Optimizing long-term water allocation in the Amudarya river delta – A water management model for ecological impact assessment

Maja Schlüter[a*], Andre G. Savitsky[b], Daene C. McKinney[c] & Helmut Lieth[a]

[a] *Institute of Environmental Systems Research, University of Osnabrueck, 49069 Osnabrueck, Germany*
[b] *Centre 'Ecology of Water Management', Environmental Committee of Uzbekistan, 13A U. Nasir Street, Tashkent 700000, Uzbekistan*
[c] *Department of Civil Engineering, University of Texas, Austin, TX 78212, USA*

*Corresponding Author:
Maja Schlüter
Institute of Environmental Systems Research
University of Osnabrueck
49069 Osnabrueck
Germany
Fax: +49 541 969 2570
mschluet@usf.uni-osnabrueck.de

Abstract

In the semi-arid Amudarya delta region (Aral Sea Basin) the human-controlled hydrological regime is a major factor influencing ecosystem dynamics. Alterations to the flow of the Amudarya river, mainly to serve the needs of irrigated agriculture during Soviet times, have caused severe environmental degradation. Since independence, the former Soviet Union states of the basin are searching for new, ecologically sound, water management strategies to mitigate the damages to economy, human populations and ecosystems. To assist in the evaluation of tradeoffs in water allocation and the determination of restoration goals, we created a simple water management model for the Amudarya river and its delta region with the modeling system EPIC (originally developed by the USAID project "Environmental Policies and Institutions for Central Asia"). The water management model determines optimal water allocation in the irrigation network by multi-objective optimization in monthly time steps. Water management alternatives can be developed for a time period of up to 15 years based on changing requirements of the water users (e.g. as a result of increased water use efficiency in agriculture), inflow to the delta (e.g. increase in water use upstream), priorities of the optimization criteria (e.g. reflecting policy decisions) or introducing minimum flow requirements to selected canals. Historic salt dynamics of the Tyuyamuyun reservoir system at the entrance to the Amudarya delta were investigated and EPIC was extended to treat such multi-body reservoir systems. The model was calibrated and tested using a high water (1994) and a low water (1997) year. Modeled water allocation takes place in accordance with observational data. The model reacts well to changes in allocation priorities given by the user. Application of the model to a 14-year characteristic time period was successful. The model constitutes a main module of an integrated GIS-based simulation tool that facilitates the evaluation of the ecological effects of alternative water management strategies in the Northern Amudarya delta.

Keywords: water management model, multiple objective optimization, Amudarya river delta, long term water availability, ecological assessment, EPIC modeling system

Introduction

Severe alterations to the hydrological regime of the Amudarya river over the past 40 years have caused serious degradation of the environment in the lower Amudarya delta.

Desertification processes initiated by the continuous decrease in river flow have significantly changed the once diverse ecosystems. The deltaic lakes, pastures and riverine forests have been, and still are, to a large extent, the means of existence for the local human population. Their importance has even increased with the loss of the fishing industry in the Aral Sea. Water availability in the delta is determined by water use practices in the upper and middle reaches as well as in the irrigated southern part of the delta. Allocation of the transboundary water resources of the Aral Sea Basin between the five states of the former Soviet Union is still based on existing quotas of the Soviet time. Those quotas, defined mainly to serve irrigation water needs, will stay valid until a regional water resource management strategy is formulated (Agreement, Almaty 1992). The need for adjustments to these regulations to achieve sustainable water management is widely accepted (Dukhovny & Sokolov, 1996; International Crisis Group, 2002; Djaloobaev, 2002). Future water management will have to account for changing needs in agriculture, the demands of the ecosystems in the deltas and littoral of the Aral Sea, potential increase in water intake from Afghanistan, effects of climate change, or other physical or socio-economic factors. In numerous statements the five states have declared that the Aral Sea and its deltas are entitled to certain volumes of water released from the Amudarya, Syrdarya and collector drain water (e.g. Agreement on joint activities in addressing the Aral Sea, 1993). Experts provide different assessments of the actual amount necessary to stabilize the environmental situation in the delta areas of both inflowing rivers and the level of the Aral Sea itself, with values varying between 10-35 km^3 per year (Letolle, 1996; ICWC, 1998; Shiklomanov, 1998; Micklin, 2000; UNESCO, 2000; FAO Aquastat, 2003). Current results of the GEF/Worldbank Aral Sea Basin Project suggest that minimum flow requirements of the deltaic wetlands of the Amudarya river, whose mean discharge is estimated at 74 km^3/year, amount to approximately 6 km^3/year (IFAS 2002). In low water years a minimum of 3.2 km^3 should be maintained. This does not include water allocated for the stabilization of the western part of the Aral Sea, which would account for another 15 km^3/year. Next to the quantity of water allocated to the environment, its quality is of equal importance. To conserve the remaining deltaic lakes and semi-natural vegetation to the desired extent, a certain amount of freshwater input is necessary. Water allocated to the environment consisting mainly of drainage water with high salinity and pollution, will not be suitable for ecosystem restoration and instead should be used for stabilizing the level of the Aral Sea.

Historic data reveal that the inflow to the Amudarya river delta at the gauging station Darganata (see Fig. 1) varied between 16.5–59 km^3 annually in the 1990's, of which 10–15.6 km^3 were used for irrigation. There is thus, in high water years, a large surplus of good quality water that can be used for ecosystem restoration while in dry years water does not even suffice for current irrigation needs.

The rather general and widely agreed upon conclusion, that the environment needs to receive more water in the future, is rarely further specified. A definition of "the environment", in the sense of the ecosystems and ecosystem services that are most valuable and should be preserved, is missing. Without a common understanding it will be difficult to develop a concept for an ecologically and economically sound use of the water allocated for ecological purposes for rehabilitation of the ecosystems in the basin. The determination of the minimum amount and quality of water and its spatio-temporal distribution essential to achieve optimal ecological benefits and the desired rehabilitation effects is a complex task. It involves many tradeoffs (e.g., between different geographical regions in the basin, between the small and big Aral Seas and the deltas of the Amudarya and Syrdarya rivers, between riverine forests and water bodies, etc.) that can only be resolved by an integrated and adaptive approach. An exploration of potential options can facilitate the determination of the main ecological objectives for future sustainable water management that are agreed upon between all involved parties.

The water management model presented in this paper facilitates the development of alternative future water management scenarios for the Amudarya river on a rather large spatio-temporal scale as the basis for evaluation of their potential ecological effects in the delta region. To account for the interconnectivity of the entire river system, the model was developed for the whole Amudarya river with special emphasis on the delta region. It was constructed using the modeling system EPIC (Environmental Policy and Institutions for Central Asia) (McKinney & Kenshimov 2000; McKinney & Savitsky, 2001). This system allows the automatic creation and solution of General Algebraic Modeling System (GAMS) models (Brooke et al., 1998) dealing with river basin management (McKinney & Savitsky, 2001). The original EPIC system was developed by hydrologists and water engineers from Central Asia and the University of Texas at Austin, USA, within the framework of an USAID project with the same name.

The aim of this work is to provide a tool that models optimal water distribution between competing users in the complicated network of the Amudarya river and the major irrigation canals under given physical and management constraints and potential policy decisions. For the special case of the Amudarya delta region the EPIC modeling system was extended to treat the multi-body reservoir located at the entrance to the Amudarya delta region.

The Amudarya River

Although the focus of the impact assessment is on the delta region of the Amudarya river, surface flow in the entire river beginning with its two major contributors was modeled. The hydrological regime in the delta is almost completely determined by the discharge from the mountains and irrigation withdrawals in the upper, middle and lower reaches. To test new water allocation strategies for the delta region, the situation in the upper and middle reaches has to be taken into account. Therefore, the entire river network is included in the model, although with varying levels of detail. The resolution of the channel network in the upper and middle reach is not as high as in the delta region.

Deleted: will be

The Amudarya river is the larger of the two rivers of Central Asia that feed the Aral Sea. The size of its catchment is about 250,000 km^2. It begins with the confluence of the rivers Pyandj and Vakhsh in Tajikistan, and in the upper-reach it forms the border between Tajikistan, Uzbekistan and Afghanistan. From the mountains it flows into the desert lowlands of Turan through Uzbekistan and Turkmenistan and drains into the Aral Sea. Along the main

Deleted: once fed

river there are two reservoirs with hydroelectric power stations, representing the main structures for management of water flow and salinity, several distribution points to serve irrigation water needs, main and side inflows, including return flow, and water intake for communal needs (Fig. 1). According to its hydrological and water balance characteristics, the river basin can be divided into three parts: upper, middle and lower reaches (Ismaiylov, 1994). The upper reach, down to the river station Kerki, is in a hydrological sense the main runoff generating zone of the basin. This region is favorable for hydroelectric power generation. Flow contributions to the river occur only in the first 180 km (Shulz, 1965). Together the Pyandj and Vakhsh rivers contribute approximately 83% of the runoff of the Amudarya. They are fed by glaciers and high altitude snows which determine their flow regimes. In March the flow increases, reaching its maximum in June, July and August and a minimum in January and February. The annual runoff can vary by 2.5 times (Shulz, 1965). In former times about 49% of the Amudarya discharge or 39 km^3 would reach the Aral Sea. Approximately 9 km^3 were lost to evaporation and infiltration (Shulz, 1965).

Deleted:

Deleted: 89

Deleted: .

