf{x}^*$ satisfy equation set $\mathbf{g_1}$. Since equation set $\mathbf{g_1}$ and $\mathbf{g_2}$ are related by **x**, values satisfying $\mathbf{g_1}$ will generally provide appropriate initial values for $\mathbf{g_2}$. Therefore, $\mathbf{x}^i = \mathbf{x}^*$ provides an appropriate starting point for **mod2**.

Step 3: Add one more piece to **mod2**, and set the initial value of **x** as, $\mathbf{x}^\mathbf{i}$=$\mathbf{x}^*$, set the initial value of **y** as, $\mathbf{y}^\mathbf{i}$= $\mathbf{y}^*$, where both $\mathbf{x}^*$ and $\mathbf{y}^*$ result from the solution of **mod2**. Also set the initial value of $\mathbf{z}^\mathbf{i}$ as $\mathbf{z}^\mathbf{i}$= $\mathbf{z}^\mathbf{0}$, the fixed value of **z** used in **mod1** and **mod2.** Solve **mod3** as:

$$\begin{aligned}
&\mathbf{x}^i = \mathbf{x}^* \\
&\mathbf{y}^i = \mathbf{y}^* \\
&\mathbf{z}^i = \mathbf{z}^0 \\
&\max \quad f(\mathbf{x},\mathbf{y},\mathbf{z}) \\
&\text{Subject to:} \\
&\mathbf{g}_1(\mathbf{x}) \le 0 \\
&\mathbf{g}_2(\mathbf{x},\mathbf{y}) \le 0 \qquad\qquad (5\text{-}33) \\
&\mathbf{g}_3(\mathbf{x},\mathbf{y},\mathbf{z}) \le 0 \\
&\mathbf{x}^l \le \mathbf{x} \le \mathbf{x}^u \\
&\mathbf{y}^l \le \mathbf{y} \le \mathbf{y}^u \\
&\mathbf{z}^l \le \mathbf{z} \le \mathbf{z}^u
\end{aligned}$$

where $\mathbf{x}^i = \mathbf{x}^*$ (updated by **mod2**) and $\mathbf{y}^i = \mathbf{y}^*$ satisfy equation sets $\mathbf{g}_1$ and $\mathbf{g}_2$, and provide appropriate initial values for $\mathbf{g}_3$. Actually, **mod3** is just equivalent to the original model, with appropriate initial values for all variables.

This approach was coded in GAMS, and the "piece-by-piece" approach used to solve the model can be implemented based on the restarting facility of GAMS. For the model we present above, the solve statements can be written as:

***GAMS* mod1 *s* solu1**

*(solve **mod1** and save the solution to **solu1**)*

***GAMS* mod2 *r* solu1 *s* solu2**

*(solve **mod2** starting from **solu1** and save the solution to solu**2**)*

***GAMS* mod3 *r* solu2**

*(solve **mod3** starting from **solu2**)*

By the command in the first statement, **mod1** is solved and $\mathbf{x}^*$ is found, and **mod1** and its solution are saved to **solu1**, a set of files specifying the GAMS model and its solution base. In the second statement, **mod2** is solved by starting from **solu1**, and $\mathbf{x}^*$ is automatically taken as the initial value of **x** for **mod2**. **mod2** and its solution ($\mathbf{x}^*$ updated by **mod2** and $\mathbf{y}^*$) are saved to **solu2**. In the third statement, **mod3** is solved by starting from **solu2**, and $\mathbf{x}^*$ and $\mathbf{y}^*$ are automatically taken as the initial value of **x** and **y** in **mod3**, respectively.

One may expect that the computing time with the proposed "piece-by-piece" approach is significantly more than the time in which the original model is solved directly. Computation experiments show no significant time increase with the proposed approach. Actually, this approach is based on two "tricks": solving smaller models and solving a model with better initial values. Both of these tricks can reduce computing time, as demonstrated through the following example.

5.4.2 An example for the "piece-by-piece" approach

As an example, we use the "piece-by-piece" approach to solve the integrated hydrologic-agronomic-economic model for short-term analysis described in Chapter 3. This is a huge model for currently available solvers. We tried to solve the model directly using MINOS5 and CONOPT2, the two popular NLP solvers used in GAMS, but both solvers were unable to find feasible solutions, even with very relaxed feasibility tolerances. That is to say, we could not solve the model directly with the currently available solvers, which motivates the use of the "piece-by-piece" approach.

The short-term model does have the special structure required by the proposed approach. We define the following sub-models:

mod1: *flow balance,*
crop production functions,
mod2: **mod1**+*salinity balance*
mod3: **mod2**+*effect of soil salinity on crop evapotranspiration*,
mod4: **mod3**+
tax-salt discharge relationships, and
investment constraint on infrastructure improvement.

In **mod1,** we assume the crop production is only related to soil water stress, neglecting the effect of soil salinity. Salinity balance is added to **mod2**. The purpose of **mod2** is simply to find appropriate values for salinity, as well as flow, but the inter-relationships between soil salinity and crop evapotranspiration are not included in **mod2.** These inter-relationships 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 an appropriate value for salinity is found, these complications make the model difficult to solve. This is why we do not include the inter-relationships between soil salinity and crop evapotranspiration in **mod2**, but include it in **mod3**, in which appropriate initial values for both flow (water) and salinity are available.

Economic relationships such as the tax-salt discharge relationships, and the investment constraint on infrastructure facilities are not included in **mod1**, **mod2** or **mod3**, but are added to **mod4**, which is equivalent to the original model. The solution of **mod3** provides initial values for flow (storage) and salinity, which satisfy all constraints in the original model, except the added economic relationships. Therefore, solving **mod4** with the initial values found from **mod1**, **mod2** and **mod3,** should be easier than solving the original model directly. Although the current available solvers fail to solve the original model directly, with the "piece-by-piece" approach, we find feasible solutions for the original model.

The solve statements are:

GAMS **mod1** ***s*** **solu1**

*(solve **mod1** and save the solution to **solu1**)*

GAMS **mod2** ***r*** **solu1** ***s*** **solu2**

*(solve **mod2** starting from **solu1** and save the solution to solu2)*

GAMS **mod3** ***r*** **solu2** s **solu3**

*(solve **mod3** starting from **solu2** and save the solution to **solu3**)*

GAMS **mod4** ***r*** **solu3** s **solu4**

*(solve **mod4** starting from **solu3** and save the solution to **solu4**)*

Table 5.7 shows the computing time and objective value for each model. From **mod1** from **mod4**, the model size increases; however the number of infeasibility decreases. The first model, **mod1**, is the most relaxed model, and it has the largest objective value; while the last model, **mod4**, is the most constrained and has the lowest objective value, which represents the objective value for the original model.

Comparing the computing time, we find that it takes the least time to solve **mod3**, and longest time to solve the final model, **mod4**. The computing time for solving each model depends on two factors: (1) the change from the previous (base) model, (both from **mod2** to **mod3** and from **mod3** to **mod4**, the changes are relatively small); and (2) the inter-relationships between the added piece and the existing pieces in the previous model. From **mod2** to **mod3**, the effect of soil salinity on crop evapotranspiration is added, and from **mod3** to **mod4**, the tax-salt discharge relationships, and investment constraints are added. The computing time result shows that the soil salinity – crop evapotranspiration relationships added to **mod3** have less effect than the economic relationships added to **mod4**.

By the “piece-by-piece” approach, the solution from one step are taken as initial values for the model in the next step. Generally the value of a variable should be updated step by step as more pieces are added to the model. Figure 5.12 demonstrates this point by showing the Toktogul Reservoir release during all these steps. The curves of **mod2** and **mod3** are very close, while the curve of **mod4** is significantly different from **mod3**, which again shows that less change from **mod2** to **mod3** than from **mod3** to **mod4**.

Table 5. 7. **Statistics of models at different steps.**

Models	Number of Equations[1]	Number of Variables[1]	Number of nonzero elements[1]	Number of nonzero NLP elements[1]	Number of initial infea-sibility[2]	Comput-ing time (s) [3]	Objective value[4]
mod1	5846	8714	31030	11011	2556	2866	4.45
mod2	8282	13310	53561	28987	1155	3595	4.19
mod3	9866	13706	56657	30571	60	1769	4.15
mod4	9874	13713	57200	31099	7	3801	4.14

[1] from model statistics in GAMS output files;
[2] the models are solved by solver CONOPT2, these numbers are the numbers of infeasibilities in the first iteration;
[3] time resource-usage from GAMS output files, with machine Pentium-300 mHz;
[4] total benefit.

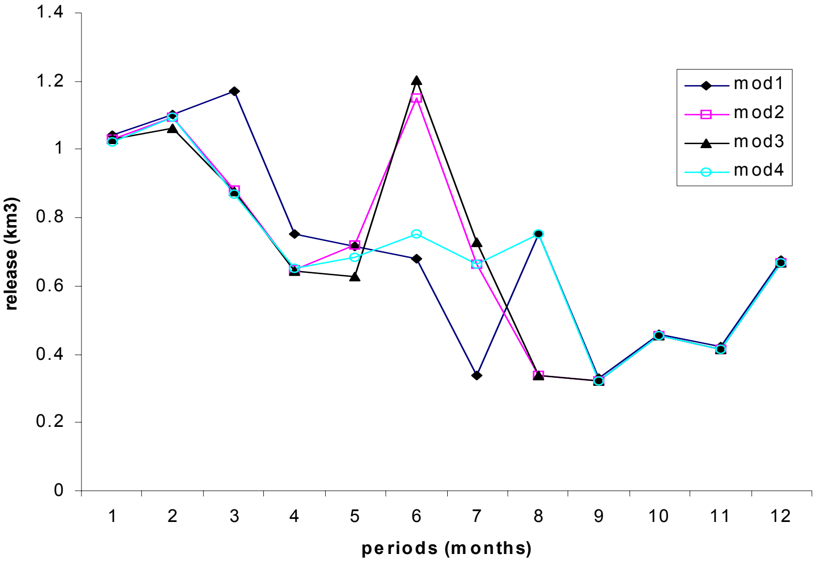


Figure 5. 12. Comparison of reservoir release from the models at different steps

5.4.3 Summary and discussion

The “piece-by-piece” approach proposed in this research can be applied to solve large NLP models that have the special structure as specified above. A series of sub-models are defined, the first model starts with a basic “piece” of the original model, and more pieces are added to the successive sub-models. The last model in the series is equivalent to the original model. The approach takes advantage of the restart facility in GAMS to solve the series of models step by step, and the solution from the model in one step is 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 approach is successfully used to solve the short-term model developed in Chapter 3, even though current available NLP solvers are unable to find a feasible solution when used to solve the original model directly.

The special structure required by this approach is similar to a simulation modeling structure that is common in engineering. For example, in water quality simulation models, water flow is generally first calculated through a water balance, and then the constituent concentration is calculated through constituent mass balance with the known water flow velocities. The “piece-by-piece” approach provides a method based on the currently available solvers to solve these problems formulated as holistic optimization models.

The approach also provides a method to solve a model including multiple compartments, like the integrated hydrologic-agronomic-economic model developed in this research. As discussed in Section 3.2.6, the "compartment modeling" approach is more widely used for large complex models, since it is relatively easy to solve each compartment instead of the entire system at once. However, the loose connection between compartments may not be effective for transferring information between components. For "holistic modeling", modeling components are tightly connected in one consistent model, and information transfer between compartments is treated endogenously. However, generally less complexity should be enclosed. As we have demonstrated, the “piece-by-piece” approach can implement the "holistic modeling" in procedures similar with the "compartment modeling" approach, but still keep information transform between compartments endogenously.

5.5 SUMMARY

This chapter presents three approaches for solving difficult water resources management models that are large, nonlinear and nonconvex. The GBD-based approach can be used to search for approximate global optimal solutions to large nonconvex nonlinear models; the GA-LP can be used to find approximate global solutions or feasible solutions for large models with high nonlinearity and nonconvexity; and the “piece-by-piece” can be applied to solve large linear or nonlinear models with multiple compartments. All these approaches require some special model structures.

Chapter 6

The Long-Term Dynamic Modeling Framework for Sustainability Analysis

6.1 LONG-TERM WATER RESOURCES MANAGEMENT MODELING

The major concern of sustainability is to take account of the long-term impacts that will result from decisions and actions taken today. To assess these impacts, we attempt to predict what will happen and guess what future generations would like us to do now in our generation (ASCE and UN/IHP, 1998). Then we take predictions of adverse future consequences into account to decide what to do to satisfy our immediate demands and desires without compromising those of future generations. In long-term water resources management, we face uncertainties on both the water supply and the water demand side due to the climatic and socio-economic changes in the future (Gleick, 1989; Lettenmaier et al., 1996).

We need an analytical framework that can not only simulate the long-term consequences of the short-term irrigation and drainage activities, but also provide solutions for informed short-term decisions so as to avoid long-term disasters. This is the motivation for the long-term dynamic modeling framework described in this chapter. In the rest of this section, we discuss some basic issues for this framework.

6.1.1 Time scales

The appropriate time scale for measuring sustainability in water resources systems depends on the characteristics of the studied problem. As a general guideline, the Committee on Water Problems of the United Nations (1976) suggested that short-term planning refers to a period of one year, medium-term planning to 4-7 years, and long-term planning to 15 -30 years. This classification has been used by many regions and countries to make their short-, medium-, and long-term plans. An appropriate time scale for sustainable water resources management may also need to be subject to the following considerations:

(1) The time horizon should be long enough to reflect climate changes from hydrologic records. However, global climate changes will make the forecasting of future climatic tends more complex (Gleick, 1986).

(2) The time horizon should be so long that the effects from some short-term activities can be identified. For example, soil salinity accumulation may not have serious negative impacts until some years later when it might exceed the crop salinity tolerance; waterlogging and groundwater pollution problems often take a long time to appear.

(3) The time period should be long enough so that the turning point for a water resources system shifting from a sustainable state to an unsustainable one can be located, if it exists, within the period. The turning point is a mark for the occurrence of some irreversible disasters (Biswas, 1993).

For the purpose of sustainability analysis, generally, it is better to use a longer time horizon based on the considerations above. However, with a longer time frame, there will be more uncertainties, which may make the modeling work more complex, or far diverted from the real condition. The three considerations above form a lower bound for the time horizon; an upper bound is often constrained by data availability and modeling capacity.

6.1.2 Long-term changes and uncertainties

The assumption behind the long-term modeling is that we can predict some of the uncertainties about the future. Long-term modeling should be able to flexibly adapt to the inevitable changes and uncertainties so as to maintain the robust water resource systems designed and operated today. In the following we briefly discuss the long-term changes and uncertainties on both the water supply and water demand sides.

6.1.2.1 Changes and uncertainties in water supply

The major uncertainties on the water supply side result from climate variabilities or changes. Climate and the global hydrological cycle are in fact the different sides of the same process of water exchange in the ecosphere, based on the global energy balance and the global atmosphere circulation. Therefore, climate changes will exert profound impacts on flow in natural streams and rivers, and on water distribution in artificially designed water systems, especially in semi-arid territories (Golubev, 1993). For instance, Revelle and Waggoner (1983) found that if precipitation decreased by 10% in the western United States, then mean annual runoff would decrease between 12% and 50% in different parts of that territory. The impact of potential climate changes on water resources management has been the topic of many recent studies (e.g., Nemec and Schaake, 1982; Nash and Gleick, 1991; Kirshen and Fennessey, 1993; Kaczmarek et al., 1996); a comprehensive review was presented by Lettenmaier et al. (1996). These studies have concluded that the reaction of water resources systems to climate change may be even more non-linear than to runoff. For example, Nemec and Schaake studied the Pease river in the south-western USA, and the results show that if precipitation drops by only 10%, the guaranteed supply of a certain amount of water will require expansion of the volume of an existing water reservoir by 150-200%.

Global climatic changes, the so-called greenhouse effects, further complicate future water resources planning. Resulting from the increase in the atomospheric concentration of greenhouse gases (including carbon dioxide [CO_2], nitrous oxide [N_2O], and ozone [O_3] etc.), the greenhouse effects include higher temperatures, changes in precipitation patterns and sea level, and alterations in the frequency and intensity of major storms. Most predictions of global climatic changes are based on computer simulations using general circulation models (GCMs) of the atmosphere. GCMs solve the conservation equations that describe the geophysical fluid dynamics of the atmosphere, in a discrete space and time step. GCMs can be used for long-term climate forecasting. Generally, GCMs have been successfully used for representing large-scale features of the atmosphere, such as the evolution of major storm fronts, but the surface processes, such as precipitation and streamflow, are poorly reproduced, even at the scale of large continental rivers (Miller and Russell, 1992).

Pollution from human activities is responsible for potential changes in water quality now and in the future. The physical and chemical properties of water sources have been changing ever since human activities such as agriculture, industry, and domestic uses, etc., have increased the fluxes of matter through water drainage systems. The report of the Global Environmental Monitoring System (GEMS, 1988) provides a comprehensive discussion about potential water quality due to various types of pollution. It is well accepted that water pollution comes from two different sources: point and non-point. Point source pollution comes from municipal sewage treatment plants and industrial waste. The main sources of non-point pollution are agriculture, livestock raising, and human settlements without sanitation.

Unlike the stochastic nature of water quantity, water quality changes can be controlled. Water quality standards have been an important tool for water quality management and control. The polluters may have to pay either a penalty if the effluents do not meet the established standards or a tax that is proportional to the accumulative degree of pollution. But penalty and taxation as tools to control water quality are difficult in dealing with the non-point sources (Golubev, 1993).

6.1.2.2 Changes and uncertainties in water demand

Population plays a fundamental role in predicting future water availability, use and quality. According to Serageldin (1995), the world population is projected to increase by 50% over the next 30 years. Per capita water supplies worldwide are already a third lower now than 25 years ago. Based on the current trends, the demand for water may increase up to 650% in the next three decades. By 2025, 90% of population growth will take place in urban areas, increasing the demand for water of suitable quality for domestic, municipal and industrial use and for waste treatment. On the other hand, population pressure will increase the demand for food, putting further pressure on water supplies for irrigation. It is estimated that half to two-thirds of the increment in food production in the future will have to come from irrigated land. Population pressure will also push other economic activities such as industry and construction that will also demand more water.

Water demand in the future will also depend on the overall social and economic development. In many developing countries, rapid urbanization and economic growth already lead to serious water shortages. For example, in northern China, several major cities already face serious water shortages due to the economic development in recent years. Irrigation is the world's main water user, taking 70% of all water consumed. In arid and semi-arid countries the figure is much higher. In Egypt, for instance, it is estimated as 98% (Golobev, 1993). Due to the large water allocation to agriculture, many countries are under strong pressure to reallocate water used for irrigation to other uses. The potential changes include adjusting crop patterns to replace plants using more water with those using less water, and within industry, limiting the sections with large water demand.

Technology will play a very important role in future water uses. In agriculture, increasing irrigation efficiency provides a great potential to save water. Many methods are used for improving irrigation efficiency through maintenance of optimal soil humidity in the root zone and reduction of evaporation without loss of crop harvest yield. Transition from traditional gravity systems to sprinkler irrigation can increase efficiency by up to about 40% and, from sprinkler to drip systems, a further 20% (Postel, 1985). In industry, the main strategic technological approach is to recirculate water within the factory once it is withdrawn from a source. In the USA, by the year 2000, every unit of water withdrawn for industrial purposes will be used up to17 times, which will be much higher than 3.4 times, the ratio in the late 1970's (Postel, 1985).

Legal, institutional and political approaches have been used to control water demand. A classic example occurs in Sweden. In the mid-1960s, a law was passed forcing industry to recirculate its process water resulting in a very rapid decline in industrial water demand (Falkenmark, 1977).

As a summary, the changes and uncertainties in future water demand depend on multiple factors, including population increase, socio-economic development, technology improvement and legal, institutional and political factors. The strategies for water demand management should combine all these factors considered here.

6.1.3 Complexity - tradeoff between short-term and long -term objectives

The short-term objective and the long-term objective are neither totally consistent, nor totally in conflict with each other. The short-term objective results from decisions and actions under given conditions, while the long-term objective concerns the sustainability of the expected benefit in the future, as well as current desires. In the case of a water planning and management problem for a time horizon of thirty years, for example, the short-term objective searches immediate benefits/profits in a short time period, e. g., a year, assuming water supply and demand conditions are known. The long-term objective, on the other hand, is subject to the uncertainties during the whole time horizon, which can only be predicted with potential errors. It considers the inter-relations between decisions made in short time periods, and searches a way to avoid the impacts of current decisions on future benefits. Put in another way, the long-term objective results from adjusting the short-term decisions to reach a balance between the current and future benefits, in which, the immediate demands and desires are satisfied at most, but those of future years are not compromised.

The long-term modeling framework should include the short-term decisions in a dynamic form. A single short-term decision will affect its following ones, and all consecutive short-term decisions, if not appropriate, may cause problems for the future. The long-term modeling framework will dynamically manipulate those short-term decisions, trace the long-term consequences, and provide a control mechanism for planning purposes based on a long-term objective that will be specified taking into account sustainability criteria.

The sustainability criteria described in Chapter 2 are incorporated into the long-term dynamic modeling. In the rest of this chapter, we first discuss how to quantify these criteria and bring them into an analytical modeling framework; then we describe the procedures for implementing the long-term dynamic modeling framework.

6.2 QUANTIFICATION OF SUSTAINABILITY CRITERIA

6.2.1 Quantification of risk criteria: reliability, reversibility, and vulnerability

In long-term water resources development and management, risk always exists subject to both natural uncertainties in river basins (e.g., hydrologic fluctuations) and inappropriate anthropogenic activities (e.g. excessive withdrawal of water and excessive pollution discharge). The long-term accumulative effects (e.g. waterlogging and soil salinity accumulation) may make the risk in water resources management more serious year by year, which may finally lead to unavoidable disasters and irrecoverable negative effects. As discussed in Chapter 2, risk in water resources management may be evaluated in three aspects: how often a system failure happens (*reliability*), how long periods of unsatisfactory performance are likely to last (*reversibility*), and how serious a system failure is (*vulnerability*). In this section, we propose a way to capture risk quantitatively in the long-term management of irrigation-dominated river basins. The risk criteria are expressed in terms of irrigated area and water for environmental and ecological use. For an irrigation-dominated river basin with a semi-arid climate, like the Syrdarya basin, these two terms may reflect the risk involved in the performance of the river basin for a long-term planning.

Irrigated area is to be sustained for the agricultural production system. The maintenance of irrigated area of a farm is affected by water availability, soil salinity, and groundwater table level (waterlogging), as well as irrigation and drainage facilities. In some dry years, farmers will reduce irrigated area due to shortage of irrigation water. If soil salinity seriously affects crop growth, the crop field may be rotated to another crop with higher salt tolerance, or just left unplanted for some seasons for salt leaching. Because of ineffective drainage, the groundwater table may rise into the root zone of the irrigated crop, and the capillary rise will be increased, resulting in waterlogging. In the long-term modeling, the model will trace the water shortage status, soil salinity accumulation and the groundwater table year by year. Appropriate control over these items will be imposed to avoid reduction of irrigated area. However, if the problems are not avoidable within the multiple objective decision framework, irrigated area will be reduced in order to avoid further deterioration of water and soil quality. In addition, irrigated area may increase because of the need of agricultural development, and decrease due to urbanization and other socio-economic factors.

Besides the consideration of total irrigated area, the determination of irrigated area for various crop fields is also an important decision for economic efficiency and environmental preservation regarding water applications. Crops with high yields and high net revenues are economically attractive. However, for the purposes of environmental preservation, crops with less consumptive water use are preferred so that less water is withdrawn for irrigation. In the long-term modeling developed in this research, the irrigated area for various crop fields is determined within a short-term period, i.e., one year, while the total irrigated area, as an inter-year decision variable, is determined within the inter-year control framework. Therefore, both the total irrigated area and the area for individual crop fields are considered in the long-term modeling.

In irrigation-dominated river basins with arid or semi-arid climate, there is often a conflict between irrigation water use and ecological and environmental water use. Excessive diversion of water from rivers for irrigation can bring serious ecological and environmental problems. As we introduced in Chapter 1, the Aral Sea environmental disaster has resulted from excessive water withdrawals for irrigation, which is responsible for the current unsustainable state of the basin. Environmental quality is often associated with long-term accumulative impacts. To sustain the environmental quality, as a long-term objective, water uses must be subject to ecological and environmental constraints.

As a summary, in irrigation-dominated basins with an arid or semi-arid climate, like the Aral Sea basin, irrigated area and environmental water use may reflect the sustainability of the agricultural production system and its associated environmental system. In the following, we describe the quantification of the risk criteria in content of these items.

For irrigated area, the ratio of actual irrigated area (*AIA*) to the target irrigated area (*TIA*) in each year is computed as:

$$RIA^{y} = \frac{AIA^{y}}{TIA^{y}} \tag{6-1}$$

where the actual irrigated area (*AIA*) in each year results from the long-term modeling. The target of the irrigated area (*TIA*) in each year, assumed to be an external policy-oriented parameter in this research, can result from irrigation planning in a river basin, which depends on many factors including crop production requirement, policy on food trading, financial constraints, as well as land availability.

For ecological and environmental water use, we compute the ratio of actual ecological and environmental water use (*AEW*) to its planning target (*TEW*),

$$REW^{y} = \frac{AEW^{y}}{TEW^{y}} \tag{6-2}$$

where, *AEW* is computed in the long-term modeling. The target of ecological and environmental water use (*TEW*) is also an input to the long-term modeling. Estimation of this item can be based on historical records and further ecological and environmental investigation in the study area. For the case study of this research, we take this item as the annual inflow to the Aral Sea. Historical records show the amount of inflow to the sea in the years with various hydrologic levels (Micklin, 1993). In Central Asia, many research projects have been trying to find what minimum amount of inflow is needed for recovery of the declining inland lake in different hydrologic years.

Based on the two items defined above, we express *Reliability, Reversibility, and Vulnerability* in Table 6.1.

The overall risk criteria may be estimated as:

$$REL = w_{ia} \cdot REL_{ia} + w_{ew} \cdot REL_{ew} \tag{6-3a}$$

$$REV = w_{ia} \cdot REV_{ia} + w_{ew} \cdot REV_{ew} \tag{6-3b}$$

$$VUN = w_{ia} \cdot VUN_{ia} + w_{ew} \cdot VUN_{ew} \tag{6-3c}$$

where *REL* is the reliability, *REV* is the reversibility, *VUN* is the vulnerability, and *w* is the weight assigned to the two aspects, sustaining the irrigated area and the environmental water supply. We have $w_{ia} + w_{ew} = 1.0$.

Table 6. 1. Calculation of risk criteria

Risk Criteria	***Irrigated Area (IA)***	***Ecological Water Use (EW)***
Reliability	$REL_{ia} = \sum_{y} RIA^{y} / Y$	$REL_{ew} = \sum_{y} REW^{y} / Y$
Reversibility	$REV_{ia} = YF_{ia} / Y$	$REV_{ew} = YF_{ew} / Y$
Vulnerability	$VUL_{ia} = \min_{y} RIA^{y}$	$VUL_{ew} = \min_{y} REW^{y}$

where **YF_{ia}** is the number of consecutive years in which $RIA^{y} < 1 - \alpha_{ia}$, α_{ia} represents a percentage which specifies a safety threshold. For example, $\alpha_{ia} = 10\%$ means at most 10% of the planned irrigated area can be reduced, and if $RIA^{y} < 1 - \alpha_{ia} = 90\%$, the performance is a failure. The strictest condition is that $\alpha_{ia} = 0\%$. Similar definitions apply for **YF$_{ew}$**, which are the numbers of consecutive years in which $REV^y < 1 - \alpha_{ew}$.

6.2.2 Quantification of environmental integrity criterion

In terms of environmental integrity, the following aspects are considered in the modeling: surface and ground water salinity, soil salinity, flow release for ecological use (to the Aral Sea), and minimum flow requirements through river reaches. Surface and groundwater water quality are closely related to the excessive salt discharge from crop fields that is controlled by a penalty tax (eq. 3-31) in the long-term modeling. As described in Chapter 3, Section 3.4.4, soil salinity is a variable in the crop production function. Therefore, this item is related to agricultural profit that is to be both optimized in the individual yearly models and controlled by other related criteria in the long-term modeling. Flow release for ecological use (to the Aral Sea) is directly formulated in the objective function of the yearly models, and also directly considered in the water supply criteria, as discussed above. Minimum flow requirements are handled as hard constraints in the yearly models. Therefore, in the long-term modeling flow release for ecological uses and minimum flow requirements are directly controlled, the others are indirectly controlled through connections with other items. For the items indirectly controlled, i.e. surface and ground water salinity, and soil salinity, we define an index that can be directly included in the long-term objective function, as below:

$$envi = \max_{dm}\left(\max_{yr}(Sws_{dm}^{yr})\right) + \max_{dm}\left(\max_{yr}(Sgw_{dm}^{yr})\right) + \max_{dm,fd}\left(\max_{yr}(Sso_{dm,fd}^{yr})\right) \qquad (6\text{-}4)$$

where

yr = year,

dm = demand site,

$envi$ = index for environment integrity,
Sws = surface water salinity,
Sgw = groundwater salinity, and
Sso = soil salinity in crop field fd.

Equation 6-4 finds the sum of the maximum salt concentration (salinity) in surface water, groundwater, and soil in the crop root zone. As can be seen in the following, the index for the criterion of environment integrity, *envi*, is minimized in the objective function of the long-term modeling, so that those salinity items discussed above ca be directly controlled.

6.2.3 Quantification of equity criteria and socio-economic acceptability

The equity criteria in this research are assumed to assure people at different locations in a river basin have equal opportunities in agricultural development, and to keep water use benefits increasing, or at least not decreasing, evenly through all years. Before we give a quantitative expression of these criteria, recall that in Chapter 3 the total water use benefit for the region of the river basin in year y was defined as

$$TWB^{y} = \sum_{dm} IP_{dm}^{y} + HP^{y} + BE^{y} \qquad (6\text{-}5)$$

The changing rate of *TWB* between year y and y-1 is computed as:

$$\gamma^{y} = \frac{TWB^{y} - TWB^{y-1}}{TWB^{y-1}} \qquad (6\text{-}6)$$

where $y=2,3,..\ Y$.

Inter-year Equity (TEQ):

The *inter-year equity* (*TEQ*) is expressed as the standard deviation of γ^y, y= 2, .. Y;

$$TEQ = \sqrt{\frac{\sum_{y=2} (\gamma^y - \bar{\gamma})^2}{Y-2}} \tag{6-7}$$

where $\bar{\gamma} = (\sum_{y=2} \gamma^y)/(Y-1)$.

Spatial Equity (SEQ):

To express the *spatial equity* (*SEQ*), for each demand site, we calculate the average changing rate of the irrigation profit over all years,

$$rd_{dm}^{y} = \frac{IP_{dm}^{y} - IP_{dm}^{y-1}}{IP^{y-1}} \tag{6-8}$$

$$\overline{rd}_{dm} = \frac{1}{Y-1} \cdot \sum_{y} rd_{dm}^{y} \tag{6-9}$$

where rd is the annual benefit changing rate for each demand site, and $\overline{rd}$ is the average benefit changing rate over all years for each demand site.

The *spatial equity* (*SEQ*) is calculated as the standard deviation of $\overline{rd}$ over all demand sites.

$$SEQ = \sqrt{\frac{\sum_{y} (\overline{rd}_{dm} - \overline{\overline{rd}})^2}{DM-1}} \tag{6-10}$$

where $\overline{\overline{rd}}$ is the average of $\overline{rd}$ over all demand sites, and *DM* is the number of demand sites.

Socio-Economic Acceptability (SEA):

Socio-economic acceptability (*SEA*) in the study area is expressed as the ratio of the total water use benefit to the total investment over all study years.

$$SEA = \frac{\sum_{y} TWB^{y}}{\sum_{y} \sum_{dm} INV_{dm}^{y}} \tag{6-11}$$

where all the items have been defined before.

With this criterion, normally, it is expected that $\partial SEA / \partial INV > 0$; however, when the river basin system enters or is close to an unsustainable state, $\partial SEA / \partial INV < 0$, which means more investment decreases the total social benefits in the region, and external economic aids are necessary for the system to recover to a sustainable state. That is the current condition in the Aral Sea basin. The local republics could not afford the recovery of the environmental disaster, and international sources are needed.

Based on the quantification of these sustainability criteria, we describe in the following how these criteria can be integrated with the long-term dynamic modeling.

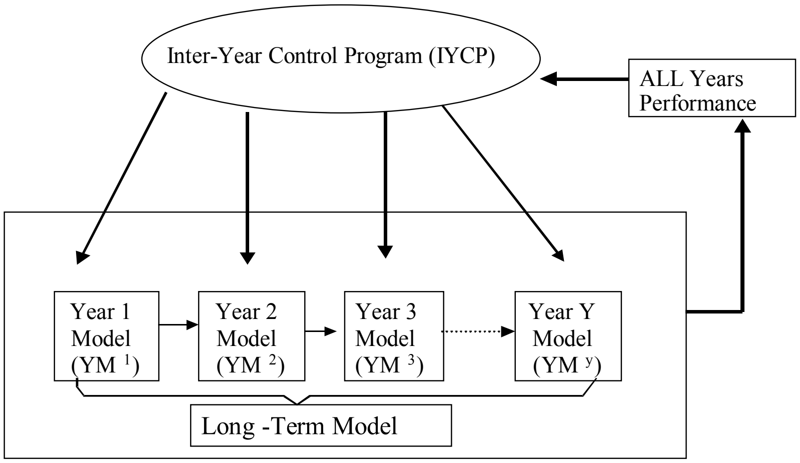


Figure 6. 1. A simple structure of the long-term modeling framework

6.3 COMPOSITION OF THE LONG-TERM DYNAMIC MODELING FRAMEWORK

As illustrated in Figure 6.1, the long-term modeling framework is composed of an *Inter-Year Control Program (***IYCP***)* and a series of *Yearly Models (***YM***)*. The **IYCP** is the program that realizes the transition of status between years, and controls the performance of the system within the whole time horizon. A **YM** has the same formulation as the short-term model discussed in Chapter 3, which includes essential hydrologic, agronomic and economic relationships. All yearly models have the same structure but with different initial conditions and inputs. The ending condition from the **YM** in year y is the initial condition of the **YM** in year $y+1$. The **IYCP,** the **YM**, and the connection between them are described in the following.

6.3.1 The inter-year control program (IYCP)

The function of the **IYCP** is to (1) connect the YMs and form a framework with multiple years; (2) control the performance of each yearly model; and (3) search for a better performance of the modeling system over the whole time horizon. The connection between the **IYCP** and the **YMs** is realized through a control loop, in which the **IYCP** sends 'proposals' to each **YM**, and the total years' performance, resulting from all **YMs**, is fed back to the **IYCP**. The total years' performance is characterized by the sustainability criteria described above. The 'proposals' on **YMs** comprise the inter-year variables stated in the following:

WSU^{y} is the water sustained at the end of year *y*, which is a vector of inter-year variables representing *water sustained* from each hydrologic year for future use. The term *water sustained* (*WSU*) means the volume of water that will be saved in reservoirs, at the end of a hydrologic year, which may be used in future years, assuming the reservoirs in a river basin have the capacities for multiple year flow regulation. The initial water available at the beginning of a year is equal to the water sustained at the end of the previous year. Therefore, one **YM** is connected to both its previous and following year;

EDS_{dm}^{y} is the water distribution efficiency in year *y* for demand site *dm*; EDN_{dm}^{y} is the drainage efficiency in year *y* for demand site *dm*; and $EIR_{dm,fd}^{y}$ is the irrigation efficiency in year *y*, for crop field *fd* at demand site *dm*. These three items indicate the performance of the irrigation and drainage system. The **IYCP** creates various alternatives for these items and proposes them to each yearly model to compute their effectiveness.

$IA_{dm,fd}^{y}$ is the irrigated area in year *y* for crop field *fd* at demand site *dm*. As discussed before, irrigated area is a comprehensive indicator of the sustainability of the agricultural production system. **IYCP** proposes the irrigated area for each crop concerned at each demand site, year by year, within the whole time horizon. However, as we will discuss later, the irrigated area in each year will finally be determined in the **YM,** since it may be reduced due to water shortage, excessive soil salinity, and waterlogging, for example.

The tax rate (tax_{dm}^{y}) is for excessive salt discharge in year *y* for demand site *dm.* As an economic incentive, a tax is imposed to prevent excessive salt discharge. In a long-term view, the tax rate may vary from demand site to demand site, and from year to year, due to the salinity in water and soil systems, the climatic situation, as well as the irrigation and drainage practices. The **IYCP** controls salt discharge through imposing various tax rates to different demand sites and in different years.

These inter-year decision variables will be determined in the **IYCP** and then sent to each **YM** as given parameters. The **IYCP** controls individual **YMs** by assigning them appropriate values of the above items. The procedure takes a number of iterations until the total years' performance can not be improved further. The procedure is implemented through a GA-LP approach introduced in Chapter 5, which is described in detail below.

6.3.2 The yearly model: decomposition and approximation

The yearly model has the same formulation as the short-term model described in Chapter 4. However, the short-term model is a large-scale nonlinear, nonconvex model. Including such a sub-model into the long-term modeling framework will result in a model which is very difficult, if impossible, to solve using currently available computational capacity. Therefore, several measures are taken to make the framework tractable. First, the inter-year variables discussed above, which are endogenous variables in the short-term model, now are fixed input parameters to the **YMs**. This converts many nonlinear relationships in the

YM to linear ones. As endogenous variables in the short-term model, the water distribution efficiency (EDS_{dm}^{y}), irrigation efficiency ($EIR_{dm,fd}^{y}$), and drainage efficiency (EDN_{dm}^{y}) make the water and salinity balances at the basin, the demand site (farm), and the field levels all nonlinear in the model; the irrigated area brings nonlinearity to the calculation of irrigation profit (eq. 3-31, and 3-34), as well as the equations of water and salt balances in the crop field (eq. 3-18, 19, and 25). With these items as input parameters in the model, all the related nonlinear items in those equations become linear.

The bilinear items where the flow variables multiply the concentration variables still remain nonlinear even with the input parameters from the **IYCP,** which makes the solution of the model rather complex and time-consuming. To overcome this problem, as shown in Figure 6.2, the salt balance equations ($\mathbf{SM}^{y}$) are separated from the flow balance equations ($\mathbf{FM}^{y}$). In the $\mathbf{FM}^{y}$, the flow balance is computed in each month, and the soil salinity in the crop field is treated as constant over the whole crop growth season. When the flow sub-model $\mathbf{FM}^{y}$ is solved, the monthly flow solution is aggregated into seasonal flow, which is taken as the input parameter in the seasonal salt mass balance sub-model ($\mathbf{SM}^{y}$). The $\mathbf{SM}^{y}$ only includes the salt balance relationships, and it has only seasonal salt concentrations as variables. With the seasonal flow parameters from the $\mathbf{FM}^{y}$, all constraint equations in the $\mathbf{SM}^{y}$ are linear. The objective function of $\mathbf{SM}^{y}$ minimizes the salt accumulation in the root zone, which is a linear equation too. Therefore, the $\mathbf{SM}^{y}$ is a linear model.

With the interaction between the **IYCP** and the **YM** and the decomposition of **YM** into $\mathbf{SM}^{y}$ and $\mathbf{FM}^{y}$, we have the linear model $\mathbf{SM}^{y}$, and most of the nonlinear equations in the $\mathbf{FM}^{y}$ are linear. The remaining nonlinear equations in $\mathbf{FM}^y$ include (1) the hydropower generation equation where the release variables are multiplied with the reservoir head variables; (2) the actual crop evapotranspiration calculation (eq. 3-21, 23, and 24); and (3) the groundwater extraction calculation (eq. 3-20). The linearization of these equations is described as below.

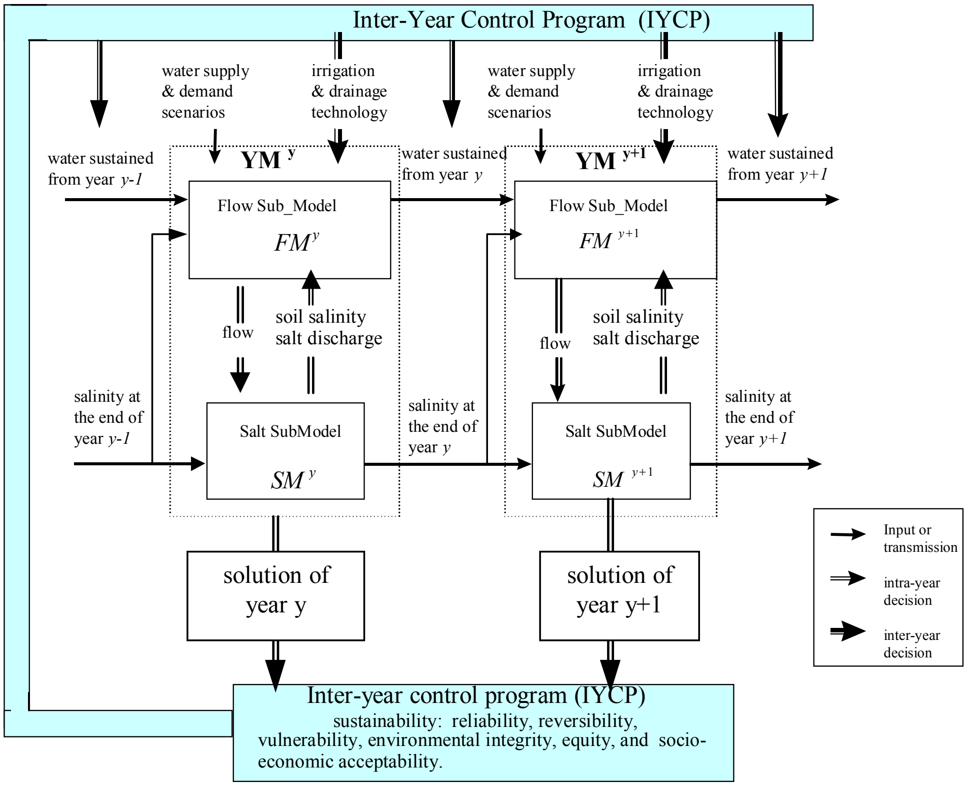


Figure 6. 2. Decomposition and integration of the long-term modeling framework

.

