Development of an integrated GIS-based simulation tool to support ecologically sound water management in the Amudarya river delta

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Summary

Extensive use of the Amudarya river waters for irrigation has severely impacted the ecosystems in the Aral Sea Basin. Ecosystem degradation is most pronounced in the river's delta region. The need to provide more water to the environment has been acknowledged by the concerned basin states. Although, rehabilitation goals have not been formulated yet and water needs of the environment over time and space are mainly unknown. Integrated approaches are needed to balance water allocation between conflicting users, such as the environment, agriculture and human population. This study aims at providing a scientific, computer-based framework for analysis of tradeoffs in water allocation in the Amudarya river delta, development of alternative water management strategies and assessment of their ecological effects.

Quantitative, semi-qualitative and qualitative knowledge on hydrology and ecology of the Amudarya delta has been structured and formalized into a set of coupled models that are integrated into a GIS-based simulation tool. The tool facilitates direct and easy evaluation of dynamic riverine landscape changes based on the presently available data and ecological expert knowledge. Various modeling approaches have been applied to do justice to the different data and information types available. Integration of all models in GIS facilitates spatially-explicit landscape-based analysis of water management strategies or changes in water availability in the delta over a 28-year time period. The TUGAI tool has been implemented in ArcView, which also serves as user interface for scenario development and simulation. Future policy or management measures are modeled as objectives and constraints to multi-objective optimization of the spatio-temporal water distribution in the delta using a water allocation model. The projected river flow determines mean annual groundwater level and flooding regime based on spatially-explicit statistical and rule-based methods. The resulting ecological state of the delta is assessed on an annual time scale with the help of a habitat suitability index for riverine Tugai forests. Tugai forests, which are typical for the delta prior to degradation, serve as an indicator for a "healthy" state of the delta environment. The tool allows qualitative comparison of alternative strategies using color coded maps, tables and graphs. All models have been validated as much as possible with monitoring data and expert knowledge.

The tool discerns well spatial habitat quality differences within and between scenarios of different management strategies. Uncertainties and their influence on model outcomes can easily be assessed. First analysis show that management strategies improving environmental quality in the delta region without depriving agriculture of its needs are realistic. Potential for ecosystem rehabilitation lies for example in the use of excess water in high water years.

The tool provides a framework for discussion and evaluation of alternative management options and can support goal finding processes and the formulation of ecologically-sound water management strategies. Limitations of the given approach in view of its application for decision support and interpretation of results are discussed. Knowledge gaps and type of data needed for integrated ecological impact assessment in the area are identified.

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1 Introduction

Ecological effects of water management policies are receiving increasing attention in water management worldwide. The ecological and economic benefits of rehabilitation of floodplain ecosystems for flood prevention, to maintain ecological services such as filtration of water and air, protection against erosion, maintenance of biodiversity, etc. are valued and taken into account in future water management activities. Integrated, non sector oriented management fosters coordinated development and management of water and related land resources (GWP Technical Advisory Committee 2000). The importance of participatory approaches to design better management strategies is acknowledged. Scientifically based computer tools for reasoning and decision support facilitate an integrated view on water resources management issues and participation of stakeholders in decision finding. Their potential as a framework for policy making processes in complex resource management situations is growing.

To achieve an effective, sustainable management of water resources, the often conflicting needs of all water users in a river catchment, including those for ecology, need to be taken into account. Scientific research can assist in assessing needs, indicating possible development paths of a system under given policy choices as well as evaluating their risks and consequences. Next to quantitative descriptions of system dynamics, that are important for an understanding of functional relationships and general behavior, approaches are needed that provide reliable statements on the consequences of human actions for the environment (Blumenstein et al. 2000). Decision support systems and resource management studies have been designed for various river basins to assist in resolving resource management conflicts (e.g. Columbia River Basin (Roe & van Eeten 2002), CALFED (California, Wilkinson 2003), Everglades (Florida, DeAngelis et al. 1998), WAVES (Brazil, Gaiser et al. 2003)). Those, often large scale approaches, aim at supporting the assessment of measures, their analysis and discussion and assist in policy determination. They provide non experts and experts with a mean to test different management options without having to implement them in reality, risking uncertain outcome. With their help, limits of potential actions and inherent uncertainties can be studied. The consequences of proposed measures become evident and can be discussed.

The question of a sustainable management of water resources appears to be very urgent in arid Central Asia, where non-rational use of water resources has caused unprecedented damage to humans and ecosystems. Future water deficiency is a serious threat to people and economies. Water management over the past 50 years was oriented mainly to serve the needs of irrigated agriculture (Micklin 2000). During the Soviet Union the Aral Sea Basin in Central Asia was turned into the world's third largest producer of cotton (Micklin 2000). The consequent severe alterations to the hydrological regime of the basin's two major rivers and overuse of resources have brought about degrading ecosystems and deteriorating socio-economic conditions.

The five newly independent Former Soviet Union States of the basin have recognized the problems and need for action. For the past twelve years since political independence, solutions have been searched and numerous projects and studies, often internationally funded, have been realized. Especially in the delta region of the Amudarya river the bad ecological situation has been the target of many efforts, but little has changed so far.

The environment in the delta has been proposed as additional water user that is entitled to certain amounts of water from the rivers and irrigation drainage (WARMAP 1997). A definition of the "environment", in the sense of ecosystems and ecosystem services that are most valuable and should be preserved, has not been made so far. Without a common understanding of needs and goals it will be difficult to develop concepts for ecologically and economically sound use of water allocated for ecosystem rehabilitation. The determination of minimum amount and quality of water and its best spatio-temporal distribution to achieve highest possible ecological benefits and the desired rehabilitation goals is a complex task. It involves tradeoffs between different geographical regions in the basin, e.g. upstream and downstream, between the deltas of the Amudarya and Syrdarya rivers and the Aral Sea and within the deltas between different ecosystems, such as riverine forests and water bodies. They can only be resolved by an integrated and adaptive approach. Solutions to improve the ecological situation in the delta region have to be found, taking the conflict on water resources and the difficult socio-economic situation into account.

An exploration of potential water management options can support the determination of ecological objectives that are agreed upon between all involved parties. A common goal or vision target, as e.g. developed in the Aral Sea Basin Vision (UNESCO 2000), is essential for the success of measures. Although, the water-related Aral Sea Basin Vision only accounts for the environment in a very general way. To make best possible use of scientific knowledge for policy making, methods have to be developed to transfer scientific insight to political decision making. This includes methods to assess the effects of proposed measures and to measure their outcomes and success. In the ecological context measures are needed to assess the ecological quality of a region that results from water management or rehabilitation measures.

The **Amudarya river delta** is an example which is most suitable to study issues of scientifically based decision making and management. As an end user of water of the Amudarya river, which is the larger of the two rivers of the Aral Sea Basin, it has been most severely affected by alterations to the hydrological regime of the river. The once diverse ecosystems of the floodplains are threatened by desertification, caused by decrease of flooding events, lowering of the groundwater table, soil salinization and agricultural activities. Deltaic lakes, pastures and riverine forests, which have been the living basis of the local human population, have largely disappeared. The remaining are under high utilization pressure. Water supply to the delta varies significantly interannually and is to a large extent determined by water use practices along the entire river.

Water management in the delta region has to serve conflicting needs. Agriculture accounts for the largest water use, withdrawing over 90% of the available resources, and receives highest priority in water allocation. The bias towards irrigation has been a major cause of the degradation. Next in priority are drinking water needs of the local population. Deltaic lakes receive water only in high water years, when they serve as water reservoirs. Other ecosystems are not considered in water allocation so far. New strategies are needed to balance water distribution between the different water users to receive highest possible benefit of the resource. While agricultural, industrial and human water demands can be determined rather straightforward, the quantitative, qualitative and temporal water requirements of ecosystems are more difficult to assess and their benefits problematic to value. This thesis investigates ecological aspects of water management in the delta, because their consideration in future management is urgent but very difficult due to the complex resource allocation situation. Water allocation to the environment is seen in the context of current and potential future irrigation practices. Socio-economic aspects of water management that are equally important go beyond the scope of this study and are only considered as the general framework for the determination of alternative strategies.

The **aim of the thesis** is to facilitate a scientifically based exploration of alternative water management strategies in the Amudarya delta region as to their effects on the ecological state of the northern semi-natural part of the delta. Vast amounts of knowledge, experience and data on the delta and its hydrological and ecological characteristics and dynamics have been gathered by scientists, engineers, practitioners and local people. The objective of the work is to structure and formalize this information into a GIS-based simulation tool to facilitate a first quick assessment of the response of deltaic ecosystems to water management measures.

The work investigates methods to integrate quantitative, semi-qualitative and qualitative information into a spatially-explicit, simple simulation tool. The tool shall facilitate qualitative comparison of alternative water management strategies through scenario analysis with regard to their ecological consequences on a medium spatial and temporal scale. The aim is to provide decision makers and stakeholders with a simple method to study alternative spatio-temporal water allocation schemes. Those future scenarios are made to test the potential for an improvement of the ecological situation, while at the same time taking the needs for agriculture into account.

The construction of such an integrative tool demands a thorough analysis of the delta system with respect to the interdependencies between hydrological regime and ecological situation. It is aimed to formalize the acquired knowledge in modules using different approaches to best represent the given type of information and their future use in the entire tool. The development of the tool will reveal knowledge and data gaps that will have to be filled for a more comprehensive and advanced scientifically based decision support.

The spatio-temporal distribution of water allocated to the environment will determine its usefulness for a given ecosystem. Water made available in winter will not have much effect on the ecological situation, as will water that is diverted onto the dried out sea bed, as it is practiced in high water years at present. The tool thus has to be spatially-explicit and dynamic. Because many ecosystems react slowly to changes it should encompass a rather long time period. Balancing timing and spatial distribution of the water will be one of the main tasks to be studied with the proposed tool.

The aim of the tool is to help to structure the problem of water allocation to the environment, facilitate analysis of tradeoffs and uncertainties, foster discussion between stakeholders and support a goal finding process. Its development is motivated by the fact that resource and ecosystem management decisions in the Amudarya delta have to be taken today with the limited information available. The integrated tool shall help to make best use of this available information and to determine areas where new knowledge is most urgently needed. Its application in joint seminars with water managers, hydro-engineers, ecologists and decision makers, will raise awareness for ecological consequences of proposed measures and the understanding of interdependencies.

The approach is innovative in that it combines different qualities and types of information from several disciplines in an integrated tool. This is achieved by applying different methods at different scales and levels of sophistication in a problem oriented way.

The **objectives of the thesis** can be summarized as following:

- to analyze the delta system with an emphasis on hydrological and ecological aspects
- to select approaches for model development that best suit the available information and project system responses on temporal and spatial scales the selected ecosystems respond to.
- to determine a measure for the ecological condition of delta ecosystems
- to formalize the knowledge in a spatially explicit, landscape-based simulation tool to assess ecological effects of alternative water management options
- to make the knowledge easy to use, accessible and understandable for policy making
- to determine uncertainties and their implications
- to determine knowledge gaps and data demand for future comprehensive decision support

2 Aral Sea Basin and Amudarya river delta

The delta system of the Amudarya river has to be seen in the context of the whole river basin. It is influenced by hydrological processes as well as management decisions that take place at the catchment or even basin scale. The total extent of the basin is nearly 1.8 million km^2, located largely in the catchments of two major rivers that drain into the Aral Sea: those of the Amudarya (0.95 million km^2 or 53% of the basin) and Syrdarya (0.45 million km^2 or 25%). The basin is shared by five countries of the Former Soviet Union, southern Kazakhstan, southern Kyrgyz Republic, most of Turkmenistan, and all of Tajikistan and Uzbekistan, which together account for 86.6% of the basin, and Afghanistan and Iran (fig 1). While Iran's part of the basin is small, Afghanistan's part is substantial since it contributes approximately 15% to the average annual flow of the main rivers.

Figure 1: Political Map of Central Asia. The Amudarya and Syrdarya river draining into the Aral Sea are indicated. The major Karakum Canal diverts water from the Amudarya to Turkmenistan. The study area is located in Uzbekistan (modified after Magellan Geographic 1999)

Because of the aridity of the climate agriculture in the lowlands of the Aral Sea Basin is dependent on irrigation. Ancient and present day irrigation areas are concentrated along the basin's rivers. The intensification of irrigated agriculture in Soviet Central Asia to cover the Soviet Union's demand for raw cotton was mainly supported by the waters of the Amudarya and the Syrdarya rivers. In 1960 the total water intake in the Aral Sea Basin was approximately 60.600 million m^3. By 1990 it had almost doubled to more than 116.00 million m^3, of which 90% was allocated to irrigation. Population in the same time rose by more than 2.7 times and the irrigated area increased by 1.7 times to 7.95 million ha (ICWC 2001). Already in 1997, the supply of water for irrigation under the current system fell short by 17% of the quantity needed; in 1998, it was 22% and in 2000, when it was compounded by a severe drought, the shortfall was 40% (UNECE 2002).

The need for changes to water management are widely accepted and called for today. Sustainable water management and agriculture are the focus of the majority of major international projects in the region. The non-rational use of the basin's resources has been forced knowingly accepting its serious environmental costs. The best known implication of this policy is the disappearing Aral Sea, once the world's forth largest lake. It has lost more than 75% of its volume and half of its surface because of the decrease in inflow from the Amudarya and Syrdarya rivers.

From 1961 to 1980 the river inflow to the Aral Sea from both rivers was 53% of the average long term level observed from 1891 to 1960 (53 km^3). In the next ten years from 1971 to 1980 it reduced to 30%, going down to only 6% from 1981 to 1990 were a series of low water years occurred. The following nine years 1991 to 1999 it increased to 13% of the average long term level again (ICWC 2001). Today humans and ecosystems in the delta regions of both large rivers but also in the entire basin are severely affected by a multitude of water related problems.

2.1 General socio-economic characteristics of the basin countries

The Former Soviet Union republics of Central Asia turned into five independent states in 1991. Since then, political and economic transformation and changes in the legal and institutional settings are undertake, but they proceed much slower as initially anticipated. The economies have greatly suffered under the breakup of the Soviet Union. They are only slowly recovering, partially due to the immense legacy they have inherited. Today's socio economic indicators (table 1) give a short impression of the current day situation, although the official statistics should be taken with some care.

Table 1: General socio-economic statistics for the Former Soviet Union States of Central Asia for the year 2000 (data from UNDP Human Development Report 2002)

	Kazakhstan	Kyrgyztan	Tajikistan	Turkmenistan	Uzbekistan
Total Population	16.2	4.9	6.1	4.7	24.9
Fertility rate (per woman) 1995-2000	2.1	2.9	3.7	3.6	2.9
Rural population	44.2	65.6	72.4	55.2	63.3
Life Expectancy at birth	64.1	67.8	67.6	66.2	69
Infant mortality rate (per 1000 births)	60	53	54	52	51
GDP per capita (PPP$)	5871	2711	1152	3956	2441
GDP per capita annual growth rate (%) 1990-2000	-3.1	-5.1	-11.8	-8.0	-2.4

As can be seen in the negative growth GDP growth rates the states have not yet recovered from the changes and reached their past economic potential. Agriculture is the main sector of the economy and rural population is thus high in all countries. Privatization in agriculture has been officially declared but only to some small extent realized. Uzbekistan is the largest of the five Aral Sea Basin countries and will have to carry the biggest share of the necessary changes (Micklin 2000). In Uzbekistan the government still plays the primary role in the management of agriculture and the system of state orders is still retained for two key crops: cotton and grain (Micklin 2000).

Water has no real costs so far, although attempts to introduce water pricing are undertaken already for some time, acknowledging the importance of this mechanism to achieve water savings in agriculture.

2.2 Irrigated agriculture in Central Asia

Many present day problems in the Aral Sea Basin and the Amudarya delta have their origin in past developments. Central Asia is a region with a very ancient farming culture with first people occurring in the Amudarya delta approximately 4000 BC. The development of landscape and cultures took place in a consistent manner driven by the process of aridization as well as social and economic developments (Tvetinskaya et al. 2002).

At the end of the 19th century the Russians started an expansion of irrigated agriculture Central Asia. Massive collectivization took place and traditional irrigation was destroyed. Irrigation systems were often not built properly in order to expand the area as fast as possible. By the 1980s the flow of the Amudarya was largely controlled. The average water withdrawal rose to 17.000-20.000 m^3/ha with up to about 10000m^3/ha (ca. 50%) loss (Micklin 2000). Only 20-30% of the inter-farm and on farm canals are lined to reduce infiltration. Today in Uzbekistan almost 50% of irrigation systems need reconstruction. The expansion of irrigated agriculture during Soviet times was not accompanied by the development of agricultural processing industry (Saiko & Zonn 2000). With independence today occurs to be a great handicap.

The expansion of irrigated agriculture reached a peak during the 1960s to 1980s, leading to the construction of an immense irrigation network including the world's largest canal - the 1400 km long Karakum canal. The high yields achieved at the beginning of the intensification of agriculture could not be sustained for long, due to the rapid degradation of the soils caused by improper management and cropping patterns. Consequently more and more fertilizers and pesticides were used to keep yields at the required level. Salinization of the soils due to water logging caused by raising groundwater tables and excessive use of water for irrigation further accelerated the degradation of agricultural lands and decrease in productivity. Desertification is a major problem that endangers many irrigated areas especially in the delta regions.

2.3 Current water allocation policies in the Aral Sea Basin

2.3.1 Water allocation quotas

In Uzbekistan water management and its connection to agriculture and energy are political issues of highest priority. Allocation of the transboundary water resources of the Aral Sea Basin between the five states of the former Soviet Union is up to today 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 will be formulated (Agreement, Almaty 1992). The need for adjustments to these regulations to achieve a sustainable water management and account for changing needs in agriculture, the demands of the ecosystems in the delta and littoral of the Aral Sea and the potential increase in water intake from Afghanistan, etc. is widely accepted (Dukhovny & Sokolov 1996, International Crisis Group 2002, Djaloobaev 2002).

2.3.2 Transboundary water management and institutional framework

Transboundary water management in the Aral Sea Basin is determined by the Interstate Commission for Water Coordination (ICWC). It is composed of the ministers of water resources of the five former Soviet Union States of the Basin. At quarterly meetings they set and adjust the limits of annual water consumption from the two main rivers for each state as well as the operational modes of the large reservoirs. Water allocation and management is determined on the basis of current water availability and forecasts as well as projected economic development. The allocation scheme is a continuation of the system codified under the Ministry of Water Management of the former USSR (Micklin 2000). ICWC also determines the annual water releases to the Aral Sea and its delta regions as well as minimum discharge in the rivers and canals (sanitary levels). As was the case under the Soviet system, the water-sharing scheme is heavily tilted towards irrigation and the interests of the downstream riparian states (Micklin 2000).

The executive bodies of ICWC are the river basin authorities (BVOs) Amudarya and Syrdarya, the secretariat and the Scientific Information Centre (SIC-ICWC). The BVOs are in charge of planning and managing water flow schedules and water resources distribution, as well as direct implementation of decisions of ICWC on water allocation, schedules of river flow and releases as well as water quality control.

2.4 The Amudarya river delta

2.4.1 Geographic overview, climate and general hydrology

The delta of the Amudarya river is located in the Turan sub-zone of the desert zone between 40-43°N and 58-62° E. It has an area of approximately 28.500 km^2 with a length of 400km and a maximum width of 250km. In administrative terms the delta belongs to the Uzbek province Khorezm, the autonomous Republic Karakalpakstan and the Tashouz district in Turkmenistan. From a **hydrological** perspective the delta region begins with the Tyuyamuyun reservoir system (TMGU), a single-year reservoir which almost completely regulates water supply to the delta area (fig 2). The reservoir is situated at the end of a long river stretch where the Amudarya flows mainly through desert. After the reservoir it enters the rich floodplains of the delta area. Generally the area between TMGU and the former coastal city of Muynak is referred to as the Amudarya delta. In a geomorphological sense the beginning of the modern delta is located close to Nukus, the capital of the autonomous Republic of Karakalpakstan. In this work the delta region will be referred to in the general sense. With the name "Northern Amudarya delta" the non-irrigated area north of the gaging station Kyzyljar is identified.

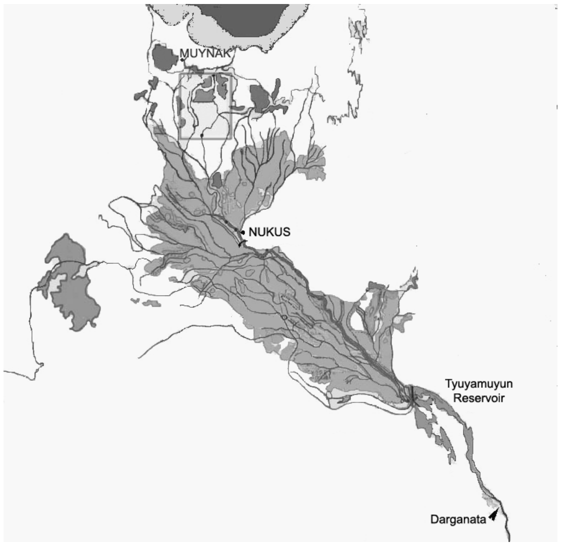


Figure 2: The Amudarya river delta. Irrigated areas are shown in darker colors. The enclosed area in the northern delta depicts the study area. Tyuyamuyun reservoir at the entrance to the delta controls water supply to the delta.

The northern part of the delta is a region with subtropical **climate** (fig. 3). The average annual temperature in the delta region lies below 18°C. Potential evapotranspiration is high with values varying approximately between 800 to 1200 mm/year (Letolle & Mainguet 1996, Ressl 1999). Annual precipitation amounts to only about 100 mm (Bakhiev 1994) and falls mainly in fall and early spring (October, November and March). The mean monthly temperature is -6°C in January and 28°C in July with extremes reaching from -30°C to 48°C. There are frequent winds, in 60% of the cases North or North-East, carrying dust and salt from the Ust-Urt plateau and the dried out sea bed to the delta. Estimates of the deflated material range between 13 and 230 million tons/year, with the most probable being between 15 to 150

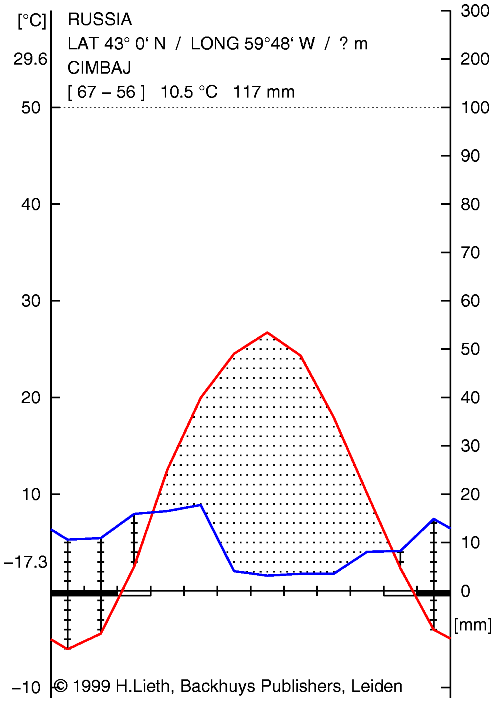


Figure 3: Climate diagram of Chimbay, located in the northern delta region. Data are 67-year (temperature) and 56-year averages (precipitation). The warmest month is 29.6°C, the coldest -17.3°C. (Source: Climate Diagram World Atlas, Lieth et al. 1999)

million tons (Micklin 2000). The entrained salts, which potentially pose a serious threat to agriculture, ecosystems and human health, are only a small fraction of approximately 1 % of the particles.

In the quaternary sediments of the lower reach of the Amudarya river there are two water-bearing **groundwater** horizons. Aquifers are located in the high quaternary and modern alluvial deposits (Krapilskaya 1987). The water bearing layer is between 10 to 60m thick. Surface runoff makes a major contribution to the recharge of the groundwater aquifers that in the delta plains are located close to the surface (Letolle & Mainguet 1996). The recharge by river or canal waters can under certain circumstances lead to the formation of groundwater lenses of 20-50m thickness near the rivers and canals. The formation of such ground water lenses is not well understood. The decrease in river runoff has caused a severe lowering of the groundwater tables in non-irrigated areas. In the northern part of the delta the anthropogenic changes of the groundwater table are most severe. In this part environmental processes are influenced by two major factors: the decrease in river runoff and the lowering of the Aral Sea. For the environmental modeling in this work it is assumed that the effect of the retreat of the Aral Sea on the groundwater has stabilized before the 1990's. The direct influence of the Aral Sea on the ecosystems in the northern delta region has already ceased in the 1970's

(Novikova 2001).

Due to incision of the river, the river bed has lowered by several meters, e.g. 3.8 m in Khorezm in the southern delta (Letolle & Mainguet 1996) and up to 6 m close to Porlatau in the Northern delta (Novikova et al. 2001). This has additionally enhanced the lowering of the groundwater table. Side canals that were not deepened do not receive water any longer. Other parts of the delta, mainly close to irrigated areas and deltaic reservoirs are regularly inundated by drainage or access river waters in high water years. In those areas water logging and secondary salinization are major problems. The mineralization of the groundwater varies between 2 and 57g/l (Ressl 1999), which makes it in many cases unsuitable for irrigation and unfavorable for most vegetation. Generally a decrease in the seasonal fluctuations of surface and groundwater levels can be observed (Treshkin 2001).

Soils in the river plain are mainly alluvial meadow soils and alluvial boggy-meadow or meadow soils with high humus content and low salinity in the upper layer (Treshkin 2001). In the Amudarya delta the thickness of the sediments varies between 35 and 140 m (Letolle & Mainguet 1996). They were formed by complex layering of sediments transported by the river. Delta soils typically display a natural development from new deposited alluvial sediments to boggy and semi-boggy soils, meadow, meadow desertifying, desert takyrlike and takyr soils, meadow salinized soils and finally solonchaks (salt pans) (Kust 1999). In general most soil development processes are accelerated by human influence. Aridization is severe in the delta area where the area of hydromorphic soils has decreased from 633.800 ha in 1953 to 77.6 ha in 1979 (Kouzmina & Treshkin 1997).

2.4.2 Ecology of the delta region

The Southern and Central parts of the delta are mainly used for agriculture and thus vegetation is mostly controlled by man (fig 4) . In the Northern part and along the main river there are still remnants of the former natural vegetation. Under natural conditions the landscape in the delta region developed through constant interaction of the river and the surrounding land. Changes in the river network formed the landscape which in its turn caused changes in the direction and intensity of the surface and subsurface runoff. Before the 1960s in high water years about 7.000 km^2 of the delta area were 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. Today about ten lakes are reported, whose total water area varies significantly inter- and intra-annually, but does not exceed 75 thousand ha. Natural lakes, which have to be fed by extra water, account for only 5 thousand ha (SIC/ICWC 2001).

The major vegetation once dominating terrestrial ecosystems in the delta area were reed and weed communities as well as riverine Tugai forest. Due to the absence of floods and the lowering of the groundwater table to 3-15m, most hydromorphic communities have dried

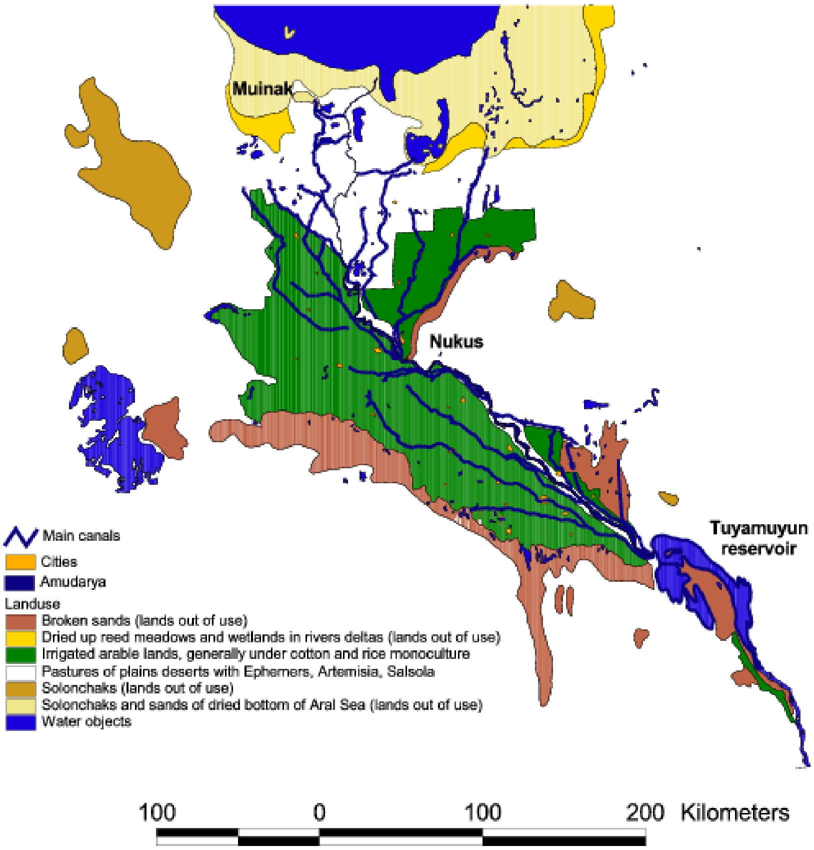


Figure 4: Landuse in the Amudarya delta. Large areas of the delta are used for irrigated areas. At their margin lands are strongly degraded and not used any longer. The dried out sea bed is visible in the north. (data source: Aral Sea GIS, Micklin et al. 1998)

out and were replaced by drought or salt resistant vegetation such as *Artemisia sp, Tamarix sp. and Salsola sp.*. 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. Today the land area covered with solonchaks (salt pans) increased to more than 30%. The remaining ca. 110.000 -120.000 ha of wet areas covered with weeds are used as pastures. They mainly consist of reeds (*Phragmites australis*) and camel thorn (*Alhagi sp.*). By now families of salt tolerant plants are the most important group of the plant community.

The **wetlands** in the delta areas were important recruitment areas for many fish from the Aral Sea (fig 5). With the beginning of the lakes retreat some species could survive by migrating into the rivers. Wetlands in Uzbekistan are internationally recognized as globally and regionally important habitats for rare and endangered species, especially migratory birds. Since Central Asia is located along one of the major migrating routes towards Africa many species- some of them already rare (Crane, Flamingo, etc.)- depend on their existence. Uzbekistan has signed the Ramsar convention which should help it bring its wetland conservation

Figure 5: Mezhdureche reservoir in the northern Amudarya delta, summer 2000

goals to an international level (UNECE 2001). The remaining delta lakes are an important fishing ground for the local population were mainly grass carp (*Ctenopharyngodon idella*), silver carp (*Hypophthalmichthys molitrix*) and snakehead (*Channa argus warpachowskii*) are caught. Formerly muskrat hunting was another important income. The harvest of muskrat skins in the delta has fallen to less than 3000 skins per year from 650000 in 1960 (Micklin 1988).

The typical riverine **Tugai** forests (fig 6) covered 70% of the territory of the lower Amudarya river reach (Kouzmina & Treshkin 2001). 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). Tugai forests are characteristic tertiary relict floodplain forest along the rivers and in the deltas in arid Central Asia and Western China (Treshkin et al. 1998). They are very well adapted to the conditions in the delta region, being able to withstand strong variations in abiotic conditions such as long droughts or seasonal floodings. Tugai complexes around the Aral Sea are habitats for about 60 species of mammals, more than 300 species of birds and 20 species of amphibians, some of them rare, like the Bukharan deer or the wild ass. Damage of the fragile vegetation due to overgrazing by domestic animals, competition for the available resources and illegal hunting have almost led to the extinction of some of those species. The ecological value of Tugai is mainly seen in the conservation of biodiversity, the shading and protection of settlements and water courses against storms and airborne pollutants and salts as well as erosion. They have various economic significance as a provider of wood and fodder, pasture for domestic animals, as well as hunting ground for game such as wild boar, tolai hare, badger, fox and Khiva pheasant (Treshkin 2001). Several typical Tugai

Figure 6: Tugai forest along a canal. The impact of animal grazing is visible in the little undergrowth. The forest is in rather good condition, due to its closeness to a drainage channel. Summer 2000.

plants such as licorice are harvested and exported to be used for tobacco and food industries as well as medicine.

The decline in groundwater level, an increased mineralization and pollution of water courses, soil salinization and the spread of xerophytic and halophytic vegetation, deflation and aeolian accumulation as well as salt storms are the main processes of anthropogenic desertification (Saiko & Zonn 2001). Agriculture is an additional factor contributing to the disappearance of the natural delta vegetation since large areas were converted into agricultural land. The pressure on the remaining patches by pasturalism and logging is very high.

2.4.3 Agriculture and People in the Delta Region

In the 1990's approximately 44% of the total agricultural area in the delta was devoted to cotton production. In the past years a decrease of the area under cotton in favor of wheat production has been observed. The wheat is needed to feed the people in the delta who

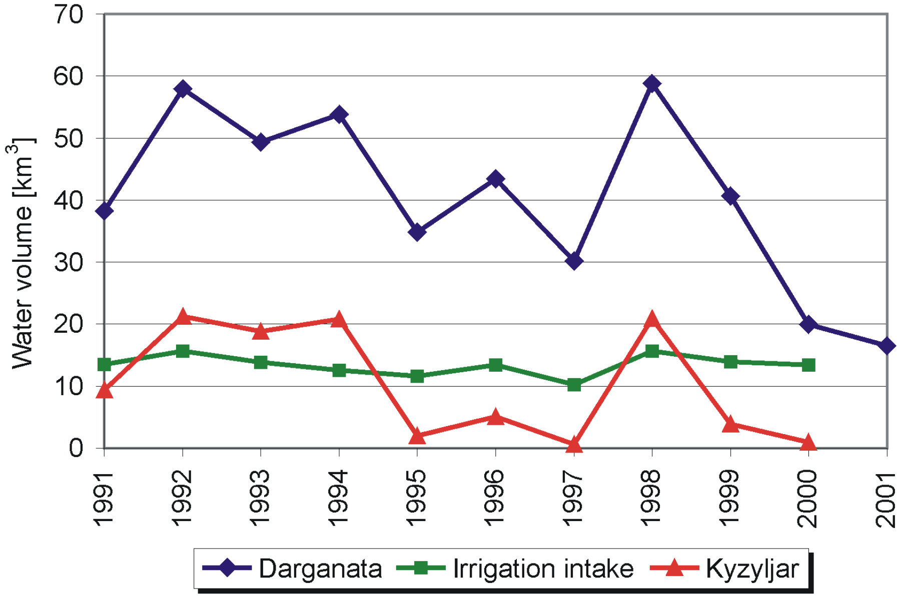


Figure 7: Water supply to the delta region in the 1990s and beginning of 2000 at the gaging station Darganata. Water withdrawals for irrigation and discharge to the northern, non-irrigated delta area, at the gaging station Kyzyljar. Irrigation intakes are rather constant, while inflow to the delta and its northern part vary strongly interannually. (Data from Uzbek Main Hydrometereological Service)

have been deprived of many of their former incomes such as fishing in the Aral Sea. Cotton production is located mainly in the southern part of the delta, while in the northern part rice prevails. Even in the extreme low water years 2000 and 2001, rice was planted, often with the knowledge that chances are small that water will suffice to grow it to harvest. Many dried out rice fields were observed in 2001, where the poorly grown dead sprouts served cows and camels as pasture.

The ongoing process of soil salinization seriously affects agricultural production. In 1997 about 94% of the soils in Karakalpakstan were salinized. A comparison of crop yield declines in the Aral Sea region shows that the most drastic reduction took place in the Northern delta area with yields of all analyzed crops at least one fold below average in Karakalpakstan (SIC/ICWC 2001). The naturally high productive rangelands and hayfields also significantly decreased which negatively affected cattle breeding and the number of sheep and goats. Transmission losses in the mostly unlined channels are very high amounting e.g. in Turkmenistan to 28% of the total water used for irrigation. The overall efficiency of the irrigation system is estimated at approximately 45% (O'Hara 1997).

While highly salinized soils cannot be used for agriculture any longer, medium salinized soils have to be leached in winter and spring. The resulting drainage waters further salinize downstream lands and pose a threat to ecosystems and people that use the rivers as source of drinking water. Even though the amount of fertilizers and pesticides used has decreased in the past years due to financial problems many substances still remain in the soil from the past and leach into groundwater and rivers. Next to the environmental problems in the delta region, people suffer most from the deteriorating socio-economic situation. For the fishermen of the delta the disappearance of the Aral Sea has deprived them of their income. Uncertain water availability and the bad condition of the soils, as well as other traditions, make agricultural activities very riskily. Next to this ongoing process of political and societal transformation aggravates the problems.

2.5 Ecological rehabilitation of the delta area

Many initiatives and plans to restore the delta region have been designed and many studies produced. Most of them emphasize water management issues with the goal to store as much water as possible in the delta area in high water years. Initiatives to create artificial reservoirs on the dried bottom of the Aral Sea were started already in 1987. They were aimed to conserve the natural environment and rehabilitate local production bases such as fishing, mink culture, and irrigated agriculture. Reservoirs were created in former bays of the Aral sea. The maintenance of those reservoirs brings along several problems, mainly connected to the stable supply of water from the Amudarya river.

A series of low water years, as e.g. observed in 1999- 2001, results in the drying up of these shallow water bodies. They are actually not an efficient means of storing water because of their large surface area that causes large evaporation losses. The silt load of Amudarya river is very high, and with 40 million tons/year sedimentation in these water bodies will reduce their capacity and their functioning. Nevertheless their realization is the major restoration larger scale effort currently undertaken in the Amudarya delta region (SIC/ICWC 2000).

2.6 Delta area considered in the simulation study

The selection of the delta of the Amudarya river as an exemplary area for this study was motivated by several considerations.

- As an end user of the river water it is most severely impacted by natural and anthropogenic changes to river flow and experiences the greatest inter-annual variances in water availability.
- The delta area is also strongest affected by the occurrence of extreme low water years. During the drought of 2001, the upstream areas of Uzbekistan and Turkmenistan received 85- 100% of their share while the delta region received less than 50% (Le Moigne 2003). Thus water availability in the delta underlies high uncertainties which have to be taken into account in planning and management.

- In high water years excess water mostly flows unused to the dried out sea bottom, since the water holding capacity of the delta reservoirs is rather small. Reasonable use of this water should be explored.
- The delta region is one of the most important irrigation areas for Uzbekistan and Turkmenistan, the need for changes in land and water management is very urgent but due to conflicting interests very difficult.
- It is a confined area with a single controlled water input via the Tyuyamuyun reservoir in the South, bordered in the West and East by the Karakum and Kyzylkum deserts, in the North East by the Ust-Urt plateau and in the North by dried sea bed of the Aral Sea.
- The strong degradation of the ecosystems has visible impact on the socio-economic and health situation of the local population and changes are needed to secure their living basis.
- Improvement of the ecological situation in an area that some call an "ecological disaster zone" has been declared a goal of national politics and international assistance for the past 10 years. Much information has been gathered on its condition. Many solutions to mitigate the crisis have been proposed but rarely implemented.
- This information and knowledge is very scattered and mostly focused on one specific aspect of the problems in the delta region lacking any connection to the overall situation.
- Collecting, structuring and formalizing this knowledge will allow for an integrated view and provide an approach for assessment and goal finding.

The prototype assessment tool developed within this work was realized for the northern, non-irrigated part of the Amudarya delta (fig. 2). The northern area is the largest part of the delta where semi-natural ecosystems still prevail. Agricultural areas are only small and often abandoned. The insecure water supply at the end of the river makes the region rather high risk for irrigated agriculture, which again became clear in the two years of drought in 2000 and 2001 where more than 90% of the harvest was destroyed (in 2000) or fields could not be planted at all (in 2001). On the other hand in high water years large quantities of access water reach the Northern delta. It is thus a dedicated area for other water and land use concepts.

3 Modeling Approach

3.1 Rationale and General Considerations

The modeling approach selected to represent the response of the delta system to changes in water availability had to satisfy multiple demands. It should reflect the characteristics of the available information and should facilitate the simulation of the development of the system on a medium spatio-temporal scale in a way suited for decision and management support. The applied methods should make best use of the heterogeneous information (see section 4) since no additional field sampling or laboratory experiments were possible. They should represent hydrological and landscape dynamics on scales major ecosystems in the delta respond to. The results should facilitate an estimation of potential future trajectories of the delta system as well as their evaluation with respect to their ecological implications. Those challenges were met by separating the studied system into subsystems and treating each subsystem with the approach most suitable for the data availability, disciplinary methods and given problems. The subsystems are then combined as modules in a comprehensive modeling system. When linking different models in an integrated tool, issues of scale, especially the choice of the right temporal and spatial scales for linking the different disciplinary models, are important and difficult (Antle et al. 2001).

Many different methods are available to model the response of ecosystems to human induced changes, starting with classical deductive process-based approaches that use differential or difference equations to e.g. newer mostly inductive methods using machine learning techniques. The advantages and disadvantages of some of the major approaches within the context of the given problem and their application range are summarized below.

The aim of model formulation in this study is to find an approach that does justice to the little data available, the rather large spatio- and temporal scale of interest, the limited time available and the demands of decision making and planning in a specific situation. The latter demands for results that are as realistic as possible. One of the main purposes of the construction of the tool is to condense empirical facts in order to make them applicable for resource management decisions (Wissel 1992). The selection of the modeling approach best suited for a given subsystem is thus strongly influenced by the question how the quality of the chosen methods and results can be evaluated as to their realism and applicability.

3.2 Review and discussion of approaches and their application

The aim of the given work provided the framework for the study of methods, software tools and real world applications in resource or ecosystem management projects. Questions were studied as to the scope of the methods, their limitations, the difference between top-down and bottom up approaches and the scales on which they are valid.

3.2.1 Process/physically based models

Analytical models seek to develop rigorous and provable statements about systems and often focus on global descriptions. Physically based mathematical models of processes are probably one of the oldest methods for modeling ecological processes. Because of their strict mathematical framework (structural rigidity) they can easily be tested by a variety of existing tests. On the other hand, their rigid framework limits their ability to represent the often ill-defined or not-quantifiable phenomena in ecology. Highly complex systems cannot be analytically solved. Process-based models, and any other models as well, are faced with two major difficulties: to obtain reliable parameters and to include ecosystem properties into the models (Joergensen 1999). Although, they are an excellent method to describe physical or biological processes whose analytical relationships are well known and solvable e.g. in time averaged hydrological modeling. In distributed models that attempt to incorporate spatial heterogeneity data demand often sharply increases. In the case of this study data demand is one of the major factors prohibiting the application of physically based surface and groundwater models and the use of already existing hydrological software.

Application of process based models is often hampered by the insufficient availability of physical parameters in their spatial and temporal distribution. The dominating input variables are often not recorded spatially explicit. Additionally simplifying assumptions required when formulating differential or difference equations can make the resulting models difficult to interpret when applying them to real ecosystems (Whigham & Fogel 2003). The many parameters and constants needed are often difficult to select and calibrate. In complex models parameter selection based on measured data becomes an issue due to the nonlinear behavior of the model as a whole.