Currently, on the upper reach one large reservoir is in operation: Nurek reservoir and another one is in planning and construction: Rogun reservoir. Mainly, the operational regimes of the upstream reservoirs are determined by the demands of water users in the entire Amudarya river basin. The middle reach, from Kerki to the Tyuyamuyun dam, and the lower reach, down to the former Aral Sea, are zones of river water usage. The intensive use of river water in the upper and middle reaches, mainly for irrigation, leads to water shortages and strong decreases in water quality in the lower reach. To counteract this problem the Tyuyamuyun reservoir (TMGU) was built in the early 1980s. Its role and significance are determined by the demands of the users in the lower reach of the Amudarya river.

The Tyuyamuyun reservoir consists of four separate reservoir bodies – the TMGU main, Kaparas, Sultansandjar and Koshbulak reservoirs (Fig.2). Weirs between the main reservoir and Kaparas and the main reservoir and Sultansandjar manage the water level difference between the reservoirs. Water exchange between Sultansandjar and Koshbulak cannot be managed. Constructions on the Kaparas reservoir were carried out to use this reservoir as a drinking water supply for the delta region in the future. The Tyuyamuyun system of reservoirs was built in a depression with high salt accumulations in the soil. These salt deposits are slowly dissolving into the reservoir water bodies leading to an elevated salinity of their waters. After a sharp increase in salinity shortly after construction the process is slowly leveling out but still contributes to an elevated salinity, which has to be carefully managed.

Downstream of the Tyuyamuyun reservoir the river flows into alluvial sediments of the historic delta. The modern delta, also known as the lower delta, begins at the Takhiatash dam close to Nukus. Before the 1960s, in high water years about 7,000 km^2 of the delta area was covered by floods or lakes (Shulz, 1965). The decrease in inflow to the delta and the lack of regular inundation of its plains lead to a strong decline of the number of lakes and their area, with about 10 lakes left today. The groundwater level has lowered and the formerly vast areas of riverine Tugai forests have shrunken from approximately 225,000 ha in the 1950s to presently ca. 33,000 ha (Treshkin, 2001). Salinization due to the absence of flooding, secondary salinization close to irrigated lands and aeolian input from the dried seabed has seriously degraded the soils. These processes have led to changes in the vegetation from mainly reeds, canes and hydrophilic plants to drought and salt resistant species.

Modeling approach

The selection of an appropriate model or modeling tool to map the spatio-temporal surface water distribution was guided by the aim to provide a tool for the investigation and evaluation of the effects of human introduced changes to surface runoff. It was assumed that regional climate patterns remain the same over the modeling period. The model should be simple and easy to use for interactive scenario analysis and impact assessment without demanding much modeling experience from the user. Sensitivity analysis to assess uncertainties should be readily facilitated. Policy and management options on a small (e.g., changes in the channel network or the requirements of single canals) and large (e.g., reduction of inflow to the delta region) scale should easily be implemented in the model and tested.

Models to assess ecological and economic impacts of alternative strategies of water allocation in irrigated river basins with water deficit problems have in the past years been developed for numerous river basins (see for example Wardlaw & Wells, 1996; Reca et al. 2001; Draper et al. 2003; Letcher & Jakeman, 2003). Those models apply an integrated economic-hydrological approach to a river basin management situation. For the Amudarya river so far few models have been developed to predict water flow and water quality. Ismaiylov et al. (1994) applied a generic simulation model for the management of volume and salinity of river waters in catchments with strongly developed irrigated agriculture to the Amudarya Basin. Their main focus was to determine water management alternatives that would keep water salinity within certain norms taking into account the inflow of high salinity return waters. Two scenarios of future water use were calculated, one with a maximum expansion of irrigated agriculture in all countries and one with no further expansion, given different extents of return flow into the river and alternative schemes of water use. The authors show that there are possibilities to manage the river waters in a way that increases river water quality significantly without seriously affecting the volume of water.

Raskin et al. (1992) applied the WEAP modeling system (integrated water demand-supply analysis) for scenario analysis and evaluation of water management strategies in the Aral Sea Basin by simulating current water balances. The model treats water demand and supply issues. Based on an analysis of 1987 data and predicted runoff for the years 1988-2020, it was concluded that under a “business-as-usual” scenario there will be a lack of water for water users in the lower reach of 89% in a low water year and 39% in a normal year. Since the model was made in the 1980s it does not represent the current day situation. Both models mentioned treat the lower reach of the Amudarya as one single, strongly simplified line and the Tyuyamuyun reservoir as one single reservoir. The latter prohibits accurate simulation of reservoir outflow salinity due to the situation described above. In order to provide spatially distributed inputs to the ecological assessment, modeling a detailed river network including all major canals is necessary. Needs of the delta ecosystems are not accounted for in the described models, with the exception of water quality issues.

Based on the experience gathered with the WEAP modeling system, local scientists developed a series of allocation models, mostly not published in open literature. The model WP (Razakov et al., 1998) was developed to model historic water and salt balances in the Tyuyamuyun reservoir based on runoff and salinity observations from 1981-1990. Within the framework of this study the model was expanded with additional data of 1991-2000. Water and salt balance calculations with WP were used in the development of the EPIC Amudarya model described here.

Since the high resolution input data needed for physically based, distributed models were not available and a detailed, realistic representation of the physical processes governing the hydrological cycle was not needed, given the aims of the study, river basin analysis tools such as HEC-RAS (Brunner, 2002), SWAT (Srinivasan et al., 1997, Arnold et al., 1998) or MIKE-11 (Havnø et al., 1995) were not suitable. The lack of spatial and non-spatial data, which in practice have often been available only for small areas (Andersen et al., 2001), would prevent a comprehensive analysis (Srinivasan et al., 1997). Unfortunately, a GIS of the Amudarya river basin, that could be used to obtain the needed input data, is not available. In the arid lowlands of the middle and lower reaches of the river, precipitation and side inflow to the river are minimal and can be neglected. Climate as a driving force can be modeled implicitly through the hydrograph provided as input to the river network. Therefore, a rainfall-runoff model was not needed. Using only the channel routing modules of such modeling systems was also prohibited by the lack of data on channel cross sections needed to model channel flow with standard approaches such as the Manning equation (SWAT), Muskingum method and kinematic wave approach (HEC-RAS, Mike-11) or the Saint-Venant equations (Mike-11). The automatic extraction of flood plain topography from a digital elevation model (DEM) was not possible because a high resolution DEM for the whole river basin does not exist. Given the data availability and the above mentioned goals, a conceptual water balance model using a multi-criteria optimization routine to determine optimal water allocation seemed to be most suited. Experiences in the Lower Ayun irrigation system (Bali, Indonesia), where a simulation model (Wardlaw & Wells, 1996) was compared to an optimization model, showed that the optimization model better manages to allocate the resource and achieves higher potential water savings than the simulation model (Wardlaw & Barnes, 1999). Additionally an optimization model can more easily be extended to include economic aspects such as water pricing or maximum crop yield into the objective function.

An optimization-based water allocation model for the Amudarya river was developed by the University of Texas at Austin and the Tashkent Institute of Engineers for Irrigation and Mechanization of Agriculture (McKinney et al., 1997a). This model considered the distribution of water between irrigated areas in the Amudarya basin and the salinization of the water in the basin. A more detailed model was also developed for the Kashkadarya River basin which also considered drainage flow from individual irrigation districts. The Scientific Information Center of the Interstate Coordination Water Commission (SIC-ICWC) has developed operational models to manage water distribution along the Amudarya river.

Model Description

The water management model developed in this study in the modeling system EPIC is based on experiences from the above mentioned earlier models and tailored to facilitate the assessment of ecological effects of water management measures. The experience of the EPIC developers with water management issues in the Aral Sea Basin also proved to be an advantage of choosing this framework. Models created in EPIC perform optimization calculations for operation of a river network according to a ranked list of objectives given by the "water manager". EPIC provides an interface for automatic network and model creation, as well as data input, input of limits to reservoirs and channel flow, setting of the objective weights and visualization of the results.

River Network. The river and irrigation network is formally represented by two mathematical objects:

- Nodes, representing sources, users, points for water intake, controls and reservoirs, where water balances are calculated, and
- Arcs, that transfer characteristics of water quantity and quality between groups of nodes (McKinney & Savitsky, 2001).

Distances are not accounted for in the network and the river and canals are represented the same. A schematic network of the Amudarya river consisting of the main tributaries located in the upper reach (Vakhsh, Pyandj, Kafirnigan and Kunduz rivers), the Amudarya river itself, the two main reservoirs (Nurek and Tyuyamuyun), the main canals in the upper and middle reach (Karshi, Amu-Bukhara, and Karakum canals) and the major canal network in the delta area was created (Fig.1). In the delta region all major canals diverting water to the irrigated areas and drainage water collectors were included as well as some (old) river branches and canals in the northern delta that might play an important role for ecosystem restoration (Table 1). The selection of the major canals was based on maps, on schemes of the Uzbek Main Hydrometeorological Service as well as on a digitized canal network in the Aral Sea GIS (Micklin et al., 1998). They are also the only canals where water withdrawal data were available to the authors over a period of 5-10 years. All canals are defined as users that dictate water distribution according to the requirements that are assigned to them by the water manager. Some of the major lakes or lake systems were introduced as reservoirs or as sinks that receive water not needed anywhere else (Table 2).

Node types. The EPIC modeling system allows the user to define various types of nodes in the network. Each node serves a different purpose. The types of nodes are:

- *User nodes* - points where water is removed from the system by consumption. Return water may be generated at user nodes and returned to the system.
- *Mouth nodes* - points where rivers enter large water bodies, such as oceans and inland seas.
- *Reservoir nodes* - points where water storage facilities exist.