The hydropower generation is approximately expressed as a linear relation with water release through the turbines,

$$hydro\ power = \alpha_1 \cdot release + \alpha_2 \qquad (6\text{-}12)$$

This equation is fitted based on the results from the hydropower generation model developed for the case study area by McKinney and Cai (1997), which includes nonlinear power generation equations. For each reservoir with a hydropower station, a series of hydropower and reservoir release values from the model were used to obtain the above linear equation by regression. The regression function was tested and the result was comparable to that of the model by McKinney and Cai (1997). The coefficients in the regression equations are shown in Table 6.2. It is to be noted that among the five reservoirs listed in Table 6.2, all reservoirs except for the Toktogul reservoir have an approximately constant head in their practical runs.

Table 6. 2. Coefficients in the linearized power generation equations

Hydro. Stations	α_1	α_2
Toktogul	386.051	-5.001
Kurpskaya	245.521	0.000
Tashkumur	138.975	0.000
Shamli	74.122	0.000
Utchkurgan	82.227	0.000

The nonlinear items in the expression of the actual crop evapotranspiration include *kat*, the coefficient of the soil water stress effect for transpiration (eq. 3-23), and *kap*, the coefficient of the soil water stress effect for bore soil evaporation (eq. 3-24). Assuming the soil moisture $Z^t_{dm,fd} \geq 1.1 \cdot Zw_{dm,fd}$ (*Zw* is the soil moisture at the wilting point), Equation 3-23 is directly linearized as:

$$kat^{t}_{dm,sa,fd} = 0.4301 \cdot \left(\frac{Z^{t}_{dm,sa,fd} - Zw_{sa}}{Zs_{sa} - Zw_{sa}} \right) + 0.5699 \qquad (6\text{-}13)$$

with R^2 equal to 0.9575.

With the same assumption as above, Equation 3-24 is linearized as:

$$kap^{t}_{dm,sa,fd} = 0.5739 \cdot \left(\frac{Z^{t}_{dm,sa,fd} - 0.5 \cdot Zw_{sa}}{Zs_{sa} - 0.5 \cdot Zw_{sa}} \right) + 0.4261 \qquad (6\text{-}14)$$

with R^2 equal to 0.9984. The items in these two equations have been defined in Chapter 3.

In the groundwater extraction expression (eq. 3-20), the groundwater depth is the only variable. We simply replace the variable with a constant parameter, which is the annual average value of the groundwater depth. Thus Equation 3-20 will not contain any variable.

With these decompositions and approximations, the yearly model ($\mathbf{FM}^{y} \& \mathbf{SM}^{y}$) only contains linear relationships, and it can be solved by a linear programming solver.

6.4 IMPLEMENTATION OF THE LONG-TERM DYNAMIC MODELING FRAMEWORK

Figure 6.2 also presents the composition of the long-term dynamic modeling framework, as well as the connections within the framework. The implementation of the long-term dynamic modeling framework includes (1) the procedure for solving the yearly model in each year; (2) the transition from year to year; and (3) the inter-year control for searching for a better solution in the whole time horizon. This section describes these issues and presents a framework for the long-term dynamic modeling.

6.4.1 Procedure for solving the yearly model

As described above, the yearly model (**YM**) is decomposed into a flow-balance based model ($\mathbf{FM}^y$) and a salinity-balance based model ($\mathbf{SM}^y$). The $\mathbf{FM}^y$ contains all the relationships of the yearly model, except for the salinity balance equations, and the objective value of $\mathbf{FM}^y$ is related to the outcome of the $\mathbf{SM}^y$. The feed-back from the $\mathbf{SM}^y$ to the $\mathbf{FM}^y$ includes two items: the soil salinity affecting coefficients *ks* (eq. 3-22) and the excessive annual salt discharge (*ESD*) to the river system from each demand site. In the $\mathbf{FM}^y$, the soil salinity coefficients *Ks* affect the value of the actual crop evapotranspiration (eq. 3-21), and the excessive salt discharge is related to the penalty tax included in the objective function. At the beginning, the $\mathbf{FM}^y$ is run with initial *ESD* and *Ks* given by estimation, and in the following iterations, the values of these items are solved from the $\mathbf{SM}^y$. The iterations between the $\mathbf{FM}^y$ and the $\mathbf{SM}^y$ continue until the change of the objective value of the $\mathbf{FM}^y$ is below a prescribed tolerance.

This simple iteration procedure may not yield a global solution for the yearly model. Considering the computing complexity in the long-term framework, however, this method is considered currently. The actual purpose of the iterations between the two sub-models is to find an approximate optimal solution for a yearly model, considering the soil salinity effect and the salt discharge control. We assume a precise optimal solution within individual years is not necessary for the purpose of the long-term modeling.

Due to water shortages, soil salinity and waterlogging conditions in individual years, the crop yield may decline to levels unacceptable to farmers. These conditions are controlled by the following rules: (1) the ratio of actual crop evapotranspiration to the reference evapotranspiration should not be less than 0.5, which in fact is an empirical rule based on the FAO water-yield relationship

(FAO, 1979); (2) the soil salinity coefficient, *Ks,* should not be less than 0.5, which means yield damage due to salinity should not be more than half of the normal yield; and (3) the groundwater table should not be above a critical threshold. The critical groundwater table mostly depends on the rooting depth of the crop, the efficiency of irrigation water use and on the hydraulic characteristics of the soil. These rules are implemented by the following measures:

- **(a)** If the ratio of actual crop evapotranspiration to the reference evapotranspiration is less than 0.5 for a crop, then reduce the irrigated area of that crop by a fraction so that the ratio on the remaining area will be at least 0.5. The area reducing fraction is determined in the procedure shown in Figure 6.3.
- **(b)** If the soil salinity coefficient, *Ks*, is less than 0.5 for a crop, then reduce the irrigation field application efficiency by a fraction, which means using more water for salt leaching. Also the reducing fraction of field application efficiency is also determined in the procedure shown in Figure 6.3.
- **(c)** If the groundwater table is above the critical level, then drainage will be pumped and disposed at an evaporation pond to make the groundwater table below the critical level, which is actually practiced in the study area. This measure is endogenously implemented in the $\mathbf{FM}^y$ by setting the drainage disposal equal to the excessive drainage.

The procedure is executed in a conditional loop frame as shown in Figure 6.3, including the iterations between the $\mathbf{FM}^y$ and the $\mathbf{SM}^y$ and the controlling measures specified above.

```
$IA = IA^{IYCP}$
$IAN = 0$
$EIR = EIR^{IYCP}$
(Assigning initial values for the irrigated area, IA, and the irrigation application efficiency, EIR, using the values from the IYCP; IAN is defined as area remaining fallow due to water shortage and salinity)

$ks = ks0$
$EDS = EDS_0$
(Assigning initial values for the soil salinity coefficients and excessive salt discharge)
While ( $obj - obj0 > tol$ or $\frac{ETA}{ET_0} < 0.5$ or $ks > 0.5$
{
    (While the difference between the objective value of $\mathbf{FM}^y$ in the current iteration and the last iteration is less than a pre-defined tolerance, or the salinity coefficient is less than 0.5, or the actual ET is less than half of the reference ET, do the loop)

        If ( $\frac{ETA}{ET_0} < 0.5$ ) then $IA = IA \cdot (1-\delta)$, $IAN = IAN + IA \cdot \delta$
        (Irrigated area is reduced by a fraction $\delta$ )

        If ( $K_s > 0.5$ ) then $EIR = EIR \cdot (1-\sigma)$

        (Field application efficiency is reduced by a fraction $\sigma$ )
                Solve $\mathbf{FM}^y$ by maximizing profit

                $aflow = flow^{FM}$
        (Calculate the aggregated seasonal flow based on the solution of the $\mathbf{FM}^y$)

                Solve $\mathbf{SM}^y$ for calculating the salinity variable

        $ks = ks^{SM}$
        $EDS = EDS^{SM}$

        (Update the values of the soil salinity coefficients and the excessive salt discharge, and back to check the running condition for next iteration)
        }
```

Figure 6. 3. Procedure to solve the yearly model

6.4.2 Implementation of the connection between the yearly models

The connection between the yearly models maintains the dynamic relationships from year to year in the long-term modeling framework. Basically, the ending conditions of year *y* form the starting conditions of year *y+1*, and we need to set the status in the last period of the $\mathbf{YM}^{y}$ as the initial condition of the first period of $\mathbf{YM}^{y+1}$. With respect to flow, at the end of each year, some amount of water will be sustained for the use in the next year, which is specified by WSU^{y}, an item from the **IYCP**. Further, the storage of reservoirs, the groundwater table, and the soil moisture in the root zone at the end of year *y* are set as the initial values of these items in year *y+1*, so that the surface water, groundwater storage and soil water storages can keep their continuity. With respect to salinity, the seasonal salt concentrations from $\mathbf{SM}^{y}$ will be set as the initial salinity for $\mathbf{SM}^{y+1}$. That is to say, the salt concentrations at the end of the nongrowing season of year *y* are the salt concentrations at the beginning of the growing season of year *y+1*. The connection between the yearly models is shown in Figure 6.3. The salt concentrations in surface and groundwater storage and the salinity in the soil of the root zone are transferred to the next year.

The irrigated area from year to year should also keep its continuity in order to trace the waterlogging and salinity conditions in the long-term time horizon. Year by year, new area may be added to a crop, or part of the primary area of a crop may be cut due to many factors such as urbanization, crop rotation, as well as water shortage, excessive soil salinity, and waterlogging. We use the procedure described below to keep the continuity of irrigated area.

For one year (*y*), irrigated area for one crop may be reduced due to water shortage and soil salinity, and we assume the reduced area (*RIA*) is left unplanted in that year, but the soil water and salinity balances are still determined for the area in the model. In year *y+1*, the initial irrigated area for that crop is equal to:

$$IA0_{cp}^{y+1} = RIA_{cp}^{y} + IA_{cp}^{y} \pm \Delta IA_{cp}^{y+1} \tag{6-15}$$

where $IA0_{cp}^{y+1}$ = *Initial* irrigated area of crop *cp* in year *y+1*,

RIA_{cp}^{y} = Reduced irrigated area of crop *cp* in year *y*,

IA_{cp}^{y} = Actual irrigated area of crop *cp* in year *y,*

ΔIA_{cp}^{y+1} = Planned added or cut area for crop *cp* in year *y+1*.

The initial soil moisture and soil salinity for year *y+1* are calculated as the area-weighted average value of the three components in the above equations, respectively. The soil moisture and salinity with IAN_{cp}^{y} and IA_{cp}^{y} are from the $\mathbf{FM}^{y}$ and the $\mathbf{SM}^{y}$, respectively. For ΔIA_{cp}^{y+1}, the soil moisture and salinity take the average values of the whole cropping area within one demand site.

6.4.3 Solving the long-term dynamic modeling

The implementation of the long-term modeling includes (1) determining the inter-year control variables through the inter-year control program (**IYCP)**; (2) solving the yearly models year by year; (3) calculating the the performance over the whole time horizon based on the results from all yearly models; and (4) executing iterations between the **IYCP** and the **YMs**. The GA & LP approach described in Chapter 5 is used to solve the long-term dynamic modeling framework.

Figures 6.4 and 6.5 show diagrams of the implementation of the GA & LP program. The GA program starts the first generation by randomly creating a prescribed number of individuals (IND_{ni}^{ng}, *ni=1, 2, ... NI*), and each individual is represented as an alternate solution of the inter-year control variables:

$$IND_{ni}^{ng} = (WSU^{y}, EDS_{dm}^{y}, EDN_{dm}^{y}, EIR_{dm,fd}^{y}, IA_{dm,fd}^{y}, tax_{dm}^{y}) \qquad (6\text{-}16)$$

and each generation (GEN^{ng}, *ng=1, 2, ... NG*) is represented as a group of individuals:

$$GEN^{ng} = \{IND_{1}^{ng}, IND_{2}^{ng}, IND_{3}^{ng}, \ldots\ IND_{NI}^{ng}\} \qquad (6\text{-}17)$$

Actually, the individual inter-year control variables should be indexed by generation number (*ng*) and individual number (*ni*), but the notation would be too cumbersome here so it is suppressed in eq. 6-16.

Each individual represents an alternative solution of the inter-year decision variables. For each individual, the genetic algorithm selects values for the inter-year control variables within their prescribed ranges. These values with an index $y = 1, 2, \ldots Y$ (number of years considered in the model) are then input into the corresponding yearly model $\mathbf{YM}^{y} (= \mathbf{FM}^{y} + \mathbf{SM}^{y})$ (*y=1, 2, ... Y*), which is solved year by year with the year-to-year transitions described above. That is to say, with each individual, the modeling framework simulates the long-term system performance, while optimizing the decisions within each individual year under the given proposal from the inter-year variables.

The results from the **YMs** are input into a fitness calculation program to determine the fitness of each individual in the current generation. The fitness calculation is based on the sustainability criteria expressed in equations 6-1 to 6-

10. Considering all these criteria, we have a multiple criteria evaluation problem. Some of the indices are to be maximized, and the others are to be minimized, according to their formulation (eq. 6-1 to 6-11), which is to:

$$\left\{ \begin{matrix} max\ REL;\ min\ REV;\ min\ VUN;\ min\, ENVI; \\ min\ TEQ;\ min\ SEQ;\ \text{and}\ max\ SEA \end{matrix} \right\} \tag{6-18}$$

The objective function of the **IYCP** is formulated as a weighted sum of these multiple objectives, and the objective variable (*OBJ*) is to be minimized:

$$\begin{aligned} OBJ = wrel \cdot\ (1 - REL) + wrev \cdot\ REV + wvun \cdot VUN \\ + wenv \cdot ENVIN + weq \cdot TEQ + wseq \cdot SEQ + wsea \cdot SEA^{-1} \end{aligned} \tag{6-19}$$

where, *wrel, wrev, wvun, wenv, weq, wseq*, and *wsea* are weights (or scaling factors) assigned to corresponding criteria. The objective variable, OBJ, is set to be minimized, and the two items, "*1-REL*" and "SEA^{-1}", are used in the objective function to make the indices "REL" and "SEA" to be maximized. All other indices are directly minimized in the objective function. The genetic algorithm calculates this objective for each individual of one generation, and thus determines the fitness value of the individual, that is,

$$FITNESS_{ind}^{ng} = OBJ^{-1}(IND_{ni}^{ng}) \tag{6-20}$$

where the value of fitness is equal to the inverse of the objective variable, *obj*, which is minimized in the long-term modeling, i.e., a lower value of *obj* corresponds to a higher value of fitness of an alternative solution.

The best individual has the highest fitness. The fitness of an individual depends on the effects from the decisions in each year, and represents an evaluation of the individual according to the prescribed sustainability criteria.

The GA searches the best individual from generation to generation. Based on the fitness for all individuals in one generation, the GA determines the probability for each individual to be selected to "mate" for the creation of the individuals in the next generation that theoretically include better individuals than the prior generation. From generation to generation, the program will gradually approach the globally best individual which represents the optimal solution of the inter-year decision variables. This optimal solution will provide the best proposal for the yearly models with respect to the sustainability criteria discussed before. The optimal decisions within each year (i.e., short-term decisions) are searched by the procedure described in Figure 6.3.

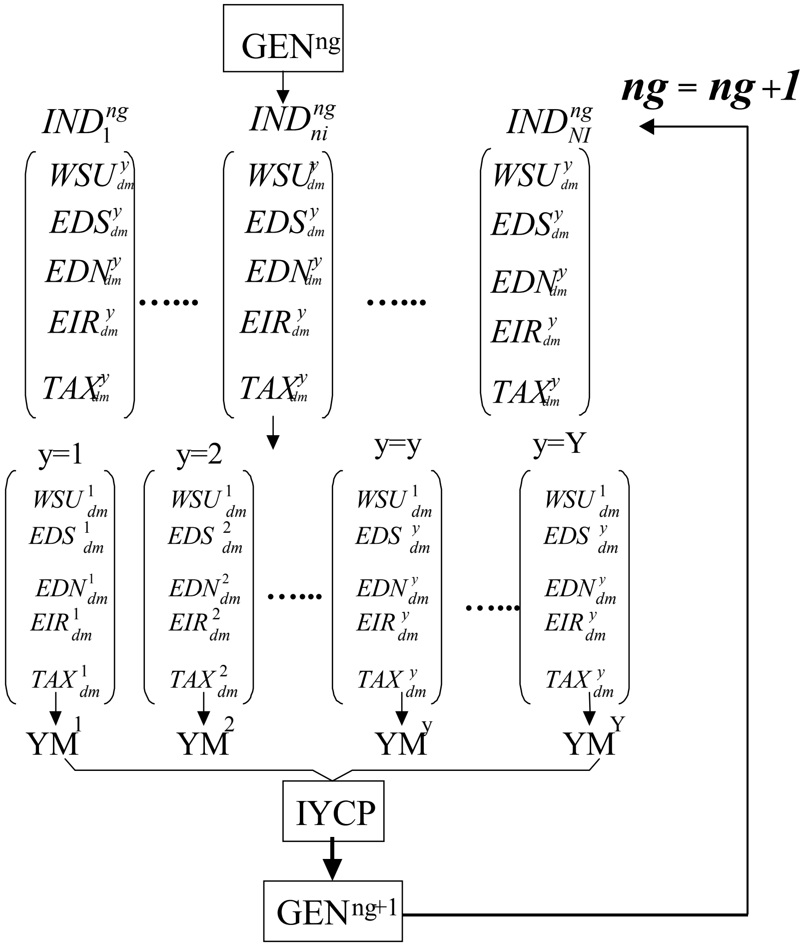


Figure 6. 4. Genetic algorithm implementation of the inter-year control program

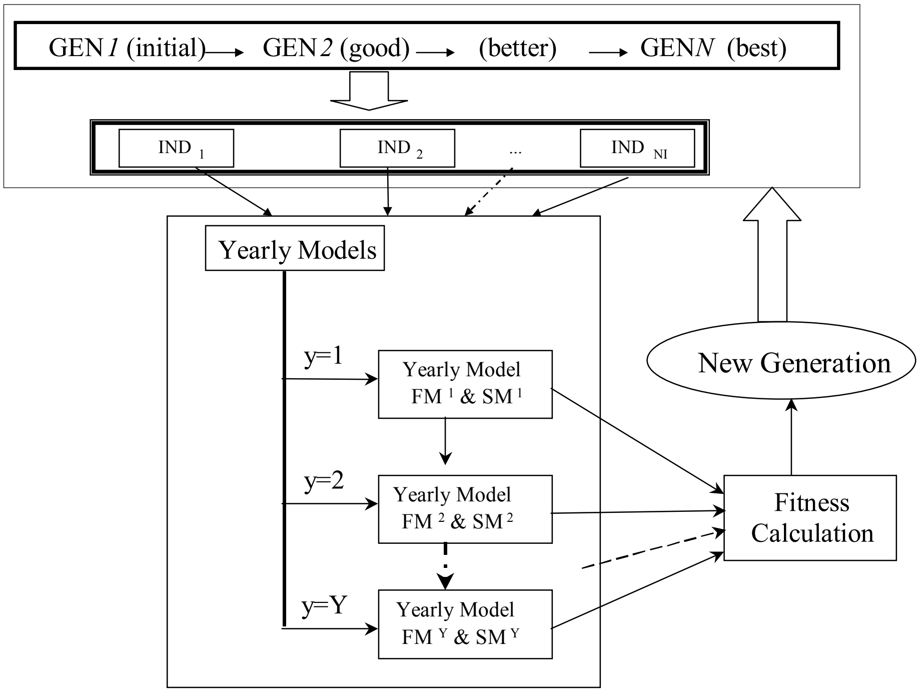


Figure 6. 5. Genetic algorithm implementation sketch of the inter-year control program

```
Randomly create the first generation
  $GEN^1 = (IND_1^1, IND_2^1\ IND_3^1\ \ldots IND_{NI}^1)$
$= \{\ (WSU^y, EDS_{dm}^y,\ EDN_{dm}^y,\ EIR_{dm,fd}^y, IA_{dm,fd}^y,\ tax_{dm}^y)_1^1,$
    $(WSU^y, EDS_{dm}^y,\ EDN_{dm}^y,\ EIR_{dm,fd}^y, IA_{dm,fd}^y,\ tax_{dm}^y)_2^1,$
    $\ldots$
    $(WSU^y, EDS_{dm}^y,\ EDN_{dm}^y,\ EIR_{dm,fd}^y, IA_{dm,fd}^y,\ tax_{dm}^y)_{NI}^1,$
  $\}$
For $GEN^{ng}$ ng = 1 ... NG

{
        For each individual in $GEN^{ng} = \{IND_1^{ng}, IND_2^{ng}, IND_3^{ng}, \ldots\ IND_{NI}^{ng}\}$
        {
            Run the $\mathbf{YM^y} (= \mathbf{FM^y} + \mathbf{SM^y})$ for each year (y=1, 2, ... Y)
            Calculate $FITNESS_{ind}^{ng} = OBJ(IND_{ni}^{ng})$ based on outputs from all $\mathbf{YM^y}$
        }
        Create $GEN^{ng+1}$ based on $FITNESS_{ind}^{ng}$ with $IND_{ni}^{ng}$ ni=1 to NI
}
```

Figure 6. 6. Procedure for the long-term dynamic modeling

The inter-year control variables, i.e., the decision variables in the **IYCP**, are limited by some bounds and constraints, which are described below.

- Water saved for future use at the end of year y is bounded by prescribed lower and upper bounds depending on the hydrologic condition of the year:

  $$\underline{WSU}^y \leq WSU^y \leq \overline{WSU}^y \tag{6-21}$$

  where the upper bounds is the total available reservoir storage in the basin, and the lower bound is an empirical value depending on hydrologic condition of the year. The lower bound is smaller in dry years than in wet years. The determination of the lower bound is also related to reservoir operation rules set for specific purposes such as flooding control and emergency water supply.

- Since water delivery & distribution, irrigation and drainage are related to long-term permanent systems, and assuming that system maintenance is well done, then water delivery & distribution efficiency, irrigation efficiency, and drainage efficiency are not reduced over time. Therefore besides the lower bounds (current level) and upper bounds (a value less than 1.0), an inter-year relationship of these items is defined as:

  $$EDS_{dm}^{y+1} \geq EDS_{dm}^{y} \tag{6-22}$$

  $$EDN_{dm}^{y+1} \geq EDN_{dm}^{y} \tag{6-23}$$

  $$EIR_{dm}^{y+1} \geq EIR_{dm}^{y} \tag{6-24}$$

- The irrigated area for each crop at a demand site is bounded by empirical ranges. However, the sum of crop areas over all crop fields must remain below the total available area in one demand site:

$$\sum_{fd} IA_{dm,fd}^{y} \leq TIA_{dm}^{y} \qquad (6\text{-}25)$$

- the penalty tax rate on excessive salt discharge is constrained by ranges varying from year to year.

$$\underline{tax}_{dm}^{y} \leq tax_{dm}^{y} \leq \overline{tax}_{dm}^{y} \qquad (6\text{-}26)$$

where the lower and upper bounds for penalty tax rate are estimated based on the scenarios defined for short-term analysis, as presented in Chapter 4, Section 4.3.3.5.

The variable bounds are directly implemented in the GA. When the GA chooses a value for a variable, it must be within the prescribed variable bound. However, the constraints other than direct bounds on the variables may not be automatically satisfied by the solution created by the genetic algorithm. For example, the genetic algorithm chooses the values of the irrigated area for all crops at one demand site within their prescribed ranges. However, the sum of these values may be above the total available irrigated area at the demand site. Generally a penalty is defined based on the magnitude of the violation of the constraint, and it is incorporated into the objective function (expression of the 'fitness'). In this research, we simply apply a post-modification to the solutions of the genetic algorithm, based on the relationships expressed in equation (6-19 to 6-22). For irrigated area (eq. 6-22),

$$\text{If } \sum_{fd} IA_{dm,fd}^{y} > TIA_{dm}^{y} \text{ then}$$

$$IA_{dm,fd}^{y} = IA_{dm,fd}^{y} \cdot \frac{TIA_{dm}^{y}}{\sum_{fd} IA_{dm}^{y}}, \text{ thus}$$

$$\sum_{fd} IA_{dm,fd}^{y} = TIA_{dm}^{y} \tag{6-27}$$

and for water distribution, irrigation and drainage efficiencies (eq 6-18 to 6-20), taking water distribution efficiency *EDS* as an example:

$$\text{If } EDS_{dm}^{y+1} < EDS_{dm}^{y}, \text{ then}$$

$$EDS_{dm}^{y+1} = EDS_{dm}^{y} \tag{6-28}$$

The modified **GA** solutions satisfy all prescribed variables and relationships. However, for a general GA model, this post-modification may lose some useful “genes”, and further research has to be done on this issue.

6.5 SUMMARY

This chapter presents a viable modeling framework for sustainability analysis in long-term water resources management**.** concepts related to the long-term modeling for sustainability analysis in water resources management were discussed. The critical issue for this modeling is to trace and control long-term consequences resulting from short-term “wait-and-see” decisions, with predicted changes and uncertainties on both water demand and supply in the future. The long-term system performance is controlled by specifically prescribed sustainability criteria with respect to water supply risk, equity, environmental integrity, and socio-economic acceptability. A modeling framework is described to incorporate the quantified sustainability criteria into mathematical formulas. The modeling framework is composed of a series of yearly models (**YM**) and an inter-year control program (**IYCP**). The yearly model includes the essential hydrologic, agronomic, economic, and institutional relationships described in Chapter 3. However, for computing efficiency, it is formulated as a linear model by approximation and decomposition, and it is solved by an integrated simulation and optimization procedure. The inter-year control program is implemented by the GA-LP approach described in Chapter 5. An application of this modeling framework to the case study area is presented in the next chapter.

Chapter 7

Sustainability Analysis – An Application of the Long-Term Dynamic Modeling Framework

7.1 INTRODUCTION

In this chapter, the long-term dynamic modeling framework described in Chapter 6 is applied to water resources planning and management for the case study area, the Syrdarya River basin in Central Asia. The time horizon for the modeling is 30 years.

First, the data required by the model for the case study, as well as the assumptions with regard to the case study are described. Emphasis is put on the appropriate prediction and expression of the long-term changes and uncertainties of both water supply and demand, which are essential to the long-term modeling analysis.

It goes beyond the effort of this research to calibrate and verify the modeling framework for solving the problems in the study area. This will need further work in data collection and verification, as well as a more in-depth study of the water management problems in that area. However, based on the current data availability and the current understanding of the problems, the effectiveness of the modeling framework applied to the case study area is demonstrated i.e., how effectively it can be used to analyze sustainability in the river basin. The limitations of the modeling framework are also addressed.

The modeling framework traces the long-term consequences resulting from year-to-year decisions, such as soil salinity accumulation, waterlogging, quality reduction in surface and ground water, irrigated area reduction, and ecological water depletion due to excess water withdrawal. These consequences may put sustainability at risk in the study area, an irrigation-dominated river basin situated in an arid climate. Based on the modeling output, these consequences are displayed and analyzed.

Since the sustainability of the irrigation and environmental systems is associated with long-term changes and uncertainties, scenario analysis based on possible changes and uncertainties in both water demand and water supply are conducted to ensure a robust modeling analysis. Based on the outputs from various scenarios, sustainability is analyzed with respect to the risk on water supply, environmental integrity, equity and socio-economic efficiency. The tradeoffs existing among these aspects are also discussed.

Although the results from the modeling output may not provide really applicable solutions to the current problems experienced in the Syrdarya River basin, it is hoped that the modeling results provide timely information for informed decision-making for the long-term water resources management in the river basin, including the operations of hydrologic systems, improvements of irrigation and drainage facilities, and economic incentives and institutional directives.

The purpose of this chapter is thus to demonstrate that the prototype long-term dynamic model can be used as an effective tool for sustainability analysis, and to search for potential solutions for long-term water resources management in the case study area.

7.2 DATA AND ASSUMPTIONS

Data and assumptions described for the short-term model in Section 4.2 will be used for the yearly model in the long-term modeling framework, where appropriate. In this section, we describe the data that change from year to year in both water demand and supply. Some data related to scenario analysis, which are required but currently not available, are estimated based on data available in the literature. The assumptions involved in the long-term modeling for the case study area are also addressed.

7.2.1 Data and assumptions in water demand

Water demand considered in the modeling framework includes irrigation and non-irrigation water demand. Irrigation water demand depends on the irrigated area and the water requirement per unit of area. The total available irrigated area for each demand site and the irrigated area for various crops within each demand site will likely change in the next 30 years. Many experts suggest a reduction of the current irrigated area, or at least the abandonment of new irrigated area expansion. However, some districts are still developing new irrigated area in order to increase food supply security. The official plans for irrigated area in the study area are not available for this research. Therefore we simply project the total irrigated area in four scenarios based on different changing rates of the irrigated area in next 30 years, such as –10%, 5%, 10% and 58%. An increase of the current total irrigated area by 5% in next 30 years is assumed to be the “best estimation” (baseline). It seems to be impossible for the irrigated area in the basin to increase by 58% in next 30 years, and here we define an extreme case so as to study how severely the irrigation associated environment is affected. It is assumed that irrigated area increases evenly across all demand sites. The current irrigated area is presented in Table 4.10, and the projected irrigated area (relative value to the current value) of the scenarios defined above is shown in Table 7.1.

The demand of hydropower in the upstream country in next 30 years is also shown Table 7.1.

Table 7. 1. Projections of total irrigated area and industrial and municipal water demand in the Syrdarya River Basin. Data are relative to the current values in Table 4.10 and Table 4.22.

Year	*Irrigated Area Change in 30 years*				*M&I Water Demand*		*Hydropower Demand*[*]
	-10%	*5% (baseline)*	*10%*	*58%*	*Normal*	*High*	
1	1	1.00	1	1.00	1.00	1.00	1
2	0.993	1.01	1.003	1.02	1.01	1.03	1.005
3	0.992	1.01	1.006	1.04	1.01	1.06	1.009
4	0.99	1.01	1.009	1.06	1.02	1.09	1.014
5	0.988	1.02	1.012	1.08	1.02	1.12	1.017
6	0.986	1.02	1.015	1.1	1.02	1.16	1.021
7	0.983	1.02	1.018	1.12	1.03	1.2	1.025
8	0.981	1.03	1.021	1.14	1.04	1.24	1.029
9	0.978	1.03	1.024	1.16	1.05	1.28	1.033
10	0.977	1.03	1.027	1.18	1.06	1.32	1.037
11	0.975	1.03	1.035	1.2	1.07	1.35	1.041
12	0.972	1.04	1.039	1.22	1.08	1.38	1.045
13	0.968	1.04	1.042	1.24	1.09	1.41	1.049
14	0.964	1.04	1.046	1.26	1.1	1.45	1.054
15	0.96	1.04	1.05	1.28	1.11	1.49	1.058
16	0.958	1.04	1.054	1.3	1.12	1.53	1.062
17	0.956	1.04	1.058	1.32	1.13	1.57	1.067
18	0.954	1.04	1.061	1.34	1.14	1.61	1.072
19	0.952	1.04	1.065	1.36	1.15	1.64	1.078
20	0.95	1.05	1.07	1.38	1.16	1.67	1.081
21	0.944	1.05	1.074	1.4	1.17	1.7	1.087
22	0.942	1.05	1.078	1.42	1.18	1.74	1.092
23	0.938	1.05	1.082	1.44	1.19	1.78	1.097
24	0.932	1.05	1.085	1.46	1.2	1.82	1.102
25	0.928	1.05	1.088	1.48	1.21	1.85	1.107
26	0.922	1.05	1.091	1.5	1.22	1.88	1.113
27	0.916	1.05	1.093	1.52	1.23	1.91	1.119
28	0.91	1.05	1.095	1.54	1.24	1.94	1.124
29	0.905	1.05	1.098	1.56	1.25	1.97	1.129
30	0.9	1.05	1.1	1.58	1.25	2.00	1.135

[*] Estimated based on Harza (1995). The yearly hydropower demand in 1990 is 9500 MKW. The monthly distribution is 11%, 17%, 9%, 8%, 6%, 6%, 6%,6%, 6%, 8%,8%, and 11%, from Jan. to Dec.

As described in Chapter 6, irrigated area for different crops is determined by the inter-year control program (**IYCP**). Without much loss of reality, we assume that crop patterns change every five years. The **IYCP** reallocates irrigated area for each considered crop every five years. The projected total irrigated area forms an upper bound for the total irrigated area calculated from the modeling.

The non-irrigation water demand includes industrial, domestic, and environmental water demands. Growth in population and incomes will be mainly responsible for increased domestic water requirements. Moreover, institutional, political, and technical factors can influence future water demand. We make a projection of the future 30 years' municipal and industrial (M&I) water demand based on the work of Raskin (1996). The projection includes a normal and a high scenario that are shown in Table 7.1. The ecological water demand, which is the annual inflow requirement of the Aral Sea, is estimated according to hydrologic conditions in each year. The requirement is set as 15.5, 12.0, 10.0, 7.0, and 5.0 km^3 in very wet, wet, normal, dry, and very dry years based on historical records. It is assumed that inflows below the corresponding requirement will cause environment damage in the form described in Chapter 4, Section 2. The definitions of these hydrologic years are discussed in the following section.

7.2.2 Data and assumptions in water supply

Water supply in future years mainly depends on climatic changes, water storage and distribution capacities, as well as financial, institutional and political constraints.

Hydrologic fluctuation patterns are important in estimating future water availability. Generally, historical fluctuations are used to represent future patterns, if time series data for many elements of the river basin are available. In the Syrdarya River basin, river flows have been altered with extensive irrigation development and many hydrologic records cannot serve as proxies for historic patterns. Raskin et al. (1992) applied a simple method to project future hydrologic patterns for the Aral Sea basin, in which five categories of water-type years, *Very Wet, Wet, Normal, Dry*, and *Very Dry*, are used to represent hydrologic patterns. These five hydrologic-level years correspond to different hydrologic occurrence probabilities in conventional frequency analyses. The frequency analysis of an annual inflow record at a representative river point provides a sequence of hydrologic-level years. This sequence is then adjusted to explore alternative assumptions of future hydrologic patterns. The monthly inflow data of 1950-1982 at the Naryn gauging stations were used in estimating the basin's hydrologic-level sequences during the 1988 – 2020 period, which is shown in Table 7.2.

Table 7. 2. Hydrological fluctuations from 1988 -2020, after Raskin et al. (1992)

Years	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
Hydrologic Levels	N	N	VW	N	N	W	VW	VD	D	N	N
Years	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Hydrologic Levels	N	N	N	W	N	W	D	N	W	N	N
Years	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Hydrologic Levels	VD	N	D	D	D	W	N	N	N	D	D

Notation: N: normal, D: dry; VD: very dry, W: wet, VW: very wet.
The long-term model starts in 1991, covers 30 years, and ends in 2020.

The method used by Raskin et al. assumed hydrological homogeneity across the basin. In this research we do not have time series data for many small tributaries, and the existing records for some tributaries are obviously affected by irrigation practices through return flow. In addition, insufficient data are available to separate return flow from the flow records. Because of these limitations, this research follows the simple method used by Raskin et al. (1992).

For every source, the monthly inflows in a normal year are taken as the base, and ratios of the inflows in other hydrologic-level years to the base were computed by Raskin et al., and shown in Table 7.3.

Table 7. 3. Ratios of monthly inflow in different hydrologic years to those in the normal year, after Raskin et. al (1992).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Very Wet	1.15	1.10	1.45	1.10	1.11	1.25	1.30	1.42	1.47	1.46	1.54	1.25
Wet	1.06	1.02	1.19	1.05	1.05	1.09	1.14	1.21	1.23	1.23	1.27	1.13
Normal	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Dry	0.99	0.89	0.83	0.76	0.70	0.70	0.70	0.70	0.94	0.99	0.95	0.92
Very Dry	0.90	0.81	0.76	0.69	0.50	0.50	0.50	0.50	0.60	0.90	0.87	0.83

The same method is applied to specify precipitation data. From the hydrologic fluctuation sequences in Table 7.2, the probability of the five hydrologic-level years is calculated as 3.3% (*Very wet*), 16.7% (*Wet*), 52.0% (*Normal*), 21.3% (*Dry*) and 6.7% (*Very Dry*), respectively. It is assumed that those probabilities also apply for precipitation at each demand site in the same period. A representative precipitation record (92 years) is selected at upstream, mid-stream, and downstream of the basin, respectively. The above probabilities are applied to each of the representative precipitation records to classify the record into the above five types of hydrologic years based on the amount of annual precipitation. In each class, the average monthly precipitation is calculated, and it is used to represent the monthly precipitation corresponding to the hydrologic types. The ratios of monthly precipitation in various hydrologic years to that in a normal year are shown in Table 7.4.

Table 7. 4. Ratios of monthly precipitation in different hydrologic years to those in a normal year.

Hydrologic Levels	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
						Upstream						
Very Wet	1.21	1.21	1.25	1.20	1.19	1.25	1.34	1.36	1.38	1.40	1.45	1.23
Wet	1.10	1.06	1.24	1.09	1.09	1.13	1.19	1.26	1.28	1.28	1.32	1.18
Normal	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Dry	0.99	0.92	0.87	0.80	0.74	0.73	0.74	0.75	0.94	0.99	0.99	0.95
Very Dry	0.77	0.69	0.65	0.59	0.45	0.54	0.56	0.55	0.65	0.77	0.74	0.71
						Midstream						
Very Wet	1.50	1.40	1.67	1.38	1.61	1.47	1.63	1.48	1.46	1.68	1.82	1.21
Wet	1.24	1.01	1.43	1.29	1.43	1.14	1.25	1.10	1.13	1.48	1.70	1.17
Normal	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Dry	0.80	0.73	0.65	0.69	0.67	0.48	0.65	0.42	0.54	0.64	0.96	0.79
Very Dry	0.29	0.57	0.46	0.34	0.26	0.27	0.35	0.30	0.39	0.51	0.73	0.82
						Downstream						
Very Wet	1.72	1.61	1.92	1.59	1.85	1.60	1.78	1.61	1.59	1.83	1.99	1.32
Wet	1.43	1.38	1.61	1.42	1.42	1.47	1.54	1.55	1.53	1.66	1.72	1.25
Normal	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Dry	0.88	0.80	0.72	0.76	0.73	0.53	0.72	0.46	0.59	0.71	1.06	0.87
Very Dry	0.33	0.65	0.52	0.39	0.30	0.31	0.40	0.35	0.45	0.58	0.84	0.95

It is assumed that no new reservoirs will be built in the next 30 years. Moreover, it is expected that the current major reservoirs in the basin will be well maintained, and that their storage will keep the current conditions (Table 4.4). In this case study, we focus on the performance of the current reservoir systems, although new reservoirs and extended storage of existing reservoirs could be included in the modeling framework at specific stages.

Groundwater is an important source in the basin, although the current groundwater pumping is far less than river water withdrawals. We assume that groundwater availability will increase by 20% of the current capacity during 1991-2020.

The effective agricultural water supply depends on the overall water distribution and application efficiency, as well as on the water storage capacity.

As discussed before, water distribution efficiency (considering water loss from the outlet to the crop field), and irrigation application efficiency (considering water loss in the crop field) are related to canal lining and irrigation systems, respectively. We assume that these efficiencies, as well as the drainage efficiency that is critical to soil quality protection, will be improved in the coming years, and that the current status will be at least well maintained. As described in Chapter 6, these anthropogenic improvements will meet the investment constraint, and they are defined as inter-year control variables in the long-term modeling framework. That is to say, the long-term modeling will determine in which year and at what magnitude the water distribution and application efficiency related to permanent facilities should be chosen. The current values of water distribution efficiency, drainage efficiency, and irrigation efficiency are already shown in Table 4.16 – 4.17, which are the lower bounds of these items in the long-term modeling. As various lower bounds for different demand sites and different crop fields, the upper bounds for these items may also vary spatially. Due to the insufficient data, we assume the upper bounds for these items are the same at all demand sites and crop fields for the long-term irrigation system planning.

According to EC (1995), if the unlined canals, covering three quarters of the total canals, become lined, then the distribution efficiency will increase to 75%; if most farm canals are lined with concrete, then the distribution efficiency will increase up to 85%. Therefore, we set the upper bound of the water distribution efficiency as 85% in the next 30 years. In some area of the basin, the percentage of irrigated area that is drained is up to 85%, although large differences exist in different areas. We assume this percentage for the whole basin will not be over 85%. As for the irrigation efficiency, which is defined as the field application efficiency (eq. 3-9), EC (1995) estimated the overall field application efficiency in the basin will increase up to 70% if modern technologies are used to the existing furrow systems. Clemmens and Dedrick (1994) showed that the typical potential application efficiencies for well-designed and managed irrigation systems could be up to 80 – 90%. We assume that the irrigation efficiency is up to 85% in the next 30 years, which means some advanced irrigation systems such as drip and sprinkler irrigation systems are going to replace some of the furrow irrigation systems.

Further, to reduce the computing work, we assume that the condition of water distribution and application may be improved every five years in during the next 30 years.

7.2.3 Other data and assumptions

In the long-term modeling, the tax rate on excess salt discharge is chosen by the inter-year control program (**IYCP**) based on the lower and upper bounds ($10.0 – $300 per ton of salt mass) which are consistent with those used for the scenario analysis in Chapter 4, Section 4.3.3.5. Other economic data such as water supply prices, crop costs and prices may change considerably in the future. However, currently, we are not able to get enough information about these changes to include them. Therefore, we assume that there will be no changes of these items in the study time horizon. This limitation can be removed in the future through connecting economic forecasting to this modeling framework.

