# Environmental Policy and Technology Project

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**NEW INDEPENDENT STATES**

# REPORT ON MODEL DEVELOPMENT
**Aral Sea Regional Allocation Model for the Amudarya River**
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# Executive Summary

Ongoing research on efficient water allocation is taking place in the Central Asian Republics at the Institute of Engineers for Irrigation and Mechanism of Agriculture (IEI), Tashkent, Uzbekistan and in the USA at the University of Texas at Austin (UT Austin). Cooperation between these two institutions and other agencies, ministries, or institutes in the Republics has allowed the development of a water allocation model for the Amudarya River of the Aral Sea basin. This model supports the planning of water distribution between water economical districts in the Amudarya basin. In addition, the model takes into account the salinization of water in the basin. A more detailed model has also been developed for the Kashkadarya River basin which considers irrigation runoff or drainage from individual irrigation districts.

The work undertaken in this project was conducted under the Regional Cooperation activities of the Central Asian Regional Office of the US Agency for International Development (USAID) sponsored Environmental Policy and Technology Project (EPT). EPT is tasked with promoting regional cooperation and policy development between and among the Central Asian Republics, with technical assistance from U.S. experts and institutional counterparts. The work described in this report is part of EPT's applied demonstration project program of Delivery Order 8 (DO8). It is in support of the request for new research in the area of water management to support EPT work in Central Asia on the problems of the Aral Sea.

This report describes the model development activities undertaken by Dr. Daene C. McKinney of UT Austin and Dr. Akmal K. Karimov of IEI and others in the project team for the development of the Amudarya water allocation model.

. The overall objectives of the project were to:

- Develop a Geographic Information System (GIS)-based decision support system for regional water resources planning that is applicable to the river basins of the Aral Sea region, and

- Demonstrate this system for portions of the Aral Sea basin: the Amudarya River and Kashkadarya River basins.

The decision support system integrates the advantages of GIS techniques into regional water resource allocation modeling. GIS software has a powerful capacity to represent real world water resource systems, and it can provide very useful information for building water resource allocation models. In this project the real-world water resource system and the abstract mathematical model are integrated in the GIS environment. Changes to the system in the real world can be input to the GIS and they are automatically reflected in an updated mathematical model.

The modeling system developed here is an interface between the GIS software, ARCVIEW, and its object-oriented scripting language AVENUE, and GAMS, a mathematical optimization software package. The water resource system is represented by maps, tables and

charts in ARCVIEW. A mathematical model based on a network representation of the water resources system is used for water allocation, and GAMS is used to solve this model. Given the coverages and attributes which describe the water resource system in the real world, the modeling system (1) transfers geographic information into a form compatible with the mathematical model; (2) based on the geographic information, it builds a multiobjective optimization model in a format compatible with GAMS; (3) it calls the GAMS software to solve the model; and (4) the system displays the results in the GIS format.

The GIS-based decision support system for regional water resources planning was demonstrated for portions of the Aral Sea basin: the Amudarya River and Kashkadarya River basins.

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# Acknowledgments

# About the Authors

The work done unde this project was conducted at the Tashkent Insititute of Engineers for Irrigation and Mechanization of Agriculture (TIIMSKH) and The University of Texas at Austin.

Project leaders Dr. A Kaimoc and Dr. D. McKinney are from TIIMSKH and The University of Texas at Austin, respectively. In addition the following people also worked on this project: Professor S. Sh. Mirzaev, TIIMSKH, Dr. G. Khasankhanova, Institute Uzmeliovodproekt, Dr. F. E. Rubinova, Hydrometeorological Survey of Uzbekistan, Dr. I. Khabibullaev, Dr. T. Mukhamedjanov, Dr. G. Mjelskaya, and Dr. I. Gracheva, Institute of Hydrogeology and Engineering Geology.

# Introduction

The problems of the Aral Sea basin have received much attention in the past eight years, and aid efforts to alleviate some of these problems have been ongoing since 1992. The major source of these problems lies in the previous government's program of land reclamation to convert desert land into irrigated farms. This resulted in an irrigated area of over 7.2 million hectares (ha) in the basin. Water for these irrigation projects was abstracted from the Amudarya and Syrdarya Rivers, the main sources of water for the Aral Sea. As a result of these massive water diversions, the size of the Aral Sea began to decrease in the 1960's and the salinity rose dramatically. Other environmental and public health damage was also incurred as a result of this program, such as ecosystem destruction, species extinction, groundwater pollution, and atmospheric dust pollution.

The Aral Sea basin is comprised of two main river basins, the Amudarya and the Syrdarya Rivers, covering an area of approximately 690 thousand sq. km. Much of the hydrological, climatological, and environmental data relevant to the basin can be found in the report of the World Bank Project 1.1 (1996). The average availability of water in these basins is 120 km$^3$ including surface and ground water. The Aral Sea is the terminal lake at the outflow of these rivers, and for the past several centuries it has maintained a level of approximately 54 m with a volume of about 1000 km$^3$ and a surface area around 66 sq. km. (6 million ha). The average annual inflow to the Aral Sea was 49 km$^3$. Diversion of water from the rivers to irrigated agriculture has resulted in a flow to the sea of 9 km$^3$, the desertification of approximately 2 million ha and the sea level to decline to about 36 m with a salinity lever of 28-30 g/L.

Many suggestions have been made to stabilize the level of the Aral Sea and rehabilitate the ecosystems near the sea (the so called "disaster zone"). It has been estimated that 30-35 km$^3$ of inflow to the sea is needed to stabilize the water level at the current 36 m height. However, this may require a very large reallocation of water away from the agricultural sector of the riparian states of the basin. Current targets are to provide 22-25 km$^3$ of inflow to the sea by the year 2010. This quantity of inflow would help to slow the rate of environmental degradation in the area, but it will not maintain the current sea level or restore it to previous level. However, the value of this water in preventing further ecological damage must be assessed (Anderson, 1997) and compared to the value of continuing to use this water for agricultural production before rational allocation decisions can be made.

Rehabilitation of irrigation systems in the region is obviously one of the most immediate and efficient methods of achieving water conservation in the region. Retirement of marginal lands from irrigated agriculture is another economically efficient way of achieving water savings. The management of salinity in the Aral Sea basin is important from the standpoint of water quality, human health and agricultural productivity. All of these problems are basin wide and require solutions that consider the complementary effects of decisions in one sector or geographic area on other areas of the basin.

The allocation of water resources in the Aral Sea basin is a critical issue for the riparian states of the basin. The sustainability of their future economic growth and environmental health depends on it. Efficient and comprehensive analytical tools are needed in order to make the rational water allocation decisions necessary to achieve sustainable water use strategies for the Amudarya and Syrdarya River basins. The development of analytical tools, techniques and mathematical models for integrated analysis of factors affecting water resources planning and operational decision-making in the Aral Sea basin has been called for under the World Bank Aral Sea Program, Project 1.1 (World Bank, 1996). These tools must be able to analyze the consequences, both environmental and economic, of water allocation decisions at both the river basin scale and the local, administrative district scale.

Ongoing research on efficient water allocation is taking place in the Central Asian Republics at the Institute of Engineers for Irrigation and Mechanism of Agriculture (IEI), Tashkent, Uzbekistan and in the USA at the University of Texas at Austin (UT Austin). Cooperation between these two institutions and other agencies, ministries, or institutes in the Republics has allowed the development of a water allocation model for the Amudarya River of the Aral Sea basin. This model supports the planning of water distribution between water economical districts in the Amudarya basin. In addition, the model takes into account the salinization of water in the basin. A more detailed model has also been developed for the Kashkadarya River basin which considers irrigation runoff or drainage from individual irrigation districts.

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# Findings

## Overview

A description of the modeling system is included in the next section. The overall objectives of the project were to:

- Develop a Geographic Information System (GIS)-based decision support system for regional water resources planning that is applicable to the river basins of the Aral Sea region, and

- Demonstrate this system for portions of the Aral Sea basin: the Amudarya River and Kashkadarya River basins.

The decision support system integrates the advantages of GIS techniques into regional water resource allocation modeling. GIS software has a powerful capacity to represent real world water resource systems, and it can provide very useful information for building water resource allocation models. In this project the real-world water resource system and the abstract mathematical model are integrated in the GIS environment. Changes to the system in the real world can be input to the GIS and they are automatically reflected in an updated mathematical model.

The modeling system developed here is an interface between the GIS software, ARCVIEW (ESRI, 1996), and its object-oriented scripting language AVENUE, and GAMS (Brooke et al., 1992), a mathematical optimization software package. The water resource system is represented by maps, tables and charts in ARCVIEW. A mathematical model based on a network representation of the water resources system is used for water allocation, and GAMS is used to solve this model. Given the coverages and attributes which describe the water resource system in the real world, the modeling system (1) transfers geographic information into a form compatible with the mathematical model; (2) based on the geographic information, it builds a multiobjective optimization model in a format compatible with GAMS; (3) it calls the GAMS software to solve the model; and (4) the system displays the results in the GIS format.

Since all of these steps are done within ARCVIEW, all of the functions of ARCVIEW can be used by the modeling system. The modeling system adds additional functions and tools to ARCVIEW so that user can use it as a flexible water resources allocation decision support tool. The user needs to prepare the coverages and attributes describing the water resource system by digitizing them or taking them directly from some sources. Once the coverages and attributes are prepared, the modeling system will transfer the information into an abstract network by identifying the spatial relations among and between the geographic elements of the water resource system and create the data files necessary for the mathematical model in an interactive way. The modeling system provides tools for the user to modify or edit the network by adding or deleting nodes and links as needed for planning purposes, policy rules, or user interests. Some features of

a water resource system, such as hydropower stations, and treatment plants, which may not have been represented in the original coverages, can be added to the network.  The resulting network is the base of the water resources allocation model, and when it is ready, the user can activate the model generation tool, then the system will create a GAMS model based on the available information about the system.  This is an interactive process, in which the user makes some choices, such as the model type (linear or nonlinear), planning objectives, policy constraints and enters some parameters, such as the initial values for certain variables, or targets for objectives.  After the GAMS input files have been created, the modeling system calls the GAMS software to solve the model.  Finally the user can use the result view tool to see the modeling result in ARCVIEW.

## System Philosophy

The GIS-based decision support system is based on a philosophy of water resource system modeling which attempts to integrate the "real world" and the mathematical models used to support water resources decision making through the following steps: (1) representation of the "real world" by maps in the GIS, (2) representation of the water resource system by a network constructed from the GIS maps, and (3) allocation of the water in the system by solving a mathematical model constructed from the network representation.  Water resources management alternatives are developed and analyzed using the system through a multi-objective decision analysis framework where: (1) decision maker preferences can be expressed in the model through the use of the user interface, (2) social, environmental and economic objectives may be included in the model, and (3) tradeoffs between objectives can be analyzed with model.

## System Design

To achieve the project objectives within the framework of the system philosophy, a GIS-optimization system was designed and implemented.  This included the development of an interface between two popular software packages: (1) ARCVIEW, a powerful yet user friendly GIS package, and (2) GAMS (the General Algebraic Modeling System), a mathematical optimization modeling software system.  The resulting adaptive decision support system can: represent the existing water resources system in the GIS, update the GIS data base to reflect changes to that system, incorporate new model techniques through updated model scripts, and analyze new alternatives proposed by users.  Figure 1 shows the structure of the GIS-based decision support system (DSS) for regional water allocation.
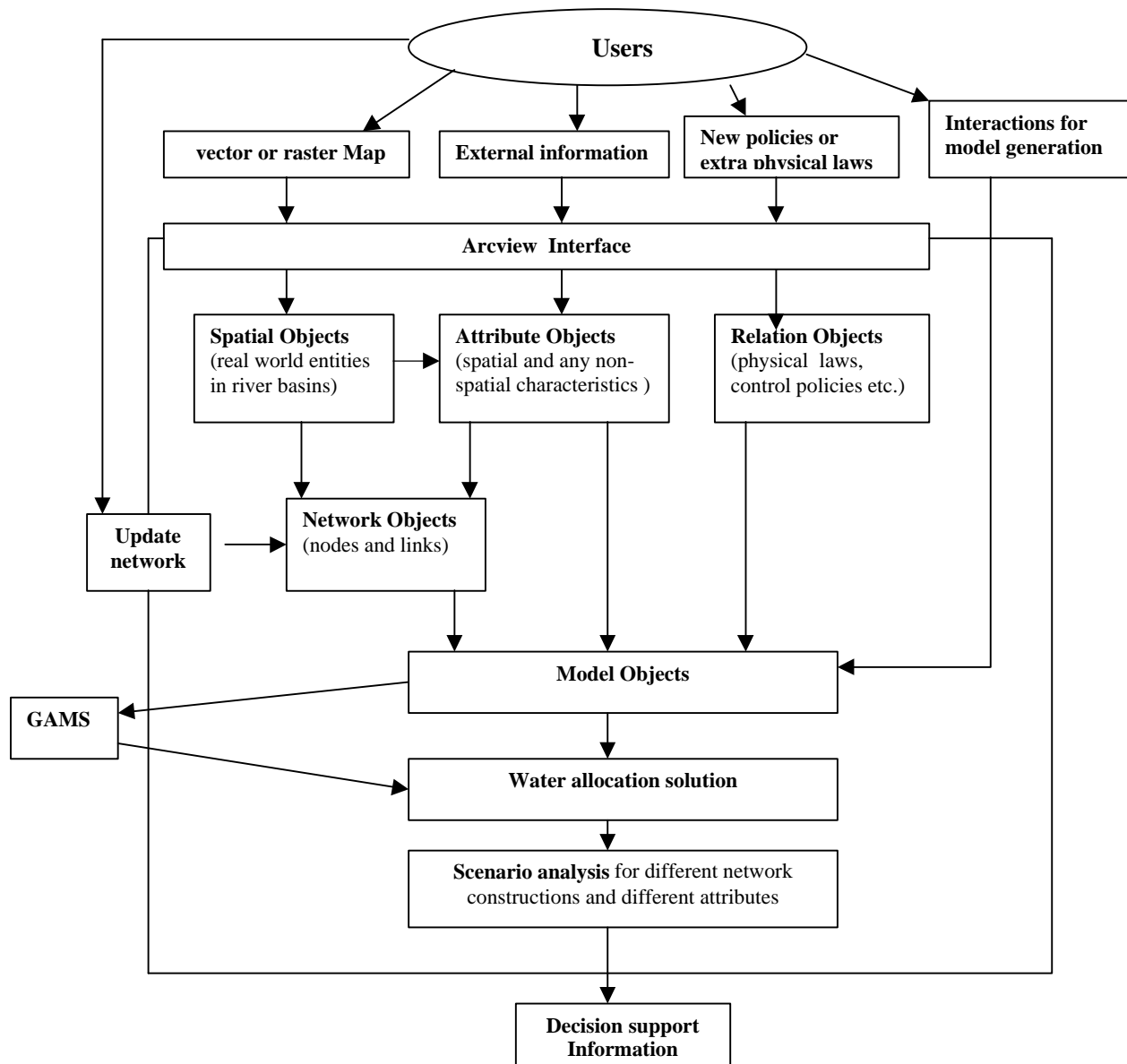
**Figure 1.** System structure scheme of the GIS-based DSS for regional water allocation.