Conceptual models as a simplification of process-based models facilitate modeling of large spatial and temporal scales where physically based models are too complex and the necessary resolution of the input parameters is not available. Their drawback lies in the fact that some of the model parameters are not directly physically based and cannot be measured.

3.2.2 Statistical Models

Statistical approaches are widely used in determining species - environment relationships based on empirical knowledge. They specify how outputs depend on inputs with only limited insight into underlying causal relationships. The derived relationships can be brittle. They do not promote the understanding of a system but are easy to construct (given adequate data). For specific resource management or assessment problems they are useful because they provide rather precise results that are close to reality (Guisan & Zimmermann 2000). Statistical approaches are mainly static and are based on the equilibrium assumption. They will in most cases only apply to the situation for which they have been developed.

Common methods used in statistical approaches are regression functions, correlation analysis, decision trees and Bayesian approaches. Bayesian decision analysis also allows the incorporation of uncertainties about inputs and outcomes (Harwood 2000).

3.2.3 Optimization

Optimization approaches seek to find optimal solutions relative to well defined objectives and subject to specific constraints. The focus of those approaches is rather on global descriptions. The finding of the optimal solution, especially in large complex problems, where the search space is large, can be difficult.

3.2.4 Fuzzy sets and fuzzy logic

A fuzzy approach is the integration of a fuzzy concept into conventional methods of knowledge processing and data analysis. It thus is an extension of conventional measures which is capable of utilizing imprecise, heterogeneous and uncertain data. Imprecise data is formalized by using fuzzy sets, imprecise knowledge by using fuzzy logic. Fuzzy set theory is particularly suited for problems where vague expert knowledge and imprecise information (Salski 2003). Conventional classification methods ignore the continuous nature of ecological parameters and the uncertainty of data, which can result in misclassification. Through the introduction of fuzzy sets without sharp boundaries it allows a more adequate approach to the often not clearly defined memberships found in ecological problems. Fuzzy knowledge based modeling is useful in cases where there is no analytical model for the relations or where there is an insufficient amount of data for statistical analysis (Salski 2003).

Moreover, fuzzy set theory gives a possibility to incorporate different types of information to find the best possible representation of the given system (Silvert 2000). Additional information that is stored in the other types can thus be used for the given problem. Those advantages motivated the choice of a fuzzy approach in the development of the Tugai habitat suitability index in this study. A detailed description of the use of the fuzzy set theory and fuzzy logic for the development of the habitat suitability index for the Tugai forests in the delta region can be found in Rüger (2002).

3.2.5 Neural Networks

Neural networks can be seen as an extension of conventional statistical methods. The mapping of the input variables on the output variables is learned supervised or unsupervised by a set of nodes that process the information in the given direction (feed-forward and recurrent neural networks). The network learns to recognize the pattern in the data and to classify it accordingly. Neural network methods have been developed extensively with different techniques used for data analysis such as clustering of environmental data, data mining, optimization and knowledge processing (Maier & Dandy 2000).

Artificial Neural Network (ANN) models are often not significantly different from a number of standard statistical models, but they are extremely valuable as they provide a flexible way of implementation. Neural networks are often used in more complex, specific problems of particular applications (Maier & Dandy 2000). ANNs cannot account for trends since they cannot extrapolate beyond the range of the training data.

Artificial neural networks would be a good method to map some of the environmental variables used in this study.

3.2.6 Evolutionary computation

Evolutionary computation has been developed based on the biological principles of evolution and reproduction. They represent a method for incorporating adaptation into ecological models, since the algorithms of the model evolve after the rule of survival of the fittest. The rules governing ecological systems are built through dynamic evolution. The model is able to adapt to changes in the environmental conditions by producing "offspring" populations that are better suited to the given situation. Their inputs are non stationary (Wigham & Fogel 2003). A model constructed with e.g. a genetic algorithm will find a good solution of a problem but not necessarily the optimal. On the other hand the solution will simulate adaptation and be robust. Structural dynamics are incorporated. Genetic algorithms are often used in combination with traditional methods for parameter optimization and the development of structurally dynamic models (Wigham & Fogel 2003). Evolutionary computation can handle large search spaces in an efficient manner even when the structure in the search space is not well understood. It can be used for equation discovery (optimization of differential and difference equations) or to tune the parameters of an equation, for rule discovery or to model individual or cooperate behavior. Genetic algorithms have been used in hydrology e.g. for estimation of reservoir operation (McKinney & Lin 1994, Cai et al. 2001.)

3.2.7 Conclusions

While traditional differential and difference equations and many statistical models are deductive and often aimed at general principles and understanding, most of the machine learning approaches are inductive, bottom up approaches. The popularity of bottom up approaches such as genetic algorithms, cellular automata, and agent based modeling to study complex systems can partially be accredited to the view that coherent, global behavior can emerge from the collective activities of relatively simple, locally interacting components (Mitchell et al. 1994, Wu & David 2002). They are mostly tailored for specific applications with the major aim to represent the given situation as good as possible. Top down approaches rather represent broad ecological principles to produce detailed patterns observed in nature (Morral 2003).

Several authors point out that the best use of these models is in mixed hybrid applications that use the advantages of standard (equation- based and statistical) methods together with the possibilities of the newer ones. E.g. the quality of a neural network can be enhanced by considering statistical methods in the model building process, data preprocessing, the determination of adequate model inputs and model validation (Maier & Dandy 2000), evolutionary and network techniques or fuzzy and network approaches can be combined (Wieland 1997).

3.3 Selected overview of modeling approaches for assessment and decision support

A focus of watershed modeling and management in arid regions is the evaluation of potential changes in the quantity of surface runoff, subsurface flow and groundwater recharge caused by climate change, landuse change and water management measures. In temperate regions a major isswater quality is the major issue of concern, which in semi-arid and arid regions often is restricted to water salinity issues.

Numerous modeling studies in both regions have been designed to study and assess changes to floodplain ecosystems caused by changes in land and water use. In the following an exemplary selection is presented. The Across Trophic Level System Simulation (ATLSS) and the INFORM/MOVER system are examples of ecological studies for practical ecosystem rehabilitation efforts. The experiences of the ATLSS significantly influenced the development of the Tugai tool presented in this work, mainly in the selection of the approach to map ecosystem response.

3.3.1 Everglades Restoration Study (ATLSS)

The Across Trophic Level System Simulation (ATLSS) for the restoration of the Florida Everglades simulates the responses of the Florida Everglades (ca. 10.000km^2) to changes in the hydrological regime. It was designed to provide a framework that can synthesize what is known about the past and the present of southern Florida's ecosystems and project their future under changing circumstances to make useful predictions of the ecological consequences of a given restoration plan (DeAngelis et al. 1998). Its major goal is to investigate the relative response of various interconnected trophic levels to different hydrological scenarios over a thirty- year planning horizon (Duke-Sylvester & Gross 2002). The study focuses on effects of restoration of the natural flow regime on the fauna of the Everglades.

ATLSS is a set of integrated models that simulate a system response on several hierarchical levels. To model processes at several trophic levels, and thus different spatial and temporal scales, different model approaches are used: (i) Process based models for the lower trophic levels such as periphyton, zooplankton, macrophytes, micro- and macrobenthos, benthic insects etc., (ii) structured population models for fish and macro invertebrates and habitat suitability models for selected species such as birds and alligators and (iii) individual based models for the top-level predators (e.g. the Florida panther) and their prey (e.g. white tailed deer) (fig 8). The models are integrated across a spatially explicit landscape model of the Florida Everglades (DeAngelis et al. 1998). Up to now no integration on the higher level is achieved so far (DeAngelis, personal communication 2000).

Within the study spatially explicit species habitat models (SESI, Curnutt et al. 2000) were developed for several species. They relate ecological characteristics to the species' needs which have been described by experts in form of rules. The rules are either binary (limits of a species) or quantitative (a value reflects the relative potential of a site). Spatial sequences are considered by incorporating neighboring cells into the habitat evaluation of a single cell. Habitat indexes are the ratio of the value in a cell to the maximum possible value.

SESI models have a temporal component and are based on a landscape structure. They facilitate the comparison of one management strategy to a base scenario or to another scenario. For the landscape structure developed in the GIS the surface elevation, vegetation type and physical structures were regarded as static elements, while surface water levels were accounted for dynamically. Vegetation biomass, types of plant tissue (forage quality), etc. is modeled with size structured process models (functional group models, individual based) e.g. as input for the white tail deer model (DeAngelis et al. 1998, Duke Sylvester & Gross 2002). The emphasis of the approach is on spatial patterns of differences between two different management scenarios (Curnutt et al 2000).

Those rather simple index models have proven to be valuable tools for a first assessment of ecological effects. For practical planning and implementation of restoration efforts they have been favored because of their relatively short development time. They were used extensively in restoration planning for the restoration of the Florida Everglades (Curnutt et al 2000).

The highly complex, detailed individual-based or age/size group structured models occurred less useful for assessment of changes to the ecosystem for restoration purposes, because of difficulties in validation and the long development time. These types of models are more useful for research and to address theoretical aspects (DeAngelis, personal communication 2000).

3.3.2 INFORM/MOVER

The model system INFORM (Integrated Floodplain Response Model) developed by the "Bundesanstalt für Gewässerkunde" (Giebel 2002, Rosenzweig 2002, Fuchs 2002) is discussed representatively for the wide range of statistical or rule base habitat distribution models. With INFORM changes to floodplain vegetation caused by alterations of the medium term mean river stage are assessed with the help of spatially explicit habitat distribution models in Mover (MOdel for VEgetation Response). The environment-species relationships and thus the response of a species or species group to changes in the environment are either derived by rules and correlation tables based on expert knowledge (Rosenzweig 2002) or through statistical multivariate analysis, mainly canonical correspondence analysis (Hettrich & Rosenzweig

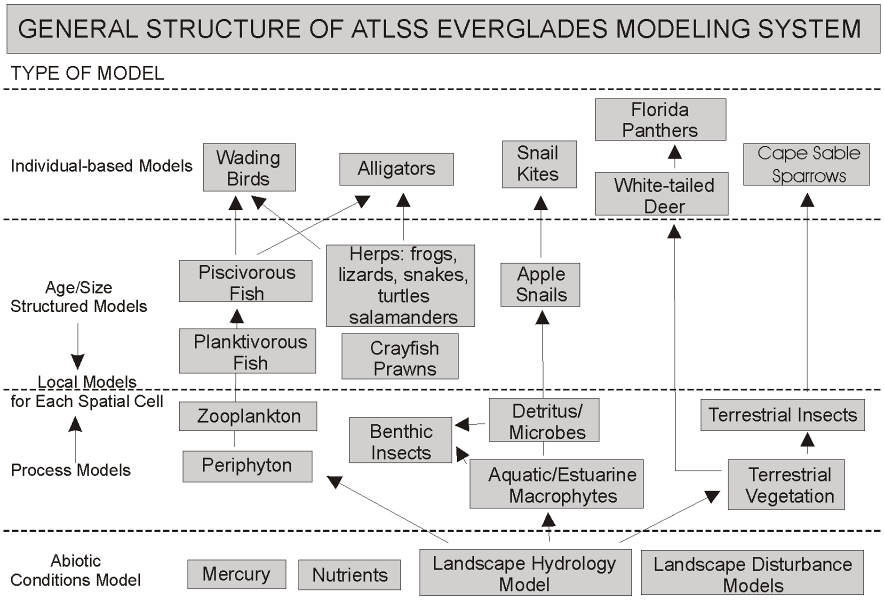


Figure 8: Model dependencies of the Across Trophic Level System Simulation (ATLSS) in the Florida Everglades. Model hierarchy and realized approaches are depicted. (ATLSS, redrawn from www.atlss.org)

2002). The potential optimal or near optimal vegetation of each grid cell is based on the calculated environmental conditions that are simulated by detailed hydrological, hydraulic and hydrogeological models. Soil water content is the major hydrological parameter that determines species composition at a given site. It is dependent on groundwater and flooding dynamics that result from changes to water table height in the river reach. Other static habitat parameters characterize the individual sites and help to diversify the vegetation results. The simulated species distribution is then evaluated by comparing the results with a reference scenario. A distance of the cell from the optimal of the predicted species group is multiplied with the amount of cells and then summed. This value acts as evaluation criteria. A decrease in the sum of distances implies a better fit of the species composition to the abiotic situation in the study area (Hettrich & Rosenzweig 2002). The results are categorized in conflict risk classes. A major disadvantage of the approach is that rules determining vegetation of a site are specific for a river reach, because they map the realized niche of the species. They thus include other site specific characteristics, such as biotic interaction.

Multivariate approaches to determine species-environment relationships for in habitat distribution modeling is a commonly used approach in vegetation modeling. Statistical methods to determine the species response to changes in the environment can only be applied when the underlying data correspond to a certain standard, including a sufficient number of replicate samples, that are independent and random. Unfortunately such a dataset has not been available for floodplain vegetation in the Amudarya delta (see 6.3).

3.4 Realization for Amudarya river delta

The goal to operate on existing knowledge of the delta region, collected in various studies and projects, posed the challenge to incorporate very heterogeneous information into model construction and evaluation. This challenge has been met by selecting different approaches to formalize the available hydrological and ecological knowledge. Given the goals of the modeling in this work and the available data and information a mixed approach has been selected.

Structure of the tool Three different modules have been developed for 1) water management and the resulting spatio-temporal water distribution, 2) for key environmental factors that are affected by changes to the hydrological regime and 3) for evaluation of the environmental changes with respect to their effect on the ecological situation. The integration is achieved through a modified GIS, that serves as a common user interface but also as framework for the environmental module. The selection of the approaches was thus also determined by the demand that all models are compatible with the spatially- explicit representation in the GIS. The links between the individual modules is described in the discussion of the water management model (section 5) and the environmental models (section 6). The implementation of the tool is described in section 7. For implementation the GIS software ArcView is used.

For **hydrology** the EPIC (Environmental Policies and Institutions for Central Asia) modeling system, developed by a project of the United States Agency for International Development with the same name, was used for model construction. Water allocation is modeled with a multi-objective optimization approach. Water is distributed to irrigational and other users under given management and policy constraints. Optimization offers the advantage, that optimal water allocation is determined by the solving routine and does not have to be investigated by many simulations. Additionally an optimization approach has been introduced to the region to resolve allocation conflicts before and water managers are familiar with it. This is an advantage when developing alternative management scenarios together with hydro-engineers and hydrologists of the region.

Changes in **environmental variables** that result from changes to the surface flow regime are best represented using statistical and rule-based approaches. Time series data on surface runoff and groundwater level in the delta region facilitated a rather straightforward approach. Within the aim of the study and on the large spatio- temporal scale under investigation, mechanistic groundwater flow models were not appropriate nor feasible.

For evaluation of **ecosystem response** a habitat suitability index approach has been selected. It provides an easy qualitative means to assess the impacts of changes to the hydrological regime on the habitat of selected representative species. The results can be directly compared to a reference or other management scenario, which is a desirable feature for interactive scenario development and analysis with a group of people. The success of index models in the Everglades Restoration Study further supported the choice of this method.

3.5 Integrating GIS and Hydrological/Environmental Modeling

Many attempts have been undertaken to integrate distributed hydrological models with GIS, mainly for spatial data retrieval and preprocessing and for visualization of model results. Several hydrological software tools have interfaces with GIS. GIS can provide information on channel geometry, terrain and channel slope, soil type, land use, spatially explicit micro climate, etc. that are important inputs for e.g. precipitation-runoff models. To facilitate a tighter coupling beyond data preprocessing and visualization, hydrological tools have been developed that allow for hydrological modeling directly in the GIS (e.g. in ARCGISHydro, ESRI 2000). GIS in hydrological modeling also assists in delineation of the river network that is then used in the hydrological model (e.g. HEC-GeoRas, US Corps of Engineers).

Decision Support Systems have benefited from the incorporation of GIS in the aspects of data base, interface and model integration. As a database it not only brings the spatial dimension into traditional water resource data bases but also has the ability to integrate various social, economic and environmental factors related to water resources planning and management.

GIS is an invaluable tool for landscape ecology since it allows for a spatially explicit view and thus the incorporation of spatial heterogeneity into the assessment of land use changes. In environmental modeling GIS are used widely for spatial data retrieval and visualization of results. Its spatial analysis functions can be used for modeling and analysis of results. Direct implementation of ecological models in the GIS is still rather rare.

In this study the GIS is used in all of the above mentioned functions and as the model platform for the environmental models and the common user interface for the composite tool.

3.6 Spatio-temporal Scales

Temporal Modeling of discharge in the river and the major channels is performed in monthly time steps. Seasonal variations in water availability are very important for ecological processes. Monthly time intervals are common in hydrology although especially for simulation of small scale floods, a higher resolution would be desirable. Since data to delineate the extent of flooding events are not available and information on the occurrence of a flood in a specific month was considered sufficient for the ecological assessment, the monthly time step was chosen for the hydraulic modeling. The ecological impact of floodings is assessed on the monthly time step and then aggregated to the annual level. Groundwater dynamics are simulated in annual intervals, because aquifer response to the highly variable surface flow could not be modeled at lower resolution. Ecological impact assessment is performed on the annual time scale since significant changes in habitat conditions for the species under consideration take place on rather long time scales. The resolutions chosen were a compromise between the demands of the different disciplinary models, data and computing time constraints and the aim to evaluate medium term effects.

Spatial ”The scale of mapping and modeling adopted, and the level of detail at which the spatial habitat suitability model can operate, are crucial to the application of this approach in resource management” (Kliskey et al. 1999). The spatial resolution of a pixel in the GIS on which the grid-based modeling is performed was chosen at 300 *300 m. This was a compromise between the resolution meaningful for the selected ecosystem, the Tugai forests, the resolution of the input variables river runoff and groundwater table elevations and computational time constraints.

4 Knowledge Acquisition and Data basis

4.1 Data and types of information

Data and information on hydrology and ecology were collected from the following sources:

- Official governmental and scientific databases (Hydrology, GIS, Vegetation)
- Maps (physical entities, e.g. lakes, channel width, geomorphology, vegetation distribution)
- Satellite Images for delineation of environmental variables (e.g. flooded area, estimates of groundwater depth, physical entities, e.g. canal network)
- Literature (ecology, hydrology)
- Expert Knowledge (ecology of delta ecosystems, physiology of plants, environmental relationships, history of landscape)
- Questionnaires for expert interviews to classify environmental variables
- Joint field work with experts (ecology, landscape)

The data/information represent different types, such as:

- spatial/non-spatial
- qualitative/quantitative
- time series/single measurements
- high resolution/low resolution
- uncertain to varying degrees

Several longer stays in Uzbekistan over a period of four years (1999-2002) and a three-month research visit to Moscow have been used for data and model acquisition, database and joint field work, and interviewing of experts in various fields. The former centralized research and monitoring system, which concentrated all information in Moscow or in the capitals of the Region, made it necessary to collect data not only locally in the delta region, but also in Tashkent, the capital of Uzbekistan, and Moscow. The hierarchies in research from Moscow to the major capitals to the regions is still existent today. Since independence scientists in Central Asia have only very limited financial means to conduct their research.

In the delta region data collection on ecology and the general situation in the delta was carried out in tight cooperation with Dr. Treshkin, Dr. Mamutov, Dr. Joldasova and Dr.

Pavlovskaya from the Institute of Bioecology of the Karakalpak Branch of the Uzbek Academy of Sciences. Dr. Savitsky in Tashkent provided his hydrological database, a model for the Tyuyamuyun reservoir at the entrance to the delta and the EPIC (Environmental Policy and Institutions in Central Asia) modeling system. He assisted in the construction of a water management model for the Amudarya river in the EPIC modeling system with special emphasis on its delta. Additionally in Tashkent background information on the general situation in Uzbekistan and the delta in particular were gathered. Scientists from the Institute of Water Problems of the Russian Academy of Sciences in Moscow, who are continuing their scientific work in the delta region after the breakup of the Soviet Union, provided data and information on the landscape and vegetation of the delta. Those were mainly Dr. Novikova and Dr. Kouzmina from the Laboratory of Dynamics of Terrestrial Ecosystems who have made their database and expert knowledge gathered within 20 years of field work in the delta available for the conduct of this study.

Any kind of information, qualitative in the form of experience of an expert or local scientists or quantitative compiled in a database, was checked and tested on its credibility, consistency and value for model construction to represent the hydrological regime and the responses of the landscape and ecosystems to alterations in the regime. The quality of the input data is a major factor determining the quality of the models that will be developed and integrated.

4.2 Hydrological database

Most data on runoff and physical properties of the river and canal network of the Amudarya river and its delta region as well as average daily surface runoff values (m^3/s) at major gaging stations, inflow at the head of canals and reservoir characteristics were obtained from the Main Hydrometereological Service of Uzbekistan in Tashkent and the Amudarya river basin authority (BVO). Additional time series of reservoir volumes in the four body reservoir system Tyuyamuyun from the WP modeling system (Razakov et. al 1998). Data on maximum and mean discharge in the main irrigation channels in the delta area were retrieved from the WARMIS (Water Resources Management Information System) data base (WARMIS 1997).

The political changes in the region at the beginning of the 1990's, caused a partial collapse of the state hydrometereological monitoring system in Uzbekistan. Routine hydrological monitoring was not carried out at some measuring stations for several months in 1991 and 1992. Some of the records from gaging stations thus have data gaps in the years 1991 and 1992. For analysis they were filled using standard hydrological techniques. From 1993 onwards all official records are complete. Regular recordings of discharge in the main irrigation channels in the delta region, registered in the Hydromet database, start differently from the year 1991, 1993 or 1996.

Data on groundwater level in the delta, especially in its Northern non-irrigated part are scarce and difficult to obtain. Monthly measurements of water table height and annual measurements of water salinity at 43 wells in the delta region for the years 1989 -1999 could be acquired from the Central Asian Irrigation Institute (SANIIRI - 12 stations) and the Karakalpak Hydrogeological expedition in Nukus (3 stations). 15 of those wells were located in the northern delta region (table 2). Missing water table elevation values for individual wells in certain years were estimated based on the values of the preceding and succeeding years (wells 132, 207, 209 : years 1998/1999; wells 93, 103, 111: year 1995).

Table 2: Data of groundwater monitoring wells in the northern Amudarya delta used for groundwater model development in this study (data provided by SANIIRI and the Karakalpak Hydrogeological expedition)

Well No	Longitude (utm)	Latitude (utm)	Elevation NN	Elevation DEM	data range	Comment
132	4792610	10661800	59.88	60.0	1992-1995	
62	4782380	10677060	62.36	62.5	1990-1999	complete
188	4773980	10683300	62.74		1990-1999	complete
95	4842300	10665100	56.57	55.5	1990-1999	
94	4831400	10660900	56.94	56.0	1990-1999	complete
209	4811100	10663300	57.78	57.5	1991-1997	
207	4802100	10667430	59.71	60.0	1991-1997	
93	4792500	10666910	60.58	60.5	1990-1999	1995 missing
154	4806560	10655800	57.18	56.5	1991-1998	
115	4820580	10660300	57.00	56.5	1991-1999	
113	4808200	10689700	59.50*		1991-1999	complete
223	4807000	10693600	57.50*		1990-1999	complete
103	4843800	10701600	54.10	53.0	1989-1999	1995 missing
112	position estimated from map		56.50*		1991-1999	one measurement/year
111	position estimated from map		56.70*		1991-1999	one meaurement/year, 1995 missing

*elevation estimated from DEM

To complement the groundwater data, and for comparison with simulated groundwater elevations in this study, an expert estimation of present groundwater table depths in the delta region was performed using a landscape classification approach (see Matson & Fels 2001). The vegetation expert Dr. Novikova estimated mean annual groundwater level and mineralization for every landscape unit in the delta from a satellite image of the year 2000 based on the given geomorphology, vegetation and field experience. The estimated values were integrated into a geomorphology map of the Aral Sea GIS (Micklin et al. 1998). The estimated values will be cross checked with an analog hydrogeological map obtained for the north-western part of the delta with isolines of groundwater table depth in spring 1997. This map was obtained from the Central Asian Institute of Irrigation (SANIIRI).

4.3 Vegetation database

The database of Novikova et al. contains original data from field research carried out from 1978 to 2000 by the authors together with data from scientific publications and archives from 1947 -1994 (Novikova et al. 1998). It consists of data on species composition, coverage, state of the vegetation, abiotic variables e.g. height of groundwater table, soil salinity, and anthropogenic disturbances such as grazing and fire for individual sampling sites. Since 1998 most of the sites have been georeferenced in the field using Global Positioning System (GPS) technology. The location of sites described before the use of a GPS were later approximated based on location information on a geo-referenced topographical map in the GIS by the authors (Novikova, personal communication).

All datasets containing information on the riverine Tugai vegetation in the delta region have been selected for analysis. Datasets on the typical desert vegetation have been excluded. According to Russian geobotanical classification the vegetation at a site is classified into a formation and association. The formation is named after the dominant plant species. The formation characterized by e.g. *Populus arianae* (or *Populus euphratica* according to Western botanical nomenclature) as dominant species is called *Populeta arianae*. According to international standards formations in this work will be called by the name of their dominant species, e.g. *Populus euphratica*.

4.4 Geospatial database of the delta region

4.4.1 The Aral Sea GIS

A Geographic Information System (GIS) for the Amudarya delta region (Aral Sea GIS) was compiled by Micklin et al. (1998) based on maps, satellite images, statistics, data bases and ground truth data. All material in the GIS is given in the Universal Transverse Mercator (UTM) projection, zone 40. Most digitized maps were of a scale of 1:200.000 (canal network, lakes, collectors, streets, cities, etc.). The mapped irrigation network contains 7.500 channels in the delta area with a length of 22.000 kilometers (Ressl 1999). In the associated attribute database channels are differentiated by size (main and secondary) and type (irrigation channels or collectors). The GIS also provides a map of elevation contourlines based on a topographic map at a scale of 1:200.000.

The GIS maps of landscapes, geomorphology, soil properties and dominant vegetation formations are based on a satellite image of the delta of the year 1987 and field data by Novikova and colleagues (personal communication). A new landscape and vegetation classification was carried out in 2001 based on a satellite image of the year 2000 by Novikova and Aldykova. They delineated landscape units as polygons on the basis of their geomorphology. For every landscape unit descriptions of soil type and vegetation based on field investigations are given. Soil and vegetation information are thus not independent from geomorphology. Almost every polygon of more than 70 polygons was described individually with a unique combination of landscape, soil and vegetation.

The Aral Sea GIS has been studied and analyzed to assess its suitability as a database for spatial modeling. Information gaps and inconsistencies have been analyzed and the compatibility with data from the vegetation database (described above) studied.

Joint field work with the experts in the delta region in 1999 and 2001 helped to clarify measurement and classification methods and to assess data quality and reliability.

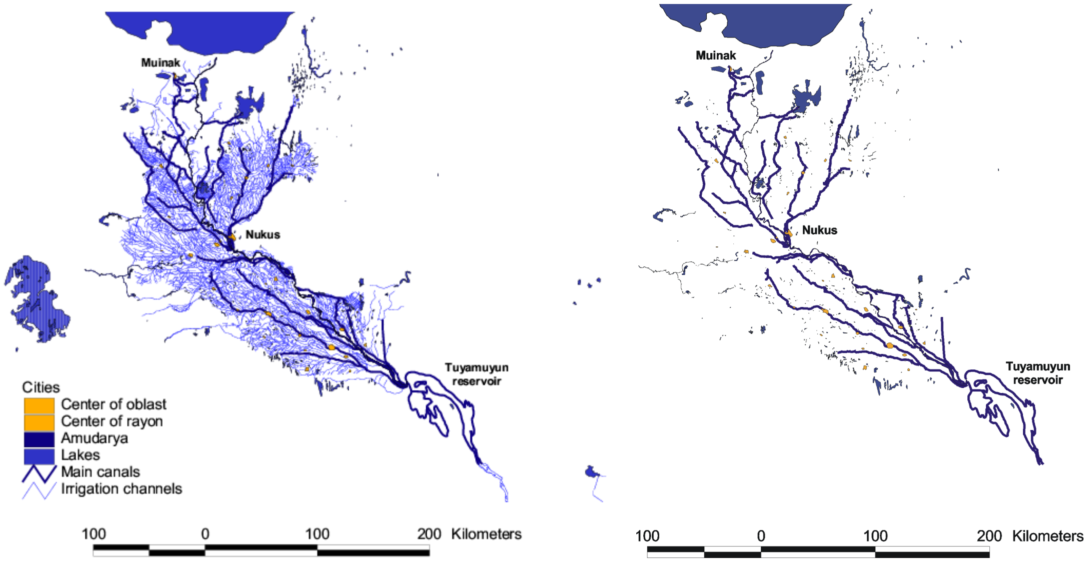
4.4.2 Modifications and Updates - the AmuGIS

Within the framework of this study it was not intended, nor possible, to extend the existing GIS with new data. Nevertheless, several updates, classifications and analysis were performed to adapt the GIS to the demands of model development and implementation in the given investigation.

Hydrology For the modeling of spatio-temporal water distribution in the main river and the major irrigation canals, all major canals have been extracted from the general canal network layer and a simplified river network created (fig 9). Several old or natural canals missing in the original channel network in the GIS were added by digitizing them from satellite images. The widths of the main river and irrigation canals have been taken from a 1:200.000 map of the delta area which is based on data from 1981/82. The map and the elevation contourlines in the GIS were also used to estimate the elevation of the river bottom. All data were added to the respective attribute tables in the GIS to be used in the environmental models (see section 6).

Several processed and georeferenced Landsat TM and MSS images for the years 1973, 1980, 1983, 1987, 1989, and 1994 are provided with the GIS. The images have been analyzed to determine the exact location of dams and flood overflow structures in the region of the Mezhdureche reservoir in the Northern delta area (fig 28). The location and extent of some important delta lakes were approximated from satellite images, although their area varies significantly inter- and intraanually. The representation of the lakes in the delta region is always only a snap shot of the lake area at a certain instant in time, since some lakes disappear completely in dry years. Areas flooded during the extreme high water year 1998 were digitized based on two satellite images from May and June, 1998 (see subsection 6.7.1).

Landscape The original geomorphology classification was reduced to five classes representing (1) river bars, (2) slopes of river bars, (3) floodlands and terraces, (4) interfluve lowlands and (5) lake depressions (fig 10). The classes correspond to the landscape classifications used by the Russian experts (Novikova et al. 1998). In cases where a direct classification was not possible, a landscape unit containing attributes of two classes (e.g. interfluve lowlands and



(a) Irrigation channel network in the Amudarya delta

(b) Reduced channel network in delta area north of Nukus

Figure 9: Irrigation network in the Amudarya river delta and the simplified network used for water allocation modeling in this study. The channels indicated in lighter color are large drainage channels. (data source: Aral Sea GIS, Micklin et al. 1998)

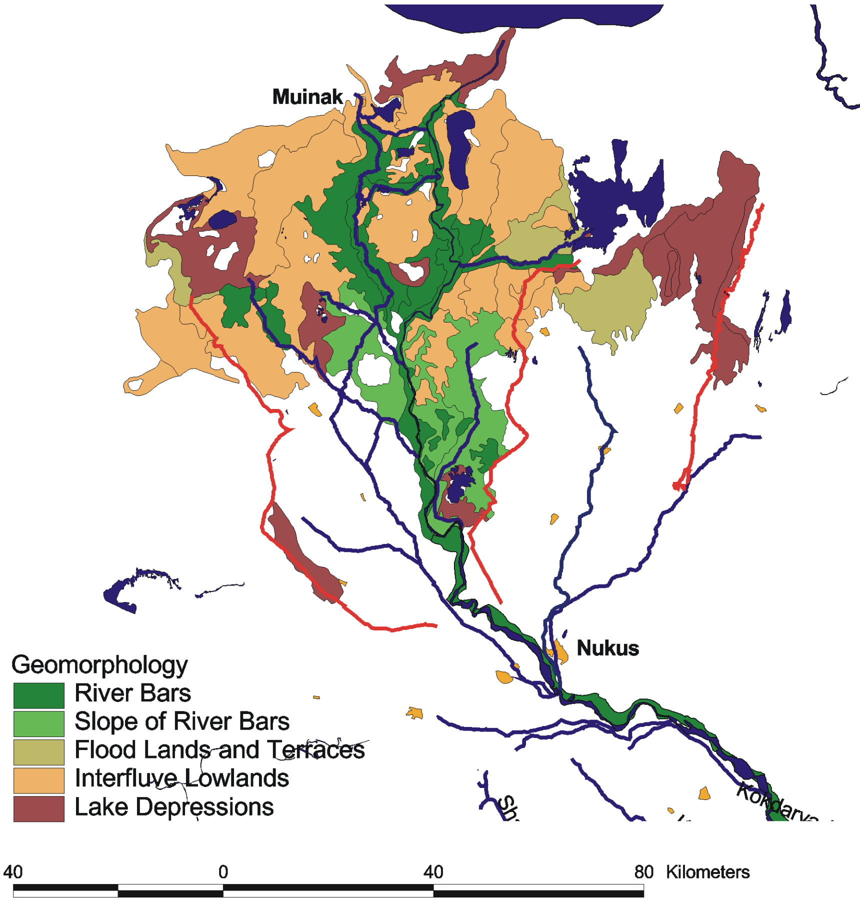


Figure 10: Classification of geomorphology in the northern delta area based on landscape maps of N. Novikova.

lake depressions) was assigned to the higher class (in this case class 5). The classification was based on the geomorphology map of 1987. Comparison with the map of 2000 revealed that in most cases geomorphology was described similar although the polygon delineation was different. The map of 2000 was only available towards the end of the study. It was used to classify those landscape units that did not fit into any of the above classes.

Based on the elevation contourlines a digital elevation model (DEM) was created by triangulation (see subsection 6.6.6).

Groundwater The datasets of the groundwater monitoring wells included information on location and height above Baltic sea level for most of the wells. Their coordinates that were originally given in a shortened Gauss-Krueger projection (transverse mercator, Krasovsky spheroid, central meridian: 57°, false easting: 10.500.000) were transformed to UTM (zone 40, Clarke spheriod (UTM-1927)). The well locations and attributes were added to the AmuGIS as a new layer to be used in the groundwater simulation. The information on the elevation of the individual observation wells was cross checked with the digital elevation model (DEM). They revealed good correspondence with deviations within a range of 50 cm. Well tops might lie up to approximately one meter above the ground, explaining the differences with the DEM. The very close correspondence of those two independent height sources is also an indicator for the accuracy of the digital elevation model. For wells without height information (well No 111, 112, 113, 223), elevation was estimated with the help of the DEM. For two wells in the north eastern part (No 112 and 111) whose location was only indicated on a schematic map, the coordinates were also approximated (see table 2).

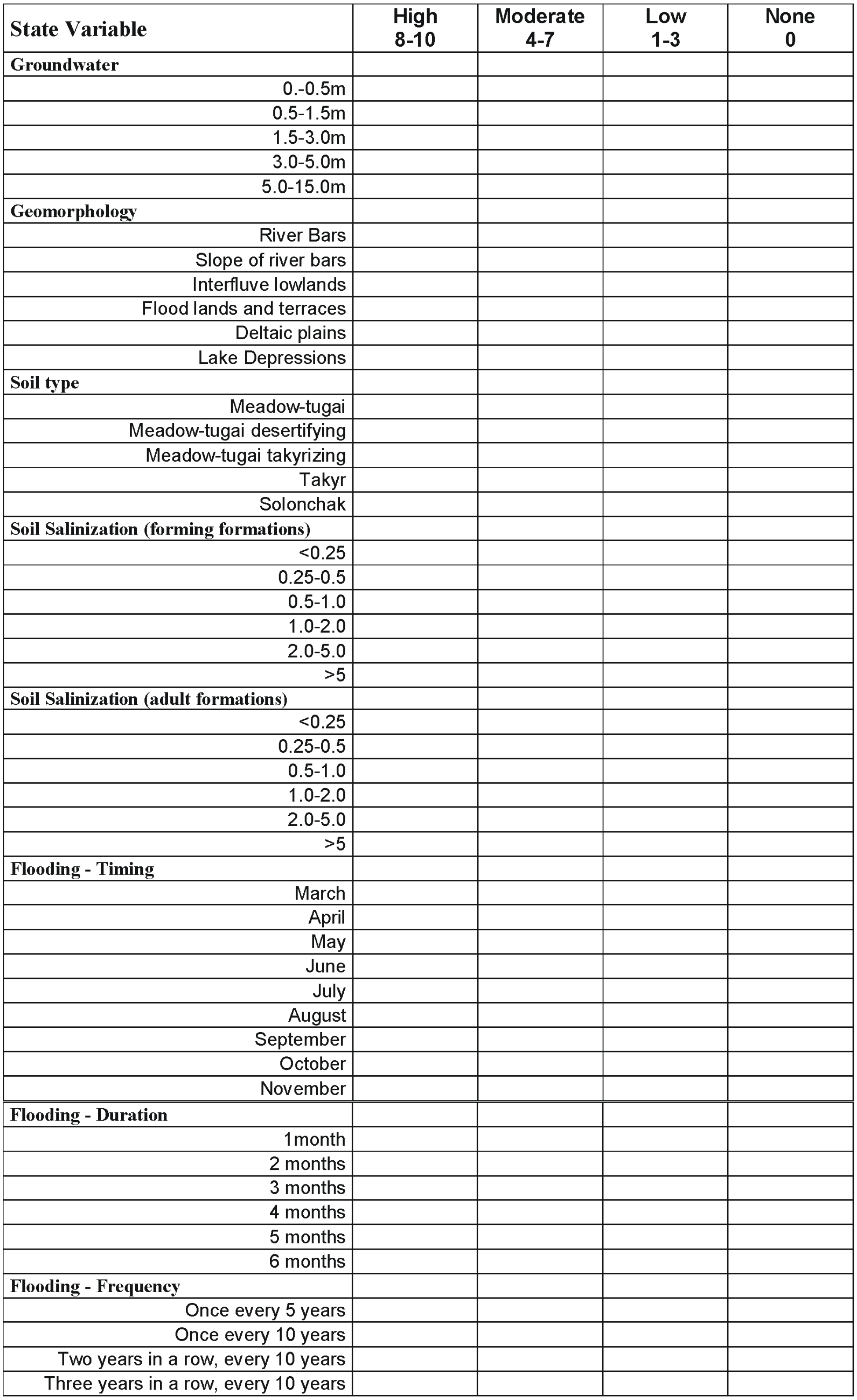
4.5 Expert knowledge

Determination of habitat requirements of delta ecosystems The following aspects of ecosystems and ecosystem development were studied with the experts in Russia and Uzbekistan: present and former vegetation in the delta, their classification, distribution, state and development over past 20 years. Dr. Novikova, Dr. Kouzmina and Dr. Treshkin were asked to determine major environmental factors influencing riverine ecosystems in the delta and to assess habitat requirements of their species.

Both Russian experts, Dr. Novikova and Dr. Kouzmina have up to 20 years of experience in the delta region with almost yearly field trips of several weeks to months. They thoroughly know all vegetation types in the delta at their specific locations as well as vegetation development in desertifying and more protected areas. Their experience and knowledge allows them to evaluate the potential of a site for any vegetation and to predict the most likely vegetation to occur on a site where site conditions are known. Dr. Treshkin from the Nukus institute provided his judgment on the delta ecosystems which is based on regular observations of Tugai forests in different seasons and under varying conditions of water availability. He gave valuable information on the state of riverine ecosystems in the delta today.

Classification of habitat variables A questionnaire was developed for evaluation of the different habitat variables and distributed to the specialists. The scientists were asked to classify the suitability of a certain variable range for the habitat of Tugai riverine forests into the four classes (1) not, (2) low, (3) medium and (4) highly suitable (fig. 11). E.g. a judgment had to be given about the suitability of a location with a groundwater level of 0-0.5 m for young (forming) and adult Tugai formations (with special emphasis on the most distributed formation *P. euphratica*). All state variables were evaluated with respect to young (forming) and old formations. They were also asked to assign weights reflecting the importance of the individual habitat factors.

The interactions of different variables as e.g. ground water level and salinization of the soils was discussed.



State Variable	High 8-10	Moderate 4-7	Low 1-3	None 0
Groundwater				
0.-0.5m				
0.5-1.5m				
1.5-3.0m				
3.0-5.0m				
5.0-15.0m				
Geomorphology				
River Bars				
Slope of river bars				
Interfluve lowlands				
Flood lands and terraces				
Deltaic plains				
Lake Depressions				
Soil type				
Meadow-tugai				
Meadow-tugai desertifying				
Meadow-tugai takyrizing				
Takyr				
Solonchak				
Soil Salinization (forming formations)				
<0.25				
0.25-0.5				
0.5-1.0				
1.0-2.0				
2.0-5.0				
>5				
Soil Salinization (adult formations)				
<0.25				
0.25-0.5				
0.5-1.0				
1.0-2.0				
2.0-5.0				
>5				
Flooding - Timing				
March				
April				
May				
June				
July				
August				
September				
October				
November				
Flooding - Duration				
1month				
2 months				
3 months				
4 months				
5 months				
6 months				
Flooding - Frequency				
Once every 5 years				
Once every 10 years				
Two years in a row, every 10 years				
Three years in a row, every 10 years				

Figure 11: Example of questionnaire used to determined suitability ranges of key habitat variables by the experts.

5 Water Management Model

In the following the three different modules of the tool - water allocation management, environmental models and ecological assessment - are presented in two sections.

5.1 Problem and objectives

The objective of the hydrological module is to simulate the spatio-temporal surface water distribution that results from a chosen management policy or changes to the discharge to the delta area. The model should distribute water between the different users according to their demands in an optimal way. Water needs for agriculture should be given highest priority in water allocation. The model should be able to realistically represent water allocation from a multi-body reservoir such as the Tyuyamuyun reservoir at the entrance to the delta. It is assumed that regional climate patterns remain the same during the modeled time period of approximately 30 years. The model should be simple and easy to use for hydrological scenario development 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 scale (e.g. reduction of inflow to the delta region) should easily be implemented in the model and tested.

5.2 Modeling approach

5.2.1 Hydrological and hydraulic models and software tools

Numerical models Among the current generation of hydrological models there are two categories: physically-based and conceptual models (Jothityangkoon et al. 2001). Physically based models operate mainly with partial differential equations of flow through porous media, overland flow and channel flow. They are numerically solved. Distributed physically based models are very data intensive. Lumped conceptual models on the contrary do not take into account the detailed geometry of the catchment or small scale variabilities. Instead, they consider the catchment as an ensemble of interconnected conceptual storages (Jothityangkoon et al. 2001).

There are a number of river basin analysis and engineering software tools including channel routing models for the simulation of hydrology, hydraulics, water quality, pollutant and sediment transport and soil water availability, e.g. HEC-RAS (Brunner 2002), SWAT (Srinivasan et al. 1997, Arnold et al. 1998), MIKE 11 (Havno et al. 1995). Most of them are based on distributed physically based models, integrating rainfall- runoff models, hydraulic routing routines and water quality models. Some, e.g. MIKE SHE (Danish Hydraulic Institute 1998), offer different approaches ranging from simple, lumped and conceptual approaches to advanced, distributed and physically - based ones. They are used to assess the effect of land use changes on runoff and water quality, to assess the impact of point and non-point pollutant sources, the effects of climate change as well as for operational questions in engineering and flood control concerning the river basin under study. Some examples are listed in table 3.