7.3 EFFECTIVENESS AND LIMITATIONS OF THE MODELING APPROACH

As described in Chapter 6, the long-term modeling framework includes a procedure for solving the yearly model and a procedure to search for better solutions through the GA&LP approach described in Chapter 5. For this case study, the parameters used in the GA&LP approach are listed as follows:

Number of Variables in GA	384
Number of Individuals	50
Length of substring	5

Probability of crossover	0.85
Probability of mutation	0.01

In the following we demonstrate the effectiveness and limitations of the modeling approach for the case study.

7.3.1 Solving the yearly model

The procedure for solving the yearly model (**YM**) is shown in Figure 6.3. In the following a practical application of this approach is presented. Tables 7.5 and 7.6 present the iterations of the yearly model, including the objective values of the current and prior iterations (*TWB*, eq. 3.40). The index of water shortage (*iws*) is calculated as the sum of slack variables (α) in the root zone water balance. These slack variables act as "additional water" supplied to the crop root zone, but they are penalized in the objective function, which can be described as:

$$\max \quad obj^* = obj - wpen \cdot iws$$

$$\text{s.t. } iws = \sum_{dm}\sum_{fd}\sum_{pd} \alpha_{dm,fd}^{pd} \qquad (7\text{-}1)$$

$$wout_{dm,fd}^{pd} = win_{dm,fd}^{pd} + \alpha_{dm,fd}^{pd}$$

where

wpen = weight assigned for the penalty item,

win = inflow to the root zone, and,

wout = outflow from the root zone. Both *win* and *wout* are variables in the yearly models (**YM**).

With the slack variable defined in the model, the yearly model will be mathematically feasible in each iteration even water supply can not satisfy water demand (note: the relative crop yield must not be less than 0.5, see Figure 6.3). A positive value of a slack variable implicates water supply can not sustain the irrigated area pre-determined by the inter-year control variable, $IA^{y}_{dm,fd}$. Therefore, in the next iteration, the irrigated area corresponding to positive $\sum_{pd} a^{pd}_{dm,fd}$ must be reduced.

The index of excess soil salinity (*iss*) is defined as the maximum soil salinity coefficient (*ks*, eq 3-22) over all crop fields and all demand sites.

In Table 7.5, the first four iterations result in negative objective values, because the values of some slack variables are positive and therefore they penalize the objective and cause it to be a negative value. Detailed output shows that water shortage occurs to two demand sites, *Low_syd* and *Fergana*, and Table 7.6 shows that for these two demand sites, the irrigated area is reduced until the water shortage index becomes zero.

Although the indices of water shortage and soil salinity are zero in iteration 6 and 7, the difference between the objective value of the current iteration and that of the prior iteration is larger than the prescribed tolerance. Therefore, iterations continue until the difference is below the tolerance in iteration 8.

Table 7. 5. Example for iterations in solving the yearly model: irrigated area reduction due to water shortage.

Iterations	*Objective values from prior iteration*	*Objective value from current iteration*	*Water shortage index (iws)*	*Soil salinity index (iss)*
1	-1637.091	-1269.66	25.394	0
2	-1269.661	-817.031	16.341	0
3	-817.032	-524.127	10.483	0
4	-524.132	-175.249	3.505	0
5	-175.251	0.672	0	0
6	0.672	0.654	0	0
7	0.654	0.627	0	0
8	0.627	0.631	0	0

Table 7. 6. Example for iterations in solving the yearly model: irrigated area reduction due to water shortage.

Iterations	**water shortage**		**irrigated area**	
	Low_syd	**fergana**	**low_syd**	**fergana**
1	7.341	18.053	433.2	1356.1
2	4.003	12.338	420.4	1308.5
3	2.809	7.673	413.5	1261.2
4	0.837	2.667	408.2	1218.3
5	0	0	408.2	1218.3
6	0	0	408.2	1218.3
7	0	0	408.2	1218.3
8	0	0	408.2	1218.3

Table 7.7 shows the iterations for another run of the yearly model. Here, the soil salinity is so high that the crop yield-water coefficient is larger than 0.5. As we described in Figure 6.3, with this condition, both the irrigated area and the irrigation application efficiency will be reduced. Detailed output shows that excess soil salinity occurs in demand site *Low_syd*, i.e., *KS('low_syd', 'other')=0.614*

(*‘other’ means a crop type, including crops other than cotton, wheat, maize forage, and alfalfa*). Between iterations 1 and 2, the irrigated area is reduced from 472.8 to 442.4 thousand hectares, and the irrigation application efficiency is reduced from 0.835 to 0.801, for crop field (“*oth_oth*”) in demand site *low_syd.*

Table 7. 7. Example for iterations in solving the yearly model: irrigated area reduction due to salinity.

Iterations	*Obj. value from prior iteration*	*Obj. value from current iteration*	*Water shortage index (iws)*	*Soil salinity index (iss)*
1	-12.915	-10.189	0	0.614
2	-10.189	0.905	0	0.432
3	0.905	0.907	0	0.322

In the first iteration *ks*('low_syd', 'other') = 0.614, irrigated area is reduced from 472.8 to 442.4, and irrigation application efficiency, eff_irr, is reduced from 0.835 to 0.801.

For each alternative of the long-term modeling solutions, the yearly model is run year by year for 30 years. As an example, Table 7.8 shows some items from the model output for each of the 30 years.

Table 7. 8. Selected items from the year by year modeling output.

Year	Hydrol. Level	*WSU*[1]	Irrigated Area (10^3 ha)	Irrigation Profit ($10^9\ \$$)	Aral Inflow (km^3)	Ground water Salinity (g/l)	Reserv. Salinity (g/l)	Soil Salinity (dS/m)	Tax Rate (100$/ton)	Salt Discharge (10^6 tons)	*EDS* at Low_syd	*EDN* at Low_syd	*EIR*[2] Low_syd (cot-foa)
1	normal	0.39	3250	1.562	8.0	1.1	0.9	0.7	1.0	53.4	0.67	0.7	0.64
2	normal	0.27	3282.5	1.543	9.5	1.1	1.1	0.6	0.83	50.1	0.67	0.7	0.64
3	normal	0.27	3282.5	1.5994	8.7	1.2	1.0	0.6	0.36	49.5	0.67	0.7	0.64
4	very wet	0.49	3282.5	1.605	12.3	1.2	1.0	0.5	0.25	47.3	0.67	0.7	0.64
5	very dry	0.03	3315	1.0075	4.5	1.3	1.1	0.6	0.45	26.2	0.67	0.7	0.64
6	dry	0.04	3315	1.1315	3.1	1.4	1.1	0.8	0.94	44.6	0.74	0.7	0.74
7	normal	0.3	3315	1.3152	4.9	1.4	1.1	0.8	0.22	52.1	0.74	0.7	0.74
8	normal	0.25	3347.5	1.3853	11.6	1.4	1.1	0.8	0.8	52.7	0.74	0.7	0.74
9	normal	0.28	3347.5	1.3479	11.1	1.5	1.1	0.8	0.27	48.3	0.74	0.7	0.74
10	normal	0.33	3347.5	1.3448	10.2	1.5	1.1	0.8	0.88	50.4	0.74	0.7	0.74
11	normal	0.25	3347.5	1.5424	11.4	1.5	1.2	0.8	0.42	61.0	0.74	0.7	0.74
12	wet	0.4	3380	1.705	12.1	1.6	1.3	0.8	0.51	68.6	0.74	0.7	0.74
13	normal	0.21	3380	1.5994	11.4	1.6	1.2	0.8	0.91	54.1	0.74	0.7	0.74
14	wet	0.51	3380	1.5514	10.7	1.6	1.1	0.8	0.88	77.4	0.74	0.7	0.74
15	dry	0.12	3380	1.5211	10.8	1.6	1.3	0.8	0.36	51.9	0.74	0.7	0.74
16	normal	0.23	3380	1.5613	6.7	1.6	1.2	0.9	0.1	61.3	0.74	0.74	0.76
17	wet	0.42	3380	1.6837	12.0	1.7	1.2	0.9	0.42	77.2	0.74	0.74	0.76
18	normal	0.34	3380	1.68	11.3	1.7	1.3	0.8	0.77	57.2	0.74	0.74	0.76
19	normal	0.47	3380	1.6032	8.9	1.7	1.2	0.9	0.68	62.7	0.74	0.74	0.76
20	very dry	0.03	3412.5	1.4638	6.2	1.7	1.4	1.0	0.39	49.2	0.74	0.74	0.76
21	normal	0.32	3412.5	1.5729	8.5	1.7	1.3	1.0	0.36	65	0.81	0.82	0.81
22	dry	0.1	3412.5	1.552	9.3	1.8	1.4	1.1	0.16	56.4	0.81	0.82	0.81
23	dry	0.15	3412.5	1.5363	3.3	1.8	1.4	1.1	0.25	65	0.81	0.82	0.81
24	dry	0.03	3412.5	1.5399	5.0	1.8	1.5	1.2	0.97	60	0.81	0.82	0.81
25	wet	0.27	3412.5	1.6848	12.4	1.8	1.4	1.0	0.13	79.2	0.81	0.82	0.81

Year	Hydrol. Level	*WSU*[1]	Irrigated Area (10^3 ha)	Irrigation Profit (10^9 \$)	Aral Inflow (km^3)	Ground water Salinity (g/l)	Reserv. Salinity (g/l)	Soil Salinity (dS/m)	Tax Rate (100$/ton)	Salt Discharge (10^6 tons)	*EDS* at Low_syd	*EDN* at Low_syd	*EIR*[2] Low_syd (cot-foa)
26	normal	0.26	3412.5	1.6314	10.9	1.8	1.3	1.0	0.27	67	0.81	0.82	0.84
27	normal	0.32	3412.5	1.6828	11.8	1.9	1.4	1.0	0.45	74.1	0.81	0.82	0.84
28	normal	0.34	3412.5	1.7107	11.8	1.9	1.4	1.1	0.22	77.6	0.81	0.82	0.84
29	dry	0.15	3412.5	1.5869	5.4	1.9	1.4	1.1	0.51	64.4	0.81	0.82	0.84
30	dry	0.02	3412.5	1.5735	4.4	1.9	1.5	1.2	0.45	69.3	0.81	0.82	0.84

Notations

[1] Water saved for future use;

[2] Field application efficiency in field cot-foa at demand site Low_syd.

7.3.2 Searching long-term solutions

The GA&LP approach searches for improved solutions at two levels: the best solution among all the individuals within a generation, and improved solutions through generations. Since the objective of the long-term modeling is found by minimization, the “best” solution is the one with the lowest objective value corresponding to the highest fitness. The objective of the long-term modeling includes multiple sub-objectives such as reliability, reversibility, vulnerability, equity, environmental integrity, and socio-economic acceptability, each with a pre-determined weight or a scaling coefficient in the objective function. (See eq. 7-2 for an example) Therefore, the “best” solution reflects a decision preference and a compromise among multiple objectives. However, it may not be the best with regard to each individual aspect.

$$\begin{aligned} OBJ &= 5 \cdot (1 - REL) + 2 \cdot REV + VUN \\ &\quad + ENVIN + 2 \cdot TEQ + 2 \cdot SEQ + SEA^{-1} \end{aligned} \tag{7-2}$$

See eq. 6-28 for definitions of each items in this equation.

Figure 7.1 shows the long-term objective value for all individuals within one generation. We choose two individuals which represent the “best” and the “worst” in the generation, respectively, according to the total objective. These individuals are compared in Figure 7.2 and Tables 7.9-11. Tables 7.9–11 show groundwater salinity, surface water salinity and soil salinity at the end of the modeling period, respectively. Figure 7.2 shows the indices corresponding to multiple criteria prescribed in the long-term modeling, and Figure 7.3 compares the annual water use benefit with the two individuals. The “best” individual is better than the “worst’ for all items. The GA always chooses the better individuals with a higher probability to create the next generation. The individual with the highest fitness in one generation represents the best solution in that generation.

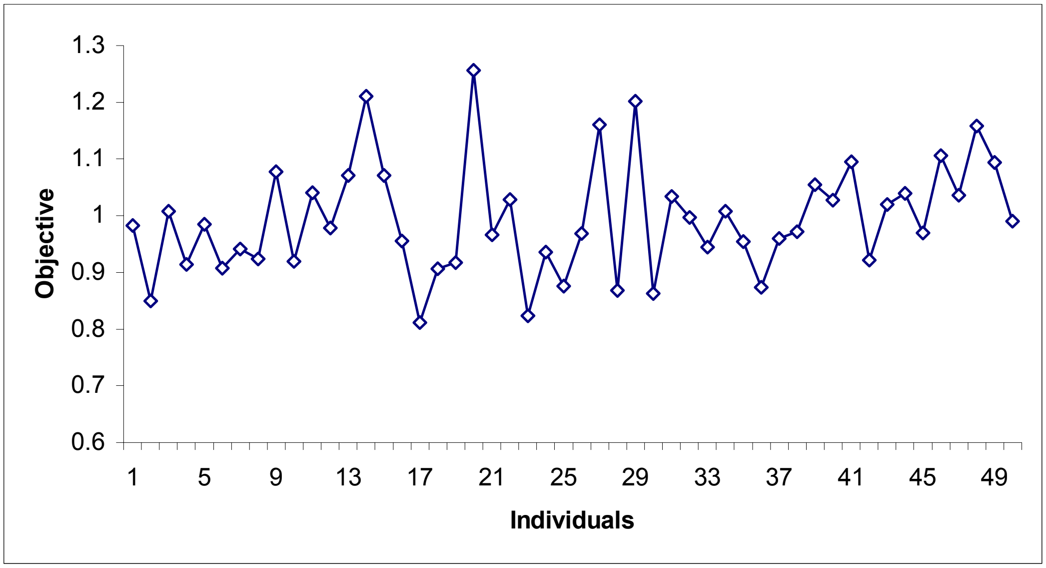


Figure 7. 1. Long-term objective value for all individuals within one generation (Generation 1).

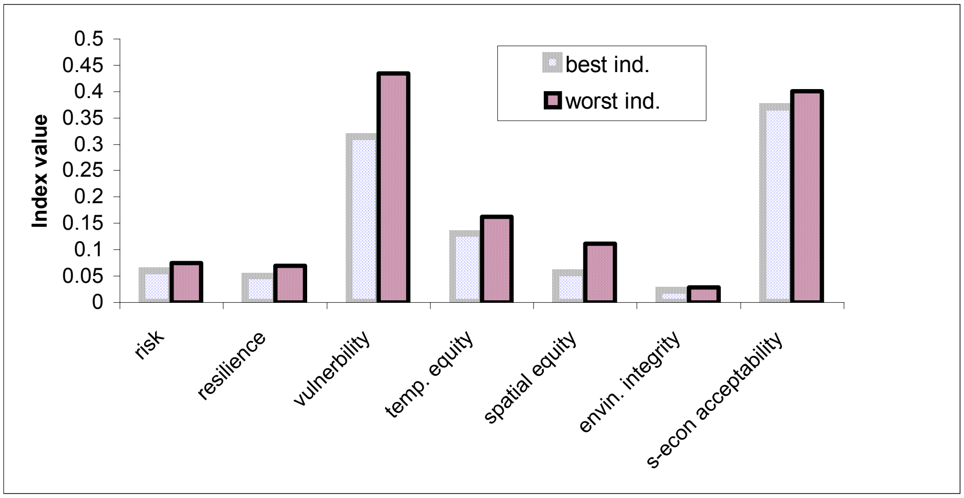


Figure 7. 2. Values of indices for multiple criteria of the "best" and "worst" individuals in one generation. All the indices in this figure are by minimization as shown in eq. 6-28 or 7-2. Due to the difference among the magnitude of these indices, scaling coefficients are applied so that these items can be normalized in the long-term objective function (eq. 7-2).

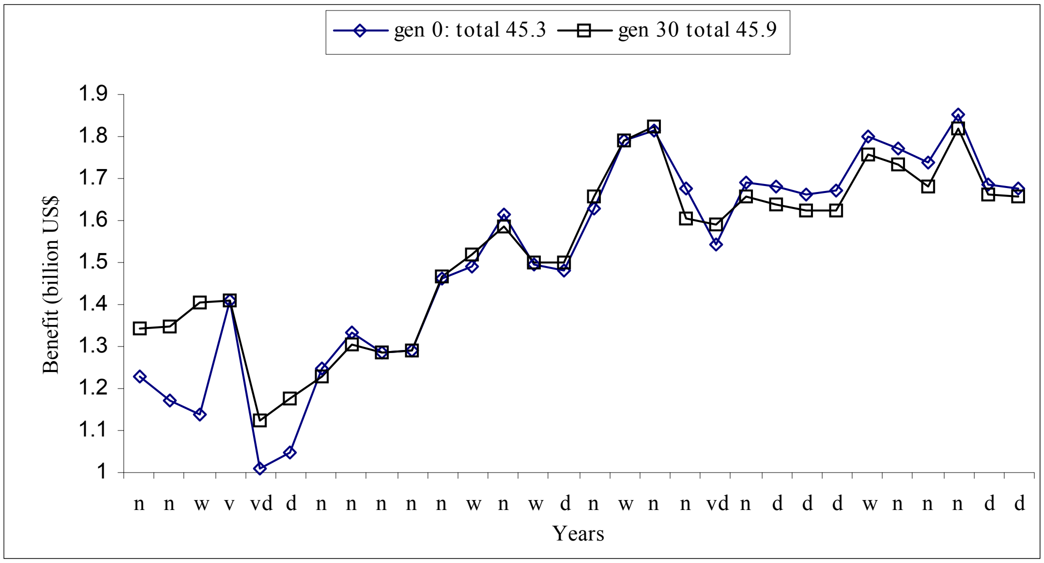


Figure 7. 3. Annual irrigation profit (*IP*) of the "best" and "worst" individuals in one generation (Generation 1)

Table 7. 9. Comparison of the best and the worst individuals within one generation – groundwater salinity (g/l)

Sites	NARYN	LOW_SYD	ARTUR	CHAKIR	MID_SYD	FERGANA
worst ind.	0.6	1.7	1.9	1.3	1.4	2.4
best ind.	0.5	1.6	1.8	1.4	1.4	2.2

Table 7. 10. Comparison of the best and the worst individuals within one generation – reservoir salinity (g/l)

Reservoirs	Chardara Reservoir	Kayrakum Reservoir	Farkhad Reservoir
worst ind.	1.3	1.9	1.8
best ind.	1.3	1.7	1.7

Table 7. 11. Comparison of the best and the worst individuals within one generation – soil salinity (dS/m)

SITES	Individuals	Crop Fields			
		Cot_foa	*Wht_maz*	*Alf_alf*	*Oth_oth*
NARYN	*Worst ind.*	0.7	0.3	n/a	0.5
	Best ind.	0.4	0.5	n/a	0.4
LOW_SYD	*Worst ind.*	0.8	0.8	n/a	7.4
	Best ind.	1.4	0.6	n/a	2.5
ARTUR	*Worst ind.*	0.5	1.6	n/a	0.9
	Best ind.	0.8	1.0	n/a	1.3
CHAKIR	*Worst ind.*	1.0	0.6	0.8	0.8
	Best ind.	0.5	0.7	0.9	1.0
MID_SYD	*Worst ind.*	1.2	0.8	0.9	2.4
	Best ind.	0.5	0.7	0.9	0.9
FERGANA	*Worst ind.*	1.5	0.9	0.9	1.4
	Best ind.	0.7	0.6	1.1	1.1

To show the improvement of the solution over generations, we compare the total long-term objective values for all individuals of generation 1, generation 15, and generation 30 in Figure 7.4. We have the following observations: (1) solutions in later generations are closer to better solutions than initial generations, that is to say, the average performance of a future generation is improved compared to the initial generations (as one would expect); and (2) the "best" solution of the later generations is better than that of the initial generations. These observations clearly show that solutions converge to better ones over generations.

Figure 7.5 shows the total objective value, and Figure 7.6 shows the values for reliability, reversibility, vulnerability, temporal equity, spatial equity, environmental integrity, and the socio-economic acceptability, of the "best" solution in each of the 30 generations. The reduction of the value of the total objective shows the improvement of the minimizing objective. An improving tendency is also shown for all the sub-items. The fluctuations of these items from generation to generation shows the tradeoff among these items, which will be discussed in detail later. The improvement of the total objective, as well as its sub-items, shows that the solution is improved through generations.

Tables 7.12-7.14 and Figures 7.7–7.8 further show the solution improvement by comparing two solutions, the best solution in generation 1, and the best solution in generation 30. Tables 7.12 –7.14 present groundwater salinity, surface water salinity and soil salinity at the end of the modeling period, respectively. Figure 7.7 shows the indices corresponding to the multiple criteria prescribed in the long-term modeling, and Figure 7.8 compares the annual water use benefit of the two individuals. In all these aspects, the solution from generation 30 is better than that from generation 1.

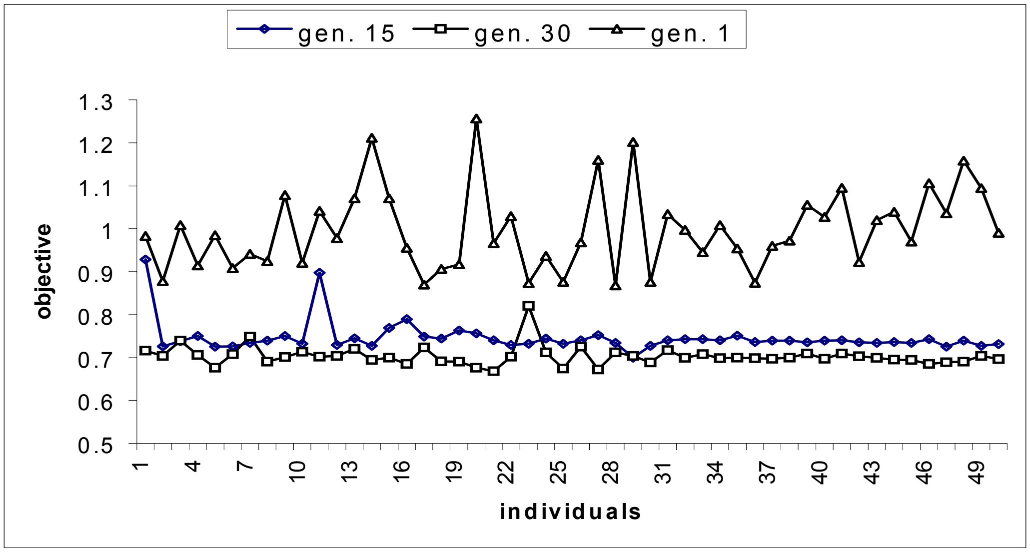


Figure 7. 4. Comparison of the total long-term objective values of generation 1, 15, and 30.

Comparisons above show that the GA-LP approach not only searches for the best solution within one generation, but also searches for better solutions through generations. We define 50 individual solutions in each generation, and the search through 30 generations does not simply mean that a better solution is found among 50*30 =1500 alternatives, since in GA, the "offspring" is always created with better "genes" of the previous generation. That is to say, the average performance of the individuals in one generation is better than its previous generations, which is demonstrated above. We find the GA-LP approach is effective in searching better solutions of a large-scale, dynamic model like the one developed in this research.

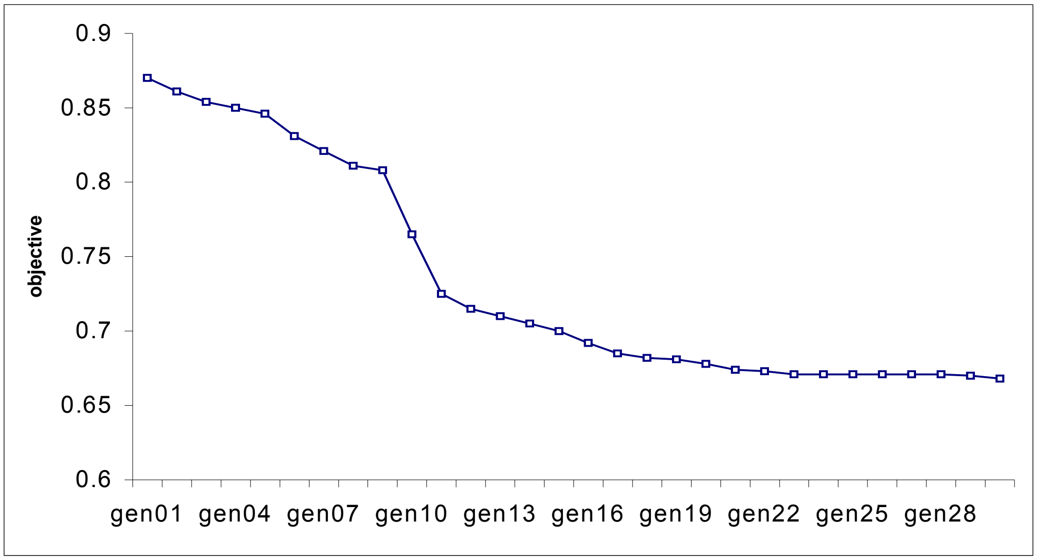


Figure 7. 5. Comparison of long-term objective resulting from different generations.

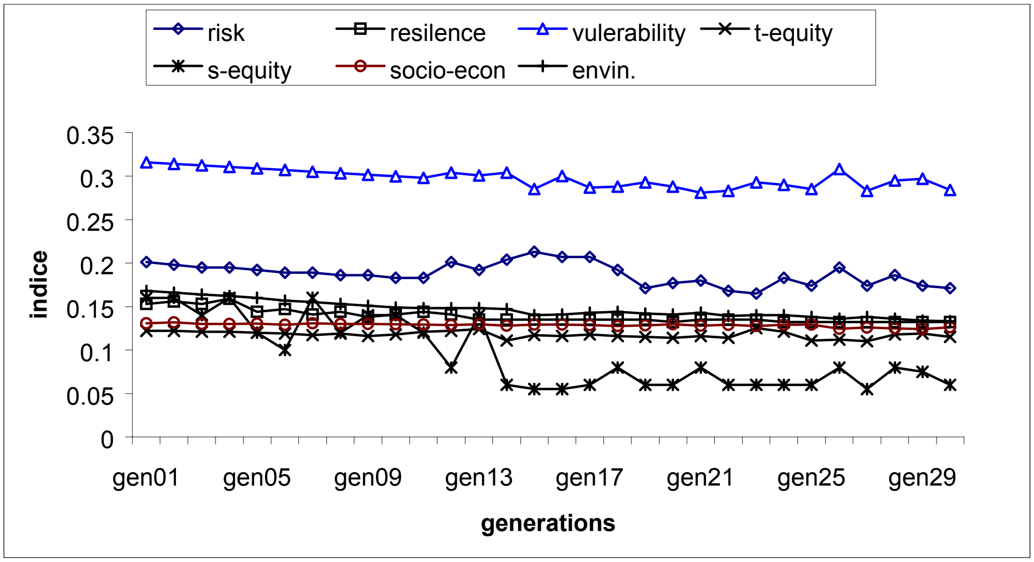


Figure 7. 6. Comparison of outputs of multiple criteria resulted from different generations.

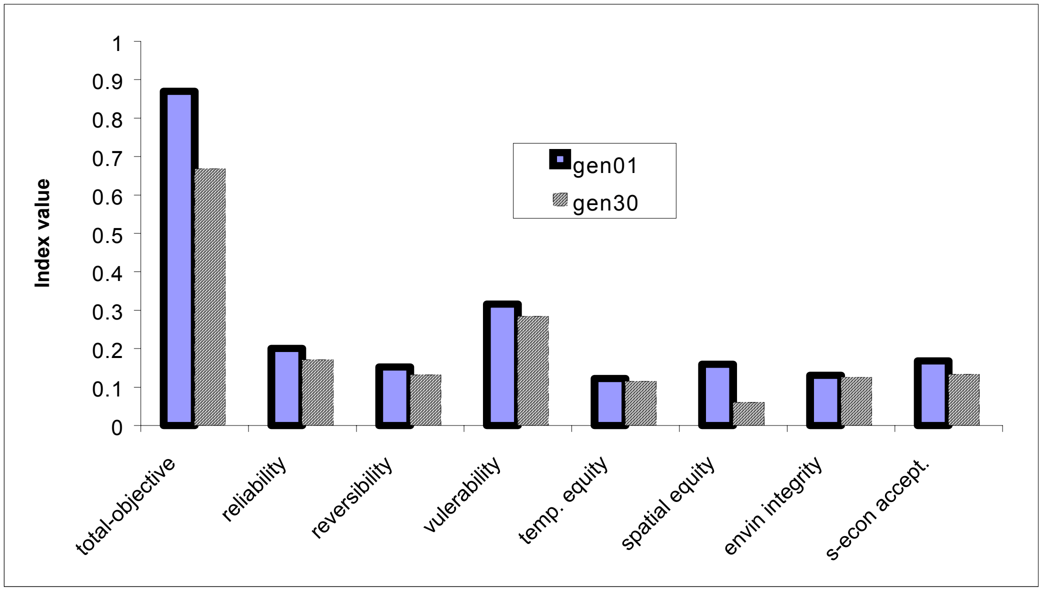


Figure 7. 7. Index values of multiple criteria resulting from gen. 1 and gen. 30.

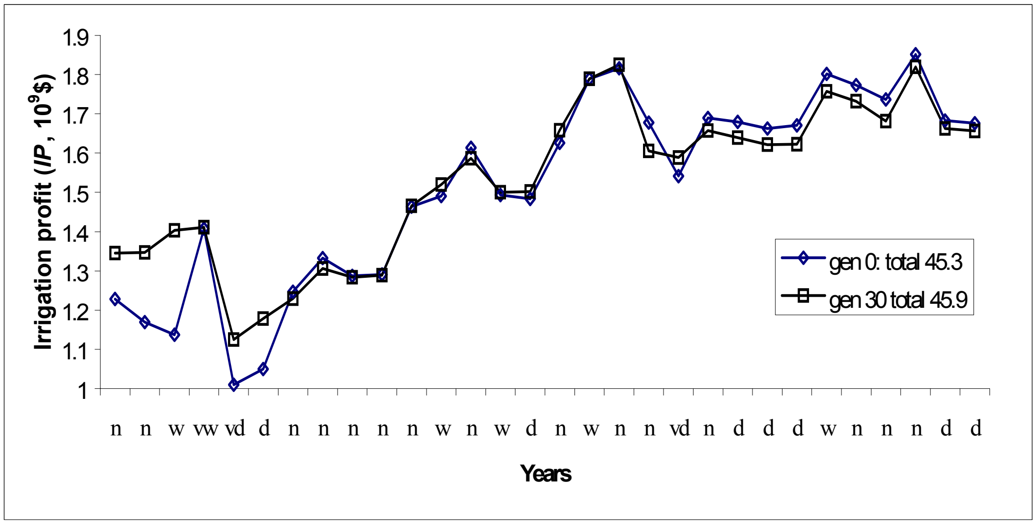


Figure 7. 8. Annual irrigation profit (*IP*) resulting from gen. 1 and gen. 30.

Table 7. 12. Comparison of the best individual in the first and the 30th generation – groundwater salinity (g/l)

Sites	NARYN	LOW_SYD	ARTUR	CHAKIR	MID_SYD	FERGANA
Gen 1	0.6	1.8	2	1.3	1.5	2.4
Gen 30	0.5	1.6	1.8	1.4	1.4	2.2

Table 7. 13. Comparison of the best individual in the first and the 30th generation – reservoir salinity (g/l)

Reservoirs	Chardara Reservoir	Kayrakum Reservoir	Farkhad Reservoir
Gen 1	1.3	1.9	1.8
Gen 30	1.1	1.5	1.5

Table 7. 14. Comparison of the best individual in the first and 30th generation – soil salinity (dS/m)

Demand Sites	Individuals	Crop Fields			
		cot_foa	*wht_maz*	*alf_alf*	*Oth_oth*
NARYN	*Worst ind.*	0.4	0.5	n/a	0.4
	Best ind.	0.2	0.4	n/a	0.4
LOW_SYD	*Worst ind.*	1.4	0.6	n/a	2.5
	Best ind.	1.2	0.7	n/a	1.2
ARTUR	*Worst ind.*	0.8	1	n/a	1.3
	Best ind.	0.7	0.9	n/a	0.8
CHAKIR	*Worst ind.*	0.5	0.7	0.9	1
	Best ind.	0.4	0.9	0.8	0.6
MID_SYD	*Worst ind.*	1.2	0.8	0.9	0.9
	Best ind.	1	0.8	0.5	0.7
FERGANA	*Worst ind.*	0.7	0.6	1.5	1.1
	Best ind.	0.8	0.7	1.1	0.9

However, just as discussed in Section 5.3, the GA-LP approach has some limitations. For this case study, the major limitation is long computing time. Considering the procedures described in Section 6.4.1, for one generation, the long-term model has to be run for each individual, and within each long-term model run, the yearly model will be run for each year. In this case study, the number of individuals is 50, and the long-term horizon is 30 years, therefore, in one generation the yearly model needs to run 50*30 =1500 times, although the grouping strategy and restarting facility described in Section 5.3 reduce the computation time in later generations. The average CPU for one generation with an Alpha Workstation UNIX 4.0D is 860 seconds.

7.4 THE BASELINE SCENARIO

The baseline scenario corresponds to the hydrologic fluctuations and normal water demands presented in Section 7.2, with 5% increase of current irrigated area in the next 30 years, and 25% increase of M&I water demand. This section presents the output of the long-term modeling with the baseline scenario. The GA-LP approach is applied for the scenario through 60 generations. This number of generations is determined experimentally. The solution by the 60th generation may not be the final global solution, however, it seems to be approximate to the final solution. Figure 7.9 shows the objective value of the best alternative in each of the 60 generations. As can be seen, (1) the curve of objective values vs. generations is almost flat in the last 10 generations, i.e. no significant changes occur in the last 10 generations; and (2) most alternatives in generation 60 are close to the best one, as shown in Figure 7.10.

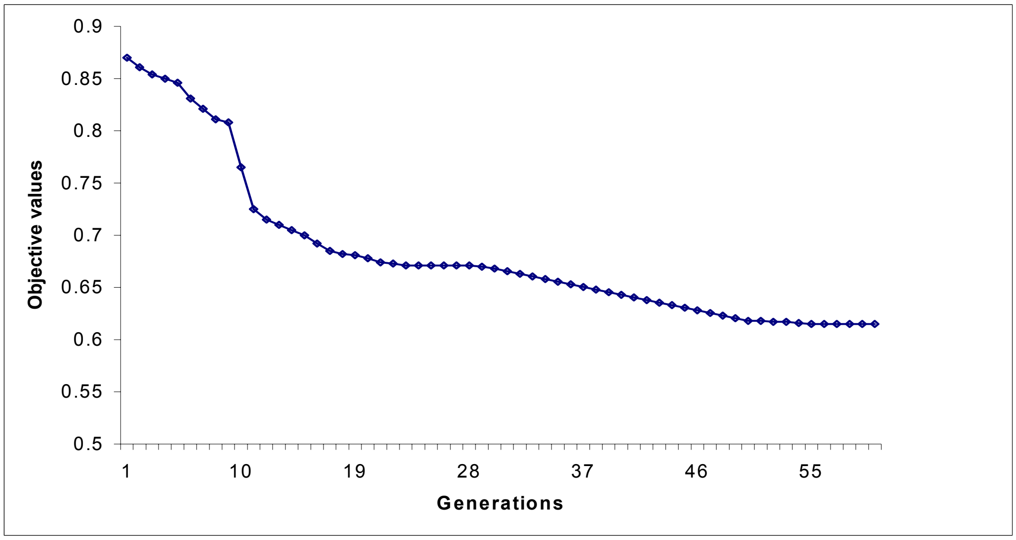


Figure 7. 9. Objective values of the best individual in each generations under the baseline scenario.

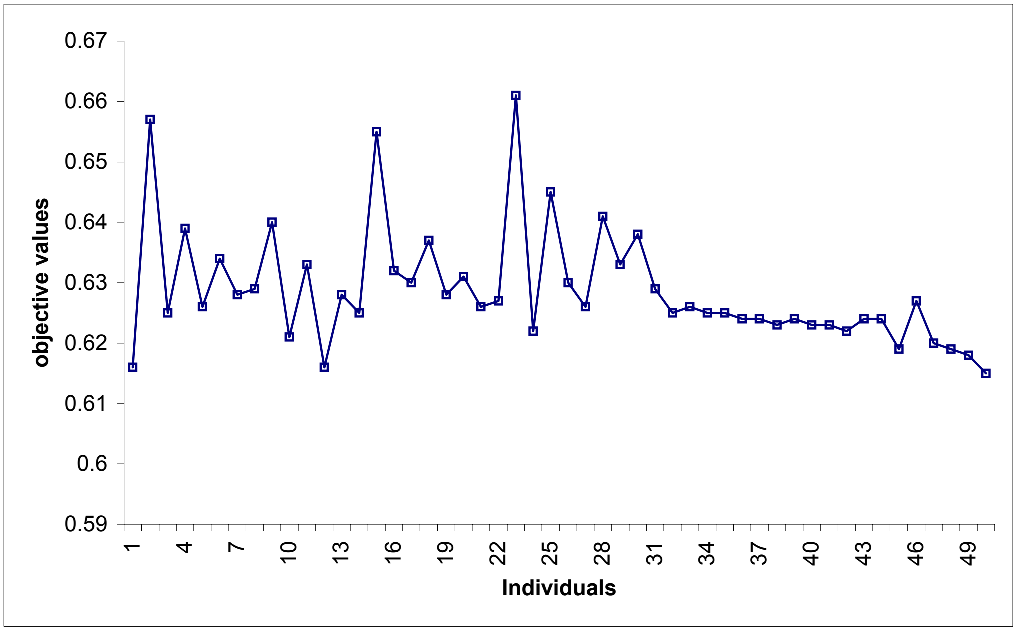


Figure 7. 10. Objective values of all individuals in generation 60 under the baseline scenario.

7.4.1 Implications of the inter-year controls

The inter-year control variables include water sustained for future use, tax rate on excessive salt discharge, irrigated area, and efficiency levels for water distribution, irrigation and drainage. Based on the values of these variables, in the following we discuss reservoir operation, salt discharge, crop pattern change, and water use facility improvement.

7.4.1.1 Reservoir operation

In Chapter 4, we discussed reservoir operation based on the short-term model output. In the long-term modeling framework, reservoir operation is controlled by an inter-year control variable, namely water sustained for future year use (*wsu*), as well as being driven by maximizing benefits within individual years. As defined before, *wsu* is the sum of all reservoir storage at the last period of a study year, which will be the initial reservoir storage available in the next year. Figure 7.11 shows this item in each year labeled by its hydrologic level, and Figure 7.12 shows their values relative to the maximum reservoir storage. The ranges of the relative values for different types of hydrologic years are 0.53 or more (very wet), 0.40 – 0.51 (wet), 0.20 – 0.45 (normal) and 0.10 – 0.17 (dry and very dry). However, the values for the same type of hydrologic years are also different, depending on the hydrologic fluctuations around the year. For a normal year, the value is around 0.2 if followed by a wet or very wet year, 0.3 –0.4 if followed by a normal year, and 0.4 –0.45 if followed by a dry or very dry year.

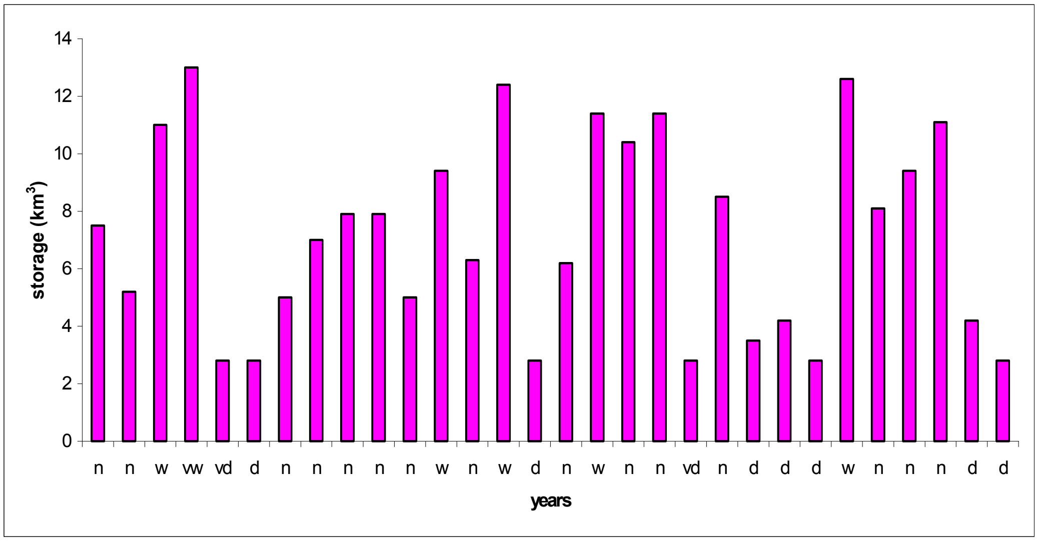


Figure 7. 11Water sustained for future use (*wsu*).

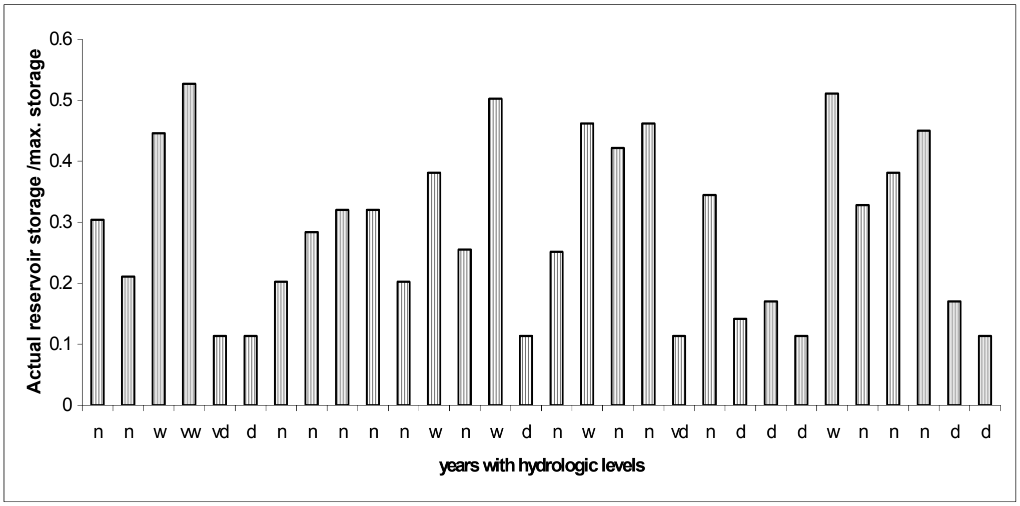


Figure 7. 12. Water sustained for future use (*wsu*) – relative values.