## System Data

The water resource allocation system requires several types of data as input, including GIS "layers" or "coverages", water supply and demand data, and physical system parameters. The coverages for the Amudarya River basin include:

- main river,
- tributaries and canals which divert water to the river basin,
- canals, which take water from the main river to demand sites,
- collector canals, which collect the return water from demand sites,
- reservoirs and lakes,
- groundwater sources (aquifers),
- demand sites, which include cities and irrigation districts or fields, and
- administrative districts or regions.

These coverages must be digitized from maps using ARC/INFO, but in many cases they can also be digitized using ARCVIEW, or another GIS system with digitizing capacity. Within ARCVIEW, the features of a coverage are saved as themes, and the attributes associated with the coverage are stored as tables. For the modeling system, all of the coverages are added to a "view" called *Coverages* in ARCVIEW. An attribute table is associated with each theme or coverage. The geographic information, such as geographic coordinates, length for lines, area and perimeter for polygons, relative location for features, etc., are stored in the attribute table.

## Water Allocation Network

The abstract water distribution network is a bridge between the geographic representation of the water resource system and the mathematical model. Traditionally, to write a mathematical model for the simulation or optimization of a water resource system, one starts by developing a system network (a directed graph which represents a system by nodes and links) from maps or other materials. But here, the modeling system extracts the network (all the nodes and links) automatically once the user supplies the coverages to ARCVIEW. In ARCVIEW, the network is represented as a view called *network*, and each kind of node or link is represented as a theme added to the network view.

The network represents the water resource distribution system explicitly. The network treats each coverage as a node, and the connection between any two coverages as a link. In the coverage view, we can see the spatial relation between two coverages, for example, a tributary intersects with a demand site; while in the network view, we see a link (line) between them, which means the tributary may supply water to the demand site. The modeling system uses the spatial relations between coverages to determine whether there is a link between the coverages which must be included in the network.

Using various GIS spatial relations, the modeling system transfers the information about a river basin from coverages into an abstract network in which the connections between coverages are represented explicitly by links or arcs. For some links, the modeling system does not specify the links simply by their spatial relations, but specifies the links with a quantity. For example, for the links from a demand site to an aquifer, because a demand site may intersect with more that one aquifer, the portions of the demand site that overlay different aquifers are measured using grids. If the grid creation button is activated, an additional coverage, called *grids*, is created by the system when. We use the grids coverage as a measuring tool in the system. For example, to find the common area of an aquifer and a demand site, the modeling system identifies the grids

intersected by both the aquifer and the demand site coverage. The area of these grids is the desired area. The size of the girds can be adjusted to provide desired accuracy. The modeling system identifies the common grids that the demand site and each of the aquifers intersect, and calculates the corresponding areas by the number of the grids and the grid size.

The modeling system identifies most links by spatial relations. However, the links which are identified only by the spatial relations may not be effective in the real world. One reason is that the spatial relations may not correspond to a coverage "link", which represents, say, a water supply or return flow path. For example, when a tributary and a main river intersect at a demand site, which means the tributary intersects with the demand site, the water in the tributary may go into the main river, instead of to the demand site. On the other hand, in some locations the water supply may not be determined by spatial relations but by some social, environmental, or political considerations.

Typically, the coverages entered in ARCVIEW represent only the current water resource system. The user may want to analyze some planned changes to the existing system, and the modeling system can be used to be prepare some variants. However, using only spatial relations, the modeling system will not define network nodes and links for the variants since they may not exist in the original coverages. It is necessary for the user to use a tool to modify or update the network for this purpose. The modeling system provides a tool by which the user can add (or delete) new (or existing) nodes and links to build a variant network.

## Multiobjective Optimization Model

A general mathematical optimization model for regional water resources allocation has been developed in this research. A multiple-objective approach is used in the model to deal with the complexity of water allocation involving multiple purposes. The model is policy-oriented and uses the mechanism of goal programming. User interactions with the model include selecting the model type (linear for considering water quantity only or nonlinear for including water quality also), specifying initial conditions and targets for objectives, setting preferences (weights) for the objectives, and setting policy control constraints. A list of the variables, sets, indices, and parameters used in the model is provided in Appendix A.

### *Objectives*

We report here on the development of multiple objective optimization models for water allocation in the Amudarya and Kashkadarya River basins of Central Asia. It is difficult to express the water management goals of a complex situation such as the Aral Sea basin as a single objective. For example while the Aral Sea needs more inflow and the agricultural sector needs more irrigation water, each republic attempts to satisfy its own demand to the extent possible. Even in a year with larger than normal rainfall, conflicts among the various planning objectives will exist. Therefore, it is appropriate to deal with the problem using a multiple objective modeling approach.

The model developed here is expected to promote the understanding of, and aid in the development of, efficient and sustainable water allocation options for the republics that rely on Amudarya and Kashkadarya River basins for their water resources. The goal is to construct a screening tool which can be used to identify good alternatives for water management that can then be discussed, debated, modified, and simulated in greater detail.

There are several objectives which one may want to consider in the management of the Amudarya basin or the Kashkadarya River basin. The modeling system allows the user to select among several objectives to be included in the analysis. By specifying different objective weights, multiple objective analysis can be performed and tradeoffs between multiple objectives can be calculated. With this goal in mind, the modeling system includes multiple objectives, such as:

- Satisfy existing or projected water demands, primarily for irrigation, to the extent possible. In order to preserve the irrigation based economy of the region, it is necessary to maintain the flow of water to the irrigation districts of the area. To achieve this, the model maximizes the satisfaction of water demand at all demand sites; to achieve this, the model maximizes RI, the ratio of supply to demand over all periods and demand sites, maximizes RMIN over all periods for each demand site, and maximizes RMI over all demand sites in each period.

$$Z_1 = \sum_{dem} \sum_{pd} RI(dem, pd) \frac{DM(dem, pd)}{TDM(dem)}$$

where the ratio of *DM* over *TDM* is a scale coefficient for water demand which helps to avoid water always going to sites that have small demands.

- Minimize the difference in water deficits among all demand sites. This equalizes the rights to water, i.e., ensures that demand sites share the available water equally, and on the other hand distributes the risk of a water shortage as evenly as possible among periods. To achieve this goal, the model maximizes *RMI*, the minimum *RI* in one period over all demand sites, and maximizes *RMIN*, the minimum *RI* of one demand site over all periods

$$Z_2 = \sum_{pd} RMIN(pd) + \sum_{pd} RMI(pd)$$

- Maximize the flow to downstream river nodes, e.g., the Aral Sea, the model maximizes the ratio of annual downstream flow to the annual upstream flow. Clearly this is a desirable objective given the precipitous drop in the surface area of the sea and the resulting ecological and economic consequences of the sea level decline. However, we must recognize the conflicts in trying to achieve this goal

$$Z_3 = \sum_{pd} \frac{Flow("downstream", pd)}{\sum_{pd} SOURCE("main\_river", pd)}$$

- Maximize hydropower generation, the model maximizes the ratio of calculated power to the users' target value

$$Z_4 = \prod_{rev \in RPLINK} \sum_{pwst} FAC\_PW(pwst)RELS(rev)$$

where *RELS(rev)* is the total release of reservoirs connected to hydropower stations. The release includes that to the main river nodes, demand sites and canals,

$$RELS(rev) = \sum_{pd}\left[\sum_{rn} RES\_N(rev,rn,pd) + \sum_{dem} RES\_D(rev,dem,pd) + \sum_{cal} RES\_CAL(rev,cal,p)\right]$$

More accurate hydropower expressions can be formulated, but as this was not the main focus of the water allocation model developed here, a simplified relationship was used. For a more comprehensive treatment of hydropower, please refer to the Syrdarya River basin study.

- Minimize the concentration of salts in the system, the model minimizes the ratio of salt concentration to the users' target value in the main river, tributaries, reservoirs and aquifers.

$$Z_5 = \sum_{sou}\sum_{pd}\frac{C_s(sou,pd)}{C_{s\_exp}(sou)} + \sum_{rev}\sum_{pd}\frac{C_r(rev,pd)}{C_{r\_exp}(rev)} + \sum_{rn}\sum_{pd}\frac{C_n(rn,pd)}{C_{n\_exp}(rn)} + \sum_{gd}\sum_{pd}\frac{C_g(gd,pd)}{C_{g\_exp}(gd)}$$

- Minimize water diverted from other basins, the model minimizes the ratio of the calculated diverted water to the users' target value.

$$Z_6 = \sum_{pd}\frac{ASOU(pd)}{A_{s\_exp}(sou)}$$

By integrating these objectives with the system's physical, political, and operational constraints into an optimization model, one can:

- Analyze the tradeoffs between the conflicting objectives of flow to the Aral Sea and satisfaction of agricultural water demand and develop a number of water allocation scenarios to aid decision making;

- Investigate the effect of uncertainties in the water supply and demands.

- Develop optimum operating rules for the principal reservoirs and surface-ground water systems of the Aral sea basin.

Through the use of the GIS-optimization decision suport interface, these objectives can be combined into a single objective function by multiplying each by a weight reflecting the importance of that objective and forming a linear combination of the objectives

$$Maximize\ Z = w_1Z_1 + w_2Z_2 + w_3Z_3 + w_4Z_4 + w_5Z_5 + w_6Z_6$$

## *Constraints*

There are three kinds of constraints in the optimization model, physical constraints (e.g., mass balances), policy constraints (e.g., upper and lower bounds on variables), and system control constraints (e.g., to maintain feasibility). The physical constraints are created by the modeling system directly, and the policy and system control constraints are specified by the user interface to the modeling system.

The physical constraints comprise the major portion of the model constraints. The concept of this kind of constraint is a physical mass balance relationship, including water and salt mass balances in the main river, tributaries, reservoirs, lakes, aquifers, and demand sites. The physical constraints also include some physical limits, such as river and canal diversion capacity, groundwater pumping capacity, hydropower generation capacity, and wastewater treatment plant capacity.

The policy constraints are added by setting upper and lower bounds for some variables. For example, the water diversion from a tributary to a demand site may not be allowed to exceed a given amount because more water is needed for downstream use.

The system control constraints are used to guide the model and keep its solution as close to real world conditions as possible. Since the solution of the model is just a numerical optimization result, sometimes using only the physical and policy constraints will not completely constraint the model solution within real world conditions. The system control constraints are used to compensate for this. Generally these constraints are added to the model by a user during the model formulation process. Currently the system can help the user set a constraint on the main river flow to keep the flow smooth from one period to the next period.

- Mass balance at demand site *dem* in period *pd*

$Groundwater\ +\ Re\,servoir\,water + River\,diversion + Local\ surface\ water + Canal\,diversion$
$= Total\ water\ \sup plied\ to\ demand\ site$

$$\sum_{gd \in GDLINK} GWP(gd, dem, pd) + \sum_{rev \in RDLINK} RES\_D(rev, dem, pd)$$

$$+ \sum_{rn \in NDLINK} N\_DMS(rn, dem, pd) + \sum_{sou \in SDLINK} S\_DMS(sou, dem, pd)$$

$$+ \sum_{cal \in CDLINK} CAL\_DEM(cal, dem, pd) + \sum_{trm \in TDLINK} T\_D\_FL(trm, dem, pd)$$

$$= TOT\_INF(dem, pd)$$

- Mass balance of water delivered to demand site *dem* in period *pd*

*Water in collectors + Infiltration + Evapotranspiration + Plant consumptive use*
*= Total water delivered to demand site*

$$\sum_{drn \in DMDRLINK} GWP(dem, drn, pd) +$$

$$\sum_{gd \in GDLINK} RTN\_D\_G(dem, gd, pd) \cdot TOT\_INF(dem, pd)$$

$$+ EVAPT(dem, pd) \cdot TOT\_INF(dem, pd) + COMSUP(dem, pd) \cdot TOT\_INF(dem, pd)$$

$$= TOT\_INF(dem, pd)$$

- Definition of *RI*, the ratio of water supply to demand

*Total water supply = Water demand \* Ratio of supply to demand*

$$TOT\_INF(dem, pd) = DM(dem, pd) \cdot RI(dem, pd)$$

where, if *DM(dem,pd)* =0, then *RI(dem,pd)* =1.