- *Simple nodes* - points in the network where water and salt balances must be calculated, but where no water storage structures exist, i.e., junctions.
- *Control points* - subgroup of simple nodes where information can be reported.

Optimization. The main optimization criterion is to minimize deficits of water delivery to all users (Part a in formulae 1 below). Other criteria, namely (i) the planned flow to the Aral Sea (Part b), (ii) the degree of filling of the reservoirs (Part c), and (iii) the demand for stability of the system (Part d) simplify and accelerate the calculations (McKinney & Savitsky, 2001) and through changes in their weights allow for the implementation of policy decisions. The objective function has the following form:

$$\text{Maximize} \quad \underbrace{p_1\left(\frac{1}{T*N_{i_{user}}}\sum_t\sum_{i_{user}}\frac{W_{in,i,t}-W_{trans,i,t}}{W_{req,i,t}}\right)}_{(a)} + \underbrace{p_2\left(\frac{1}{T*N_{i_{mouth}}}\sum_t\sum_{i_{mouth}}\frac{W_{in,i,t}}{W_{req,i,t}}\right)}_{(b)} \qquad (1)$$

$$+\underbrace{p_3\left(\frac{1}{N_{i_{res}}}\sum_t\sum_{i_{res}}\frac{Vol_{i,t}}{Vol_{i,\max}}\right)}_{(c)} + \underbrace{p_4\left(\frac{1}{T*N_{i_{user}}}\sum_t\sum_{i_{user}}\left(\frac{W_{in,i,t}-W_{in,i,t-1}}{W_{in,i,t}+W_{in,i,t-1}}\right)^2\right)}_{(d)}$$

where

p_1, p_2, p_3, p_4	dimensionless weights indicating the priority of each objective function component,
$i_{user}, i_{mouth}, i_{res}$	*i*-th node of type “user”, “mouth”, or ”reservoir”,
$N_{i_{user}}, N_{i_{mouth}}, N_{i_{res}}$	total number of nodes of type “user”, “mouth”, or ”reservoir”,
t	time step (month),
N	total number of nodes in the network,
T	total number of time steps considered in the model,
$W_{in,i,t}$	water entering node i in time step t (million m^3),
$W_{trans,i,t}$	water transiting node i in time step t (million m^3),
$W_{req,i,t}$	water required by user i in time step t (million m^3),
$Vol_{i,t}$	volume of reservoir i at the end of time step t (million m^3), and
$Vol_{i,\max}$	capacity of reservoir i (million m^3)

Part (a) of Eq. 1, the main criterion, serves to maximize the ratio of water delivery to water demand (requirement) for each user. Part (b) of this equation serves the same purpose for the "mouth" of the river, in this case the Aral Sea. Part (c) acts to keep reservoirs in the system as full as possible, thus conserving stored water. Part (d) prevents rapid changes in water flow in the network arcs and is a nonlinear term.

The following continuity equations for each node and the reservoirs act as constraints to the solution:

- *Simple nodes*: All water entering a simple node must also exit the node:

$$\sum_{i_{simple}} W_{out,i,t} = \sum_{i_{simple}} W_{in,i,t} \tag{2}$$

where

$W_{out,i,t}$ water leaving node i in time step t (million m^3), and

i_{simple} i-th node of type "simple".

- *User nodes*: Water leaving a user node comes from a combination of transit flow, return flow (generated from the water used at the node, i.e., the difference in water entering and transiting), and any local source of water:

$$\sum_{i} W_{out,i,t} = W_{trans,i,t} + (\sum_{i} W_{in,i,t} - W_{trans,i,t}) ret_{i,t} + WQ_{i,t} \tag{3}$$

where

$ret_{i,t}$ return flow coefficient (dimensionless), $0 \le ret_{i,t} \le 1$,

$WQ_{i,t}$ local source of water at node i and time t (million m^3),

and

$$\sum_{i} W_{in,i,t} - W_{trans_i,t} \le W_{req,i,t} \tag{4}$$

Formatted: Font: Arial, 11 pt

- Reservoir node: The outflow out of a reservoir node is determined by the inflow to the reservoir node, the changes in reservoir volume and the amount of water lost to evaporation.

$$\sum_i W_{in,i,t} - \sum_i W_{out,i,t} = Vol_{i,t} - Vol_{i,t-1} + e_{i,t} * \overline{A}_i \quad (5)$$

where

$e_{i,t}$ evaporation rate for reservoir i at time t (m),

$\overline{A}_{i,t}$ average surface area of reservoir i over time step t (million m^2),

Additional constraints that support the solving process or can be introduced by the user for scenario development include: (i) physical constraints, such as capacity limits for the Nurek and Tyuyamuyun reservoirs; (ii) policy constraints, such as minimum inflow to the Aral Sea; and (iii) model control constraints, such as an upper limit on changes of reservoir volumes during two consecutive time steps and upper limits on the inflow to delta lakes and reservoirs (Table 2). Users can change policy constraints to develop scenarios of water management alternatives to reflect for example changes in water use for irrigation or a desired minimum flow in a specific canal for ecological purposes. The model control constraints are needed to keep the solver from choosing unrealistic solutions, such as emptying a reservoir in one time period.

The model is a nonlinear program and it is solved by a nonlinear programming solver of the GAMS software (Minos 5, Murtagh et al., 2002). A detailed description of the EPIC modeling system for river, salt, and energy management and its application to the Aral Sea basin can be found in McKinney and Kenshimov (2000) and McKinney and Savitsky (2001).

Input Data. The following input data are needed for the model;

- Reservoir and channel capacities;
- Initial volumes for reservoirs;
- Reservoir function relating level to volume;

- Inflow at the source nodes, either historic data or results of time series analysis;
- Average monthly water use at the user nodes, either historic or scenario values;
- Estimated or measured losses (evaporation and infiltration, intake by small canals); and
- Objective weights of the water manager, reflecting policy decisions

For the purposes of calibration and validation, data for average monthly river inflow at the supply nodes, reservoir storage, and withdrawals by the canals were obtained from the responsible water management agencies (mainly the Uzbek Hydrometservice). Due to a lack of data for the river Pyandj, where most measuring stations are out of order, runoff values in the Pyandj were estimated using data from stations on the neighboring Vakhsh river and at the Kerki gauging station on the Amudarya river (gauging station where the river leaves the mountains and flows into the desert lowlands).

For scenario development upstream water supply is modeled based on historical time series or generated hydrogaphs derived from probabilistic flood frequency distributions. User demands are based on scenario dependent estimated water use.

Losses along the main river were accounted for as additional water users. Evaporation, infiltration and transportation losses, as well as intake by small canals and pumping stations, were estimated based on data from 1991-2000. Unfortunately data for the Northern Amudarya delta were rather imprecise, e.g., there were cases when flow values further downstream were higher than at the preceding station upstream for several months per year, although no significant inflow, nor a time lag, could be detected. Possibly this is the result of measurement errors. Observations made by the authors at the gauging station Kyzyljar at the beginning of 2002 indicated that in low water years measured discharges in the Northern delta might be overestimated.

The losses in the upper and middle reaches varied from 0% (winter) to 10% (spring/summer) of the runoff at Kerki. Losses in the lower reach were accounted for at the river station Samanbay (see Fig. 1) with values in the range 15 - 27% of the outflow of the Tyuyamuyun reservoir, and at the station Kyzyljar in the range 5 - 20% of the inflow at

Samanbay. According to the data, losses in the delta area are much higher than in the middle reach, possibly due to the fact that many small canals and pumping intakes are not included in the modeled river network and the higher inflow of return waters in the middle reach.

The Tyuyamuyun Reservoir. For the purposes of this work, the EPIC modeling system was extended by adding functions to allow creation and computation of multi-body reservoir systems connected via managed weirs or unmanaged canals, as is the case for the Tyuyamuyun reservoir on the Amudarya river (Fig. 2) which consists of four bodies. Accurate representation of the water flow between the reservoirs is essential for future modeling of salt transport and the salinity of the reservoir outflow to the delta region. Salt concentrations in single reservoir bodies can vary significantly depending on the amount of freshwater mixing in the individual reservoir bodies. After construction of the reservoirs in the beginning of the 1980s, the initial salt leaching was very strong. Figure 3 shows the amount of salt (thousand tons per year) dissolving into the three off-stream reservoirs over the time period 1981-2001. The dam on the main reservoir was built in 1981/82. Kaparas reservoir, which was still directly connected to the main reservoir body, was flooded in 1981-82 and salt accumulations on the bottom dissolved causing the salinity peak seen in Fig. 4. The same accounts for Sultansandjar (flooded slowly in 1983-4) and Koshbulak (flooded in 1985). The depression and second peak in salinity in Kaparas reservoir in 1993 (Fig. 4) is connected to a lowering of the water level for dam construction works so the reservoir could be used as a drinking water supply, especially in the spring period (April, May), when the quality of the Amudarya river water is poor. Low water levels in Kaparas (approximately 100m) resulting in inflow of highly saline groundwater, as well as salt leaching from the reservoir bottom and evaporation causes reservoir salinity to increase to more than 3 g/l. The process of salt leaching is slowly stabilizing in all of the reservoir bodies and can be estimated. As a result of all these factors, salinity at the main outflow of the reservoirs can be managed. This risk of high salinity and potential for management is not apparent in average monthly salinity values if a single Tyuyamuyun reservoir is used in modeling. Additionally some of the main canals in the Southern delta region originate from one of the separate reservoirs and thus depend directly on water amount and quality in this reservoir body.