The inter-year control variable, *wsu*, is not specified for individual reservoirs, but just presents a lower bound for the total reservoir storage at the last period of a study year. The end-year storage of each reservoir is determined within the yearly model (**YM**), subject to the constraint that the sum of the end-year storage of all reservoirs must not be lower than the prescribed *wsu*. The relative values of the ending storage to the maximum storage for the major reservoirs are shown in Figures 7.13-7.14. We can see that the major reservoirs on the main river, including the Toktogul Reservoir and the Kayrakum Reservoir, are not active in inter-year water flow control, compared to the reservoirs on the main tributaries including the Charvak and Andijan Reservoirs. That is to say, water saved for future use tends to be stored in reservoirs on the tributaries and the reservoir downstream of the main river, the Chardara Reservoir. The largest reservoir, the Toktogul Reservoir has a minimum storage (10% of the maximum active storage) for hydropower generation, and the ratio of its active storage to the maximum active storage reaches only 0.36 during 30 years considered in the case study. Figures 7.15–7.16 show the annual average reservoir utility efficiency (defined in Section 4.3.1.2) over all study years for five major reservoirs in the basin. The reservoirs on the tributary have higher values than those on the main river. However, Toktogul, which has a very large volume, exhibits smaller long-term fluctuations in filling and emptying, and it has the most consistent *RUE* (around 20%) of all the reservoirs.

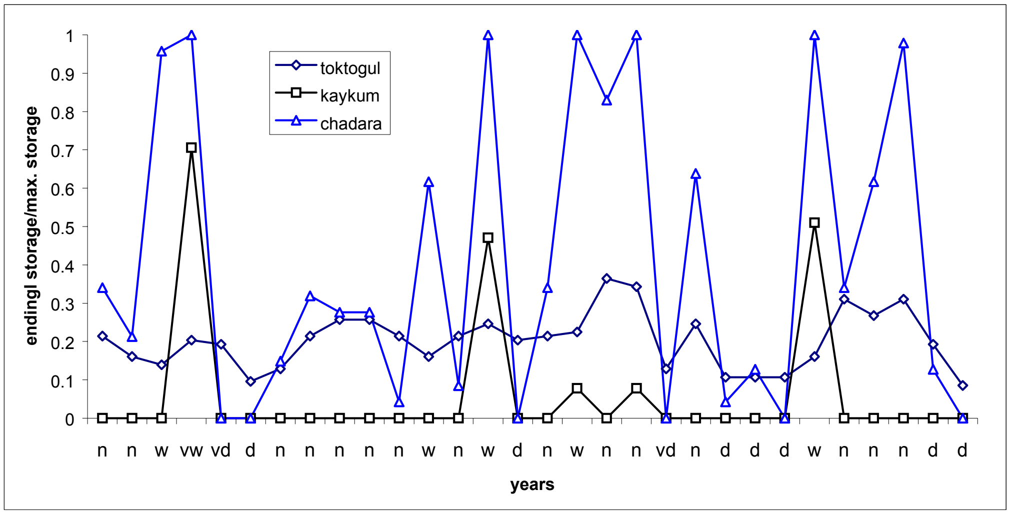


Figure 7. 13. Relative values of the end-year storage to the maximum storage for the major reservoirs.

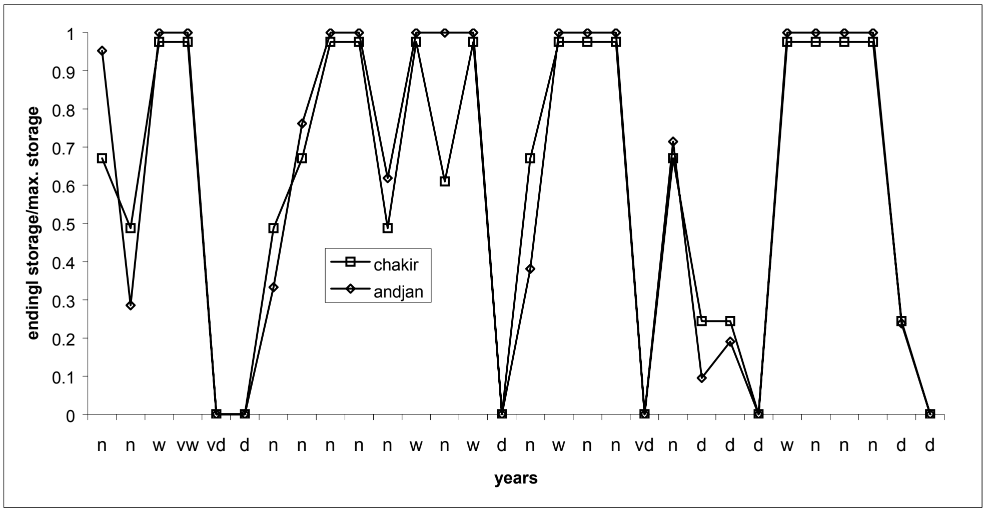


Figure 7. 14. Relative values of the end-year storage to the maximum storage for the major reservoirs.

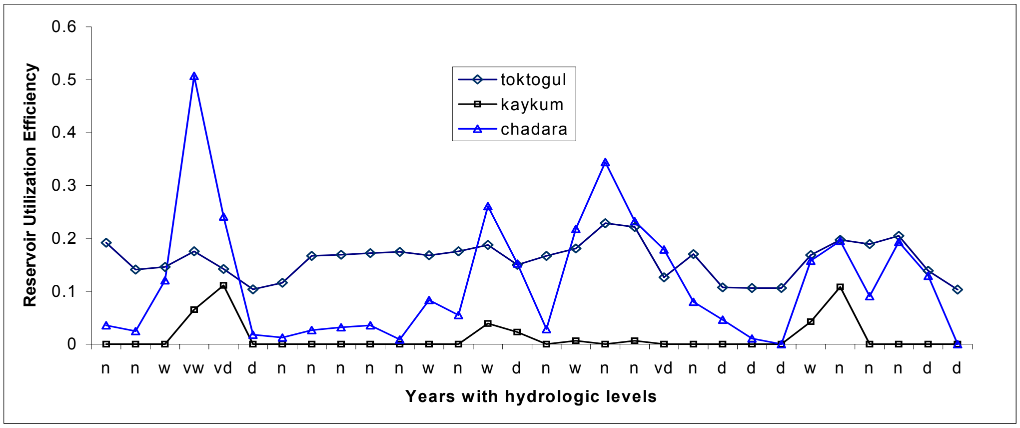


Figure 7. 15. Annual average reservoir utility efficiency.

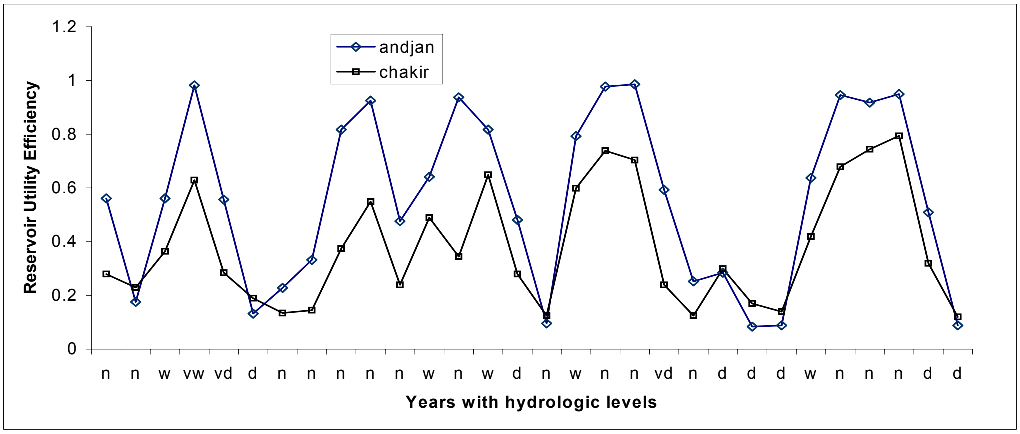


Figure 7. 16. Annual average reservoir utility efficiency.

7.4.1.2 Salt discharge control

Salt discharge is related to many factors changing with years, including hydrologic level, water withdrawn for irrigation, drainage efficiency, drainage disposal (to a nearby desert), as well as the penalty tax on excess salt discharge that is an inter-year control variable in the model. Therefore, in the long-term modeling, a monotonic relationship between the penalty tax and the salt discharge over all the study years may not exist. Figure 7.17 shows the penalty tax over 30 years. Higher values are related to wet years, while lower values are related to dry years. One reason for this relationship is that more water is withdrawn for irrigation in wet years, and as a result there is increased return flow carrying more salt to the river system. The modeling output shows even in the wet years defined in Section 7.2.2, the crop yields do not reach their maximum, because the irrigation water demand can not be fully provided. Therefore, in the wet years with more water supply, more withdrawal occurs. The excessive salt discharge in different hydrologic years is presented in Figure 7.18. This figure shows an increasing tendency of salt discharge over the years (almost doubling over 30 years), which implies an increase of water and soil salinity in the basin. Clearly, this increasing salt discharge will lead to environmental unsustainability in the long run.

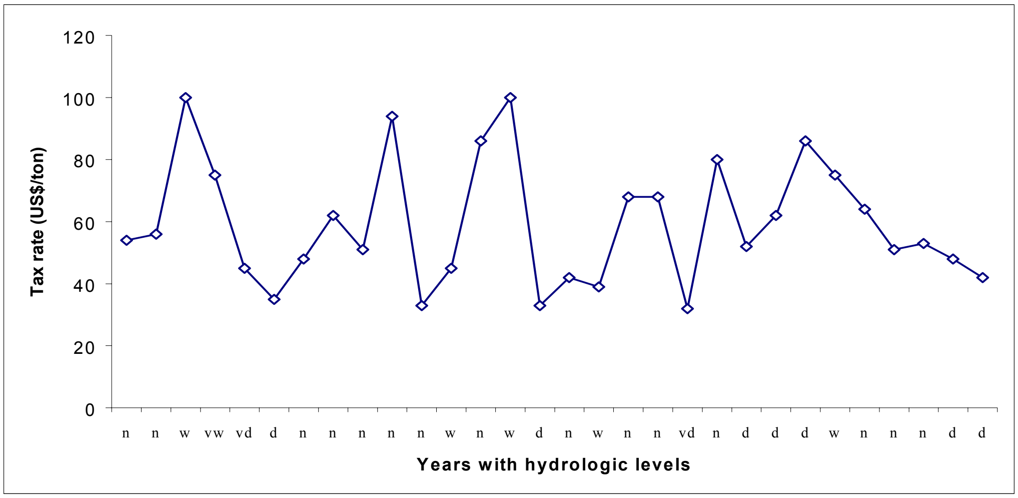


Figure 7. 17. Penalty tax on excess salt discharge vs. years.

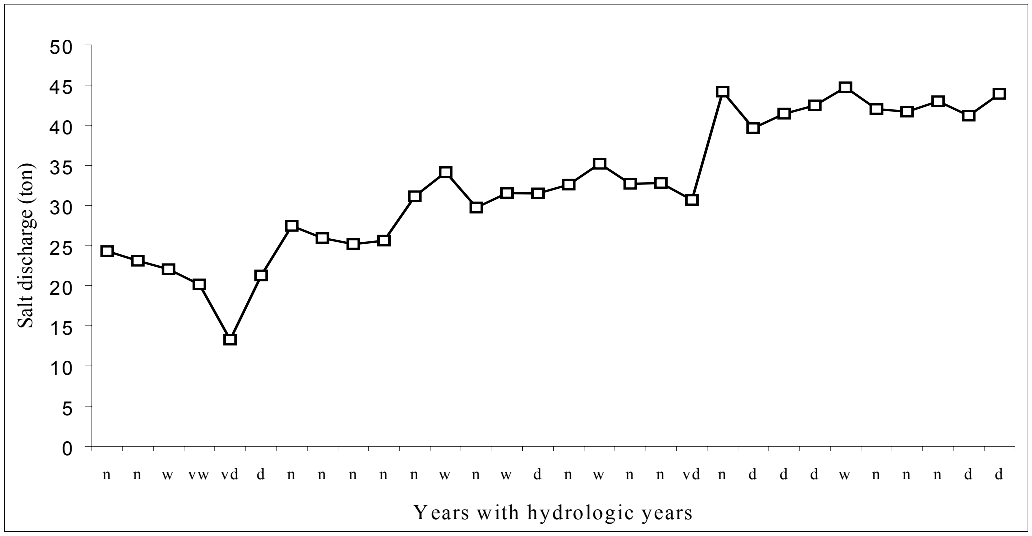


Figure 7. 18. Excessive salt discharge vs. years.

7.4.1.3 Crop pattern change

It is assumed that crop patterns may be changed every five years in the modeling period. The model determines crop patterns every five years, based on the possible range for each crop. Figures 7.19–7.24 present the crop patterns for different periods at each demand site, respectively. The crop pattern in 1987 (Raskin, 1992) is also shown in each of these figures, and then for each demand site, crop patterns from the model can be compared to the actual status in 1987.

For all demand sites, these figures show that (1) crop patterns from the model are different from those in 1987; (2) irrigated area for cotton is significantly decreased and that for wheat-maize is significantly increased compared to the area in 1987; and (3) based on the model output, irrigated area is rotated between cotton and wheat over years. Compared to 1987, irrigated area for cotton in *Fergana, Mid_syd*, and *Naryn* decreases, while it increases in *Chakir*, *Artur*, and *Low_syd*. In *Artur*, and *Low_syd*, irrigated area for other crops (including rice) is significantly lower than the actual value in 1987.

The crop pattern change shown by the model mainly reflects the requirements of water and soil quality conservation, ecological water release to the Aral Sea, and agricultural production enhancement. Cotton and wheat are the most attractive crops to produce in the basin. The long-term modeling result shows there are great changes for the irrigated area of these two crops, and field rotation is suggested between them. Cotton is more economically attractive than wheat. However, cotton needs more water for irrigation in the basin, especially in the summer season when peak irrigation withdrawal occurs. Also cotton has higher salinity tolerance, which allows water application (i.e., drainage reuse and groundwater) with higher salinity. In a long-term frame, this leads to salinity accumulation in the soil. Therefore, the rotation of these two crops reflects the objective of this modeling: sustaining irrigation-based economy without deteriorating the environment. In order to study crop patterns in future years more comprehensively, extended work is needed to incorporate more factors, such as demands for various crops, crop cost and selling price, and the changes of these items over future years, into the modeling framework.

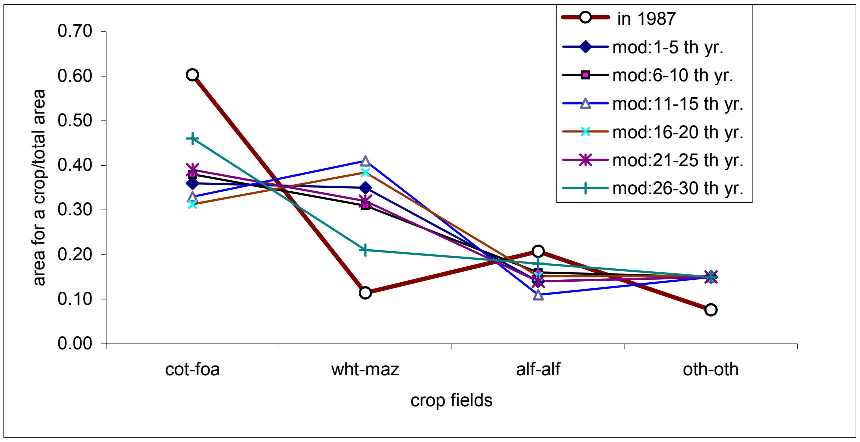


Figure 7. 19. Crop patterns in different periods for demand site *Naryn.*

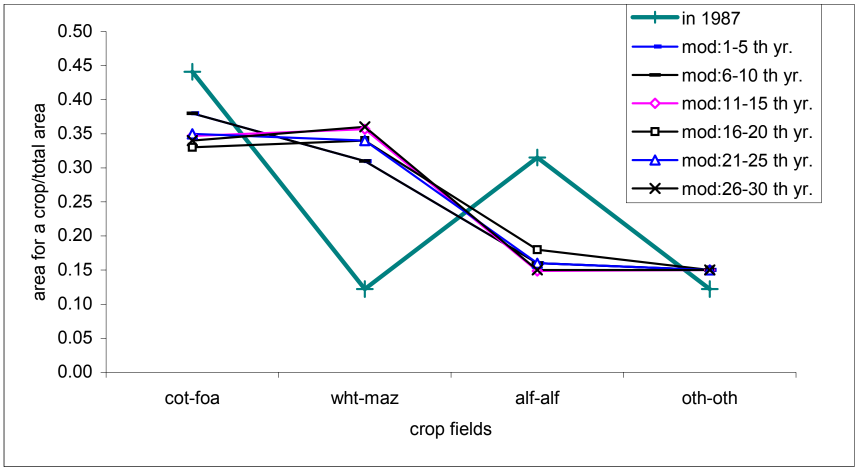


Figure 7. 20. Crop patterns in different periods for demand site *Low_syd.*

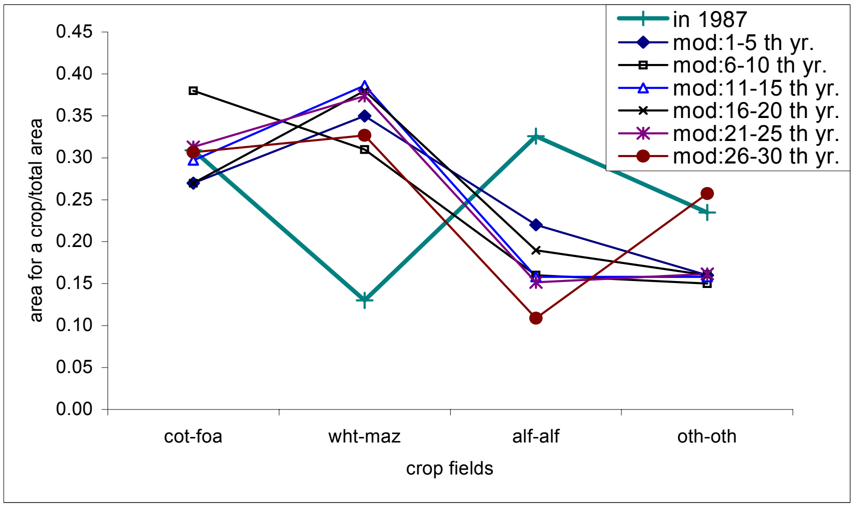


Figure 7. 21. Crop patterns in different periods for demand site *Artur.*

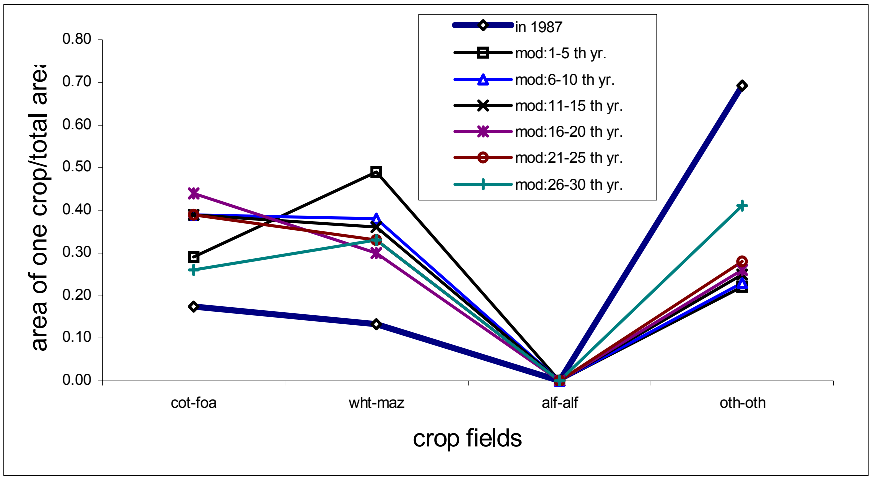


Figure 7. 22. Crop patterns in different periods for demand site *Chakir.*

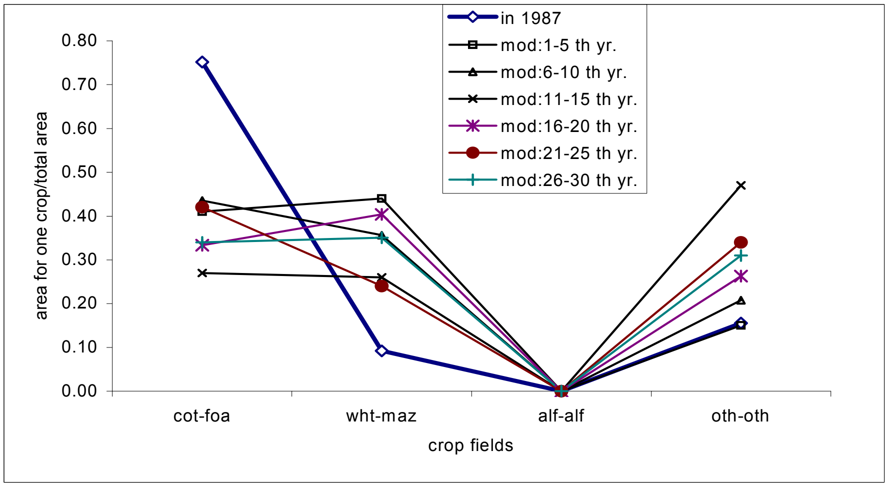


Figure 7. 23. Crop patterns in different periods for demand site *Fergana.*

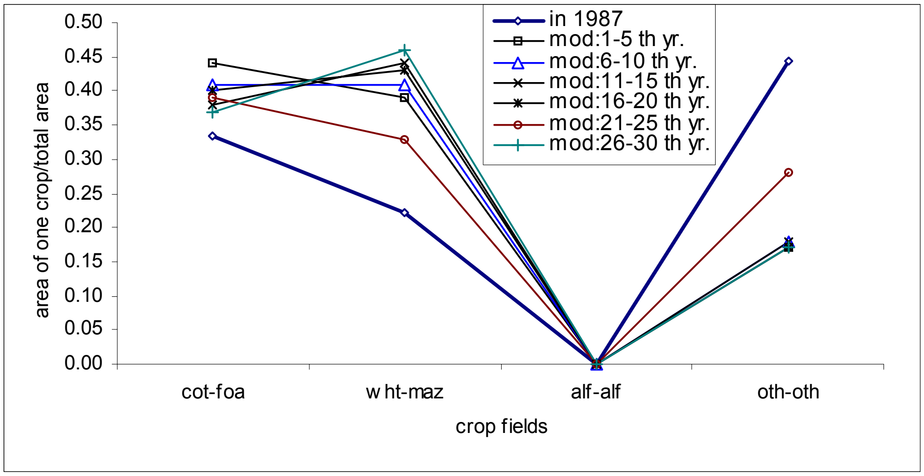


Figure 7. 24. Crop patterns in different periods for demand site *Mid_syd.*

7.4.1.4 Water use facility improvement

Three inter-year variables, including the water distribution efficiency (*EDS*), the irrigation efficiency (*EIR*), and the drainage efficiency (*EDN*), are computed in the modeling framework in order to determine the appropriate water supply and application facility improvements for sustainable water management in the area.

Water distribution efficiency vs. years is presented in Figure 7.25. For most demand sites, the value of this item in the next 30 years increases up to 0.75-0.80, which is feasible in the basin according to EC (1995). This item increases particularly in later years.

Figure 7.26 shows the drainage efficiency vs. years in each demand site. The upstream demand site, *Naryn,* has a relatively lower value over years, while all mid-stream and downstream demand sites have higher values, especially in later years. The numbers shown in this figure are within the possible ranges of the drainage improvement in the basin. Drainage is important in preventing soil salinity accumulation and waterlogging.

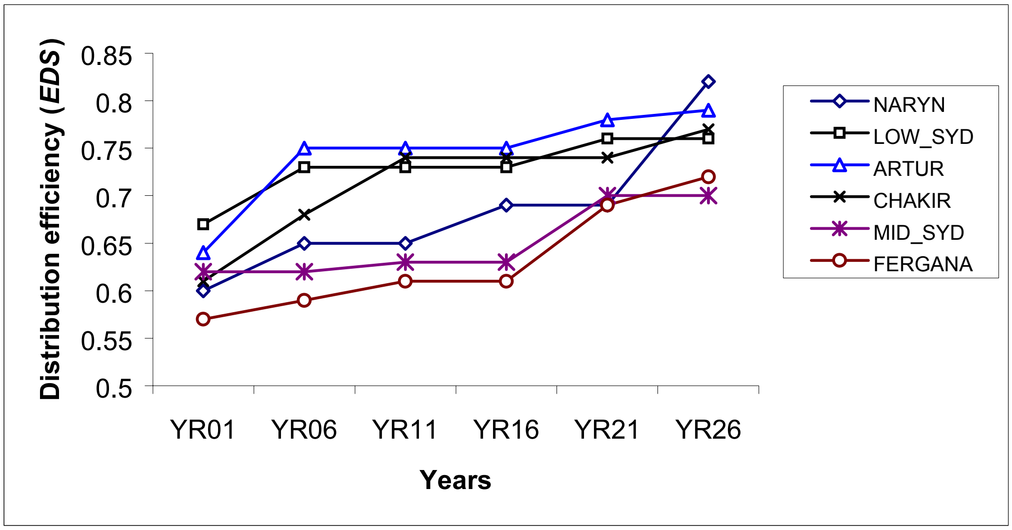


Figure 7. 25. Water distribution efficiency (*EDS*) at each demand site.

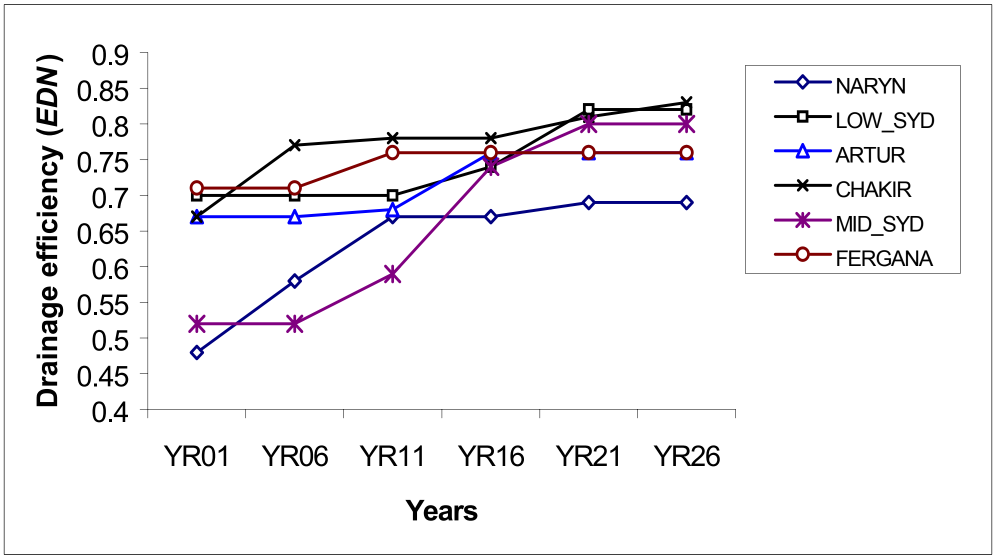


Figure 7. 26. Drainage efficiency (*EDN*) at each demand site.

Irrigation efficiency is computed for the four types of crop fields at each demand site. Figures 7.27-7.30 show this item for all crop fields in each demand site, respectively. At all demand sites, except for the downstream demand site *Low_syd*, irrigation efficiency increases significantly. This is expected because in later years both irrigation water demand and non-irrigation water demand grow significantly. Demand sites *Naryn* and *Mid_syd* have a higher irrigation efficiency for all crops in later years, whereas demand site *Low_syd* has a much lower irrigation efficiency for all crops over most years. This may be due to the high leaching requirement to mitigate the soil salinity effect in this demand site. In the last 10 years, irrigation efficiencies increase up to 0.75-0.85, which means the current major irrigation system (furrow system) needs to be replaced by advanced systems such as drip or sprinkler systems.

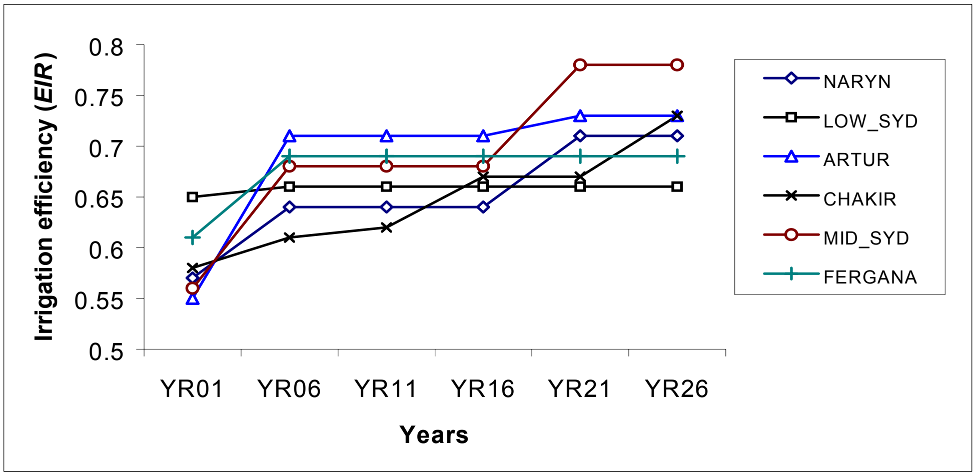


Figure 7. 27. Irrigation efficiency (*EIR*) at each demand site - in crop field cotton-forage.

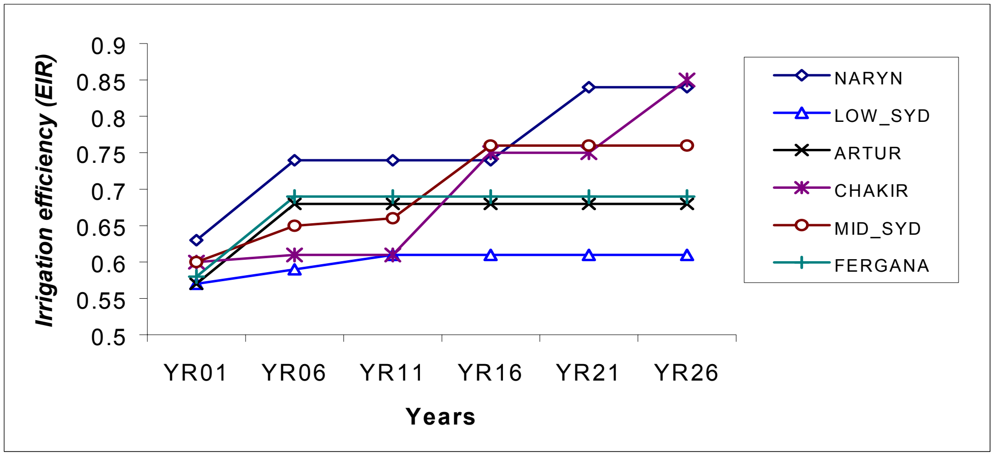


Figure 7. 28. Irrigation efficiency (*EIR*) at each demand site - in crop field wheat-maize.

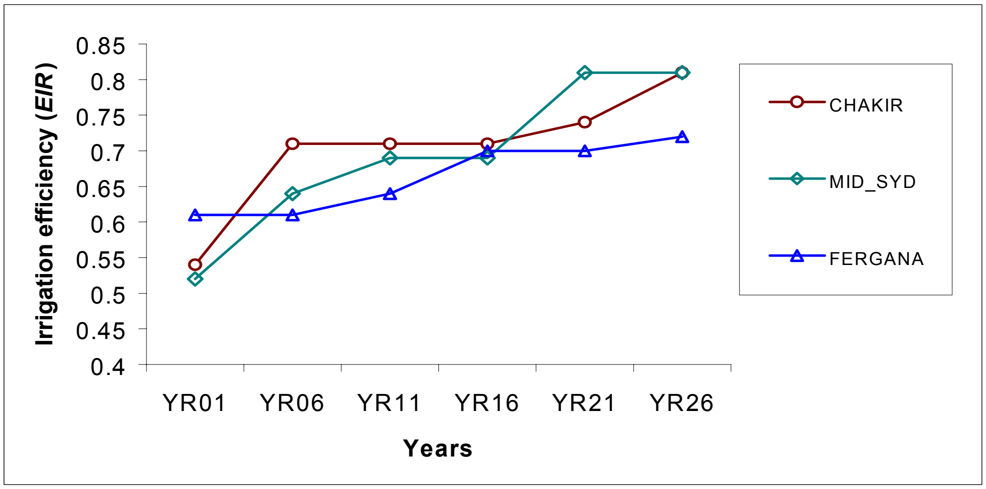


Figure 7. 29. Irrigation efficiency (*EIR*) at each demand site - in crop field alfalfa-alfalfa.

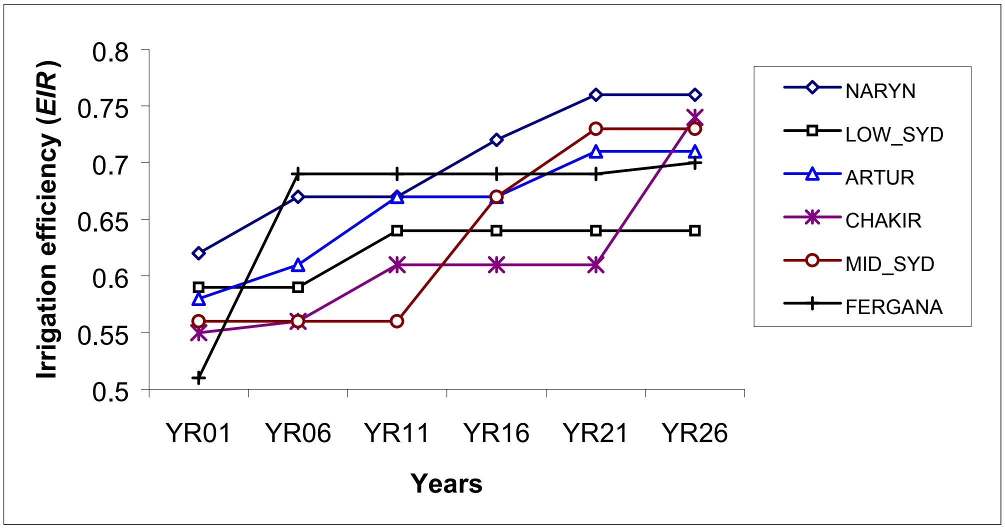


Figure 7. 30. Irrigation efficiency (*EIR*) at each demand site - in crop field other-other.

Drainage reuse is not defined as a variable in the inter-year control program (**IYCP**), but it is determined in the yearly models (**YM**) based on prescribed capacity limits and investment constraints. Figure 7.31 presents the total drainage reuse in each of the 30 years. The figure shows that drainage reuse basically occurs in very dry years and years after consecutive dry years. However, drainage reuse is recommended for the upstream demand site *Naryn* in all years. This is explainable because the salinity in drainage at this demand site is comparably low and the reuse will not create high salinity in the crop field. Demand site *Fergana*, which has the largest irrigation water demand among the demand sites has the largest amount of drainage reuse in very dry years. Drainage reuse tends to increase in later years due to increased water demands.

In the long-term model, in addition to the normal drainage facility specified by the inter-year control variable, *drainage efficiency*, we assume that additional drainage pumping and disposal to nearby deserts may be realized if the groundwater table rises over a critical level, to prevent waterlogging. This item is determined within individual years according to the groundwater table status in those years. Figure 7.32 shows the amount of drainage pumping and disposal at demand sites where waterlogging may occur. Referring to Figure 7.26, over the study years at demand site *Mid_syd*, the excess drainage pumping decreases with the increase in drainage efficiency in later years. The same shift occurs in demand site *Low_syd*. Improved drainage facilities are therefore necessary for preventing waterlogging problems at these sites.

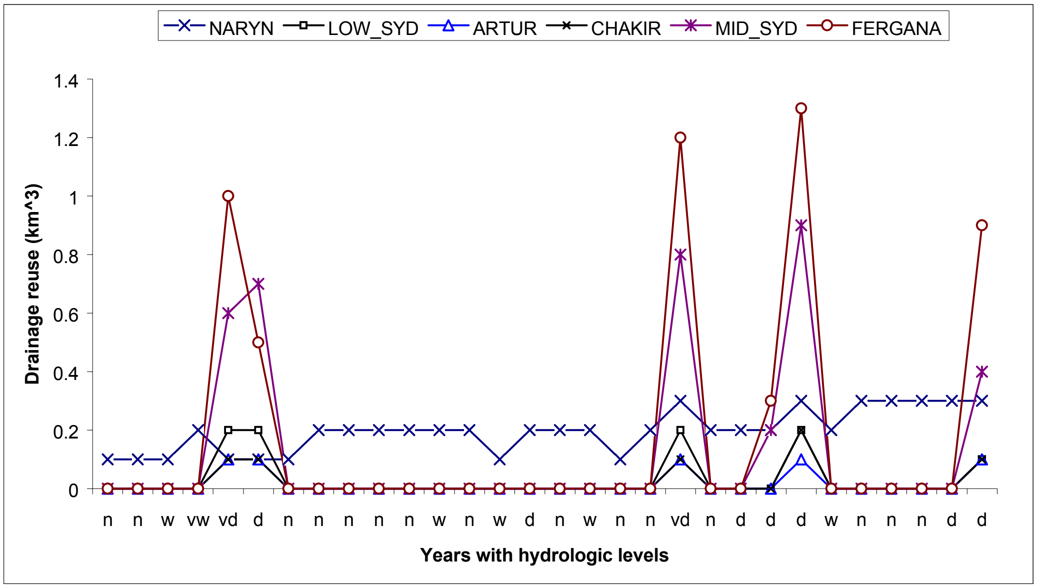


Figure 7. 31. Drainage reuse in each of the 30 years

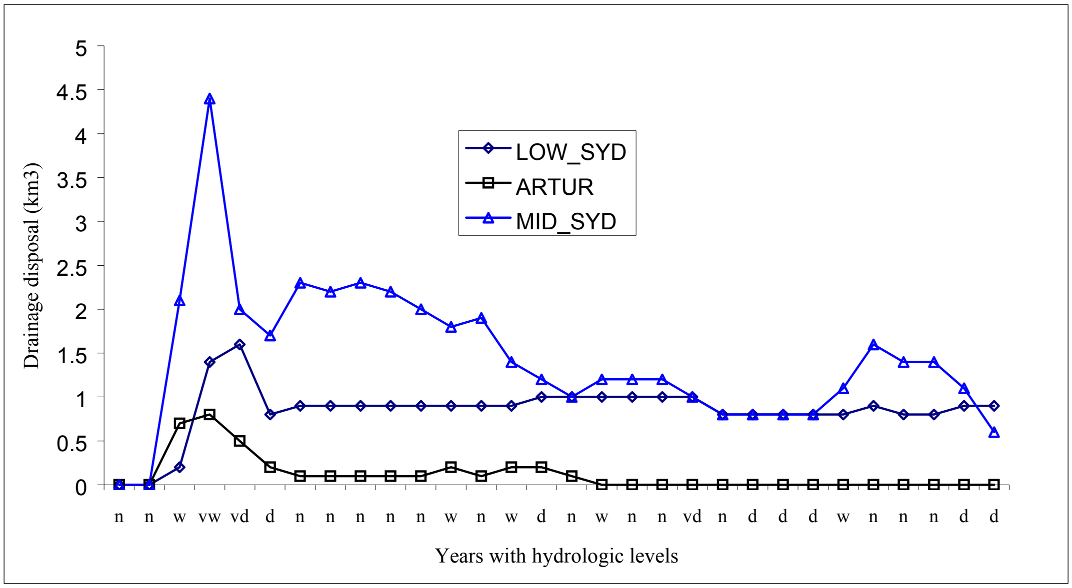


Figure 7. 32. Amount of drainage disposal at the demand sites where waterlogging may occur.

7.4.2 Water uses and long-term consequences

The long-term model traces the economic and environmental consequences of the expected water use practices during 30 years, and controls these consequences according to the prescribed sustainability criteria. In the following, the relations between irrigation water use and the associated economic and environmental impacts are explored according to the long-term modeling output under the baseline scenario.

7.4.2.1 Soil salinity

High salinity in irrigation water, poor field drainage, and a high groundwater table may lead to soil salinity accumulation over a long time. The baseline result shows that the crop fields in demand sites *Naryn,* and *Chakir* can avoid soil salinity accumulation, while demand sites *Fergana*, *Mid_syd,* and

Autur will experience increased soil salinity but no serious effects on crops occur. However, crop fields, especially the cotton fields of demand site *Low_syd*, will suffer a tremendous salinity increase, which will be above the crop salinity tolerance. Figure 7.33 shows the salinity in the crop field *cot_foa* (cotton – forage) of demand sites *Fergana, Mid_syd* and *Low_syd*, and Figure 7.34 shows the salinity in crop field *wht_maz* (wheat-maize) of the three demand sites in each of the 30 years. Soil salinity in field *wht_maz* is lower than that in field *cot-foa* since cotton has a higher salt tolerance than wheat and maize.