Their hydraulic components which 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) need data sets of channel and floodplain crossections. The lack of spatial and non-spatial data, which in practice have often been only available for small areas (Andersen et al. 2001), often prevents a comprehensive analysis (Srinivasan et al. 1997). Neither data nor a GIS that is often used to provide input data for those models was available for the entire Amudarya river basin. On the other hand, the high level of detail provided by these models was not needed for the aim of the study.

Optimization models Other methods frequently used in water management modeling are water balance models using an optimization approach. They have mainly been developed for semi-arid catchments with highly developed irrigated agriculture. Their goal is to optimize water distribution between competing users, maximizing optimal and equal water delivery to the users or crop production (e.g. Reca et al. 2001). The main focus is not the hydrological cycle and potential changes to it, but rather the optimal allocation of a scarce resource in a complicated network under different physical and management constraints as a basis for management decisions. Experiences in the Lower Ayun irrigation system (Bali, Indonesia), where a simulation model 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 its objective function.

Selected approach In the Amudarya river delta rainfall contributes only little to surface runoff. In the arid lowlands of the middle and lower reach of the river precipitation and side inflow to the river are minimal and can be neglected. Water entering the delta region has been generated further upstream in the mountain region. Climate as a driving force can be modeled implicitly through the hydrograph provided as input to the river network.

Given data availability and the scope of the model it was concluded that a model allocating water along the river and canal network to the users, based on a given or simulated inflow to its supply nodes and the needs of the users, would be most appropriate. The Central Asian EPIC modeling system for river basins with irrigated agriculture appeared to be suitable for the construction of a model of this type. It is a development environment for water allocation models using a multiple criteria optimization approach. Its interface facilitates network construction and parameterization for the given river basin. The system provides an objective function and the necessary continuity equations that constrain water flow. Analysis

Table 3: Examples of hydrological and hydraulic models and software packages

Name	Type /Characteristics	Developer	GIS-Coupling	Examples
QUALE2U	instream water quality model	USEPA		Brown & Barnwell 1987
SWAT	process-based, basin-scale, with channel routing component	USDA-ARS	yes	Arnold et al. 1998
MIKE 11/MIKE SHE	numerical river modelling tool, hydrology and hydraulics, dynamic 1-d, channel routing component, finite difference computation of unsteady flows	DHI	yes	Andersen et al. 2001
HEC-RAS	hydraulic routing in channels	HEC U.S. Army Corps of Engineers	yes	U.S. Army Corps of Engineers 1995
ANSWERS	distributed parameter, event-oriented, planning model			Beasley and Huggins 1982
WAMADSS	integrates GIS, AGNPS and SWAT into a decision support tool		yes	Fulcher et al. 1999
HBV	conceptual, dynamic, distributed rainfall-runoff model	Swedish Meteo-rological and Hydrological Institute		Bergström, 1995; Lindström et al. 1997
VIC-2L				Lohmann et al. 1998
River Ware	reservoir and river systems operations and planning modeling tool to develop multiobjective simulation and optimization models of river and reservoir systems, rule based simulation and optimization possible			Zagona et al. 2001
SFWMM	process-based, lumped and distributed, cell to cell water transfer, models the response of the hydrologic system to changes in hydraulic infrastructure or operational rules	South Florida Water Management District		MacVicar et al. 1984

of alternative management options by setting additional constraints or changing the weights in the multi-objective optimization function can easily be performed. The system was developed by McKinney & Savitsky (2001) based on work with over 40 Central Asian water and energy specialists. The experience of its developers with the Amudarya river system as well as its management was another asset of choosing this approach to realize a water allocation model for the Amudarya river and its delta region.

The EPIC modeling system has initially been developed as a tool to support annual water allocation negotiations between the states of the Syrdarya river basin. Claims of the upstream riparian countries for use of the water resources for hydroelectric power generation in the mostly fossil resources pour mountain countries and irrigation water needs in the downstream countries have caused disputes. An EPIC Syrdarya model is used to determine reservoir operation and the size of compensations in form of gas and electricity from the downstream countries to ensure water delivery in the vegetation period. Water allocation and energy production was modeled on a one year basis (McKinney et al. 1997a, Antipova et al. 2001). The results are used to determine the necessary compensations for a reduction of energy production in favor of irrigation. Another application investigated the potential for sustainable irrigation water management (Cai et. al. 2002).

5.2.2 Hydrological and water distribution models of the Amudarya river

In the past few models have been developed to predict water flow and water quality in the Amudarya river. 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 saline 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 water volume.

Raskin et al. (1992) developed the WEAP modeling system (integrated water demand-supply analysis) for scenario analysis and evaluation of water management strategies by simulating current water balances. The model treats water demand and supply issues. Based on an analysis of data of the year 1987 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 the water users in the lower reach that amounts to 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 the expected salinity of the outflow which is an essential characteristic determining future use of the water. Modeling a detailed river network including all major canals is necessary to simulate spatial water distribution as basis for the ecological assessment. In the above described models ecological needs of the delta ecosystems are not accounted for, 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 below.

A 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 Mechanism of Agriculture (McKinney et al. 1997b). This model considered the distribution of water between irrigated areas in the Amudarya basin and salinization of the water in the basin. A more detailed model was also developed for the Kashkadarya River basin which additionally 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.

5.3 Hydrology of the Amudarya river

Although the focus of the impact assessment will be put on the delta region of the Amudarya river, surface flow in the entire river was analyzed and considered for model construction. 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 reach of the river. To test new water allocation strategies for the delta region, the situation in the upper and middle reach has to be taken into account. Therefore, the entire river network is included in the model, although with varying level of detail.

The Amudarya is the larger of the two rivers of Central Asia that once fed the Aral Sea. The size of its catchment is about 300.000 km^2. It begins with the confluence of the rivers Pyandj and Vakhsh in Tajikistan and in the upper reach forms the border between Tajikistan, Uzbekistan and Afghanistan (fig 12). From the mountains it flows into the desert lowlands of Turan through Uzbekistan and Turkmenistan and drains into the Aral Sea. Along the main 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

Figure 12: Gaging stations along the Amudarya river and its contributors Vakhsh, Pyandj, Kunduz, Kafirnigan. Surkhandarya river does not reach the Amudarya any longer. Karakum and Karshi canals are major water users. (modified from Aral Sea GIS, Micklin et al. 1998)

irrigation water needs, main and side inflows including return flow, and water intake for communal needs (fig 13). According to its hydrological and water balance characteristics, the river basin can be divided into three parts: an upper, middle and lower reach (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. Contributors to the river are located only in the first 180 km (Shulz 1965). Together the Pyandj and Vakhsh rivers contribute approximately 88 % to the runoff of the Amudarya. They are fed by glaciers and high altitude snows which determines 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. In former times about 89% of the Amudarya discharge or 40 km^3 would reach the Aral Sea. Approx. 9 km^3 were lost to evaporation and infiltration (Shulz 1965). The runoff from 1959 to 2000 of major gaging stations along the rivers Vakhsh and Amudarya can be seen in figure 14.

On the upper reach at present time one large reservoir is in operation: Nurek reservoir, and another one in planning and construction: Rogun reservoir. The operational regimes of the upstream reservoirs are mainly determined by the demands of the users in the entire Amudarya river basin. The middle reach from the river station Kerki to the dam of Tyuyamuyun 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 reach, mainly for irrigation, leads to water

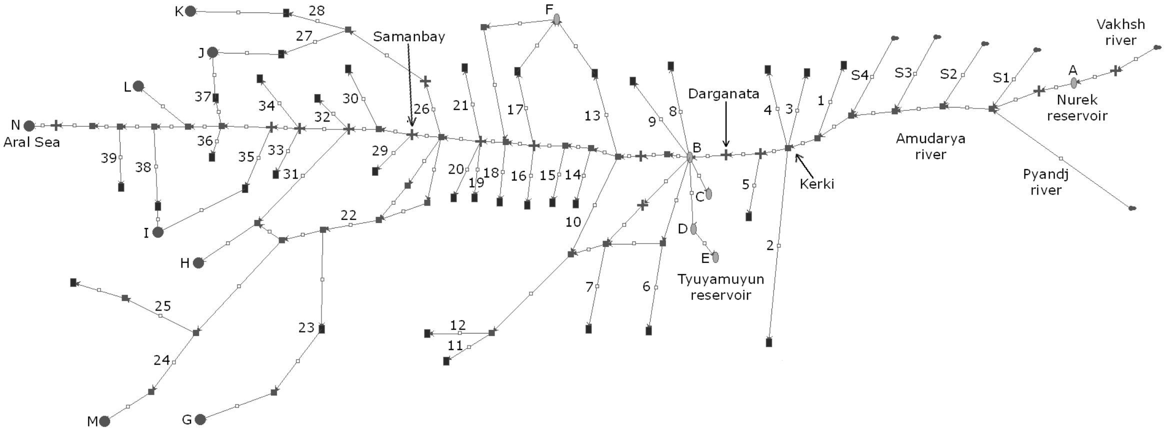


Figure 13: Scheme of the river network used for the allocation model AmuEPIC of the Amudarya river (see subsection 5.4.2). The main river, contributors, reservoirs, lakes and major irrigation canals are shown. Numbers are explained in table 4 and 5.

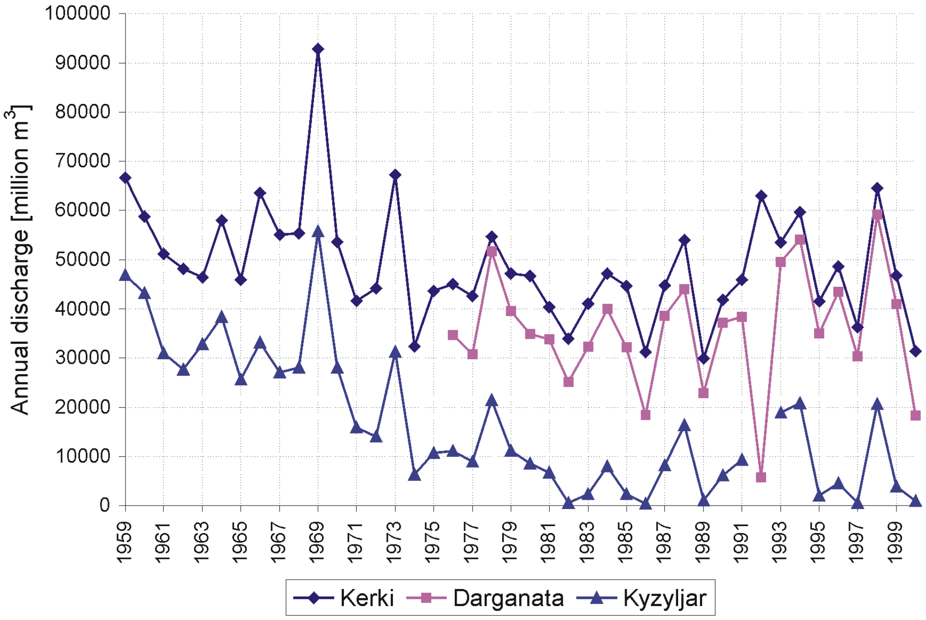


Figure 14: Runoff at the gaging stations Kerki (at the outflow from the mountains), Darganata (inflow to the delta) and Kyzyljar (northern delta region) from 1959 to 2000. Values for 1992 for Darganata and Kyzyljar are missing. (data source: Uzbek Main Hydrometereological Service)

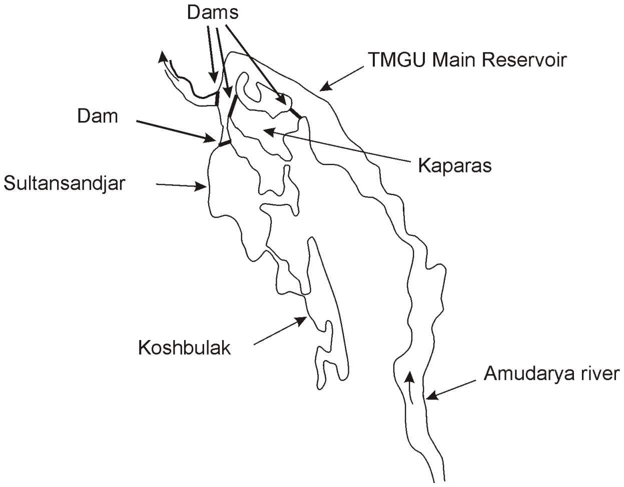


Figure 15: Scheme of the Tyuyamuyun reservoir system (TMGU) with the four reservoir bodies Tyuyamuyun Main, Kaparas, Sultansandjar and Koshbulak.

shortage and strong decrease in water quality in the lower reach. To counteract this problem the Tyuyamuyun reservoir (TMGU) was built in the beginning of the 1980s. Its role and significance is 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 reservoir, Kaparas, Sultansandjar and Koshbulak (fig 15). Weirs between the main reservoir and Kaparas and the main reservoir and Sultansandjar allow for management of 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 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 alluvium sediments of the historic delta.

5.4 Creation of the Amudarya water management model AmuEPIC

5.4.1 The EPIC (Environmental Policies and Institutions in Central Asia) Modeling System

The EPIC Modeling System facilitates automatic creation and solving of General Algebraic Modeling System (GAMS, Brooke at al. 1998) models of river basin management (McKinney

& Savitsky 2001). Models created with the system perform multi-objective optimization calculations for operation of a river network. Optimization is constrained by a ranked list of objectives given by the ”water manager”. The EPIC system provides an interface for automatic network and model creation, as well as data input, input of limits to reservoirs and channel flow, setting of objective weights and visualization of results. In this study the automatic creation of the model source code was adapted in some parts. This was necessary to provide some special features, such as the modeling of multi body reservoir systems, needed for a model of the Amudarya river.

The objective function and the continuity constraints for the optimization were taken from the modeling system. Equations to model the TMGU four body reservoir and to regulate flow between the reservoir bodies were developed within the framework of this thesis.

5.4.2 Creation of the Amudarya river model

River Network The water management model created within the EPIC modeling framework was initially developed for the entire Amudarya river, beginning with its two major tributaries, the Vakhsh and Pyandj rivers in Tajikistan. This is necessary, given the interconnectivity of the river network and the strong dependence of water availability in the delta area on water use upstream. Since the ecological assessment focuses on the delta region, the three river reaches were modeled at different levels of detail. In the upper and middle reach, only major canals, diverting water to the irrigation areas as well as some smaller supplies are represented. In the lower reach, beginning with the reservoir system Tyuyamuyun, the river and canal network is represented in greater detail.

The river and irrigation network is formally represented by two mathematical objects (McKinney & Savitsky 2001):

- Nodes, representing sources, users, points for water intake, controls and reservoirs, were water balances are calculated, and
- Arcs, that transfer characteristics of water quantity and quality between groups of nodes.

Distances are not accounted for in the network and the main river and irrigation canals are both represented in the same way. A schematic river network of the Amudarya river consisting of its main tributaries located in the upper reach (Vakhsh, side inflow to Vakhsh, Pyandj, Kafirnigan and Kunduz), the Amudarya river itself, the two main reservoirs (Nurek and Tyuyamuyun), the main canals in the upper and middle reach (Karshi canal, Amu-Bukhara and Karakum canal) and the major canal network in the delta area was created (see figure 13). In the delta region all major canals diverting water to the irrigated areas and 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 4). The selection of the major canals was based on analog maps, on schemes of the Uzbek Main Hydrometereological Service as well as on a digitized canal network in the Aral Sea GIS. They are also the only canals were water withdrawal data over a period of 5-10 years were available. 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 (table 5) were introduced as reservoirs or as sinks that receive water not needed anywhere else.

On the middle reach only the large Amu-Bukhara canal was included in the river network. Balance calculations for the middle reach revealed that water withdrawal by small canals along this river reach approximately equals the inflow of return waters from the irrigated areas (Savitsky in prep.), justifying the approach of a simplified river scheme in the middle reach.

Optimization The main optimization criterion is to minimize deficits of water delivery to all users (a). Other criteria, namely the planned flow to the Aral Sea (b), the degree of filling of the reservoirs (c), and the demand for stability of the system (d), simplify and accelerate the calculations and through changes in their weights allow for the implementation of policy and management decision (McKinney & Savitsky 2001). The objective function is given below (taken from the GAMS source code):

Maximize

$$p_1 * \frac{1}{T * N_{i_{user}}} * \sum_t \sum_{i_{user}} \frac{W_{in,i,t} - W_{trans,i,t}}{W_{req,i,t}} + p_2 * \frac{1}{T * N_{i_{mouth}}} * \sum_t \sum_{i_{mouth}} \frac{W_{in,i,t}}{W_{req,i,t}}$$

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

Where

p_1, p_2, p_3, p_4: weights (dimensionless)
$i_{user}, i_{mouth}, i_{res}$: i-th node of type "user", "mouth", "reservoir"
t: time step (month)
N: total number of nodes
T: total number of time steps
$W_{in,i,t}$: Discharge to node i at times step t (million m^3)
$W_{trans,i,t}$: Discharge passing node i at times step t (million m^3)
$W_{req,i,t}$: Discharge required by user i at time step t (million m^3)
$Vol_{i,t}$: Volume of reservoir i at time t (million m^3)
$Vol_{max,i}$: capacity of reservoir i (million m^3)

Table 4: List of major irrigation canals and old river branches included in the river network of the Amudarya river model

Name of river/canal	**Location/Type**	**Max / Norm intake capacity [m3/s]**	**Number in river scheme**
Karakum Canal	Middle reach	650/383	2
Amu Bukhara Canal	Middle reach	350/60	3
Karshi Canal	Middle reach	160/152	4
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
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. Okt	19
Sovjetyab	Lower Reach – Turkmenistan	300/250	20
Suenly	Lower reach - Karakalpakstan	394/225	22
Koundykuziak	small or old river branch/channel	-	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
Pumping Stations	Lower reach upper delta	-	17
Pumping Stations	Lower reach middle delta	-	21
Pumping Stations	Lower reach lower delta	-	32
Erkindarya	small or old river branch/channel	-	30
Raushan	small or old river branch/channel	-	31
Akbashly	small or old river branch/channel	-	33
Kipchakdarya	small or old river branch/channel	-	35
Kazakhdarya	small or old river branch/channel	-	37
Tujezhol	small or old river branch/channel	-	39

Table 5: List of deltaic lakes included in the Amudarya river model and constraints applied to lake inflow in the optimization model

Lakes in delta area	**Constraints to inflow (lower/upper) [10^6 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	100-500/10000	N

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

- for each simple and control node:

$$\sum_i W_{out,i,t} = \sum_i W_{in,i,t}$$

- for each user node:

$$\sum_i W_{out,i,t} = trans_{i,t} + \left(\sum_i W_{in,i,t} - trans_{i,t} * ret_{i,t} + reb_{i,t} \right)$$

and

$$\sum_i W_{in,i,t} - trans_{i,t} \leq W_{req,i,t}$$

- for each reservoir:

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

where

W_{out}: outflow from node i (million m^3)
$ret_{i,t}$: return coefficient (return water)
$reb_{i,t}$: coefficient for additional water sources for node i at time t
$e_{i,t}$: evaporation from reservoir i at time step t
$\bar{A}$: average surface of reservoir i

Additional constraints were introduced as

- physical constraints such as capacity limits for the Nurek and Tyuyamuyun reservoirs
- policy constraints such as a minimum inflow to the Aral Sea
- model control constraints such as an upper limit on the variation in reservoir volumes at two succeeding time steps and upper limits on the inflow to delta lakes and reservoirs (see table 5)

Scenarios of water management alternatives can be developed by changing the policy constraints to e.g. reflect a decrease in water use in irrigation or a desired minimum flow in a specific canal. The model control constraints are needed to keep the solution of the model as close to the real world conditions as possible.

In the following the model control constraints are further specified and explained.

The **Akchakul lake** (F, figure 13), which is fed mainly by drainage waters from irrigation fields, releases some of the water it receives back to the main river. To represent this loop in the model it was necessary to declare the lake as a reservoir node. Reservoir nodes, in contrast to “mouth” nodes, can have a discharge through-flow of water. In the solving process reservoirs have high priorities since they manage water distribution. This leads to a situation where the model allocates to Akchakul lake as much water as possible and allowed by the constraints on maximum volume. To prevent this unrealistic behavior upper limits have to be set to the water flow in the two canals that divert water to the reservoir (Pakhtaarna and Pumping stations upper delta; No 13 and No 17 in figure 13).

Water flow to the Northern delta region. Since there are no irrigation users in the Northern part of the delta that require specific water quantities, water distribution to the North is not a priority for the solving process. The water is rather allocated to lakes and reservoirs further south. To force the model to allocate water to the North a limit was set for a minimum inflow to the Aral Sea. It is much smaller than the values aimed at to restore the delta region. It thus leaves enough possibilities to adjust this constraint to reflect management decisions. For the same reason the inflow to the delta lakes was limited. This achieves that additional water is left in the main river and not allocated towards the lakes.

The values of the constraints were determined by try and error until the best representation of the measured discharges and reservoir volumes in the respective period were found, given the fulfillment of the user requirements. This set of model control constraints was the smallest possible to achieve a realistic model behavior. It was considered that the number of constraints to control model behavior should be kept as small as possible. Limits to discharges in canals should rather be set in scenarios to implement management decisions.

The water management model in EPIC is solved using the general purpose non linear programming solver Minos (Minos 5, Murtagh et al. 2002). The GAMS/solver system is designed to find solutions that are locally optimal. If the nonlinear objective and the constraint functions within the region defined by the linear constraints and the bounds on the variables is convex, the solution will be a global optimum. A detailed description of the EPIC Modeling system for river and energy management and its application to the Aral Sea Basin can be found in McKinney & Kenshimov (2000) and McKinney & Savitsky (2001).

Tyuyamuyun Reservoir The Epic modeling system was extended by some additional functions to allow creation and computation of multi-body reservoir systems connected via managed weirs or unmanaged canals, as it is the case in the Tyuyamuyun reservoir. The accurate representation of the water flow between reservoirs is essential for future modeling of the salt transport and the salinity of the outflow to the delta region. Salt concentrations in the single reservoir bodies can vary significantly depending on the amount of freshwater mixing into the individual reservoir bodies. After the construction of the reservoirs in the beginning of the 1980s the initial salt leaching was very strong. Figure 16 shows the amount of salt (thousand tons per year) dissolving into the reservoir water over the time period 1981-2001 as modeled with the model WP (Razakov 1998).

The dam on the main reservoir was built in 1981/82. Kaparas, which was still directly connected to the main reservoir body, was flooded and dissolving of the salt accumulations on the bottom caused the peak in salinity seen on figure 17. The same accounts for Sultansandjar 1993-4 (the reservoir was only slowly flooded) and Koshbulak 1995. The second peak in salinity in Kaparas reservoir in 1993 (fig 17) is connected to a lowering in water table height for dam construction works. They were initiated with the aim to use Kaparas reservoir as a drinking water reserve especially for the spring period (April, May), when the quality of the Amudarya river water is poor. When the water level in Kaparas drops to approximately 100m salinity increases to more than 3 g/l. This is caused by an inflow of high saline groundwater at low reservoir levels, as well as salt leaching from the reservoir bottom and evaporation. The process of salt leaching is slowly stabilizing in all reservoir bodies and can be estimated. As a result water of almost any salinity can be ”made” at the outflow from the reservoirs. This risk and potential is not apparent in the averaged salinity values given for the monthly outflow from a single Tyuyamuyun reservoir. 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 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 by man (in our case Main Reservoir, 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. The equations are listed below:

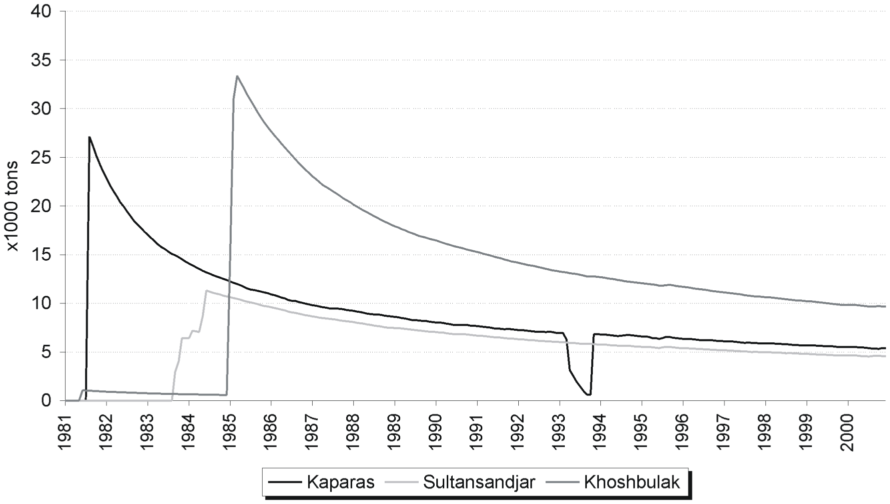


Figure 16: Amount of salt (thousand tons) leaching from the bottom sediments into the water columns of Kaparas, Sultansandjar and Koshbulak calculated with the model WP (Razakov et al. 1998).

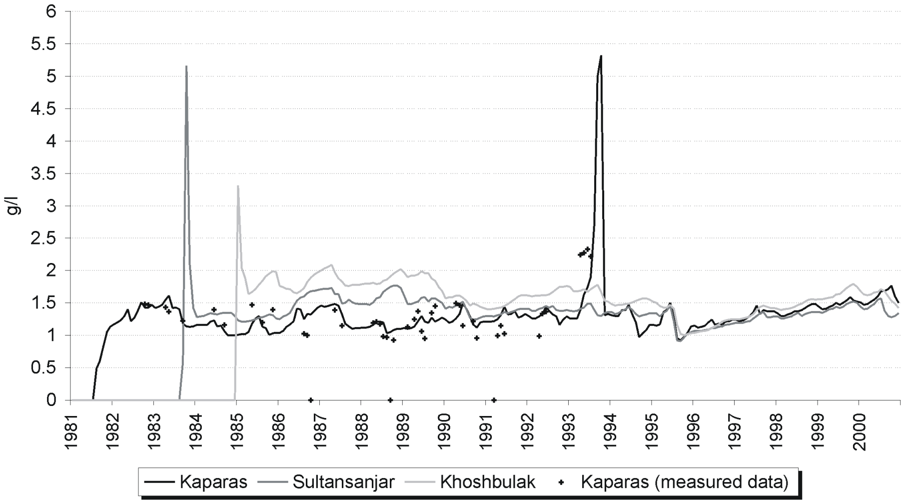


Figure 17: Salinity of water bodies in Kaparas, Sultansandjar and Koshbulak calculated with the model WP (Razakov et al. 1998). The dots represent measurement data of salinity in the Kaparas reservoir. Modeled values are monthly averages, measured data single measurements for different days of a month.

Variant1:

Managed:

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

Unmanaged:

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

Variant2:

Managed:

$$W_{i,t} < f_{i_1,i_2,t} * (|h_{i1} - h_{i2}| + (h_{i1} - h_{i2}))$$

Unmanaged:

$$0 = (h_{i_1} - h_{i_2})^2$$

Variant3:

Managed:

$$W_{i_1,i_2,t} * (h_{i_1} - h_{i_2}) > 0$$

Unmanaged:

$$0 = h_{i_1} - h_{i_2}$$

where

$W_{i_1,i_2,t}$: water exchange between reservoir i1 and i2 at time step t (million m^3)
$h_{i_1,t}$: water level in reservoir i1 at time step t
$h_{i_2,t}$: water level in reservoir i2 at time step t
f_i: coefficient of intensity of flow between the reservoirs (m^2/s)
t: time step (month)

Water level in the reservoirs is calculated according to the following equation:

$$h_{i,t} = \frac{vol_{i,t}^{\frac{1}{a_i}}}{b_i} + h_{0,i}$$

where

$vol_{i,t}$: Volume of reservoir n at time t
a_i, b_i: coefficients of reservoir i
$h_{0,i}$: minimum water level of reservoir n

Testing revealed that Variant 1 best mimics real reservoir operation as it was determined from monitoring data. It also solves best, which is probably the result of some specifics of the solver.

Testing of the model also revealed that the reservoir management determined by the solver leads to strong fluctuations of reservoir volumes between two successive months. This behavior seems unrealistic and undesirable. To avoid this behavior an additional constraint was introduced that limits changes in reservoir volume to less than 60% of the volume at the previous time step, according to the following function:

$$\triangle Vol_{i,t} \leq 0.6 * (Vol_{i,t-1})$$

The size of the allowable fluctuations was determined by testing values from 0.1-1. A value of 0.6 reveals the best results although there are measuring observations, where the difference in volumes is larger than 60%.

Input Data The following input data are needed for a model run:

1. inflow at the source nodes, either historic data or results of time series analysis
2. reservoir functions relating level to volume and surface
3. initial volumes for reservoirs
4. average monthly water use in the user nodes, either historic or scenario values
5. estimated or measured losses (evaporation and infiltration, intake by small canals)
6. reservoir and channel capacities
7. objective weights of the water manager, reflecting policy decisions

To 1. Data of average monthly river runoff in the supply nodes, reservoir storage and withdrawals by the canals for calibration and validation were obtained from the responsible water management agencies (mainly the Uzbek Hydromet Service). Missing records for the river Pyandj, where most measuring stations are out of order, were estimated using runoff data of the neighboring stations on the second tributary Vakhsh and at the first gaging station of the Amudarya river at Kerki. For the last gaging station on river Pyandj (located at 34 km from the river mouth) mean monthly runoff values for the years 1992 - 2000 were estimated by balance calculations using the mean monthly runoff at the gaging station Kerki (first gaging station after the confluences of Pyandj and Vakhsh), data on runoff at the last gaging station of the river Vakhsh and water withdrawals on the river stretch from the confluence of the two rivers to Kerki (see figure 12).

$Q_{Pyandj} = Q_{Kerki} - Q_{Nurekout} - Q_{Vakhsh} - Q_{Kunduz} - Q_{Kafirn} - Q_{Surkhan1} + Q_{Kash} + Q_{Surkhan2} + Q_{Navoi} + Q_{pump} + Q_{Karakum}$

where

Q_{Pyandj}: Mean monthly runoff (m^3/s) at the gaging station “Lower Pyandj”
Q_{Kerki}: Mean monthly runoff (m^3/s) at the gaging station “Kerki”
$Q_{Nurekout}$: Mean monthly outflow (m^3/s) from Nurek reservoir into the river Vakhsh
Q_{Vakhsh}: Mean monthly side inflow (m^3/s) to the river Vakhsh
Q_{Kunduz}: Mean monthly inflow (m^3/s) from the river Kunduz
Q_{Kafirn}: Mean monthly inflow (m^3/s) from the river Kafirnigan
$Q_{Surkhan1}$: Mean monthly inflow (m^3/s) from the river Surkhandarya
Q_{Kash}: Mean monthly intake (m^3/s) from the Amudarya river to the Kashkadarya area
$Q_{Surkhan2}$: Mean monthly intake (m^3/s) from the Amudarya river to the Surkhandarya area
Q_{Navoi}: Mean monthly intake (m^3/s) from the Amudarya river to the Navoi area
Q_{Pump}: Mean monthly intake (m^3/s) from the Amudarya river by pumping stations
$Q_{Karakum}$: Mean monthly intake (m^3/s) from the Amudarya river by the Karakum canal

Mean monthly runoff values at the gaging station Kerki and the outflow from Nurek reservoir were taken from the database of the Hydrometereological Service of Uzbekistan.

Side inflow to the river Vakhsh downstream of the Nurek reservoir was assumed constant at a mean annual runoff of 102 m^3/s. The estimate was based on the following relationship between the gaging station “Tigrovaya Balka” on Vakhsh river downstream of the Nurek reservoir and the outflow from Nurek reservoir: $y = 0.74x + 102.64$. The hydrograph of the gaging station “Garm” upstream of the reservoir was used to estimate the mean monthly values for the side inflow.

The river Kunduz is located in Northern Afghanistan and flows into the river reach of the river Pyandj that forms the border between Afghanistan and Uzbekistan. Actual runoff data for this river are not available. However, a mean monthly runoff time series from 1965 to 1975 could be acquired. The 1965-1975 average annual runoff in the river Kunduz upstream of the irrigation fields in the Kunduz river basin was 110m^3/s. The 1965-1975 time series was correlated with the 1965-1975 mean monthly runoff at the gaging station “Lower Pyandj”. The correlation $Q_{Pyandj} = 0.14 * Q_{Vakhsh} - 33$ ($R^2 = 0.66$ or $R^2 = 0.9$ without the high water year 1969) was used to estimate mean monthly runoff of the river Kunduz for the calibration years 1994 and 1997 (see below). Irrigation intake from the river was estimated at an average of 75m^3/s based on the water needs to irrigate 52.000 ha of irrigation fields in the basin. The calculated runoff minus the irrigation intake in Afghanistan was taken as the annual average inflow from the river Kunduz. Mean monthly averages were based on the hydrograph determined from historic data. The estimation of the flow in the river Kunduz by using calculated flow at the station Lower Pyandj was acceptable since the contribution of the river Kunduz to the overall flow of the river Pyandj is relatively low (<10%).

Inflow from the river Kafirnigan was also assumed constant in every year at a mean annual runoff of 160m^3/s. Both mean annual and mean monthly runoff were calculated as average for the 1930-1991 time period.

Inflow from the river Surkhandarya is only accounted for in high water years, because it is completely used for irrigation in a low water year. Mean monthly runoff values for the high water years are taken from the Hydromet database. Intakes from the Amudarya river to the Surkhandarya region, by pumping stations and by the Karakum canal were taken from data.

Single records (monthly values) that were missing in time series of gaging stations along the rivers Vakhsh, Pyandj, Kunduz, Kafirnigan, Kashkadarya, Surkhandarya and Amudarya were filled with the respective values from a complete year whose hydrograph resembled most closely the one of the incomplete year. The year with the best fit was determined by the least squares method.

To 2. The parameters for the hydraulic functions of the reservoirs relating volume to level to surface were determined with the help of EPIC through fitting the function to measurement data from the reservoirs. The measurement data were also obtained from the Uzbek Hydrometereological Service.

To 3. The initial volumes of the reservoirs were taken from data. They are mean values of reservoir filling at the beginning of a year.

To 4. User demands for the calibration years were taken as the actual measured head inflow to the respective irrigation canal. In scenario runs they can be assigned by the water manager.

To 5. 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 historic runoff data from 1991-2000. Unfortunately data for the Northern delta were rather imprecise, e.g. there were cases when runoff 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 a result of measurement errors. Observations made by the author at the gaging station Kyzyljar at the beginning of 2002 indicated that in low water years measured discharges in the Northern delta might be overestimated.

Losses in the upper and middle reach amounted from 0 (winter) to 10 % (spring/summer) of the runoff at Kerki (gaging station where the river leaves the mountains and flows into the desert lowlands). Losses occurring in the lower reach were accounted for at the river station Samanbay with values at 15-27% of the outflow of the Tyuyamuyun reservoir, and at the station Kyzyljar at 5-20% of the inflow at Samanbay (see annex). 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.

To 6. Reservoir dead volume and maximum storage were taken from data. Channel capacity limits were only assigned for model control purposes (see above). Their values were determined from technical limits to channel flow and maximum inflow to the lakes.

To 7. The objective weights are set by the water manager. To optimal serve user demands the user task should always receive weights a multitude larger than the other tasks.

Calibration The Amudarya river model was calibrated by fitting model results to observed values of reservoir volumes and river flow at selected gaging stations in the high water year 1994 and the low water year 1997. The volumes of Nurek reservoir and the Tyuyamuyun reservoir system as well as their outflows, runoff at Darganata (inflow to the delta area), runoff at Samanbay (first gaging station after the last major irrigation withdrawal) and at Kyzyljar (inflow to the Northern delta) were used as calibration points.

It appeared that optimization of the entire river network over a time horizon larger than one year was very time consuming. To facilitate computation and testing of long term (14 year) model runs the river network of the model had to be reduced to the delta area. The river and canal network of the reduced model is identical with the whole river model with the exception that the middle and upper reach are not represented. The input to the river network is modeled at the river station Darganata (see fig 13), which is the inflow to the Tyuyamuyun reservoir. Input data for user requirements and losses are based on data of the average water year 1995.

As it is aimed to test the validity of the water management model for the entire river network, as well as for a long time series, calibration and validation has been performed for both models. The whole river model is referred to as “River Model”, the reduced model as “Delta Model”. Calibration and sensitivity analysis was extensively performed for the one-year runs of the river model and to a lesser extent for the multi-year runs of the “delta” model. It was considered necessary to model the whole river to test reservoir operation of the Nurek reservoir upstream and to provide a model for modeling of changes in water allocation in the upper and middle reach.

The parameters for calibration were (1) the intensity of flow between managed and unmanaged reservoirs (”friction”), (2) the objective weights for the objective function, (3) the model control constraints (described above), (4) evaporation values for the reservoirs, (5) and the upper limit of fluctuations in reservoir volumes in the Tyuyamuyun reservoir system (see above). Observed discharge data for the gaging stations are provided as mean monthly averages from daily measurements. For comparison of observed reservoir volumes with modeled ones, the observed reservoir volume at the last day of the month were used, because model results correspond to the final volume in the reservoir at the end of the monthly time period.

Table 6 gives the parameters and their ranges used for calibration and sensitivity analysis (see below).

5.4.3 Results of calibration runs for the objective weights and validation

The main quality indicator for 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. Water distribution in reality, 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 within limits possible to calibrate and test model results by fitting them to observed data. Real life management decisions are not only complex, but taken under high uncertainty on future water availability. The optimization model does not take this uncertainty into account but rather ”takes decision” with perfect knowledge of the future situation.

As an indicator for the goodness of fit of model results, the relative mean monthly deviation and the relative annual deviation from observed data were chosen. The results of the calibration for both years and the introduced variable bounds can be seen in table 7. Nurek reservoir volumes are modeled very close to the volumes observed in the high and low water year with mean monthly deviation from observed data at 8 and 5%, respectively. For the main body of the Tyuyamuyun reservoir, which reacts much more sensitive to changes in model parameters, the mean monthly deviation amounts to 26 (1994) and 50% (1997). Modeled annual discharge from Nurek reservoir is in both years lower than observed (24% and 18%), while monthly values vary by an average of about 35%. Modeled outflow from TMGU is close to observed in the high water year 1994 (8 % higher) while it is 80% higher in the low water year 1997 (Table 7). The model obviously does not accurately account for losses upstream and in the reservoir bodies in a low water year.

Monthly deviations of the volume and output from TMGU main reservoir illustrate different allocation strategies of the real operator and the model caused by their different knowledge on future water availability (fig 18). The operator will try to keep as much water as possible in the reservoir in early spring as a safeguard against a potential lack of water during the irrigation season, while the model allocates water to the delta region already in spring. In fall, on the opposite, the 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, possible to fulfill the ”filling” objective. Besides, in fall and winter the operator will already consider the expected situation in the next year, which the model in the one year run cannot.

The overestimation of discharge in a low water year is even more pronounced further

Table 6: Parameters and their ranges used for calibration and sensitivity analysis. "River model" refers to the model of the entire Amudarya river, "delta model" to a reduced model of the delta region (see below). p1-p4 indicate the objective weights, f1-f3 the intensity of flow between to reservoir bodies of TMGW ("friction").

Model	**Parameter**	**Range**
River (one year)	p1 (user)	50-1000
	p2 (delta)	0-100
	p3 (filling)	0-100
	p4 (stability)	0-100
	Upper Limit Inflow Aral Sea [10^6 m^3]	1500
	Lower Limit Inflow Aral Sea [10^6 m^3]	0-500
	Upper Limit Inflow Akchakul [10^6 m^3]	150-5000
	Lower Limit Inflow Akchakul [10^6 m^3]	0-50
	Capacity Pakhtaarna [10^6 m^3]	1191
	Upper limit on pumping stations upper delta [10^6 m^3]	0-518
	Akchakul lake min/max Volume [10^6 m^3]	50/300
	Upper limit on inflow to delta lakes [10^6 m^3]	0-10000
	f1 (Main reservoir - Kaparas) [10^6 m^2]	1-1000
	f2 (Sultansandjar - Khoshbulak) [10^6 m^2]	1-3500
	f3 (Main Reservoir - Sultansandjar) [10^6 m^2]	1-4000
	Fluctuations in reservoir volumes (% of volume in last time step)	10-100
Delta (14 years)	p1 (user)	5-1000
	p2 (delta)	1-50
	p3 (filling)	1-500
	p4 (stability)	1-500
	f1 (Main reservoir - Kaparas) [10^6 m^2]	
	f2 (Sultansandjar - Khoshbulak) [10^6 m^2]	
	f3 (Main Reservoir - Sultansandjar) [10^6 m^2]	
	Fluctuations in reservoir volumes (% of volume in last time step)	
	Upper limit on inflow to delta lakes [10^6 m^3]	250-1000

Reservoir or gaging station	**1994**		**1997**	
	RMMD	RAS	RMMD	RAD
Nurek	0.08		0.05	
Nurek out	0.36	-0.24	0.38	-0.18
TMWU main	0.26		0.50	
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

Table 7: Results of calibration and testing for the one year model runs of the whole river model for the high water year 1994 and the low water year 1997. Numbers depict the deviation from monitoring data. RMMD = relative mean monthly deviation ((modeled-observed)/observed); RAD = relative deviation of annual discharge

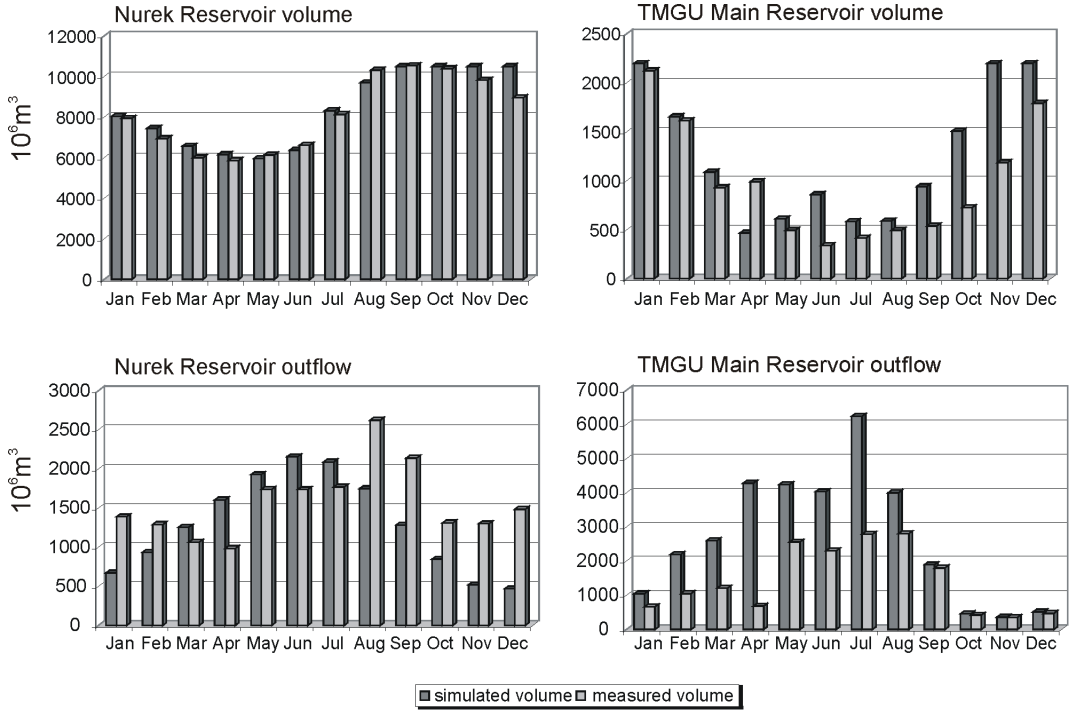


Figure 18: Modeled and measured volume at the end of each month (million m^3) in Nurek (upper left) and Tyuyamuyun Main Reservoir (upper right) for the calibration year 1997 (low water). Modeled and measured outflow (million m^3) from Nurek (lower left) and Tyuyamuyun main reservoir (lower right) in the same calibration year. Differences to measured data are larger in TMGU than in Nurek, which is located further upstream. The model releases more water to the river in the first half of the year and less in the second than the real operators (explanation see text).