To model the water exchange between the four reservoir bodies, the following features were introduced: If there are two interconnected reservoirs in the system they are connected via return links allowing water exchange in both directions. A set of managed links is defined for those reservoirs where the water level difference can be regulated (in our case TMGU Main, Kaparas and Sultansandjar). Several functions to model water exchange between managed and unmanaged reservoir bodies were tested. They were all based on the fact that water exchange in the unmanaged case has to take place according to water level differences, while in the managed case water exchange from the higher level reservoir to the lower level reservoir is determined by the model. Given the specifics of the GAMS solver, the following functions proved to be best.

- Between two managed reservoirs:

$$W_{i_1,i_2,t} < f_{i_1,i_2}\left(\sqrt{\left(H_{i_1,t} - H_{i_2,t}\right)^2} + \left(H_{i_1,t} - H_{i_2,t}\right)\right) \quad (6)$$

- Between two non-managed reservoirs:

$$W_{i_1,i_2,t} = f_{i_1,i_2}\left(\sqrt{\left(H_{i_1,t} - H_{i_2,t}\right)^2} + \left(H_{i_1,t} - H_{i_2,t}\right)\right) \quad (7)$$

where

$W_{i_1,i_2,t}$ water flow between reservoirs i_1 and i_2 during time step t (million m^3),

$H_{i,t}$ water level in reservoir i at the end of time step t (m),

$$H_{i,t} = \frac{\left(Vol_{i,t}\right)^{1/a_i}}{b_i} + H_{0,i} \quad (8)$$

f_{i_1,i_2} flow coefficient between reservoirs i_1 and i_2 (m^2/month),

a_i, b_i coefficients of reservoir i (derived from data on reservoir water surface and volume), and

$H_{0,i}$ minimum water level of reservoir i

Calibration. The model was calibrated by fitting model results to observed values of reservoir volumes and river flow at selected gauging stations in the high water year 1994 and the low water year 1997. The parameters used for the calibration were (1) the intensity of flow between managed and unmanaged reservoirs (f_{i_1,i_2}), and (2) the objective weights for the objective function (p_1, p_2, p_3, p_4). Observed discharge data for the gauging stations are mean monthly averages from daily measurements. The reservoir volume data used are the reservoir volume for the last day of the month, because EPIC results, $Vol_{i,t}$ **,** correspond to the final volume in the reservoir at the end of the time period.

Results and Discussion

The main indicator of model performance is its ability to serve user demands as requested. The model optimizes water distribution according to the given objectives and its knowledge of water availability in the entire modeled time period. The observed water distribution, on the contrary, is the result of a difficult management process composed of forecasts, expected needs, political decisions, historical experience and current legal and political settings. It is thus only possible to calibrate and test the model results within limits by fitting them to observed data. Management decisions are not only complex but are also taken under high uncertainty on future water availability. The optimization model does not take this uncertainty into account but rather “takes decisions” with perfect knowledge of the future situation.

As an indicator for the goodness of fit of the model results, the relative monthly deviation (RMD), as the mean difference of modeled and observed monthly values related to the observed value, and the relative annual deviation (RAD) from observed data were chosen.

Sensitivity Analysis

The optimization weights are a means for the manager to set the priorities of the various tasks. Sensitivity analysis showed that the model reacts in the desired way to an increase in the priority of the objective to allocate water to the river mouth (p_2) by releasing more water from the reservoir (Fig. 5A/5B – annual discharge). An increase in the stability task (p_4) has the same effect, most likely because the model allocates more water downstream in order to even out strong fluctuations between months, although in this case the effect is less pronounced. Increasing the weight of the objective to fill the reservoirs (p_3) does not show a significant increase in water stored in the reservoir. The effect of this objective might be less noticeable because of the four reservoir body system of the Tyuyamuyun reservoir with a very complicated management of water exchange between the reservoirs. The user objective weight (p_1) also does not affect model performance in a defined way, since the requirements of the users are already met with an objective weight of this task larger than 10 (given that all others are kept at one, as was the case in the sensitivity analysis).

Monthly values of **reservoir** volumes of Nurek and Tyuyamuyun are very sensitive to changes in the objective weights, especially to the objective of meeting user demands and filling the reservoir, since they determine changes in the amount and timing of water allocation. The upstream Nurek reservoir shows smaller variations in RMD than the main reservoir body of Tyuyamuyun. This is especially pronounced in the low water year 1997, probably since the range of possible variations is smaller, as has also been observed with a similar model by McKinney and Cai (1997). Nurek receives a constant input given by the user in all test runs and consists only of a single reservoir body. The inflow to Tyuyamuyun, on the other hand, is determined by the solver and water is allocated between all four reservoir bodies. A small change in the objective can thus have a significant effect on the modeled reservoir volumes and their monthly distribution. The annual discharge from both reservoirs is not sensitive to changes in the objective weights, as shown above (fig 5).

Annual discharge at the **river stations** (Fig. 5C/5D) is generally less sensitive to changes in the objective weights. At Darganata station, discharge is very constant or changes continuously with increasing weights of the objectives “delta, p_2” and “stability, p_4” as has been observed for the reservoir outflow. At the delta station, Samanbay, fluctuations of annual discharge occur but only within a range of approximately 10-15%. Mean monthly variations are also very small, with the exception of Samanbay in the low water year 1997, where modeled and observed values strongly diverge.

In general it can be said that the determination of the optimal weighting vector is difficult due to the often non-linear behavior of the model and the high correlation between the tasks of the multi-objective function. The solution is also dependent on the geometry of the feasible region, i.e., on the constraints applied to the solution. The user priority, p_1, has to always be an order of magnitude higher than the other priorities in order to ensure required water delivery to the users.

Calibration Results

Results of the calibration for both years given as RMD and RAD are summarized in Table 3. Additionally, figure 6 depicts modeled and observed monthly reservoir volumes for Nurek and TMGU Main in the low water year 1997. Reservoirs are the most important nodes for control of water distribution by the model. Nurek reservoir volumes are modeled very close to the volumes observed in the high and low water year with RMD equal to 8 and 5%, respectively (see also Table 3). Modeled total annual discharge from Nurek reservoir is in both years lower than observed (24% and 18%), while the monthly values vary by an average of about 37%.

For the main body of the Tyuyamuyun reservoir, which is much more sensitive to changes in model parameters, RMD was 26 (1994) and 50% (1997). Modeled annual outflow from Tyuyamuyun is close to observed in the high water year 1994 (8% higher) while it is 86% higher in the low water year 1997. The model does not accurately account for losses upstream and in the reservoir bodies in the low water year.

Monthly deviations of volume and outflow from TMGU main reservoir illustrate the effect of different knowledge of future water availability between the real operator and the model solver. While the model allocates water to the delta region in spring, the operator tries to keep as much water as possible in the reservoir until the growing season as a safeguard against a potential lack of water during the irrigation season (see Fig. 6). On the other hand, in fall the real manager will try to constantly release water in small amounts to avoid winter flooding and keep free capacity in the reservoir, while the model fills the reservoir, possibly to fulfill the "filling" objective. Besides this, in fall and winter the operator will consider the expected situation in the next year, which the model cannot in a one year run.

The overestimation of discharge in the low water year, as observed at TMGU outflow is even more pronounced further downstream at the gauging station Samanbay. While in 1994 the model reflects the real situation in the annual average (RAD = 0.07), but with differences in the monthly distribution (RMD = 0.78), it greatly overestimates the discharge in the low water year 1997 (RAD = 16.04, RMD = 24.32). Clearly, the model is not able to represent actual water distribution in the lower part of the delta in a low water year. It has been observed that in reality, in low water years, no water is released into the main river after the last main irrigation intakes slightly north of Nukus and thus the river at the gauge Samanbay actually remains dry.

Long term modeling of water allocation in the delta region

The calibrated model was applied to a 14-year reference period. The long term modeling of water allocation was restricted to the delta part of the model, mainly due to computational constraints. The source node of the reduced river network is located at Darganata, which is the last river node before the entrance of the delta and the reservoir complex Tyuyamuyun (see fig 1). The delta part of the model is identical with the whole basin model. Mean monthly inflow to the river network was based on a characteristic runoff time series at Darganata (1980-1993). Input data for user requirements and losses are based on data of the average water year 1995. Upper bounds on the inflow to the lakes were reduced to 250 million m^3/month.

The results of the long-term simulation is depicted in Figure 7 which shows a comparison of modeled and observed data for the outflow from Tyuyamuyun Main and the discharge at the gauging station Samanbay. The outflow from Tyuyamuyun is modeled well compared to historic data (Fig. 7A). The model captures timing and magnitude of peak discharges in summer, indicating that monthly water exchange and releases from the four bodies of the reservoir is represented accurately (deviation of total discharge = 0.04; RMD= 0.36). Although, in fall and winter periods, when discharge is generally lower, the dynamics of water release from the reservoir body in reality are not always reflected in model results. This again might be the result of the deterministic nature of the model. At the gauge Samanbay, further downstream in the delta region, model accuracy is lower (Fig. 7B). Runoff in low water years is often overestimated as has been observed in the one year scenarios. There are months in low water years where observed flow at the gauging station equals zero, while the model allocated water to this river stretch. Thus, mean monthly deviation is very large, although deviation of the total discharge at this gauging station is low (0.03). Again, natural and human induced losses in low water years are not accurately accounted for in comparison with a mean water year. The large deviation in monthly river flow in the northern delta indicates that the model does not represent current practices in water allocation. Most likely there are other water intakes that have not been taken into account in the model. Since those small scale allocation practices are not reflected in the available data basis, this needs to be discussed with local water managers and water users.