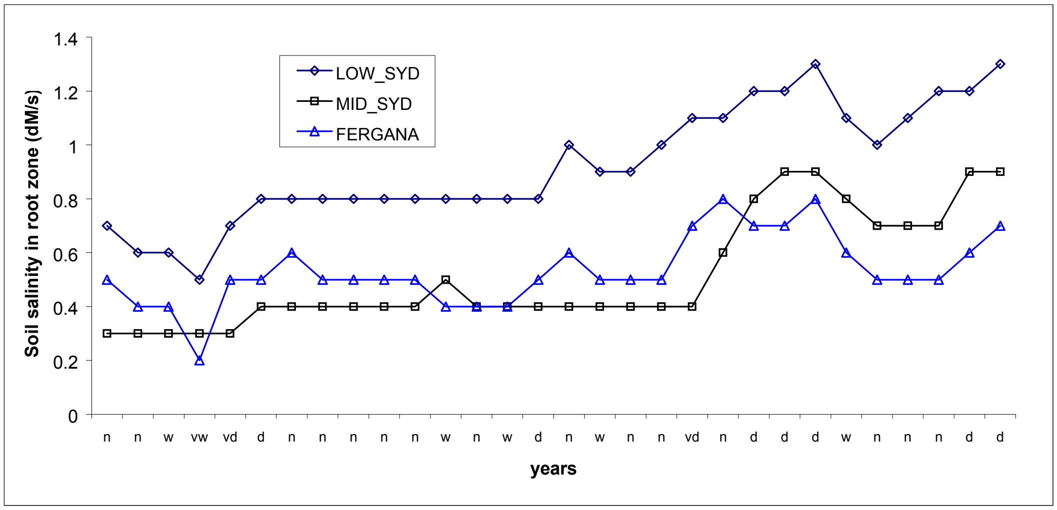


Figure 7. 33. Soil salinity in crop field *cot_foa* (cotton–forage) at selected demand sites.

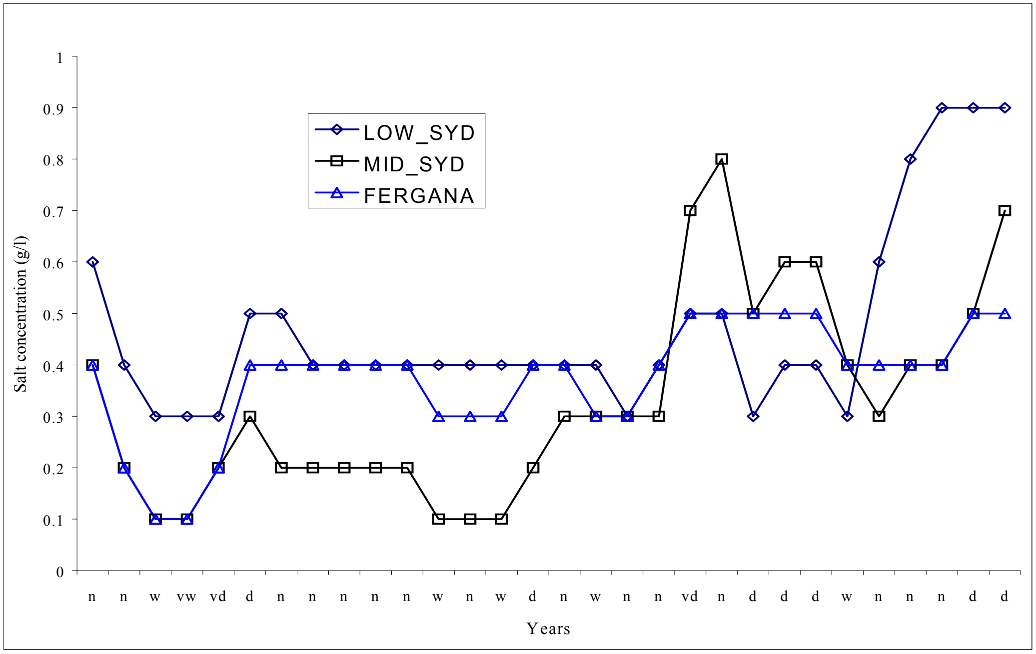


Figure 7. 34. Soil salinity in crop field *wht_maz* (wheat-maize) at selected demand sites.

7.4.2.2 Waterlogging

Because of excess application of irrigation water (low application efficiency) and ineffective drainage, the groundwater table may rise into the root zone of irrigated crops, resulting in a waterlogging situation. In the long-term modeling, we assume that if waterlogging occurs in a demand site, then additional drainage pumping and disposal must be carried out to keep the groundwater table below the critical level. Therefore, the amount of additional drainage pumping and disposal at a demand site is an indication of a potential waterlogging status at that demand site. We can see in Figure 7.32 that waterlogging problems occur at the midstream and downstream area of the basin (demand sites *Mid_syd* and *Low_syd*).

7.4.2.3 Water quality reduction

Figure 7.35 shows the salt concentration in the groundwater vs. years at each demand site. At the most upstream demand site, *Naryn*, salt concentration in the groundwater decreases, which may be due to a high initial salt concentration in the groundwater. However, all other groundwater sources are affected by the salt load from irrigation fields with deep percolation. High salt concentration (up to 2.1 g/l) occurs in the groundwater at the downstream demand site *Low_syd*, where the salt concentration in deep percolation is high. As can be seen in Figures 7.27-7.30, the irrigation efficiency in this demand site is relatively low in later years, which causes increased deep percolation and affects the groundwater quality in that region. A significant salinity increase in groundwater also occurs at demand sites *Fergana* and *Mid_syd* due to high salt concentration in deep percolation from the crop field.

Figure 7.36 shows the possible salt concentration in reservoirs on the main river. The upstream reservoir, Toktogul, is not affected. For the other three reservoirs at the midstream and downstream, however, the salt concentration increases by 1.5 times the initial concentration at the end of the study period.

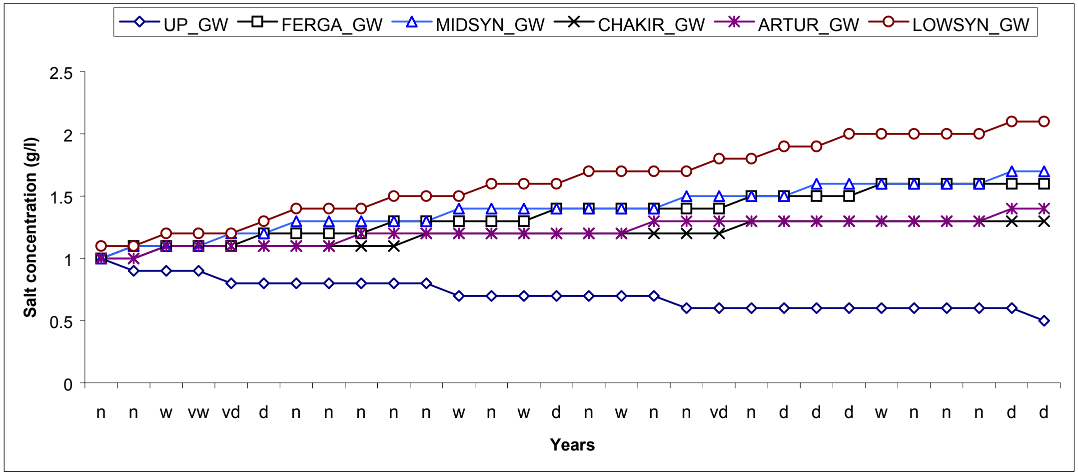


Figure 7. 35. Salt concentration in groundwater at each demand site.

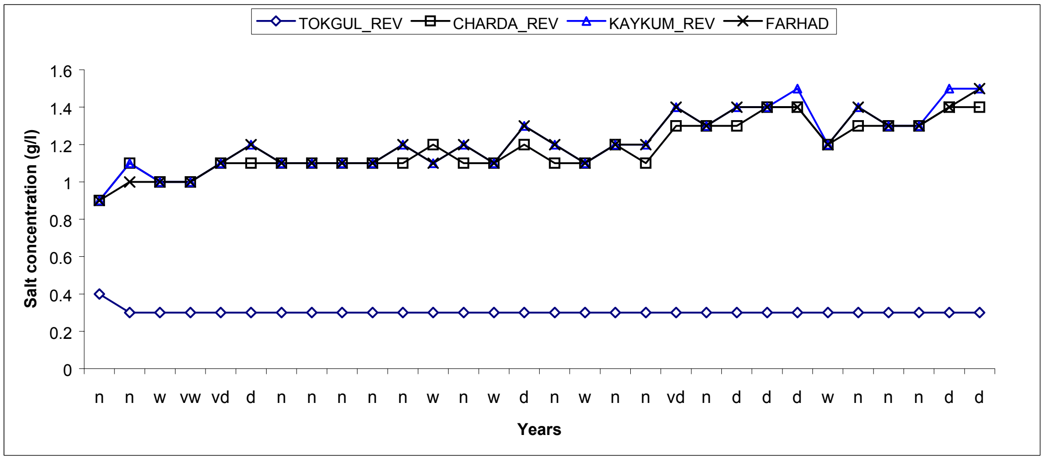


Figure 7. 36. Salt concentration in reservoirs on the main river

7.4.2.4 Environmental and ecological water depletion

The planned inflow to the Aral Sea based on the hydrologic level of each year and the calculated inflow are plotted in Figure 7.37. Generally, in *dry* and *very dry* years, the calculated inflow is below the planned flow; this occurs also in some *wet* years due to the high inflow target. In *normal* years, the required inflow is basically satisfied. Considering the total inflow over 30 years, the target of the inflow is 288 km^3, while the computed inflow from the model is 258.4 km^3, about 10% lower than the goal. This condition is closely related to river water withdrawal for irrigation.

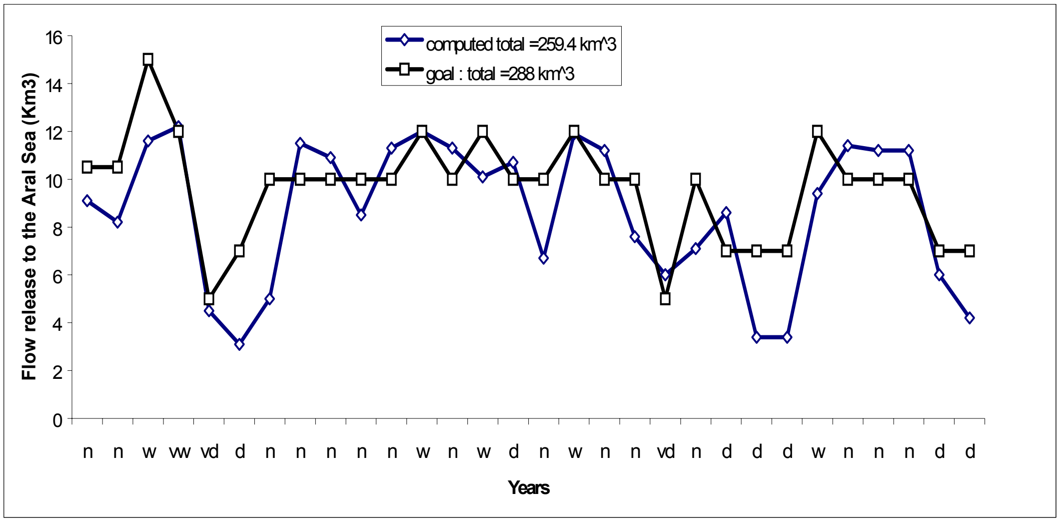


Figure 7. 37. Planned inflow to the Aral Sea vs. calculated inflow

7.4.2.5 Irrigated area reduction and decline in crop yield

In the baseline run, irrigated area only declines in *very dry* years. However, the price of sustaining the irrigated area is environmental problems, such as soil salinity accumulation (see Fig. 7.33) and water quality reduction in surface and groundwater (see Figs. 7.35 and 7.26), especially in the midstream and downstream demand sites. As we will show later, any increase in irrigated area in these demand sites will worsen these problems.

Figures 7.38-7.39 show the agricultural profit over years at each demand site, and Figure 7.40 shows the total agricultural profit in the basin over the years. The tendency of increasing agricultural profits results from the projected increase of irrigated area (Table 7.1), and possibly from improved water distribution, irrigation and drainage facilities. However, the effect from hydrologic fluctuation is obvious. In *dry* and *very dry* years, the crop yields decline. This causes a reduction of irrigation profit shown in these figures.

This section presents the results from a baseline run that is defined according to the hydrologic fluctuations and normal water demands presented in Section 7.2. The "baseline" is expected to provide a basic guess of the long-term consequences of water uses subject to the sustainability criteria. The uncertainty ranges of these consequences will be further addressed in the scenario analysis presented in Section 5.

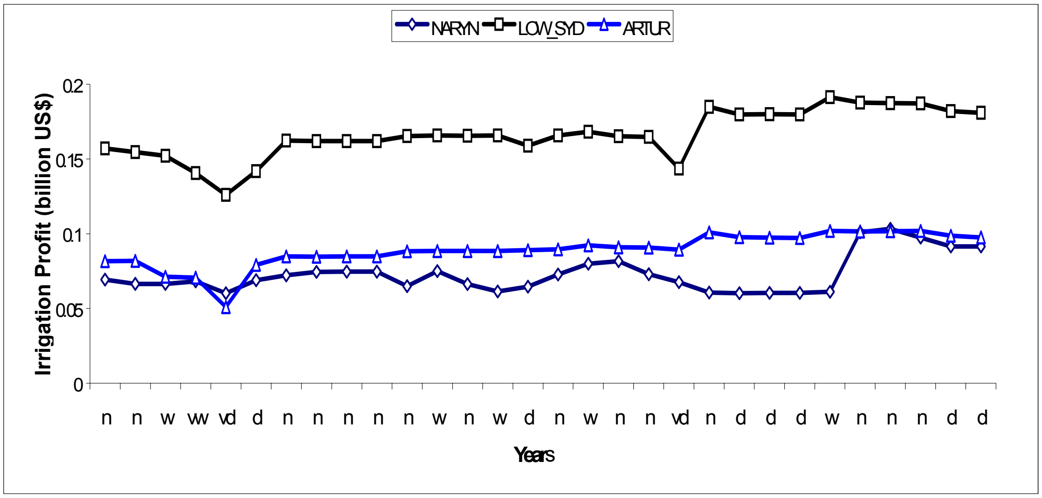


Figure 7. 38. Irrigation profit at each demand site.

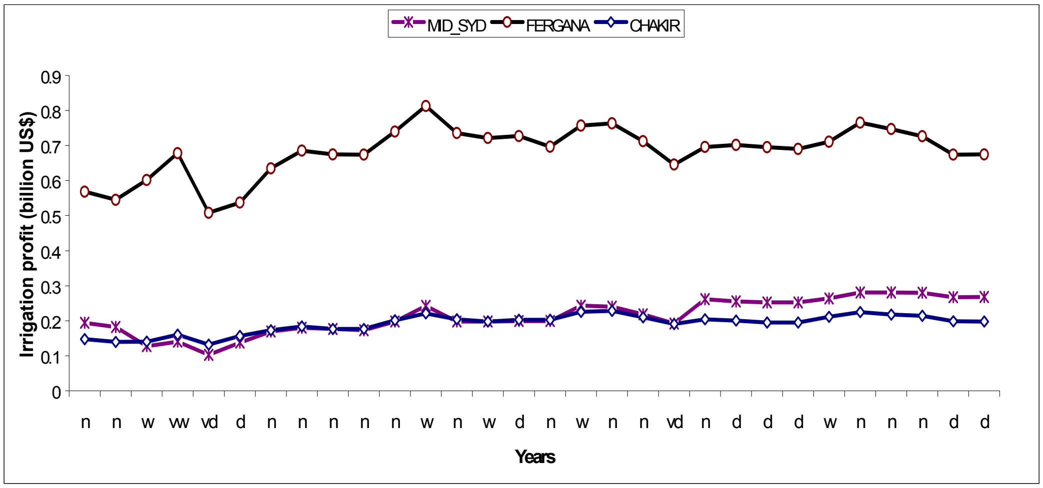


Figure 7. 39. Irrigation profit at each demand site

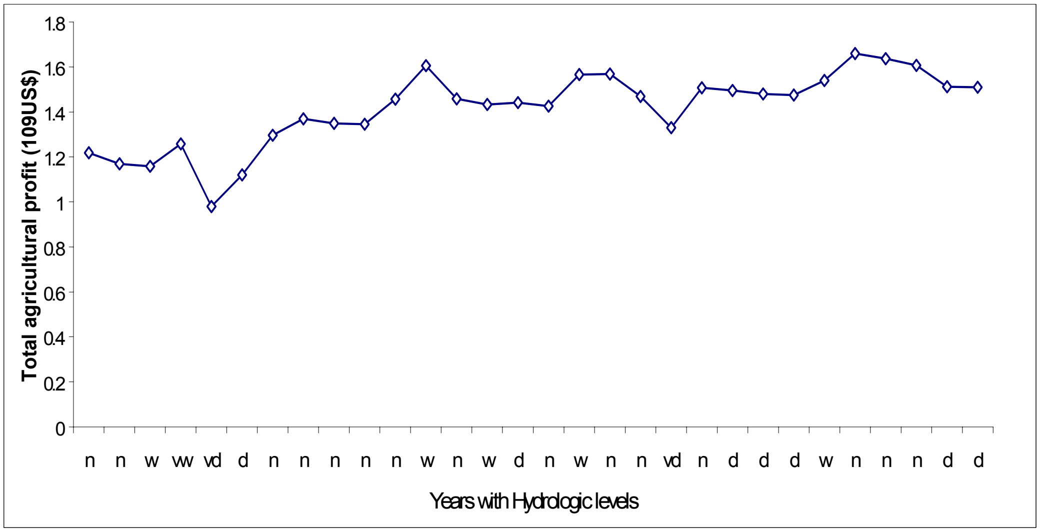


Figure 7. 40. Irrigation profit in the basin

7.4.3 Long-term modeling output vs. short-term modeling output

As mentioned before, the objective of the short-term model is to maximize benefit from water uses within a year with given hydrologic conditions and environmental constraints. This model does not take into account the criteria for sustainable water resources management that are included in the long-term modeling. The short-term modeling output has been discussed in Chapter 4, and here it is compared with the long-term modeling output. For convenience, the output from the short-term model under normal hydrologic conditions is compared to the average output of *normal years* from the long-term modeling.

7.4.3.1 Crop patterns

The irrigated area resulting from the short-term modeling is shown in Table 4.43, which shows the irrigated area for the major crops at each demand site. The allocation of irrigated area resulting from the long-term modeling is presented in Figures 7.20-7.24. The short-term modeling shows that the crop field *cotton-forage* dominates the irrigated area at all demand sites except for the downstream demand site *Low_syd*. However, in the long-term modeling framework, irrigated area for *wheat-maize* increases significantly, the pattern *cotton-forage* no longer dominates the irrigated area, and irrigated area is rotated between *cotton-forage* and *wheat-maize* over the years.

The short-term modeling also implies that the irrigated area at the downstream demand site *Low_syd* is reduced to 20% of total available irrigated area, which is not acceptable in the long-term modeling framework due to the equity concerns included in the sustainability criteria. Thus, due to the equity among demand sites, and due to even development of irrigation facilities, no reduction of irrigated area at that demand site in normal hydrologic years is suggested in the long-term modeling framework.

7.4.3.2 Irrigation profit

The total irrigation profit resulting from the short-term modeling reaches $2.75 billion in a normal year (Table 4.49). However, it is only between 1.25 to $1.64 billion in the long-term modeling (Figure 7.40). The difference is a result of several reasons. First, in the study area, cotton is the crop with the highest net profit under the given crop prices and costs (Table 4.19). From the short-term modeling, the cotton-forage area covers up to 70% of the total irrigated area, whereas in the long-term modeling, the percentage is only between 30% to 38%. Second, as shown in Table 7.15, the irrigated area is distributed differently among demand sites in the short-term and the long-term modeling. Compared to the long-term modeling, the percentages at the downstream demand sites are lower, and those at the upstream and mid-stream demand sites are higher in the short-term modeling. The downstream demand sites have lower water use benefit due to lower water quantity availability and higher water and soil salinity. Third, in the short-term modeling, we assume that the end-year reservoir storage is equal to the reservoir storage at the beginning of that period, and all inflows coming within one year can be used for water supply purposes in that year. However, for the long-term modeling, a long-term control variable, *wsu* constraints the end-year reservoir storage. Thus, some water coming in a normal years may not be used as it is saved for the following dry year.

Table 7. 15. Percentages of irrigated area under the short-term and long-term modeling

	NARYN	LOW_SYD	ARTUR	CHAKIR	MID_SYD	FERGANA
short-term	6.5%	4.0%	4.9%	14.5%	22.9%	47.2%
long-term	5.2%	13.8%	5.5%	12.3%	19.9%	43.3%
Actual percent. in 1987	5.2%	13.5%	5.2%	14.0%	21.6%	41.4%

7.4.3.3 Water and soil salinity

High irrigation profits can lead to serious water and soil quality deterioration. As discussed in Chapter 4, Section 4.3.1.3, *basin-wide salinity distribution analysis*, with the short-term modeling, at the mid-stream and downstream sites, salinity in reservoirs in the last time period increases to about 1.5 times that at the first period. Groundwater salinity does not change significantly within the one-year time frame. However, soil salinity can increase to unacceptable levels in just one cropping season, not only at downstream demand sites, but also at mid-stream and upstream demand sites (see Figure 4.9). As discussed in Section 7.4.2.3, over 30 years, salinity in reservoirs increases up to 1.5 times of that in the beginning year, soil salinity increases slightly at all demand sites except for the downstream demand site where soil salinity increases more strongly.

7.4.3.4 Reservoir operation

Reservoir operation with the short-term and the long-term modeling has been discussed in Section 4.3.1.2 and 7.4.1.1, respectively. Table 7.16 presents the reservoir utilization efficiency (*RUE*) computed based on the output from the short-term and long-term modeling, respectively. The reservoirs, Toktogul, Chardara, and Kayrakum are on the main river, and the other reservoirs presented in Table 7.16 are on the tributaries. With the short-term modeling, the values of RUE of the reservoirs on the main river are higher, while the values of RUE of the reservoirs on the tributaries are higher in the long-term modeling. The time period for reservoir operation is one month for both the short-term and the long-term modeling, and the values of RUE shown in Table 7.11 are averaged over one year (short-term) and over multiple years (long-term). Therefore, the numbers shown in Table 7.11 do not reflect the exact reservoir utilization efficiency. However, at least the figures show that the reservoir operation is different for short-term and long-term river basin management purposes in the study area.

Table 7. 16. Reservoir utilization efficiencies with the short-term and long term modeling.

	Toktogul	*Chardara*	*Kayrakum*	*Bugun*	*Andijan*	*Charvak*
short-trem	0.27	0.39	0.08	0.03	0.43	0.05
long-term[*]	0.16	0.12	0.01	0.38	0.56	0.38

[*] Average value over 30 years.

7.4.3.5 Irrigation and drainage infrastructure

Both the short-term and the long-term modeling show the necessity of improvements to the irrigation and drainage infrastructure. However, some differences can be identified for them, such as (1) the short-term modeling shows the irrigation application efficiency (*EIR*) increases to its upper bound in each crop field at each demand site, while the long-term modeling shows that the irrigation application efficiency at the downstream demand sites increases much slower than at the other demand sites (Section 7.4.1.4); (2) the short-term modeling shows that the drainage efficiency improvements are not economically attractive, while it increases over the study years and is shown to be attractive to the long-term model; and (3) the short-term modeling shows positive contributions to irrigation benefit and total benefit when drainage reuse is increased, without consideration of salinity accumulation due to drainage reuse, while the long-term modeling shows drainage reuse only take places in *very dry* years or consecutive *dry* years, and only the upstream demand site reuses drainage in all years.

It becomes clear, through the comparisons between the short-term and the long-term modeling, that the long-term modeling performs according to the sustainability criteria defined before. With respect to water supply, the long-term modeling shows consideration of reliability and equity with regard to irrigation and the environment, the long-term modeling shows a balance between irrigation profits and their associated environmental consequences through crop pattern changes and appropriate irrigation and irrigation infrastructure improvements. In the rest of this chapter, the long-term modeling is further examined through the analysis of several scenarios considering various water demands, and through a specific sustainability analysis that discusses each aspect of the prescribed sustainability criteria.

7.5 SCENARIO ANALYSIS

To explore robust relationships between water uses and associated economic and environmental consequences, we define several scenarios with specific changes in water demands:

- *Zero scenario*. This scenario assumes no change in irrigated area, crop pattern, non-irrigated water demand, water distribution facility, and irrigation and drainage facility. Put in another way, this scenario runs the current condition over 30 years only subject to hydrologic fluctuations;
- *Irrigation scenarios*. Four irrigation scenarios are defined, each of which is based on a projection of the increase rate of irrigated area (See table 7.1).

These scenarios range from low to high increase of the irrigated area by -10%, 5%, 10% and 58% in the next 30 years, respectively.

- *I&M scenario*. This scenario proposes a high increase of industrial and municipal (I&M) water demand (See table 7.1);
- *High demand scenario*. This scenario assumes both high irrigation and high industrial and municipal water demands; and
- *Flow scenario*. This scenario fully satisfies the environmental and ecological water demand.
- *Hydropower scenario*. This scenario put the highest priority on hydropower generation. That is to say, the power demand of Kyrgyzstan in winter months (October - March) will be satisfied at the greatest possibility.

The model is run under these scenarios, respectively. As applied to the baseline scenario, the GA-LP approach runs over 60 generations for each of other scenarios. The best solution of the 60th generation is taken as the final solution of each scenario for analysis.

7.5.1 What if the current status continues?

In the following, the result from the *zero scenario* is presented and compared with the result from the *baseline scenario*. Figure 7.41 shows the comparison of total agricultural profit vs. years under the *baseline* and the *zero scenario*. Irrigation profit under the *zero scenario* is reduced to 74% of that under the baseline scenario in the first year, and continually reduced to 33% in the last year. The magnitude of the reduction increases with years.

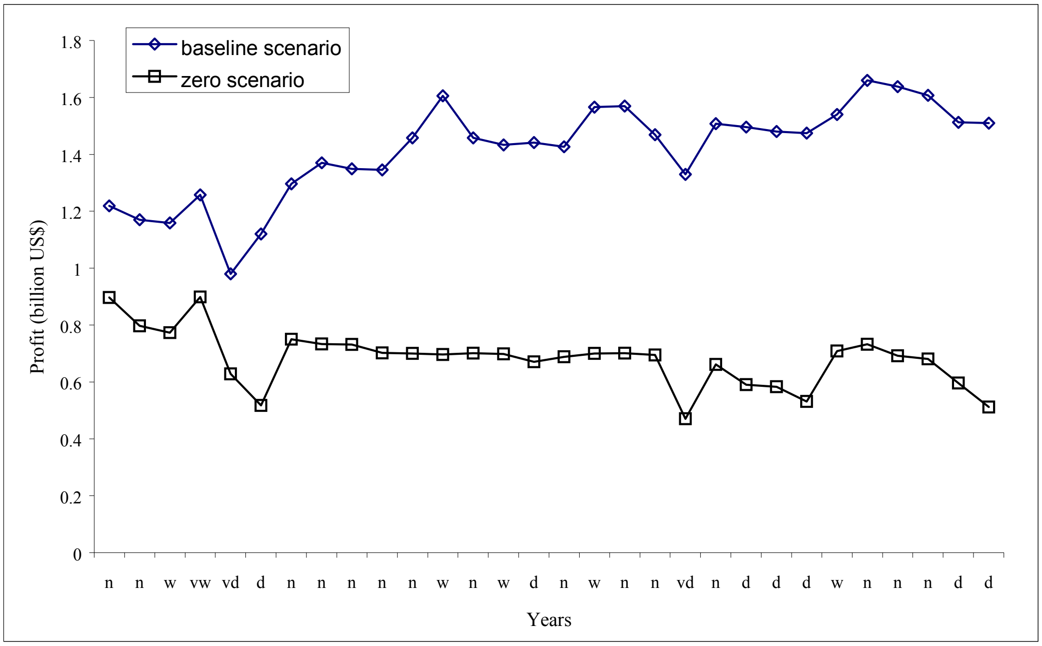


Figure 7. 41. Total agricultural profits under the baseline and the zero scenario

Among the demand sites, the midstream and downstream demand sites have a larger reduction in irrigation profit than upstream demand sites. Figure 7.42 presents the ratio of irrigation profit under the *zero scenario* to that under the baseline scenario, for selected demand sites. The figure also shows that irrigation profit under the *zero scenario* decreases more in later years due to higher water demands without simultaneous improvement in water supply and application capacities.

The inflow to the Aral Sea is also reduced in some years under the *zero scenario*, as shown in Figure 7.43. This implies that river water withdrawal under the *zero scenario* is even larger than that under the *baseline scenario* because of low water distribution and use efficiency.

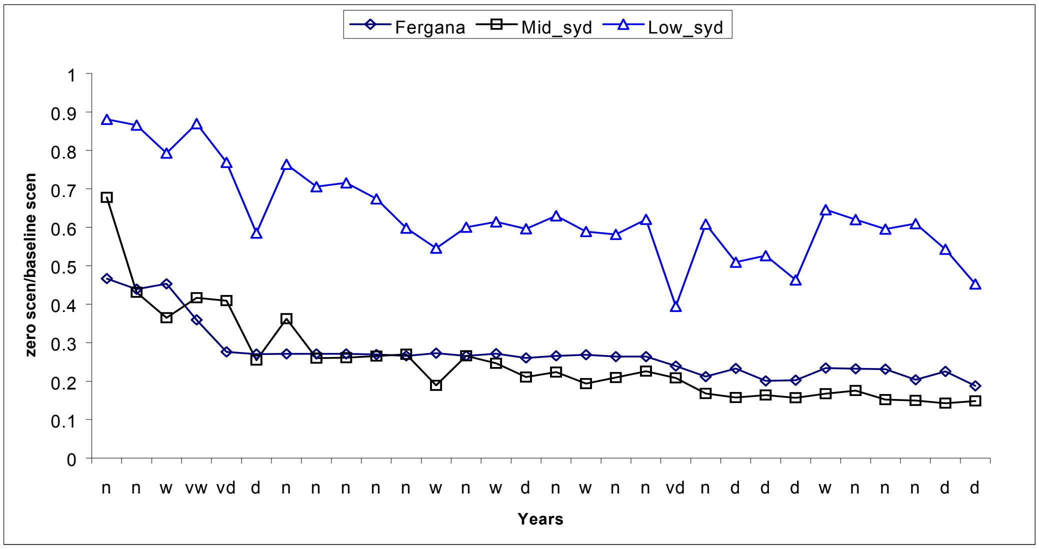


Figure 7. 42. Ratios of agricultural profit under the *zero scenario* to that under the *baseline scenario*.

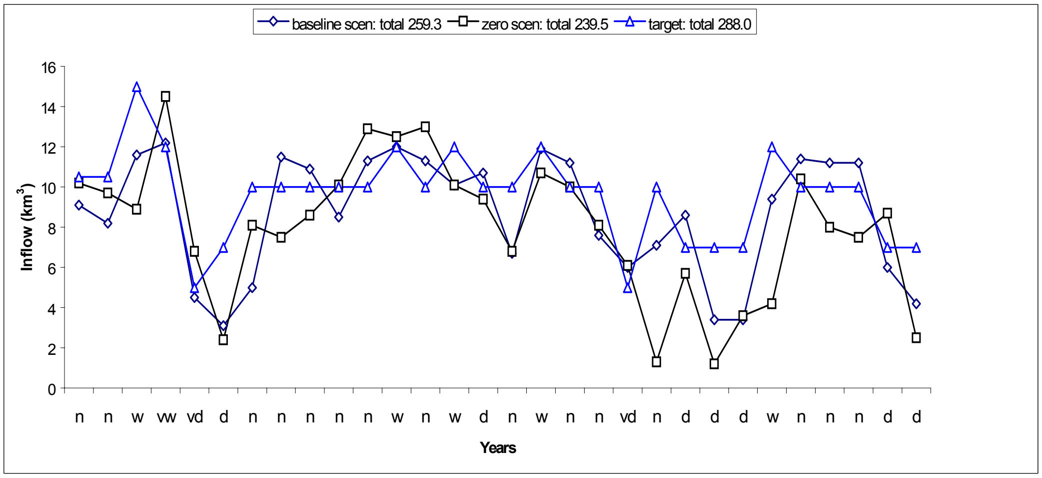


Figure 7. 43. Inflow to the Aral Sea (km^3) under the *baseline* and the *zero scenario*.

With low water distribution efficiency, more of the diverted water does not reach the crop field, but is lost to evaporation and groundwater recharge. Moreover, lower drainage efficiency allows more drainage to percolate into the groundwater. Figure 7.44 shows less salt discharge to the river under the *zero scenario* than under the *baseline scenario*. Because of less salt discharge, reservoir salinity does not increase over the years under the *zero scenario.*

As discussed in Chapter 4, Section 4.3.2.2, a low field application efficiency means more water for salt leaching in the crop root zone. Results from the *zero scenario* shows that if the current status continues, there will be a slight salinity increase (up to 0.6 g/l at demand site *Low_syd*) in the soil even at the downstream demand sites.

The groundwater salinity under the *zero scenario* shows an increasing tendency in all demand sites due to low drainage efficiency. At demand sites *Low_syd* and *Fergana,* groundwater salinity, up to 2.0 and 1.6 g/l respectively, has similar changes with that under the *baseline scenario*.

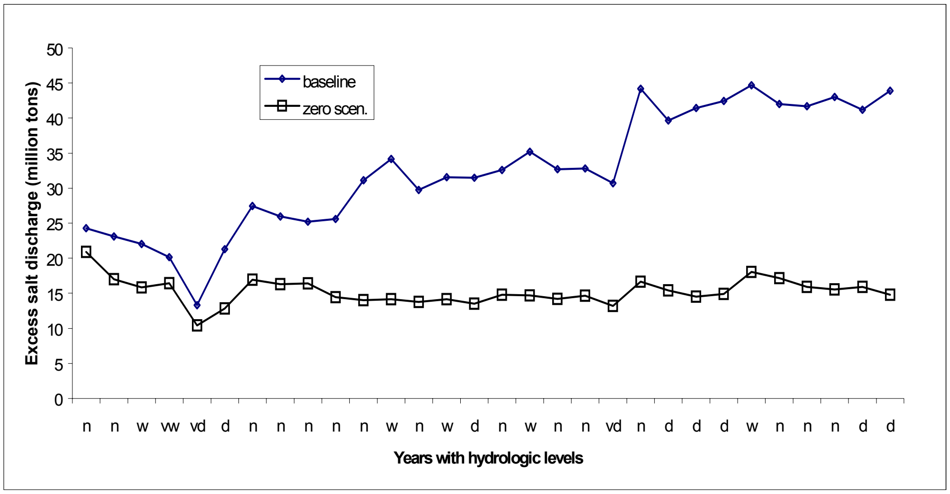


Figure 7. 44. Salt discharge to the river under the baseline and the zero scenario.

As a summary, the results from the *zero scenario* reflect a tradeoff between irrigation water supply and environmental objectives. Maintaining the current status of water supply, water use and water demand over a period of 30 years will lead to a large decline in irrigation profits although severe environment problems may be avoided.

7.5.2 What if the irrigated area decreases or increases by various rates?

In the baseline scenario, it is assumed that the total irrigated area increases by about 5% in the next 30 years. The baseline scenario is taken as one of the *irrigation scenarios*. The other *irrigation scenarios* assume the total irrigated area decreases by about 10%, or increases by 10% and 58% in the next 30 years, respectively. In the following, the results from these *irrigation scenarios* are presented.

The agricultural profits under the *irrigation scenarios* are plotted over 30 years in Figure 7.28. Irrigation profit is higher for the scenarios with higher increasing rates of the irrigated area. However, in the *very dry* years and the last one of consecutive *dry* years (year 24), the profit does not increase significantly with the irrigated area. Actually, the result shows that in these years, the area for some crops is not planted due to water shortage and excess soil salinity. Especially in the final 10 years, the soil salinity has reached up to the crop salinity tolerance in some crop fields, and part of the crop area is left unplanted. Taking the scenario with the highest increasing rate (58%) as an example, in the downstream demand site *Low_syd*, in year 22, the irrigated area for wheat-maize is reduced from 207.0 to 59.2 (1,000 ha), as in that year, soil salinity in the field of wheat-maize is up to 4.5 dS/m. Since most of the crop field is left unplanted, rainfall in the field is mainly used for salt leaching. In the following year, the soil salinity of this field is thus reduced to 3.0 dS/m, and the crop area then increases to 127.0 (1,000 ha).

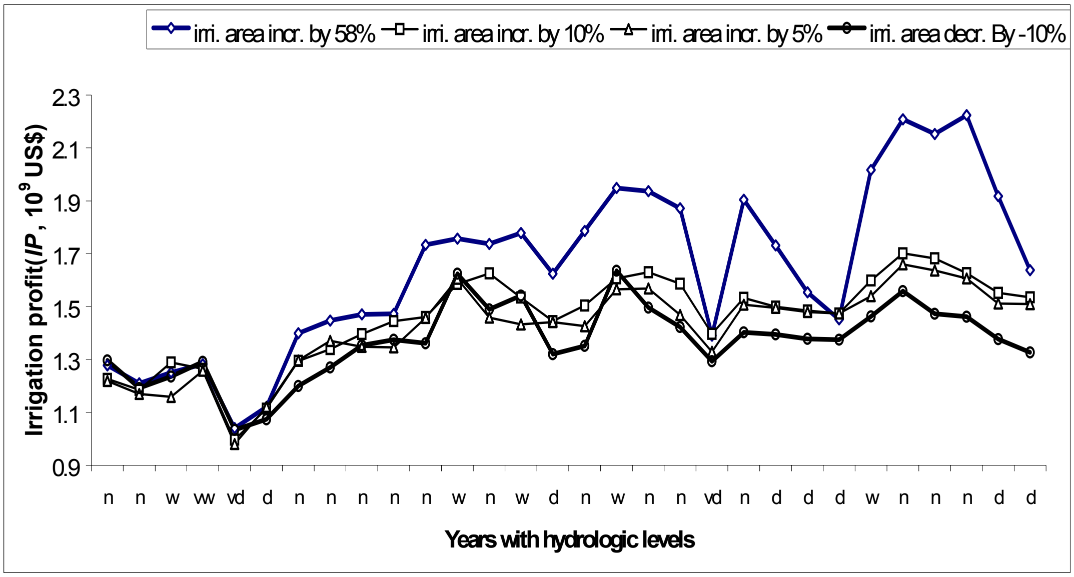


Figure 7. 45 Agricultural profits under the baseline and the irrigation scenario

Due to the increased water withdrawal for irrigation, the inflow to the Aral Sea is tremendously reduced in some years under the *irrigation scenarios* with higher irrigated area increasing rate, as shown in Figure 7.29. The total inflow in 30 years under the highest irrigation area is reduced to 60% of that under the *baseline scenario*.

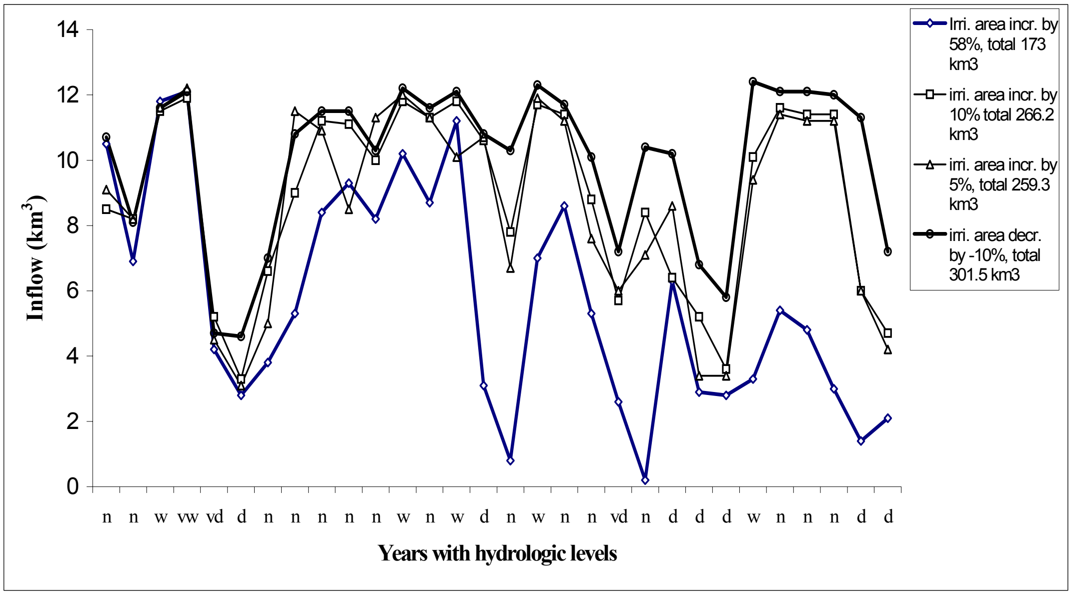


Figure 7. 46. Inflow to the Aral Sea under the baseline and the irrigation scenario

Environmental problems are expected to get worsen with increase of the irrigated area in the river basin, due to the increased irrigation water withdrawal and increased salinity discharge. The total amount of excess salt discharge under the irrigation scenario with the highest increasing rate is 1.3 times the amount of that under the scenario with a 10% decreasing rate. Figures 7.30 – 32 present the excess salt discharge, salt concentration in the groundwater, and salinity in the soil.

As can be seen, when the increasing rate of irrigated area is high, agricultural production is increased while substantial risk is imposed on soil and water quality, as well as on the environment. On the other hand, as mentioned before, during the later years, the water and soil salinity is so high that some irrigated area is left unplanted in the downstream demand sites. Therefore, it may be concluded that a larger increase in the irrigated area will further deteriorate the sustainability of the water resources system in the basin.