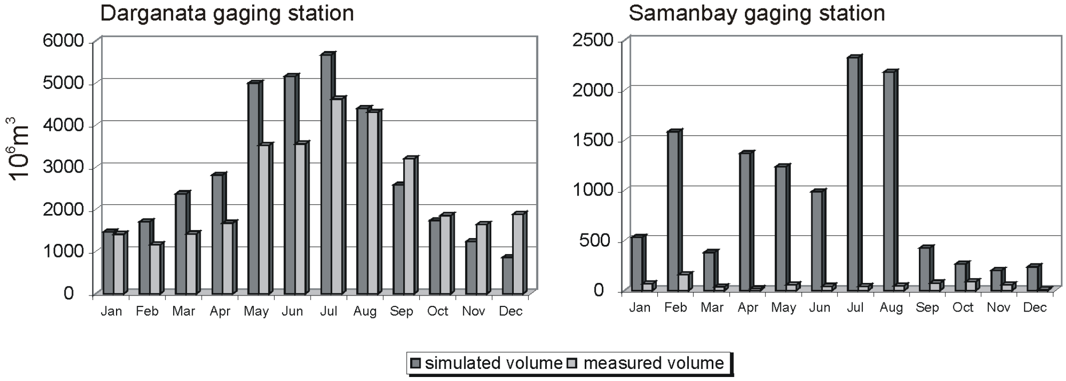


Figure 19: Modeled and measured discharge at the gaging stations Darganata (inflow to delta, left) and Samanbay (northern delta area, right) for the calibration year 1997. In this low water year modeled flow at Samanbay is highly overestimated, indicating the the model does not allocate the water according to the practices currently used in low water years.

downstream at the gaging station Samanbay (fig 19). While inflow to the delta region at Darganata is modeled fairly well, showing the same temporal distribution as explained above, flow at Samanbay is highly overestimated. This does not occur in the high water year 1994 (see annex), indicating that in a low water year water is allocated differently before it reaches Samanbay. 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.

5.4.4 Sensitivity Analysis for the river model

The objective weights user demand, filling of the reservoirs, allocation of water to the river mouth, and stability of the system, are a means for the manager to set the priorities of the various tasks. A sensitivity analysis was carried out to test the sensitivity of model results to a range of objective weights (see table 6). The analysis has shown that the model reacts in the desired way to an increase in the priority of the objective to allocate water to the river mouth by releasing more water from the reservoir (fig 20, all other figures of the sensitivity analysis are located in the annex). An increase in the stability task 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 does not show a significant increase in water stored in the reservoir. The effect of this objective might be less visible 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 also not affects 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 it was the case in the sensitivity analysis).

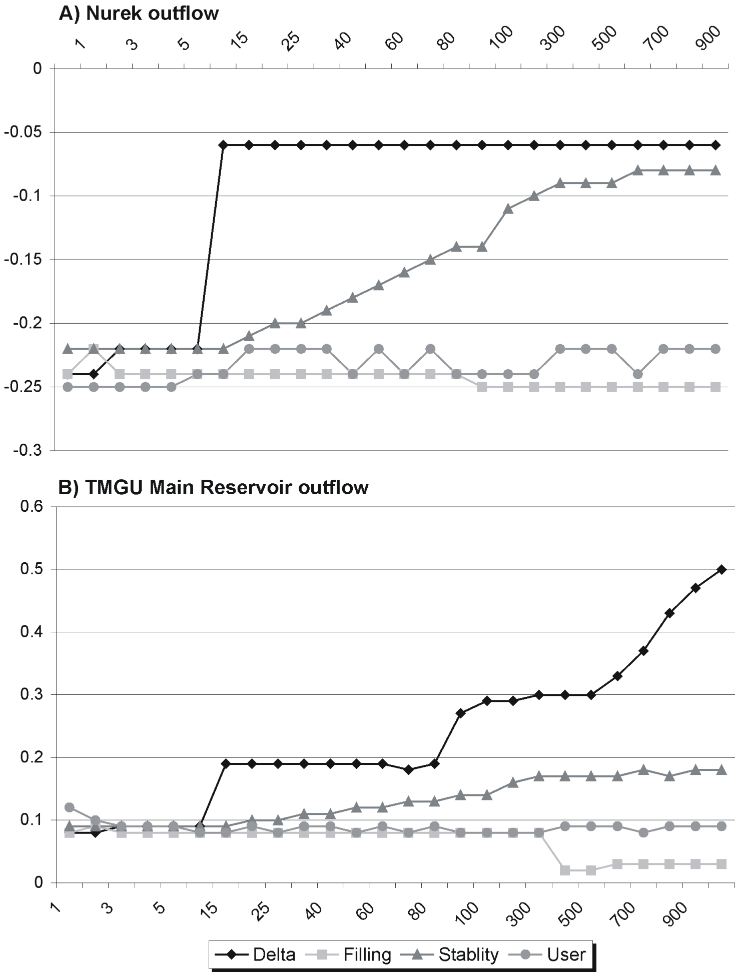


Figure 20: Mean annual deviation of the modeled discharge from a) Nurek and b) TMGU Main Reservoir from measurement data (high water year 1994) with increasing objective weights for delta (allocation to the river mouth), filling (filling of the reservoirs), stability (fluctuations between months), user (satisfying user requirements). For the sensitivity analysis for each objective the other objectives were kept constant at one.

Reservoir volumes react very sensitive to changes in the objective weights. This is most pronounced with the objectives of meeting user demands and filling the reservoir, since they determine changes in the amount and timing of water allocation. The upstream reservoir Nurek shows smaller variations in relative mean monthly error 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 EPIC 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 TMGU, 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.

Discharge at the river stations is generally less sensitive to changes in the objective weights. At Darganata annual discharge is very constant or changes continuously with increasing weights of the objectives delta and stability. At the delta station Samanbay fluctuations of the annual discharge occur, but only within a range of approx. 10-15%. Mean monthly variations are also very small, with the exception of the delta station 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. Besides the solution is also dependent on the geometry of the feasible region, that is on the constraints applied to the solution. The user priority has to always be an order of magnitude higher than the other priorities in order to ensure required water delivery to the users.

5.4.5 The Delta Model AmuEPIC

The delta model was tested with a 14-year scenario based on a characteristic time series of water supply at the river station Darganata (1980-1993). This inflow scenario is also the basis for the reference scenario BAU (business as usual), where additionally no changes are introduced to current water management practices. It thus projects future developments if everything would go on as before.

Determination of inflow to the delta for 14-year scenario The input to the delta model is the runoff at the gaging station Darganata, which is determined by the flow from the mountains and water withdrawals in the upper and middle reach. The input can be modeled based on historical time series or generated hydrographs derived from probabilistic flood frequency distributions. In this study a characteristic historical time series was selected. This was necessary since the available time series of runoff data at Darganata was not long

Table 8: Results of time series analysis for the determination of a representative sequence of years to be used as input to the "delta model" AmuEPIC.

window size	**Coeff. Variance Cv**	**Skewness Cs**	**Mean square difference**	**time period**
4	0.2564	0.2315	0.003815	1994-1998
5	0.2617	0.3116	0.000811	1978-1983
6	0.2515	0.1803	0.012567	1994-2000
7	0.1989	0.2310	0.009777	1990-1997
8	0.2273	0.2245	0.006833	1990-1998
9	0.2746	0.1182	0.029193	1978-1987
10	0.3048	0.2290	0.004266	1983-1993
11	0.2494	0.2117	0.006847	1976-1987
12	0.2375	0.2076	0.008346	1975-1987
13	0.2989	0.2520	0.001766	1981-1994
14	**0.2880**	**0.2881**	0.000083	**1980-1994**
15	0.2813	0.2612	0.000777	1978-1993
total period	0.2791	0.2893		

enough for a flood frequency analysis. A characteristic time series is defined as a sequence of years that best represent the characteristics of the entire time series. A characteristic sequence of years and their number was determined by analyzing the available series from 1971-2000 with a moving window approach. The sequence of years that best reflect the characteristics of the entire time series was selected based on the best correspondence of the correlation coefficient (Cv) and skewness (Cs) of the shortened to the entire series. The entire time series was thus split in windows of decreasing size that were moved along the series and Cv and Cs values were calculated. The best correspondence was achieved with a time series length of 14 years and the period of 1980-1994 (table 8).

5.4.6 Testing of the delta model with 14-year time series

For the delta model the parameter values for the intensity of flow between reservoir bodies ("friction") were taken from the river model without further calibration (see table 6). It was tested whether the delta model performs as good as the river model given the same calibrated parameters. The objective weights were tested and some of the model control constraints (inflow to the delta lakes and Aral Sea) were adjusted. The model performance constraints were also recalibrated for the delta model. This mainly concerns the upper limit on the inflow to the delta lakes. In order to keep most water in the main river, they were reduced from 500 million m^3 per month to 250 million m^3, which is still a realistic upper limit (see table 5).The three equations for modeling water exchange between the four reservoir bodies were also tested with the delta model. The limit to fluctuations of the reservoir volumes between two successive years occurred to be more important for the delta model than for the river model, possibly because of the longer time period modeled. The different equations to model flow between the reservoir bodies of Tyuyamuyun reservoir were also tested on the delta model, since differences were less apparent in the one-year modeling of the whole river.

The results of the long-term simulation is depicted in figure 7 showing a comparison of modeled and observed data for the outflow from the main reservoir and the discharge at the gaging station Samanbay. The outflow from TMGU is modeled well compared to the measured outflow that occurred in the modeled time period. At Samanbay further North in the delta region the model overestimates runoff in a low water year as has been observed in the one year scenarios.

Testing of the delta model revealed that its behavior is similar to the river model and it can thus be substituted for the whole river model, which considerable speeds up the solving process.

5.5 Discussion of Amudarya Water Management Model

Model testing has shown that the river model manages to allocate 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 gaging stations and the outflow of the reservoirs is 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 through setting the priorities of the objective weights, it should always be checked whether the model correctly fulfilled the desired task. It is advisable to additionally reflect policy decisions in changes of the requirements of the users, the lower limits of canal discharges and changes in the network structure.

Testing results confirmed the fact that it is difficult to model today's water allocation in the Northern delta region because of a lack of knowledge on local water allocation practices and small scale distribution patterns, as well as the network of actors and influences deciding on water distribution. This is especially significant in a low water year, where modeling revealed that water is not managed according to the given schemes but rather gets diverted along different paths. The accuracy and quality of the given 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 on this allocation system, which will always underlie strong fluctuations, will ever by known. The water allocation modeled in the Northern delta is rather a means to propose allocation alternatives and test their effect on the ecology of

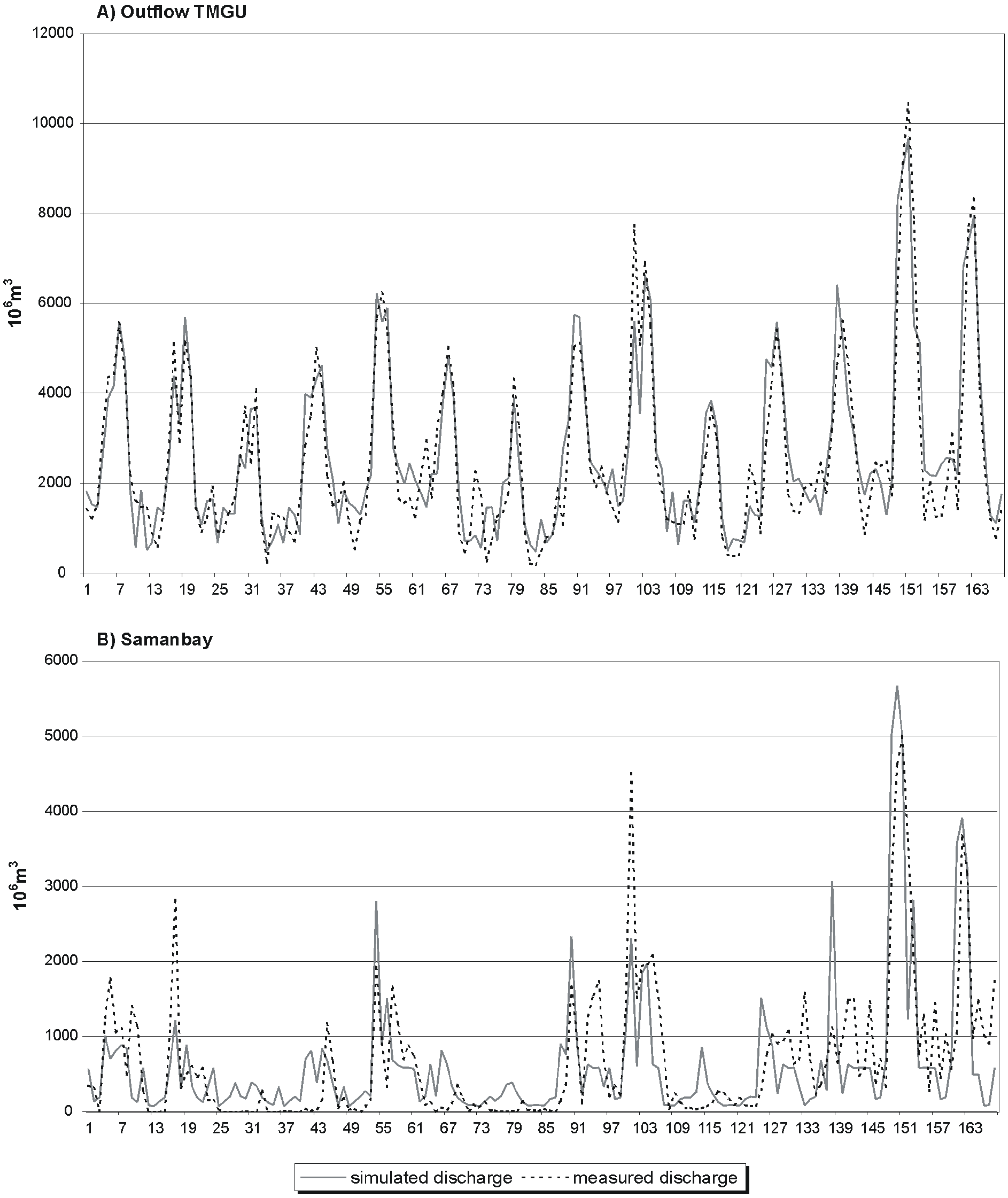


Figure 21: Modeled and observed discharge of the 14-year scenario from a) the TMGU reservoir and b) at the gaging station Samanbay. Releases from the reservoir are modeled close to the measured values. At the delta gaging station Samanbay differences are larger, indicating that the model finds other optimal solutions to spatio-temporal water allocation in the delta.

the delta region, than to achieve a detailed representation of current day allocation schemes. The testing of the model has shown that the results are within realistic limits and can be used for further assessment. The results of the 14-year scenario satisfy the need for an accurate representation of potential future tendencies as the basis for the ecological assessment.

Differences in the behavior of the optimization model compared to the 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 2002). Another interesting future development could be to have a weighting vector that can adapt to the given conditions instead of having one vector optimize over the entire time period. 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 geophysical models, the effects of measures in water management can easily be assessed. Water users, be they economic or ecological, can easily be added or removed, constraints added or changed and the objective weights changed without having to alter 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.

Because of technical reasons the optimization has to be performed twice for the first and second 14 years. Both runs start with the same initial conditions for the reservoirs. It is assumed that it is an operational goal to bring the reservoir volumes to this level at the end of the year. If the model did not achieve this at the end of the first year, the second year starts with slightly incorrect initial conditions. This could be changed by using the simulated reservoir volumes at the end of the first simulation period as the beginning values for the second period. Optimization over the two time periods considers water availability in the simulated period separately, thus when optimizing the first 14 years there is no knowledge on water availability in the second 14 years. This is actually closer to reality than the assumption that runoff in the future is known (see above).

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.

5.6 Integration of the water management model with the GIS

A coupling of the AmuEPIC delta model with the AmuGIS was needed for the spatial evaluation of the effect of long term water availability on the ecological situation in the northern delta. The river network of the delta model was georeferenced by manually assigning the arcs of the main river in AmuEPIC. The indexes used for arcs in the delta model network in EPIC were transferred as attributes to the polylines in the GIS river network. This enables direct linking of the modeled runoff values for the main river in the delta model with the GIS. The length of the river stretches in the Northern part of the delta, where the ecological assessment will be performed, is in average about 15 km. Within these 15 kilometers the runoff does not change, since evaporation and transmission losses are not accounted for at every stretch. They are summed and withdrawn at three points in the river network, as explained above (section 5.4.2) . Thus the resulting water distribution in the GIS is only an approximation of the spatially explicit water availability. For the rather coarse ecological evaluation performed with the environmental models this resolution is mostly sufficient (see discussion in 6).

6 Environmental Models and Ecological Assessment

The water management model described in the previous chapter provides the modeled spatio-temporal water distribution in the delta area based on simulated policy choices. The objective of the environmental models is to map the dynamic response of the landscape and provide a qualitative means to evaluate the their effects on ecosystems in the northern delta region. The outcomes of the evaluation procedure should enable a qualitative assessment of potential effects of management measures on the ecological state of the delta system.

6.1 Problem and objectives

The development of the ecological module was based on the following objectives and constraints:

- to facilitate a first quick assessment of potential ecological effects of water management measures
- to provide an evaluation of the general state of the ecosystems under changing environmental conditions (e.g. improvement versus desertification) rather than focusing on the specific response of a species or communities
- to map the spatio-temporal changes in key environmental variables as a function of river flow
- to capture potential long term effects and to be dynamic
- to be constructed with the heterogeneous and limited data/information available, within a limited time frame
- to be transparent and simple to convince policy makers and managers

The primary task was to find a representative ecosystem whose response to changing water distribution could serve as a measure for qualitative changes to the ecological situation in the delta region. Since aquatic and terrestric ecosystems have different demands it was decided to treat them independently. This work describes the terrestrial assessment, while the aquatic should follow later.

To evaluate potential effects of changes in the spatio-temporal water distribution on terrestrial ecosystems the selected indicator species or community should be sensible to critical changes in the hydrological regime. Vegetation is a good indicator of the ecological situation because of the immobility of plants as well as the large knowledge on the habitat requirements of species and communities. Vegetation is also an important structural characteristic for other elements of the fauna. The representative species should be critical and represent pressure at different levels in the ecosystem (Kliskey et al. 1999). Both prerequisites are met by the characteristic riverine Tugai ecosystems. Their development and state is directly dependent on the hydrological regime of the river and they have an ecological, economic and cultural value (see chapter 2.5). They have seriously degraded in the past 40 years and the need for their conservation is widely accepted. Because of their slow development time and high adaptability to short term stresses Tugai ecosystems have thus been selected as an indicator for the ecological state of the northern delta area.

6.2 Modeling Approach

The integrated ecological assessment that this study and tool supports is by itself a rather unstructured problem. Abundant knowledge and data on the ecosystems in the delta are available but very scattered in different disciplines, difficult to obtain and very heterogeneous in type and quality. The ecological knowledge is often based on empirical experience and understanding obtained in many years of field work in the different ecosystems of the delta. It is characterized by subjectivity, contradictions and is based on intuitions, perceptions and the standpoints of the experts (Bojorquez-Tapia 2002). Field data are limited and often lack either spatial context or, in case of biological variables, reference to the abiotic settings.

Short overview of modeling approaches Selection of the model approach was guided by the goal to make best possible use of all of the available information to reach the given objectives. There are a multitude of single and multi species models that predict the abundance, biomass or population dynamics of one or several species based on selected environmental driving factors. Single species models are often very detailed and do not link the knowledge of different disciplines. The character of biotic components in a landscape as a part of the ecological system is often not accounted for (Schultz & Wieland 1995). Since the realism of the model outcomes was considered more important for decision support than the understanding of basic underlying causal relationships, and due to the paucity of data, population or foodweb models were considered not suitable.

General ecosystem models, modeling energy, mass or information flow through an ecosystem, are far too complex, data and time demanding and long to develop for the aim of a first general assessment. Habitat or species distribution models as they are used e.g. in global change impact studies are more appropriate. They predict the presence of a species based on the given environmental conditions and knowledge of species requirements (Lischke 1998, Guisan & Zimmerman 2000). They do not assess the state of the given habitat and thus do not provide a direct means to measure the effect of measures. Habitat distribution models are mainly static statistical models based on the relationship between biota and its environment. Dynamic, more mechanistic models of ecosystem processes are much rarer, because of a lack of causal understanding and data for a large portion of vegetation (Guisan & Zimmerman 2000).

It is doubtful whether the prediction of species distribution in the given highly anthropologically formed environment is feasible and reasonable. The occurrence of a species in the delta area is to a large extent determined by land and water management actions. It was decided not to incorporate human influences in structuring the delta landscape into the model itself but to include it indirectly into scenario development and analysis. In an interactive setting stakeholders can introduce their views on human interaction with the environment into different scenarios or interpretation of results. The model has to provide a means to compare effects of selected water management alternatives on the species/communities potential to settle or persist. The results should provide a measure for ecological changes.

Habitat Suitability Index Models One possible measure in this sense is habitat suitability, determined spatially explicit for the selected representative species under given or simulated environmental conditions. Changes in habitat quality provide a direct, measurable and presentable qualitative means to compare different ecological settings. Habitat suitability models are often used to predict the effect of management activities on multiple species (Schultz & Wieland 1995, Curnutt et al. 2000). In combination with Geographic Information Systems (GIS) they are widely used for resources management and wildlife conservation or ecosystem rehabilitation issues (e.g. Dettmers & Bart 1999, Kobler & Adamic 2000, Store & Kangas 2001, etc.). A habitat suitability index (HSI) is a measure for the suitability of a site under the given environmental conditions as habitat for a species or species community.

Habitat suitability index models do not predict the actual or potential distribution of the species. They classify a site with respect to its suitability as a potential habitat of the species under the given conditions. The index reflects the species-habitat relationship that has been previously determined by statistical analysis or expert knowledge. Approaches differ mainly by the method utilized to map species-habitat relationships. They vary from approaches based on expert knowledge (Lauver et al. 2002) and environmental envelope techniques, to statistical ones using e.g. logistic regression (Glenz et al. 2001), canonical correspondence analysis (CCA), principal component analysis (PCA), General Linear Models (GLM), and machine learning approaches such as neural networks (Schultz & Wieland 1995) or classification trees (Kobler & Adamic 2000, Debeljak et al 2001). For habitat evaluation, methods from decision analysis such as decision trees (Kobler & Adamic 2000), multi-criteria evaluation (Store & Kangas 2001), etc. are often applied.

Most habitat suitability modeling approaches use a geographic information system as storage for the spatial information on relevant habitat variables, for data preprocessing by spatial data analysis (e.g. overlay analysis (Kliskey et al. 1999)) and visualization of the results. The spatial information is treated as static, mostly raster based and the habitat suitability is assessed for every pixel of the area of interest based on the previously determined classification rules (Eberhardt et al. 1997). The procedure of developing a Habitat Suitability Index Model normally encompasses the following steps:

1. study of the species aut- and synecological characteristics, that is its environmental requirements and its relationships to other species, determination of the key habitat variables
2. formalization of the species - habitat relationships in rules, equations, matrices or computer algorithms
3. mapping of the key environmental variables in the GIS, retrieved from satellite images, photographs, maps, measurement data and via spatial interpolations
4. application of the classification algorithm to every pixel in the area of interest
5. visualization of the result in form of color coded maps, tables etc.

When using habitat suitability models in scenario analysis for the evaluation of effects of different resource management strategies, the landscape has to be regarded as dynamic (Kliskey et al. 1999, Schultz & Wieland 1995). Most current habitat suitability index models are static and based on equilibrium assumptions. They do not allow for an assessment of changing environmental conditions in a dynamic way.

It has been attempted to capture dynamic aspects of the landscape and simultaneously use the advantages of habitat suitability index models by developing a hybrid approach. Changes in habitat factors are modeled dynamic wherever possible and necessary and then assessed by a habitat suitability index which incorporates dynamic aspects such as past conditions of the site. The choice of an approach using a habitat suitability index was a compromise between data availability, time constraints, the aim to include expert knowledge and necessity to represent and evaluate the effects of changes in the hydrological regime as accurately as possible. By coupling the water management model loosely to the GIS and using the modeled results of the spatio-temporal water distribution in the delta area as the input for simple environmental models in the GIS a dynamic landscape is provided that reflects the simulated changes in water allocation.

6.3 Ecology of Tugai ecosystems in the Amudarya delta

The definition of habitat requirements of Tugai ecosystems and selection of relevant environmental factors that affect Tugai habitat quality has been based on a thorough study of their ecology using literature, field data and exchange with experts. The selected key habitat variables and species requirements where then formalized and combined to a habitat suitability index by Rüger (2002).

6.3.1 Review of literature and expert knowledge

Many investigators define Tugai according to the local understanding of the word as “woody or woody-bush vegetation of the floodlands in desert regions” (Bakhiev et al. 1994). The largest area in Central Asia with woody-bush tugai still existing today is located in the lower reaches of the Amudarya river (fig 22) (Treshkin 1998). Tugai formations are mainly distributed on the river bars and their slopes and along major canals (fig 23) (Novikova 2001). Sometimes single communities also occur lake shores. In recent times they have also been found in dry river beds and on natural levees (Treshkin 2001).

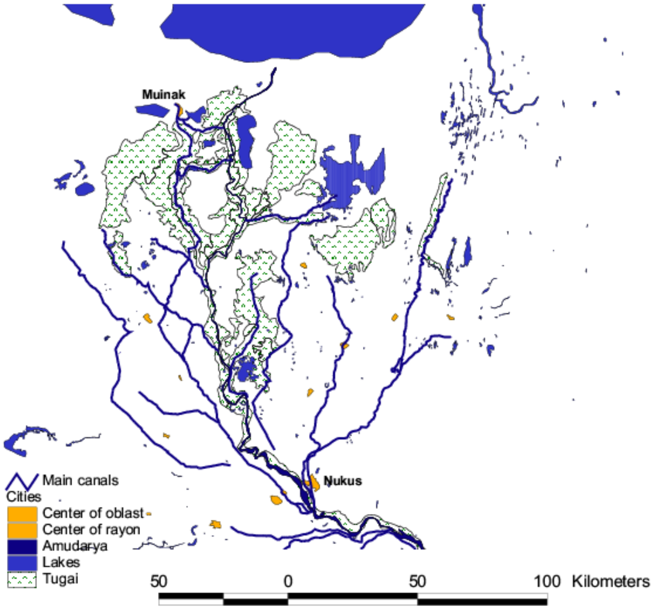


Figure 22: Distribution of woody bush Tugai in the northern Amudarya delta (data source: Aral Sea GIS, Micklin 1998 and N. Novikova)

Of the 285 plant species described for Uzbekistan about 190 belong to Tugai species (Bakhiev et al. 1994). About 40% of the species found in periodically flooded or low salinized habitats belong to the dominant groups poplar (*Populus spp.*), willow (*Salix spp.*), oleaster *(Eleagnus spp.),* tamarisk *(Tamarix spp.*), *Halimodendron sp.*, *Glycyrrhiza sp.*. At locations with permanent soil moisture with ongoing salinization processes (up to 25% salt) species such as *Tamarix spp.*, *Lycium sp.*, *Salsola sp.*, *Capparis sp.*, *Senecio sp.* prevail (Kouzmina & Treshkin 1997).

Local experts determine three different Tugai communities: woody-bush Tugai mainly dominated by *Populus euphratica*, bush Tugai with mainly *Tamarix spp.* and grass Tugai dominated by *Halostachys caspica*. Under natural conditions the three categories represent three successional stages of Tugai forests beginning with the woody-bush Tugai on fresh river alluvium. The activity of the plants lowers the groundwater table and in combination with increasing soil salinity the communities transform into bush tugai and then grass tugai (fig 24). Thus during the formation and development of Tugai communities habitat conditions are constantly changed by the communities, who in turn are affected by the changes themselves

(a) tugai along a branch of the Amudarya river in the Baday tugai natural reserve in the southern Amudarya delta

(b) Degraded tugai in the northern delta area

Figure 23: Healthy (left) and degraded (right) Tugai forests in the Amudarya delta, September 2000. The left picture is from the Tugai reserve Baday Tugai in the southern delta, the right picture from a Tugai in the northern delta.

(Bakhiev & Treshkin 1991). Community composition and structure is also influenced by competition between species (Kouzmina & Treshkin 1997). This work focuses on woody Tugai which are indicators for low salinized habitats.

Of the different plant formations that occur in Tugai forests in the deltaic floodplains of the Amudarya river, communities dominated by the poplar species *P. euphratica* are most frequent. They are followed by *Halostachys caspica* and *Tamarix ramosissima* formations.

Characteristics All major Tugai species have well developed mechanisms to adapt to the specific hydrological conditions in their arid environment, such as a very variable root system with the ability to grow side roots, a multi layered cover, etc.. As a reaction to flooding or

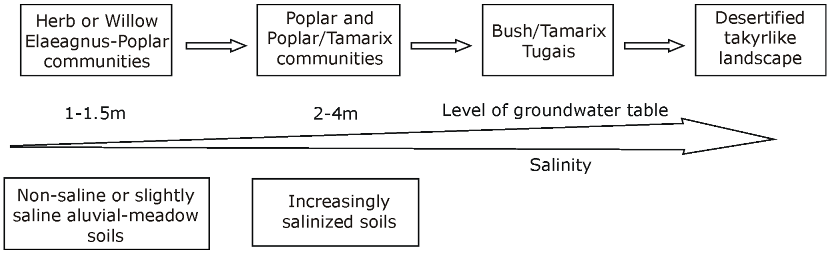


Figure 24: Development of woody-bush tugai after establishment on unformed soil (fresh river alluvium), changes in groundwater level and soils with community succession under natural conditions (after Bakhiev & Treshkin 1991)

sedimentation processes plants can develop side roots on the stems and branches (Bakhiev et al. 1994). This gives them the possibility to react flexible to changing groundwater levels and longer periods of flooding. As the water supply decreases and soil salinity increases the percentage of root biomass of bush and halophyte-bush tugai increases to ca. 65 % (Bakhiev & Treshkin 1991). With sufficient soil moisture on the contrary the above ground biomass of woody and bush tugai contributes the larger share to the total biomass (Bakhiev & Treshkin 1991).

Older Tugai trees with their long roots were better able to resist the lowering of the groundwater table and cessation of floodings. They can also bear a groundwater salinity from up to 16%. Young Tugai on the other hand have continuously disappeared (Letolle & Mainguet 1996).

Formation The genesis and development of Tugai forests is tightly connected to the hydrological regime of the Amudarya river. Tugai formations mainly establish on fresh river alluvium when natural (or anthropogenic) floods coincide with the fruit-bearing period of the main plant species in the tugais (Kouzmina & Treshkin 1997, Treshkin 2001). Under natural flow conditions the Amudarya has frequently changed its river bed, washing away river banks and creating new islands and deposits. On the newly deposited alluvium trees started to grow from seeds that were brought by wind or water. The seeds of most Tugai species can only seed on an open moist surface and under dry conditions very soon loose their ability to germ (Bakhiev et al. 1994).

After their establishment the survival of the young plants depends on subsequent flooding events that facilitate the formation of layered deposits and enable repeated seeding. Within four years the new woody-bush vegetation reaches a height of up to 3m, often in form of thick overgrowth. After about 20 years typical tree Tugais with an only weakly developed herb cover have established. Then at the age of approximately 25 to 30 years they start to die (Bakhiev et al 1994). The disappearance of the trees in most cases is not followed by new growth and the community ceases to exist. Under natural conditions, as they existed in the delta area 60-100 years ago, Tugai died at one location while new communities were formed on new alluvial deposits at others (Kouzmina & Treshkin 1997). The early death of the trees at an age of about 30 years might not be characteristic for the species but rather be a result of unsuitable environmental conditions. Trees living under better conditions can reach ages of 100 years and more *(*Treshkin 2001).

If seeded trees die or the environmental conditions are not favorable for germination of seeds vegetative reproduction through root sprouting takes place. In the past decades communities formed through vegetative reproduction are frequently found in the delta area.

Soils Tugai soils are similar to meadow soils. Through the accumulation of organic materials from the trees the reserve of nutrients in such soils is high and they are very fruitful. Tugai soils can mainly be found on the river bars with light mechanical composition, where the mineral elements can be carried away very easily (e.g. when trees are cut). (Bakhiev et al. 1994).

Soil salinization is a major problem in the delta area. Meadow solonchaks with a high degree of salinization are formed as a result of artificial watering of tugai forests located close to irrigated fields with highly mineralized drainage waters. The lack of regular washing of soils with low salinized river water during spring floods further accelerates salinization. Maximum salinization occurs in in the surface layer (10-30cm). The salinization of alluvial-meadow-tugai soils disturbs the natural development of tugai communities by halophytization (invasion of more salt tolerant species) of the tugai, the disappearance of typical woody-bush vegetation, occurrence of different tugai herb forms, that were not widely distributed in former times, acceleration of the irreversible transformation of tugai to solonchak (salt pans) vegetation and loss of species diversity (Novikova 1998).

Most tugai communities are soil-tolerant, their distribution is rather determined by soil salinity and depth of groundwater table. If high salinity persists only in the surface layer of the soil, they are still suitable for trees and bushes with deep root systems but unsuitable for perennial herbs (Novikova 2001).

Due to the fact that most woody tugai communities found in the delta today are dominated by the poplar species *Populus euphratica* and after consultation with the experts, it was decided to select *P. euphratica* and its habitat requirements as representative for Tugai communities in the delta region. It is assumed that a site with good conditions for *P. euphratica* will also be suitable for other species that generally are found in this community.

6.3.2 Ecology of *Populus euphratica* formations - Results of database analysis

The information stored in the vegetation database of Novikova et al. was analyzed to complement the information given by the experts and literature (see above) and to improve the knowledge base on Tugai vegetation in the delta area used for model construction. This was also seen as a preparation for interviewing and determination of key habitat factors. In the total number of records of 258 *Populus euphratica* formations occurred in over 90 records, followed by the formation dominated by the second poplar species *Populus pruinosa* with 34 counts. The number of occurrences of the other formations is significantly lower (fig. 25)

It was assumed that with the onset of degradation in the 1960's species number in the formations would decline. This could not be confirmed by the data. The number of species found in *P. euphratica* formations in each sampled year from 1947 to 2000 does not reveal a trend of declining species richness. The average number of plant species in the formation varies within a range of 3-18 (in 1985) with an average of 10 species (fig. 26). The low species number in year 1986 and the high in 1994 is due to the fact that only one site was sampled.

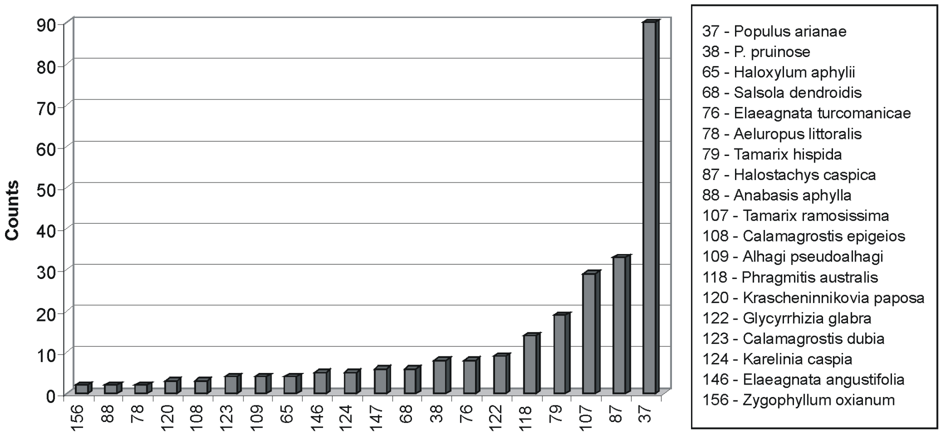


Figure 25: Number of occurrences of different Tugai formations in the database of Novikova et al.

Although, a decline of species diversity might not be detected because dominance changes with degradation and the stressed community might be classified differently.

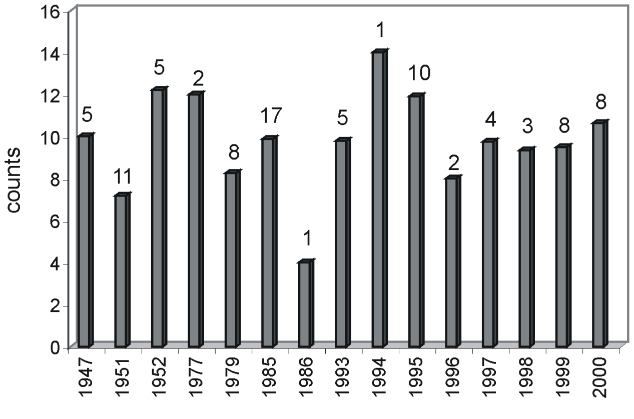


Figure 26: Average number of plant species in *P. euphratica* formations from 1947 - 2000. Numbers indicate the number of samples. (Data source: Novikova et al.)

Most occurrences of *P. euphratica* formations were found on sites where groundwater level was between 3-5m deep, followed by those sites with a level of 1-3m (fig 27). *Elaeagnata turcomanica* formations, which are also often found in Tugai habitats, were only observed on sites where groundwater was at 1-3 m below ground. Bush formations on the other hand are mostly found on sites where groundwater level is 0.5-1.5m and 5-15m for *Tamarix hispida* formations or without any clear preference for *Tamarix ramosissima*. *T. hispida* is a competitor for *P. euphratica* which is inferior to *P. euphratica* on sites that are well suitable for poplar but outcompetes them where the conditions are less good. *Halostachys turcomenica* is a grass, which does not seem to be in direct competition with *P. euphratica* and is found mostly on sites with the same composition. It has to be mentioned that from all samples the groundwater level of 1.5-3.0m was found in more than 40% of the cases and class 2 (0.5-1.5m) and 4 (3-5m) both in 20-% of the cases. The deepest groundwater level observed under *P. euphratica* formations was at 9m but they can tolerate more. The highest water table found was at less than 1m. The range of groundwater values found at sites of *P. euphratica* formations is approximately the same in the years before 1960, in the 70s and 80s and in the 1990s. No trend can be seen as with the species numbers, possibly because of the same reason. Formations will only be found in their more or less optimal habitat.

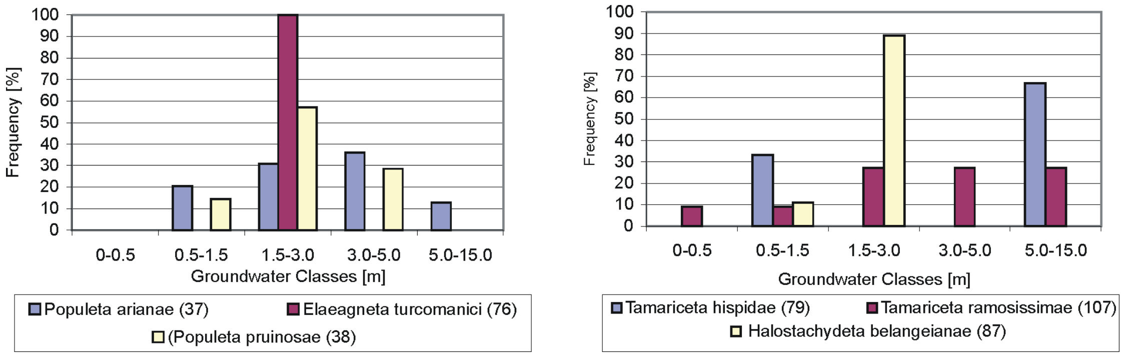


Figure 27: Counts of formation occurrences in different groundwater classes. Classification from Novikova (2000). (Data source: Novikova et al.)

It has to be pointed out that groundwater measurements were not carried out at every sampling site and that it is likely that groundwater measurements at sites where the level is very low were not performed because of technical difficulties. Assessment of the groundwater situation at *P. euphratica* sites is thus biased and can only be seen in connection with literature and other field examinations. Data analysis has to be critically viewed since some data might represent the same sites visited several times in different years. Sampling locations are not random and data thus opportunistic. Results of these analyses are very uncertain due to the little number of samples, no replica and inconsistent data collection. They are thus not suitable for statistical analysis of the species-habitat relationships. The database proved to be too incomplete, descriptive and opportunistic to be valid for sound statistical analysis. Only 37 of all sites described refer to woody-tugai vegetation and only 9 of them include complete information on abiotic environmental conditions. The few data available on abiotic factors were sometimes given in discrete values, sometimes in ranges. Sampling was not random or according to a selected sampling theme but rather reflects the always actual needs of given projects. Although the entire delta region is covered some sites have been visited regularly, some only once. The database was thus only used to obtain a general acquaintance with the vegetation and an overview of the actual range of environmental variables in the region.The information gained from database analysis was used to design a questionnaire for quantification of habitat variable values into suitability classes by Moscow and Nukus experts. The results of the interviewing are described in Rüger (2002).

Based on the database analysis the following conclusions on habitat requirements for *P. euphratica* were drawn: Groundwater levels at locations suitable for adult formations should not exceed 5m and should not rise above 1.5m. As to soil salinity young poplar communities can tolerate an average of up to 1.0 g/100g soil in 1.5m depth while adult individuals might tolerate up to 5.0 g/100g. A literature review of habitat factors for Tugai formations revealed results that are presented in table 9.

The selected variable ranges and classification of variable values into the classes highly suitable, medium suitable, low suitable and not suitable are further explained in Rüger (2002).

6.4 Expert assessment of key habitat factors for woody Tugai

The following influence diagram depicts factors influencing establishment and growth of *P. euphratica*. By determining major habitat factors for woody Tugai it was aimed to select direct predictors, e.g. resource gradients, that have a biophysical meaning in order to incorporate dynamic aspects of effect of site condition changes into the spatially explicit model (Guisan & Zimmermann 2000). The most significant effect of the severe changes in the hydrological regime in the delta area occurred on groundwater level, which in some parts of the northern delta lowered by 2-4m and more; in some places to a level of 8-10m. Naturally this is seen as the main cause for degradation of the ecosystems. The lack of regular flooding which was typical for the delta region before the 1960s, caused an increase in soil salinity because soils are not leached any longer.This is seen as another major factor contributing to desertification and degradation of the vegetation cover.