- Definition of *RMI* and *RMIN*

$$RMIN(pd) \leq RI(dem, pd)$$

$$RMI(dem) \leq RI(dem, pd)$$

- Water balance in a tributary or canal that diverts water from other basins

*Source water + Water returned from collectors + Water returned from treatment plants*
*= Water to demand sites + Water to main river + Water to reservoirs + Infiltration*

$$SOURCE(sou, pd) + \sum_{DRN \in dslink} D\_SOU(drn, sou, pd) +$$

$$\sum_{trm \in TSLINK} T\_S\_FL(trm, sou, pd)$$

$$= \sum_{dem \in SDLINK} S\_DMS(sou, dem, pd) + \sum_{rn \in SNLINK} S\_RIV(sou, rn, pd)$$

$$+ \sum_{rev \in SRLINK} S\_RES(sou, rev, pd)$$

$$+ \sum_{gd \in SGLINK} LOSS\_S\_G(sou, gd) \cdot SOURCE(sou, pd)$$

- Water balance at main river nodes

*Flow at node = Flow from upper node + Flow return  from collectors +*
*Flow from treatment plants + Flow from tributaries + Flow  from reservoirs*
*- Diversion water - Flow to canal - Infiltration*

$$FLOW(rn, pd)$$

$$= FLOW(up\_rn, pd) + \sum_{drn \in DNLINK} D\_RIV(drn, rn, pd) +$$

$$\sum_{rev \in RNLINK} RES\_N(rev, rn, pd) + \sum_{sou \in SNLINK} S\_RIV(sou, rn, pd) +$$

$$\sum_{trm \in TNLINK} T\_N\_FL(trm, rn, pd) - \sum_{dem \in NDLINK} N\_DMS(rn, dem, pd) -$$

$$\sum_{cal \in RICLLINK} N\_CAL(rn, cal, pd) - \sum_{gd \in NGLINK} LOSS\_N\_G(rn, gd) \cdot FLOW(rn, pd)$$

- Reservoir water balance

*Storage in this period = Storage in last period +*
*Water from tributaries (or source canal)*
*+ Water from main river + Water from collectors + Water from treatment plants*

*+ Water from upstream reservoirs - Release to main river - Release to canals*
*- Diversion to use - infiltration - Downstream reservoirs - Evaporation*

$$RES\_ST(rev, pd)$$

$$= RES\_ST(rev, pd - 1) + \sum_{sou \in SRLINK} S\_RES(sou, rev, pd) +$$

$$\sum_{rn \in NRLINK} FLOW(rn, pd) + \sum_{drn \in DRLINK} D\_REV(drn, rev, pd - 1) +$$

$$\sum_{trm \in TRLINK} T\_R\_F(trm, rev, pd) + \sum_{rev\_up \in RRLINK} RE\_REV(rev\_up, rev, pd) -$$

$$\sum_{rn \in RNLINK} RES\_N(rev, rn, pd) + \sum_{cal \in RCLINK} RE\_CAL(rev, cal, pd) -$$

$$\sum_{dem \in RDLINK} RES\_D(rev, dem, pd) - \sum_{gd \in RGLINK} LOSS\_R\_G(rev, gd) \cdot RES\_ST(rev, pd) -$$

$$\sum_{rev\_lo \in RRLINK} RE\_REV(rev, rev\_lo, pd) - REVAP(rev, pd) \cdot RES\_ST(rev, pd)$$

- Water balance in canals

*Water from main river + Water from reservoirs > Water to demand sites + Infiltration*

$$\sum_{rn \in RICLINK} RI\_CAL(rn, cal, pd) + \sum_{rev \in RCLINK} RE\_CAL(rev, cal, pd)$$

$$\sum_{gd \in NDGLINK} (LOSS\_ND\_G(cal, gd) \cdot \sum_{rn \in RICLINK} RI\_CAL(rn, cal, pd)$$

$$+ \sum_{dem \in CDLINK} CAL\_DM(cal, dem, pd)$$

- Water balance in collectors

*Return flow from demand sites = Return flow (untreated) to tributaries*
*+ Return flow to reservoirs + Return flow to main river*

$$\sum_{dem \in DMDRLINK} DM\_DRN(dem, drn, pd)$$

$$= \sum_{sou \in DSLINK} D\_SOU(drn, sou, pd) + \sum_{rev \in DRLINK} D\_REV(drn, rev, pd)$$

$$+ \sum_{rn \in DNLINK} D\_RIV(drn, rn, pd)$$

- Water balance in treatment plants

   *Return flow from demand sites  = Return flow (treated) to demand sites + Return flow to tributaries + Return flow to reservoirs + Return flow to the main river + Return flow to aquifers*

$$\sum_{dem \in DTLINK} D\_T\_Fl(dem, trm, pd) =$$

$$= \sum_{dem \in DTLINK} T\_D\_Fl(trm, dem, pd) + \sum_{sou \in TSLINK} T\_S\_Fl(trm, sou, pd)$$

$$+ \sum_{rev \in TRLINK} T\_R\_Fl(trm, rev, pd) + \sum_{rn \in TNLINK} T\_N\_Fl(trm, rn, pd)$$

$$+ \sum_{gd \in TGLINK} T\_G\_Fl(trm, gd, pd)$$

- Water balance in aquifers

   *Volume this period = Volume last period + Recharge from demand sites*
   *+ Recharge from reservoirs + Recharge from main river segments*
   *+ Recharge from tributaries + Recharge from canals + Recharge from treatment plants*
   *- Pumping to demand sites - Outflow*

$$GW\_ST(gd, pd) =$$

$$GW\_ST(gd, pd - 1) + \sum_{dem \in GDLINK} RTN\_D\_G(dem, gd, pd) \cdot TOT\_INF(dem, pd)$$

$$+ \sum_{rev \in RGLINK} LOSS\_R\_G(rev, gd) \cdot RES\_ST(rev, pd - 1)$$

$$+ \sum_{rn \in NGLINK} LOSS\_N\_G(rn, gd) \cdot FLOW(rn, pd - 1)$$

$$+ \sum_{sou \in SGLINK} LOSS\_S\_G(sou, gd) \cdot SOURCE(sou, pd - 1)$$

$$+ \sum_{cal \in NDGLINK} (LOSS\_ND\_G(cal, gd) \cdot \sum_{rn \in RICLINK} RI\_CAL(rn, cal, pd))$$

$$+ \sum_{trm \in TGLINK} T\_G\_Fl(trm, gd, pd) - \sum_{dem \in GDLINK} GWP(gd, dem, pd)$$

$$- FLUX(gd, pd)$$

where outflow is effective only when the aquifer volume is full and the lag time for surface water recharging groundwater is assumed to be one period (month).

- Groundwater pumping limit

  *Groundwater pumped  <  pumping capacity*

$$\sum_{pd} \sum_{dem \in GDLINK} GWP(gd, dem, pd) \leq PUMP\_CAL(gd)$$

- Salt balance at demand sites

  *( salt from groundwater  + salt from reservoir supply + salt from river supply*
  *+ salt from tributaries + salt from canal supply ) * ( 1 + salt increasing rate*
  *due to irrigation )*
  *= salt transport to  drainages +  to aquifers + to treatment plants +*
  *plant absorption  + to evaporation*

$$[\sum_{gd \in GDLINK} GWP(gd, dem, pd)Cg(gd, pd) + \sum_{rev \in RDLINK} RES\_D(rev, de, pd)Cr(rev, pd)$$

$$+ \sum_{rn \in NDLINK} N\_DMS(rn, dem, pd)Cn(rn, pd) + \sum_{sou \in SDLINK} S\_DMS(sou, dem, pd)Cs(sou, pd)$$

$$+ \sum_{cal \in CDLINK} CAL\_DM(cal, dem, pd)Cc(cal, pd)$$

$$+ \sum_{trm \in TDLINK} T\_D\_Fl(trm, dem, pd)Ct(trm, pd)] \cdot (1 + salt\_chg(dem))$$

$$= [\sum_{drn \in DMDRLINK} DM\_DRN(dem, drn, pd) + \sum_{gd \in GDLINK} RTN\_G\_D(dem, gd, pd) \cdot TOT\_INF(dem, pd)$$

$$+ com \sup(dem, pd) \cdot TOT\_INF(dem, pd)] \cdot Cd(dem, pd)$$

- Salt balance in a tributary or canal that diverts water from other basins

  *salt in source + salt from collectors*
  *+ salt from treatment plants*
  *= salt transport to demand sites + to main river*
  *+ to reservoirs + to aquifers*

$$SOURCE(sou, pd) \cdot conc0\_s(sou) + \sum_{DRN \in dslink} D\_SOU(drn, sou, pd) \cdot Cdr(drn, pd) +$$

$$\sum_{trm \in TSLINK} T\_S\_FL(trm, sou, pd) \cdot Ct(trm, pd)$$

$$= [\sum_{dem \in SDLINK} S\_DMS(sou, dem, pd) + \sum_{rn \in SNLINK} S\_RIV(sou, rn, pd)$$

$$+ \sum_{rev \in SRLINK} S\_RES(sou, rev, pd)$$

$$+ \sum_{gd \in SGLINK} LOSS\_S\_G(sou, gd) \cdot SOURCE(sou, pd)] \cdot Cs(sou, pd)$$

- Salt balance at main river node*s*

  *salt in flow at this node =*

*salt from upper node + salt flow drainages  +*
*salt from treatment plants + salt from tributaries +*
*salt from reservoirs*
*- salt transport to demand sites - to canals - to aquifers*

$FLOW(rn, pd) \cdot Cn(rn, pd)$

$$= FLOW(up\_rn, pd) \cdot Cn(up\_rn, pd) + \sum_{drn \in DNLINK} D\_RIV(drn, rn, pd) \cdot Cdr(drn, pd) +$$

$$\sum_{rev \in RNLINK} RES\_N(rev, rn, pd) \cdot Cr(rev, pd) + \sum_{sou \in SNLINK} S\_RIV(sou, rn, pd) \cdot Cs(sou, pd) +$$

$$\sum_{trm \in TNLINK} T\_N\_FL(trm, rn, pd) \cdot Ct(trm, pd) - [\sum_{dem \in NDLINK} N\_DMS(rn, dem, pd) +$$

$$\sum_{cal \in RICLLINK} N\_CAL(rn, cal, pd) + \sum_{gd \in NGLINK} LOSS\_N\_G(rn, gd) \cdot FLOW(rn, pd)] \cdot Cn(rn, pd)$$

- Salt balance in reservoirs

  *salt in this period =*
  *salt in last period + salt from tributaries (or source canal)*
  *+ salt from main river  +  salt from drainages +*
  *+ salt from treatment plants  + salt from upstream reservoirs*
  *- salt transport to main river  - to canals - to downstream reservoirs*
  *-to demand sites - to aquifers*

$$[RES\_ST(rev,pd)+stg0(rev)]\cdot Cr(rev,pd)$$

$$=RES\_ST(rev,pd-1)\cdot Cr(rev,pd-1)+\sum_{sou\in SRLINK}S\_RES(sou,rev,pd)\cdot Cs(sou,pd)+$$

$$\sum_{rn\in NRLINK}FLOW(rn,pd)\cdot Cn(rn,pd)+\sum_{drn\in DRLINK}D\_REV(drn,rev,pd-1)\cdot Cdr(drn,pd)+$$

$$\sum_{trm\in TRLINK}T\_R\_F(trm,rev,pd)\cdot Ct(trm,pd)+\sum_{rev\_up\in RRLINK}RE\_REV(rev\_up,rev,pd)\cdot Cr(rev\_up,pd)$$

$$\sum_{rn\in RNLINK}RES\_N(rev,rn,pd)\cdot Cn(rn,pd)-[\sum_{cal\in RCLINK}RE\_CAL(rev,cal,pd)+$$

$$\sum_{dem\in RDLINK}RES\_D(rev,dem,pd)+\sum_{gd\in RGLINK}LOSS\_R\_G(rev,gd)\cdot RES\_ST(rev,pd)+$$

$$\sum_{rev\_lo\in RRLINK}RE\_REV(rev,rev\_lo,pd)]\cdot Cr(rev,pd)$$

- Salt balance in canals

*salt from the main river segments + salt from reservoirs  >*
*salt transport to  demand sites  + salt transport to aquifers*

$$\sum_{rn\in RICLINK}RI\_CAL(rn,cal,pd)\cdot Cn(rn,pd)+\sum_{rev\in RCLINK}RE\_CAL(rev,cal,pd)\cdot Cr(rev,pd)$$

$$\geq[\sum_{dem\in CDLINK}CAL\_DM(cal,dem,pd)+\sum_{gd\in NDGLINK}(LOSS\_ND\_G(cal,gd)\cdot$$

$$\sum_{rn\in RICLINK}RI\_CAL(rn,cal,pd)]\cdot Cc(cal,pd)$$
$$Cc(cal,pd)$$

- Salt balance in collectors

*salt from demand sites  >*
*salt transport + to tributaries*
*+ to reservoirs + to the main river*

$$\sum_{dem \in DMDRLINK} DM\_DRN(dem, drn, pd) \cdot Cd(dem, pd)$$

$$= [\sum_{sou \in DSLINK} D\_SOU(drn, sou, pd) + \sum_{rev \in DRLINK} D\_REV(drn, rev, pd)$$

$$+ \sum_{rn \in DNLINK} D\_RIV(drn, rn, pd)] \cdot Cdr(drn, pd)$$

- Salt balance in treatment plants

*salt from demand sites * (1- salt clearance rate) =*
*+ salt transport to demand sites + to tributaries*
*+ to reservoirs + to the main river + to aquifers*

$$\sum_{dem \in DTLINK} D\_T\_Fl(dem, trm, pd) \cdot Cd(dem, pd) \cdot (1 - clr\_rate(trm, pd)) =$$

$$= [\sum_{dem \in DTLINK} T\_D\_Fl(trm, dem, pd) + \sum_{sou \in TSLINK} T\_S\_Fl(trm, sou, pd)$$

$$+ \sum_{rev \in TRLINK} T\_R\_Fl(trm, rev, pd) + \sum_{rn \in TNLINK} T\_N\_Fl(trm, rn, pd)$$

$$+ \sum_{gd \in TGLINK} T\_G\_Fl(trm, gd, pd)] \cdot Ct(trm, pd)$$

- Salt balance in aquifers

*salt in this period =*
*salt in last period + salt from demand site recharge*
*+ salt from reservoir recharge + salt from main river recharge*
*+ salt from tributary recharge  + salt from canal recharge*
*+ salt from reatment plant recharge*
*-   salt transport to demand sites - salt outflux*

$$[GW\_ST(gd, pd) + gwst0(gd)] \cdot Cg(gd, pd) =$$

$$[GW\_ST(gd, pd - 1) + gwst0(gd)] \cdot Cg(gd, pd - 1)$$

$$+ \sum_{dem \in GDLINK} RTN\_D\_G(dem, gd, pd) \cdot TOT\_INF(dem, pd) \cdot Cd(dem, pd)$$

$$+ \sum_{rev \in RGLINK} LOSS\_R\_G(rev, gd) \cdot RES\_ST(rev, pd - 1) Cr(rev, pd - 1)$$

$$+ \sum_{rn \in NGLINK} LOSS\_N\_G(rn, gd) \cdot FLOW(rn, pd - 1) \cdot Cn(rn, pd - 1)$$

$$+ \sum_{sou \in SGLINK} LOSS\_S\_G(sou, gd) \cdot SOURCE(sou, pd - 1) \cdot Cs(sou, pd - 1)$$

$$+ \sum_{cal \in NDGLINK} (LOSS\_ND\_G(cal, gd) \cdot \sum_{rn \in RICLINK} RI\_CAL(rn, cal, pd)) \cdot Cc(cal, pd)$$

$$+ \sum_{trm \in TGLINK} T\_G\_Fl(trm, gd, pd - 1) \cdot Ct(trm, pd - 1)$$

$$-[\sum GWP(gd, dem, pd) + FLUX(gd, pd)] \cdot Cg(gd, pd)$$

- Policy constraints

  Variable bounds on reservoir storage, aquifer volumes, salt concentrations, river flow limits and requirements, canal diversion capacity, collector capacity, treatment plant capacity, hydropower generation capacity, etc.