Conclusion

Past applications of the EPIC modeling system for water management modeling in the Aral Sea basin have mainly focused on its second major river, the Syrdarya (McKinney and Kenshimov, 2000). Their main task was to provide decision support for allocation tradeoffs between the needs of hydroenergy production upstream and irrigation downstream. Water allocation and energy production was modeled on a one year basis (Antipova et al., 2002). The results were used to determine the necessary compensations for a reduction of energy production in favor of irrigation.

In this study a water management model for the Amudarya river was developed within the EPIC modeling framework. The model provides a tool to develop water allocation scenarios as the hydrological basis for ecological impact assessment. The model accurately represents current water allocation for the entire basin as well as higher resolution for the delta region. The separate modeling of the four reservoir bodies of the Tyuyamuyun reservoir is feasible, although it can still be improved. The application of this detailed model to water quality issues will be an interesting next step.

Model testing has shown that the model manages the allocation of the available resources in the desired way and reacts to changes in priorities of the individual objectives - water delivery to the user, water allocation to the delta, maximum filling of the reservoirs and stability of the solution - as expected. It was feasible to determine a set of parameters and weighting vectors that produces allocation schemes very similar to those found in the high water year 1994 and low water year 1997. The annual quantity of water at the gauging stations and the outflow of the reservoirs are almost identical to the real world situation, while the spatio-temporal distribution is more variable. In scenario development the spatio-temporal distribution can be influenced by setting variable bounds. The rather complex multi-objective optimization function makes straightforward manipulation of model outcomes difficult. When implementing management decisions by setting priorities through the objective weights, one should always check whether the model correctly fulfilled the desired task. Also, it is advisable to reflect policy decisions through changes of the requirements of the users, to the upper and lower limits of canal discharges and changes in network structure.

The results given in this paper confirmed the fact that it is difficult to model today's water allocation in the Northern Amudarya delta region because of a lack of knowledge of local water allocation practices and small scale patterns, as well as the network of actors and influences affecting water distribution. This is especially significant in low water years, where modeling revealed that water is not managed according to the given schemes but gets diverted along different paths. The accuracy and quality of the model strongly depends on the quality of the input data and the information available to the water manager.

It is doubtful whether the necessary details of this allocation system, which is always prone to rapid changes, will ever by known. The water allocation modeled in the Northern delta is a means to propose allocation alternatives and test their effect on the ecology of the delta region, rather than to achieve a detailed representation of current day allocation schemes. The testing of the model has shown that the results are within realistic bounds and can be used for further assessment. Given data constraints and the emphasis on facilitating the development of long term scenarios of water availability in the delta area the model has been kept rather simple. Greater detail and accuracy is traded for the possibility of developing scenarios over longer periods, say 30 years, which is necessary to evaluate the slower changing environmental variables. The results of the 14-year scenario satisfy the need for an accurate representation of potential future tendencies as the basis for an ecological assessment.

Deleted: time period (did we explain the doubling somewhere? Otherwise have to take out)

Differences in the behavior of the optimization model compared to real-world management are a significant issue for forecasting optimal operational regimes of reservoirs. Methods to incorporate more uncertainty into operational models are being developed (Kracman et al., 2002). For the aim of scenario analysis to assess potential long term ecological effects of changes to the hydrological regime pursued in this study the “simple” optimization method is adequate. From a technical point of view the modeling system is well suited for scenario analysis because of its user friendly graphical interface. Given the integration with ecological and other geo-physical models, the effects of measures in water management can easily be assessed. Users, be they economic or ecological, can easily be added or removed, constraints added or changed and the objective weights changed without having to go to the source code. This is a major prerequisite for the use of the final tool in an interactive development of management alternatives and the evaluation of their effects.

The model is dynamic and can be extended to model time periods of up to several decades. Both characteristics are essential for ecological impact assessment. The model provides mean monthly runoff values in the main river as well as the head volumes for the major canals in the delta region that can be integrated in a Geographic Information System. They are the basis for further simulation of water availability in every canal reach as well as the dynamics of water-related environmental variables such as changes in groundwater table height or flooding regime. The changes in environmental variables are then assessed by ecological models such as a Tugai (riverine) forest habitat suitability index model (Rüger et al., in review; Schlüter et al., in review).

Degradation in the delta areas has reached a very high level, imposing doubt as to whether the ecosystems can be restored to a condition similar to former times. Efforts have been underway since the late 1980s to preserve wetlands and lakes of the northern delta area, showing some successes. There is also a question whether this is desired and appropriate under the current circumstances. Alternative vegetation communities might be established on highly saline soils and the bottom of former lakes might be used for grazing and fodder production. To answer such questions the potential of the delta region under current and proposed future water management must be assessed.

Without goals commonly agreed upon by the governments of the five Central Asian states as well as the affected people, measures for effective and ecologically sound water management can not be worked out. Water management scenarios developed with the Amudarya water management model can be a basis for discussion and evaluation of future management alternatives. Coupled with environmental and ecological models the costs and benefits of alternatives can be assessed and compared. An integrated tool will facilitate the determination of restoration goals by supporting a participatory process of selecting between alternatives involving water managers and decision makers as well as other stakeholders and the general public.

Software availability

The EPIC modeling software, documentation and a user's manual can be downloaded from the following website:

http://www.ce.utexas.edu/prof/mckinney/papers/aral/EPIC/EPICmodel.html.

The General Algebraic Modeling System (GAMS) software is needed to generate any new results from the modelling system. If the licensed GAMS solver is not available, models can be submitted for solving to the NEOS server for optimization at http://www-neos.mcs.anl.gov/neos/.

The EPIC-Amudarya model described in this paper can be downloaded from the following website: http://www.usf.uni-osnabrueck.de/projects/aral. For any questions please contact the corresponding author.

Acknowledgements

The authors would like to thank Michael Matthies for his valuable criticism and comments to the manuscript. Comments of two anonymous reviewers greatly assisted in improving the manuscript. This work was supported by the INTAS Aral Sea project No 00-1039 "Restoration and Management Options for Aquatic and Tugai Ecosystems in the Northern Amudarya delta region" and a fellowship of the German Exchange Service (DAAD) to the first author.

References

Agreement Between the Republic of Kazakhstan, the Republic of Kirgyzstan, the Republic of Uzbekistan, the Republic of Tajikistan and Turkmenistan, 1992. On Cooperation in the Field of Joint Water Resources Management and Conservation of Interstate Sources: Almaty. http://www.ce.utexas.edu/prof/mckinney/papers/aral/agreements/ICWC-Feb18-1992.pdf

Agreement Between the Republic of Kazakhstan, the Republic of Kirgyzstan, the Republic of Uzbekistan, the Republic of Tajikistan and Turkmenistan, 1993. On joint activities in addressing the Aral Sea and the zone around the Sea crisis, improving the environment, and enduring the social and economic development of the Aral Sea region: Kyzl-Orda

Andersen, J., Refsgaaard, J.C., Jensen, K.H., 2001. Distributed hydrological modelling of the Senegal River Basin – model construction and validation. Journal of Hydrology 247 200-214.

Antipova, E., Zyryanov, A., McKinney, D., Savitsky, A., 2002. Optimization of Syr Darya Water and Energy Uses. Water International 27 (4) 504-516

Arnold, J.G., Srinivasin, R.S. , Muttiah, R. S., Williams, J. R., 1998. Large Area Hydrologic Modeling and Assessment: Part I. Model development. Jawra 34(1) 73-89

Brooke, A., Kendrick D., Meeraus, A., Raman, R., 1998. GAMS - A User's Guide, GAMS Development Corporation: Washington DC.

Brunner, G. W., 2002. HEC-RAS, River Analysis User's Manual. US Army Corps of Engineers. Hydrologic Engineering Center (HEC). Davis, USA, http://www.hec.usace.army.mil/publications/pubs_distrib/hec-ras/user/user.html

Djailoobaev, A. Sh., 2002. Some Aspects of Cooperation in the Field of Water Resources in Central Asia on Issues of Flow Formation Zone. ADB Regional Consultation Workshop, Cooperation in Shared Water Resources in Central Asia: Past Experience and Future Challenges: Almaty.

Draper, A.J., Jenkins, M.W., Kirby, K.W., Lund, J.R., Howitt, R.E., 2003. Economic-Engineering Optimization for California Water Management. Journal of Water Resources Planning and Management 129 155-164.

Dukhovny, V., Sokolov, V., 1996. Water Resources Management Strategy for the Aral Sea Basin: Problems in Preparation. http://www.oieau.fr/ciedd/contributions/at2/contribution/sokolov.htm.

FAO Aquastat, 2003, http://www.fao.org/waicent/faoinfo/agricult/agl/aglw/aquastat/regions/fussr/index8.stm.

Havnø K., Madsen, M.N., Dørge, J.,1995. MIKE11 – A generalized river modelling package. In: Singh, V.P., (Ed.), Computer Models of Watershed Hydrology. Water Resources Publications: Colorado.

Interstate Coordination Water Commission (ICWC), 1998. Bulletin No 16, Scientific-Information Centre of the Interstate Coordination Water Commission: Tashkent

International Crisis Group, 2002. Central Asia: Water and Conflict. ICG Asia Report 34: Osh/Brussels

International Fund for Saving the Aral Sea (IFAS), 2002. Aral Sea Basin Program. Water and Environmental Management Project. Sub-component A1. Regional Report No. 2, Phase iii Report - Regional needs and constraints, Supporting volume, Annex I, Water-Related Environmental Values in the Aral Sea Basin.