Groundwater level and **soil salinity** were chosen as two major state variables. Both are driven by the hydrological regime and the frequency, timing and duration of **flooding**. Flooding events play a major role for establishment of new woody bush tugais. The effect of floodings on adult forests is less well known. It is assumed that the contribution of moisture to the soil is rather low (Thomas et al. 2000) but that the floods leach the soils and decrease soil salinity. This will effect the surface layers of the soil. Since adult trees root deeper a positive effect increasing habitat suitability can be questioned. Nevertheless it will also affect root sprouting. Because of these reasons it was decided to take floods into account for both adult and establishing formations but with varying importance. Before the 1960s Tugai were flooded regularly every year or once every 3-5 years depending on the local relief. Novikova (2001) determined an optimal regime of watering of mature Tugai consisting of a period of up to 20 days flooding in spring and late in summer (July-August) with a water depth on the ground of 50-100 cm. The groundwater should rise to 1.5-3 m. A flood duration of several months with water standing above ground is assessed as a negative impact. The roots

Table 9: Literature review of habitat factors for woody Tugai formations and their ranges.

	Min	**Max**	**Optimum**	**Data Source**
ABIOTIC				
Groundwater Level	0.5-1.5	5.0-15	3.0-5.0	database calculation
		5.0-15	0.5-1.5	Novikova 2001
	0.44	8	3.18 (mean)	Novikova et al. 1998
			2.5-3 (adult)	Bakhiev et al. 1994
			1.5-2 (forming)	Bakhiev et al. 1994
			1.5-2.5 (general)	Kuzmina, Novikova 1996
			1-1.5 (young)	Kuzmina, Novikova 1996
			3.3.5 (desertified)	Kuzmina, Novikova 1996
			1-2.5 m	Bakhiev & Treshkin 1991
	1-1.5m	5-6m		Bakhiev et al. 1994
Soil Salinity		<16% (young)		Bakhiev 1979
	0.2%(50cm,young)	6.6% (50cm)	1.1/0.7 (mean,median)	Database
	0.1%(100cm,adult)	4.2 % (100cm)	1.3/0.7(mean, median)	Database
		<0.25g/l (young)		Kuzmina&Treshkin 1997
		<3.4% (adult)		Kuzmina&Treshkin 1997
Salinity of Groundwater	10-16g/l			Bakhiev 1979
Flooding Frequency	At least three years in a row for new formations			Novikova (pers. comm.)
Timing of Flooding	Optimum for mature Tugai: up to 20 days in spring and late summer (July-August)			Novikova 2001
Flooding characteristics	Depth of flooding >10 <100cm, optimum 50-100cm			Novikova 2001
Geomorphology	River bars, lower terraces that are sometimes flooded,			Bakhiev et al. 1994
	Drying river alluvial, River bars			Bakhiev & Treshkin 1991
Soil Type	Alluvial-tugai, slightly salinized, little clay (adult)			Bakhiev et al. 1994
	Unformed, sandy or little clay			
	Weakly and non-salinized alluvial tugai,			Bakhiev et al. 1994
	average loamy soils (adult), poorly formed soils on stream			Kuzmina, Novikova 1996
	alluvial-meadow –tugai			Bakhiev & Treshkin 1991
BIOTIC				
Species Number	3	115		Database
			44	Kuzmina, Novikova 1996
			ca. 40	Bakhiev et al 1994
Abundance of Populus ariana	4-7 plants	41-60 plants	14-20 plants	Database
	0.1-0.2 %	>6%	0.3-0.4%	Database

of plants cannot receive enough oxygen, especially if the flood event takes place during the vegetation period, when the plant is active and needs much oxygen. A long flood during this period leads to damage of the trees.

Groundwater level, timing, duration and frequency of flooding events were selected as dynamic habitat variables that enter the overall habitat suitability index calculation. Since no reliable data on soil salinity and soil salinity changes are available, soil salinity was not explicitly included in the index. Its suitability was indirectly included with the assessment of flooding events assuming that each flood leaches the soil and lowers soil salinity to an acceptable level. This is considered a reasonable assumption by the experts.

Geomorphology at a specific location is treated as static and evaluated as to its suitability for Tugai only once in the simulation. Given the present man controlled situation in the delta and the time horizon used for simulations this simplification is appropriate. The river bed changed its course significantly before its strong regulation. Nowadays this process is slowed down and thus are changes to geomorphology. Since geomorphology affects several other variables such as flooding duration, soil composition, etc. it is used only as an exclusion variable to avoid double evaluation (see Rüger 2002). All sites that are classified as lake depressions are determined unsuitable for Tugai and excluded from further evaluation. For all other sites the geomorphology is not further considered.

Soil type which is a major variable determining vegetation distribution worldwide was neglected because of several reasons. First the experts judged it as not important for habitat suitability of Tugai. Second soil type is partially integrated in the variable geomorphology. Most sediments found in the floodplains have been brought by the river that deposits heavier material on the river bars and slopes and finer material further away e.g. in lake depressions. Clayey soils as they are common in lake depressions are not suitable for Tugai forests. Since sites classified as lake depressions are determined unsuitable, habitats with clayey soils are also excluded. Third, soil is a problematic variable since it results primarily from geology (and in the case of the Amudarya delta from the hydrological regime) but at the same time is strongly influenced by vegetation as vice versa (Lischke et al. 1998).

The ecological requirements of the Tugai communities as they were determined by the experts are valid for the natural distribution of the forests. With sufficient water for irrigation the poplar trees can also exist on other sites. It is assumed that the requirements reflect the minimum requirements of the species. As for water availability, their needs can be met by groundwater or by artificial watering.

6.5 Simulation of spatio-temporal distribution of key habitat factors in the GIS

The development of models and determination of their spatial and temporal resolution to simulate the distribution of key habitat factors in the GIS was guided by the overall goal to facilitate an ecological assessment over a rather large spatial and temporal scale. The resolution of the dynamic environmental variables should be within a range that influences habitat suitability for the Tugai forests.

The dynamics of the two major habitat variables, groundwater table and flooding regime, are simulated spatially explicit directly in the AmuGIS. The modeling approaches are described below.

6.6 Groundwater

Literature (Krapilskaya 1987, Letolle & Mainguet 1996) and data analysis (see below) and have shown that groundwater recharge in the Amudarya delta is to a large extent dependent on surface runoff. In contrast to rivers in temperate regions, the Amudarya river infiltrates into the groundwater. The aim of model development was to formalize the relationship of surface and subsurface flow to map the response of the groundwater table to changes in the hydrological regime.

A variety of methods and software tools to model groundwater flow and aquifer recharge at different levels of complexity and resolution are available. Some of them are discussed with respect to their applicability for this study at the beginning of this subsection. To understand the dynamics of the groundwater table in the delta region, data from groundwater monitoring wells have been analyzed. Based on this information empirical models have been developed and tested.

6.6.1 Groundwater modeling methods and tools

In general, total aquifer recharge consists of three components: (i) vertical recharge by land surface infiltration, (ii) horizontal recharge and discharge by groundwater inflow, and (iii) vertical recharge by channel infiltration (Ponce et al. 1999). Contribution of land surface infiltration is rather small in non-irrigated parts of the delta, since precipitation is low and there is no application of irrigation water. The quantity of horizontal recharge by groundwater flow, which is directed north -west towards the Aral Sea, is largely unknown. For modeling purposes this component is assumed to be constant. Channel infiltration on the other hand plays a significant role in groundwater recharge, since most channels are not sealed. Transmission losses, that occur until the water reaches the fields, can amount to up to 28% (O'Hara 1997). This last component is crucial for near surface groundwater dynamics that influence the habitat of terrestrial ecosystems in the floodplains. The task of the model is to map the relationship between channel flow and changes in groundwater table head, while transport processes that take place in the unsaturated soil zone can be neglected.

Deterministic approaches A mechanistic approach for determination of groundwater flow and dynamics of the groundwater table as used in modeling packages such as MODFLOW

(Harbaugh et al. 2000), SWAT (Arnold et al. 1998) or SWATRE (Belmans et al. 1993) was outside the scope of this study. Physically based, spatial modeling of groundwater flow is often limited by the high variability in hydrogeological properties that can not be mapped in the necessary detail (Sophocleous et al. 1999). They are often difficult to implement at regional scales (Matson & Fels 2001). They make use of the groundwater flow equation, a second-order partial differential equation incorporating Darcy's law of fluid flow and the equation for conservation of mass for three dimensional flow through porous media. These models are constrained by knowledge of hydrogeologic parameters and adequacy of the simplifying assumptions (Matson & Fels 2001). Most numerical models of groundwater flow and recharge require estimates of the hydraulic conductivity K. Accurate determination of this parameter is difficult since it is highly variable in time and space as a non-linear function of the soil water potential (Healy & Cook 2002). Water flow can be unsteady, especially in zones near the ground surface. Reliable estimates of K were not available for our study area. The same accounts for detailed soil maps, data on geology, aquifers, groundwater flows and groundwater extraction by wells.

Water level methods A simple method frequently used to estimate groundwater recharge is the water-table fluctuation method (Healy & Cook 2002). Recharge is estimated by changes in water table elevation over a selected time period and specific yield of the given sediment. The major premise of the method is that rise in groundwater level in unconfined aquifers is due to recharge water arriving at the water table. The recharge is calculated as (Healy & Cook 2002):

$$R = S_y * \frac{dh}{dt}$$

with

R: recharge

S_y: specific yield

dh/dt : change in water table elevation

The method does not require detailed knowledge of the processes in the unsaturated zone. The disadvantage of the method lies in the difficulties to accurately determine specific yield. It is also uncertain to which extent the inherent assumptions of the method are valid (Healy & Cook 2002). A direct application of the model to the problem of this study was not possible because no information on surface runoff or precipitation is explicitly included in the estimation of recharge and the resolution of the water table elevation data from the monitoring wells in the study area is too low. Nevertheless, the principle assumptions of this and similar methods (Shevenell 1996, Powers & Shevenell 2000) based on water table elevations have helped to select appropriate explanatory variables for the multiple regression approach ultimately used.

Selected approach Based on these considerations and the given constraints a statistical approach was chosen for groundwater table mapping in the TUGAI tool. The selection was also supported by the results of time series analysis of water table elevations in monitoring wells (see below). A multiple regression function has been developed to relate changes in water table elevations in the wells to the surface runoff at the gaging station Kyzyljar. In a first step, available time series of groundwater wells were analyzed for temporal patterns and general characteristics giving useful information for the construction of such an empirical model.

6.6.2 Time series analysis of well data

The depth of the groundwater table in floodplains and deltas of arid regions is characterized by frequent seasonal and annual fluctuations, caused by alternating hydrological cycles of the rivers and seasonality of evapotranspiration, precipitation, and irrigation (Healy & Cook 2002). Time series of monthly measurements at 12 wells from 1990 to 1999 in the northern delta region were analyzed to check for the following characteristics:

- Range of water table depth below ground and their fluctuations
- Periodicity (e.g. seasonal variations of ground water table)
- Temporal autocorrelation
- Relationship between surface runoff in the river and major canals and ground water table elevation
- Time lag of the response of groundwater levels to high runoff events in the river and possible correlation with distance to the river

The characteristics of the hydrographs have been compared to time series of flow measurements of the same period at the gaging station Kyzyljar. Kyzyljar is the last monitoring point in the river for the northern delta region. Location of monitoring wells can be seen on figure 28. At two wells in the north eastern delta area (well No 111, 112 and 103) measurements were made only once a year. They are not included in time series analysis, but are later used in the groundwater model to complement the spatial interpolation.

General statistical characteristics of the monitoring data of the analyzed wells can be seen in table 10. For the time period of 1990-1999 mean ground water table elevation in the observation wells have been registered between 2 m (No 93) and 14.6 m (No 188). As expected, wells located close to the main river or Suenly canal (see figure 28) have higher groundwater tables (62, 113, 223, 93, 209, 115, 94, 95) than those located further away (No 188, 154 & 132 and additional wells 112 (8m), 111 (9m)). The deep groundwater level at

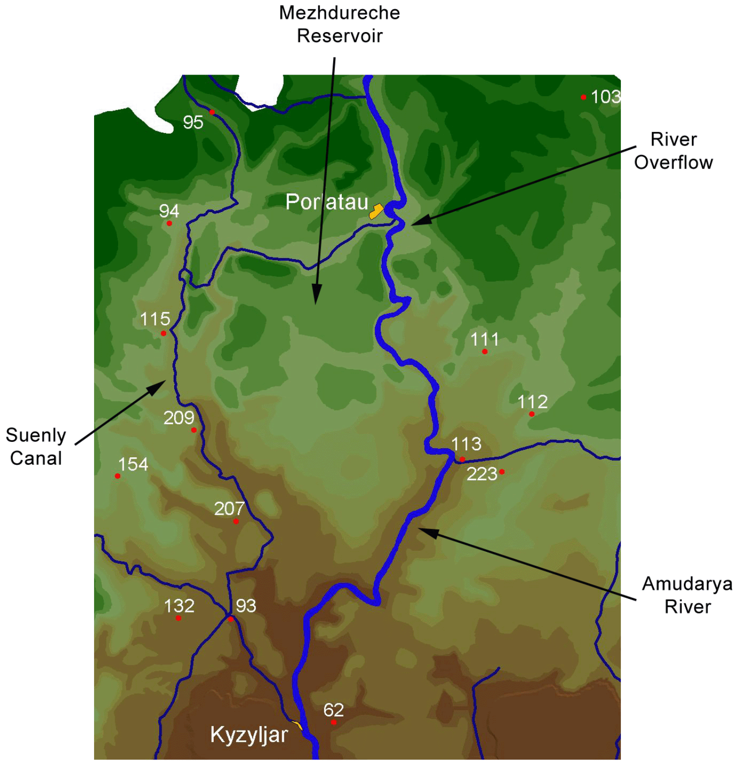


Figure 28: Location of groundwater monitoring wells in the Northern Amudarya delta region. The color coded background maps terrain elevations. Dark brown indicates highest surface terrain elevation, dark green lowest. The dots indicate wells and their IDs.

Table 10: General statistics of water table elevation data in the monitoring wells

Well No	N of cases	Minimum	Maximum	Median	Mean	S.D.	Variance	C.V.
93	100	0.33	3.75	2.06	2.01	0.737	0.543	0.368
207	69	9.58	11.19	10.63	10.54	0.467	0.218	0.044
209	58	1.98	5.26	4.04	3.83	0.992	0.985	0.259
115	95	4.76	6.23	5.67	5.61	0.359	0.129	0.064
94	119	2.25	5.36	4.15	4.13	0.533	0.284	0.129
95	118	2.06	6.17	4.53	4.15	1.061	1.127	0.256
188	120	12.90	15.75	14.71	14.62	0.654	0.428	0.045
62	120	3.00	8.96	4.44	5.07	1.763	3.107	0.348
113	108	3.75	7.58	5.63	5.81	0.928	0.862	0.160
223	120	0.61	6.16	3.61	3.62	1.617	2.615	0.446
132	80	5.20	9.22	7.17	7.14	1.173	1.376	0.164
154	104	7.59	10.96	8.97	9.10	0.910	0.828	0.100

well No 207 and the high groundwater level at the additional well No 103 (4m) cannot be explained. The coefficient of variance is lowest at stations with deepest ground water level (well No 207 and well No 188) indicating a relation between the intensity of the impulse of the surface runoff and the distance to the water table in the river. The maximum range of water table elevations observed at a single well over the monitored time period was 6 m (No 62 and 223). This is a range that can seriously affect terrestrial ecosystems.

Analysis of Seasonality The river flow time series at the gaging station Kyzyljar and the well hydrographs have been analyzed for seasonal patterns. Graphical analyses have not revealed any clear seasonality in the time series of river flow or the well hydrographs (fig 29). In the river flow time series a summer peak can be seen in most years, which is caused by the arrival of glacial and snow melt waters from the mountains arriving at the delta. Some of the well hydrographs have little pronounced seasonal patterns (e.g. No 115 & 93). Frequency and amplitude of those patterns vary in both river and well data time series. The wells shown in figure 29 represent the southern and central parts of the study area. The hydrographs of the other wells are located in the annex.

An autocorrelation analysis was carried out to check whether values at individual wells are temporally autocorrelated and whether seasonal patterns can be detected mathematically. The autocorrelation function is displayed for the river flow and the exemplary wells No 113 and 207 in figure 30 (upper row). It depicts the serial correlation coefficients for consecutive lags in a range of lags from 1 to 12. Both river runoff and well water table elevations show strong correlation with a lag of one, thus measurements that directly succeed each other are correlated. The well water table series also show correlation with a lag of two, three and sometimes even four. To test whether those correlations are significant or a result of correlation with the preceding value, a partial autocorrelation function (PACF) was calculated. PACF is an extension of the autocorrelation, where the dependence on the intermediate elements is removed (Hartung 1999). The results of the PACF can be seen in the lower row of figure 30. The plots reveal that only autocorrelation with lag 1 is significant, as can be seen with the bars that are all below the confidence intervals (red line) except for lag 1 and 2. The negative correlation with lag 2 cannot be explained. The lack of other correlations with e.g. lag 12 is another evidence for the absence of clear seasonal patterns.

Trend analysis To identify trend components and even out small scale variances the runoff and well hydrograph series were smoothed by using a moving average of means with a window size of 12 months (Hartung 1999). The results of this analysis for river flow at Kyzyljar can be seen in figure 31 and for the wells No 223, 132, 188, 062, 115 and 94 in figure 32. The results of all other wells can be found in the annex. The graphs show the original and smoothed curves. In river runoff a high water period lasting from the beginning of 1992 until the end of 1994 and a second one in 1998 as well as a low water period from the beginning of 1995 until

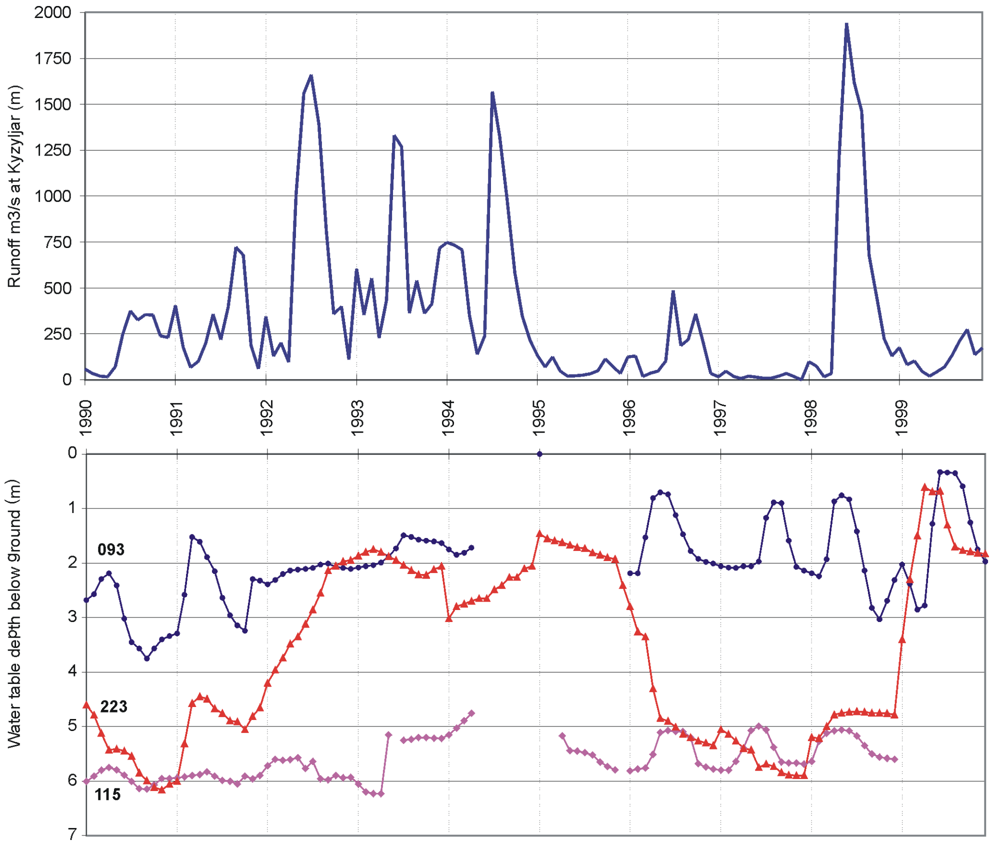


Figure 29: Mean monthly river flow at Kyzyljar (above) and mean monthly water level below ground in the monitoring wells No 115, 223 and 093 (below). (Data from Uzbek Main Hydrometereological Service and SANIIRI)

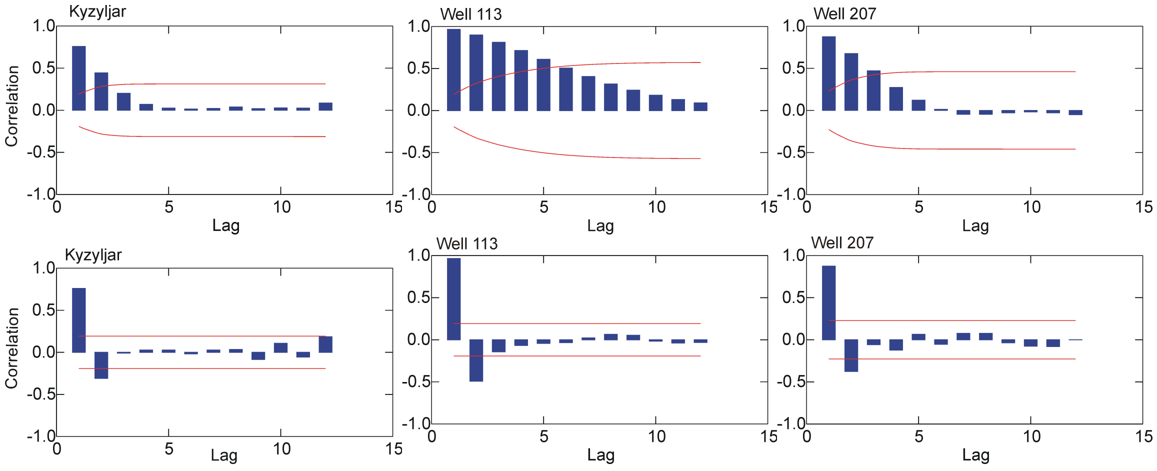


Figure 30: Plots of temporal autocorrelation (upper row) and the partial autocorrelation function (PACF) (lower row) of the river flow at Kyzyljar and time series of water table elevations in the monitoring wells No 113 & 207 for the years 1990-1999.

the end of 1997 are clearly visible. The low water period is interrupted by a medium water year in 1996.

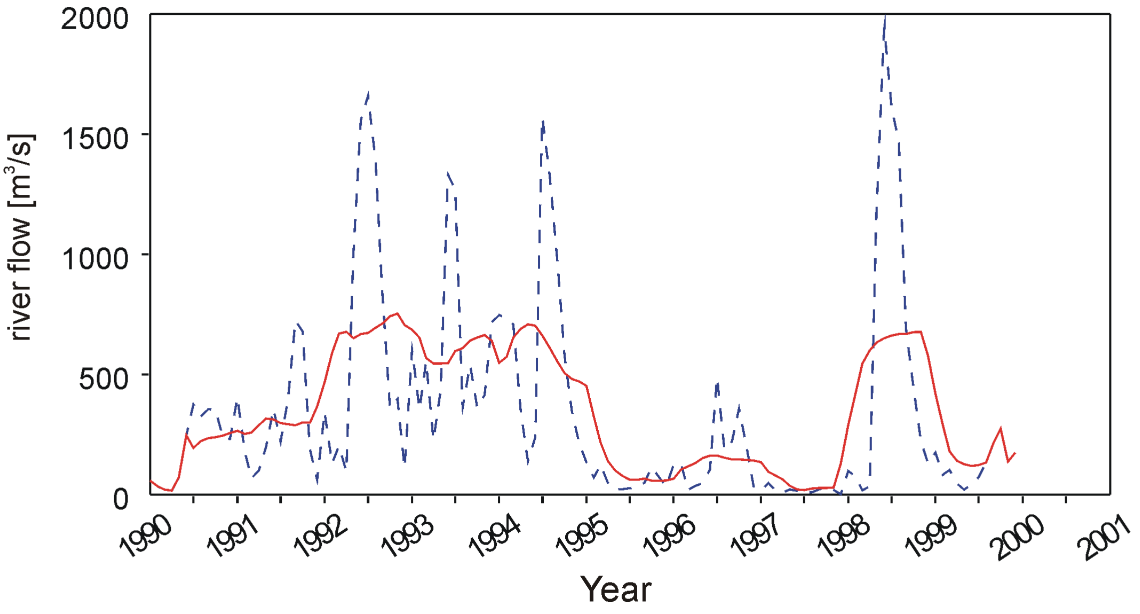


Figure 31: Original and smoothed time series of mean monthly river runoff (m3/s) of the years 1990-1999 at Kyzyljar gaging station.

Comparison of hydrographs with surface flow The smoothed series of groundwater table elevations show patterns that are similar to the river runoff series to varying degrees, with the exception of wells No 62, 93 and 94. Most series start in 1990 with rather large groundwater table depths. A tendency of increasing groundwater levels during the **high water years** 1992 to 1994 can be depicted in most wells. The echo of river flow in the pattern of the groundwater levels can be seen very well at well No 223. There, groundwater level steadily increases until the beginning of year 1993 from a value of more than 6m below ground in 1990 to a minimum depth of less than two meters in 1993. Even the slight decrease in river flow in the year 1993 is mirrored in a small lowering in between two peaks. Wells No 132, 207, 95 (see annex) have similar patterns but correspondence with river flow is less pronounced. This is mainly attributed to the fact that those wells are located further away from the main river (e.g. well No 132: 13 km , well No 223: 6km). The further away the well from the river the less it is influenced by surface water dynamics and the longer the time lag should be until the surface water impulse reaches the aquifer. Several series reach their highest ground water level in 1994 or 1995 (No 223, 132, 113 (second highest after 1992), 209, 115, 95 and 207).

In most wells the succeeding **low water years** 1995 to 1997 initiate a lowering of the water tables. In some of them decrease takes place rather fast (well No 223, 132, 113, 209

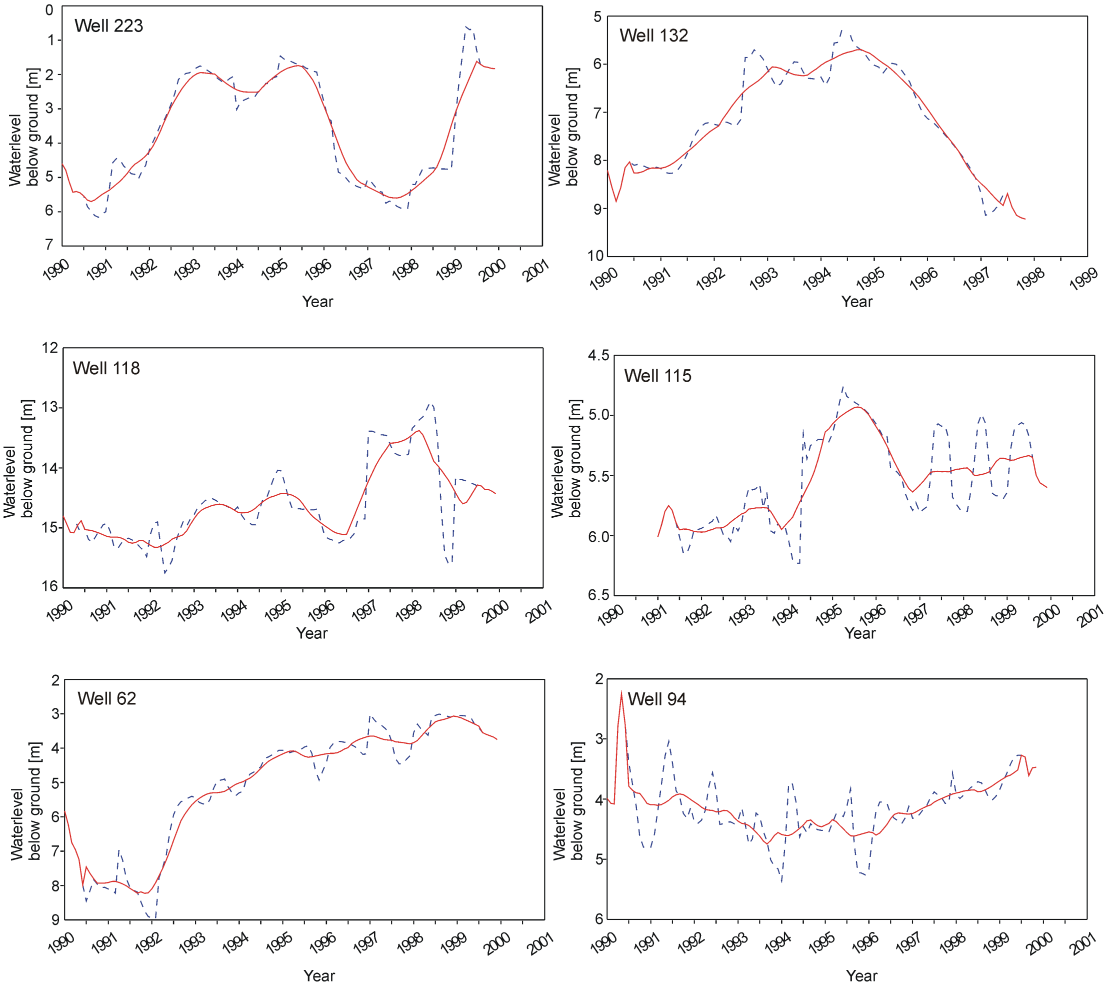


Figure 32: Original and smoothed time series from 1990 to 1999 at selected monitoring wells (window size 12, mean)

and 115).

Time lag The series of groundwater tables have also been analyzed to detect time lags in their response to river runoff. If distinct time lags exist they can be used in a regression model to properly link the response variable to its explanatory runoff. Unfortunately within the individual time series no clear time lag could be found. A decrease or increase is sometimes several months later than in the river (e.g. well No 207), sometimes at the same time (e.g. well No 113) or sometimes even prior (e.g. well 113, 188) to the increase of flow in the river. The latter might also be a long lag of a preceding event. At well No 113, which is located close to the river, the pattern matches, but its timing does not. The well water table oscillates earlier than the surface runoff. With the given data this cannot be explained.

At some wells e.g. No 115 there is evidence that a decrease in river flow affects the groundwater table faster than an increase. This might point to the fact that groundwater pumping is higher in years with low surface water flow, thus accelerating the lowering of the groundwater table.

Nevertheless, a general tendency of greater time lags at wells located further away from the river has been observed. The time lag should be the longer, the further away the well from the main stream, although flow velocities and direction of the subsurface flow also play a significant role. Shallower wells are expected to respond rapidly to increase in river runoff (Shevenell 1996). The alluvial soils of the river bars in the delta have a high hydraulic conductivity (0.55-3.85m/d (official groundwater map of 1997) with 0.8-30 m/d in the sandy, old river branches of the Amudarya river (Krapilskaya 1987)).

Influence of major irrigation channels and irrigated fields Wells No 62, 93 and 94, as well as well No 115 from 1997 onward, do not follow this common pattern. Their dynamics seem to be determined by other influences such as closeby lakes or irrigation canals, irrigated fields, pumping by wells, etc. . Irrigation canals and delta lakes might play an important role in groundwater recharge in the northern delta area. Their influence should be strongest in low water years when no or only little water is allocated to the river north of Nukus. Delta lakes that are fed by river waters are affected by the dynamics of the river, while the irrigation channel Suenly receives always more or less constant amounts. Those are almost 10 times less than in the main river in a high water year, but almost equal in a low water year. The influence of Suenly canal and the delta lakes might explain the strong increase in water table height of well No 95 in 1996, and the dynamics of well No 93. The latter is located very close (50 m) to the canal and has very high groundwater levels, which indicate that water infiltrates into the groundwater from the irrigation channel.

In the case of well No 62, where the groundwater table increases almost continually from 1992 onward, closeby irrigation fields might play a role. The well is located in an area where irrigation is practiced to some extent.

The correlation of river flow with the heads in most wells across the northern delta area confirms the assumption that groundwater flow is strongly coupled to surface flow. This is possible since the river bed is not lined. The coupling is stronger in wells located close to the river than those further away, as was expected. The importance of river runoff for recharge of the near surface ground water has been observed for other rivers, especially in arid and semi-arid regions (Ponce et al. 1999, Sophocleous 1999) but also for the floodplains of e.g. the Elbe river (Holfelder et al. 1997).

The information obtained from this analysis, especially the fact that there is an autocorrelation with lag one, will be used for model construction.

6.6.3 Formulation of groundwater model

The relationship between runoff in the river and water table elevation in the wells was approximated for each well by multiple linear regression. Explanatory variables were chosen based on the characteristics of the time series of well water table elevations and general observations described above.

In the regression function river runoff constitutes one independent variable reflecting the impulse from the surface flow on the groundwater. It was log transformed to even out the influence of very high values and strengthen the lower ones. Through transformation the runoff values become normal distributed.

A second independent variable was needed to introduce into the equation the strong dependency of a value from the value at the previous time step as determined by autocorrelation. Using water table depth at the previous time step as second explanatory variable to represent state history appeared not feasible because the response was in this case solely dominated by this feature. A predictor had to be found that represents the system at the previous state in a less strong manner. In the times series analysis it was observed that groundwater recharge is a function of the depth to the water table. The slope of the gradient between stage in the river and groundwater table determines the direction and intensity of groundwater flow. According to Darcy's law of groundwater flow in the saturated zone volumetric flow in porous media is proportional to the friction slope or hydraulic gradient (Chow et al. 1988). Darcy's law is expressed as

$$Q = -K * \frac{dh}{dl}$$

with

K = hydraulic conductivity

$\frac{dh}{dl}$= hydraulic gradient (h = water table height or hydraulic head, l= distance)

The hydraulic gradient aggregates information on the present state of aquifer recharge as well as distance to the groundwater table. It was thus chosen as second explanatory variable for the regression, in the form of the difference in water table heights between the water table in the closest river reach and the water table in the observation well (fig 34). Distance from the well to the river, as expressed in the gradient, can be neglected since regressions are made separately for every single well. This variable enters the regression with a lag of one time step, thus as the hydraulic gradient at t-1 to incorporate state history. Those two variables, river runoff and difference in water table elevations at the preceding time step, were the minimum amount of explanatory variables that allowed for a satisfactory mapping of river runoff values to the groundwater table height.

Temporal resolution It appeared that the strong monthly variations in surface runoff are not mirrored in the monthly variations of the water table elevations in the wells. Because of the absence of a constant time lag between surface event and groundwater response, which could have been included into the model, it was impossible to map groundwater levels satisfactory at the monthly time step. In several cases the resulting function was based solely on the pattern of water table elevations in the well and runoff events in the river were not reflected. An example of a multiple regression of monthly groundwater table depths at well No 113 can be seen in figure 33. The regression function explains variations of groundwater level only to approximately 40% (R^2=0.396). The dynamics of the variations are not captured well, as can be seen in comparison with the measured values. A similar picture was found with regressions based on smoothed series, with lags of 1-6 and 12 months.

Because no sound relationship at the monthly scale could be detected, it was decided to scale up to the annual scale, using mean annual runoff and water table elevations. The means even out the variable time shifts in the response and make it more likely to assign the right runoff value to the response. For the ecological assessment the annual resolution is appropriate since riverine trees can withstand short term variances but are affected by long term changes (see section 6.3). The trees can cope well with a short term lowering of the water level in a range as it has been observed in the monthly monitoring wells, where the largest difference between two successive months at a single well was

One disadvantage of using only mean annual values is the small number of measurements, which varied between 8 and 9 and the lack of a second data set for validation.

To determine the difference in water table elevations of the river and the wells to be used as the second explanatory variable, river stage had to be estimated.

The regression approach The regression equation, that was developed to simulate groundwater table elevations in the monitoring wells, has the following general form:

$$H_w^{(t+1)} = a * lnQ_n^{(t+1)} + b * (H_n^{(t)} - H_w^{(t)}) + c$$

where

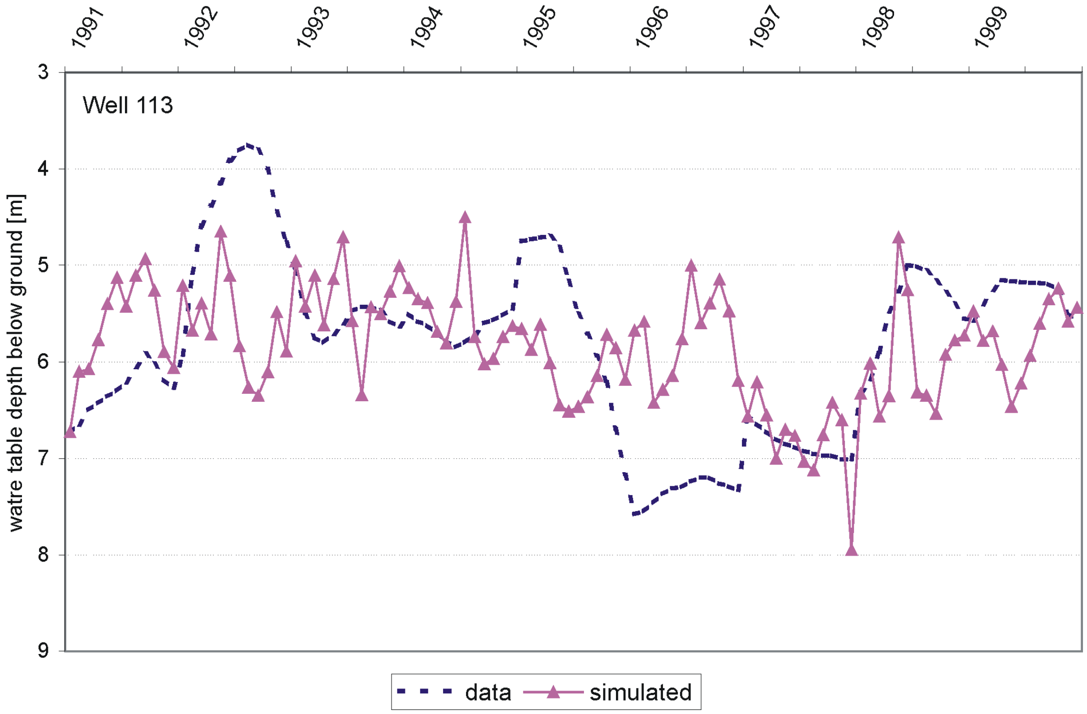


Figure 33: Monthly simulated and measured well water table elevation at well No 113 using a monthly regression function.

H_w: water level above Baltic Sea level in observation well w (m)

Q_n: runoff in closest Amudarya river reach n (m^3/s)

H_n: river stage in reach n (m)

t: time step (year)

n: river reach

w: observation well

a, b, c: regression coefficients

6.6.4 Estimation of river stage in each river reach

Unfortunately it was not possible to obtain the rating curve for Kyzyljar gaging station to calculate gage height from the flow rate. Moreover, due to the lack of data on channel geometry of the Amudarya river, river stage in the river stretches has to be estimated using a simple approximation. In the chosen simplified approach the river bed is considered as rectangular. River stage is estimated from mean annual runoff (m^3/s) in the main river channel using to the following general relationship:

$$H_n^{(t)} = \frac{Q_n^{(t)}}{v_n * w_n} + H_n^{(0)}$$

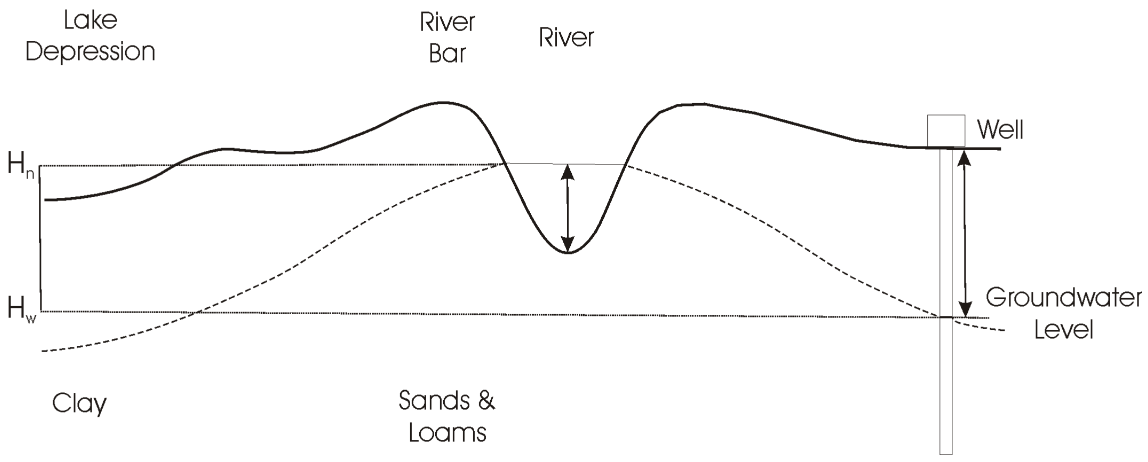


Figure 34: Scheme of the groundwater measurement and the determination of the hydraulic gradient

where

H_n= water table height above Baltic Sea level in Amudarya river reach n

Q_n= runoff in respective reach n

w_n= width of river reach n

v_n= flow velocity at respective river reach (assumed constant at the average value of 1m/s)

$H_n^{(0)}$= height above Baltic Sea level of river bottom at reach n

t= time step (year)

n= river reach

Measurements of river stage, velocity, area and width of several years at the river station Kyzyljar were used to test the validity of the estimation. The measured stage at Kyzyljar generally lies between 1.2 m and 3.6 m, with the exception of the high water year 1998. The calculated estimates, based on the same runoff values, vary between 0.2 and 6.0 m. The method clearly underestimates the stage in low water years by sometimes up to nearly two meters and overestimates in high water years. This error, nevertheless, had only small effects on the ecological evaluation, as will be discussed below.

Estimations of groundwater heads in every well were calculated based on the above described function and results were regionalized. They were compared to the groundwater map developed by Novikova (see data section) by calculating difference grids of simulated and ”expert” maps. Since in the latter the groundwater elevations are given in 5 classes (0-0.5, 0.5-1.5, 1.5-3, 3-5, 5-15) the results of the calculations have been first reclassified into the same classes. The comparison reveals that the simulated results are in many areas close to the expert map. Although, in the Southern and Central part of the delta they are simulated one to two classes too low and in the Northern part too high. In some locations the values at the river bars also deviate, which might be caused by the lower spatial resolution the expert map is based on.

The very low estimation of the river stage in a low water year possibly reflects the real situation more or less realistic. In low water years no water is allocated to the northern river stretches, although there are still official recordings. The error of a higher estimation of river stage in high water years does not significantly influence the groundwater table simulation in the wells since in the multiple regression function the river runoff component dominates the result.