- System control constraints

  Currently, these are used for flow control in the main river. These constraints account for the fact that if more water is available in one period than the next, more flow will occur in the first period, but the difference of flows in two periods should be in some reasonable range.

  e.g., if the source water in period *pd* is more than that in period *pd-1*, then

  $$FLOW(rn, pd) \geq FLOW(rn, pd - 1) \quad and$$
  $$FLOW(rn, pd) \leq r \cdot FLOW(rn, pd - 1)$$

in which $r$ is a parameter, $r > 1$.

## *Assumptions and limitations of the model*

A comprehensive model for regional water resources allocation decision support is presented here. The model describes the major physical processes in a water resource system, and these processes include flow and salt transport in rivers, reservoir operation and hydropower generation, aquifer operation and interaction between surface water and groundwater, water distribution and return flows, and water treatment. Some simplifications of those physical processes are made in the model since the complexity of the physical process creates difficulty for available optimization model solvers.

The model uses a monthly time step, which may be suitable for water resources allocation on a macro-level, but it does not have meaning for some of the physical processes. Also, in modeling the interaction of surface water and groundwater, the aquifers are treated as separate groundwater reservoirs without flow links between them. There is infiltration from surface water sources such as reservoirs, streams and canals to aquifers, but not in the reverse direction.

## System Operation

In the general operation of the system the user and the system interact in various ways to define the water resources system being studied and then generate a water allocation model for solution and display of results. These interactions include (see Figure 1):

- User - prepares coverages and attributes
- System - creates network from coverages
- User - modifies network or data using system tools
- System - creates GAMS model based on network and interactions with users
- System - calls GAMS to solve the model
- User - views results using system tools

Beyond supplying the original coverages to automatically define the network, and modifying that network by adding or deleting nodes and links, the user can further interact with the modeling system by the following actions:

- Selecting the model type: linear or nonlinear. In the linear model, no water quality issues are considered, and the run time for solution is much shorter than the nonlinear model, which includes salt transport and salt mass balance.

- Specifying initial values for some variables, for example, the initial storage of reservoirs and available groundwater volume. The model is sensitive to the initial conditions and different initial conditions lead to different results. The selection of the initial conditions reflects the

user's opinion to the risk associated with the water allocation plans resulting from the model solution. A worst case initial condition should lead to lower risk in the water allocation plan. The user may try several alternatives of the initial conditions, and then select an appropriate one.

- Specifying targets for the objectives, which includes setting the salt concentration targets for streams, reservoirs and lakes, and aquifers, and the target for inter-basin water transfer if there is such a diversion.

- Setting the upper and lower bounds for some variables.

- Setting the user's preference for the objectives (objective weights). This interaction can be used to select which objectives to include in the analysis; setting a zero weight for an objective will exclude it from consideration.

- Setting parameters in the system control constraints.

Since the model is created from the network, the model formulation depends on the network configuration. If the network includes all the nodes and links described above, the modeling system will create a model that includes all the objective and constraint equations related to the nodes and links in the network. Examples of such models for the Amudarya and Kashkadarya River basins are included below.


## System Installation

The modeling system files have been archived in single files, one for each river basin, using PKZIP or WINZIP. The files are called aral.zip for the Amudarya River system and karshi.zip for the Kashkadarya River system. These systems can be installed by the following steps:

1. Create a new folder on drive C of the computer. Name the folder "aral1" for the whole Amudarya River basin, and "karshi1" for the Kashkadarya River basin;

2. Copy all the files and directories from the disks into the folder. If you are using the ZIP files, use PKUNZIP or WINZIP to open the zipped file and then extract all files to the folder.

The steps involved in operating the system are illustrated here:

- **Open the Project.** Activate ARCVIEW, and select "Open Project" from the "File" menu and switch to the project folder "karshi1" and locate the project name karsh.apr to work with the Kashkadarya River basin or "aral1" and locate the project name aral.apr to work with the Amudarya River basin, and then open the project by clicking "OK" in the prompt window. Now the project is open, and you will see some tool buttons just below the window menu.

- **View the Geographic Coverage**. In the view list, double click "Coverages", and this view is opened. The view shows the real world that the system deals with.

- **Create the Function Network.** Now use view "Coverages" just opened to create the functional network based on the geographic coverage shown in the view. To do that, click the item "Network" in the menu, and three sub-items for next choice. First click "Add Nodes", and a new view namely "Network" is then opened and the themes representing various nodes are added automatically into this view. After nodes are added, choose "add links" from the menu item "Network". This step takes a little longer since the AVENUE programs must examine the various spatial relationships existing in the real world representation, and identify all the links for the functional network. During this step, a couple of pauses are set to show the progress and if the user confirms the status, by clicking OK, the process continues. Then the links are shown in view "Network".

- **Modify the Network.** Click "modify network" from item "Network" in the view menu, there is a message window to tell the user how to modify the network. Several tools (buttons) are available for network modification. These are described in the following:

- **Add nodes.** Click the "add node" button,  and a menu appears for the user to select the types of nodes to be added: reservoir on main river, reservoir on tributary, river node on main river, demand site, surface source, power station, or treatment plant. When the node type has been selected, the modeling system will ask the user to specify the name of the node, the location of the node in the view and the connections of the node with other nodes. For example, if the user chooses to add a power station, the modeling system first ask the name of the station, and then ask which reservoir the station is associated with. There is another button  for adding a node, which allow the user to select the location in the network for the note to be added. Click the button, and then click the place where to put the node, and then specify the type and the name of the node just as above, the new node will show up in the network.

- **Add links.** Activate the "add link" button , and then select the starting point (node) of the link to be added to the view. Then a window will appear to ask the user to select the class that the link to be added belongs. After that a window will notify the user of the node type of the end point of link to be added, and the user may select the end point of link. If the selected type is not compatible with the selected feature, the system will show an error message. For example, if one wants to add a link between a river node and a demand site. First select the "add link" button, select the river node, select the link type "from river node to demand site" in the menu, and finally select the demand site node. When the link has been added, select the "view update" button,  and the specified link will be added to the view.

- **Deleting nodes & links.** Activate the "delete nodes & links" tool,  and then select the node or link to be deleted. A window will appear to let the user select which kind of node or

link is to be deleted.  After selection, the node or link is ready to be deleted.  If the selected type is not compatible with the selected feature, the modeling system will show an error message.  When the node or link has been deleted, select the "view update" button, and the link just specified will be deleted from the view.  It is not necessary to select the "view update" button every time.  One can specify several additions or deletions, and then use the "view update" button a single time.  When the selected point is not a feature (node or link) in the current view, or the user selected a feature which is not compatible with the selected feature types, the modeling system will display an error and the user may try again.

Default networks have been prepared for both river basins.  If the user wants to use the default network, just go to the project menu and click the button ![icon]. Then the default network will replace the current network, if it exists.  Note that if the user does not want the current network to be replaced by the default, then the current network should be saved under a new file name.

- **Input/Update Data**.  Since all of the attribute data is stored with nodes in the system, the attribute data is classified by the type of nodes.  Therefore before updating the attribute data, the user must know the type of nodes with which the attribute data is connected.  To input or update the attribute data, select the "data input & update" button, and then select one node in the network.  A menu will display the type of data stored with this node.  After selecting the data type, the system will show the default data in a table (for some data types, the system also shows the data in a chart).  The user can modify the data in this table or just take the default value.

- **Create General Algebraic Modeling System (GAMS) Model Code.**  Select the GAMS model generation button, ![icon] and then the modeling system will begin the interactive process of model generation.  The user is asked to set various values for the initial conditions, policy targets by following the system messages.  For most items, the system will provide default values or conditions, and the user can either take or modify these default values.  Before some interactions, the system will give a message to tell the user what to do in the next step, and the user is recommended to read those messages carefully when they first use the system.  After the GAMS input file has been created, the modeling system will let the user run GAMS to solve the model which has been constructed.

- **Running GAMS Model Code.**  The modeling system creates four GAMS files:

    1. lp_m.gms (or nlp_m.gms)        GAMS solution options
    2. nd-lk.txt                               GAMS model sets, tables and parameters
    3. equ.txt,                                 GAMS variables and equations
    4. opt.txt                                   GAMS result output report

The file lp_m.gms is created if the user has selected the option for a linear model (for no salt balance).  The file nlp_m.gms is created if the user has selected the option for a linear

model (including salt balance).  The user can view and edit those files in any text editor.  All these files are stored in the directory \karshi\gams or \aral\gams.

The linear model, which does not consider water quality (salt balance), should find a optimal solution to the problem if the reasonable data has been input.  If the solution status from GAMS is other than "optimal solution", such as "unbounded solution" or "infeasible solution", the user is recommended to check the data by using the "data input & update" button.  In case there are some compilation errors, the user can open the file lp_m.lst (or nlp_m.lst, for the nonlinear model) in the directory in which the project is saved to see the errors.

The nonlinear model is more complex than the linear model.  If the nonlinear model gives a result other than "optimal solution", we recommend that the user modify the upper and lower bounds for the concentration variables.  The user can also try to modify the parameters set in the option file "minos5.opt" in any text editor.  For the details on solving nonlinear models with GAMS, refer to (Brooke et al., 1987).

- **View Results.**  click the "result view" button , and then follow the message boxes to make some choices and see the results that are of interest.  The results are displayed as charts, tables, and message boxes.  The user can open those files in any text editor.


## Example –Amudarya River basin

An example of applying the modeling system to water allocation in the Amudarya River basin is presented in this section.


## *GIS Representation*

The coverages making up the GIS representation of the Amudarya River basin water resource system are shown in Figure 2.
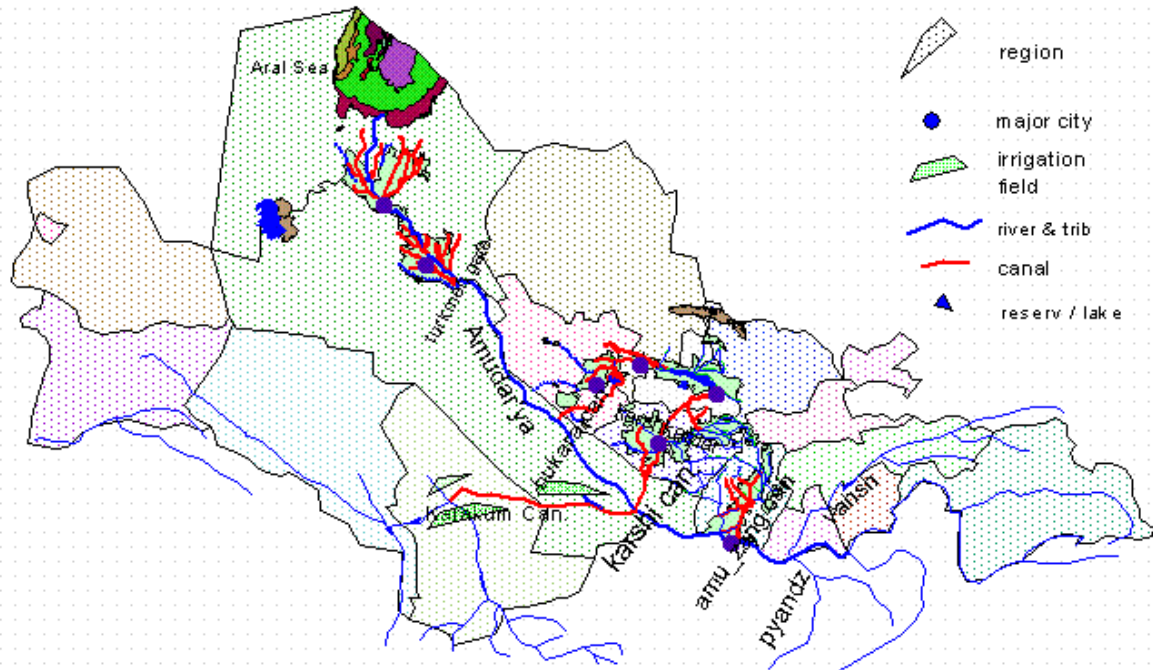
**Figure 2.** GIS coverages for the Amudarya River basin.