Deleted: ¶

Deleted: I

Ismaiylov, G. Kh., Veliev, F.I., Degtyarev, G.M., 1994. A model for the management of the volume and mineralization of a river flow. Vodnye Resursy 21 (3) 271-282. [in Russian]

Deleted: ¶
¶
Water-Related Environmental Values¶

Kracman, D., McKinney, D.C., 2002. Stochastic Optimization of the Highland Lakes System in Texas, Technical Report, Center for Research in Water Resources, University of Texas at Austin.

Letcher, R.A., Jakeman, A.J., 2003. Application of an Adaptive Methods for Integrated Assessment of Water Allocation Issues in the Namoi River Catchment, Australia. Integrated Assessment 4 (2) 73-89.

Létolle, R., Mainguet, M., 1996. Der Aralsee: eine ökologische Katastrophe. Springer: Berlin

McKinney, D.C., Karimov, A. K., Cai X., 1997. Report on Model Development: Aral Sea Regional Allocation Model for the Amudarya River. US Agency for International Development, Environmental Policy and Technology Project, Central Asia Regional EPT Office: Almaty.

McKinney, D.C., Cai, X., 1997. Multiobjective Optimization Model for Water Allocation in the Aral Sea Basin. In: Proc. 3-rd Joint USA/CIS Joint Conference on Environmental Hydrology and Hydrogeology, pp. 44-48, American Institute of Hydrology: St. Paul, MN.

McKinney, D.C., Kenshimov, A.K., 2000. Optimization of the use of water and energy resources in the Syrdarya river basin under current conditions. Technical report. US Agency for International Development, Environmental Policies and Institutions for Central Asia (EPIC): Almaty.

McKinney, D.C., Savitsky, A.G., 2001. EPIC Modeling System Guide - Water, Salt & Energy Management Problems, http://www.ce.utexas.edu/prof/mckinney/papers/aral/EPIC/EPICmodel.html.

McKinney, D.C., Kenshimov, A.K. Optimization of the Use of Water And Energy Resources in the Syrdarya Basin Under Current Conditions, http://www.ce.utexas.edu/prof/mckinney/papers/aral/00-06-W/EPIC-00-06-W.htm.

McKinney, D.C., Savitsky, A.G., EPIC Modeling Software, http://www.ce.utexas.edu/prof/mckinney/papers/aral/EPIC/EPICmodel.html.

Micklin, P., Reimov, P., Ptichnikov, A., Novikova, N., Kapustin, G., Ressl, R., 1998. Aral Sea GIS: Nukus.

Micklin, P. 2000. Managing Water in Central Asia. The Royal Institute of International Affairs: London.

Murtagh, B.A., Saunders, M.A., Murray, W., Gill, P.E., Raman, R., Kalvelagen, E., 2002. GAMS/MINOS: A solver for large-scale nonlinear optimization problems. http://www.gams.com/solvers/minos.pdf.

Raskin, P.H.E., Zhu, Z.S.D., 1992. Simulation of Water Supply and Demand in the Aral Sea Region. Water International 1755-67.

Razakov, R.M., Savitsky, A.G., Tikhonova, O.H., Timoshenko, C.U., Podgornov, U.U., Reizvich, H.V., 1998. Water regime model for the Amudarya with possibility of predicting pollution transport. In: Ecological Research and Monitoring of the Aral Sea Deltas. A basis for restoration. UNESCO Aral Sea Project, 1992-1996. Final Scientific Reports, UNESCO: Paris.

Reca, J., Roldan J.A.M., Lopez, R., Camacho, E., 2001. Optimisation model for water allocation in deficit irrigation systems, I. Description of the model. Agricultural Water Management 48 103-116.

Rüger, N., Schlüter, M., Matthies, M. A fuzzy habitat suitability index for *Populus euphratica* in the Northern Amudarya delta (Uzbekistan). In review.

Schlüter, M., Rüger, N., Savitsky A.G., Novikova, N.M., Matthies, M., Lieth, H. An integrated simulation tool for ecological assessment of alternative water management strategies - a case study of the Amudarya river delta. In review.

Shiklomanov, A. I., 1998. The Aral Sea Problem and Interbasin Water Diversions. State Hydrological Institute: St. Petersburg.

Shulz, V.L., 1965. Rivers of Central Asia. Gidrometeoizdat: Leningrad. [in Russian]

Srinivasan, R., Ramanarayanan T., Wang, H., Jayakrishan, R., 1997. Hydrological Modelling of the Rio Grande/Rio Bravo Basin. Final Report. Texas Natural Resources Conservation Commission:Texas

Treshkin, S.E., 2001. Transformation of Tugai ecosystems in the floodplains of the lower reaches and delta of the Amu Dar'ya and their protection. In: Ecological Research and Monitoring of the Aral Sea Deltas. A basis for restoration. Book 2. UNESCO Aral Sea Project, 1997-2000. Final Scientific Reports, UNESCO: Paris

UNESCO (United Nations Educational, Scientific and Cultural Organization), 2000. Water Related Vision for the Aral Sea Basin, Division of Water Sciences, UNESCO: Paris

Wardlaw, R.B., Wells, R.J, 1996. Competition for water resources in agriculturally-based economies: a case study of an assessment approach used in Bali. Proceedings of the Institution of Civil Engineers/Water, Maritime & Energy 118 (2) 55-65

Wardlaw, R.B., Barnes, J.M., 1999. Optimal Allocation of Irrigation Water Supplies in Real Time, Journal of Irrigation and Drainage Engineering 125 (6) 345-354.

Table 1 Supply nodes (S1-S4), user nodes (1-4, 6-28, 30-31, 33-39; mostly intake of main canals delivering water to irrigation zones) and nodes for calculation of losses (5, 29,32) included in the modeled river network. The numbers correspond with the nodes in the river scheme in Figure 1. The delta is mainly located in Uzbekistan, in the administrative regions Khorezm and Karakalpakstan. The latter is an autonomous republic. Parts of the delta are located in Turkmenistan which also receives water from the Tyuyamuyun reservoir system (TMGU).

Name of the river/canal	Location/Type	Max / Approved capacity [m^3/s]	Number in river scheme
Side Inflow to Vakhsh	Upper reach		S1
Kafirnigan	Upper reach		S2
Kashkadarya	Upper reach		S3
Surkhandarya	Upper reach		S4
Upstream users	Upper reach		1
Karakum Canal	Upper reach	650/383	2
Amu Bukhara Canal	Middle reach	350/60	3
Karshi Canal	Upper reach	160/152	4
Losses upper/middle reach			5
Pyatnakarna	Lower reach - Khorezm	-	6
Dashouz Canal	Lower reach - Turkmenistan	300/250	7
Right Bank Channel	Lower reach - TMGU	-	8
Drink Canal	Lower reach - TMGU	-	9
Tashksaka	Lower reach – Khorezm	700/500	10
Gazavat/Shavat	Lower reach – Khorezm/Turkmenistan		11/12
Pakhtaarna	Lower reach - Karakalpakstan	460/440	13
Urgencharna	Lower reach - Khorezm	-	14
Oktyabrarna	Lower reach - Khorezm	-	15
Klychniyazbay	Lower reach - Khorezm	255/240	16
Kipchakbuzsu	Lower reach – Khorezm	45/40	18
Jumabaysaka	Lower reach - Khorezm	12/10	19
Sovjetyab	Lower reach - Turkmenistan	300/250	20
Suenly	Lower reach - Karakalpakstan	394/225	22
Koundykuziak	Lower reach - Karakalpakstan	-	23
Left Bank Collector	Lower reach - Karakalpakstan	-	24
Kungrad-Muynak Canal	Lower reach - Karakalpakstan	-	25
Risovij	Lower reach - Karakalpakstan	-	27
Kyzketken	Lower reach - Karakalpakstan	900/370	28
Losses lower reach I			29
Pumping Stations (upper, middle, lower delta)		-	17/21/32
Erkindarya	Old river branch/channel	-	30
Raushan	Old river branch/channel	-	31
Losses lower reach II			32
Akbashly	Old river branch/channel	-	33
Kipchakdarya	Old river branch/channel	-	35
Kazakhdarya	Old river branch/channel	-	37
Tujezhol	Old river branch/channel	-	39

M. Schlüter et al.

Table 2 List of delta lakes included in modeled river network. Numbers correspond to those used in figure 1.

Lakes in delta area	Limits to inflow (lower/upper) [million m^3]	Number in river scheme
Akchakol	50/300	F
Sudoche Lake I & II	0/1000	G/M
Mashankol	0/1000	H
Yiltyrbas	0/1000	J
End of Collector No 4	0/1000	K
Mezhdureche	0/1000	I
Dumalak Lake System	0/1000	L
Aral Sea	10-200/3888	N

M. Schlüter et al.

Table 3: Results of calibration and testing for the one year model runs of the whole river model. RMD = relative monthly deviation from observed data |(modeled-observed)/observed|; RAD = relative annual deviation. Values exceeding 0.5 are marked.