6.6.5 Model formulation for individual wells

Regression models have been developed individually for every well. This was necessary because of heterogeneous soil conditions, impacts of groundwater pumping and other site specific characteristics that are not included in the general regression model but significantly influence groundwater recharge. The regression method is a black box approach, where processes in the unsaturated zone, before the water reaches the aquifer are neglected. These unknown factors are implicitly included in the constants of the specific regression for each well.

Multiple linear regression was performed with the statistical package Systat using the least squares method. Model construction for every well was based on the following assumptions:

- Surface and subsurface flow are coupled.
- A temporal resolution of one year is appropriate for the aim of assessing the response of Tugai habitat to changing environmental conditions.
- The influence of other factors than river flow and hydraulic gradient is small enough to be neglected or is represented by river dynamics.

Regressions have been made for every monitoring well using mean annual river runoff at Kyzyljar and in the succeeding river reaches, estimated river stage and mean water table depth in the well. River flow in the nearest river reach and hydraulic gradient are the explanatory variables as explained above. Quality of model fit was assessed with the coefficient of determination (R^2) and the mean deviance from observed values. The first is the ratio of the variance of the simulated values to the variance of the observed (see below) (Hartung 1999).

$$R = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \overline{y})^2}$$

with

y_i= observed

$\hat{y}_i$= estimated

The impact of the assumptions and model quality on the groundwater table elevations will be discussed in section 7.6.8.

General discussion of model results Regression coefficients, R^2 and mean deviance of all regression models together with some characteristics of the wells are depicted in table 11.

Table 11: Regression results for the monitoring wells in the northern delta area using the delineated regression function $H_w^{(t+1)} = a * lnQ_n^{(t+1)} + b * (H_n^{(t)} - H_w^{(t)}) + c$ (n=7-9). R^2 is the coefficient of determination, mean deviation the mean deviation of estimated from observed values.

Well No	Well NN [m]	Canal bottom NN [m]	Distance to River [km]	a	b	c	R^2	Mean deviation
62	62.4	56.5	2.8	-0.003	0.635	4.418	0.61	0.59
93	60.6	56.5	7.0	0.096	-0.115	1.101	0.51	0.34
94	56.9	51.5	22.4	0.040	0.140	3.970	0.16	0.25
95	56.6	50.0	15.7	-0.131	0.188	4.746	0.13	0.42
103	54.1	50.0	21.1	-0.205	-0.300	4.674	0.10	1.89
111	56.7	53.0	6.0	0.088	-0.018	7.966	0.02	0.57
112	56.5	53.0	9.7	0.122	-0.118	7.893	0.59	0.13
113	59.5	54.0	1.0	-0.570	-0.915	10.345	0.76	0.58
115	57.0	53.0	21.0	0.133	-0.046	4.923	0.39	0.29
132	59.9	56.5	12.5	-0.584	-0.037	10.061	0.61	0.51
154	57.2	54.0	32.0	0.345	0.188	5.810	0.55	0.46
188	62.7	56.5	6.3	0.204	0.131	12.200	0.27	0.43
207	59.7	54.0	17.0	0.085	-0.073	10.405	0.71	0.38
209	57.8	54.0	21.0	-0.349	-0.534	5.656	0.63	0.06
223	57.5	54.0	5.7	-0.258	-0.194	5.110	0.08	1.26

Both coefficients vary strongly, indicating very heterogeneous conditions in the area, bad model determination or insufficient quality of data. The sign of coefficient "a" , which is the proportionality coefficient for the relationship between river runoff and groundwater can be interpreted directly. A negative sign indicates an increase in groundwater level with increasing river flow, because of the positive sign of constant c (water table below ground has been included as positive values) and vice versa. The sign of the coefficient for the gradient on the contrary is dependent on the value of the gradient. If river stage is higher than groundwater table elevation it will be positive and a negative sign of the coefficient will also indicate increase. With a negative gradient and a positive sign it will be opposite, a fact that happens at well No 93 (see below). While river flow determines the basic level of groundwater recharge, its dynamics are mainly determined by the gradient. This was intended by the construction of the model (see above).

The measure R^2 is only taken as an indicator for the general fit of the model and is complemented with the deviance which is much judged important for the use of model results for ecological assessment. According to those two measures the regressions represent the relationship well at wells No 113, 62, 112, 207, 209, 132, 154, and 93. At well No 115 results are reasonably well. Mean deviation at those wells is maximal 0.59 m, with monthly deviations varying within a range of 0.1 (wells No 112, 207, 115) and 1.68 (well No 62). The model does not explain the dynamics of well water table elevations at well No 103 and 223. Here R^2 is very low and mean deviance is very large. Well No 103 is located far north east, in a part of the delta where water is currently only seldom released into the river. It can be assumed that the river north of Porlatau is dry for most of the time. This influences models at well No 103 as already mentioned, but also No 94 and 95. Although, for the latter the picture is slightly different (see below), because they are located close to the irrigation channel Suenly and several lakes that are fed by the Amudarya (See fig 28)

For wells No 188, 111, 94 and 95 the coefficient of determination indicates that models do not explain the variance of the observed values. However, mean deviances are within acceptable ranges (0.25-57m).

Distance to the main river has some influence on the results, with closer wells showing better correlation than those further away. Although, especially for wells close to Suenly canal this tendency cannot be confirmed, possibly because flow in the irrigation canal to some extent mimics flow in the river (see below).

The constructed models are the best that could be developed with the limited data available. Since information on groundwater levels is crucial for ecological assessment, it was decided to use the models for spatial interpolation and habitat suitability determination, keeping their limitations in mind. The generally low mean deviations (with the exception of well No 103 and 223) support this decision. To evaluate the course of the estimated hydrographs in relation to the measured variances in groundwater level and assess the significance of deviances for ecological assessment, simulated and measured value for all well have been plotted in figures 35 to 38.

The results of the models are discussed in view of the location of the well, its distance from the main river, proximity to the irrigation canal Suenly, the size of the deviation and a potential influence of irrigated lands in the vicinity of the well. The influence of model deviations on their application in the tool, especially with regard to Tugai habitat evaluation is discussed at the end of each well paragraph.

The lack of independent monitoring data prohibits true validation of the model. Fictive river runoff values were used to test the validity of the approach for extreme values of river flow that persist over a longer time period. In a “high water” scenario river flow was kept constant at 1.000m^3/s, for a low water scenario constant at 20m^3/s for 28 years. The highest mean annual runoff officially recorded at Kyzyljar in the period from 1980 to 2000 was 672 m^3/s (1992), the lowest 17 m^3/s (1986). Additionally the response of the groundwater elevation to a constant increase in surface runoff (an increase of the mean annual average runoff every year by 100m^3/s) was checked. It was assumed that in the first case groundwater levels should either increase or remain constant with high runoff and decrease or stay constant with low runoff. With annual increase the groundwater levels should also increase. Both assumptions proved true in most cases. The results of the extrapolation for each well are discussed below together with the model results.

Model results for individual wells In figure 35 it can be seen that timing and course of lowering and rising of the groundwater table at well No **113** are modeled well. Well No 113 is located closest of all observation wells to the Amudarya river. Its water table variations are consequently most severely influenced by river runoff, as was already determined in the time series analysis. The strong influence of river flow and gradient at the previous time step is also reflected in the extrapolation in the “high water” and “low water” scenarios Water table differences between the two scenarios amount to almost 3m. In both scenarios water table elevation quickly rises or lowers to a certain level, oscillates for several years and then stabilizes. The scenario of constant increase in surface runoff causes a strong increase in water levels from 6m almost to the surface. Oscillation of the values in all cases indicates that the model is sensitive to small changes in the value of the gradient. Deviances to measured values at this well are less than one meter and should not affect the evaluation of this habitat variable for the calculation of Tugai habitat suitability.

Variations of groundwater levels at well No **223** are not explained by the regression function as already discussed above. Measurement data show variations within a range of more than three meters, while model results vary only within one meter. Model results fall between three to four meters within the middle range of the measurement’s distribution. This deviation can affect Tugai habitat evaluation. Measurements vary within a sensitive range of groundwater levels for the Tugai forests and capture different “qualities” which are not reflected in model results. Especially higher groundwater levels of up to 2m below ground are judged critical for the habitat of Tugai forests because of the effect of secondary salinization. This effect makes the insufficient representation at well no 223 significant for model outputs. In the extrapolations water levels in the well never go below 5.6m as was measured in 1997, but even in the low water scenario stay at 4.2m. The well is located close to well No 113, which is modeled well. With given data and knowledge the large difference between the behavior of the hydrographs of the two wells cannot be explained. For well No 223 and 103 at least one of the governing assumptions of the model is not valid.

As mentioned above well No **93** is located very close to Suenly canal and its groundwater dynamics are probably more severely influenced by runoff dynamics of this canal then by river runoff. The low regression coefficient with river runoff confirms this assumption. It would be more correct to include flow in Suenly canal into models of those wells. This was not possible because no data on discharge in the canal, except for the head of the canal were available. High water and low water have only little effect on water table height in the well. With increasing runoff they increase slightly to about 1m. Since water table depths are generally very little they are less suitable for Tugai and will only be judged highly suitable if they stay at a level below 1.5m.

At wells No **112** and **207** model and observation data agree well. Both wells have very low water table heights that show little variation. Influence of river discharge and hydraulic gradient is low, as can be seen from the low regression coefficients (table 11). When extrapolated for 28 years, groundwater table levels hardly ever change. With increase in discharge groundwater tables increase slightly, but only within a range of approximately 50cm. For the given situation model results thus can be trusted.

At well No **209** which is located slightly northwest of well No 207 has measured water table is much higher and reacts more sensitive to changes in river flow. In the low water year 1995 the model predicts a groundwater elevation which is about one meter higher than observed. All other values and the general pattern vary within an acceptable range. The extrapolation reveals a much stronger reaction to changes in runoff than with the previous wells. Difference in groundwater table elevation at this well between high and low is approximately 2 m. The same accounts for increase in runoff, where water table increases from more than three meters below ground almost to the surface.

For well No **111** model results are less promising. The model does not predict observed variations in groundwater table elevations. Groundwater levels are deep and thus little suitable for Tugai forests. Measured variations are not within a sensitive range of the variable. As long as estimated groundwater depths are within the range of 8-10m below ground as observed the results can be used for habitat evaluation.

Water table elevations at well No **115** are generally predicted higher than the observed elevations. The difference lies within a range (maximal 50 cm) which is not significant for the Tugai habitat. River runoff and hydraulic gradient only play small roles in determining the groundwater hydrograph.

Well No **154** is also one of the deeper wells, although variation is larger here than in the ones previously described. Again regression results are within maximal ca. 60cm off the observed values and thus do not influence Tugai evaluation. Well water table heights are influenced by changes in river runoff with approximately 2m difference between the simulated low and high water scenario. At this well an increase in river flow leads to a decrease of water level in the well, which is contrary to all other wells except well No 62. While at well No 62 this might be caused by surface irrigation the causes for this behavior at well No 154 are not obvious. As those dynamics cannot be completely explained and an artifact or error in

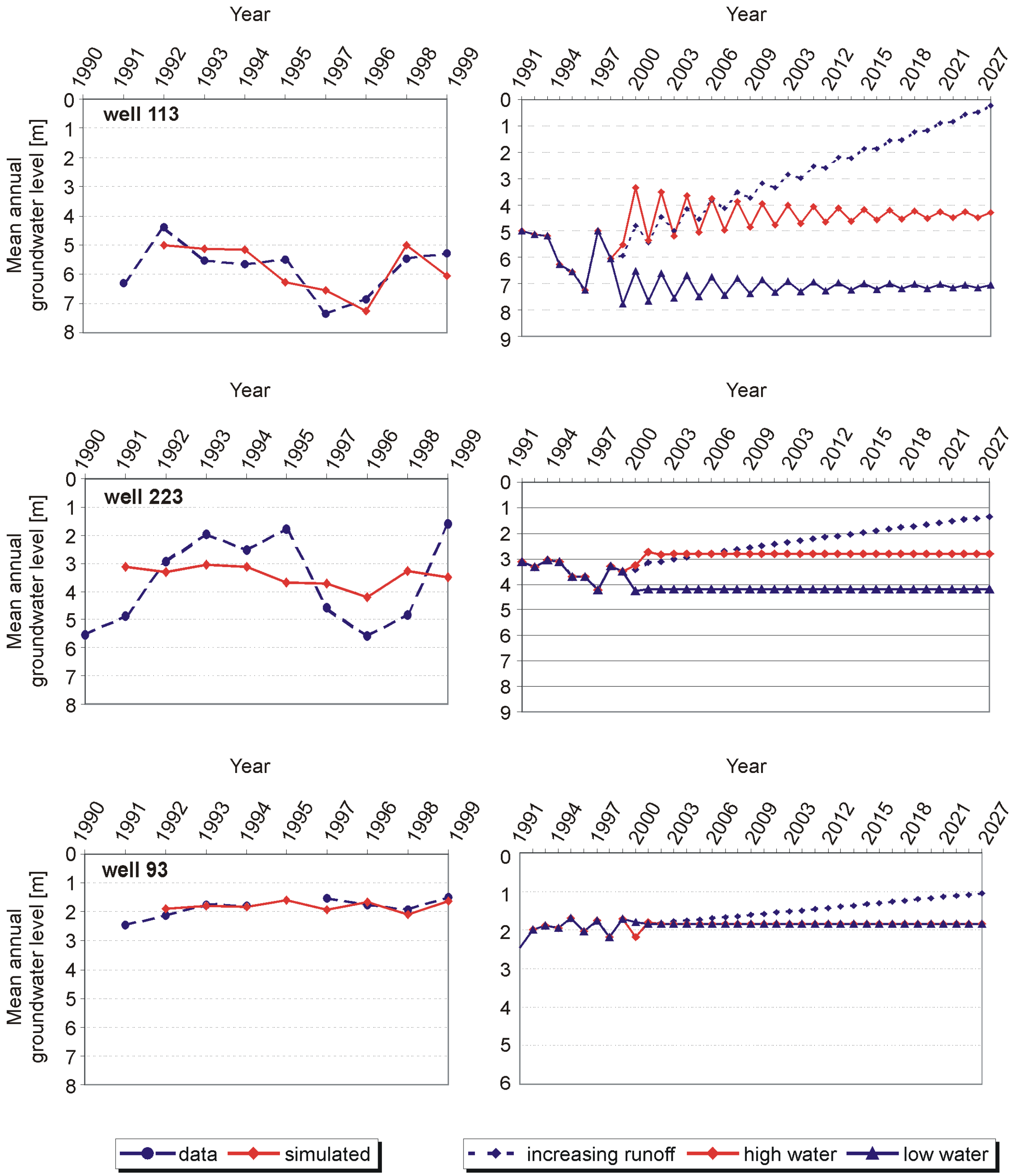


Figure 35: Modeled and observed waterlevels at selected monitoring wells (left) and testing of the regression models with a "high water" (1000m^3/s average annual river flow) and "low water" (20m^3/s average annual river flow) scenario, and a scenario where mean annual river flow increases every year by 100m^3/s.

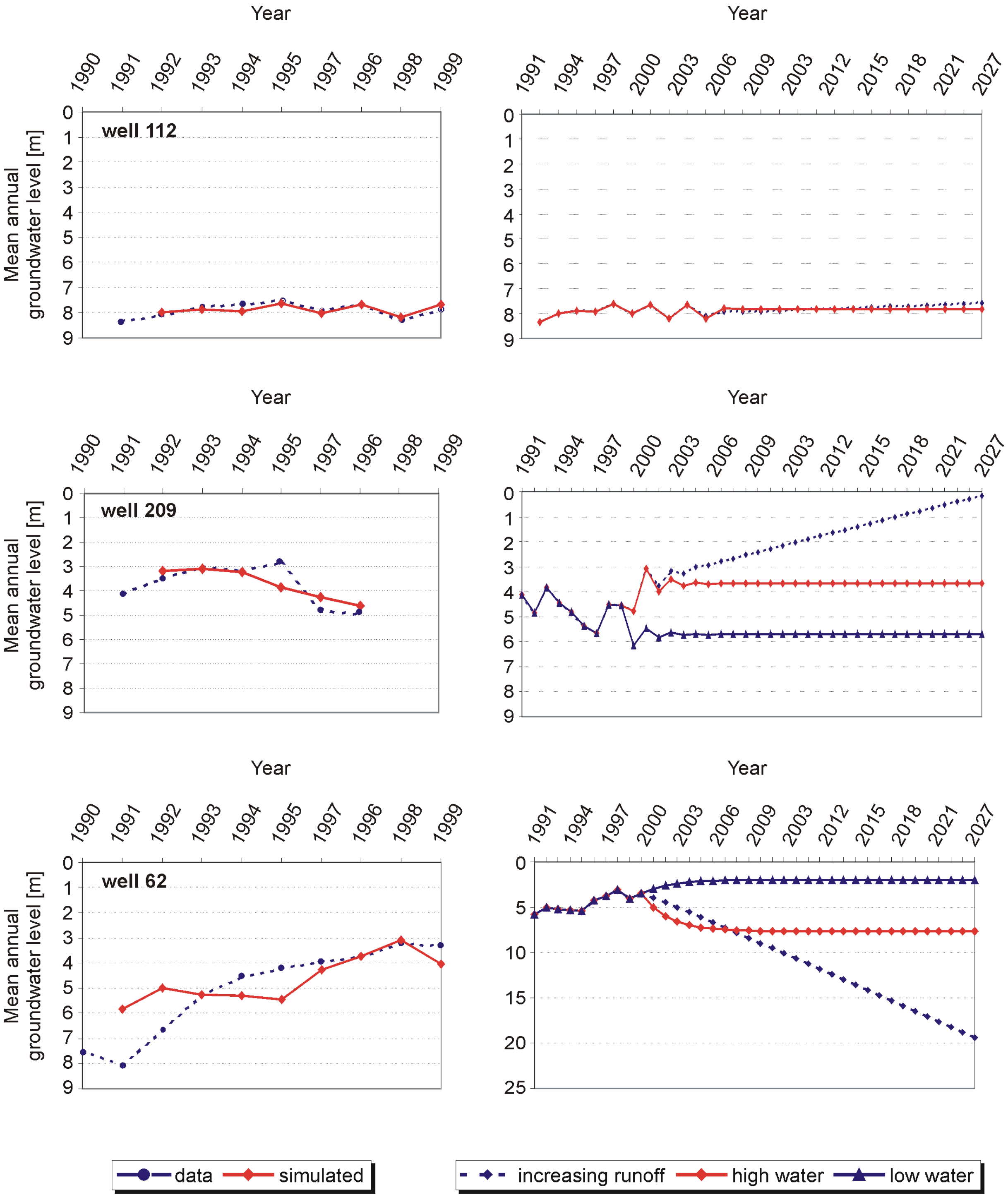


Figure 36: Modeled and observed waterlevels at selected monitoring wells (left) and testing of the regression models with a “high water” (1000m^3/s average annual river flow) and “low water” (20m^3/s average annual river flow) scenario, and a scenario where mean annual river flow increases every year by 100m^3/s.

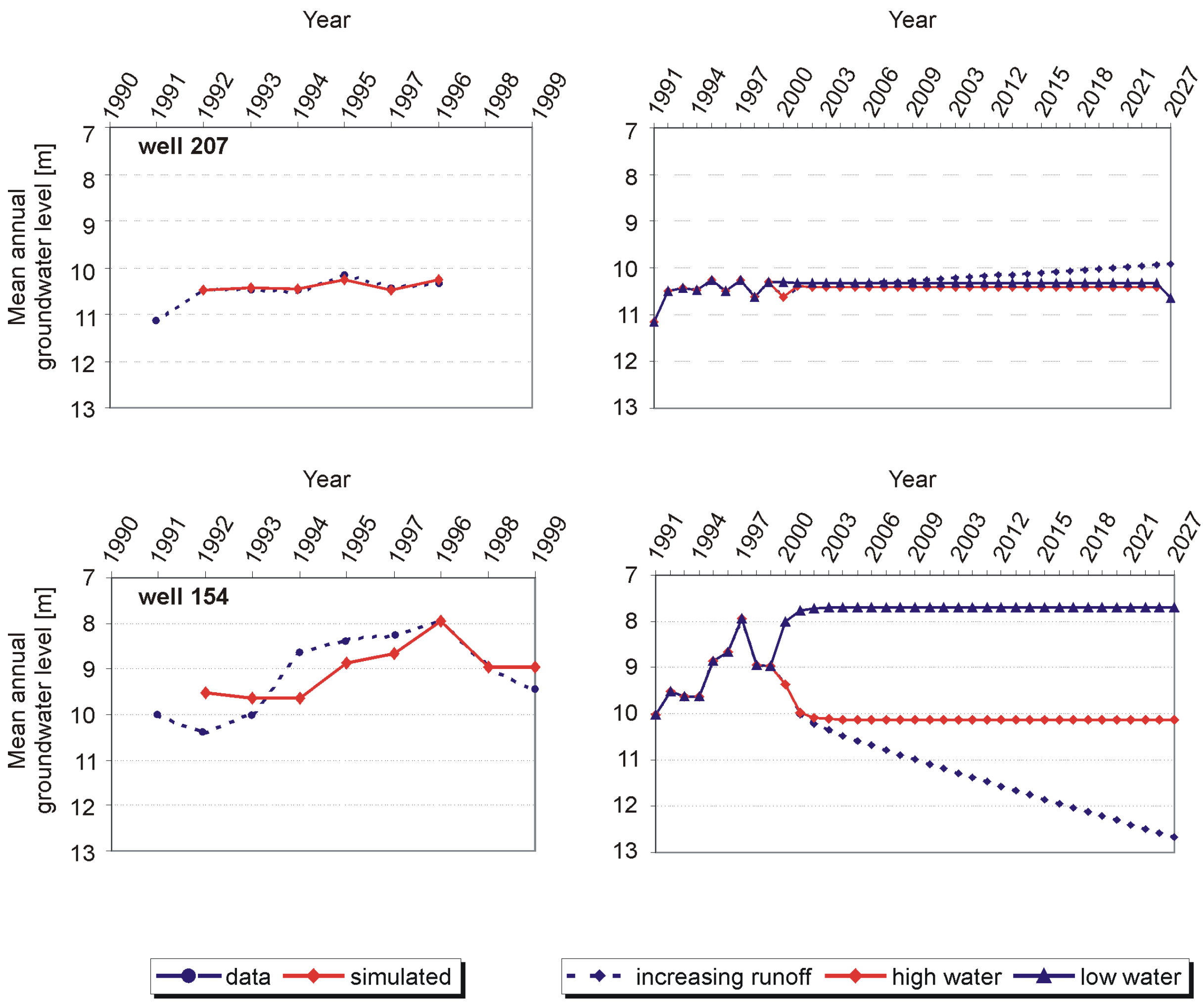


Figure 37: Modeled and observed waterlevels at selected monitoring wells (left) and testing of the regression models with a "high water" ($1000 m^3/s$ average annual river flow) and "low water" ($20 m^3/s$ average annual river flow) scenario, and a scenario where mean annual river flow increases every year by $100 m^3/s$.

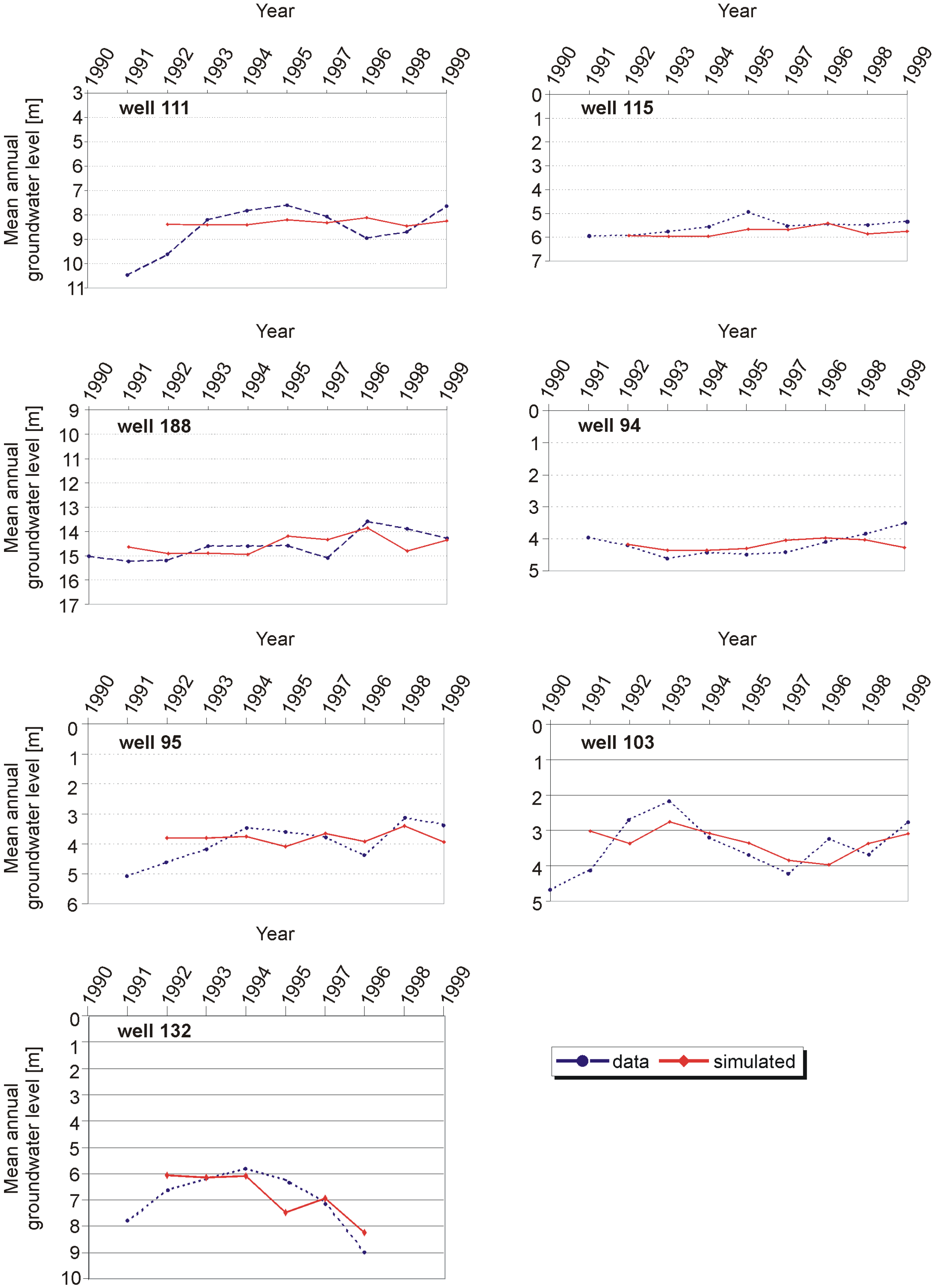


Figure 38: Modeled and observed waterlevels at selected monitoring wells.

the model cannot be completely ruled out, Tugai evaluations in the area of this well should be critically viewed. Although, since groundwater levels are generally low and thus rather unsuitable for Tugai forests, and the well is located at the periphery, this affects the overall evaluation of the Northern delta area only marginally.

Well No **62** shows the same contradictory dynamics as well No 154. The model predicts an increase in water table elevation later and not as continuously as the observed increase. At the beginning simulated levels are approximately two meters higher than measured. The difference then lowers to less than one meter. The hydrograph of this well is untypical and almost not influenced by river discharge (regression coefficient: 0.003). Interpretation of habitat suitability index results in the area of this well should be made with care, because other influences most likely determining site conditions (e.g. irrigation, see above). In extrapolation the decrease in level with increasing surface discharge is even more pronounced than in well No 154. It has to be concluded that the regression model is not valid for this well for values that are outside the range of the observed. The same accounts for well No **188** which is only included to support the spatial interpolation of the groundwater table elevation.

Wells No **94**, **95** and **103** are too far north, in an area with little river flow, as that their hydrographs can be explained to a large extent by flow in the river, as explained above. It was decided to include those wells into spatial simulation of groundwater table elevations because of the small variation they showed over the monitored time period. Unfortunately no information on this northernmost part of the delta were available to improve the estimation. Most likely in both cases nearby lakes determine groundwater recharge, since water levels are rather high. For scenarios where river flow increases in the northern part the models might not be valid.

Generally it can be said that those wells where model fit is not very good are in most cases not significant for Tugai habitat evaluation because they are located at the periphery or their groundwater levels are too low to be assessed suitable. They will be used for regionalization as additional data points to enhance the interpolation especially at the boundaries of the study are. Not including them would most likely cause greater error because the number of data points for the interpolation would be too little. Absolute values should not not be taken as prediction and assessment only performed relative to a reference scenario that was determined with the same underlying assumptions. Due to the limited data set and the lack of true validation, results should always be seen as relative and interpreted with caution.

The fact that extrapolations with constant low and high river runoff do not lead to a constant decrease or increase in the groundwater level but rather its stabilisation at a certain level, point to the fact that the history of a site, included with the past gradient, does not play a significant role.

6.6.6 Implementation of ground water simulation in AmuGIS

The regression models for every well have been implemented as spread sheet models directly in the AmuGIS. Initial values for the simulation runs are the 1999 mean annual water table elevations above Baltic Sea level in the wells and mean river flow at Kyzyljar.

The spatio-temporal water allocation pattern that was determined for a given scenario by the AmuEPIC water management model is integrated into the GIS by mapping mean monthly flow in every river reach to the corresponding reach in the river network in the AmuGIS. All further calculations are performed in GIS via a sequence of AVENUE scripts, mainly using the data stored in attribute tables of river and well shapes. Based on monthly flow values mean annual river flow and mean annual stage height in every reach is calculated using the relationship described above (see subsection 6.6.4). Based on mean annual river flow and stage in the closest river reach and past groundwater level in the observation well, the ground water level above Baltic Sea level in each individual well for 28 years is estimated using the multiple regression function. The closest river reach was assigned to each well by hand. Spatial interpolation between the wells is then performed for every simulation year by triangulation using the Delaunay method (Pache 2000).

With this procedure the three closest data points are joined by a triangle and the elevation of the surface interpolated between them. Points outside of the surface are thus independent from data within the triangle. The method has difficulties when data points are too far apart, when triangles are too small and distorted as well as at the borders of the study area. Both problems occur in this study with the spatial interpolation of the simulated well water table levels as can be seen below. For the triangulation both water table in the observation wells and water table height in the main river were used. The groundwater table elevations were introduced as mass points, representing the nodes of the triangles. The lines of equal water table height in a river reach are treated as soft breaklines that make up the side of a triangle. Soft breaklines were chosen, because there is no distinct break in slope at the river but rather gradual changes in groundwater elevation.

Suenly canal which crosses through the simulated area might influence groundwater table elevations by infiltration. Regionalization of the groundwater elevations including the water levels in the Suenly canal were carried out and tested with the landscape groundwater map. It revealed worse results, possibly because the influence of Suenly canal is confined to a rather small area around the canal. The fact that no significant statistical relationships between runoff at Suenly and well hydrographs could be found additionally proved against using water table elevation in the canal as second breaklines in the interpolation. Groundwater levels in areas close to the canal might thus be slightly underestimated.

The annual maps of groundwater surface elevation above Baltic Sea level were then subtracted from the digital elevation model to receive the ground water level below ground. The resulting maps of the groundwater level are transfered as inputs to the habitat suitability index model (see chapter 6.8).

6.6.7 Results and Validation of the regionalized groundwater elevations

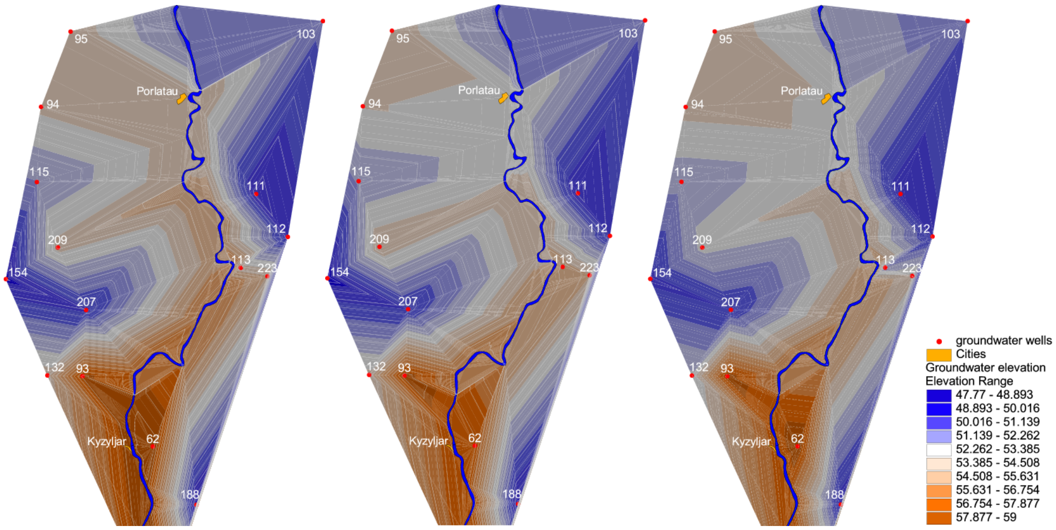
Figure 39, upper row, depicts the results of a 28 - year simulation of groundwater levels using the hydrological input of the "business as usual (BAU) " reference scenario. In this scenario no changes are introduced to current water management practices. The inflow to the delta is represented by a characteristic historic time series of 14 years that is used twice (see section 6.6.4). The figure shows groundwater level in meters above Baltic sea level for the high water year 13 (runoff in the Amudarya river reaches in the simulated area: 38-741m^3/s), the mean water year 14 (38-465m^3/s), and the low water year 17 (33-77 m^3/s). The large ranges in simulated values are the result of the optimization by the water management model. The water is distributed to deltaic lakes instead of diverting it to the Aral Sea and thus the last river stretch after Porlatau receives only little water. This is in accordance with observed water management. For comparison and validation historic groundwater table levels at monitoring wells of three similar years were regionalized using the same method (fig 39, lower row). The high water year 1992 (mean annual runoff at Kyzyljar: 672m^3/s), the mean water year 1991 (298 m^3/s), and the low water year 1999 (123 m^3/s) were selected.

Graphs of the mean annual groundwater level in the wells are given in the annex.

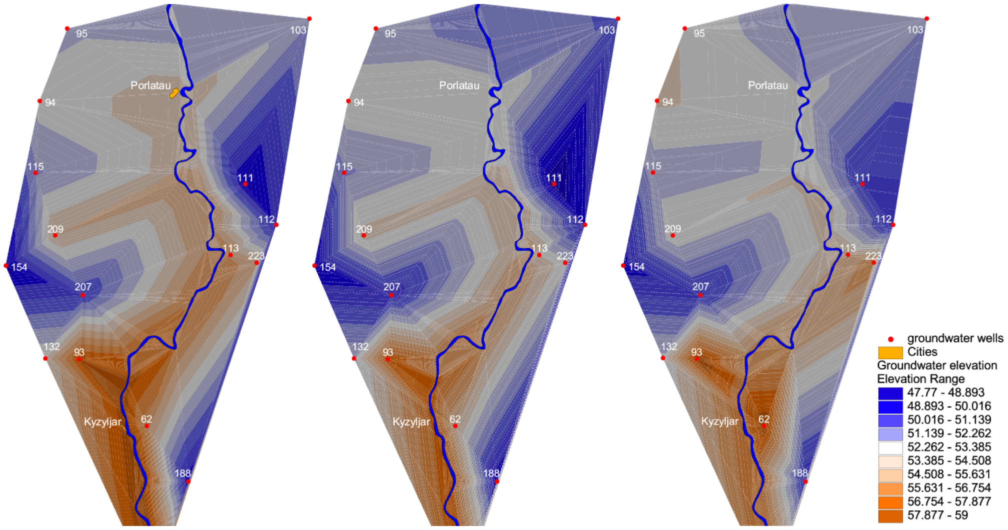
Results Both, reference scenario and historic years show clear differences in groundwater elevations between a high and a low water year. In the simulated high water year 13 the groundwater table is generally higher than in the low water year 17. The mean water year 14 lies in between. This can best be seen with the tongue of high groundwater heads along the Amudarya river (see figure 39).

In some areas, where the relief indicates a lake depression, simulated water levels are above ground. This was mainly observed in regions that are flooded in high water years (especially in the Mezhdureche reservoir) and was thus considered correct.

In the southern part of the delta an interesting phenomena can be observed, both in scenario and historic maps. Groundwater level at wells No 93 and 62 are generally high, producing a hill in the groundwater surface around these wells. In low water years the maps show an incline of the groundwater surface towards the river, thus groundwater flows towards the river. This might be an artifact because of the rough estimation of river stage which underestimates stages in low water years. On the other hand it might reflect a change in groundwater flow towards the river in low water years, which seems realistic. Krapilskaya (1987) describes dome shaped unevenness in the groundwater surface as characteristic for the irrigated areas of the Amudarya delta. In the case of wells No 93 and 62 they might be caused by irrigation or the effects of Suenly canal, as discussed before. Thus this is probably a realistic pattern and not a flaw of the model or the spatial interpolation.



Reference scenario BAU in year 13 (high water), 14 (medium water year) and 17 (low water)



Interpolation of historic values, 1992 (high water), 1991 (mean water year), 1999 (low water)

Figure 39: Results of spatial groundwater simulation for the reference scenario "Business as Usual" and spatial interpolation of groundwater levels in the years 1991, 1992 and 1999. Dots indicate monitoring wells and their ID. Lines depict contourlines of equal water table elevation.

Irregularities The edge that breaks the groundwater surface through Mezhdureche reservoir and in the North eastern part is caused by discrete changes in river bottom that occur at the boundary between two river sections. A higher resolution of river bottom elevation would weaken this irregularity. Since the major break is located inside the reservoir, which in reality will be flooded most of the time and where groundwater table elevations are generally high, it will not exert too much influence on the evaluation results. This is a problem of triangulation because triangles in this region are rather large. The same occurs at the northeast towards well No 103.

In some years (e.g. year 17) around well No 113 a very steep gradient towards station 223 occurs. At well No 113 groundwater levels fluctuate strongly interannually (see annex). The sensitivity of the model at well 113 to changes in the gradient as has been observed before. This results in a situation where levels are in some years significantly higher than in the surrounding wells and in some years lower. Although, the results also show, that the effect is rather regional. The effect of the on the overall assessment can be reduced by using aggregated measures in the final evaluation of habitat suitability, e.g. the sum or average of the habitat suitability over a certain period of time. This will even out some of the fluctuations that might be incorrect at the higher temporal resolution. Figures of groundwater level dynamics of at all wells in the BAU scenario are located in the annex.

Extrapolation The low and high water scenarios previously introduced to test the individual regression models were run in the GIS model and their spatial patterns compared. Figure 40 shows the difference grid of the 28-year- mean of the two scenarios (low water - high water). Generally differences in groundwater table elevation between low and high scenarios are highest close to the river and decrease with distance from river. This confirms that the individual regressions capture the distance dependence of river infiltration. The figure gives an impression of the spatial extent of the contradictory behavior at wells No 64 and 154. At both wells groundwater table elevations increase with low water and decrease with high water as has already been observed when analyzing their hydrographs. The entire western boundary of the simulated area north of well No 207 up to well No 95 is affected. Around well No 65 a smaller area of approximately 30-40 km^2 is affected.

The mean annual water table over the entire simulated area stabilizes with high runoff at 2.90-2.91 m and with low runoff at 4.47 m. In the BAU reference scenario it lies between 3.45 and 4.45 m.

Validation To test the validity of the regionalization of the groundwater elevations contours of selected years were derived in GIS and analyzed. They are superimposed on the groundwater surface in the figures. Their spacing is 0.5m. The contours reveal realistic pictures of groundwater flow and with a few exceptions do not cross.

The pattern of the groundwater flow is similar in all years. Groundwater flows generally from the river towards the eastern and western borders of the investigated area. In the area of the Mezhdureche reservoir the groundwater flow is directed south west towards the groundwater well No 207 and 154. In the high water year gradients from the river towards the wells located to both sides are steeper than during low or mean water.

The map of simulated groundwater flow was also compared to a groundwater map of the year 1997. Unfortunately the scanned map is of low quality and covers only the delta area north of the Mezhdureche reservoir and the dried out sea bottom. On the map the 50.00 isoline is located around Mezhdureche reservoir, which corresponds well with the calculated isolines. The drop of the modeled isolines towards the south west cannot be found on the map. This might be attributed to the fact, that further west of well 154 Sudoche reservoir is located, pushing the isoline in reality towards the North east. Sudoche is fed regularly by drainage waters. Since the groundwater table elevations around the reservoir are not included in the simulation the values at the boundary of the regionalized area might be too low. This is another evidence that the simulated elevations around well No 154 should be interpreted carefully.

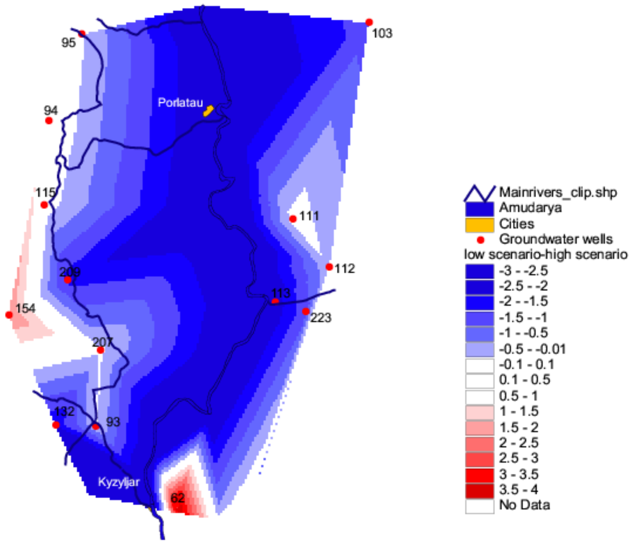


Figure 40: Difference of the low and high water scenario (highwater - lowwater). Blue indicates positive values, red a negative difference. The "atypical" behavior of the models at wells No 62 & 154 is visible in the red area. Here groundwater levels decrease with increasing river flow. Generally differences are largest along the river.

6.6.8 Discussion of groundwater model

Approach Statistical approaches to water table mapping have not been widely applied yet (Matson & Fels 2001). The rather simple statistical approach developed in this study was selected because it is able to capture long term average groundwater dynamics on a regional scale, which is the scale to assess the response of the terrestric ecosystems. The rather "free" choice of the best explanatory variables in a regression approach made it possible to operate with the data available without having to make crude estimations of hydrogeological parameters. A statistical approach can take into account more of the spatial variability in average water table depth on a regional scale than mechanistic approaches (Matson & Fels 2001). In our case spatial variability is taken into account by developing specific equations for every well.

To assess changes in habitat quality in the delta average groundwater level variations over longer time scales are most important. Statistical models are useful in estimating long-term averages (Matson & Fels 2001), while they cannot simulate the response to short term environmental stresses. Short term stresses are considered less important for a general assessment of the ecological effects of water management strategies, although this has to be further investigated from the ecological side.