## *Network Representation*

The network representation of the Amudarya River basin water resource system are shown in Figure 3. This network was generated automatically by the modeling system from the coverages shown in Figure 2.
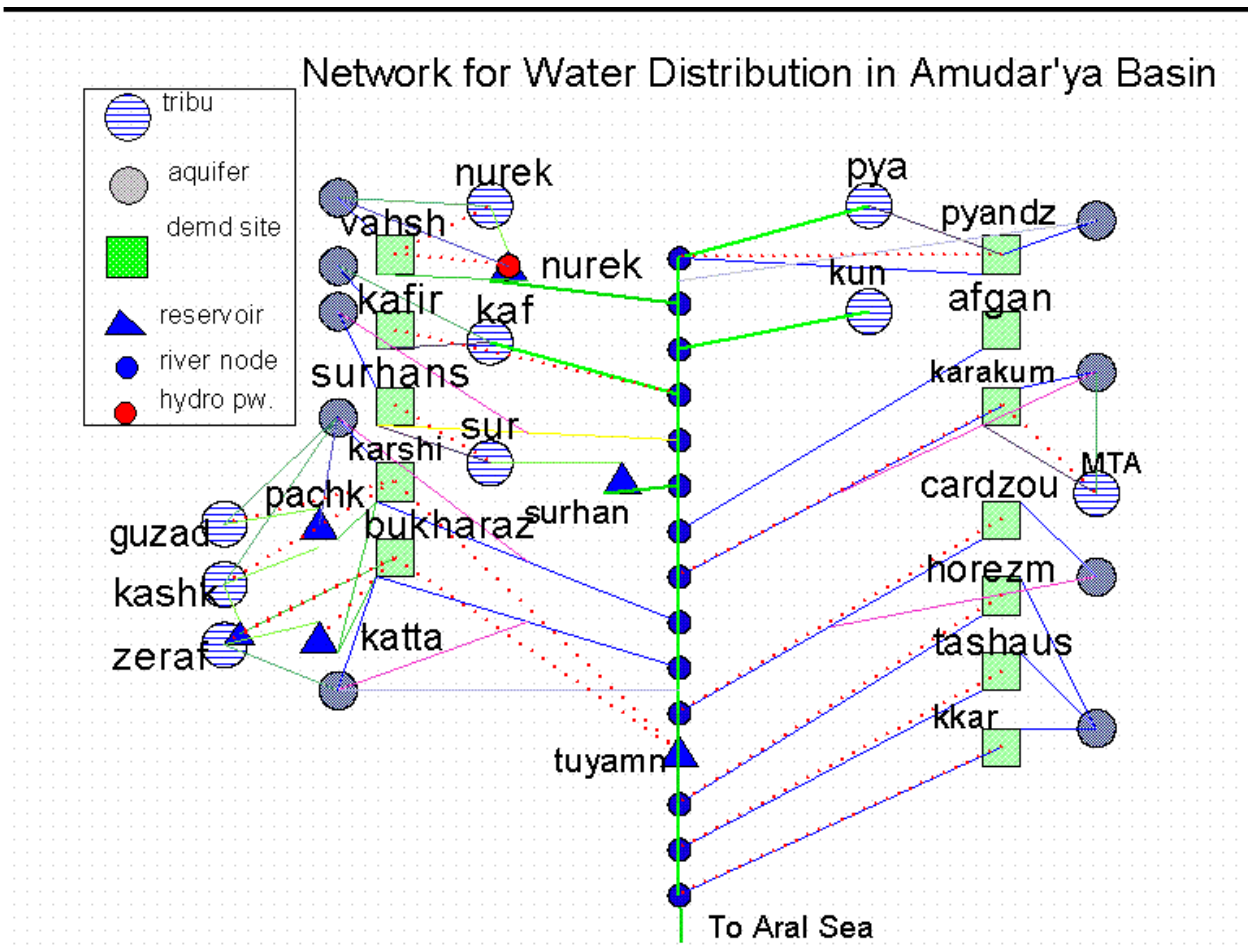
**Figure 3.** Network representation of Amudarya River basin.

## Water Supply Data

Available sources of groundwater supply are listed in Table 1 (Raskin et al., 1992). Water availability for the basin in various years corresponding to different hydrological conditions of dry (total supply = 39.2 km$^3$/yr), normal (total supply = 78.8 km$^3$/yr), and wet (total supply = 87.2 km$^3$/yr) is listed in Table 2 (Raskin et al., 1992). Note that the water availability in a normal year is less than the demand.

**Table 1.** Groundwater Supply in the Amudarya Basin (km$^3$/yr) (Raskin et al., 1992).

| Source | Capacity (km$^3$/yr) |
|---|---|
| PYANDZ | 0.275 |
| VAHSH | 0.173 |
| KAFIR | 0.495 |
| SURHANS | 0.416 |
| KARAKUM | 0.299 |
| KARSHI | 1.03 |
| BUKHARAZ | 0.414 |
| CARDZOU | 0.591 |
| Lower Amu | 0.343 |
| Total | 4.036 |

**Table 2.** Water Supply (km$^3$/yr) in the Amudarya River Basin [Raskin et al., 1992]

| Dry year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NUREK | 0.205 | 0.186 | 0.268 | 0.512 | 0.958 | 1.615 | 1.993 | 1.873 | 0.958 | 0.501 | 0.358 | 0.286 | 9.713 |
| PYANDZ | 0.506 | 0.457 | 0.954 | 1.373 | 1.82 | 2.709 | 3.188 | 2.598 | 1.652 | 0.993 | 0.784 | 0.587 | 17.621 |
| KUNDUZ | 0.058 | 0.06 | 0.07 | 0.128 | 0.165 | 0.301 | 0.291 | 0.242 | 0.137 | 0.091 | 0.066 | 0.059 | 1.668 |
| KAF | 0.08 | 0.083 | 0.269 | 0.478 | 0.677 | 0.701 | 0.531 | 0.332 | 0.167 | 0.162 | 0.127 | 0.102 | 3.709 |
| SURDARYA | 0.043 | 0.044 | 0.153 | 0.33 | 0.475 | 0.482 | 0.291 | 0.183 | 0.08 | 0.076 | 0.065 | 0.048 | 2.27 |
| GUZADARYA | 0.002 | 0.001 | 0.009 | 0.036 | 0.018 | 0.016 | 0.009 | 0.003 | 0.003 | 0.005 | 0.004 | 0.004 | 0.11 |
| KASHKADARYA | 0.016 | 0.018 | 0.078 | 0.13 | 0.115 | 0.122 | 0.093 | 0.05 | 0.027 | 0.019 | 0.017 | 0.015 | 0.7 |
| ZERAF | 0.052 | 0.042 | 0.079 | 0.105 | 0.189 | 0.436 | 0.575 | 0.513 | 0.248 | 0.127 | 0.093 | 0.072 | 2.531 |
| MTA | 0.048 | 0.037 | 0.097 | 0.232 | 0.118 | 0.084 | 0.034 | 0.034 | 0.035 | 0.06 | 0.061 | 0.07 | 0.91 |
| TOTAL | 1.01 | 0.928 | 1.977 | 3.324 | 4.535 | 6.466 | 7.005 | 5.828 | 3.307 | 2.034 | 1.575 | 1.243 | 39.232 |
| **Normal year** | | | | | | | | | | | | | |
| NUREK | 0.352 | 0.352 | 0.352 | 0.318 | 0.459 | 0.838 | 1.567 | 2.642 | 3.26 | 3.063 | 1.566 | 0.858 | 15.627 |
| PYANDZ | 0.835 | 0.754 | 1.575 | 2.184 | 2.896 | 4.309 | 5.072 | 4.133 | 2.628 | 1.639 | 1.295 | 0.969 | 28.289 |
| KUNDUZ | 0.095 | 0.099 | 0.116 | 0.204 | 0.262 | 0.478 | 0.462 | 0.385 | 0.218 | 0.15 | 0.109 | 0.097 | 2.675 |
| KAF | 0.133 | 0.138 | 0.448 | 0.765 | 1.083 | 1.122 | 0.85 | 0.531 | 0.267 | 0.271 | 0.213 | 0.17 | 5.991 |
| SURDARYA | 0.073 | 0.075 | 0.26 | 0.533 | 0.769 | 0.779 | 0.47 | 0.296 | 0.13 | 0.129 | 0.111 | 0.081 | 3.706 |
| GUZADARYA | 0.003 | 0.002 | 0.014 | 0.055 | 0.027 | 0.024 | 0.013 | 0.005 | 0.005 | 0.008 | 0.007 | 0.006 | 0.169 |
| KASHKADARYA | 0.027 | 0.029 | 0.128 | 0.205 | 0.183 | 0.193 | 0.147 | 0.08 | 0.043 | 0.031 | 0.028 | 0.024 | 1.118 |
| ZERAF | 0.09 | 0.072 | 0.136 | 0.172 | 0.31 | 0.716 | 0.944 | 0.842 | 0.407 | 0.219 | 0.161 | 0.124 | 4.193 |
| MTA | 0.07 | 0.054 | 0.14 | 0.336 | 0.171 | 0.121 | 0.049 | 0.05 | 0.051 | 0.087 | 0.089 | 0.101 | 1.319 |
| TOTAL | 3.23 | 3.2 | 5.92 | 4.49 | 8.81 | 11.22 | 14.52 | 13.44 | 5.7 | 3.47 | 1.92 | 2.85 | 78.77 |
| **Wet year** | | | | | | | | | | | | | |
| NUREK | 0.458 | 0.414 | 0.597 | 1.143 | 2.137 | 3.603 | 4.446 | 4.178 | 2.136 | 1.117 | 0.798 | 0.637 | 21.664 |
| PYANDZ | 1.079 | 0.975 | 2.036 | 2.929 | 3.884 | 5.78 | 6.803 | 5.544 | 3.525 | 2.119 | 1.674 | 1.253 | 37.601 |
| KUNDUZ | 0.122 | 0.127 | 0.149 | 0.272 | 0.35 | 0.638 | 0.616 | 0.513 | 0.29 | 0.193 | 0.14 | 0.125 | 3.535 |
| KAF | 0.166 | 0.173 | 0.561 | 0.998 | 1.413 | 1.463 | 1.109 | 0.693 | 0.349 | 0.339 | 0.266 | 0.213 | 7.743 |
| SURDARYA | 0.09 | 0.093 | 0.321 | 0.691 | 0.996 | 1.01 | 0.61 | 0.384 | 0.168 | 0.159 | 0.137 | 0.1 | 4.759 |
| GUZADARYA | 0.003 | 0.002 | 0.017 | 0.067 | 0.033 | 0.029 | 0.016 | 0.006 | 0.006 | 0.009 | 0.008 | 0.007 | 0.203 |
| KASHKADARYA | 0.033 | 0.036 | 0.16 | 0.265 | 0.236 | 0.25 | 0.191 | 0.103 | 0.055 | 0.038 | 0.035 | 0.03 | 1.432 |
| ZERAF | 0.118 | 0.95 | 0.178 | 0.237 | 0.426 | 0.984 | 1.298 | 1.158 | 0.56 | 0.287 | 0.211 | 0.163 | 6.57 |
| MTA | 0.088 | 0.068 | 0.177 | 0.425 | 0.216 | 0.153 | 0.062 | 0.063 | 0.065 | 0.11 | 0.112 | 0.128 | 1.667 |
| TOTAL | 2.157 | 2.838 | 4.196 | 7.027 | 9.691 | 13.91 | 15.151 | 12.64 | 7.154 | 4.371 | 3.381 | 2.656 | 85.174 |

## *Water Storage Facilities*

The major water storage facilities of the Amudarya basin are listed in Table 3 (Raskin et al., 1992).

**Table 3.** Major Water Storage Facilities of the Amudarya Basin (Raskin et al., 1992).

| Reservoir | Dead storage capacity (km$^3$) | Active storage capacity (km$^3$) | Total storage capacity (km$^3$) |
|---|---|---|---|
| Nurek | 6 | 4.5 | 10.5 |
| Surhan | 0.06 | 0.74 | 0.8 |
| Chimk | 0.2 | 0.3 | 0.5 |
| Katta | 0.06 | 0.84 | 0.9 |
| Tyuman | 2.34 | 5.0 | 7.34 |
| Pachk | 0.15 | 0.16 | 0.31 |

## *Water Demand Data*

The water demands used for the Amudarya basin are listed in Table 4 (Raskin et al., 1992). These demand figures represent the conditions in approximately 1987.