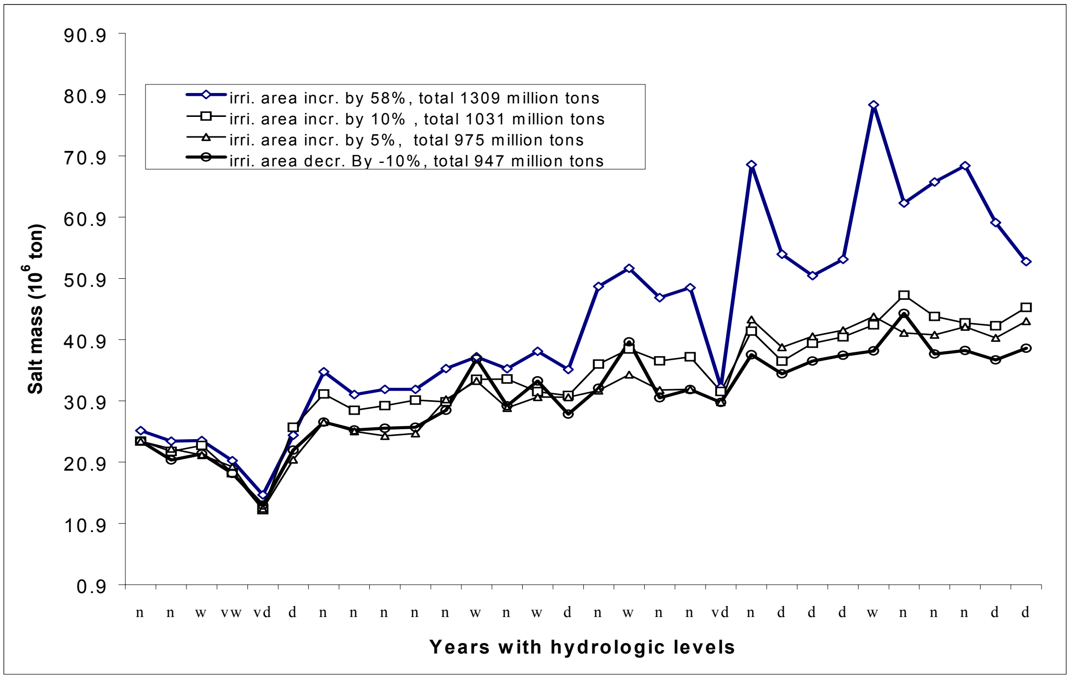


Figure 7. 47. Excessive salt discharge to the river system

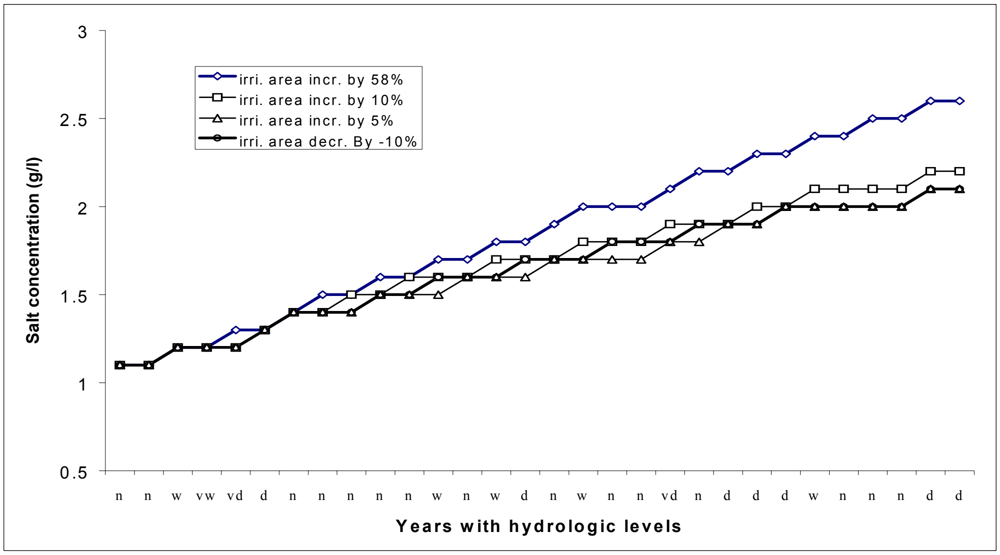


Figure 7. 48. Salinity in the groundwater at demand site *Low_syd* under the baseline and the irrigation scenarios

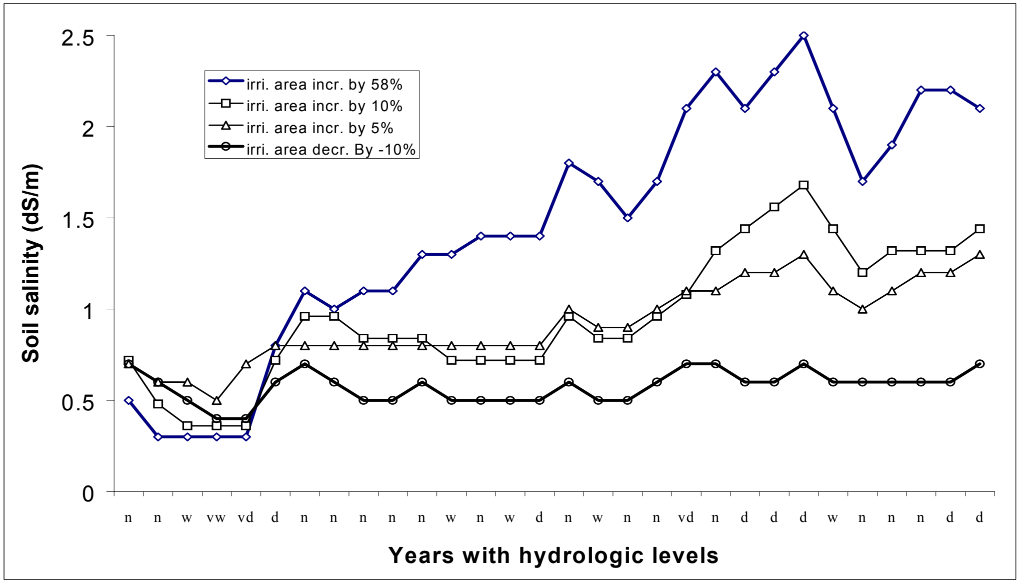


Figure 7. 49. Salinity in the soil (demand site: *Low_syd,* and crop field *cotton-forage*) under the baseline and the irrigation scenario.

7.5.3 What if the I&M water demand increases rapidly?

Due to the anticipated rapid socio-economic development in the basin, more water may be needed for industrial and municipal purposes. In the *baseline scenario*, I&M water demand is assumed to increase by 1% per year, and in the *I&M scenario*, the increasing rate is up to about 3% per year. In year 30, the I&M water demand is 2 times of the demand in year 1. Since we assume that the I&M water demand must be satisfied as a model constraint, more I&M water demand will affect both irrigation water supply and ecological water use. This is discussed in the following based on the results from the *M&I* scenario.

Figure 7.50 presents two ratios comparing the *I&M scenario* and the *baseline scenario* over years. One is the ratio of total irrigation profit, and the other is the ratio of inflow to the Aral Sea under the *I&M scenario* to the inflow in the *baseline*. The minimum ratio of agricultural profit is about 86%, while the minimum ratio of inflow to the Aral Sea is about 31%, and both minimum ratios take place year 24. In very wet years, the effect is less severe, while in very dry years or years after consecutive dry years, the effect is considerable.

Water and soil quality is slightly better in this scenario compared to the baseline, due to less water withdrawal for irrigation. The groundwater salinity in downstream demand site *Low_syd* increases to 1.9 g/l in year 30, which is lower than 2.1 g/l under the *baseline scenario*. The highest water salinity occurs in the *Kayakum* Reservoir at 1.4 g/l. This is slightly lower than the 1.5 g/l under the *baseline scenario*. Soil salinity in the cotton-forage field at *Low_syd* in year 30 is also slightly lower (1.2 g/l vs. 1.3 g/l).

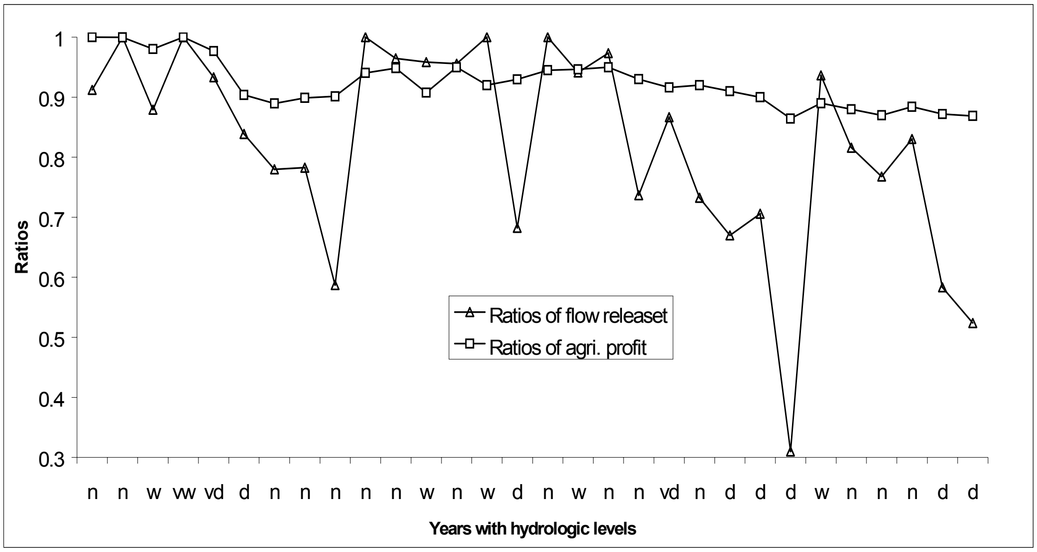


Figure 7. 50. Comparison of total agricultural profit and Aral Sea inflow: ratios of the I&M scenario to the baseline scenario.

7.5.4 What if both the irrigated area and the I&M water demand increase rapidly?

The *high demand scenario* combines the water demand assumptions in both the *irrigation scenario* (the highest irrigated area expansion) and the *I&M scenario*, assuming that the irrigated area increases by 2% per year, and that the non-irrigation water demand increases by 3% per year.

Figure 7.51 shows the ratios of agricultural production, and each of them shows comparisons of the *irrigation* and *high demand scenario* with respect to the *baseline scenario*, respectively. Ratios under the *high demand scenario* are lower than those of the *irrigation scenario*, because under the former, more water is used for non-irrigation purposes. Particularly in dry and very dry years, irrigation profit does not increase although the irrigated area increases. Part of the irrigated area is actually left unplanted due to water shortage or/and high soil salinity. This condition is more apparent in the *high demand scenario* due to the high demand for both the irrigation and non-irrigation water.

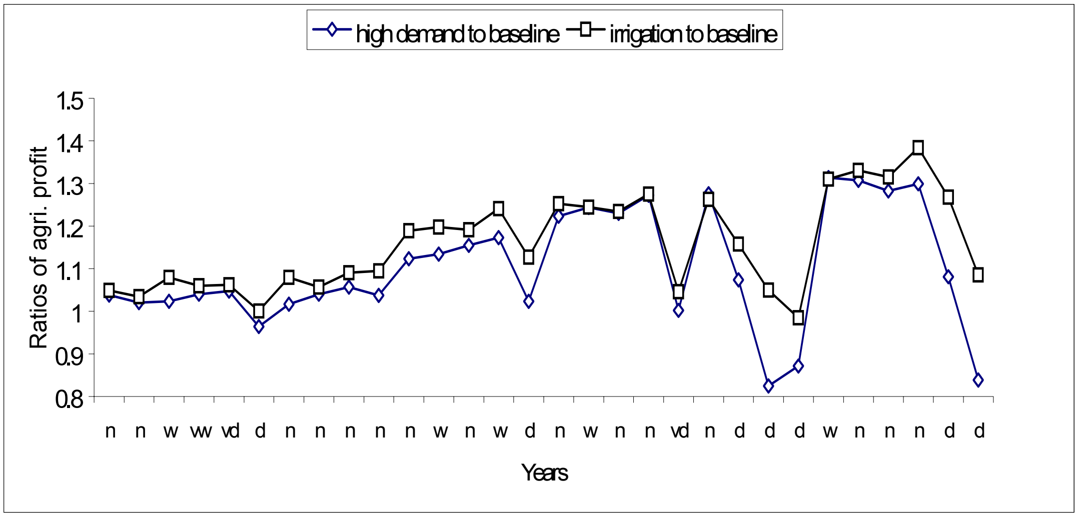


Figure 7. 51. Comparison of total agricultural profit under the *irrigation scenario* and the *high demand scenarios*: ratios relative to the *baseline scenario*.

The results show that the inflows to the Aral Sea are much reduced due to the high demand for both irrigation and non-irrigation water under the *high demand scenario*, as shown in Figure 7.52. The total amount of inflow in 30 years is 258, 173, and 143 km^3 under the *baseline*, *irrigation* and *high demand scenarios*, respectively. The inflow is about one half of the inflow target (288 km^3) under the *high demand scenario*. Thus, rapid increases in irrigation and I&M water demands will continually reduce the inflows to the Aral Sea.

Changes in water and soil quality are shown in Figures 7.53-7.56. Basically, the impacts under the *high demand scenario* are higher than in the *baseline scenario* but lower than in the *irrigation scenario*. We notice that the sequence of irrigation water supply from high to low is: *irrigation*, *high demand*, and then *baseline scenario*, and water and soil salinity from high to low follows the same sequence. Here, again we see that irrigation water withdrawal is critical for the conditions of water and soil salinity.

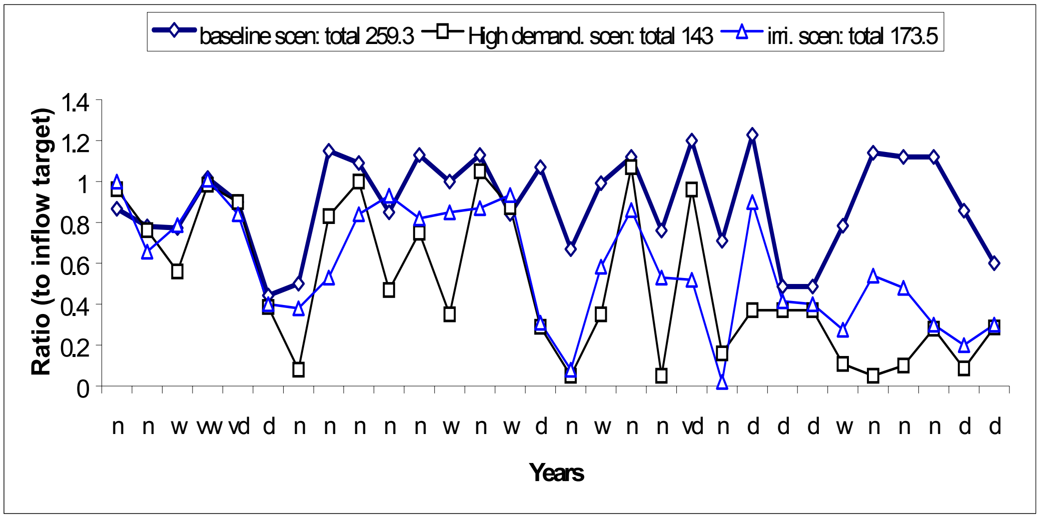


Figure 7. 52. Comparison of inflow to the Aral Sea under the *baseline*, the i*rrigation*, and the *high demand* scenario: ratios relative to the inflow target.

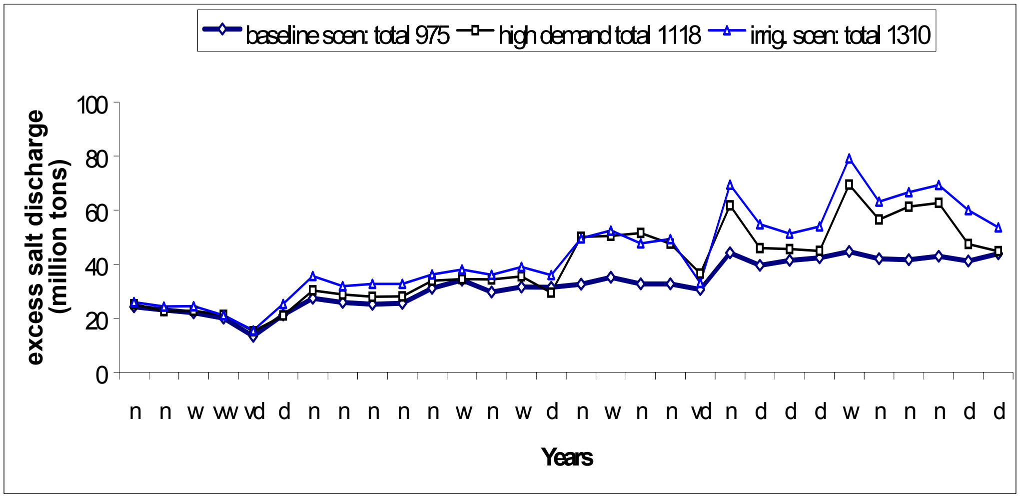


Figure 7. 53. Comparison of water and soil quality under the baseline, the irrigation, and the high demand scenarios – excess salt discharge

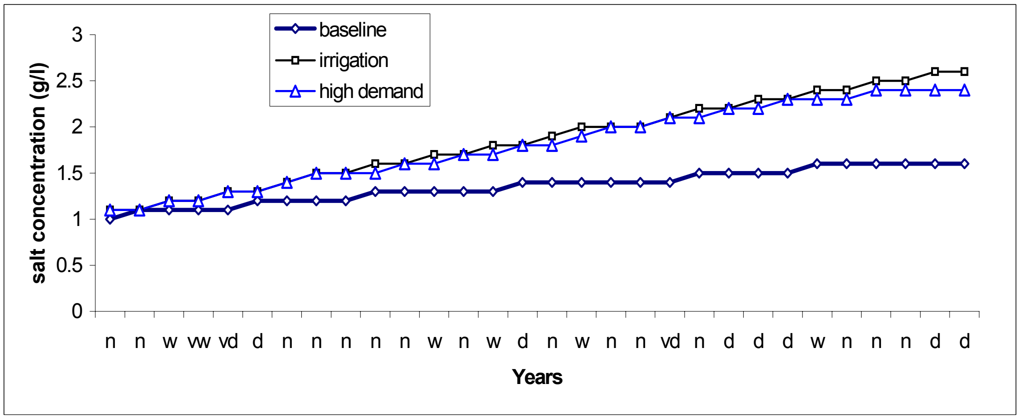


Figure 7. 54. Comparison of water and soil quality under the baseline, the irrigation, and the high demand scenarios – groundwater salinity at demand site *Low_syd.*

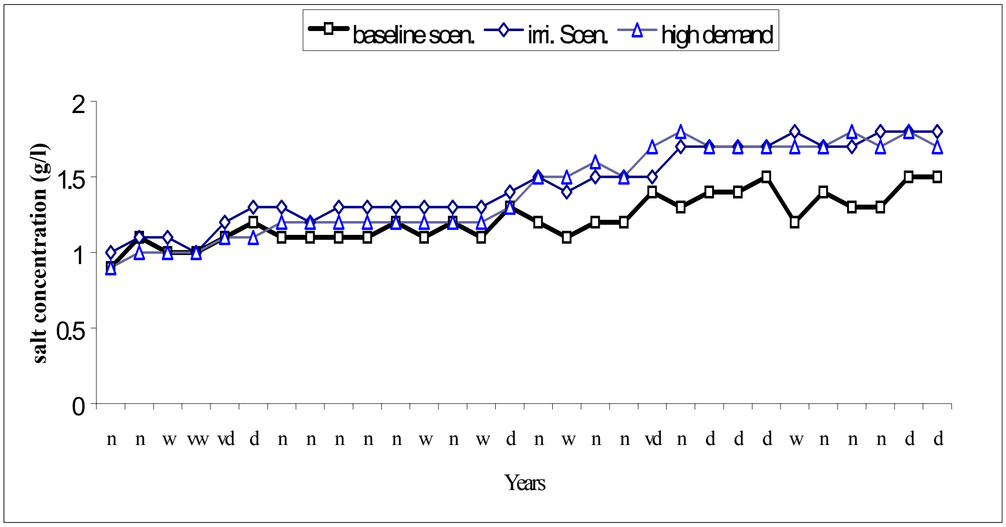


Figure 7. 55. Comparison of water and soil quality under the baseline, the irrigation, and the high demand scenarios – surface water salinity of the *Kayakum* Reservoir

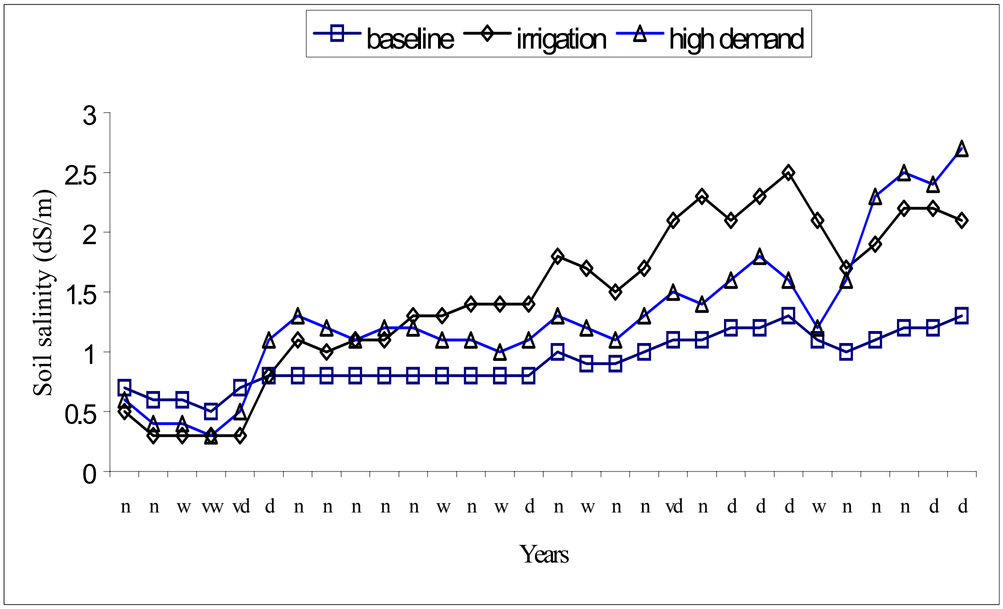


Figure 7. 56. Comparison of water and soil quality under the baseline, the irrigation, and the high demand scenarios – soil salinity in field cotton-forage at demand site *Low_syd.*

7.5.5 What if the target of release to the Aral Sea is fully satisfied?

Under this scenario, we assume that the target inflow to the Aral Sea is satisfied in all years. It is found that even under this constraint, the irrigated area is still not affected much. However, the agricultural profit is considerably reduced due to lower crop yields. Figure 7.57 shows the total agricultural profit under this scenario and the *baseline scenario*. The profit is more affected in wet years, because the flow target in wet years is high. The total value of irrigation profit in all years under the *flow scenario* is about 90% of that under the *baseline scenario*. The excessive salt discharge in 30 years under the *flow scenario* is 948 million tons, slightly less than the 975 million tons under the *baseline scenario*. Impacts on salinity in the surface and groundwater water and on the soil salinity under this scenario are close to those under the *baseline scenario*.

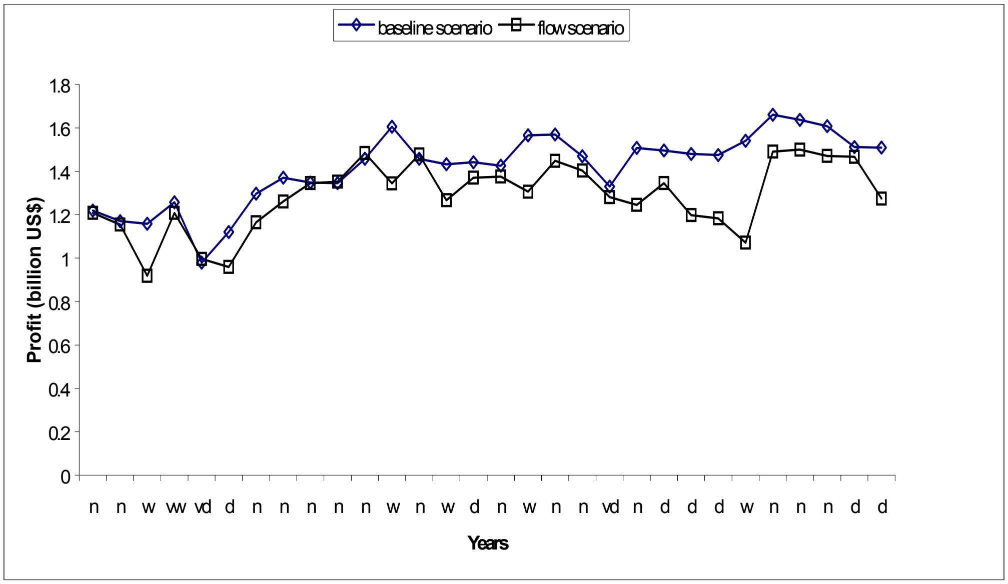


Figure 7. 57. Total agricultural profit under the baseline and the flow release scenario

7.5.6 What if the first priority is put on hydropower generation?

Hydropower generation is considered in the long-term modeling by including net hydropower profit in the total benefit of water uses in the basin. Because the magnitude of the hydropower profit is far less than the irrigation profit in the whole river basin, hydropower generation will have less priority than irrigation in the modeling, if no additional constraint is included in the model. However, as mentioned before, in the real world, the upstream country Kyrgyzstan, who depends on hydropower for most of its power supply, especially in winter period, attempts to hold more water coming in vegetation period in the Toktogul Reservoir for hydropower generation in winter period. This arises a major negotiation between Kyrgyzstan and downstream countries who need more water for irrigation in the vegetation period. One alternative is to have Kyrgyzstan not hold water in vegetation period, while the downstream countries help Kyrgyzstan to get some reimbursement in power generation, for example, trading coal to Kyrgyzstan at a cheap price. All other scenarios defined above assume this policy is feasible, and then hydropower generation resulting from the modeling under those scenarios is much lower than that in the current reality.

The *hydropower scenario* assumes Kyrgyzstan holds enough water in the Toktogul Reservoir so that hydropower generation in winter months will meet the demand as much as possible. This scenario is implemented by putting a penalty item in the objective function of the yearly model (**YM**). If hydropower generation in winter months is less than the demand, the objective (the total benefit of water uses) will be penalized. A large weight is assigned to the hydropower penalty item so that hydropower generation gets higher priority than other water uses including irrigation and environmental and water uses. In the following the result from the *hydropower scenario* is compared to that from the *baseline scenario,* which shows the effect from the upstream hydropower generation to the downstream irrigation is then studied.

Figure 7.58 shows the agricultural profit resulting from the *baseline scenario* and the *hydropower scenario*, respectively. The values of agricultural profit under the *hydropower scenario* are lower than those under the *baseline scenario* in all years. The hydropower generated in non-vegetation months (October – March) resulting from the two scenarios is presented in Figure 7.59. The values of hydropower are higher under the *hydropower scenario* than those under the *baseline scenario* in all the years. For both the irrigation profit and the hydropower, the differences between the two scenarios are relative small in wet years, and large in dry years, which reflects the effects of water scarcity to water uses in the river basin.

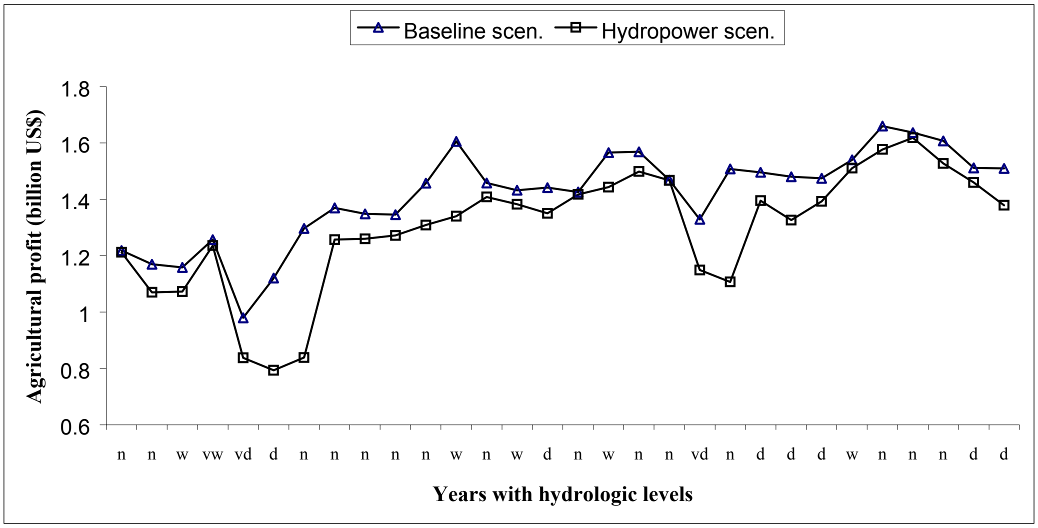


Figure 7. 58 Irrigation profit (*IP*) under the *hydropower scenario* and the *baseline scenario.*

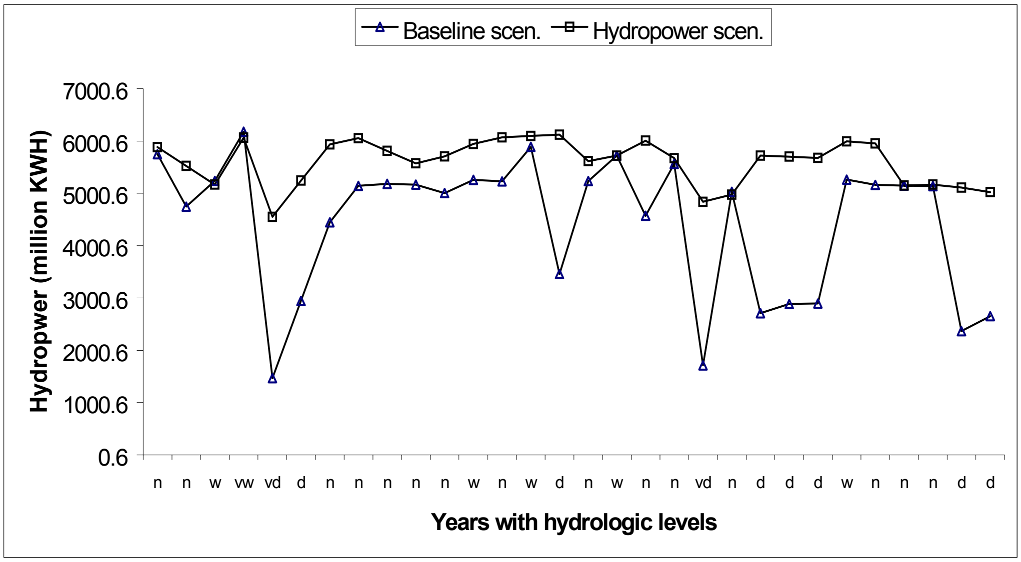


Figure 7. 59. Hydropower in non-vegetation months (Oct.-Mar.) under the *hydropower scenario* and the *baseline scenario*

Under the *hydropower scenario*, the performance of the major reservoirs is quite different from that under the *baseline scenario*. Figures 7.60-62 compare the reservoir utilization coefficients for the three reservoirs along the main river, including Toktogul, Kayrakum and Chardara Reservoir. As discussed in Section 7.4.1.1, these reservoirs, especially Toktogul and Kayrakum Reservoir, are not very active in the inter-year flow control. However, under the *hydropower scenario*, we see the significant increase of the reservoir utilization coefficients, especially in normal and wet years. Therefore, we may conclude that the upstream hydropower generation has a critical role in the decision of the operation rules of the major reservoirs.

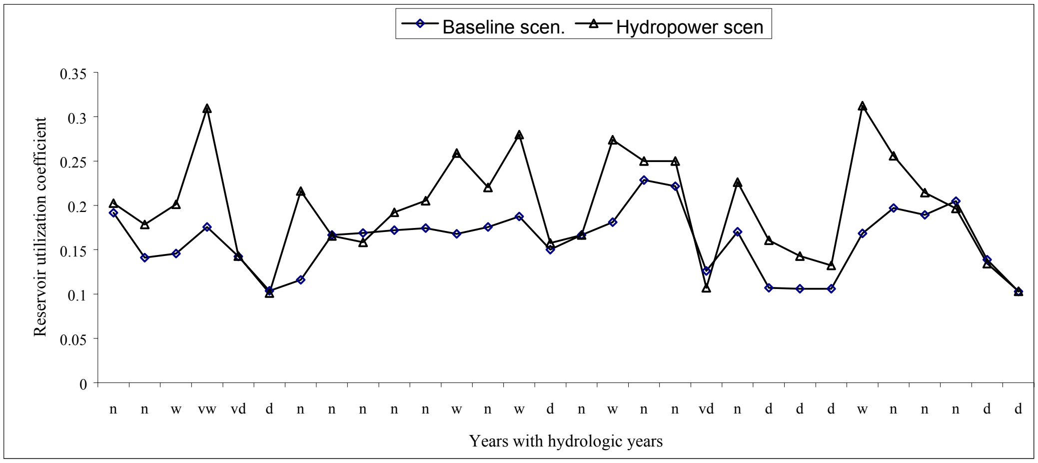


Figure 7. 60. The Toktogul Reservoir utilization coefficient under under the *hydropower scenario* and the *baseline scenario*.

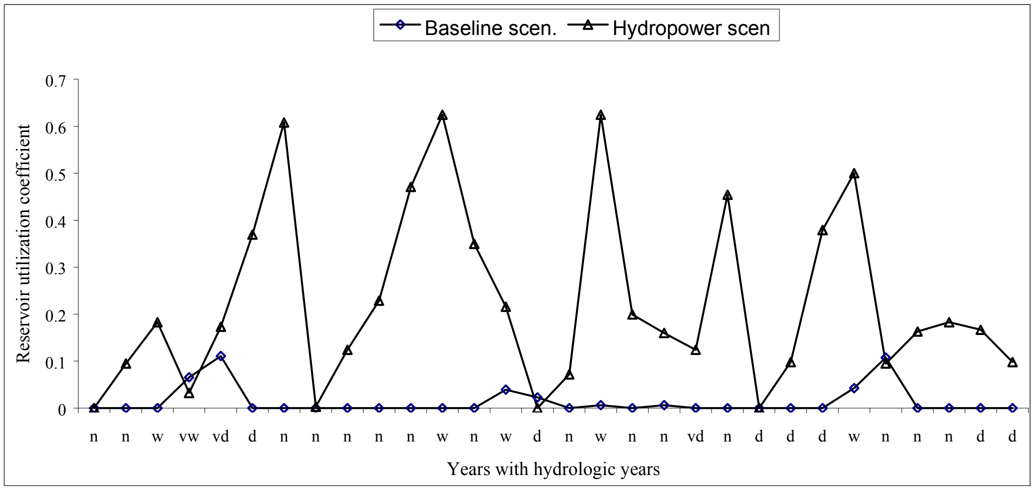


Figure 7. 61. The Kayrakum Reservoir utilization coefficient under the *hydropower scenario* and the *baseline scenario*.

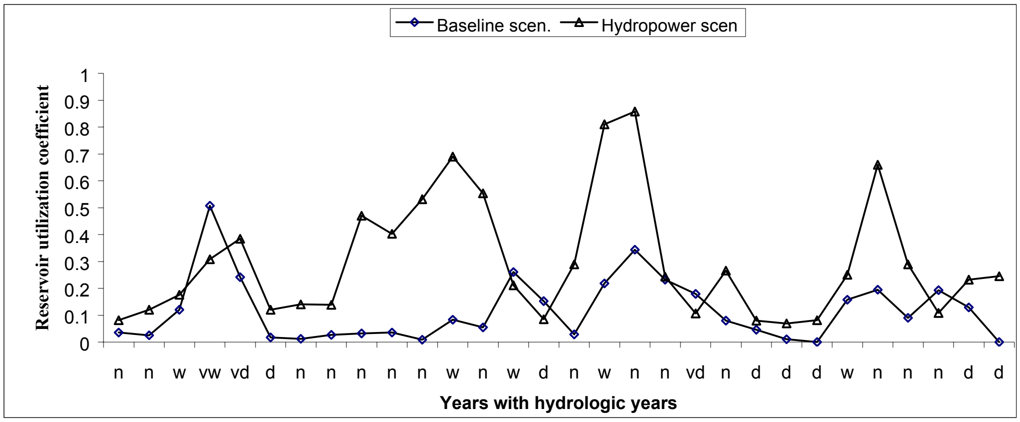


Figure 7. 62. The Chardara Reservoir utilization coefficient under the *hydropower scenario* and the *baseline scenario*.

7.6 SUSTAINABILITY ANALYSIS

Based on the results from the scenarios presented above, in this section the sustainability criteria defined in Section 6.2 are analyzed. The inter-relationships between the prescribed sustainability criteria are discussed, as well as different aspects of these criteria. Throughout the analysis in this section, the in-depth sustainability status of the water resources system in the study area is described.

7.6.1 Water supply reliability

Water supply reliability is defined in terms of reliability, reversibility, and vulnerability with respect to irrigated area and environmental water use. The irrigated area refers to the total irrigated area in the basin, and the environmental water use is defined as the annual release to the Aral Sea from the Syrdarya River. Figure 7.63 shows two ratios under the *baseline scenario*. One is the ratio of the computed irrigated area to the planned irrigated area, and the other is the ratio of computed flow to the Aral Sea to the prescribed flow target, over all study years. The irrigated area is sustained over the years while the flow to the Aral Sea fluctuates with the hydrologic levels in the study years. However it should be noted that crop yields fluctuate with hydrologic levels, too.

Referring to Section 6.4.1, the irrigated area can be sustained under an assumption that the water-yield coefficient (eq. 3-4) is larger than an empirical value (0.5, suggested by FAO, 1979). The water-yield coefficient is a function of soil water moisture and soil salinity. Therefore, under the baseline scenario, the water and salinity condition will not cause much reduction in irrigated area. However, as discussed before, at the downstream demand site, *Low_syd*, the irrigated area is considerably reduced in some dry years.

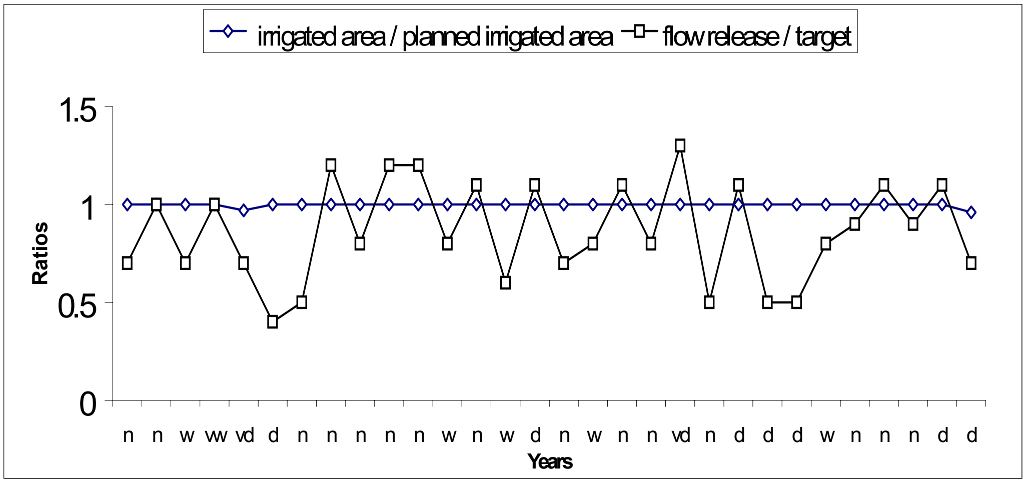


Figure 7. 63. Ratios of computed irrigated area to the planned irrigated area, and ratios of computed flow to the Aral Sea to the flow target, under the baseline scenario.

Figure 7.64 presents the numbers of consecutive failure years in each year for both irrigated area and flow release to the Aral Sea. A failure year with regard to irrigated area is defined as a year with the ratio of computed irrigated area to the planned area less than 0.85. The same critical value is specified regarding to the flow to the Aral Sea. The distribution of these numbers over the years reflects the resilience (reversibility) of the water supply system. No failure year occurs to irrigated area, but the ratio of flow to the Aral Sea to the flow target is less than 0.85 in three consecutive years (year 23, 24, and 25).

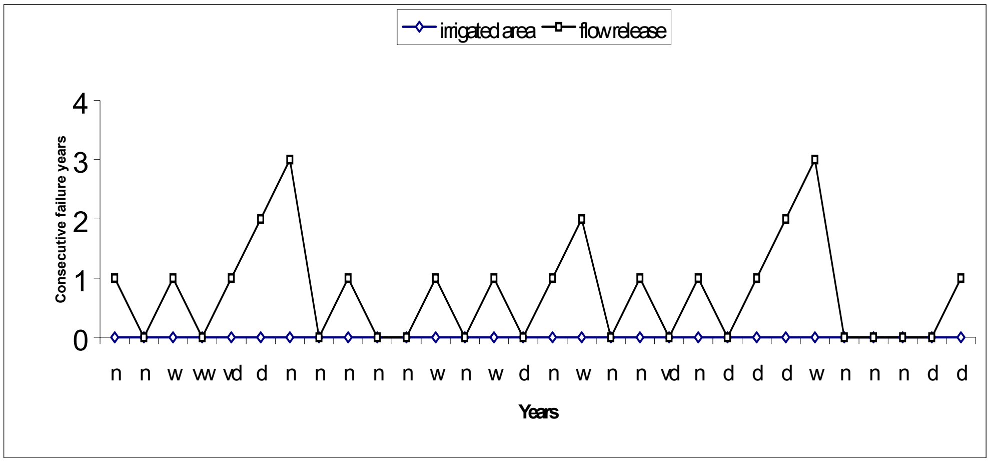


Figure 7. 64. Numbers of consecutive failure years for both irrigated area and flow release to the Aral Sea.