Furthermore the use of a statistical approach prohibits the examination and explanation of underlying causal mechanisms. The actual ground water flow and processes of groundwater recharge remain unknown. The approach is therefore only valid for the area for which it was designed. When more data will become available the approach should be further tested and adapted if necessary.

Questions that would be interesting to study in order to test and further improve the approach to medium scale water table mapping are e.g.:

- What are the factors that determine the time lag in aquifer response to surface runoff?
- How does the history of a given site, also with respect to the influence of the retreat of the Aral Sea, influences groundwater dynamics?
- What is an appropriate temporal resolution to capture significant surface runoff events?
- What is an appropriate spatial resolution to adequately represent variability in soil characteristics, etc.?

The time lag between an impulse from the surface water (in our case the river runoff) and water level rise in the wells is not the time for water to flow to the monitoring point, but the time required to transmit an impulse (e.g. a pressure pulse) in the aquifer (Shevenell 1996 , Holfelder et al. 1999). There are a multitude of factors involved. The time delay is related to the recharge rate, the soil water content and the depth to the water table. The range and the velocity of propagation of ground water pressure waves caused by changes in the water level in the river are dependent on the actual condition of the aquifer (tense or not tense). (Holfelder et al. 1999). Additionally the storage coefficient in the aquifer determines the magnitude of water level rise (Shevenell 1996).

Methods The rough estimation of water table height in the river, which is based on estimations of the elevation of the river bottom and assumes that the width of the river does not change in the different river reaches, does not affect the results of the individual regression models, since it enters them as a well specific constant. It does play a significant role in the spatial interpolation of the water table since river stages are elevation points of the groundwater surface.

The spatial interpolation is based on several simplifications that influence spatial resolution and accuracy of model outcomes. Water table height in the river reaches is not continuous but discrete with only one value for a reach of several kilometers length. The abrupt drop in water table elevation between each reach leads to irregularities in the groundwater surface, as discussed above. Those effects are localized and can be solved by higher spatial resolution of the river reaches. Data on geometry of the river channel or a higher resolution digital elevation model are needed, which are not available so far. With the simple GIS-based spatial interpolation changes in soil characteristics are neglected and therefore only general, long wave changes in water table elevation are mapped. For a general assessment of changes in habitat quality this is sufficient. Small scale events have to be considered when planing site specific measures.

The intensity and duration of a runoff event plays a significant role for groundwater recharge. By using annual averages of river runoff the effects of short term pulses is lost. It is assumed that the individual regression at every well captures the significant characteristics in a high and low water year. Although testing revealed that the response of groundwater elevations to changes in discharge are modeled well, the magnitude of increase or decrease has to be taken with care.

Healy and Cook (2002) conclude that the history of the changes in water table prior to a recharge rise play an important role, because soils are more easily wetted than drained. By including an estimation of the hydraulic gradient of the previous time step as explanatory variable into the regression we tried to capture those historic “influences”. Although just one time step back might not be sufficient.

Results A statistical model is at best a good representation of the statistical characteristics of the data (Clarke 1994). The time series of groundwater table elevations are considered representative for situations that are expected in the future. Regional groundwater dynamics will only be represented well, if the well hydrographs used to develop the models cover the range of possible responses in the area of interest. The differences in model equations as well as their variable behavior indicate that different ranges have been mapped. Although it cannot be ruled out that there are regions whose groundwater dynamics are not adequately represented by the model of the nearest well. Models might not be valid for input values that lie outside the range of values that were used to determine the statistical relationship. Generally the range of environmental parameters used for the establishment of a model should not be smaller than the range found in the study area (Hettrich & Rosenzweig 2002). Models has been tested successfully for values that are within a realistic range of runoff events in the area, but any changes to the boundary conditions of the present day situation are not covered.

Model results are valid for the habitat evaluation procedure at the annual scale and a spatial resolution of 300x300m. Because of the small number of monitoring wells this spatial resolution might not be supported by the data. The evaluation will not be carried out on a pixel basis but will consider larger areas, thus lowering the resolution to some extent.

Changes in groundwater flow direction that appeared in the spatial model in the southern part of the study area is considered a realistic reaction of the model to the decrease in river flow. Rorabaugh (1964) has found his equations for discharge from a groundwater aquifer to a stream also valid for rising or lowering of a surface water body, where flow will be reversed depending on the water table elevations, indicating a flow towards or from the river. Holfelder et al. (1999) made similar observations in the floodplains of the Elbe river, where flow direction of the groundwater changes periodically, dependent on the case history of the groundwater, that is water level and hydraulic gradient.

Uncertainties Data and approach are subject to many uncertainties such as:

- Data Quality. Little is known about the accuracy of water table elevation or terrain elevation measurements. There are no replicate measurements available for any measurement point.
- Calculation of annual averages. Annual averages of groundwater table elevations are based on single monthly measurements, which are only snapshots in time.
- Errors of spatial interpolation. The triangulation is only a rough estimation of the spatial distribution of the variable.
- Errors of input data. The runoff data are also subject to error which propagates through the models via the regression and the spatial interpolation.

The explanatory variables used to simulate the response of the water table elevation were selected based on theoretical considerations, time series analysis, understanding of causal relationships and a process of try and error. Since model results generally represent observational data well, it is assumed that the model captures all relevant influencing factors. If there are significant changes in factors that do no explicitly enter the regression equation as explanatory variables the mapping might be incorrect. Influencing factors that might affect the outcomes are:

- additional inputs to the aquifer other than infiltration from the main river and a general subsurface baseflow, such as an increased or decreased horizontal subsurface flow, significant changes to the surface canal network, a strong increase in inundated areas, etc.

- additional outflows, such as increased groundwater pumping

Flood events can have strong influence on the groundwater table elevation (Sophocleous & Schloss 2000). At the level and frequency they occur in the present day delta, and at the spatial scale considered, it was assumed that their influence on the groundwater table can be neglected. A general effect of flooding events is incorporated in the simulation through the influence of high river runoff. If flooding frequency and duration change significantly, which is not expected in the near future, the model approach should be adapted.

Observations have shown that water infiltrating into the dry river bed in the Northern delta region is pumped out regularly. This significantly accelerates the lowering of the ground water table in this region. Due to a lack of data on the groundwater pumping this cannot be included in the model so far. In the extreme low water year 2000 110.000m$^{3\ddot{}}$/day were extracted from 839 wells in Karakalpakstan. 33.000 m^{3}/day were used for drinking water, 3.000 for irrigation and 60.000 for other purposes, which are not further explained. (State Committee for Geology and Natural Resources, 2001). So far we assume that the effect of pumping is either only local and short term or shows a certain pattern that is captured in the regression, although groundwater pumping is significant in low water years and should in future be considered.

Conclusions The effects of those uncertainties and shortcomings are often a function of the spatial and temporal resolution at which model results are interpreted. The simple model is suitable for estimating long term averages with rather low spatial resolution, within the limitation outlined above. Given availability of data and the conclusions that will be drawn from model predictions, the given approach seems appropriate and maps general trends in groundwater table elevations with an adequacy that is sufficient. The scope of the model is for ecological evaluation based on organisms that react slowly to environmental changes and show high adaptability. Short term effects, e.g. pumping in low water years, are not considered important. The given models are not suitable for management of vegetation at a specific site, where absolute values of groundwater level and soil moisture become important.

Furthermore it has to be pointed out that results of simulations of the TUGAI tool are intended for a qualitative comparison of alternative scenarios. Values are thus always considered relative to a reference or a comparison scenario. Most of the uncertainties mentioned above do thus not seriously affect the interpretation of the result. Nevertheless it should be tested e.g. within which range of input variables the groundwater estimations are still realistic and statistical confidence levels or ranges of possible values should be presented (Healy & Cook 2002). This can be achieved by comparing the model to independent monitoring data, if available.

6.7 Flooding regime

6.7.1 Modeling of flooding events

The occurrence of floods was modeled with a simple rule based approach. The model uses a threshold value of runoff at the gaging station Kyzyljar, beyond which a flood occurs. The threshold was determined by analysis of historic time series data of mean monthly runoff at Kyzyljar for the years 1956-2000 and knowledge of years and months when floodings occurred. The changes to discharge to the delta with the construction of the Tyuyamuyun reservoir were taken into account. The last great flood that people in the delta remembered was in 1969, followed by smaller floods in 1973, one in 1978 and a large one in 1998. In 1992 there was no flood although mean annual discharge was even higher than in 1998 (see table 12). Based on those observations the threshold for the first flood in a year was set at a mean monthly runoff of 1900m^3/s. For every flood that succeeds directly after the first flood the threshold is set at 1600 m^3/s. This rule is based on the assumption that the first flood facilitates the “overspill” of the second and all succeeding floods, because dams are already broken. The value of 1600 was chosen to map the observed duration of a flood of two to three months. Lowering the second threshold to 1400 did not cause any changes in the flooding events in the BAU reference scenario.

Table 12: Mean monthly runoff at Kyzyljar (m^3/s) in the extreme high water years

Year	Jan	Feb	Mar	Apr	Mai	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
1969	187	495	1050	**2160**	**2000**	**3470**	**3530**	**3350**	**1690**	1190	1150	947	**1760**
1973	263	168	20	721	1260	**2240**	**2520**	1460	1590	953	431	248	**990**
1978	31	45	24	383	994	1340	**2540**	1040	399	795	428	147	**676**
1992	343	130	202	97	1010	1560	1680	1390	909	359	398	111	**672**
1998	83	75	17	34	1215	**1941**	**1617**	1463	579	447	223	190	**662**
2000	224	63	15	10	8	11	6	4	5	5	8	5	**30**

The extent of a flood was delineated from Spot satellite pictures of the flood in May and June 1998 (fig 41). The pictures were georeferenced and transformed to UTM projection used in the AmuGIS and the extent of the floods manually digitized (fig 42). It is further assumed that every flood in the first month has the extent of the May flood in 1998 and every succeeding flood that of the June flood. The flood extents differ mainly in the flooding of the south eastern part of the simulated area.

Hydraulic structures installed especially in the Northern delta area to manage high water events guarantee that excess water is guided to certain areas. As long as those structures do not change the simple estimation of the flooded area used in this model is appropriate. The major structure is an overflow dam in the Amudarya river located at the north eastern end

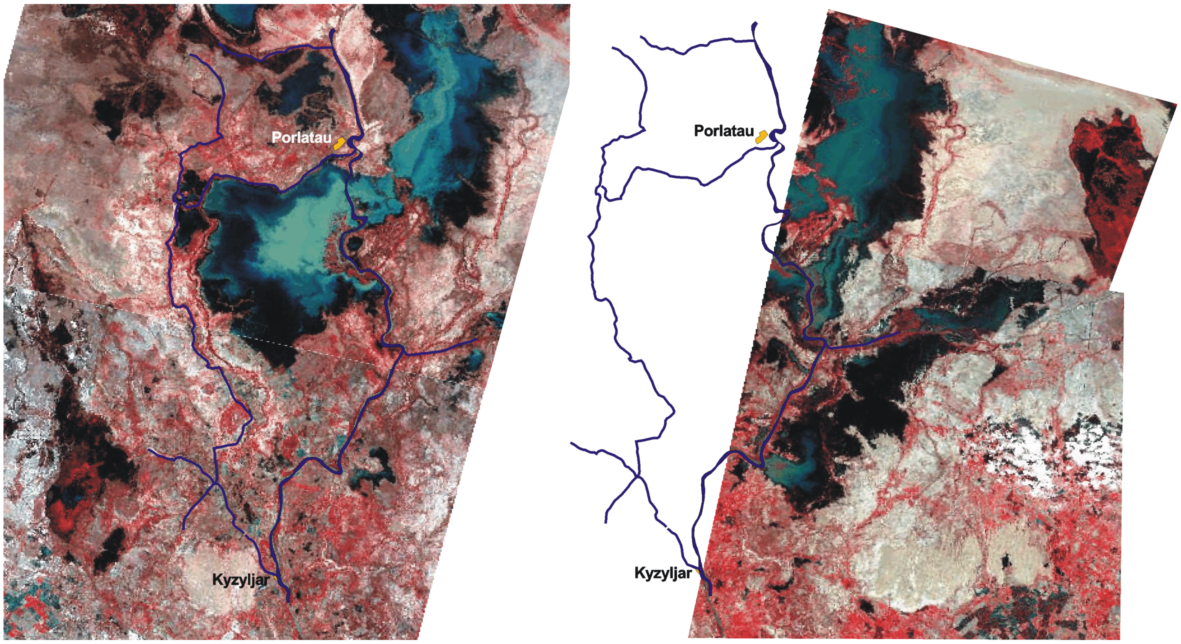


Figure 41: Georeferenced satellite images of the 1998 flood in May (left) and June (right) in the AmuGIS.

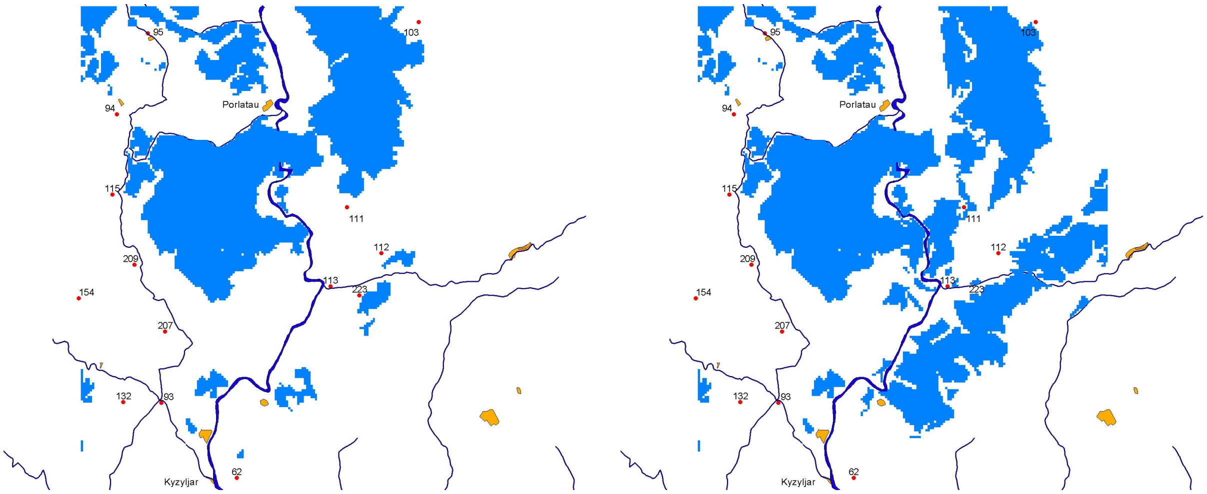


Figure 42: Delineated flooded areas from the above satellite pictures for a new flood (left) and every directly succeeding flood (right).

of the Mezhdureche reservoir close to the village Porlatau (see figure 28). Its upper margin is set at 57.00 above Baltic Sea level at which excess water is diverted to the north eastern depression of the Dumalak lake system. This can clearly be seen on the satellite images. The primary management goal in a high water year is to store as much water as possible in the delta reservoir bodies such as Mezhdureche reservoir, Muynak bay reservoir and Sarbas reservoir, as can be seen on the images. During the flood in 1998 water was first diverted into the reservoirs in the Northern delta and directed into the depression in the north east. In the second month (June 1998) water also overflowed at a point further south of the overflow (see arrow on figure). Since this break takes place in a sharp curve it is assumed that the river destroyed the embankment or a dam and spilled in the depression east of the river.

6.7.2 Discussion of flood model

By assuming that a flood in the first high water month is identical to the May and in every succeeding month to the June flood in 1998 the extent of some floods might be overestimated. The flood in 1998 rather depicts the maximum extent of a flood. Thus in the evaluation of the habitat suitability the effect of flooding of sites located further away of the river might be overestimated. Additional information by satellite images, maps or experts should be used to classify different sizes of floods.

Flood models are often constructed in GIS with the help of a digital elevation model. Based on e.g. a hydrodynamic flood model water table elevations in the river are determined and a grid of the water surface is created in a GIS. The inundation zones are then determined by calculating the difference between the topography and the water level grids (e.g. Oberle et al. 2000). This approach is widely used but not applicable to the Amudarya delta region because of several reasons. As mentioned before lack of geometric information on the river channel makes the use of a hydrodynamic model impossible and water table elevations in the river have to be estimated by a very crude method. They would not be suited to model inundated area. Reliable information on the height of river bars is also lacking. Next to that the very flat territory demands for a very high resolution digital elevation model. Moreover the terrain in the delta area constantly changes, which additionally complicates the task. Thus the rough estimation of flooded area as practiced here is the best that is possible within the given constraints of time and data. The limitations of the flood model have to be taken into account when developing scenarios of alternative water allocation in the delta region. The effects of changes in the flooded area can not be assessed, but the tool is a first step for an evaluation of the occurrence of floods under different allocation scenarios and their effect in general.

6.7.3 Evaluation of the flooding events with respect to habitat suitability for *Populus euphratica*

The results of the flood model for each 28 year scenario are a series of 336 monthly flood maps. These are evaluated spatially-explicit in the AmuGIS with respect to timing of the flood, its duration and the number of years since the last flood event has occurred at the respective site. They are aggregated to annual maps of flooding timing, duration and evaluation of the flooding history as input maps for the HSI model.

The timing of a flood event in a year is the month of the beginning of the flood in the respective year. The flooding duration is the number of months of a successive flood. The time since the last flood at a respective site is assessed in form of a flood impact factor. It decreases the suitability of a flood with respect to its frequency by 13% in every year where no flood occurs. If a flood event takes place the site receives an impact factor of 1. The flooding frequency (ff) of a site in year x is the sum of the impact factors of all floods that occurred at the site up to year x. It is determined by the following equation (after Rüger 2002):

$ff(x) = ff(x-1) * 0.87 + i(x)$

with x being the year of evaluation and ff(x) the flooding frequency of year x, i(x) the flood impact factor of the current year, which is 0 if no flood occurs and 1 with a flood. The initial ff and ft values are the values for the year 1999 based on the flood that occurred in 1998. The initial flooding frequency value of the flooded cells is thus 0.87 and the flooding timing 5 (May) or 6 (June). The deduction of the impact factor is described in detail in Rüger (2002).

6.8 The habitat suitability index model for Tugai communities

6.8.1 Description of the Indices

Habitat suitability indices developed by Rüger (2002) assess geomorphology, flooding duration, flooding frequency, flooding timing and groundwater level simulated by the models described above with respect to their effect on habitat quality of a given site for Tugai communities. The habitat variables are aggregated to a composite index on an annual time scale.

The development of the individual and the composite indices was based on expert evaluations, analysis of expert interviews and literature studies of the suitability of different value ranges of each variable for the growth and viability of *P. euphratica*. The collected qualitative and semi-quantitative knowledge was formalized using an approach of the fuzzy set theory (Rüger 2002).

Habitat suitability indices were developed for adult and establishing *Populus euphratica* formations since their habitat requirements, especially with respect to groundwater level, flooding timing and flooding frequency, differ significantly. The indices vary in the variables that are considered, their association rules as well as the combination to the composite suitability index. The indices are summarized in table 43. Their plausibility was checked by Rüger. Index results of the testing year 1999 differ only in small areas along some river stretches and in the south eastern part of the study area from the real distribution of woody Tugai vegetation in the year 2000. A detailed discussion of the testing of the index model can be found in Rüger (2002).

Index	Variables	Combination	Comments
Estab - 1	gm, gwl, ft, fd	$hsi_{total} = min\{hsi_{ft}, hsi_{fd},hsi_{gwl}\}$	
Adult - 1	gm, gwl, ft, fd, ff	$hsi_{total}=1/3*(2*hsi_{gwl}+(hsi_{ff}*(hsi_{ft}*hsi_{fd})^{1/2})$	
Estab - 2	gm, gwl, ft, fd, hsi_{past}	$hsi_{total} = (hsi_{past}*(hsi_{gwl}*hsi_{flood})^{1/2})^{1/2}$	
Adult - 2	gm, gwl, ft, fd, ff	rule based, combines of groundwater level and flooding suitability (flooding suitablity = $hsi_{ff}*(hsi_{ft}*hsi_{fd})^{1/2}$)	more sensitive to floodings, groundwater levels are judge more severely than with index Adult-1

gm: geomorphology

ft: flooding timing

ff: flooding frequency

gwl: groundwater level

fd: flooding duration

hsi: habitat suitability index

$hsi_{past}(x+1) = 0.7*hsi_{past}(x)$

$hsi_{flood} = (hsift*hsifd)^{1/2}$

Figure 43: Variables and association rules for the different habitat suitability indices developed by N. Rüger (2002).

6.8.2 Discussion of Habitat Suitability Model

HSI models have been criticized because of their assumption of a linear response of a species to habitat parameters, the lack of stochastic and temporal effects on habitat suitability and their lack of statistical methodology (Dettmers and Bart 1999).

The use of expert knowledge to assess changes of environmental conditions with respect to their suitability for a certain species or community has several drawbacks. As with all empirical approaches expert information describes the realized niche of a species. It describes its actual distribution which is also a function of interspecific competition, human induced site conditions etc.. The same accounts for potential adaptation of a species to changing environmental conditions that are not accounted for.

The experts describe situations that they are familiar with. Unknown combinations of e.g. site conditions are difficult to evaluate. Competitive relationships between species and community succession on a site are expressed indirectly through the classification of environmental variables into different suitability classes. Thus e.g. low groundwater level and possibly high salinization caused by absence of flooding will lead to low suitability of the site for adult or establishing Tugai vegetation. This site might be colonized by *Tamarix sp.* which under these conditions outcompete *Populus euphratica.*

Testing HSI models is rather difficult due to the lack of spatially explicit data on habitat variables as well as species distribution or species response to environmental management. Kliskey et al. (1999) propose the use of bootstrapping methods for evaluating confidence intervals for HSI.

The habitat suitability can indicate regions that are most suitable for the conservation or rehabilitation of the modeled species but it cannot provide site specific management advice.

7 Integration of models into the TUGAI simulation tool

The Tugai tool has been realized in GIS. Here, all three modules, the water management model AmuEPIC, the groundwater and flooding module and the habitat suitability index model TugaiHSI, are linked (fig 44). GIS provides not only the framework for spatial modeling, taking into account ecologically important spatial heterogeneities. It also provides several other features needed for integration such as:

- communication with all modules through its graphical user interface
- simulation of the spatio-temporal distribution of key habitat variables
- visualization and spatial analysis of results

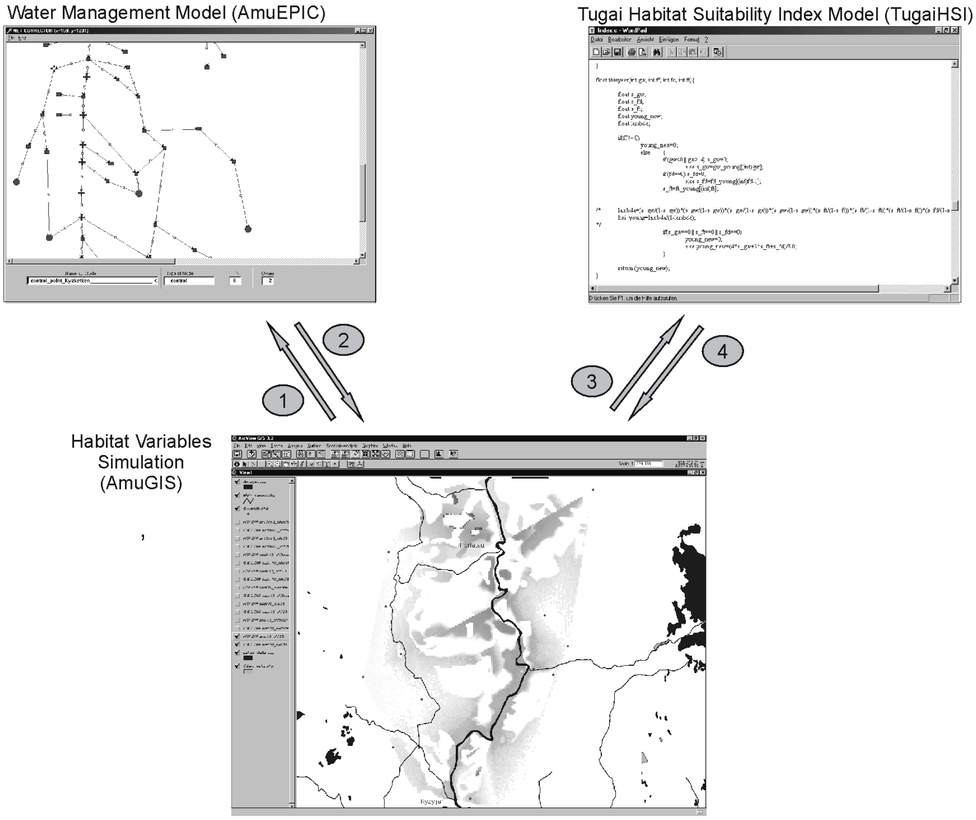


Figure 44: Overview of TUGAI Tool. The three modules AmuEPIC, AmuGIS and TugaiHSI are integrated in a GIS. AmuEPIC is a multi-objective water allocation model developed in the EPIC modeling system, AmuGIS are statistical and rule based spatially explicit models of environmental variables and TugaiHSI is a fuzzy-based Habitat Suitability Index developed by Rüger (2002). The numbers indicate successive steps of scenario development, simulation and analysis of results.

7.1 Technical realization

For implementation of the tool the GIS software ArcView was chosen, mainly because it is widely distributed among government agencies in Central Asia. This will ease distribution of the tool to decision makers and planners in future. ArcView provided a development environment to manage data transfer between the modules and to customize user interaction with the tool.

The tool was realized as an ArcView project customized with a special menu for simulation. The core of the tool are a number of AVENUE scripts that are executed in ArcView. AVENUE scripts not only call the models, they also regulate data transfer, perform calculations, manage representation on the screen and spatial analysis. For spatial interpolation in the groundwater module and spatial analysis of the results the extensions “Spatial Analyst” and “3-d Analyst” are used. The AmuEPIC water management model and the HSI index calculation are called from the GIS via special menu items (see paragraph “user interaction”). All other software needed, such as the user interface for the water management model AmuEpic and the GAMS solver for the optimization are included in the database of the tool and called from ArcView.

For every scenario run a new directory is created, where all results are saved. Data transfer between the different modules is realized through ASCII files, which in the case of the export to TugaiHSI include spatial information of the grid cells.

7.2 General description

The numbers 1-4 in figure 44 indicate successive steps of scenario development, simulation and evaluation of results. All steps are carried out in ArcView via the special menu item “Scenario Analysis”. In step number one AmuEPIC is called for the development of the water management scenario. In the second step the results are transfered back to the GIS river network and changes in environmental conditions are simulated. Third, the TugaiHSI index is called to assess spatially-explicit the simulated annual groundwater levels and information on the flooding regime. The results of the evaluation are then returned to the GIS for visualization and analysis (step 4).

Figure 45 depicts a system diagram of the tool. The three modules are shown in the large boxes “Delta Hydrology”, “Environmental Conditions” and “Ecological Assessment”. The block “Delta Hydrology” encompasses all steps and calculations that are carried out in the AmuEPIC water management model. “Environmental Conditions” integrates all simulations of changes in environmental variables, thus the groundwater and flooding module. The “Ecological Assessment” refers to the Tugai Habitat Suitability index that has been developed by Rüger (2002).

The tool offers the possibility to investigate two different levels of future challenges to water management in the Amudarya delta. The first concerns factors that are external to water management in the delta and thus cannot be influenced by water managers in the

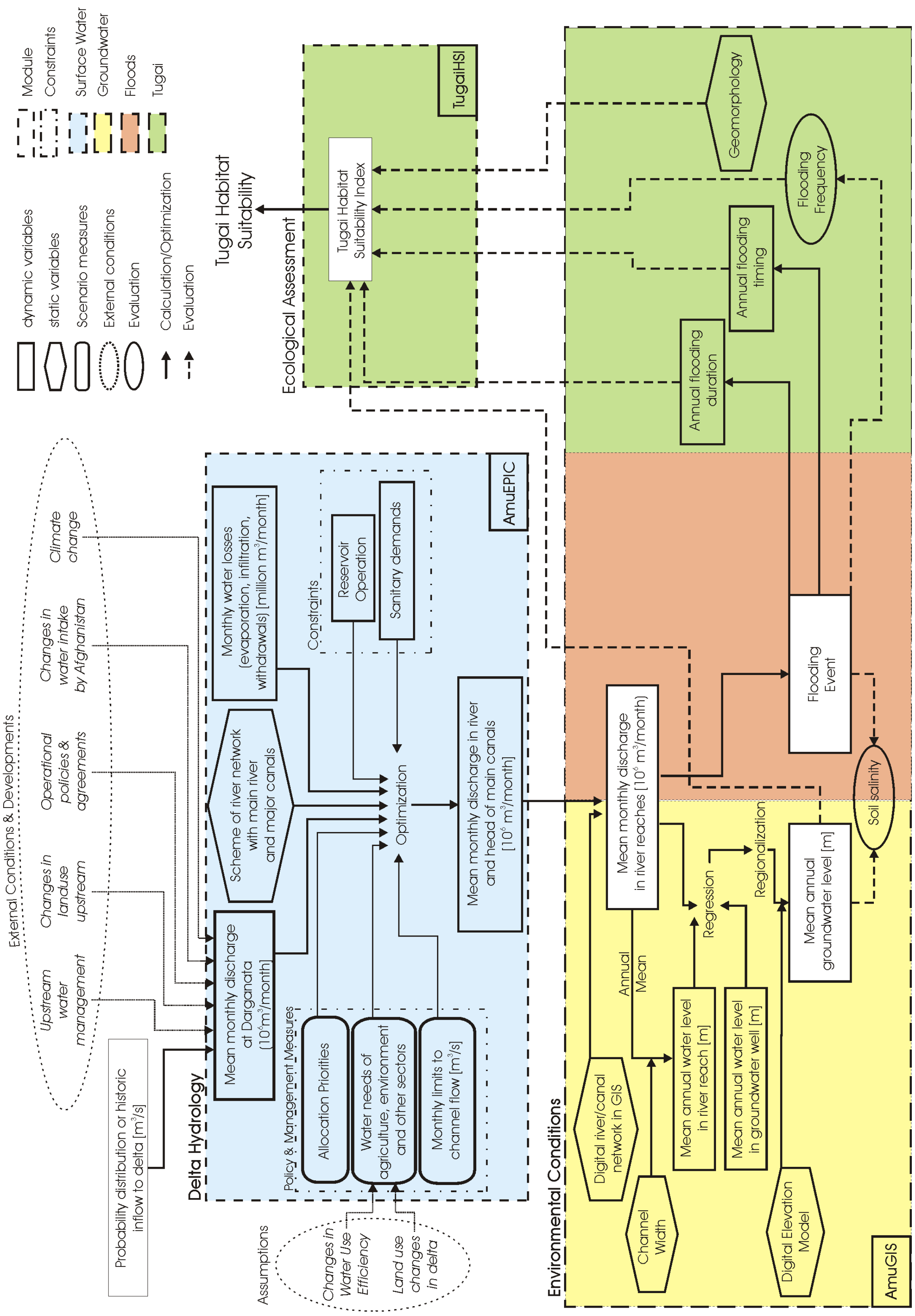


Figure 45: System Diagram for the TUGAI tool. The three modules AmuEPIC, AmuGIS and TugaiHSI and model and user interactions are shown.

delta itself. These external conditions and developments that influence water availability in the delta might be changes in water management upstream or climate change. In scenario development these influences are realized through changes in the inflow to the delta region (see “external conditions and developments”, fig 45). On the level of the delta itself, water management measures can be introduced in the module **AmuEPIC**. Those measures might alter the spatio temporal water distribution, for example to favor a specific region or divert more water to the northern part of the delta, or water needs of agriculture or any other user. The priorities of water management in the delta can be changed to e.g. provide more water to areas suitable for Tugai forests. After setting the scenario inflow to the delta (the external conditions and developments) and determining all management measures in the delta by setting constraints and priorities (policy and management measures), AmuEPIC searches for the optimal solution under the given constraints.

Modeled water distribution in the AmuEPIC river and canal network is then automatically linked with the river reaches in **AmuGIS** in 28 maps each depicting mean monthly river runoff in the main river for the twelve months of each year (see section 5.6). Mean annual river runoff together with the groundwater table elevations in the wells at the previous time step are the inputs for the regression model. Results are regionalized to obtain groundwater level below ground for every pixel of the study area (see chapter 6.6). Mean monthly river runoff is also the input for the flooding module to determine monthly flooding events. Their duration, flooding timing and frequency is assessed and aggregated to annual maps (see chapter 6.7).

After completion of all calculations in the GIS the index **TugaiHSI** is called to evaluate the environmental conditions of the “habitat pixels” in the GIS with respect to their suitability for Tugai forests for every simulation year (see chapter 6.8). The index is indicator of the effects of the management measures and chosen inflow scenario and can be compared with a reference scenario or other management scenarios. The results of the index calculation are returned to the GIS, visualized in annual maps and analyzed (see below).

7.3 Data flow

Data flow though the tool can be seen on figure 46. The different modules are called by the user from ArcView. All visualization in form of maps and table is carried out in ArcView. The flow diagram depicts the process of one scenario run, from the implementation of measures to analysis of results.

7.4 User interaction, scenario development and analysis

The user interacts with the tool through the graphical user interface of the GIS via the menu “Scenario Analysis” and the interface of AmuEPIC via the menu “Water”. Models and simulations in the tool are called successively by the items of the GIS menu. Scenario

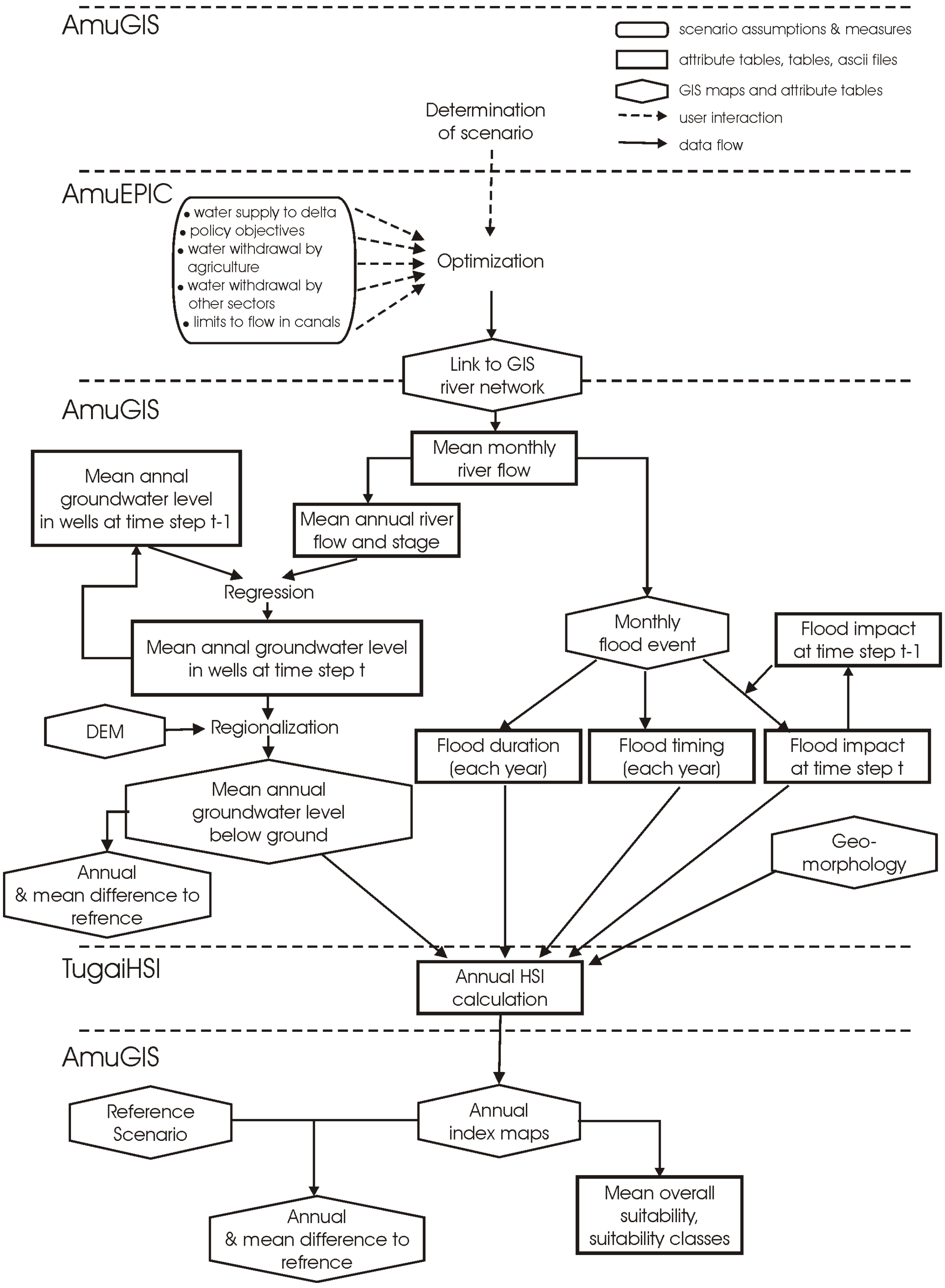


Figure 46: Flow diagram of the TUGAI tool. AmuEPIC, AmuGIS and TugaiHSI are the three modules of the tool that are integrated in GIS.

development is performed in AmuEPIC, using the interface of the EPIC modeling system (McKinney & Savitsky 2001).

To develop a water management scenario and introduce measures the user can set the following variables and parameters:

- inflow to the delta (external conditions and developments)
- upper and lower constraints of flow in selected canals
- outflow from the reservoirs
- inflow to delta lakes
- flow to the northern delta/Aral Sea
- needs of agricultural users
- needs of environmental users
- needs of other users (e.g. population, fish farming or industry)
- objective weights of the objective function, reflecting policy decisions such as more flow to the river mouth

Additionally he can introduce new canals and users.

All user interaction takes place through the GIS menu items that are shortly described below:

- “Scenario directory” - creates the scenario directory
- “Scenario development” - calls the AmuEpic interface where the user introduces all scenario assumptions and measures
- “AD flow and floods” - links the results of the AmuEPIC optimization with the AmuGIS river network and determines flooding events.
- “Flood evaluation” - aggregates and evaluates the flood events as input for the index calculation, displays flood maps of months where floods occur
- “GWL calculation” - calculates the groundwater regressions, the triangulation and subtraction from the DEM, displays the annual groundwater maps
- “HSI calculation”- calls the index calculation, visualizes the results
- “Result display” - displays results of former scenario runs

- "Result analysis" - calculates the difference and the difference of the means of annual groundwater and HSI of scenario runs and the reference (BAU) scenario (no changes to current inflow and water management)
- "Clear View" - clears the view of the GIS from all scenario themes (maps)

For scenario development in AmuEPIC the following menu items are provided by the EPIC modeling system:

- "Working directory" - selection of the scenario directory
- "Network creation" - introduction of new canals or new users
- "Data input" - input of the water supply to the delta and water needs of the users
- "Constraints" - input of lower and upper limits to flow in river and canals and to volumes of the reservoir
- "Objective weights" - input of the objective weights for the four objectives "water supply to users", " flow to delta", "final storage of reservoirs" and "stability of the solution"

7.5 Visualization and analysis of results

Next to the visualization of the results of the annual groundwater levels and HSI in annual maps, statistical characteristics of every simulation year are calculated and visualized in tables. This includes mean annual groundwater level and habitat suitability index for the entire simulated area and a list of floods and their duration. The number of cells in classes of a HSI interval of 0.1 is determined and visualized in charts.

Spatial analysis options include the calculation of difference grids of management and reference BAU scenario for every year, as well as the difference of the total mean of all years of management and reference scenario.

The spatially explicit modeling facilitates an evaluation of results by the percentage and area of sites whose habitat suitability has changed as a result of the proposed management option.

The automation of most procedure's in the GIS and its interface facilitate easy use of the tool for people that are not very familiar with GIS and computer based modeling in general.

The tool and a tutorial are included on a CD provided with this thesis.

8 Scenario development and testing of the tool

Scenario development and testing of the tool will be carried out using Index 1 adult (see section 7.8). Rüger (2002) has shown that the results of Index 1 and Index 2 adult differ only slightly. Index 2 is more sensitive to floods than Index 1. Since the estimation of flooded area is highly uncertain it was decided to test the tool with the index that less emphasizes this habitat variable. The indices for establishment of Tugai communities are mainly dependent on the suitability of the flooding regime, since the seeds need a flood to germ.

8.1 Scenario development

Several different scenarios were developed to test the tool and its applicability for decision support in ecological aspects of water management issues. The scenarios cover a realistic range of different water allocation strategies and changes in inflow to the delta. The selected scenarios are summarized in table 13.

Table 13: Description of change in scenario assumptions and measures for selected alternative water allocation scenarios

Scenario	BAU	SUPL+10%	SUPPL-10%	ARAL10	USER-1%	SUPL+35%
Inflow to delta	14-year time series	**10% increase in monthly inflow, 14-year time series**	**10% decrease in monthly inflow, 14-year time series**	14-year time series	14-year time series	**35% increase in monthly inflow, 14-year time series**
Water use for irrigation	average historic values	average historic values	average historic values	average historic values	**decrease of 1% in water use every year**	average historic values
Minimum Inflow to Aral Sea	1.94 km^3/year (10-200x10^6 m^3/month)	1.94 km^3/year (10-200x10^6 m^3/month)	1.94 km^3/year (10-200x10^6 m^3/month)	**10km^3/year (200-2000x10^6 m^3/month)**	1.94 km^3/year (10-200x10^6 m^3/month)	1.94 km^3/year (10-200x10^6 m^3/month)
Maximum inflow to delta lakes	250x10^6 m^3/month	250x10^6 m^3/month	250x10^6 m^3/month	250x10^6 m^3/month	250x10^6 m^3/month	250x10^6 m^3/month

All scenarios are compared to a reference scenario (BAU - Business As Usual) without any changes to current water management practices or water inflow to the delta. Increase or decrease in inflow to the delta as in scenarios SUPL+10% and SUPL-10% can take place as a consequence of alterations to water management further upstream, e.g. water savings in agriculture in the upstream irrigation areas, farming of less water intensive crops, increase in water intake by Afghanistan, climate change, etc.. A change in discharge by 10%, or in average approximately 3.6km,^{3} is a rather cautious assumption. It is estimated that at least 10-20 km^3/year could be saved in agriculture (ICWC 1998). On the other hand Afghanistan is entitled to 5-10km^3/year. The scenario of an increase of inflow by 35% (SUPL+35%) was selected to test model behavior with the size of inflow to the delta at Darganata as it was in average before the 1960s. The 1938-1960 mean annual inflow to the delta at the gaging station Chatli which is located slightly further downstream of Darganata, was approximately 46 km^3.

In the period 1980 -1994 the average inflow was 36 km^{3}of which approximately 13 km^3 were used for irrigation (data of the Uzbek Hydrometservice). An increase of the scenario inflow to 135% is equal to a mean annual discharge at Darganata of 48.5 km^3.