**Table 4.** Water Demands (km$^3$/yr) in the Amudarya River Basin (Raskin et al., 1992).

| Demand Site | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PYANDZ | 0 | 0.01 | 0.04 | 0.04 | 0.04 | 0.04 | 0.06 | 0.08 | 0.04 | 0.02 | 0 | 0 | 0.37 |
| VAHSH | 0 | 0.1 | 0.53 | 0.4 | 0.39 | 0.46 | 0.71 | 0.96 | 0.53 | 0.24 | 0 | 0.08 | 4.4 |
| KAFIR | 0 | 0.08 | 0.36 | 0.29 | 0.26 | 0.33 | 0.51 | 0.66 | 0.36 | 0.18 | 0 | 0.04 | 3.07 |
| AFGAN | 0 | 0 | 0 | 0.01 | 0 | 0.01 | 0.01 | 0.01 | 0 | 0 | 0 | 0 | 0.04 |
| SURHANS | 0 | 0.12 | 0.63 | 0.47 | 0.46 | 0.55 | 0.85 | 1.12 | 0.63 | 0.29 | 0 | 0.09 | 5.21 |
| KARAKUM | 0.67 | 0.62 | 0.66 | 0.84 | 1.76 | 1.89 | 1.98 | 1.84 | 1.44 | 1.19 | 0.89 | 0.75 | 14.53 |
| KARSHI | 0.58 | 0.43 | 0.42 | 0.74 | 1.02 | 1.06 | 1.11 | 1.09 | 0.87 | 0.73 | 0.68 | 0.65 | 9.38 |
| BUKHARAZ | 1.19 | 1.09 | 0.9 | 0.7 | 1.5 | 2.49 | 3.09 | 2.64 | 1.22 | 0.74 | 0.11 | 0.26 | 15.93 |
| CARDZOU | 0.03 | 0.13 | 0.29 | 0.24 | 0.52 | 0.86 | 1.11 | 0.87 | 0.21 | 0.07 | 0.01 | 0 | 4.34 |
| HOREZM | 0.02 | 0.11 | 0.32 | 0.1 | 0.39 | 0.48 | 0.58 | 0.56 | 0.08 | 0 | 0 | 0.01 | 2.65 |
| TASHAUS | 0.18 | 0.2 | 0.37 | 0.32 | 0.42 | 0.53 | 1 | 0.87 | 0.06 | 0 | 0 | 0.26 | 4.21 |
| KKAR | 0.56 | 0.31 | 1.4 | 0.34 | 2.05 | 2.52 | 3.51 | 2.74 | 0.26 | 0.01 | 0.23 | 0.71 | 14.64 |
| TOTAL | 3.23 | 3.2 | 5.92 | 4.49 | 8.81 | 11.22 | 14.52 | 13.44 | 5.7 | 3.47 | 1.92 | 2.85 | 78.77 |

## *Results*

Using the data presented above, two example model solutions for the Amudarya River basin are presented in this section. This first solution considers the supply of water to irrigated agriculture to be of primary importance and the maintenance of water quality (salinity management) to be of lesser importance. Two examples are provided to show the tradeoff between water supply and salt control. In example 1 more weight is given to the water supply

objective, while less weight is given to the salinity management objective. In example 2 more weight is given to the salinity management objective, and less weight is given to the water supply objective. In each example tables show the ratio of water supply to demand for each demand site in each month, water supply from a source to a demand site in each month, reservoir and aquifer storage at the end of a month, flow volume through each main river reach in each month, and salt concentration in reservoirs, aquifers, major tributaries and main river reaches. Table 5 and Figures 4 - 7 show the comparison of the results in the two samples.

Table 5 and Figure 4 compare the average ratio of water supply to demand vs. months in the two examples. Since more weight is put on water supply in example 1, the monthly average ratios of water supply to demand are larger than those in example 2 which has more weight on salinity management. The differences are larger in the summer months, since water demands are higher in these months. In Figure 5, we can see that the monthly salt concentrations in the downstream part of the main river are lower in example 2 than those in example 1, and Figure 6 shows the salinity concentrations in the downstream aquifer in example 2 are lower than those in example 1. Figure 7 shows the flow to the Aral Sea in the two examples. Increased flow to the Aral Sea results when more weight is put on salt management.

The tradeoff presented in these examples demonstrates the effect of water supply on water quality (salt concentration) in the Amudarya River basin. The model can be used as a tool to perform such tradeoff analyses. This type of analysis can provide decision makers with information about the magnitude of water supply when salt management techniques are applied in the basin.

**Table 5.** Comparing the two Amudarya River basin examples.

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Average ratio of water supply to demand for all demand sites | | | | | | | | | | | | |
| Example 1 | 0.88 | 0.95 | 0.91 | 1.00 | 1.00 | 1.00 | 0.94 | 0.88 | 1.00 | 1.00 | 1.00 | 1.00 |
| Example 2 | 0.76 | 0.80 | 0.90 | 1.00 | 0.76 | 1.00 | 0.87 | 0.86 | 0.83 | 1.00 | 1.00 | 1.00 |
| Salt Concentration (g/L) in the downstream of the main river | | | | | | | | | | | | |
| Example 1 | 4.8 | 6.3 | 5.6 | 6.6 | 4.9 | 5.5 | 4.5 | 5.5 | 5.6 | 4.5 | 3.3 | 3.6 |
| Example 2 | 4.6 | 4.9 | 4.3 | 5.3 | 4.0 | 3.8 | 4.2 | 4.3 | 4.6 | 3.6 | 3.1 | 3.1 |
| Salt Concentration (g/L) in the downstream aquifer | | | | | | | | | | | | |
| Example 1 | 9.2 | 8.3 | 8.8 | 11.1 | 9.6 | 9.6 | 10.0 | 10.1 | 11.5 | 11.6 | 11.0 | 11.5 |
| Example 2 | 7.0 | 7.1 | 6.7 | 7.4 | 7.6 | 6.8 | 7.2 | 8.8 | 9.3 | 7.0 | 5.0 | 4.3 |
| Flow (km$^3$) to the Aral Sea | | | | | | | | | | | | |
| Example 1 | 0.47 | 0.47 | 0.68 | 1.37 | 1.37 | 2.73 | 5.46 | 5.46 | 5.46 | 2.93 | 1.17 | 0.47 |
| Example 2 | 0.79 | 0.54 | 0.82 | 1.64 | 1.64 | 3.11 | 6.23 | 6.23 | 6.23 | 4.96 | 1.98 | 0.79 |
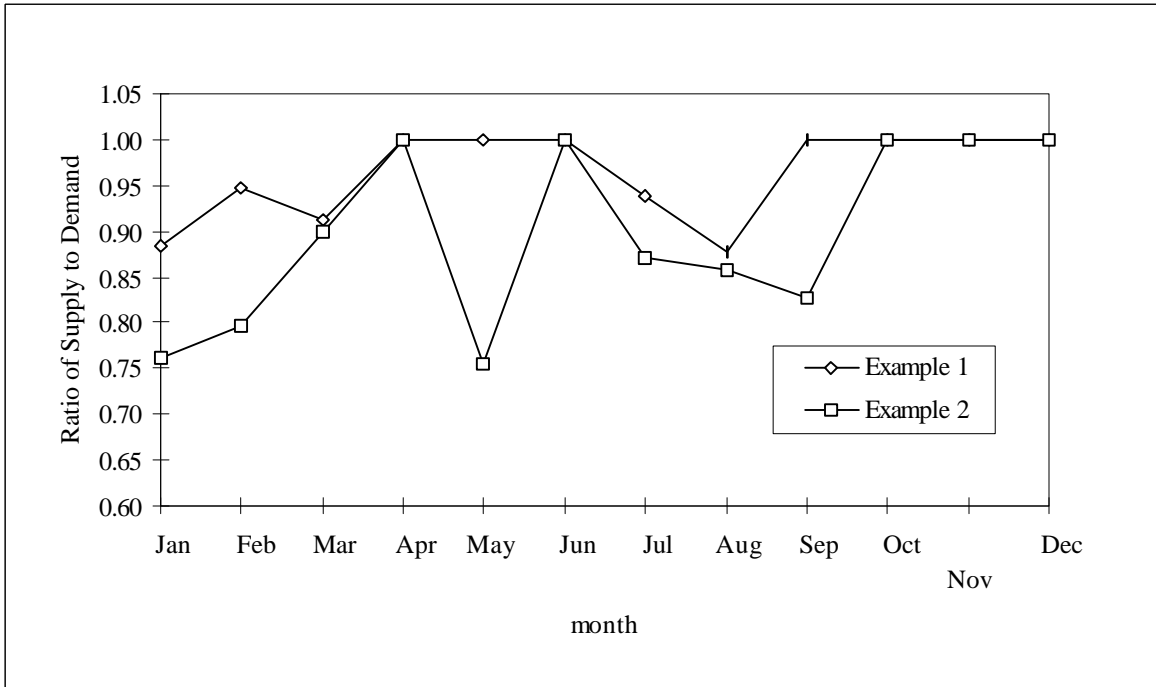
**Figure 4.** Average ratio of water supply to demand in each month for the two Amudarya River basin examples.
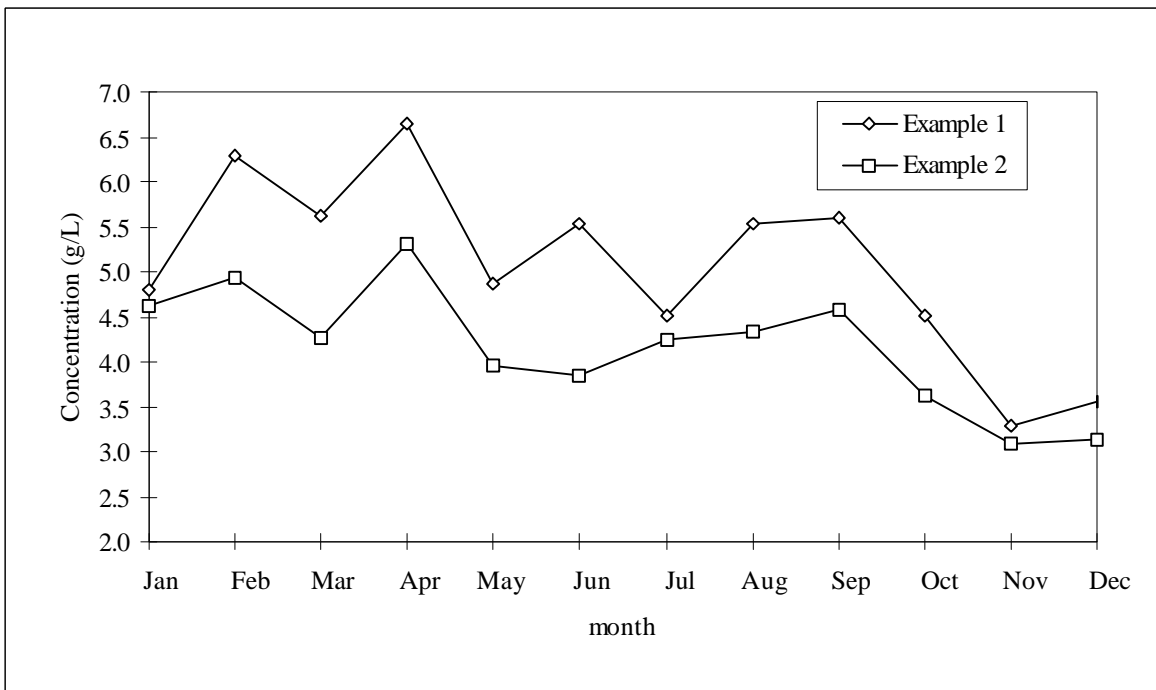


**Figure 5.** Salt concentration in the lowest modeled reach of the main river for the two Amudarya River basin examples.
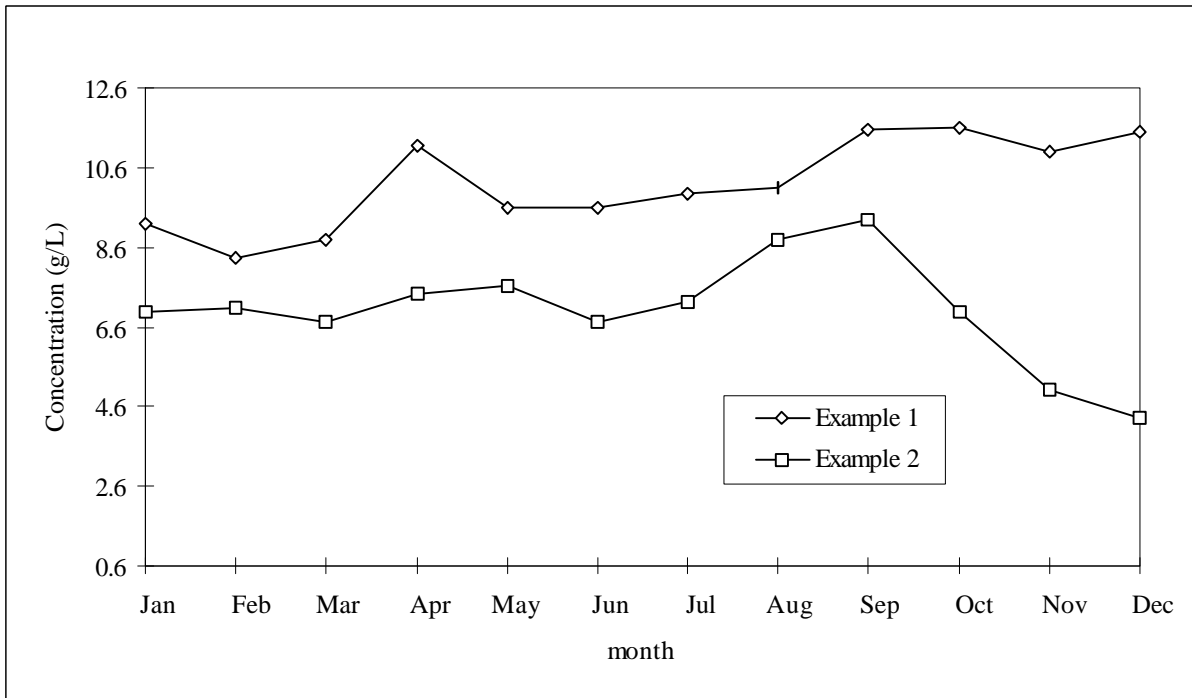
**Figure 6.** Salt concentration in downstream aquifer for the two Amudarya River basin examples.
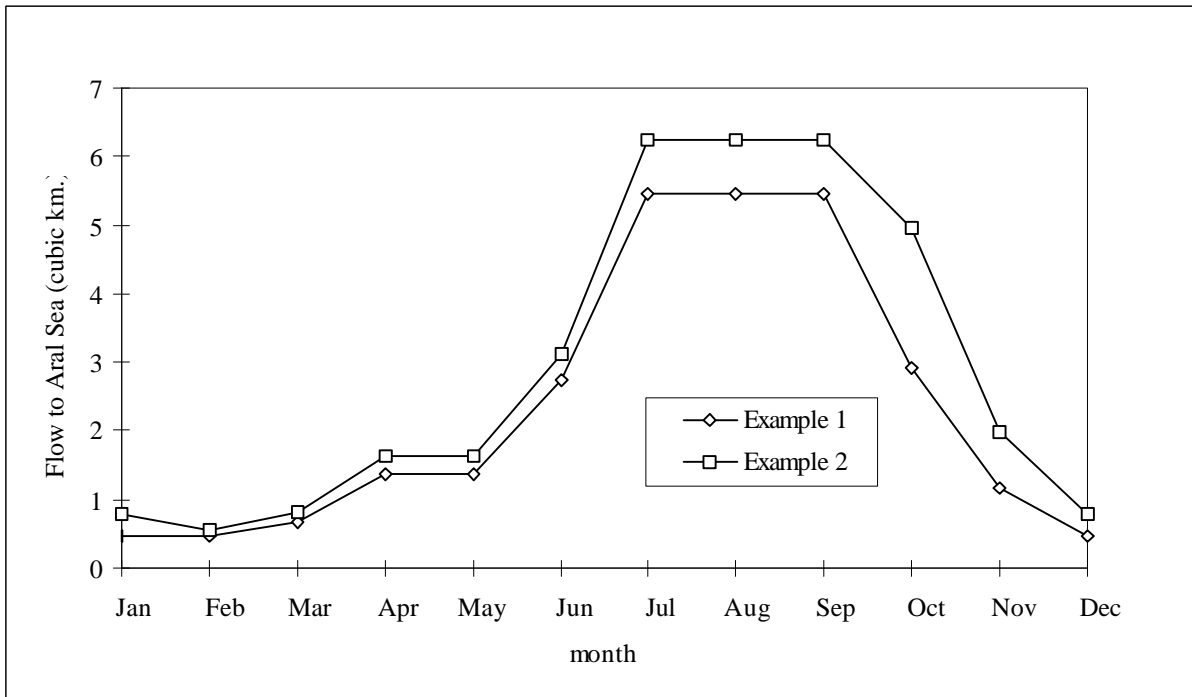


**Figure 7.** Flow to the Aral Sea for the two Amudarya River basin examples.

# Example – Kashkadarya River basin

An example of applying the modeling system to water allocation in the Kashkadarya River basin is presented in this section.