Reservoir or gauging station	**1994**		**1997**	
	RMD	RAD	RMD	RAD
Nurek	0.08	-	0.05	
Nurek out	0.36	-0.24	0.38	-0.18
TMGU main	0.26		0.5	
TMGU main out	0.31	0.08	**0.95**	**0.86**
Kaparas	0.25	-	0.39	
Sultansandjar & Koshbulak	0.15	-	0.39	
Darganata	0.23	-0.12	0.34	0.16
Samanbay	**0.78**	0.07	**24.32**	**16.04**

M. Schlüter et al.

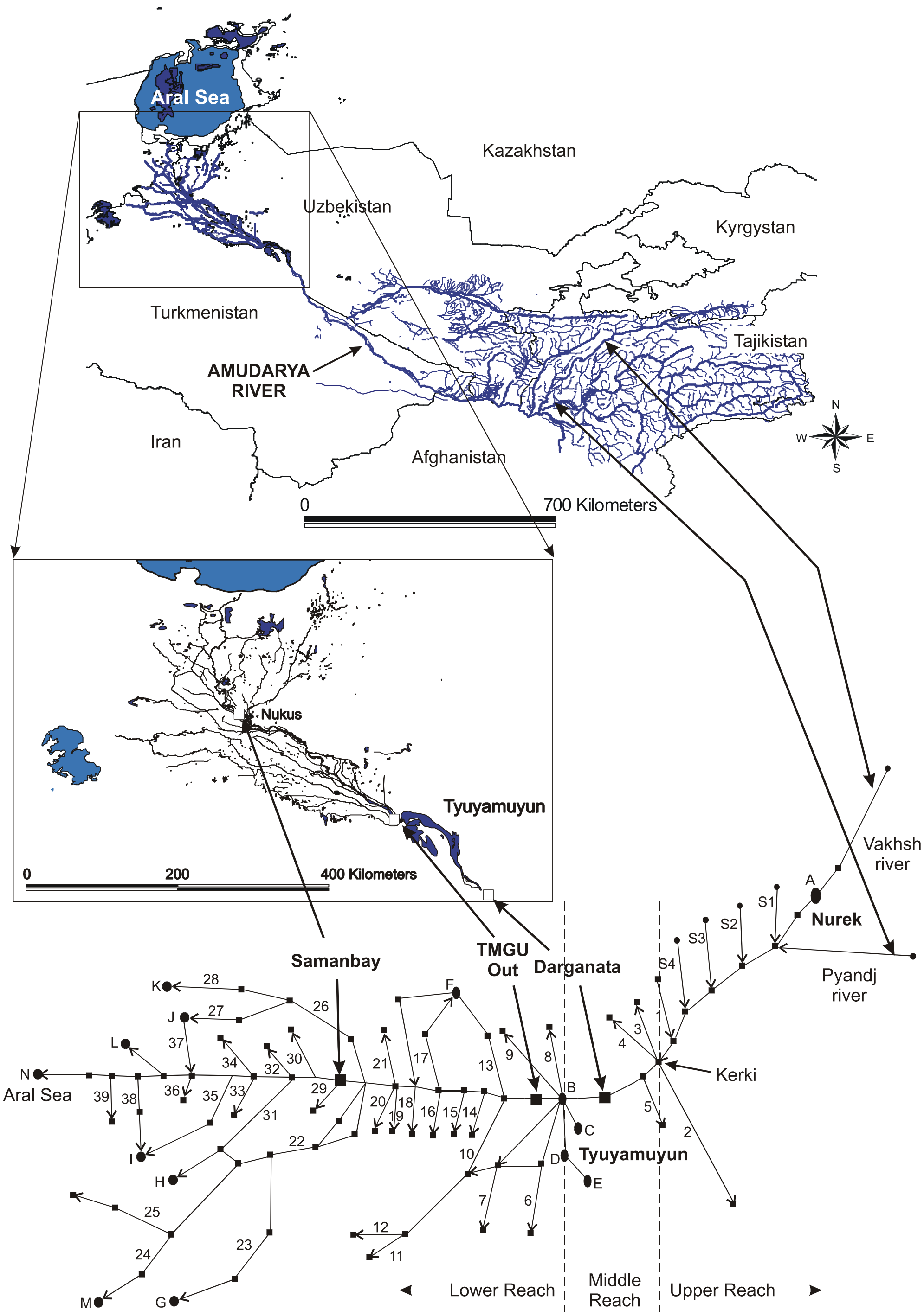

Fig.1

M. Schlüter et al.

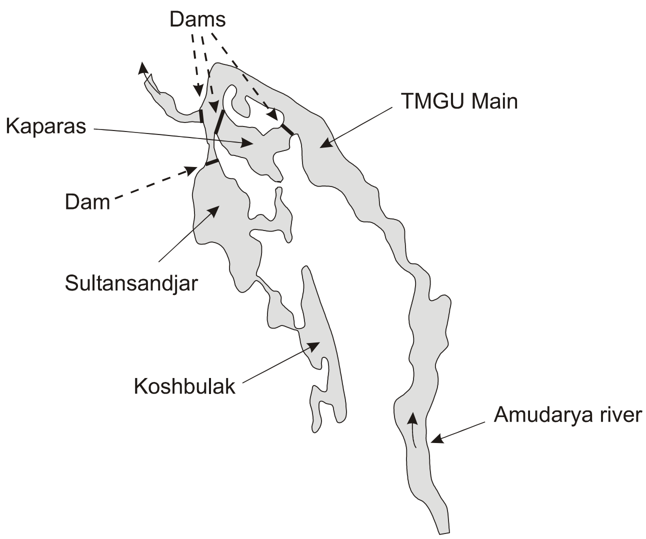

Fig. 2

M. Schlüter et al.

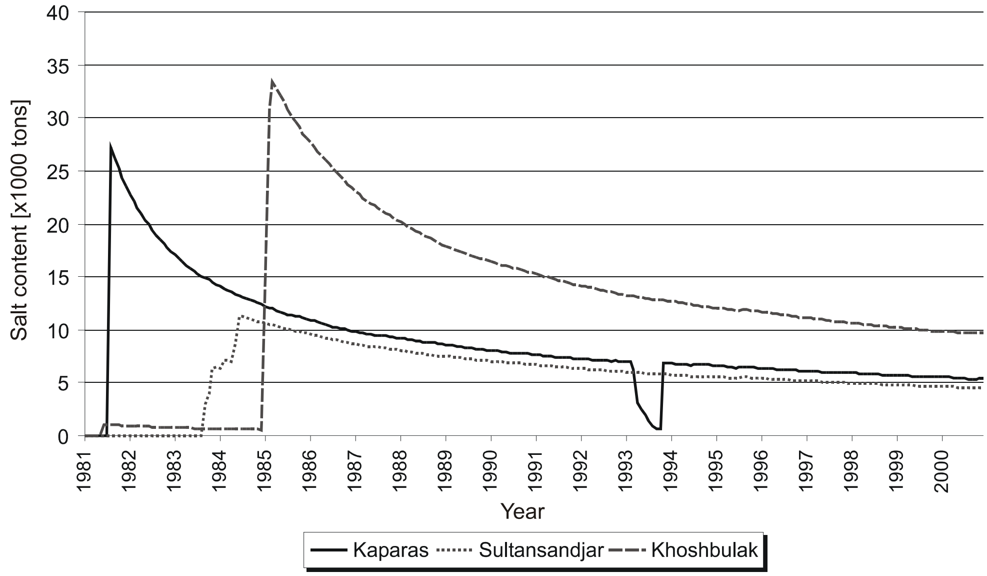

Fig. 3

M. Schlüter et al.

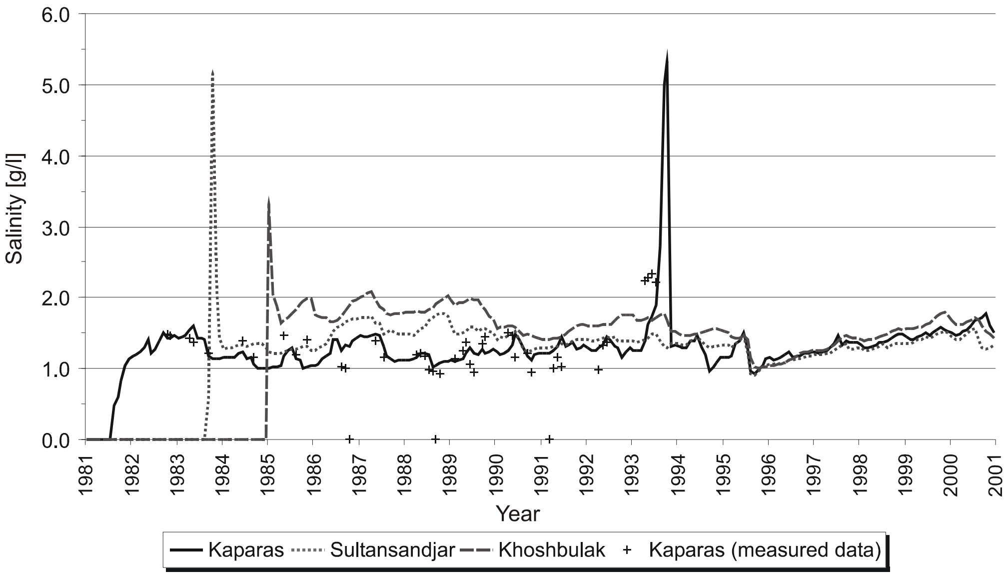

Fig. 4

M. Schlüter et al.

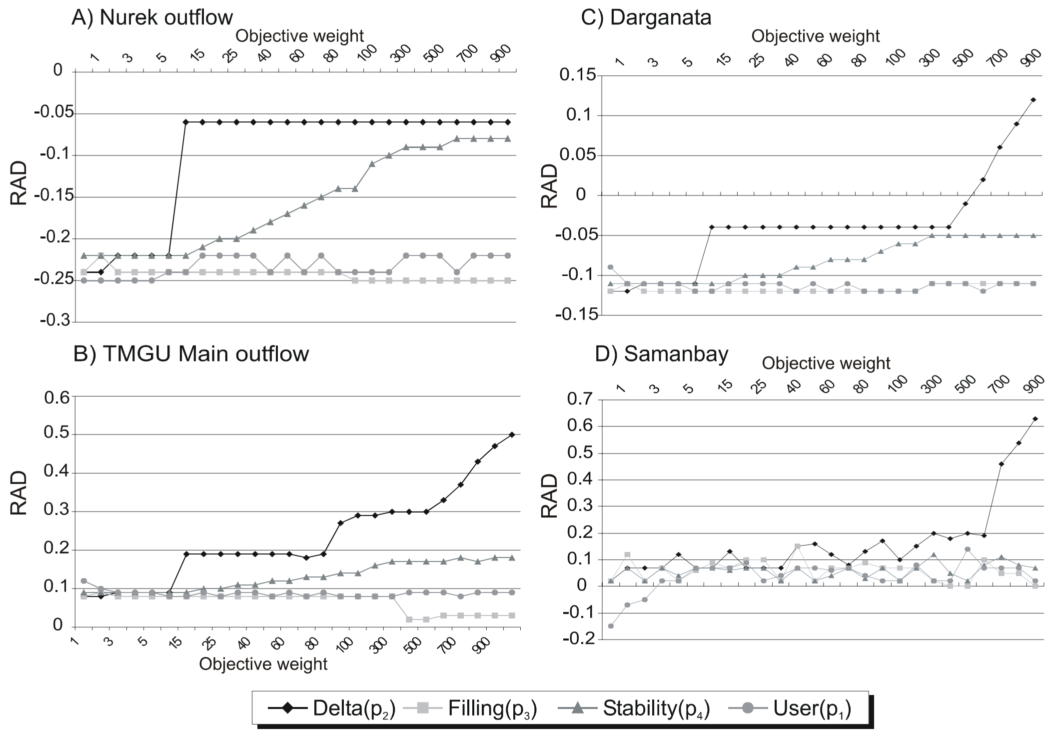

Fig. 5

M. Schlüter et al.

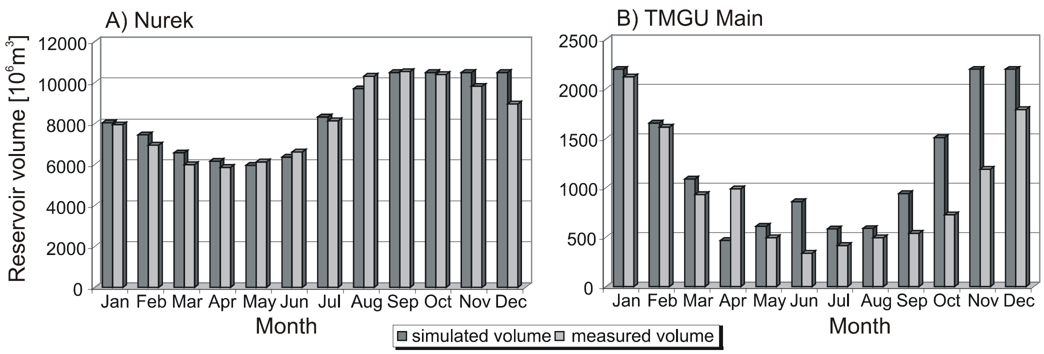

Fig. 6

M. Schlüter et al.

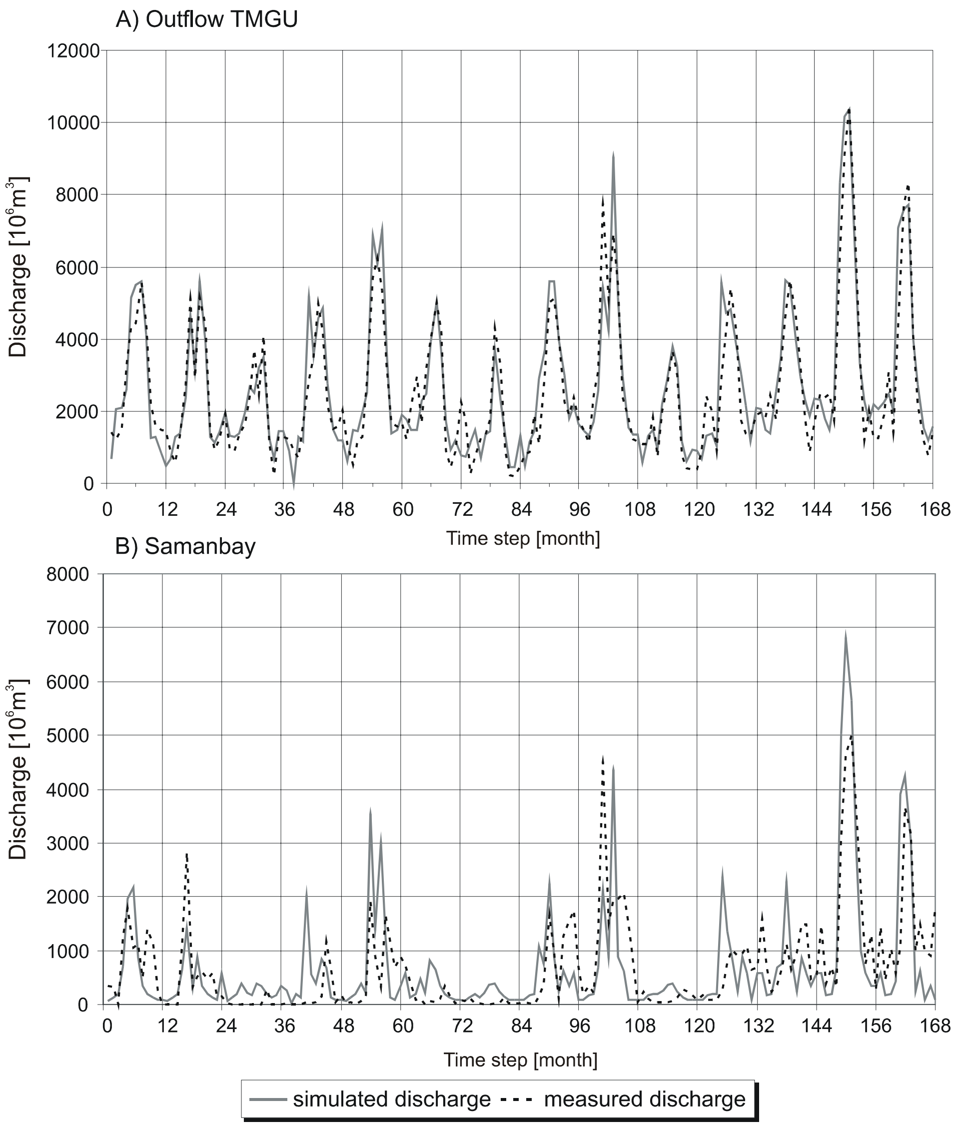

Fig. 7

M. Schlüter et al.

Fig.1 Map of the Amudarya river basin located in the countries Tajikistan, Kyrgyzstan,Afghanistan, Turkmenistan and Uzbekistan and drains into the Aral Sea. The lower map shows the delta region which is treated in greater detail in the modeled river network. Below the nodal network diagram as it is represented in the EPIC model (not to scale) is given. The three river stretches and the river nodes that are used for calibration and sensitivity analysis are indicated. The numbers on arcs are explained in table 1. S1-S4: supply nodes; 1-39: user nodes and losses; A-F: reservoirs; G-M: delta lakes; N: Aral Sea

Fig. 2 Scheme of the Tyuyamuyun reservoir system (TMGU) at the inflow to the Amudarya delta region. The four reservoir bodies TMGU Main, Kaparas, Sultansandjar, and Koshbulak and the flow direction of the Amudarya River are indicated.