The vulnerability of water supply is represented by the maximum risk, i.e., the minimum *RIA* (ratio of actual irrigated area to the target of the irrigated area) and *REW* (actual ecological release to the target). Under the *baseline scenario*, the maximum risk for irrigated area is 2%, while for the flow to the Aral Sea, it is 72%.

Table 7.17 shows the items related to the criterion of water supply reliability under the various scenarios defined above. The mathematical definitions of these items are given in table 6.1. Under the *zero scenario*, 97% of irrigated area will be sustained over the study period, no failure year for irrigated area occurs, and the maximum risk is 11%. Recalling the discussion in Section 7.5.1, the crop yield may decrease dramatically even if irrigated area is not reduced much. For the flow into the Aral Sea, the *zero scenario* presents an unacceptable solution: only 44% of the flow target can be satisfied, 17 consecutive failure years may occur, and in some years, there is almost no inflow to the sea (i.e. the risk is up to 99%). The conditions are similarly negative for the *high demand scenario*. The *zero scenario* shows that poor technologies in water distribution, irrigation, and drainage impose negative impacts on water supply reliability, while the *high demand scenario* shows that excessive increase in water demand can also reduce the water supply reliability. Comparing the values under the *irrigation scenario* and the *I&M scenario*, we find that the excessive increase in irrigation water demand has a stronger effect on water supply reliability, as well as on other aspects of sustainability in the water resource system of the study area, as discussed later.

Table 7. 17. Indices of water supply reliability under various scenarios

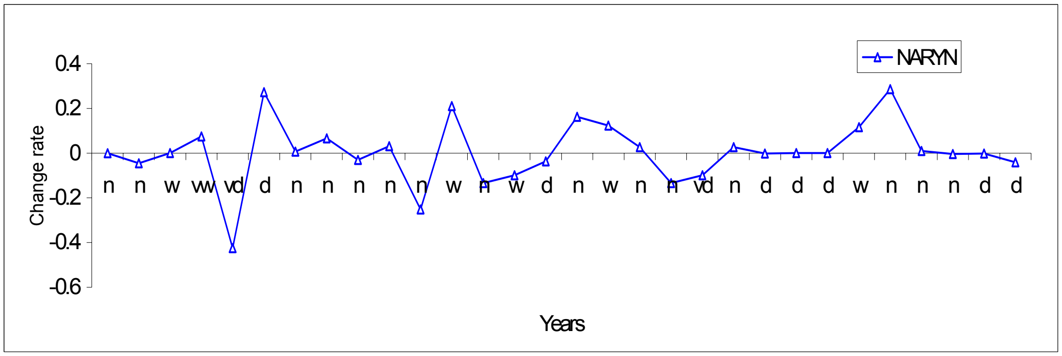
Scenarios	REL_{ia}	Rel_{fl}	Rev_{ia}	Rev_{fl}	Vul_{ia}	Vul_{fl}
Baseline	1.00	0.85	0	3	0.02	0.56
Zero scenario	0.97	0.44	0	17	0.11	0.99
Irrigation scenario(highest)	0.96	0.59	0	8	0.09	0.97
I&M scenario	1.00	0.74	0	5	0.02	0.68
High demand Scenario	0.96	0.49	0	10	0.11	0.97
Flow scenario	0.94	1.00	1	0	0.15	0.00

In the *flow scenario*, we assume that the prescribed flow target to the Aral Sea is satisfied in all years. Even under this condition, the irrigated area is not much affected since 94% of irrigated area will be sustained. The maximum irrigated area reduction is 15% of the projected area in 30 years.

In summary, in various cases, irrigated area in the study area can be sustained, but the crop yield may decline dramatically under some cases. The flow into the Aral Sea is sensitive to technological and water demand conditions. Excessive increase in water demands, especially irrigation water demand, and poor conditions in the water distribution and application system, will most probably reduce the reliability of water supply in the study area.

7.6.2 Equity

As described in Section 6.2.3, equity is considered in both spatial and temporal terms with respect to water use benefits over all years in the time horizon and over the spatial domain. Figures 7.65 (1)-(5) show the changing rate of water use benefits from year to year (eq. 6-5) at each demand site. Figure 7.66 presents the changing rate of the total water use benefit in the basin over all years. The spatial equity is expressed as the standard deviation of the average changing rate over all demand sites (eq. 6-9), and the temporal equity is expressed as the standard deviation of the changing rate of the total water use benefit in the basin over all years (eq. 6-6). Therefore a larger value for these items shows a more intensive fluctuation. Some statistics relating to changes in the water use benefits under various scenarios are displayed in Table 7.18.



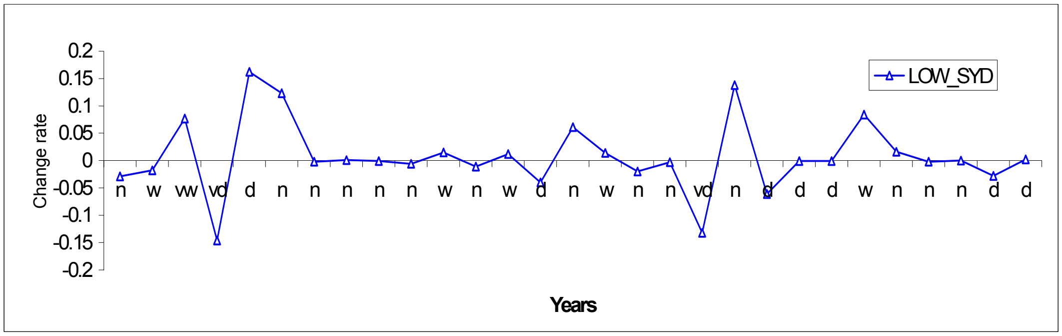
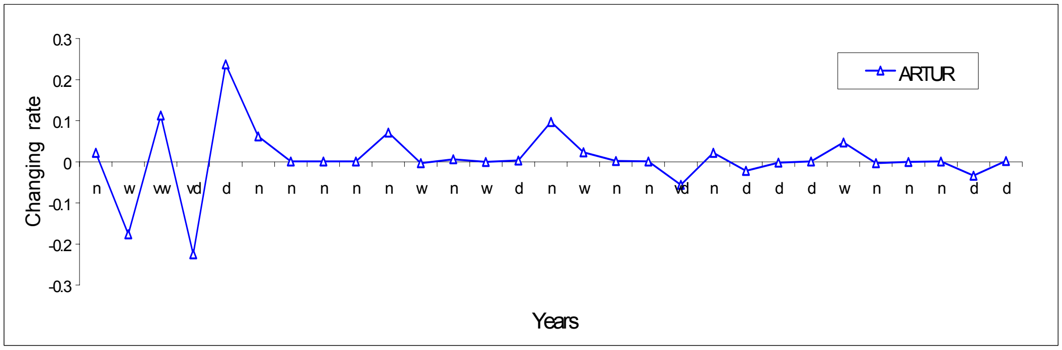


Figure 7. 65 (1)-(2) Changing rates of water use benefit at each demand site.



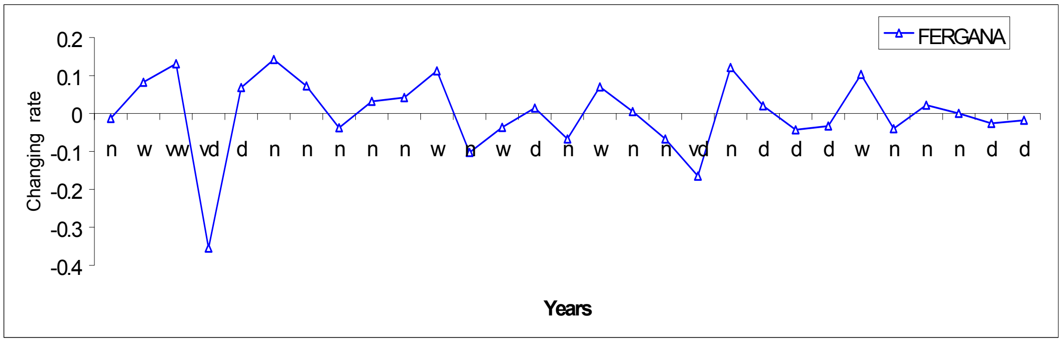


Figure 7. 65 (3)-(4) Changing rate of water use benefit at each demand site.

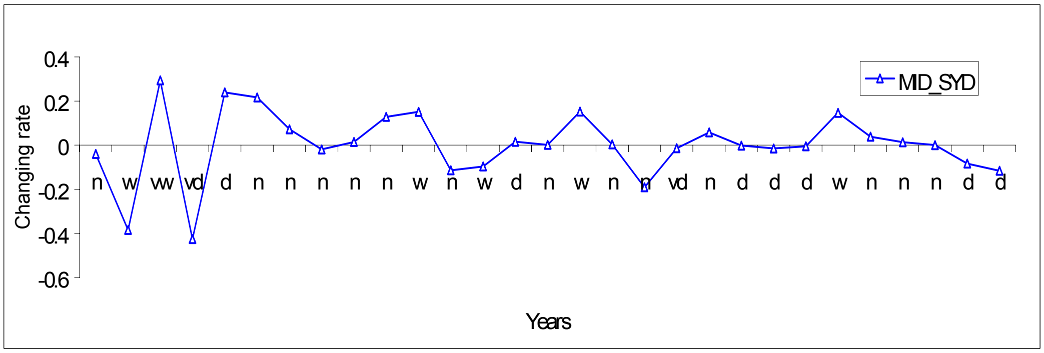


Figure 7. 65 (5) Changing rate of water use benefit at each demand site.

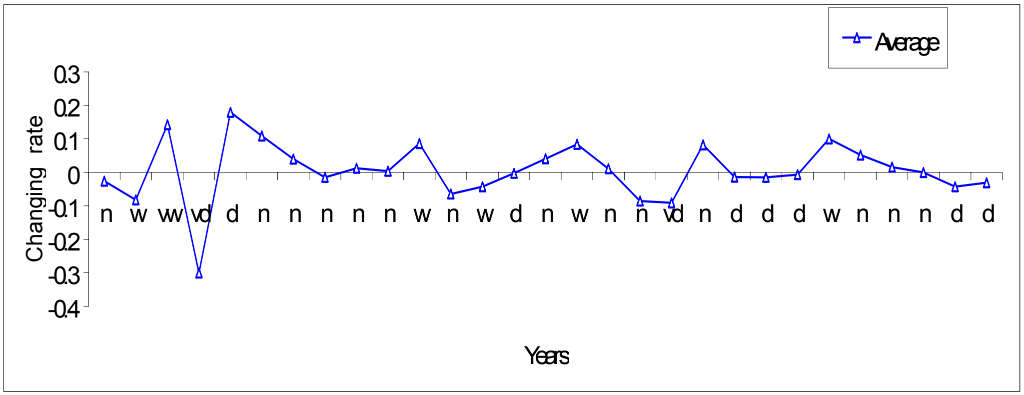


Figure 7. 66. Changing rate of water use benefit, average value over all demand sites.

Table 7. 18. Indices of equity: statistics of increasing rate of water use benefit under various scenarios

Scenarios	Annual increasing rate in the whole basin				Long-term average increasing rate			
	Min.	Max.	Mean	Variation	Min.	Max.	Mean	Variation
Baseline	-0.266	0.181	0.006	0.11	-0.015	0.008	0.001	0.01
Zero scenario	-0.758	0.24	-0.039	0.195	-0.062	-0.02	-0.04	0.01
Irri. scenario	-0.387	0.421	-0.03	0.24	-0.024	0.0124	0	0.02
I&M scenario	-0.465	0.234	-0.01	0.13	-0.027	0.001	-0.001	0.01
High dmd. scenario	-0.296	0.405	0.016	0.18	-0.054	0.005	-0.02	0.03
Flow scenario	-0.246	0.301	0.007	0.12	-0.085	0.006	-0.026	0.03

Actually the advanced water storage and delivery infrastructure in the basin provides substantial facilities for mitigating the effect of uneven distribution of water sources in the basin. Based on these facilities, appropriate policies can be implemented to make water evenly available to different demand sites in the basin. When comparing the values of the spatial equity index under various scenarios, it can be seen that excessive water demand for irrigation, industrial and municipal, or environmental water uses may cause uneven development among the demand sites. These conditions have less effect on upstream demand sites, and more on downstream demand sites, since 70% of the water sources in the river basin stem from the upstream areas of the basin.

The temporal equity issue seems to be more significant than the spatial equity issue in the river basin. For example, under the baseline scenario, the changing rate of the total water use benefit in the basin over all years ranges from –0.40 to 0.12, the average value is 0.0, and the standard deviation is 0.11. The temporal equity is affected by changes in water demand over the years, as well as hydrologic fluctuations. The standard deviation is larger under the scenarios with higher water demands including the *high demand scenario* and the *zero scenario*, as can be seen in Table 7.18. The *zero scenario* has relatively low water distribution and water use efficiency, which indirectly increases water demand.

7.6.3 Environmental integrity

The criterion of environmental integrity is implemented in the long-term modeling by minimizing the highest salt concentration in surface water (reservoir) and groundwater, as well as soil salinity in the crop field over all years. Since soil salinity is embedded in the crop yield function (eq. 3-21), the control of soil salinity is also indirectly involved in maximizing crop production. The environmental impacts have been discussed in Section 7.5. An excessive increase in irrigation water withdrawals will impose significant negative impacts on water and soil quality in the study area. Table 7.19 presents the maximum salt concentration in surface water and groundwater. Table 7.20 presents the crop area weighted average soil salinity at each demand site in the first year and in the last year. The conclusions based on these two tables are similar to the ones already stated in Section 7.5: (1) excessive increase in irrigation water will significantly increase water and soil salinity in midstream and downstream areas of the basin; and (2) the downstream demand site will be most seriously affected in surface water, groundwater, and soil salinity.

Table 7. 19. Indices of environmental integrity: maximum salt concentration in surface and ground water.

Scenarios	Groundwater salinity			Surface water salinity		
	Low_syd	*Mid_syd*	*Fergana*	*Chardara*	*Kayrakum*	*Toktogul*
Baseline	2.08	1.72	1.59	1.06	1.47	0.4
Zero scen.	2.04	1.54	1.56	0.97	1.16	0.4
Irri. scen.	2.69	2.30	1.88	1.15	1.83	0.4
I&M scen	1.93	1.84	1.60	1.03	1.46	0.4
High dm. Scen.	2.39	2.23	2.00	0.96	1.71	0.4
Flow scen.	2.02	1.68	1.58	1.13	1.46	0.4

Table 7. 20. Indices of environment integrity: crop area weighted average soil salinity at each demand site in the first year and in the last year.

Scenarios	Years	*NARYN*	*LOW_SYD*	*ARTUR*	*CHAKIR*	*MID_SYD*	*FERGANA*
Zero scen	Year 1	0.209	0.567	0.267	0.400	0.300	0.400
	Year 30	0.209	0.457	0.265	0.407	0.312	0.404
Baseline	Year 1	0.258	0.700	0.317	0.400	0.347	0.451
	Year 30	0.304	0.852	0.697	0.604	0.553	0.737
Irrigation scenario	Year 1	0.261	0.630	0.300	0.400	0.385	0.415
	Year 30	0.455	2.990	0.757	0.661	1.362	1.323
I&M scenario	Year 1	0.300	0.700	0.300	0.400	0.338	0.446
	Year 30	0.331	1.092	0.638	0.551	0.552	0.859
High dmd. scenario	Year 1	0.282	0.600	0.256	0.400	0.356	0.400
	Year 30	0.392	3.132	1.099	0.643	1.119	1.416
Flow scenario	Year 1	0.258	0.700	0.317	0.400	0.347	0.451
	Year 30	0.352	0.889	0.714	0.624	0.553	0.737

7.6.4 Socio–economic acceptability

Under the criterion of socio-economic acceptability, we evaluate investments for water development facilities, with respect to the corresponding water use benefits. The benefits include profit from irrigation, profit from hydropower generation, and benefit from environmental water use. Investments include those for improving water distribution, irrigation and drainage, drainage reuse, and disposal/treatment facilities. Table 7.21 presents the sum of the benefits and investments over all study years under various scenarios. Under the *zero scenario*, no investment takes place, but compared to other scenarios, a big decline in profits occurs. This shows that some improvements of water development facilities will be necessary for sustaining the economy that heavily depends on irrigated agriculture in the area. However, as shown before, compared to other scenarios, water and soil salinity problems are less serious under this scenario. This environment benefit is not directly included in the total benefit shown in Table 7.21.

Table 7. 21. Indices of socio-economic acceptability: benefits and investments

Scenarios	Total Water use Benefit (TWB) in 30 years (billion US$)	Total Investment (INV) in 30 years (billion US$)
Baseline	46.85	0.21
Zero scen.	26.27	0
Irri. scen.	43.75	0.36
I&M scen.	45.77	0.25
High dmd. scen	41.09	0.37
Flow scen.	44.08	0.2

Comparing the *baseline scenario* and the *high irrigation scenario*, we see that the *baseline scenario* has larger benefit with smaller investment. Thus, the socio-economic acceptability of the *baseline scenario* is better than the *irrigation scenario* with high irrigation water demand. Under this scenario, excessive irrigation water use not only reduces instream water uses, but also creates water and soil salinity problems that eventually lead to substantial decline in crop yields.

If we compare the *I&M scenario* to the *baseline scenario*, we see that the former has less total benefit but larger investment. However, it should be noted that the benefit from M&I water uses is not counted in the benefit presented here. Therefore, the *I&M scenario* with high demand of industrial and municipal water may not necessarily be inferior to the *baseline scenario* with respect to socio-economic acceptability.

Obviously, there is a tradeoff between irrigation water diversion and water release to the Aral Sea. The scenario with full satisfaction of the Aral Sea inflow target has almost the same water development investment as the baseline scenario, but the former has less benefit. As defined before, the *inflow scenario* is equal to the *baseline scenario* in all aspects except that the full inflow target to the Aral Sea is pre-decided for the scenario. The comparison here implies that under the prescribed economic measurement of the irrigated agriculture profit and the measurement of the benefit from environmental and ecological water use, full satisfaction of the Aral Sea inflow target may not be economically efficient under the specific conditions. However, these economic measurements are counted with uncertainties. Further research will be necessary to come to more robust conclusions.

7.6.5 Tradeoff between multiple criteria

Above, the individual performance of the four criteria has been discussed. The inter-relationships between these criteria are addressed in the following. Tradeoff relations exist between these criteria, particularly between water supply reliability and environmental integrity, between equity and economic efficiency (socio-economic acceptability). In this sense, The GA-LP approach can provide a number of alternatives consisting of different combinations of these criteria.

As mentioned before, the GA-LP searches better solutions by examining candidate solutions through "generations", a group of solutions that are assumed to evolve gradually, and to reach a fixed level finally. In later generations, most of the candidate solutions are similar regarding to their fitness. However, these candidates may still represent different solutions to the problem, and each of these candidates may be recognized as an alternative, as presented in Table 7.22.

The first three alternatives are all based on the baseline scenario. They yield a very close total objective value, and they have the same or very close values for indices of reversibility and environmental integrity. Alternative 3 is different from the other two in the economic index and the equity indices (temporal and spatial equity), as well as the reliability index. Note that all indices are minimization-induced, i.e., the smaller, the better. Compared to the other two, Alternative 3 has a better economic efficiency, but equity is worse both in time and in space. Moreover the risk in water supply is higher. Alternative 1 is preferred to alternative 2 in economic efficiency, but it is worse with regard to spatial equity.

Alternatives 4 and 5 are based on the high water demand scenario; their objective values are very close. Alternative 4 is preferred to alternative 5 in environmental integrity, but has a worse performance in water supply reliability and economic efficiency.

A systematic tradeoff analysis can be carried out by running a number of scenarios in which the different criteria are given different weights, and then summarizing the performance of these criteria under various runs.

Table 7. 22. Comparison of alternatives for tradeoff analysis

Alternatives	Risk[1]	Rev[2]	Vul[3]	Teq[4]	Seq[5]	Econ[6]	Envi[7]	Objective[8]
Alternative 1	0.072	0.05	0.285	0.106	0.005	0.3387	0.124	0.615
Alternative 2	0.072	0.05	0.284	0.109	0.003	0.3414	0.124	0.617
Alternative 3	0.076	0.05	0.286	0.118	0.009	0.3274	0.124	0.615
Alternative 4	0.07	0.05	0.306	0.119	0.005	0.3520	0.134	0.682
Alternative 5	0.06	0.05	0.281	0.116	0.004	0.3610	0.143	0.685

[1] Risk of water supply,
[2] Reversibility of water supply,
[3] Vulnerability of water supply,
[4] Temporal equity,
[5] Spatial equity,
[6] Socio-economic acceptability,
[7] Environmental preservation,
[8] Total objective.

7.7 SUMMARY

This chapter presents the prototype long-term dynamic modeling as a useful tool for sustainability analysis in water resources management in an irrigation-dominated river basin. Water resources planning and management over a period of 30 years in the Syrdarya River basin is studied as an example of the application of the long-term dynamic modeling framework. Data requirement and availability for both water demand and water supply aspects have been described. The effectiveness and limitations of the GA-LP modeling approach developed in Chapter 5 are discussed based on a detailed modeling result analysis. It can be concluded that this approach is effective in identifying good solutions for a large-scale, long-term model like the one developed in this research.

In order to analyze the relationships between water uses and long-term economic and environmental consequences, a baseline scenario and a number of other scenarios have been defined and run. Under each scenario, the long-term consequences associated with specific water uses are simulated, displayed, and compared with those under the baseline scenario. Analysis is addressed with respect to each aspect of the pre-defined sustainability criteria and the inter-relationships between the criteria.

Due to incomplete data, the findings for the study area from the modeling result analyses may need further verification. The major findings include:

(1) The current irrigated area may be sustained in the study years, and at the same time, 90% of the target of flow release to the Aral Sea can be satisfied, with modest water and soil salinity increase, under appropriate crop pattern changes and water distribution and application facility improvements. However, in *very dry* years (frequency of 6.7%) and consecutive dry years, crop yields and flow release flow to the Aral Sea will both considerably decline. Full satisfaction of the

flow release target will reduce irrigation profit by 10%. High demand of industrial and municipal water will reduce both crop yield and the flow release, but the irrigated area can still be sustained;

(2) Improvements of current water supply and use facilities are necessary to sustain the agricultural production system in the basin. If the infrastructure remains the current level, the irrigation profit (*IP*) will continually decrease, by 26% in the first year, and 67% in the last year.

(3) Excessive increase in irrigated area will significantly degrade the water and soil environment, and finally, even the crop production system;

(4) The upstream demand site (*Naryn*) seems to be free of water and soil salinity problems, and the two demand sites (*Chakir* and *Artur*) which mainly depend on tributaries for their water supply are less affected in water and soil salinity. *Fergana*, which is the largest irrigation water demand site, may suffer substantial groundwater salinisation. The midstream demand site, *Mid_syd*, is found to have potential waterlogging problems, and the downstream demand site, *Low_syd*, suffers from the most severe water and soil salinity problems.

(5) Cotton fields will likely decline, without dominating irrigated area at all demand sites. Cotton-forage fields and wheat-maize fields will rotate over some years.

(6) Satisfying the power demand in winter months at the upstream demand sites will reduce the irrigation profit (*IP*). In some dry years IP decreases by 28% compared to the *baseline scenario*.

In this case study, we assume that the period up to 2020 follows one series of hydrologic fluctuations. Although this series may reflect some hydrologic changes in the study years, it is very limited to capture hydrologic uncertainties, which is required for sustainability analysis in water resources management. More supporting data and innovative methodology are needed to incorporate comprehensive hydrologic uncertainties into the modeling framework developed in this research.

Chapter 8

Summary and Conclusion

This research develops a modeling framework for quantitative analysis of sustainable water resources management at the river basin scale. Sustainable development has been recognized as a sound philosophy for today's world. In light of this philosophy, broad guidelines and principles have been identified for sustainable water resources management that are critical to regional development, particularly in arid and semi-arid areas of the world. In order to apply these guidelines and principles to the designing, operating and maintaining of water resources systems in specific regions, we need to translate them into operational concepts, and translate the qualitative descriptions into quantitative analysis. In this work, we specify the problem as one of long-term water resources management in river basins with arid and semi-arid climate, where irrigation is the major water user, and the main pollution to the environment is salinity resulting from poor irrigation practices. Sustainable water management is defined to ensure a stable and flexible water supply capacity for crop water demands, and at the same time to keep a stable relationship between irrigation practices and the associated environment. An innovative systems approach has been developed to model and analyze sustainability issues related to water resources management.

The modeling framework of this research is distinguished from those in previous literature first in its integrated hydrologic-agronomic-economic-institutional approach to modeling at the river basin scale. Modeling sustainability presupposes essential relations between water uses and the associated long-term consequences at an appropriate spatial scope. In this research, a river basin is defined as a natural spatial unit for sustainability analysis in water resources management, and essential hydrologic, agronomic, economic and institutional relationships are integrated into a coherent analytical framework at the river basin scale to reflect the interdisciplinary nature of water resources problems.

The hydrologic component includes flow and salinity balance and distribution from crop field to river network. Both in-stream and off-stream water uses are considered. Emphasis is put on irrigation, in which on-farm water application and salinity transport are simulated. Deep percolation to groundwater, return flow to river system, and their salinity are calculated in both short- and long-term time frames, in order to evaluate the environmental impacts associated with short- and long-term irrigation practices, such as waterlogging, soil salinisation, and surface and groundwater water quality reduction.

A crop production function that includes water and salinity variables is the critical connection between the multiple components in the integrated model. Based on an empirical yield-water relationship (FAO, 1977) and an empirical yield-salinity relationship (Mass and Hoffman, 1979), a nonlinear crop production function is derived and applied in the model. In this crop production function, crop yield is a function of both soil moisture and soil salinity, which are resulted from soil water and salinity balance directly, and are further related to water and salinity balance in the entire river basin network. That is to say, through the crop production function, crop yield is related to the performance of the entire hydrologic system. Furthermore, crop production, which is equal to crop yield multiplied by crop area, determines the irrigation profit involved in the economic relationships of the model. Therefore, the newly developed crop production function connects the hydrologic, agronomic and economic components together into an endogenous system.

Economic relationships determine water use benefits from irrigation, hydropower generation, and environment water use, subsidy for infrastructure investments, and penalty tax on excessive salt discharge. Profit from irrigation is calculated as crop revenue minus cropping cost and water supply cost; profit from hydropower generation is equal to revenue from power sale minus hydropower generation cost; and benefit from environment water use is formulated based on an empirical assessment of the value of water flow release for environmental purposes. The total investment for infrastructure improvements in the basin is assumed to equal to the government input plus the tax revenue on excessive salt discharge. The subsidy allocation among different demand sites, different crop fields, and different facilities (water delivery system, irrigation and drainage system, drainage reuse and disposal system etc.), is determined from the model by maximizing total water use benefit in the whole basin, as well as by the prescribed sustainability criteria in the long-term modeling. Penalty tax, as an economic incentive, is imposed on excessive salt discharge with the return flow from crop fields to rivers. Values of this item are determined for years with different hydrologic conditions in the long-term modeling.

Institutional directives are considered in the model too. It is assumed that there is such a central authority in the river basin who can make decisions, standing on the overall socio-economic benefits and environmental impacts in the region of the river basin. With this assumption, instead of fix-quantity proposals for water use rights, empirical water demand functions based on the crop production function for individual demand sites are specified, so that optimal inter-demand site and inter-crop water allocations can be identified from the modeling. In particular, externalities that are resulted from excessive water diversion and salt discharge by upstream demand sites, and produce negative effects to downstream demand sites, are controlled in the model through the river basin network by the prescribed equity criteria.

Essential hydrologic, agronomic, economic and institutional relationships are integrated in an endogenous modeling framework implemented at the river basin scale. Outputs from the modeling framework are examined in terms of economic efficiency, equity, environmental impact, and risk from hydrologic uncertainties, which shows the modeling framework can provide policy instruments designed to make more rational economic use of water resources.

Another aspect of this modeling framework different from others is incorporating prescribed sustainability criteria into the long-term modeling so as to control short-term decisions. In the context of this research, sustainability criteria are proposed in terms of water supply reliability, environmental system integrity, equity in water allocation, and socio-economic acceptability. Water supply reliability considers the frequency of system failures (risk), the system resilience (reversibility), and the magnitude or the severity of a system failure (vulnerability). Environmental system integrity ensures no irreversible, cumulative impacts on water and soil salinity, as well as the ecological system. Equity assumes even distribution of water accessibility for irrigation development among different demand sites (spatial equity) and from current to future (temporal equity). Socio-economic acceptability considers the economic efficiency of infrastructure investments. Criteria in these aspects are expressed in mathematical forms based on the items resulting from the modeling. These expressions are specifically defined for the case study area of this research, and they are subject to changes if applied to other study areas. The indices of the multiple criteria then are normalized into the objective function of the long-term modeling, with a weight or a scaling factor for each index (eq. 6-19).

The third innovative development of this modeling framework is a combined inter-year optimal decision model (the yearly model, **YM**) and an inter-year control program (**IYCP**). The integrated hydrologic-agronomic-economic-institutional model at the river basin scale, which is applied to a one-year time horizon with 12 periods, is defined as a short-term model. The objective function of the short-term model is to maximize the total water use benefit within one year. The major state variables include reservoir storage, groundwater table, soil moisture, and soil salinity. The major decision variables include water withdrawals, reservoir releases, groundwater pumping, drainage disposal and reuse, water allocation and source blending for crops, efficiencies in water delivery, irrigation, and drainage, irrigated area for different crop fields, and tax rate on excessive salt discharge.

For the long-term modeling framework, the time horizon is extended to 30 years. The long-term modeling framework is composed of a series of yearly models (**YM**) and an inter-year control program (**IYCP**). The yearly model includes the same relationships as the short-term model. However, for computing efficiency, it is formulated as a linear model by approximation and decomposition, and it is solved by an integrated simulation and optimization procedure. All yearly models have the same structure, but different initial conditions and inputs. Transmissions between the yearly models are maintained by setting the ending condition from the **YM** in year y as the initial condition of the **YM** in year $y+1$. The **IYCP** has two functions. One is to provide "proposals" to the yearly models by generating the inter-year control variables, including water sustained at the end of individual years, efficiencies in water delivery, drainage, and irrigation, crop acreage, and tax for excessive salt discharge. The other is to evaluate the outputs from all yearly models, according to the prescribed sustainability criteria, and calculate the fitness of each proposal based on the long-term objective function discussed above.

In the long-term modeling, the long-term consequences resulting from short-term "wait-and-see" actions (decisions in the yearly models), with predicted changes and uncertainties on both water demand and supply in the future, is traced and controlled. Therefore, in the combined short-term and long-term modeling framework, short-term decisions are directed by both short-term desires and long-term adjustments. The long-term decision making attempts to reach a long-term optimality: satisfying the immediate demands and desires without compromising those of future years.

The Syr Darya River basin in Central Asia is the case study area of this research, where a great need exists for water policy analysis tools of the type developed in this research. The basin network includes 11 river reaches, 11 reservoirs, 6 aquifers, 5 hydropower stations, and 6 water demand sites located from upstream to downstream of the basin. Within each demand site, three soil plots, sandy clay (*scl*), loam (*l*), and sandy loam (*sl*) are identified (only for the short-term model, and a lumped soil type is used for the long-term model). For each soil plot, five crops are considered, including cotton, forage, wheat, maize, and alfalfa (perennial forage), and these crops are grouped into four types of crop combinations according to the historic crop patterns in the area. The study area chosen in this research has one of the most complicated human water development systems in the world, with one of the most well-known unsustainable water management cases too.

In the Syr Darya River basin, the expansion of irrigation in the last 30 years has produced serious environmental and ecological consequences, including the increase of salinity in surface and groundwater water, waterlogging, soil salinity accumulation, as well as the depletion of inflow to the Aral Sea. The question answered through the case study is: can such a high level of irrigated agriculture be sustained while preventing or minimizing adverse environmental and ecological impacts? For this research, what we are more interested in is whether we can use the modeling framework developed in this research to provide useful information for decision making in solving the problems of the case study area.

Both a short- and long-term model are applied to the case study. Data heavily depend on several previous research projects for the river basin. A complete model calibration and verification are beyond the effort of this research. For the short-term model, comparisons show the results from the model are close to those in the published papers or reports (e.g., EC, 1995; Raskin et al., 1992). The short-term model was also judged by some local professionals.

Detailed short-term and long-term analyses based on the modeling outputs are demonstrated for the study area. The short-term analytical issues include operation of water storage facilities (reservoirs and aquifers), irrigation and drainage management, agronomic analysis, economic analysis, and uncertainty analysis. It is shown that hydrologic system operations are derived by both agricultural production and in-stream water use (for hydropower generation and ecological use). Irrigation and drainage management, including the determination of the appropriate infrastructures, has important contributions to the outcomes of water uses. Economic analysis explores the economic values of water uses under various scenarios of hydrologic conditions and infrastructure status. Economic incentives, including water supply prices, crop prices and taxes on excess salt discharge, are shown to have profound influences on the decisions in hydrologic and agronomic components. Output from the short-term model shows some in-depth interactions among multiple components in the integrated model. However, the short-term decisions result in some unsustainable statuses of the river basin system, including large increase of soil and water salinity.

The long-term model is used for an in-depth analysis of sustainability in water resources management of the case study area. The effects of the inter-year controls on reservoir operation, salt discharge control, crop pattern change and infrastructure improvement are demonstrated, which shows the short-term decisions are adjusted by the inter-year controls, as well as optimized within individuals years. The long-term consequences of water and soil salinity, water flow depletion from ecological uses, as well as irrigated area reduction and crop yield reduction, are simulated. In order to search a robust relation between water uses and the associated environment in a long-term time frame, *a baseline scenario* based on the "best" estimated data, and a number of other scenarios have been defined and run for various water demand and supply cases. Finally, analysis is addressed with respect to each pre-defined sustainability criteria, as well as the tradeoffs between the criteria.

The output from the long-term modeling is compared to that from the short-term modeling in terms of some intra-year decisions and results, such as reservoir operation, infrastructure improvement, crop acreage, irrigation profit, and water and soil salinity. For reservoir operation, the short-term modeling shows the reservoirs on the main river take the main role in intra-year flow regulation; the long-term modeling finds the reservoirs on the main tributaries (Andijan Reservoir and Charkir reservoir) are active in inter-year flow regulation, even more than the reservoirs on the main river. Differences are also shown in infrastructure improvements. From the short-term modeling, the irrigation efficiency (field application efficiency) increases to the upper bound (about 0.85), the drainage improvement is not economically attractive, and drainage reuse is attractive even in a normal year. All of these may be beneficial to the intra-year irrigation profit, however they may lead to unsustainable states with regard to high salinity in water and soil. From the long-term modeling, the irrigation efficiency gradually increases up to a moderate level in 30 years, especially in downstream demand sites (*Low_syd and Artur*), the drainage improvement is attractive, and drainage reuse is only preferable in dry years, except for the upstream demand site (*Naryn*), where salinity is low in field drainage. The short-term and long-term modeling result in different irrigated area for various crops. From the short-term modeling, the cotton-forage field dominates the irrigated area. The irrigated area at the downstream demand site (*Low_syd*) is significantly reduced due to water shortage and high salinity even in a normal year. The long-term modeling shows a significant increase of irrigated area for wheat-maize, and a rotation between cotton-forage and wheat-maize over the study years. No significant reduction of irrigated area occurs at the downstream demand site except in dry years. As expected, the short-term modeling results in a higher irrigation profit (up to 2.75 billion dollars in a normal year) than the long-term modeling (up to 1.68 billion dollars in a normal year). As a sacrifice, the short-term modeling ends with a high increase of salinity in surface water (by 1.5 times), and soil salinity over crop salinity tolerances in most of the demand sites. Based on these comparisons, we can see that the long-term modeling reflects the prescribed sustainability criteria. It shows consideration of reliability and equity in water supply, and also shows a balance between irrigation profits and their associated environmental consequences through appropriate crop pattern changes and infrastructure improvements.

Various scenario analyses of the long-term modeling show the states of the irrigation system and the associated environment, with consideration of sustainability. If the current conditions, including crop patterns and infrastructures continue in the future 30 years, agricultural profit will continually decrease with years, and the decreasing magnitude increases with years. Compared to the *baseline scenario*, the agriculture profit in the first year decreases by 26%, and in the last year (the 30th year) by 67%. For an agricultural economy depending on irrigation in the Syr Darya River basin, the continuation of the current condition will not maintain sustainability in the area, even no further environmental impacts are found under this case. Improvements of current water supply and use facilities, as well as the adjustment of current crop patterns, are necessary to sustain the agricultural production system in the Syrdarya River basin.

Excessive increase in irrigated area will significantly degrade the water and soil environment, and finally, even the crop production system. A number of scenarios with different increase of the irrigated area are analyzed. It is found that although the irrigation profit increases with the irrigated area, flow release to the Aral Sea decreases. Even a small increase of irrigated area will put the environment on risk, and high irrigation expansion will most probably destroy the environment, as well as the irrigation system itself.

The *baseline scenario*, with 25% increase of the non-irrigation water demand and 10% increase of the irrigated area in the next 30 years, is recommended to decision-makers for further consideration. Under this scenario, an increasing tendency is shown for the irrigation profit, except in some *dry years*; 90% of the target of flow release to the Aral Sea can be satisfied, with modest water and soil salinity increase. However, in *very dry* years (frequency of 6.7%) and consecutive *dry years*, crop yield and flow release flow to the Aral Sea will both considerably decline, which shows that some extra measures such as delivering water from other basins and increasing drainage treatment, may be necessary to deal with the drought.

The conflict between irrigation withdrawal and flow release to the Aral Sea is one the most important concerns in the study area. Compared to the *baseline scenario*, the *flow scenario* shows full satisfaction of the flow release target will reduce irrigation profit by only 10% within the next 30 years. Therefore we may conclude that the conflict between irrigation withdrawal and flow release to the Aral Sea may be mitigated by appropriate policies and infrastructure improvements as demonstrated in the *baseline and* the *flow scenarios.*

Negotiation between hydropower demand at the upstream country and irrigation demand at downstream countries remains another important issue of decision making in the study area. The *hydropower scenario*, assuming that hydropower demand in winter months will be satisfied as much as possible, shows satisfaction of the hydropower demand will reduce irrigation profit in all types of hydrologic years. In *very dry years*, the irrigation profit is reduced by up to 28%, compared to that under the baseline scenario. The *hydropower scenario* results in higher reservoir storage utilization for the reservoirs on the main river than other scenarios, in which we assume that Kyrgyzstan does not hold water in the vegetation period, while the downstream countries help Kyrgyzstan to get some reimbursement in power generation in winter months.

Analysis is addressed for each aspect of the prescribed sustainability criteria, as well as the inter-relations of those criteria. For water supply reliability, we find with the assumptions on farmers' decision (crop yield can not be lower than half of the maximum crop yield), irrigated area may be sustained under various water supply conditions, even crop yield may decline dramatically with dry years. Flow to the Aral Sea is sensitive to technological and water demand conditions. Excessive increase in irrigation water demands and poor technological conditions will most probably destroy the sustainability of both irrigation-dependent agricultural economy and the environment in the river basin.

Considering environmental integrity, analysis is made for individual demand sites, as well as the entire river basin. The upstream demand site (*Naryn*) seems to be free of water and soil salinity problems, and the two demand sites (*Chakir* and *Artur*) which mainly depend on tributaries for their water supply are less affected in water and soil salinity. *Fergana*, which is the largest irrigation water demand site, may suffer substantial groundwater salinisation. The midstream demand site, *Mid_syd*, is found to have potential waterlogging problems, and the downstream demand site, *Low_syd*, suffers the most severe water and soil salinity problems.

Equity analysis shows that the uneven spatial distribution of water sources in the basin can be mitigated by substantial facilities and appropriate policies, and then all demand sites have almost equal opportunity for their irrigation development. The total water use benefit is affected by changes in water demand, as well as hydrologic fluctuations over the years. The inter-year equity problem is more significant than the inter-site equity in the basin, especially with high water demand for both irrigation and non-irrigation purposes.

Economic efficiency analysis shows that large increase in irrigated area is not economically efficient, i.e., larger investment results in less profit. As mentioned before, continuation of current technology status (zero investment) will result in large loss of water use benefit.

For the inter-relations of all prescribed criteria, analysis shows that tradeoff relations exist between these criteria, particularly between water supply reliability and environmental integrity, and between equity and economic efficiency.

Due to the incomplete data availability and limited efforts in this research, findings from the modeling conducted in this research may not be thought as the real solutions to the problems in the basin, before they are verified by further work. However, the modeling framework clearly demonstrates the powerful capacity of analyzing water resources management problems in the study area, and shows implications for long-term reservoir operations, water supply and use facility improvements, irrigated area develop and crop patterns in the basin for sustaining the agricultural production system and the environment of the study area.

Solving large-scale nonlinear water resources management models has been identified as one of the difficulties in water resources systems analysis. The models developed in this research can not be solved directly using currently available algorithms. Three approaches are presented in this research for solving these large, nonlinear and nonconvex models. The general bender's decomposition (GBD) based approach can be used to search for approximate globally optimal solutions of large nonconvex nonlinear models. An example including a large number of bilinear equations (flow * constituent concentration) shows that the GBD-based approach solves the model faster than some popular nonlinear algorithms such as MINOS and CONOPT2.

The combined genetic algorithm and linear programming (GA-LP) can be used to find approximate global solutions or feasible solutions for large models with high nonlinearity and nonconvexity. It is robust in finding approximate global or feasible solutions to complex NLP models. The approach is used to solve the long-term model. It is also used to solve a typical multiple-reservoir operation model. With the increase of the model size, the convergence time increases approximately linearly (i.e., there is no indication of a "curve of dimensionality").