## *GIS and Network Representations*

The coverages making up the GIS representation of the Kashkadarya River basin water resource system are shown in Figure 8 along with the network representation of the basin water resource system for the basin. This network was generated automatically by the modeling system from the coverages.
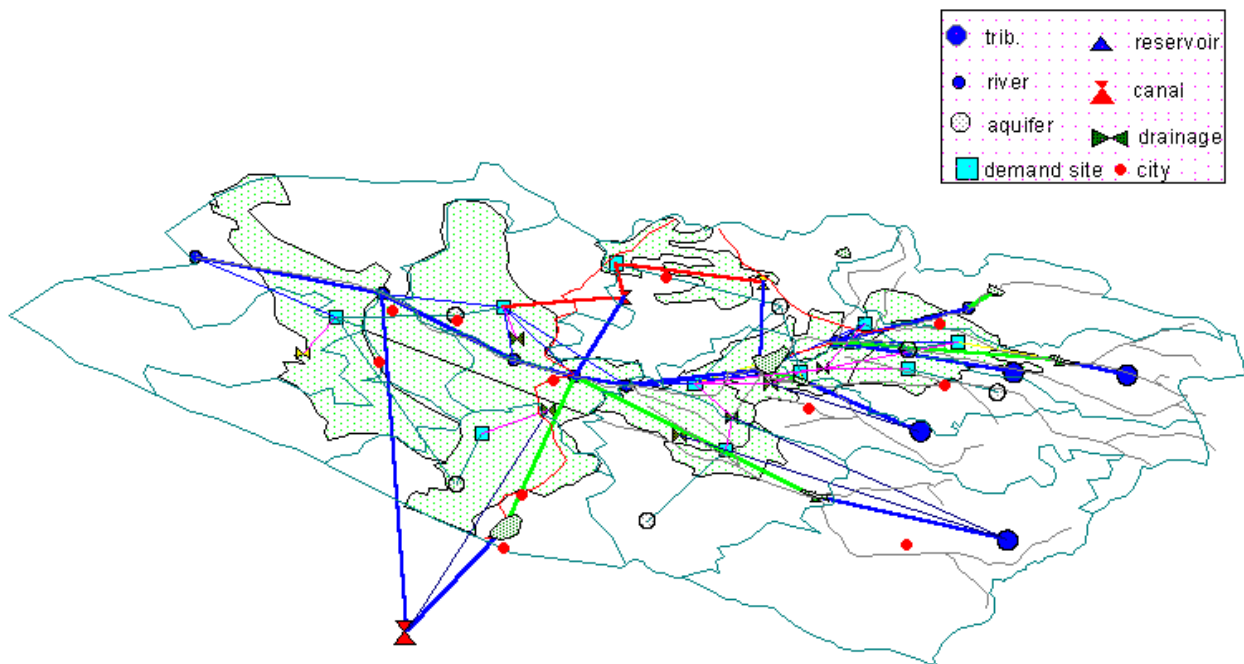


**Figure 8.** GIS coverages and model network for the Kashkadarya River basin.

## *Water Supply Data*

Available sources of groundwater supply in the Kashkadarya River basin are listed in Table 6 (A. Kh. Karimov, personal communication, 1996). Water availability for the basin in various years corresponding to normal hydrological conditions (total supply = 3298.1 million m$^3$/yr) is listed in Table 7 (A. Kh. Karimov, personal communication, 1996).

**Table 6.** Groundwater Supply in the Kashkadarya River Basin (km$^3$/yr).

| Source | Capacity (km$^3$/yr) |
|--------|---------------------|
| Zap_kash | 320 |
| Prav_kash | 184 |
| Kitab | 350 |
| Langar | 70 |
| Lev_kash | 210 |
| Guza | 98 |
| Total | 1232 |

**Table 7.** Water Supply (km$^3$/yr) in the Kashkadarya River Basin.

| Normal year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Total |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-------|
| Akcu | 30 | 35 | 50 | 60 | 50 | 74 | 90 | 90 | 80 | 75 | 60 | 60 | 754 |
| Yakab | 6 | 10 | 15 | 30 | 40 | 50 | 60 | 70 | 80 | 60 | 40 | 20 | 481 |
| Tankiz | 10 | 20 | 30 | 40 | 50 | 50 | 60 | 70 | 80 | 60 | 30 | 15 | 515 |
| Guzar | 1.5 | 1.7 | 12 | 43 | 23 | 19 | 3 | 3 | 3 | 3 | 2 | 2 | 116.2 |
| Karshi | 33 | 36 | 160 | 265 | 236 | 250 | 191 | 103 | 55 | 38 | 35 | 30 | 1432 |
| TOTAL | 80.5 | 102.7 | 267 | 438 | 399 | 443 | 404 | 336 | 298 | 236 | 167 | 127 | 3298.2 |

## Water Storage Facilities

The major water storage facilities of the Kashkadarya basin are listed in Table 8 (A. Kh. Karimov, personal communication, 1996).

**Table 8.** Major Water Storage Facilities of the Kashkadarya Basin.

| Reservoir | Dead storage capacity (km$^3$) | Active storage capacity (km$^3$) | Total storage capacity (km$^3$) |
|-----------|-------------------------------|----------------------------------|---------------------------------|
| Akbai | 40 | 100 | 140 |
| chmik | 22 | 420 | 442 |
| Gisar | 105 | 80 | 185 |
| kamas | 1.2 | 24 | 25.2 |
| pachk | 50 | 240 | 290 |
| talim | 70 | 1500 | 1570 |

## Water Demand Data

The water demands used for the Kashkadarya basin are listed in Table 10 (A. Kh. Karimov, personal communication, 1996). These demand figures represent the conditions in approximately 1995.

**Table 9.** Water Demands ($10^6$ m$^3$/yr) in the Kashkadarya River basin.

| Demand Site | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mosk | 2.9 | 5.5 | 45.4 | 162.3 | 233.3 | 200.8 | 88.7 | 9.7 | 18.3 | 23.9 | 1.5 | 1.5 | 793.5 |
| Guzar | 2.9 | 26.0 | 14.0 | 4.0 | 22.3 | 62.4 | 82.5 | 71.2 | 32.2 | 11.2 | 22.7 | 11.6 | 363.0 |
| Shoz | 33.4 | 32.5 | 158.9 | 320.6 | 439.9 | 411.5 | 151.6 | 53.4 | 107.7 | 51.9 | 30.7 | 15.6 | 1807.7 |
| Kash1 | 49.3 | 148.0 | 161.7 | 164.7 | 201.8 | 452.8 | 715.0 | 530.7 | 222.1 | 68.9 | 49.3 | 96.4 | 2860.7 |
| Akcu | 7.3 | 2.0 | 1.8 | 3.8 | 13.8 | 75.2 | 119.4 | 116.1 | 50.5 | 6.1 | 2.9 | 2.9 | 401.8 |
| Vereh | 8.7 | 5.9 | 3.0 | 5.4 | 13.8 | 57.5 | 84.9 | 80.5 | 34.4 | 5.1 | 3.3 | 3.6 | 306.1 |
| Chmik | 24.7 | 47.4 | 42.7 | 49.7 | 47.7 | 133.1 | 181.3 | 157.4 | 66.4 | 59.9 | 57.0 | 23.7 | 890.8 |
| Kash2 | 10.2 | 54.6 | 42.5 | 23.3 | 111.2 | 245.1 | 218.6 | 296.5 | 101.1 | 34.5 | 47.6 | 42.2 | 1227.4 |
| Yakab | 11.6 | 2.9 | 9.4 | 54.2 | 82.2 | 78.0 | 35.0 | 5.8 | 3.8 | 4.6 | 2.9 | 2.9 | 293.3 |
| Tankiz | 11.6 | 2.2 | 2.2 | 2.6 | 5.7 | 17.5 | 27.8 | 27.3 | 12.8 | 2.8 | 2.9 | 2.9 | 118.3 |
| TOTAL | 162.4 | 327.1 | 481.5 | 790.6 | 1172 | 1734 | 1705 | 1349 | 649.3 | 268.8 | 220.7 | 203.2 | 9062.7 |

## *Results*

Using the data presented above, two example model solutions for the Kashkadarya River basin are presented in this section. This first solution considers the supply of water to irrigated agriculture to be of primary importance and the maintenance of water quality to be of lesser importance. Two examples are provided to show the tradeoff between water supply and salt control. In example 1 more weight is given to the water supply objective, while less weight is given to the salt management objective. In example 2 more weight is given to the salt management objective, and less weight is given to the water supply objective. In each example tables show the ratio of water supply to demand for each demand site in each month, water supply from a source to a demand site in each month, reservoir and aquifer storage at the end of a month, flow volume through each main river reach in each month, and salt concentration in reservoirs, aquifers, major tributaries and main river reaches. Table 10 and Figures 9-12 show the comparison of the results in the two examples.

Figure 9 compares the average ratio of water supply to demand vs. months in the two examples. Since more weight is put on water supply in example 1, the monthly average ratios of water supply to demand are larger than those in example 2 which has more weight on salt management. The differences are larger in the summer months, since water demands are higher in these months. In Figure 10, we can see that the monthly salt concentrations in the downstream part of the main river are lower in example 2 than those in example 1, and Figure 11 shows the salt concentrations in the downstream aquifer in example 2 are lower than those in example 1. Figure 12 shows the flow in the lower reaches of the Kashkadarya River in the two examples. Increased flow to the Aral Sea results when more weight is put on salt management.

The tradeoff presented in these examples demonstrates the effect of water supply on water quality (salt concentration) in the Kashkadarya River basin. The model can be used as a tool to perform such tradeoff analyses. This type of analysis can provide decision makers with

information about the magnitude of water supply when salt management techniques are applied in the basin.

**Table 10.** Comparing the two Kashkadarya River basin examples.

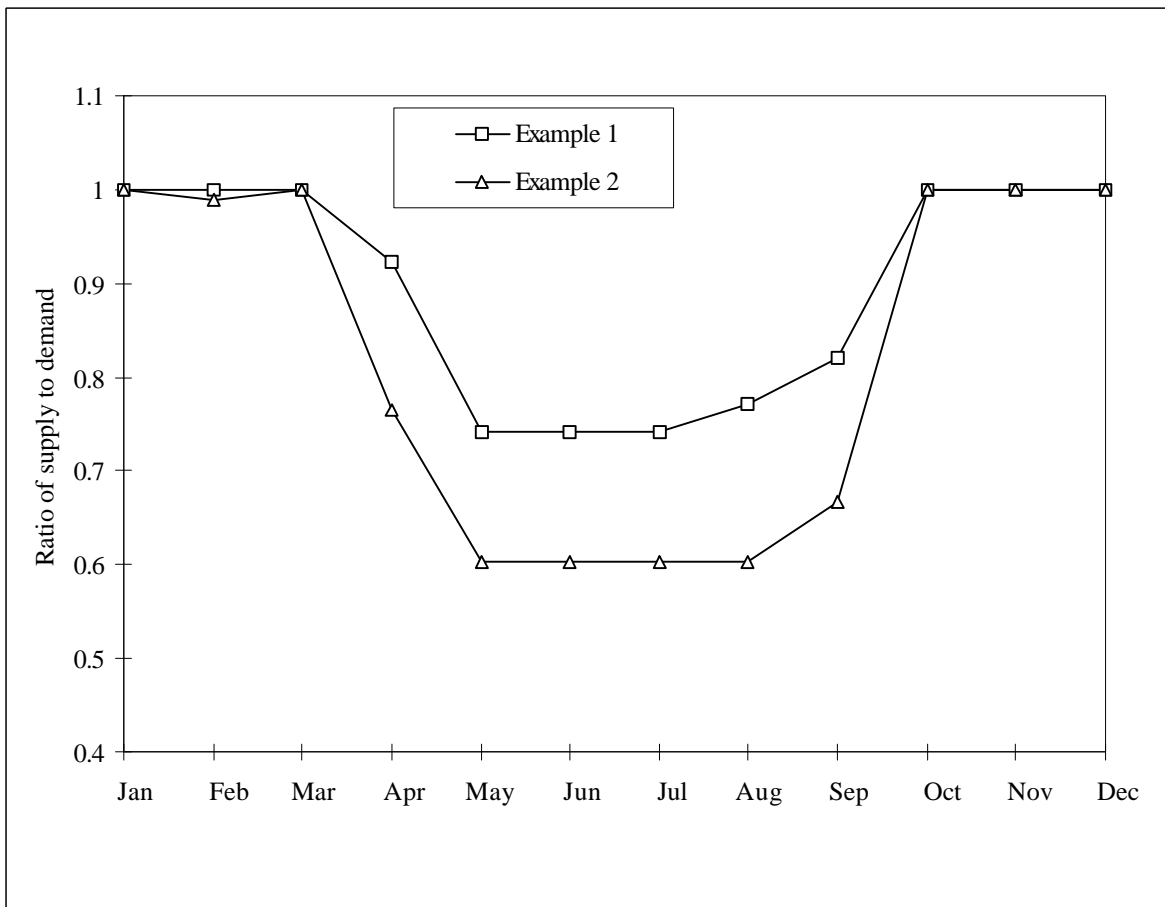| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Average ratio of water supply to demand for all demand sites | | | | | | | | | | | | |
| Example 1 | 1 | 1 | 1 | 0.92 | 0.74 | 0.74 | 0.74 | 0.77 | 0.82 | 1 | 1 | 1 |
| Example 2 | 1 | 0.99 | 1 | 0.77 | 0.60 | 0.60 | 0.60 | 0.60 | 0.67 | 1 | 1 | 1 |
| Salt Concentration (g/L) in the downstream of the main river | | | | | | | | | | | | |
| Example 1 | 3.5 | 4.1 | 5.7 | 7.4 | 9.8 | 10.0 | 10.0 | 11.0 | 11.0 | 9.5 | 10.0 | 5.6 |
| Example 2 | 3.5 | 3.8 | 5.0 | 6.7 | 9.0 | 7.4 | 6.4 | 9.5 | 7.7 | 8.9 | 8.5 | 4.9 |