Fig. 3 Amount of salt (thousand tons) leaching from the bottom sediments into the water columns of Kaparas, Sultansandjar and Koshbulak calculated with the model WP (Razakov et. al 1998). The leveling out of salt leaching from the reservoirs after dam construction is visible.

Fig. 4 Salinity of water body in Kaparas, Sultansandjar and Koshbulak calculated with the model WP (Razakov et. al 1998). The initial increase in salinity caused by the leaching out of the bottom salts is clearly visible in 1983 (construction of dam on Sultansandjar), 1985 (dam on Koshbulak) and 1993 (dam on Kaparas). The dots represent measured data of salinity in the Kaparas reservoir. Modeled values are monthly averages; measured data are single measurements at different days of the month.

Fig. 5 Relative annual deviation (RAD) from observed data (high water year 1994) of the modeled discharge from the reservoirs a) Nurek and b) TMGU Main Reservoir and at the river stations c) Darganata and d) Samanbay with increasing objective weights for delta (allocation to the mouth), filling (achieving maximum volume of the reservoir), stability (decreasing fluctuations between months), user (satisfying user requirements). For the sensitivity analysis for each objective the other objectives were kept constant at one.

Fig. 6 Modeled and measured volume at the end of each month (mlnm^3) in a) Nurek and b) Tyuyamuyun Main Reservoir for the calibration year 1997 (low water)

Fig. 7 Modeled and observed discharge a) from the TMGU reservoir and b) at the gauging station Samanbay of the 14 year scenario.