The "piece-by-piece" approach is applied to solve the short-term model that is large and nonlinear, and includes multiple compartments. The special structure required by this approach is similar to a simulation modeling structure that is common in engineering, and the advantage of this approach is providing a method based on the currently available solvers to solve problems formulated as holistic optimization models.

Although all these approaches require some special model structures, they can be used to solve a large range of water resources management models, and models in other related fields too.

A great wish of this research is to bring the philosophy of sustainability into traditional water resources management modeling. From conceptual specification to model development, and from data preparation and model test, to result demonstration, the modeling framework developed in this research is strongly recommended as a useful analytical tool for sustainability analysis in water resources management in river basins with substantial irrigation water demand. Within this modeling framework, essential hydrologic, agronomic, economic, and institutional relationships are integrated into an endogenous system at the river basin scale, and thus the integrity of water resources systems and inter-relationships between water application, economic welfare and environmental impact can be reflected and analyzed. This provides a way for quantitative analysis of the relationships of decisions-benefits-consequences, which is required in sustainable water resources management. Sustainability analysis also requires methods for tracing and controlling long-term consequences which are resulted from short-term decisions, as well as long-term changes and uncertainties in both water demand and supply. It also requires methods for handling the tradeoffs between current and future so that the spirit of sustainability can be reflected: satisfying the immediate demands and desires without compromising those of future years. The modeling framework provides such methods through combined short-term optimal decisions and long-term controls based on the prescribed sustainability criteria. Overall, the most important output of this research may be developing, solving and analyzing mathematical models for sustainability analysis in water resources management. This research may be added as another successful story of applying systems approach for water resources management.

However, in formulating, solving and analyzing the modeling framework developed in this research, a number of limitations become apparent. The modeling framework includes multiple components, and assumptions are made for each of these components. In this research, no rigorous study has been conducted to show how these assumptions within the different components affect each other and how they affect the modeling output if they are combined together in an endogenous system. Further research is needed to verify the inter-relationships between the hydrologic, agronomic, environmental, and institutional components integrated in the model.

Uncertainties with data of these components may be cross-dependent, and if put together but not well handled, they may distort the model output. A systematic approach to treat uncertainties within multiple components of an endogenous system is necessary to make this system robust in realistic analysis.

Also apparent is the limitation of data availability. Although data from several previous projects are used in this research, a lot of required data, especially the forecast data about system future status are still not available, and they could only be estimated or guessed. Obviously, this kind of modeling framework, which requires data from multiple components and data from both current and future periods, will not make any sense if not enough data are available. Additionally, multidisciplinary data and mixed types of data (i.e. experiment data, statistical data, and empirically estimated data) require attention with respect to their temporal and spatial resolution when they are used in an endogenous system.

Although the long-term dynamic model is solved effectively by the GA-LP approach, the computing time is long and the application of the model to real world problems may be limited. Fortunately, the structure of the long-term modeling framework shows great potential for using parallel computing algorithms, which will tremendously save computing time. As discussed in Section 7.3, within one generation, the yearly model will be run for each individual. Actually there is no requirement for the sequencing of the runs. That is to say, all individuals can be run simultaneously. Parallel algorithms are recognized to conduct this kind of work very efficiently.

Besides these limitations discussed above, some weak points exist with the components included in the modeling framework, which will be most subject to change in the future. First, the modeling framework heavily depends on how the sustainability criteria are expressed mathematically. Obviously it will be very difficult, if not impossible, to define general forms of those criteria, even for a single case study. The mathematical expressions of sustainability criteria in this research are closely related to our understanding of the specific problems in the study area. Furthermore, those multiple criteria are simply normalized in the objective function by weights or scaling factors that reflects the relative importance of each criterion. If this modeling framework is applied to another river basin, then the definitions and mathematical expressions of the sustainability criteria will be changed based on the specific conditions in the basin.

The modeling framework heavily depends on some empirical relationships in hydrologic, agronomic, and economic components. Although these relationships are claimed to be suitable universally, the parameters should be calibrated to the study area, and the assumptions with these relationships should be checked carefully according the specific conditions in the study area. Particularly, in the economic relationships, prices (crop prices and hydropower prices) and costs (water supply costs, hydropower generation costs and cropping costs) are assumed to be constant over all study years in the long-term model. However, these items will change in the future. For practical use of the long-term modeling, either we need to provide better estimations to these parameters, or we need to include more economic relationships in the model so that some of these items such as crop prices can be determined within the model (Rosegrant et. al. 1995).

As a summary, with all these limitations and weaknesses, to bring this work from research to practice, the following work is needed in the future: (1) checking all assumptions involved in different components of the model according to the conditions in the real world; (2) checking and changing the mathematical forms of the sustainability criteria until they can effectively reflect sustainability in water resources management in the basin; (3) updating and verifying data, especially those parameters that are included in some important empirical hydrologic, agronomic and economic relationships, like the crop production functions. For those parameters that are highly uncertain, sensitivity analysis should be conducted for them; (4) verifying model output; (5) analyzing uncertainties with the data. An innovative methodology is needed to incorporate comprehensive hydrologic uncertainties into the long-term modeling framework, and to handle uncertainties in multiple components systematically; and (6) defining and running more scenarios to search robust and comprehensive policies for the study area.

It may be worth reflecting on the value of this research as a Ph.D. dissertation in water resources engineering, i.e. developing such as a tool for policy analysis in water resources management. Researchers in various fields, such as civil and agricultural engineering, agronomy, economics and public affairs, all develop and apply their own models for water resources management problems. This research attempted to bring their work together. At a first glance, nobody should doubt this is a great idea. The progress of operation research and computer software and hardware, as well as substantial research in each of these fields, already or very likely provides the necessary conditions for people to build an integrated model for water resources management in the real world. However, this work seems to be ambitious for a single dissertation, and the author was worried about being trapped into what was beyond his ability and about being diverted from what he should focus on. Fortunately, based on all previous work cited in this dissertation, the study here reaches a viable modeling framework for sustainable water resources management.

In short, although this work has its limits in theory and application in water resources management, it shows the feasibility, effectiveness, and range of possible analysis of advanced mathematical modeling in analysis of sustainability, a concept of utmost importance that will strongly influence the future water resources management.

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Vita

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Appendix A

Deterministic form of a Chance-Constrained Model with Nonlinear Constraints

Mays and Tung (1992) gave the deterministic form for a linear chance-constrained model with random parameters on the right-hand-site of the equations, like

$$\begin{aligned} &\min \ \mathbf{cx} \\ &s.t. \ P(A\mathbf{x} \le \tilde{\mathbf{b}}) \ge \mathbf{a} \end{aligned} \qquad \text{(A-a1)}$$

where the right hand side coefficient $\tilde{\mathbf{b}}$ is random, and **a** is a vector of specified reliability of compliance (or confidence). Here we show a general model, linear or nonlinear, with random parameters on the right-hand-site of the equations has the same deterministic form as the linear model. The model can be written as:

$$\begin{aligned} &\min \ f(\mathbf{x}) \\ &s.t. \ P(\mathbf{g}(\mathbf{x}) \le \tilde{\mathbf{b}}) \ge \mathbf{a} \end{aligned} \qquad \text{(A-a2)}$$

where *f(x)*is the objective function, and **g(x)** is a vector of constraint equations. Both *f(x)* and **g(x)** can be linear or nonlinear.

Assuming the random RHS coefficient $\tilde{\mathbf{b}}$**,** has a cumulative density function (CDF) $\mathbf{F}_{\tilde{\mathbf{b}}}$, with mean $\boldsymbol{\mu}_{\tilde{\mathbf{b}}}$ and standard deviation $\boldsymbol{\sigma}_{\tilde{\mathbf{b}}}$. Equation (A-b2) is equivalent to:

$$P(\tilde{\mathbf{b}} \le \mathbf{g}(\mathbf{x})) \le 1 - \mathbf{a} \qquad \text{(A-a3)}$$

which is expressed in terms of the CDF of the random RHS coefficient, $\mathbf{\tilde{b}}$, as,

$$\mathbf{F_{\tilde{b}}(g(x)) \leq 1 - a} \tag{A-a4}$$

Using the standardized variate of the random RHS coefficient, that is, $\mathbf{Z_{\tilde{b}} = (\tilde{b} - \mu_{\tilde{b}})/\sigma_{\tilde{b}}}$, Equation (A-a4) can be expressed as:

$$\mathbf{F_{Z_{\tilde{b}}}\left(\frac{g(x) - \mu_{\tilde{b}}}{\sigma_{\tilde{b}}}\right) \leq 1 - a} \tag{A-a5}$$

The deterministic equivalent of the stochastic model in (A-a2) is the inverse of equation (A-a5):

$$\mathbf{\frac{g(x) - \mu_{\tilde{b}}}{\sigma_{\tilde{b}}} \leq F^{-1}_{Z_{\tilde{b}}}(1 - a)} \tag{A-a6}$$

which can be written as

$$\mathbf{g(x) \leq \mu_{\tilde{b}} + Z_{\tilde{b},1-a} \cdot \sigma_{\tilde{b}}} \tag{A-a7}$$

Appendix B

Notes on the Genetic Algorithm Program

The genetic algorithm appied in the GA-LP approach is based on a Fortran program, UTBGA (Unievrsity of Texas Binary-Code Genetic Algorithm), developed by Dr. Min-der Lin and Dr. Daene McKinney in Center for Research in Water Resources (CRWR), the University of Texas at Austin. It was modified in this research so that it could be used in the GA-LP approach, described in Chapter 5 and further in Chapter 6. Basically the primary program was split into four parts as described in Table A.b1.

Table A.b 1 Components of the genetic algorithm applied in the GA-LP approach

Sub-programs	Function	Input	Output
INIT	Create the first generation randomly.	Parameters required by the genetic algorithm, including bounds of the decision variables.	• Values for the inter-year control variables, put in four files, area.in, eff.in, wsf.in, and tax.in, described in Appendix I. • The first generation saved in an output file.
GEN	Create offspring generations based on the fitness of the pervious generation.	• Parameters required by the genetic algorithm, including bounds of the decision variables; • Previous generation saved in an output file; and • Fitness values of the individuals in the previous generation.	• Values for the inter-year control variables, put in four files, area.in, eff.in, wsf.in, and tax.in, described in Appendix I. • The generation saved in an output file.
GROUP	Group similar individuals	Individuals created from INIT or GEN	Grouped individuals
FIT	Calculate fitness of individuals. This program can also be coded in the GAMS model.	External modeling result for individual, from the GAMS model in this research.	Fitness for individuals, saved in an output file.

The combined GAMS model and the genetic algorithm are run through a batch file. The batch file used in a UNIX machine is shown in Figure A.b1.

```
#!/bin/ksh    (operation system specification)
echo  GA-LP approach
echo
echo   generate initial generation
       init                                (create the first generation)
echo
echo
        cp emp res_gen.dat                 (renew a result file)
echo
echo  interactive process between GA and GAMS
echo  set the number of generations
echo
      ngen=300
while [ ngen -ne 0 ]
do
          ngen=`expr $ngen - 1`
          echo generation $ngen
          gams longm  lo=0                 (run the GAMS model)
          echo entering GA
          fit                              (calculatw  fitness)
          cat res.out>>res_gen.dat
          gen                               (create a  new generation)
          gp                                (group similar individuals)
          echo entering GAMS
done
```

Figure A.b1. A List of the job file for running the long-term model in the UNIX system

Appendix C

Generic Analysis of the Network-Based Water Allocation System

We first derive some generic relationships of yield-water, and yield – salinity within an irrigation demand site, and then extend the relationships to include the effect from upstream diversion and drainage load. For simplicity, we use a diagram shown in Figure A.c1, including an upstream demand site and a downstream demand site. What is presented within a demand site is shown in Figure 3.6. The following derivation should be referred to these two figures.

The symbols used in this section are defined as below:

y = crop yield,
s = soil salinity,
m = soil moisture,
w = water available to the crop field,
s_w = salt concentration in water applied to the crop field,
d = diversion to a downstream demand site,
s_d = salt concentration in diverted water (d),
q = downstream river flow,
s_q = salt concentration with q,
$\bar{d}$ = diversion to a upstream demand site,
$\bar{s}_d$ = salt concentration with $\bar{d}$,
$\bar{q}$ = downstream river flow,
s_q = salt concentration with $\bar{q}$,
$\bar{r}$ = return flow from the upstream demand site,
$\bar{s}_r$ = salt concentration with $\bar{r}$,

i = inflow to the river reach between two demand sites,

s_i = salt concentration with i,

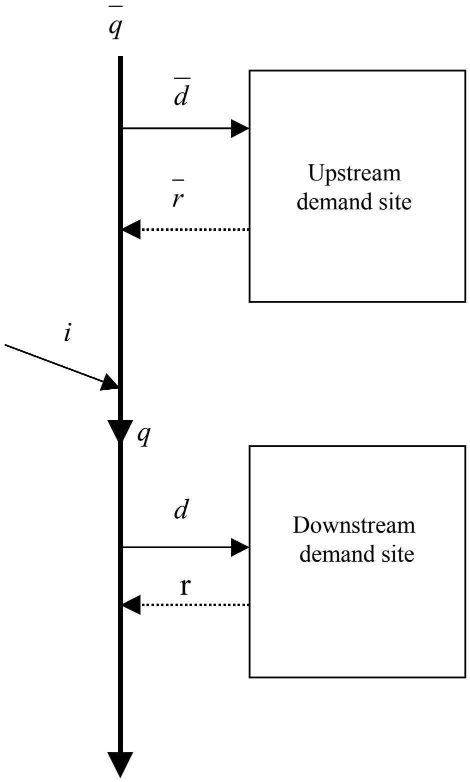

Figure A.c1 A simple diagram of the river basin network for water allocation

With the definitions of the items above, generic equations describing relationships among these items can be written as:

$$y = f_y(m, s) \tag{A-c1}$$

$$m = f_m(w | m0, pe) \quad \text{(A-c2)}$$

$$s = f_s(w, s_w | m0, ss0, pe) \quad \text{(A-c3)}$$

$$w = f_w(d | eds, eir, lw, dr, wac) \quad \text{(A-c4)}$$

$$s_w = f_{s_w}(d, s_d | eds, eir, lw, s_{lw}, dr, s_{dr}, wac) \quad \text{(A-c5)}$$

$$d = f_d(q | po, pc, wp) \quad \text{(A-c6)}$$

$$s_d = s_q \quad \text{(A-c7)}$$

$$q = \overline{q} - \overline{d} + \overline{r} + i \quad \text{(A-c8)}$$

$$s_q = \left[(\overline{q} - \overline{d}) \cdot s_{\overline{q}} + \overline{r} \cdot s_{\overline{r}} + i \cdot s_i \right] / q \quad \text{(A-c9)}$$

$$\overline{r} = f_{\overline{r}}(\overline{d}, s_{\overline{d}} | eds, eir, edn, edp, dr, lw, s_{lw}, s0, m0, tax) \quad \text{(A-c10)}$$

$$s_{\overline{r}} = f_{s_{\overline{r}}}(\overline{d}, s_{\overline{d}} | eds, eir, edn, edp, dr, lw, s_{lw}, s0, m0, tax) \quad \text{(A-c11)}$$

The items showing the conditions for the above equations are specified as:

dr = drainage reuse,

s_{dr} = salt concentration in drainage reuse (*dr*),

po = policy controls,

pc = physical capacity,

wac = water allocation among crops,

wp = water supply price,

tax = tax on excessive salt discharge,

lw = local water source,

s_{lw} = salt concentration in local source,

pe = precipitation infiltrated into the root zone,

$s0$ = initial soil salinity (previous soil salinity accumulation),

$m0$ = initial soil moisture,

and *eds*, *eir*, *edn*, and *edp* are defined as before.

It should be noted that some of these items, such as drainage reuse (*dr*), water allocation among crops (*wac*) and irrigation and drainage infrastructure levels (*eds*, *eir*, *edn*, and *edp*), are decision variables in the equation (A-c4) and (A-c5). Since we want to focus on the analysis of the effect from upstream demand site, those internal decisions within a demand site are treated as given conditions in equation (A-c1)-(A-c11).

The partial differential equations of crop yield (*y*) with other items are derived based on the relationships (eq. A-c1 – A-c11), and we discuss these derivations in the rest of this section.

In the beginning, we define:

$$f_s^y = \frac{\partial f_y}{\partial s} \qquad \text{(A-c12)}$$

$$f_m^y = \frac{\partial f_y}{\partial m} \qquad \text{(A-c13)}$$

When soil salinity is over the crop tolerance, $f_s^y < 0$, otherwise $f_s^y = 0$. For a specific growth stage, there is a point of soil moisture that is best for crop growth (Vaux and Pruitt, 1983). Below this point, $f_m^y > 0$, and above this point, $f_m^y < 0$. For proper irrigation purpose, we should have $f_y^m > 0$.

In equation (A-c2), soil moisture (*m*) is a function of *w*, the water applied to the crop field, with conditions of initial soil moisture (*m0*) and precipitation (*pe*); soil salinity (*s*) is a function of both water (*w*) and salt concentration in the water (s_w), with the same conditions as soil moisture, plus initial soil salinity (*s0*). We have:

$$f_w^y = \frac{\partial y}{\partial m} \cdot \frac{\partial m}{\partial w} = f_m^y \cdot f_w^m \qquad \text{(A-c14)}$$

$$f_{s_w}^y = \frac{\partial y}{\partial s} \cdot \frac{\partial s}{\partial s_w} = f_s^y \cdot f_{s_w}^s \qquad \text{(A-c15)}$$

where, $f_w^m > 0$ before soil moisture reaches the field capacity, and $f_{s_w}^s > 0$. Since $f_m^y > 0$ and $f_s^y < 0$, we have $f_w^y > 0$ and $f_{s_w}^y < 0$.

The value of f_w^m depends on initial soil moisture (*m0*) and precipitation (*pe*), we have $\partial f_w^m / \partial(m0) < 0$ and $\partial f_w^m / \partial(pe) < 0$. Besides *m0* and *pe*, the value of $f_{s_w}^y$ also depends on *s0*, the initial soil salinity, we have $\partial f_{s_w}^s / \partial(pe) < 0$, and $\partial f_{s_w}^s / \partial(s0) < 0$.

From equation A-c4, water available to crop use may include local water (surface and ground sources), water withdrawal from the river system, and drainage reuse. Water withdrawal finally available for crop use is equal to the total withdrawal minus delivery and distribution loss, and field loss. Under these conditions, the crop yield (*y*) is related to water withdrawal (*d*) as:

$$f_d^y = \frac{\partial y}{\partial d} = \frac{\partial y}{\partial m}\frac{\partial m}{\partial w}\frac{\partial w}{\partial d} + \frac{\partial y}{\partial s}\frac{\partial s}{\partial w}\frac{\partial w}{\partial d} + \frac{\partial y}{\partial s}\frac{\partial s}{\partial s_w}\frac{\partial s_w}{\partial d}$$

$$= f_m^y f_w^m f_d^w + f_s^y f_w^s f_d^w + f_s^y f_{s_w}^s f_d^{s_w} \qquad \text{(A-c16)}$$

$$= f_m^y f_w^m f_d^w + f_s^y \left(f_w^s f_d^w + f_{s_w}^s f_d^{s_w} \right)$$

where the water-only item $f_m^y f_w^m f_d^w$>0, since f_y^m, f_m^w, $f_w^d > 0$. The value of f_d^w depends on all the conditions associated with equation (A-c4). Better canal lining (high delivery and distribution efficiency), and better irrigation system (high irrigation efficiency) will make the value of f_w^d larger. Since f_w^d is with a specific crop field, larger fraction of diversion distributed to the crop field will increase the value of f_w^d. The decision on water allocation among crops depends on the economic value of water applied to the crop, as well as some policy requirements.

Since $f_s^y < 0$, the effect from salinity in the water withdrawal to the value of f_d^y depends on the value of $f_w^s f_d^w + f_{s_w}^s f_d^{s_w}$, in which $f_d^w, f_{s_w}^s \geq 0$, and the value of f_w^s and $f_d^{s_w}$ depends on more conditions. From equation (A-c15), water applied to crop field is blended with multiple sources. Generally salt concentration in drainage and groundwater is high, water with low salinity is used to dilute the water with high salinity. In this way, water withdrawal dilutes the water applied to crop field, i.e, $f_w^s < 0$. However, when the salinity in water withdrawal is higher even than the local sources, then $f_s^w > 0$, and it will make

$f_s^y f_w^s f_d^w < 0$, which means salinity in water withdrawal produce negative impact to water withdrawal for irrigation purpose. The similar explanation can be made to the value of $f_d^{s_w}$.

The partial differential relation between crop yield (*y*) and salinity in water withdrawal (*s_d*) is:

$$f_{s_d}^y = \frac{\partial y}{\partial s_d} = \frac{\partial y}{\partial s}\frac{\partial s}{\partial s_w}\frac{\partial s_w}{\partial s_d} = f_s^y f_{s_w}^s f_d^{s_w} \qquad \text{(A-c17)}$$

where, $f_{s_w}^s, f_{s_d}^{s_w} > 0$, given $f_y^s < 0$, we have $f_{s_d}^y < 0$

We can further relate crop yield (*y*) to river flow (*q*), and salinity in river water (s_q). Based on equation (A-c5) and equation (A-c16), we have

$$f_q^y = \frac{\partial y}{\partial q} = \frac{\partial y}{\partial d}\frac{\partial d}{\partial q} = f_d^y f_q^d \qquad \text{(A-c18)}$$

where f_d^y has been discussed above. Considering the downstream flow requirement and diversion capacity, the larger river flow allows larger diversion, which generally leads f_q^d >0, and thus f_q^y >0. However, the value of f_q^d also depends on the water price, which presents an economic incentive for water withdrawal. The increase of water price causes the decrease of water value of the demand site, and when the water value of the demand site is reduced to zero f_q^d =0, i.e., water withdrawal will not be related to river flow.

From equation (A-c7), s_q and s_d are identical, therefore, $f_{s_q}^y$ is identical to $f_{s_d}^y$, and $f_{s_d}^y < 0$.

By now we have discussed the partial differential relationships of crop yield with water available to the crop, water withdrawal to the demand site, river flow, and the salinity associated with these items. Decisions specified with these relationships include water withdrawal, water allocation among crops, source blending for irrigation and infrastructure improvements on water delivery and on-field use. In the following we discuss the extended relationships which relate the crop yield at one demand site to water withdrawal, return flow, and salinity in return flow at the upstream demand site. Equations (A-c19) – (A-c20) present these relationships respectively.

$$f_{\bar{d}}^{y} = \frac{\partial y}{\partial q}\left(\frac{\partial \bar{r}}{\partial \bar{d}} - 1\right) + \frac{\partial y}{\partial s_q}\frac{\partial s_q}{\partial \bar{d}} = f_q^{y}\left(f_{\bar{d}}^{\bar{r}} - 1\right) + f_{s_q}^{y} f_{\bar{d}}^{s_q} \qquad \text{(A-c19)}$$

and

$$f_{\bar{d}}^{s_q} = \left[\left(\bar{q} - \bar{d} + \bar{r} + \bar{i}\right)\left(f_{\bar{d}}^{\bar{r}} \cdot s_{\bar{r}} - s_{\bar{q}}\right) - \left(\bar{q} \cdot s_{\bar{q}} - \bar{d} \cdot s_{\bar{q}} + \bar{r} \cdot s_{\bar{r}} + i \cdot s_i\right)\left(f_{\bar{d}}^{\bar{r}} - 1\right)\right] \cdot \left(\bar{q} - \bar{d} + \bar{r} + \bar{i}\right)^{-2} \qquad \text{(A-c20)}$$

in which $f_{\bar{d}}^{\bar{r}}$ is a critical factor. If $f_{\bar{d}}^{\bar{r}} = 1$, then, $f_{\bar{d}}^{y}$ is simplified as

$$f_{\bar{d}}^{y} = \frac{f_{s_q}^{y}\left(s_{\bar{r}} - s_{\bar{q}}\right)}{\bar{q} - \bar{d} + \bar{r} + \bar{i}} \qquad \text{(A-c21)}$$

Given $f_{s_q}^{y} < 0$, equation A-c17, and $\bar{q} - \bar{d} + \bar{r} + \bar{i} = q > 0$, if $s_{\bar{r}} - s_{\bar{q}} > 0$ (which is the normal case in reality), then $f_{\bar{d}}^{y} < 0$, which implies even upstream diversion does not affect river flow to downstream ($f_{\bar{d}}^{\bar{r}} = 1$), the increase of salinity in return flow due to the diversion will still make negative contribution to downstream crop yield. In reality, if soil salinity is high at upstream irrigated fields, then upstream withdrawal will both reduce downstream flow, and increase salinity in downstream flow. As shown in equation (A-c19), if $f_{\bar{d}}^{\bar{r}} < 1$ (i.e., the magnitude of return flow change is less than that of the diversion change, which is generally true in areas with (semi) arid weather.), the negative effect from flow reduction is apparent, and the effect from salinity is also negative, except

$$\left(\bar{q} - \bar{d} + \bar{r} + \bar{i}\right)\left(f_{\bar{d}}^{\bar{r}} \cdot s_{\bar{r}} - s_{\bar{q}}\right) - \left(\bar{q} \cdot s_{\bar{q}} - \bar{d} \cdot s_{\bar{q}} + \bar{r} \cdot s_{\bar{r}} + i \cdot s_i\right)\left(f_{\bar{d}}^{\bar{r}} - 1\right) < 0 \tag{A-c22}$$

and assuming $s_i = s_q$, solve for $s_{\bar{r}}$, and we get

$$s_{\bar{r}} < s_{\bar{q}} \tag{A-c23}$$

which means if salinity in return flow is lower than that in flow to downstream, then in the expression of $f_{\bar{d}}^{y}$, the effect from salinity is not negative. However, this case is very rare in reality.

Crop yield (y) is related to return flow at the upstream demand site as in the following equations:

$$f_{\bar{r}}^{y} = \frac{\partial y}{\partial q}\left(1 - \frac{\partial \bar{d}}{\partial \bar{r}}\right) + \frac{\partial y}{\partial s_q}\frac{\partial s_q}{\partial \bar{r}} = f_q^y\left(1 - f_{\bar{r}}^{\bar{d}}\right) + f_{s_q}^{y} f_{\bar{r}}^{s_q} \tag{A-c24}$$

and

$$f_{\bar r}^{s_q} = \left[\left(\bar q - \bar d + \bar r + \bar i\right)\left(s_{\bar r} - f_{\bar r}^{\bar d} \cdot s_{\bar q}\right) - \left(\bar q \cdot s_{\bar q} - \bar d \cdot s_{\bar q} + \bar r \cdot s_{\bar r} + i \cdot s_i\right)\left(1 - f_{\bar r}^{\bar d}\right)\right] \cdot$$

$$\left(\bar q - \bar d + \bar r + \bar i\right)^{-2} \tag{A-c25}$$

Again, $f_{\bar r}^{\bar d}(= f^{-1}{}_{\bar d}^{\bar r})$ is a critical factor of $f_{\bar r}^{y}$. If $f_{\bar r}^{\bar d} = 1$, then, $f_{\bar r}^{y}$ is simplified as

$$f_{\bar r}^{y} = \frac{f_{s_q}^{y}\left(s_{\bar r} - s_{\bar q}\right)}{\bar q - \bar d + \bar r + \bar i} \tag{A-c26}$$

which is the same with $f_{\bar d}^{y}$ when $f_{\bar d}^{\bar r} = 1$ (eq. A-c20). $f_{s_q}^{y} < 0$, $s_{\bar r} - s_{\bar q} > 0$, then $f_{\bar r}^{y} < 0$.

Normally we have $f_{\bar r}^{\bar d}(= f^{-1}{}_{\bar d}^{\bar r}) > 1$, and then the flow effecting item to $f_{\bar r}^{y}$, $f_{q}^{y}(1 - f_{\bar r}^{\bar d})$<0, which implies the return flow from the upstream demand site does not simply increase the flow to the downstream, because $f_{\bar r}^{\bar d}(= f^{-1}{}_{\bar d}^{\bar r}) > 1$ means large return flow corresponds even larger diversion, and finally the flow to downstream is reduced. Only if $f_{\bar r}^{\bar d}(= f^{-1}{}_{\bar d}^{\bar r}) < 1$, that is to say, only if a smaller diversion produces larger return flow, does the return flow make positive contribution to the downstream flow. That is hardly true in the real world.

Finally the relation between crop yield (y) and salt concentration in return flow from the upstream demand site is shown as:

$$f^{y}_{s_{\bar{r}}} = \frac{\partial y}{\partial s_{\bar{r}}} = \frac{\partial y}{\partial s}\frac{\partial s}{\partial s_w}\frac{\partial s_w}{\partial s_q}\frac{\partial s_q}{\partial s_{\bar{r}}} = f^{y}_{s} f^{s}_{s_w} f^{s_w}_{s_q} f^{s_q}_{s_{\bar{r}}} \qquad \text{(A-c27)}$$

$$f^{s_q}_{s_{\bar{r}}} = \frac{\bar{r}}{q} \qquad \text{(A-c28)}$$

and further, by equation (A-c17), $f^{y}_{s_{\bar{r}}}$ is written as:

$$f^{y}_{s_{\bar{r}}} = \frac{\bar{r}}{q} \cdot f^{y}_{s_q} \qquad \text{(A-c29)}$$

As discussed above, $f^{y}_{s_q} < 0$, and then $f^{y}_{s_{\bar{r}}} < 0$.

$f^{y}_{\bar{d}}$, $f^{y}_{\bar{r}}$ and $f^{y}_{s_{\bar{r}}}$ show the effect of upstream water withdrawal and drainage to the crop production of a downstream demand site, and they provide an analytical form for the externality involved in water allocation in a river basin. $f^{\bar{r}}_{\bar{d}}$ $(= \partial \bar{r} / \partial \bar{d})$ is critical to the effect from upstream withdrawal, as well as return flow. The increase of $f^{\bar{r}}_{\bar{d}}$ will reduce the flow effect, but will increase the salinity effect.

As discussed above, water price (*wp*) can be taken as an economic policy to control the water withdrawal by a demand site. A high water price will reduce the marginal value of water withdrawal and then force the demand site to withdraw less water. Therefore a higher water price set up for an upstream demand may discount the negative effect to the downstream demand site, at some loss of avenue of the upstream demand site due to the less water supply.

Tax on excessive salt discharge may force a demand site to reduce the amount of drainage or the salt concentration in drainage, or the both. The amount of drainage can be reduced through on-field drainage disposal. However, as shown in equation (A-c19), the reduction of drainage amount may make the “flow effect” more serious. Drainage treatment for river discharge will reduce the “salinity effect” while keeping the “flow effect” unaffected. A tradeoff relationship exists between the cost of drainage disposal or treatment, and the economic damage of the downstream demand site due to the “flow effect” and “salinity effect” from the upstream demand site.

In this research, instead of a complete, more detailed analytical form of all hydrologic-agronomic-economic relationships, a mathematical programming model is developed to include these relationships at a whole river-basin scale with an extension to crop field. Quantitative analysis will be conducted based on output from the model.

Appendix D

Glossary

α_{ia}	percentage which specifies a safety threshold for irrigated area
γ	change rate of *TWB* between year *y* and *y-1*
$\bar{\gamma}$	average of γ
γ_d	change rate of benefit for each demand site
ε	price elasticity of demand
α	intercept calibrated to "normal" production in the crop price function
β	market share of the commodity in the crop price function
a_i , β_i	constant coefficients in reservoir topological equations
$\Delta(IP)$	change of irrigation profit
$\Delta(R)$	change of ratio of assumed to primary efficiency
$\Delta(TWB)$	change of total water use benefit
ε'	elasticity of demand of water
λ	Lagrangian multipliers
ψ_0	soil osmotic potential due to the presence of solved salts
ψ_m	soil matric potential, resulting exclusively from the soil matrix
Φs	saturated soil matric potential
Δt	time duration of one period
η	ratio of groundwater discharge to rivers to groundwater table

σ_v	standard deviation
ρ	computing time discounting coefficient
$\mathbf{o}$	vector, intermediate variables that are only related to flow and storage variables
$\mathbf{q}$	vectors of flow and storage (volume) variables
$\mathbf{s}$	vectors of slack variables
$\mathbf{u}$	vector of Lagrange multipliers for the constrain
$\mathbf{a}, \mathbf{b}, \mathbf{c}$	vectors of parameters
$\mathbf{g}_1, \mathbf{g}_2, \mathbf{g}_3$	vectors, sets of equations
$\mathbf{x}, \mathbf{y}, \mathbf{z}$	vectors of variables
$\mathbf{x}^0, \mathbf{y}^0, \mathbf{z}^0$	initial values of vectors **x, y,** and **z,** respectively
$\tilde{\mathbf{b}}$	stochastic variable/parameter, right-hand side
$\tilde{\mathbf{A}}$	stochastic variable/parameter, technological coefficients
(*n, n2*)	all links from n to *n2*.
(*n1, n*)	all links from *n1* to n,
A	reservoir surface area, and
AEW	actual ecological and environmental water use
AIA	actual irrigated area
AIA	actual irrigated area (*AIA*)
AINV_DN	annual investment for improving drainage collection systems
AINV_DN	annual investment for improving drainage collection systems
AINV_DP	annual investment for improving drainage disposal/treatment systems
AINV_DP	annual investment for improving drainage disposal/treatment systems
AINV_DS	annual investment for improving water delivery & distribution systems
AINV_DS	annual investment for improving water delivery & distribution systems
AINV_IR	annual investment for improving irrigation system
AINV_IR	annual investment for improving irrigation systems applications
AR	artificial recharge to aquifers

ASF	crop field area in which soil salinity is over crop salinity tolerance
B	the slope of the yield-salinity curve at salinity values in the range $S_e > S'$
BT	binary string of a number of bits
c	soil's pore connectivity index
C	salt concentration with flow
cdn	cost per unit of drainage collection (not including fixed investments)
cdr	cost for per unit drainage collection (not including fix investment)
cdt	cost per unit of drainage disposal (not including fixed investments)
cdt	cost for per unit drainage disposal (not including fix investment)
$CETA$	cumulative actual evapotranspiration
$CETM$	cumulative maximum evapotranspiration
cg	groundwater pumping cost
cmp	consumptive use rate of the non-irrigation water supply
cp	crop patterns
cpw	power generation cost
cr	cost for per unit drainage reuse
$d(K_s)$	change of K_s, and
D_REV	delivery from reservoirs to a farm $[L^3]$
D_REV	delivery from reservoirs to a demand site $[L^3]$
D_RIV	diversion from rivers to a demand site $[L^3]$
D_RIV	diversion from rivers to a farm $[L^3]$
dm	demand sites
DN	drainage from a crop field, including surface drainage and subsurface drainage
DP	deep percolation
drn	natural drainage to reservoirs, constant parameter in the model
DS	discharge from the aquifer associated with the demand site
dy	change of crop yield

dz	change of the soil moisture
EB	ecological water use value
ECe	soil saturated extraction in dS/m
ECg	salinity in groundwater extraction
ECp	salinity in the percolation, expressed as electric conductivity [dS/m]
ECr	salinity in tailwater expressed as electric conductivity
ECw	salinity in water application, expressed as electric conductivity [dS/m]
ECw	salinity in the water application, expressed as electric conductivity [dS/m]
ECw	salinity of irrigation water in dS/m
EDN	drainage efficiency**,** the ratio of drainage from field to total percolation
EDS	water delivery & distribution efficiency
EDT	ratio of drainage disposal/treatment to total drainage
EIR	irrigation efficiency, the ratio of total water infiltrating into crop root zones over total water
env	index for environment integrity
ER	effective rainfall [L]
ET_0	reference crop evapotranspiration
ETA	actual evapotranspiration [L]
ETA	actual evapotranspiration [L]
ETM	maximum evapotranspiration
ev	economic benefit from environmental water uses
Evap	evaporation rate in length, constant parameter
fc	fixed crop input cost per unit area
fd	crop fields
G	number of generations in the genetic algorithm
GD	depth of water table
GE	groundwater extract by absorption [L]
GINP	government investment for infrastructure

grechg	groundwater recharge
gws	groundwater salinity, and
H	reservoir surface elevation
hg	groundwater level
HP	profit from power generation
I	number of individuals in the genetic algorithm
IAN	area remaining fallow due to water shortage and salinity
IM	income of demand site *dm* in year *y*
IND	an individual of a generation
Inflow	stream inflow
inflow0	normal annual inflow to the sea by historic records
INV	annual investment and operating/maintenance cost
inv_dn	annual investment for increasing one unit of drainage
inv_dp	annual investment for increasing one unit of drainage disposal in
inv_ds	annual investment for per unit of water saving from delivery systems
inv_ir	annual investment per unit of water saving from irrigation systems
IR	infiltrated precipitation [L]
K	hydraulic conductivity
k_{ap}	coefficient of soil water stress effect for soil evaporation
k_{at}	coefficient of soil water stress effect for transpiration
kat	the coefficient of soil water stress effect for transpiration
kc	crop evapotranspiration coefficient
kct	crop transpiration coefficient
ks	coefficient of soil salinity effect
ky	crop yield response factor varying among crop growth stages
lbd	lower bound in the GBD-based approach
LS	local surface water source
m	soil connectivity and tortuosity coefficient

MES	salt mass in return flow in excess of what was presented in the original diversion
mv	marginal value of water
n	water supply or demand nodes in the river basin network
n1	a from-node in the river basin network
n2	a to-node in the river basin network
NG	prescribed number of generations in genetics algorithms
NI	number of individuals in a generation (genetic algorithm)
NP	natural recharge to aquifer
NREV	net revenue from irrigation at a demand
Obj	objective value
pcp	crop selling price
PDEM	power demand
PM	groundwater pumped [L^3]
PN	percolation in crop fields in [L]
PN	percolation in a crop field, the amount of water leaving root zones to downward soil layers
ppw	power selling price
PW	hydropower generation
Q_{in}	inflow during a time period
Q_{out}	outflow during a time period
RD	root zone depth [L]
REL	reliability
RELS	flow to downstream reservoir(s)
REUSE	drainage reuse [L^3]
REV	reversibility
rev	reservoir
rfe	evaporation loss rate of the return flow

rgp	the ratio of government investment to the local investment
RIA	reduced irrigated area
RUE	reservoir utilization efficiency (RUE)
RUSE	drainage reuse
s	aquifer storativity
S’	salinity threshold for a crop
Sa	areas with specific soil types
SBD	subsidy for improving water use capacities
S_e	average root zone salinity, in saturated soil extract
SEA	socio-economic acceptability
SEQ	spatial equity
Sgw	groundwater salinity
sim	index *of* similarity (*sim*) between these two individual
SL	surface water leakage
SM	salt balance sub-model
Sp	salt in percolation
SR	surface runoff (tailwater)
Sso	soil salinity in crop field *fd*
Ssw	surface water salinity
st	crop growth stages, $st \subset t$
ST	storage at the end of a time period.
STR	reservoir storage
t	time periods (months)
T	number of the time periods
tax	tax imposed on excessive salt discharge
TEQ	inter-year equity
TEW	target of A*EW*
TIA	the target irrigated area in each year

TIA	target of IA)
TIA	total irrigated area at a demand site
T_{LP}	time for linear programming
Tol	tolerance
TP	cumulative transpiration by the crop
TPM	Maximum TP
TR	total rainfall
TS	total available water storage in a river basin
$TSBD$	total available subsidy
tt	index of the time series
tw	average tail water level constant parameter in the model
TWB	total social benefit for the region of the river basin
TWB	total water use benefit (TWB)
$TYLD$	total yield of crop cp from all fields at all demand sites in the river basin
ubd	upper bound in the GBD-based approach
V_c	economic value of water with a crop
V_d	economic value of water with a demand site
$veco$	socio-economic value from per unit of ecological water use under the condition of water scarcity
VUN	vulnerability
WA	water available to a crop $[L^3]$
WAF	total water applied to crop fields
$WAPF$	total water applied to crop fields, including diversion, local surface source, and groundwater
WD	total water diversion from rivers and reservoirs, including local sources
WDA	diverted water available for use in a demand site
WDN	drainage from a crop field, including surface drainage and subsurface drainage

WDP	deep percolation
WDR	historic water use right
WDT	amount of drainage disposed in a demand site
WECO	water for ecological use
wenv	weights (or scaling factors) assigned to *env*
WEU	water effectively used by crops
WFLD	surface water allocated to crop fields [L^3]
w_{gs}, w_{ss}, w_{ws}	weights assigned to *gs, ss*, and *ws*, $w_{gs} + w_{ss} + w_{ws} = 1.0$
WIF	water infiltrating into crop root zones, NOT including effective rainfall
win	inflow to the root zone
withdw	withdrawal to water demand sites, constant parameter
wout	outflow from the root zone
wpen	weight assigned for the penalty item
wrev	weights (or scaling factors) assigned to *rel*
wrev	weights (or scaling factors) assigned to *rev*
wsea	weights (or scaling factors) assigned to *sea*
wseq	weights (or scaling factors) assigned to *seq*
WSF	water shortage (water demand minus water demand)
WSMI	water supply for municipal and industrial use
WSU	water sustained at the end of a year
wteq	weights (or scaling factors) assigned to *teq*
wvun	weights (or scaling factors) assigned to *vun*
YA	actual crop yield
$\boldsymbol{YF_{gs}}$	number of consecutive years in which $RGS^{y} > \alpha_{gs}$
$\boldsymbol{YF_{ss}}$	number of consecutive years in which $RSS^{y} > \alpha_{ss}$
$\boldsymbol{YF_{ws}}$	number of consecutive years in which $RWS^{y} > \alpha_{ws}$
YM	maximum yield without either water stress effect or soil salinity effect

Z	soil moisture content in root zone in percentage
Zs	moisture content at field capacity
Zw	moisture content at wilting point