**Figure 9.** Average ratio of water supply to demand in each month for the two Kashkadarya River basin examples.
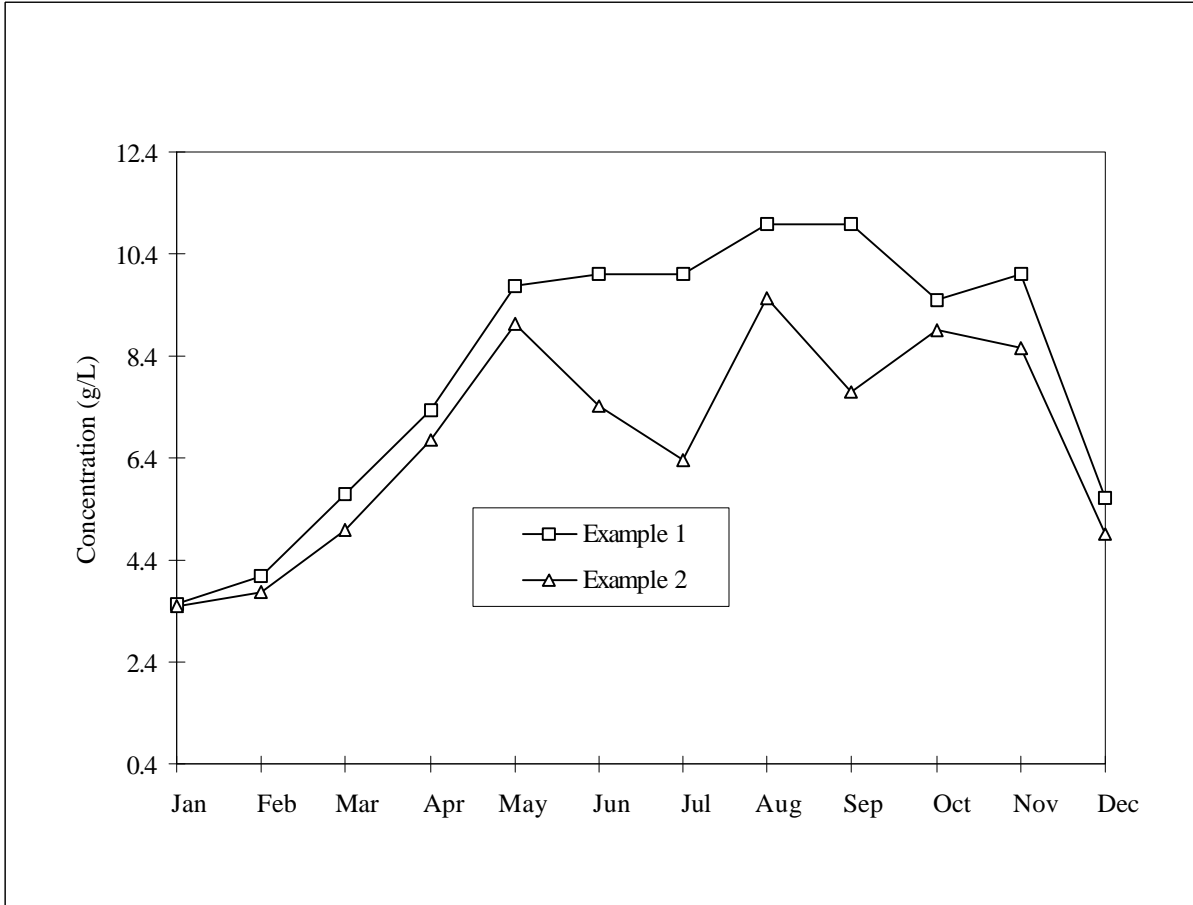
**Figure 10.** Salt concentration in the downstream of the main river month for the two Kashkadarya River basin examples.
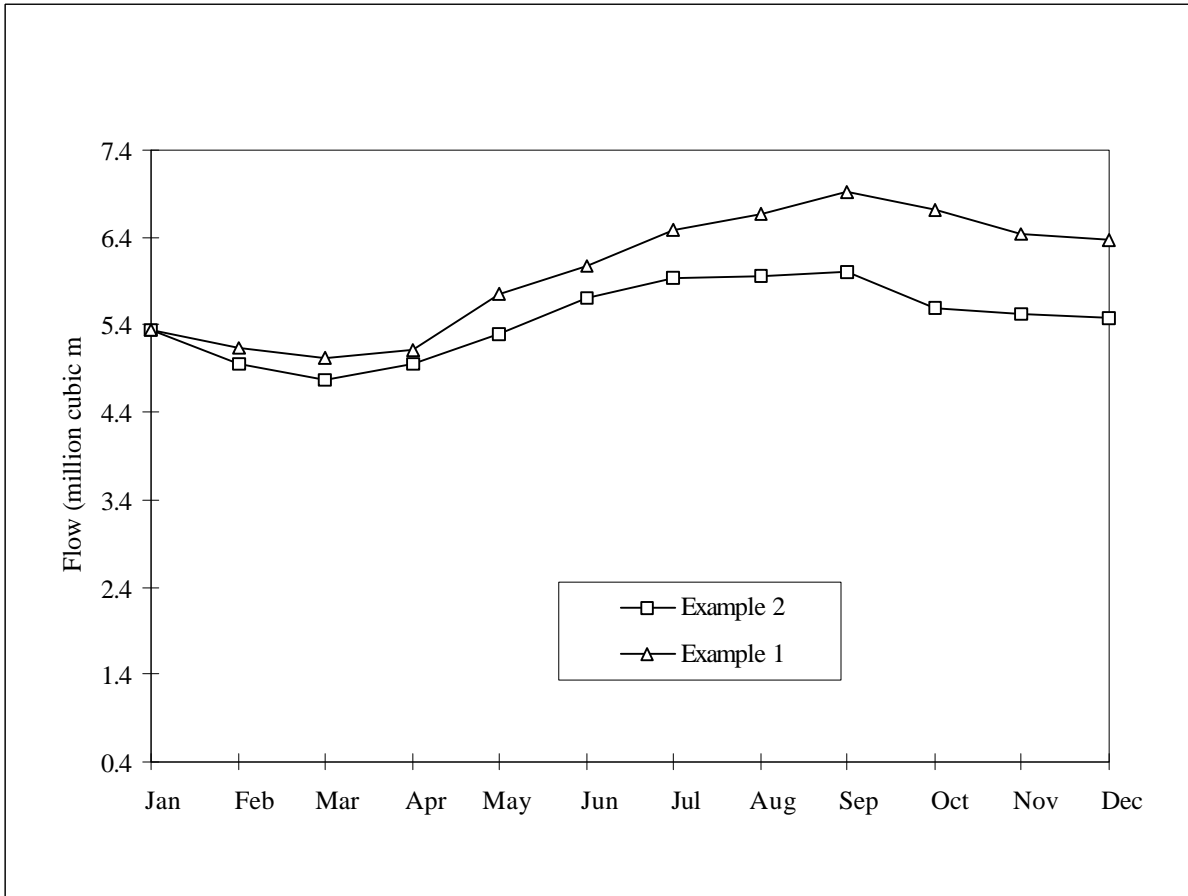
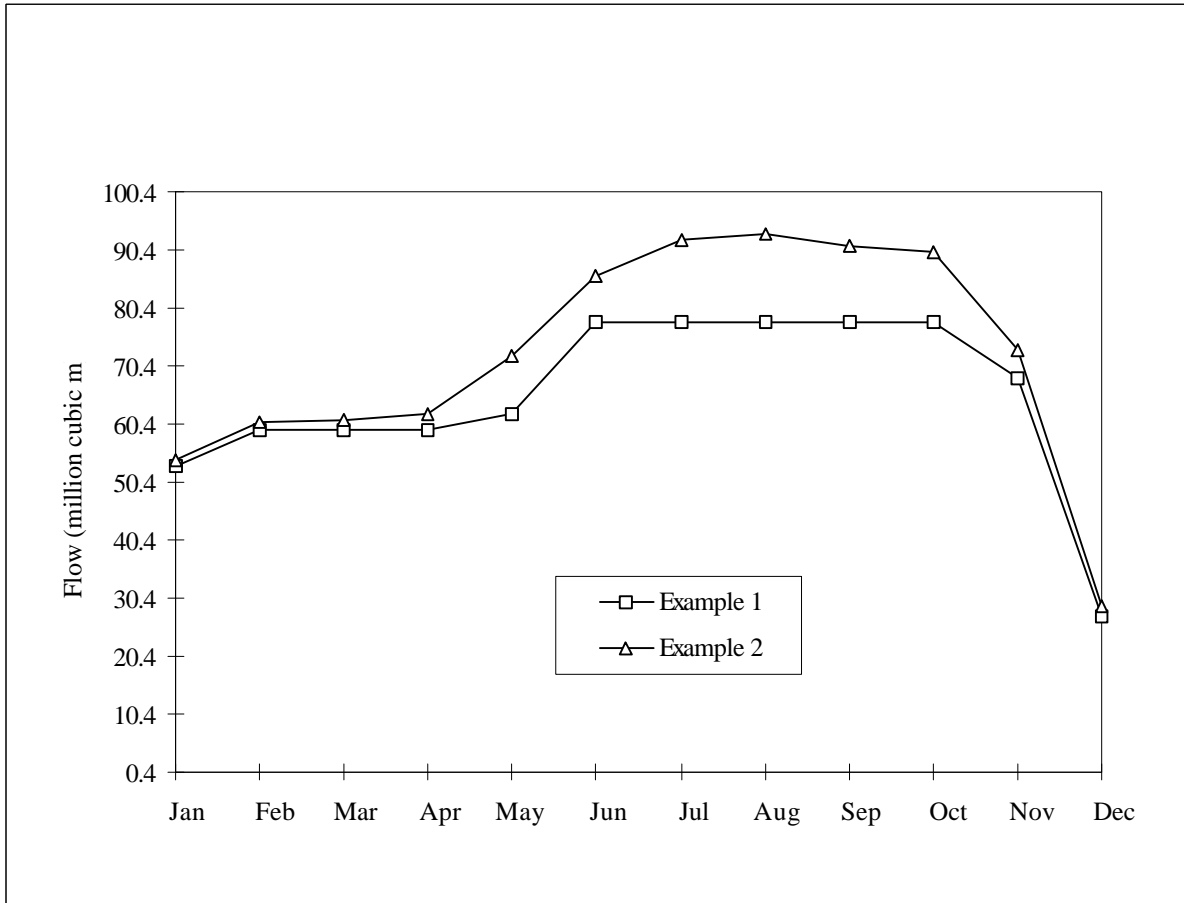**Figure 11.** Salt concentration in the downstream aquifer for the two Kashkadarya River basin examples.

**Figure 12.** Flow in the downstream aquifer for the two Kashkadarya River basin examples.

**Section 3**

# Conclusions and Recommendations

In this project a water allocation model for the Amudarya River of the Aral Sea basin was developed. In particular:

- A Geographic Information System (GIS)-based decision support system for regional water resources planning that is applicable to the river basins of the Aral Sea region was developed, and

- The modeling system was demonstrated for portions of the Aral Sea basin: the Amudarya River and Kashkadarya River basins.

This model supports the planning of water distribution between irrigation districts in the Amudarya basin. In addition, the model takes into account the salinization of water in the basin. A more detailed model was developed for the Kashkadarya River basin which considers irrigation runoff or drainage from individual irrigation districts.

The modeling system is an interface between the GIS software, ARCVIEW, and the optimization software GAMS. The GIS software developed in this project is completely compatible with the data base of the Aral Sea region being developed under the European Union WARMAP project. Thus, the results of this research are directly and immediately usable in that system. It is recommended that the results of this project be made available to the WARMAP project and that their use be encouraged. In addition, the optimization models developed in this project are compatible with the goals of the World Bank Aral Sea Basin Program, Project 1.1. The models developed here, along with their close link to the GIS data base, may serve as useful tools for the researchers working to develop a regional water resources strategy under the Interstate Council for the Aral Sea (ICAS).

**Section 5**

# References

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World Bank, *Developing a Regional Water Management Strategy: Issues and Work Plans,* Aral Sea basin Probram Technical Papers Series, Washington DC., April 1996.