The scenario ARAL10 implements the policy measure of allocating more water towards the Aral Sea. Draft agreements between the basin states envision 14 km^3/year to be allocated towards the Aral Sea in an average year. The water management model is constrained to allocate at least 10km^3 per year to the river reach north of the former gaging station Porlatau. Currently this river reach only rarely receives water since even in high water years the water is diverted into a depression before it reaches this last stretch. Water supply to the northern lakes close to Muynak is mainly managed through the Mezhdureche reservoir.

The scenario USER-1% simulates changes to water management in agriculture in the delta area itself. It is assumed that the water demand for irrigation is reduced by 1% every year. This scenario simulates gradual spatio-temporal changes to water allocation in the delta area.

8.2 Results of scenario runs in comparison with the reference scenario

River Runoff The mean annual runoff at the gaging station Kyzyljar for every scenario run can be seen in figure 47. Changes to the amount of discharge to the delta are applied to the discharge at Darganata and the water management model searches for an optimal allocation of the surplus or manages the deficiency. The graphs depict the resulting discharge to the Northern delta area, which is in most cases larger than the change to the input at Darganata. For SUPL+10% e.g. the runoff is between 100 and 150% of the runoff at Kyzyljar in the reference scenario. For the SUPL+35% runoff increases by 140-290%. For SUPL-10% it lies between 55 and 100% of the runoff in BAU.

Runoff at Kyzyljar is lowest for all years with the SUPL-10% scenario and highest with the SUPL+35% and ARAL10 scenario, as expected. The generally high values for the ARAL10 scenario show that the water management model allocates water towards the Aral Sea as desired. In the other scenarios, even when the water quantity is higher than in the reference scenario additional water is not necessarily allocated to the Northern area but to lakes further south. In the ARAL10 scenario the demands of the users are only to 94% satisfied, with respect to 96% in all the other scenarios.

The differences between scenario and reference runoff values are generally lower in low water years than in high water years. The constraints posed to the solution of the optimization problem are higher in low water years than in high water years and additional water is rather used to satisfy the water demand of the users. This also affects the interannual variances which are highest in the SUPL+35 scenario and lowest in the ARAL10 scenario. The gradual decrease in water use by the irrigation users is reflected in an increase in runoff of the USER-1% scenario in the second 14-year period. The peak in the second high water year 27 is higher than the one in year 13.

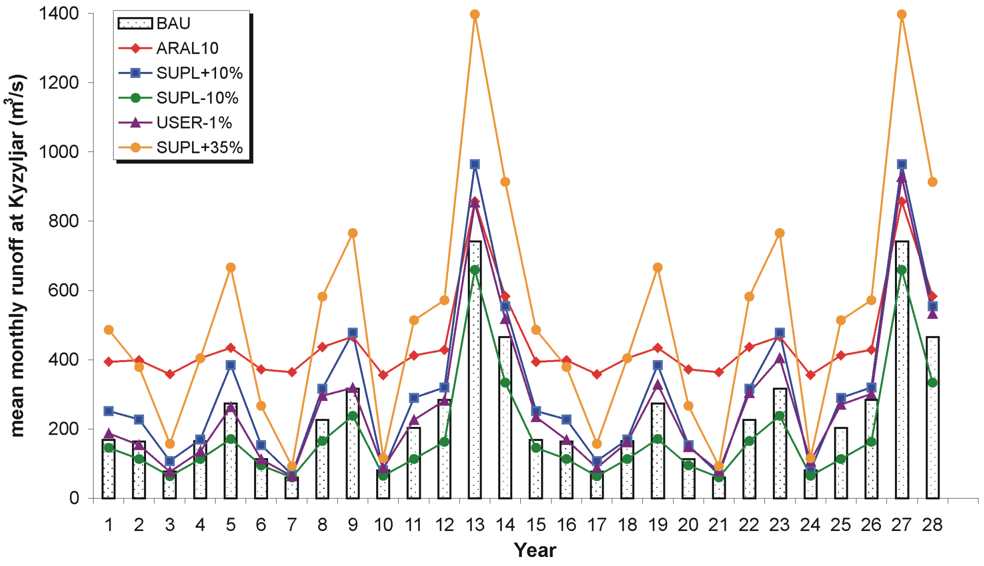


Figure 47: Simulated mean annual runoff (m^3/s) at the gaging station Kyzyljar in reference and management scenario over a 28-year time period.

Floods Table 14 gives an overview of the floods that occur in the different scenarios and the overall average groundwater levels and habitat suitability indices.

Table 14: Simulated occurrence of floods in the reference and management scenarios; mean groundwater and habitat suitability values for the entire time period

FLOODS	BAU	SUPL+10%	SUPL-10%	ARAL10	USER-1%	SUPL+35%
Year (Months)						5 (6)
						9 (7)
	13 (5-7)	13 (5-7)	13 (7)	13 (5-7)	13 (5-7)	13 (5-8)
		14 (7)			14 (6)	14 (5-7)
						19 (6)
						23 (7)
	27 (5-7)	27 (5-7)	27 (7)	27 (5-7)	27 (5-8)	27 (5-8)
		28 (7)			28 (6-7)	28 (5-7)
Mean gw level	4.45	4.36	4.50	4.05	4.41	3.97
Mean HSI Value	0.56	0.58	0.56	0.56	0.58	0.57

For scenario ARAL10 occurrence and duration of floods is exactly the same as in the reference scenario. In the low inflow scenario SUPL-10% the duration of the two floods is reduced from three to only one month. The other scenarios show increases in the number of flooding events, with additional floods in varying months of the years 14 and 28. In scenario USER-1% the flood in year 27 is two months long. The continuous increase in water flow in the river increases flooding duration in the second high water period in USER-1%. In scenario SUPL+35% floods occur every 1-5 years. In the additional years (year 5, 9, 19, 23) flood duration is only one month. In the years 14 and 28 floods are longer than in the other scenarios.

The mean groundwater levels of the different scenario runs show the same tendencies of lowest level with lowest discharge and highest with the forced discharge towards the Aral Sea. For the mean HSI the trend is less clear, with the higher supply scenarios showing only slightly higher means and ARAL10 at the same level as the reference scenario.

Groundwater Figure 48 shows the mean annual groundwater levels for the entire area and the five scenarios. Groundwater levels basically reveal the same tendencies as observed in the runoff series. Here the scenario SUPL+35% leads to the highest groundwater levels, closely followed by ARAL10. The latter shows very constant groundwater levels opposed to SUPL+35% and SUPL+10 where variance is very strong. Scenario SUPL-10% has the lowest groundwater levels. The increase in runoff in the USER-1% scenario is also reflected in the groundwater levels, which in the average slightly increase. The mean groundwater levels in all other scenarios are identical in both 14 year series indicating that the different initial value in year 15 does not seriously affect the groundwater level. Scenarios with the highest variability in runoff show the highest variability in groundwater levels.

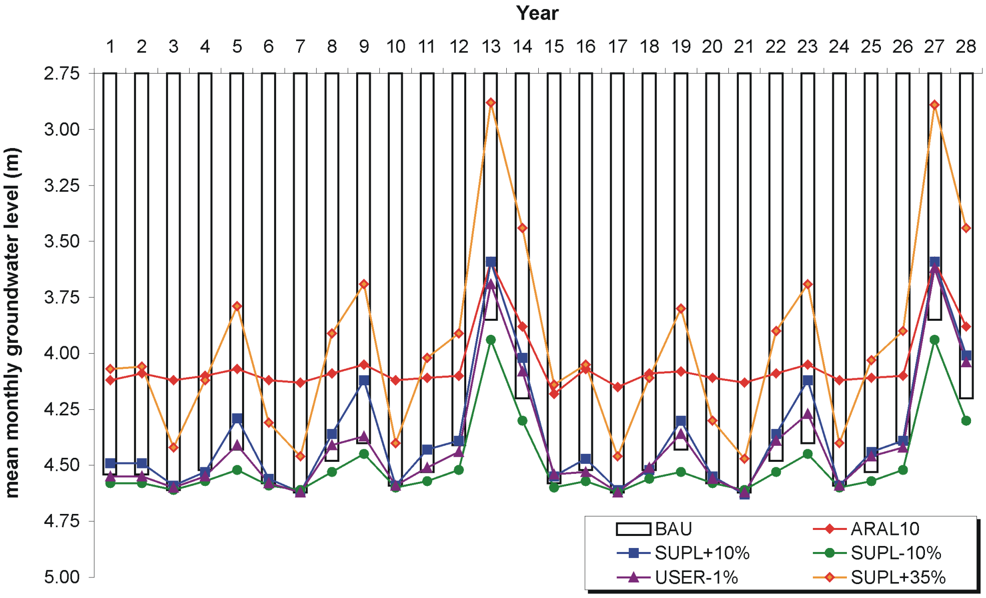


Figure 48: Simulated mean annual groundwater levels (m) in the reference and management scenarios.

Habitat Suitability Indices Mean annual values of the Habitat Suitability index show little variance between the scenarios (fig 49). Especially in the first 14 years there are hardly any difference of mean HSI to the reference scenario. Only the HSI value for the SUPL+10% scenario is slightly higher at the beginning and SUPL-10% and ARAL10 are slightly lower in year 5. After the first flood in year 13 this picture changes. SUPL+10% and USER-1% increase stronger and then decrease less. Their values stay about 0.04 higher than in the other scenarios. Values for ARAL10 and SUPL-10% stay at the reference scenario levels. SUPL+35% starts at lower values and then increases earlier, since there is a flood already in year 5. Values then remain rather constant with two sharp decreases in the high water years. This might be caused by the long flooding in those years which are assessed negatively (see below). This and the stronger increase of SUPL-10% is most likely an effect of the influences of floods. This will be discussed in detail with the spatially explicit analysis below. The mean values of habitat suitability and of groundwater level are important for an analysis of temporal aspects of groundwater level or index development. To study spatial aspects, analyses are carried out using the resulting GIS maps of groundwater table and habitat suitability index.

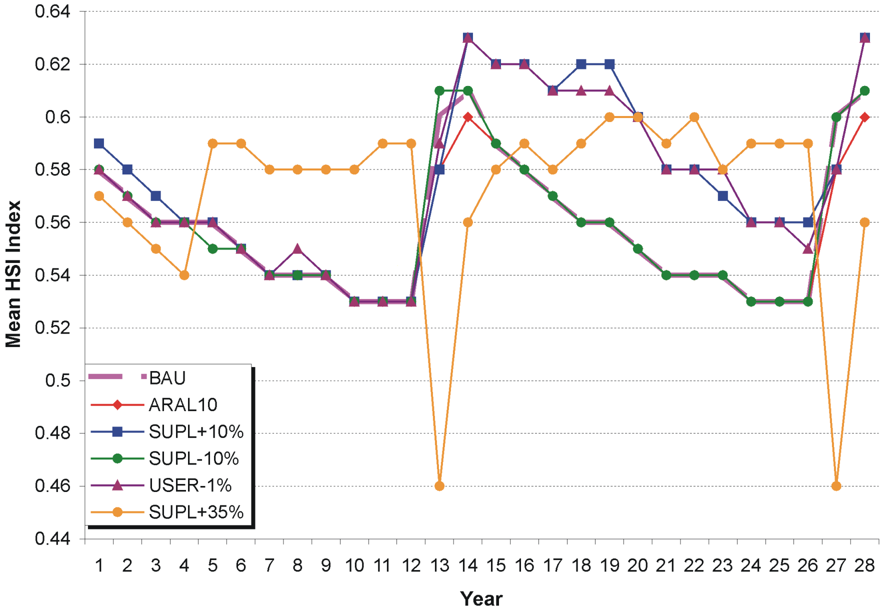


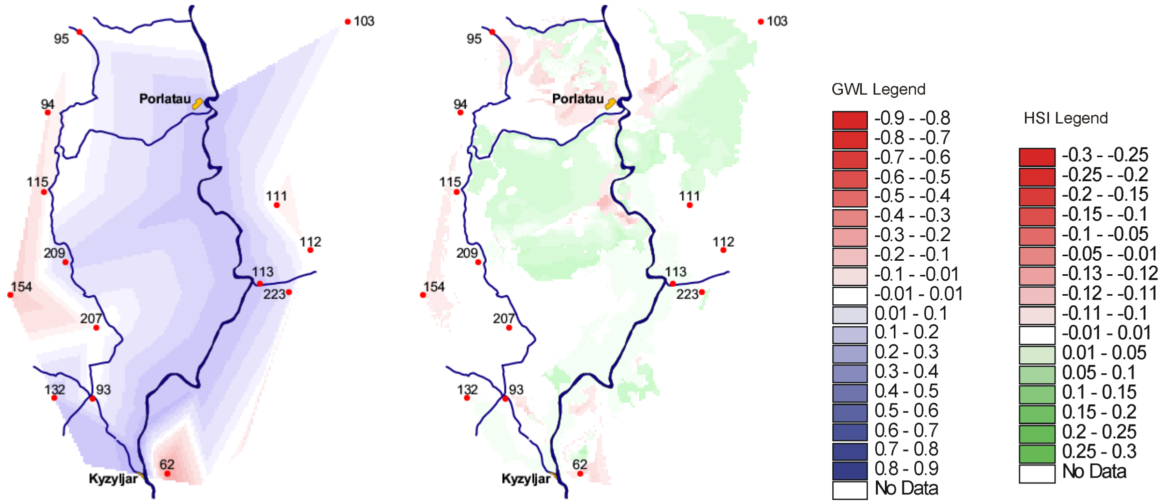
Figure 49: Simulated mean annual habitat suitability indices (HSI) in the reference and management scenarios.

Spatial patterns The results of the selected scenario runs in comparison with the reference scenario are depicted in the following figures (fig 50- 54). The figures map the difference between the scenario and the reference scenario (e.g. ARAL10 - BAU). Positive changes are coded blue for the groundwater levels and green for the habitat suitability index, negative changes are indicated in red. The intensity of the color reflects the amplitude of the difference. To assess the overall effect of a measure the mean of the 28 year groundwater and habitat suitability values at each site were calculated and compared to the mean of the reference scenario. To analyze the effect of the measure in high and low water years and at the end of the simulated period a high water year (year 13), a low water year (year 24) and the last year (year 28) were mapped.

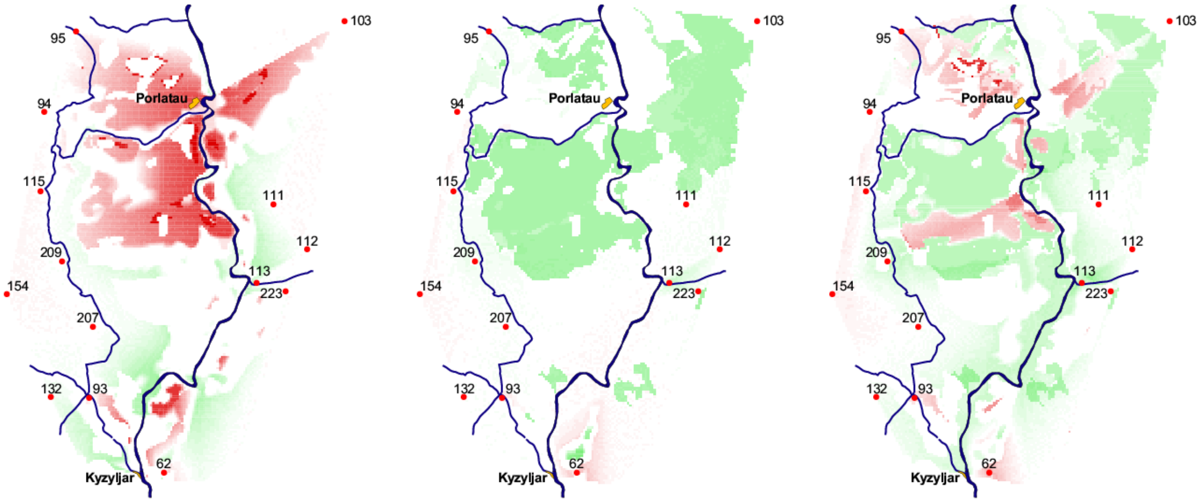
The change in groundwater level is always highest along the river as has already been observed in the testing of the groundwater model. The opposite trends in the south eastern and western area are also apparent in all scenarios. Increase is highest for the SUPL+35% and ARAL10 scenario as already seen in the mean values above. For the SUPL-10% scenario groundwater decreases most in the southern area closed to the river.

8.2.1 10% more inflow to delta region (SUPL+10%)

With an increase in inflow to the delta region by 10% the average habitat suitability index in the 28 years increases in most of the northern part of the simulated area with respect to the reference scenario (fig 50). In the north western part the quality of some areas has decreased mainly because of increased groundwater levels. The north western part is next to the Mezhdureche reservoir, characterized by many small depressions, that are filled with water in high water years (see figure 28). A groundwater level close to the surface is thus realistic. The largest increase in suitability occurs in the Mezhdureche reservoir and the north-eastern area which is caused by the floods in year 14 and 28 that do no occur in the BAU. In the high water year 13 the suitability of the reservoir area and the Northern area turn worse due to increasing groundwater levels. In reality these areas would be flooded and thus Tugai forests could rarely survive. The southwestern corner shows an increase in suitability because the increasing groundwater levels are assessed positive. In the low water year 24 suitability is everywhere higher than in the reference scenario except around well No 62 and 154, where the groundwater trends are reversed. In the southwestern corner the increase in groundwater level was not sufficient. There is a trade-off in groundwater level increase where sites with previously low levels become more suitable and sites where the level is already close to the surface become unsuitable. In the last simulation year suitability has increased along the main river on the river bars. The irregularities in the groundwater regionalization cause the lower HSI values in the center of the reservoir and the north east. There is a flood in July of year 28 which positively affects suitability.



(a) Mean GWL (b) Mean HSI



(c) HSI Year 13 (d) HSI Year 24 (e) HSI Year 28

Figure 50: Scenario SUPL+10%. Difference grid of the scenario and the reference scenario BAU. Mean gwl and mean HSI (above); HSI of high water year, low water year and last year (below). Red colors indicate a worsening of the situation compared to the BAU scenario, blue and green an improvement.

8.2.2 10% less inflow to delta region SUPL-10)

With a decrease in inflow by 10% there is a worsening of average habitat suitability especially in the southern part in areas that are not flooded any longer (fig. 51). The situation is similar in the individual years but in some cases more pronounced. In the high water year the flood lasts only one month as opposed to three months in the reference scenario. A flood of one month is valuated higher than a flood of three months causing the increase in HSI in the reservoir and north eastern area. In the southern area the flood is missing and groundwater levels decreased. The quality of habitats along the river decreases. The same applies to the last simulation year. In the low water year differences are less pronounced as already seen in the mean runoff and groundwater values above.

8.2.3 Constant inflow to Aral Sea of 10km^3/year (ARAL10)

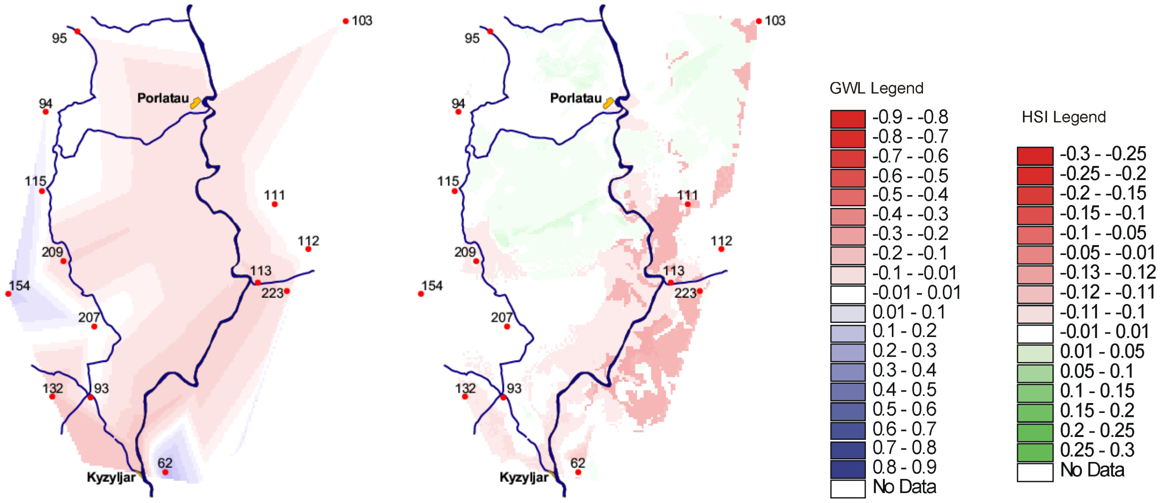
The increase in water flow towards the Aral Sea leads to an average increase in habitat quality along the river bars (fig 52) and along a belt at the southern border of the depression at Mezhdureche. The increase in suitability along the river north of Porlatau is caused by the increase in river discharge to this northern river stretch. This only happens in the present scenario. The higher runoff leads to an increase in groundwater level, which has a positive effect on the habitat suitability. As observed before there is a decrease in suitability in areas with low terrain. The high and low water years differ only slightly since variations in groundwater level are only small (see above).

8.2.4 1% per year less water for irrigation USER-1%)

A reduction in water use in agriculture increases average habitat suitability in the reservoir area and the north east, similar to SUPL+10% (fig 53). Although there is no increase along the river bars as with other scenarios. The increase in flow only slowly affects habitat suitability, mainly in the second 14 year period as can be seen in the last simulation year. Here increase occurs almost everywhere, especially along the rivers in the southern part. As in SUPL+10% there is a flood in the last year, although here it lasts two months and is thus valuated slightly lower. In the high water year the negative effect of the high runoff on critical groundwater levels is slightly less pronounced than in SUPL+10%. There is an increase in HSI in the central eastern part in some distance to the river. This might be attributed to the fact that the groundwater has risen only slightly and thus improved habitat suitability on the slopes of the river bars, but not on the higher elevated river bars themselves.

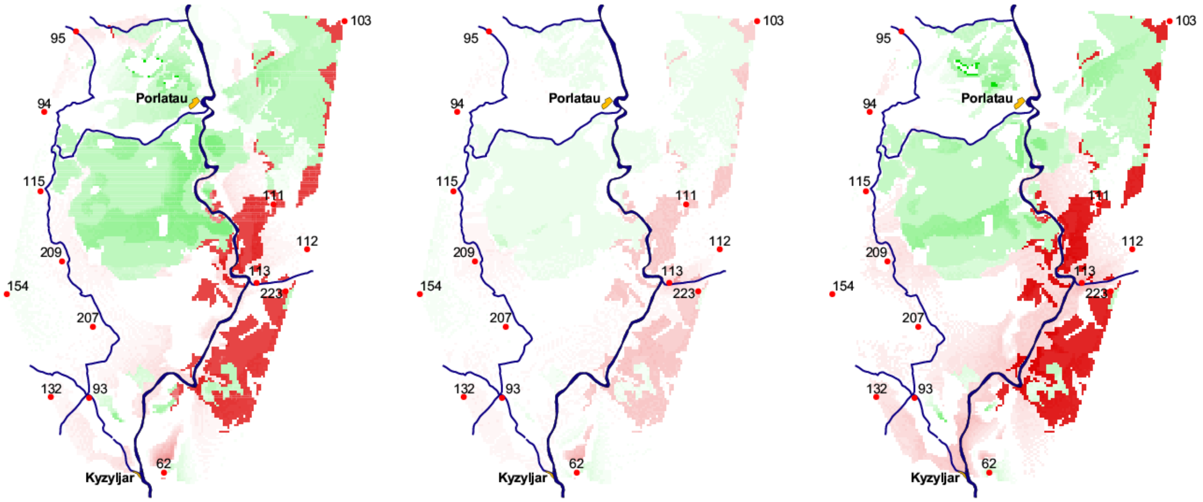
8.2.5 35 % more inflow to the delta region SUPL+35%)

Restoring the river flow to the values before 1960 leads to a general increase of mean habitat quality across most of the Northern delta fig 54). Again the low level in the north western lake rich part is a realistic exception. The four month flood in the high water year and the high groundwater levels explain the decrease in suitability along most of the river and in the depressions in year 13. The sequence of one month floods year 5, 9, 19 and 23) lead to the



(a) Mean GWL

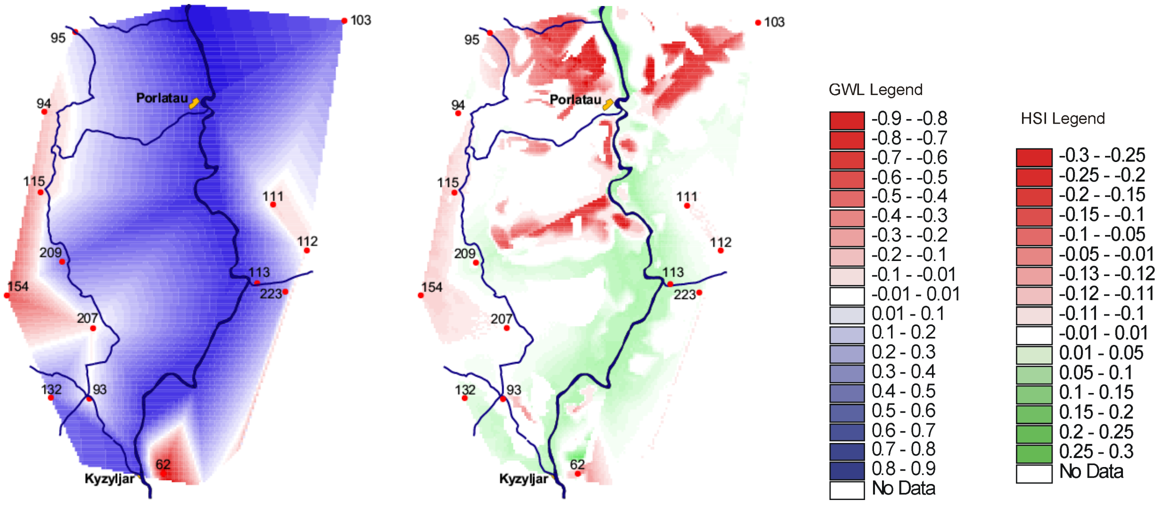
(b) Mean HSI



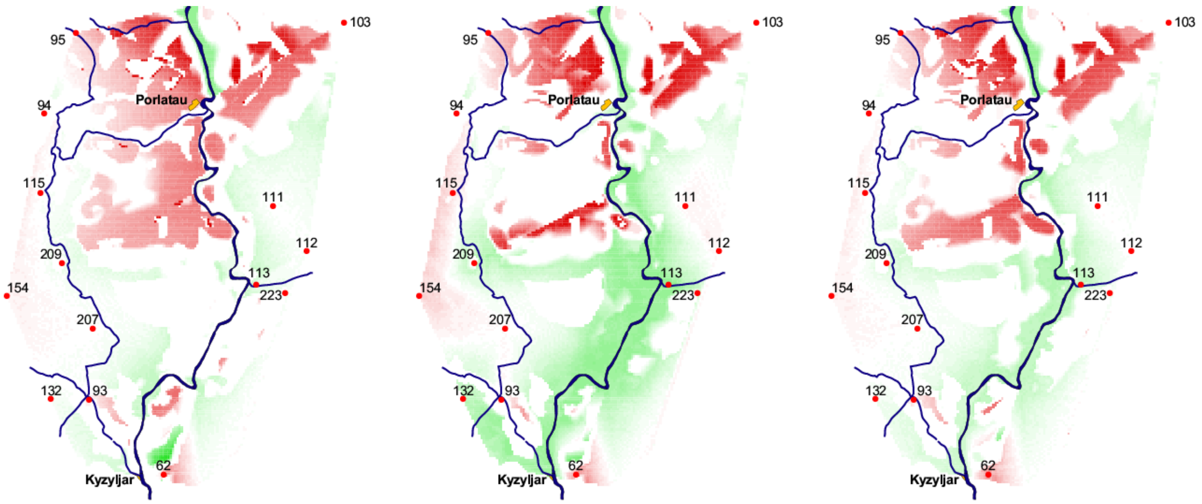
(c) HSI Year 13

(d) HSI Year 28

Figure 51: Scenario SUPL-10%. Difference grid of the scenario and the reference scenario BAU. Mean gwl and mean HSI (above); HSI of high water year, low water year and last year (below). Red colors indicate a worsening of the situation compared to the BAU scenario, blue and green an improvement.

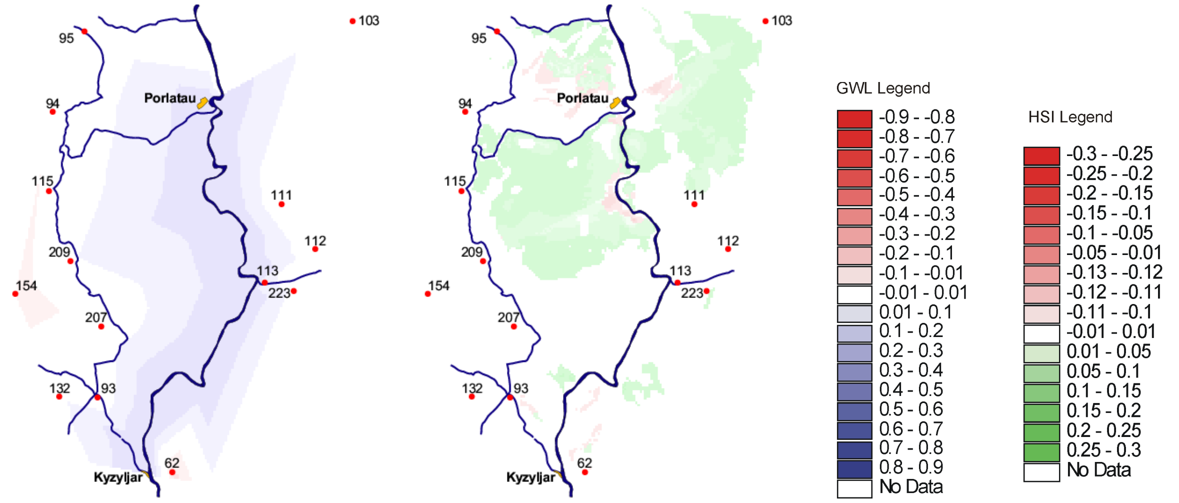


(a) Mean GWL (b) Mean HSI

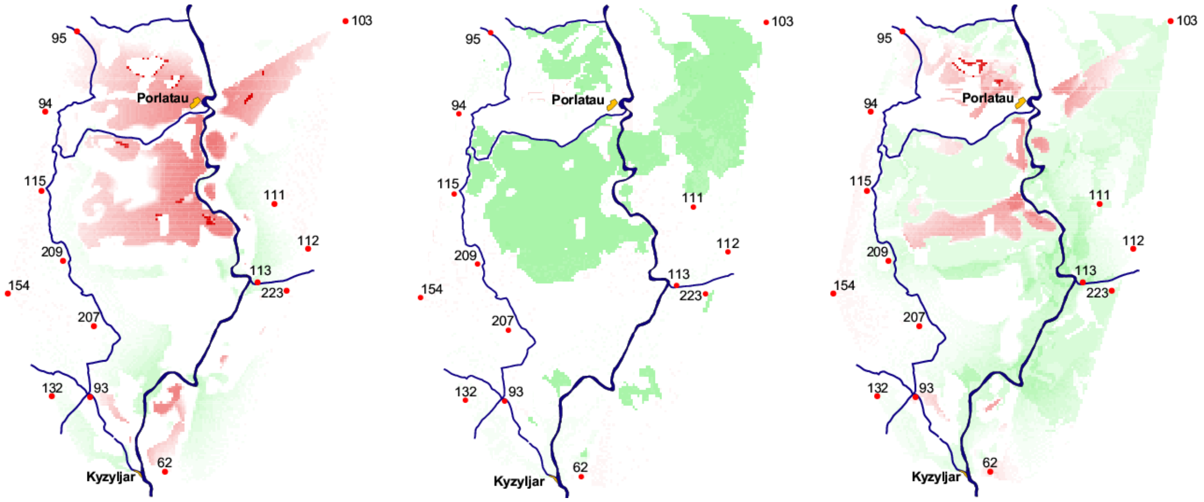


(c) HSI Year 13 (d) HSI Year 24 (e) HSI Year 28

Figure 52: Scenario ARAL10. Difference grid of the scenario and the reference scenario BAU. Mean gwl and mean HSI (above); HSI of high water year, low water year and last year (below). Red colors indicate a worsening of the situation compared to the BAU scenario, blue and green an improvement.



(a) Mean GWL (b) Mean HSI



(c) HSI Year 13 (d) HSI Year 24 (e) HSI Year 28

Figure 53: Scenario USER-1%. Difference grid of the scenario and the reference scenario BAU. Mean gwl and mean HSI (above); HSI of high water year, low water year and last year (below). Red colors indicate a worsening of the situation compared to the BAU scenario, blue and green an improvement.

mostly high evaluation in the low water year 24. In the last year the low lying parts are assigned worse values, mainly because of the long flood in year 28 and groundwater levels, while the southern parts and stretches along the river are better.

8.3 Discussion of scenario results

The selected scenarios differ not only in the quantity of water allocated to the delta area (SUPPL +10, SUPL-10, SUPL+35% and USER-1%) but also in its spatial ARAL10) and temporal distribution (USER-1%).

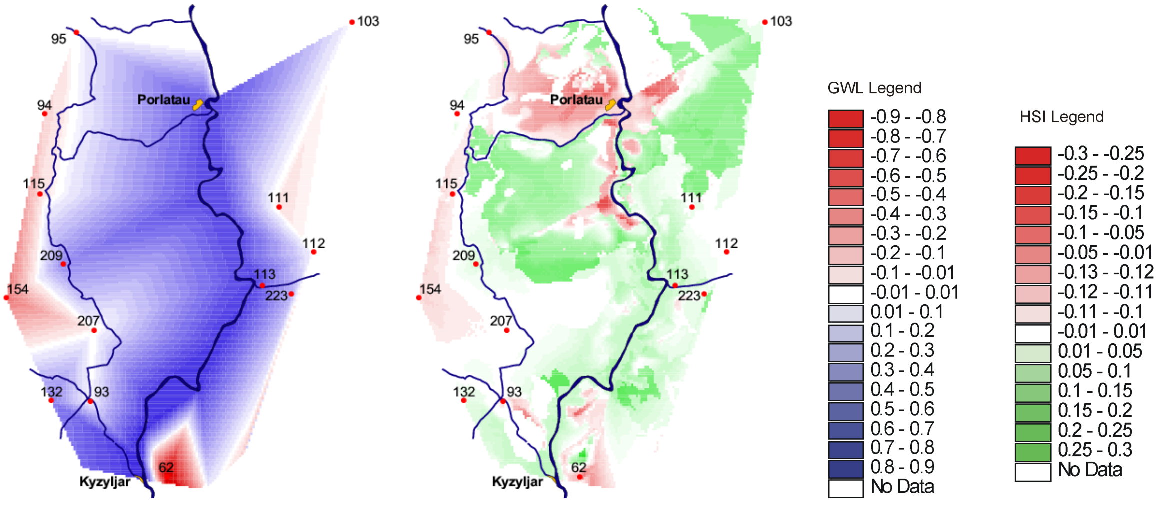
River Runoff and Floods The AmuEPIC water management model reacts in the desired way to the scenario requirements and allocates the water accordingly while respecting user demand. An increase in runoff leads to an increase in flooding events of varying duration and timing. Water is allocated to the river stretch north of Porlatau only if there is an explicit demand introduced as constraint into the water management model. Otherwise water is diverted to the lakes and the overflow further south. The model remains stable even with very high input runoff values, which was tested with scenario SUPL+35%. The 28-year average inflow to the delta region assumed in this scenario is higher than is realistic in the nearer future.

Floods have a significant influence on the habitat suitability evaluation, which can be seen very well in the SUPL-10% scenario. The lack of a flood at a site that in the reference scenario was ind undated in the specific year will lower its suitability with respect to the reference. The factor flooding duration also significantly influences habitat assessment, which can be seen in the high water scenarios where the floods become longer and thus less suitable.

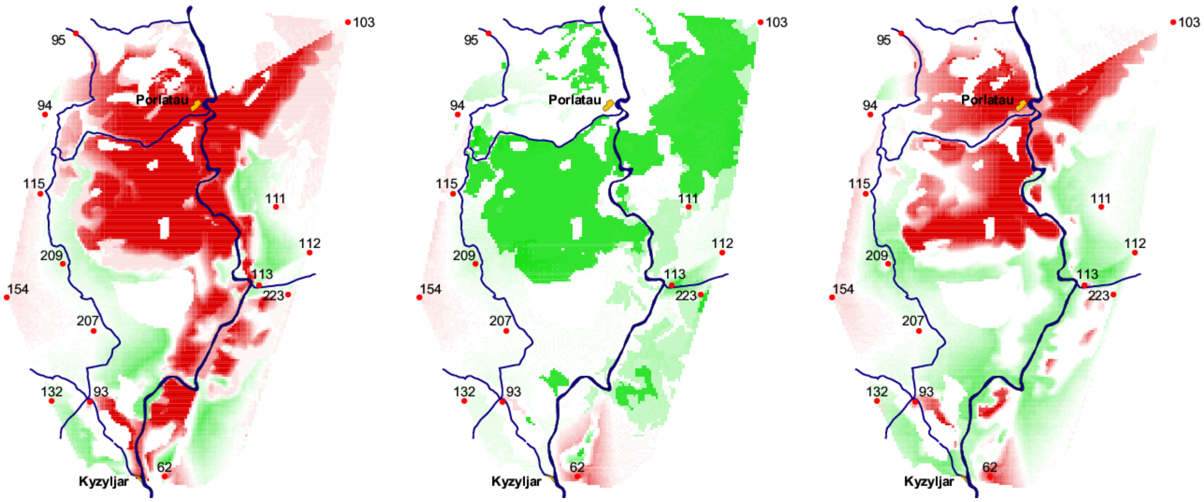
Groundwater In the sequence of the mean, non -spatial, annual groundwater level values no history effect as it was included in the regression model is visible. Mean annual values are repeated in the second 14 years, with the exception of the USER-1% scenario where the runoff increase over time. There are slight differences at individual sites, but they are not strong enough to influence the mean value. The runoff seems to affect the results of the regression models stronger than the gradient of the previous year.

The groundwater simulation overestimates groundwater values in the Northern part, which distorts the habitat index evaluation.

Habitat Suitability Index The mean annual, non-spatial index results, that show little variation between the different scenarios, reveal the importance of spatial analysis. The mean HSI values do not capture the differences in the scenarios because a change in input variables can lead to an increase and decrease of the index values at the same time but at different places depending on the evaluation of the individual site. Thus positive and negative changes



(a) Mean GWL Difference (b) Mean HSI Difference



(c) HSI Difference Year 13 (d) HSI Difference Year 24 (e) HSI Difference Year 28

Figure 54: Scenario SUPL+35%. Difference grid of the scenario and the reference scenario BAU. Mean gwl and mean HSI (above); HSI of high water year, low water year and last year (below). Red colors indicate a worsening of the situation compared to the BAU scenario, blue and green an improvement.

even out. HSI values in the individual cells cover the entire range of values between 0 and 0.96. The effects of the different scenarios as analyzed above seem realistic.

With an increase in water availability there is an increase in habitat suitability especially along the rivers. The river bars and their slopes are the natural habitats for the Tugai forests under non disturbed conditions. In the scenario that mimics "natural" runoff volumes (SUPL+35%) mainly the areas along the river become more favorable, thus confirming the validity of model outcomes. It is also anticipated that the site conditions along the northern stretch, which at present hardly receives any water, will improve with water allocation. This effect can clearly be seen in the ARAL10 scenario, which is the only scenario that allocates significant amounts of water to this stretch. The increase in HSI values along the river show that the model realistically represents the effects of increased runoff with no increase in floods. In this scenario no additional floodings occur, but groundwater levels are higher due to higher runoff.

The decrease in areas where the water table comes very close to the surface and that are regularly flooded is also realistic. Those sites are assessed less suitable for the Tugai forests and in future will rather play a role in the management of the aquatic ecosystems. Those sites are mostly located in depressions that in high water years will be filled with water.

It is questionable whether the strong negative influence of high groundwater levels in the determination of the index is justified. With the establishment of trees the groundwater table at most sites will lower. The negative effect of secondary salinization, which is the major reason for the lower rating of high groundwater tables in the index calculation, thus decreases fast.

On the contrary the good assessment of low lying areas in former water filled depressions under a low water scenario has to be taken with caution, since at those sites elevated soil salinity may negatively affect site quality.

9 Discussion

Discussions of the individual modules can be found in sections 5 and 6. Following is a general discussion of the chosen approach, of the integrated tool and its applicability to the given problem of water allocation in the Amudarya delta. Data and knowledge gaps that were discovered in developing the tool are pointed out.

9.1 Discussion of the TUGAI tool

Scenario analysis has shown that the tool discerns well habitat quality differences within one scenario as well as between scenarios of different water use or allocation strategies. The realistic responses of the models to chosen inputs ascertains that the selected habitat variables reflect key habitat requirements of the indicator species. Model outcomes are differentiated and complex. In their integrated assessment they go beyond the capabilities of individual experts because of the long time frame and the rather large spatial scale they consider.

Integration of water allocation modeling with assessment of landscape and ecological changes facilitates an integrated approach to water allocation management that does justice to the complex situation and problems in the Amudarya delta. The scope of the integrated tool is to facilitate discussion and evaluation of alternative management options by providing an estimation of ecological effects of the proposed measures. Rather large spatial and temporal scales have to be taken into account because of the interconnectivity of the irrigation networks in the the delta and the Amudarya river basin as a whole and the large time scales on which riverine ecosystems react to environmental changes. For ecological evaluation spatial heterogeneity has to be explicitly taken into account. All these constraints and the aim to use available information and data of various quality posed great challenges to model development. It has been decided to apply simplifications that are needed for model formulation for the given task rather to the approach and model structure than to estimation of a multitude of parameters. Parameters were complemented by expert knowledge. Most geo-physical and ecological processes have been treated as black box. It was believed that this approach is more appropriate for the given task, because the limitations of the approach can more easily be assessed and communicated to the users. Moreover, relative assessment is the major goal, since changes to ecological quality can only be assessed in relation to a reference state. Results should not be seen as absolute values or predictions.

The validity of the developed models nevertheless could not completely be ascentained. This question can only be resolved to some extent by use of the tool and observation of developments in the delta area. Although the ecological assessment is based on expert experience, through the integration with hydrology and the landscape, unknown aspects might appear. Adaptive management, which is an interactive process of policy development, implementation of measures in the real world, assessment of results and refining or change of the strategy, is a means to validate and improve assumptions and tools.

A scientific sound validation of model outcomes, especially the evaluation of specific sites, is only to some extent possible due to the use of qualitative information and the paucity of data on ecosystem response under changing conditions. The models were tested against monitoring data wherever possible. Nevertheless, the validity of assumptions as e.g. the low habitat suitability value of sites with a high groundwater level cannot be totally proven. This has to be taken into account when evaluating model outcomes. Again, expert judgment might be the best means to check the realism of the results. Scenarios should be developed and analyzed in collaboration with experts. This will at the same time facilitate the development of realistic assumptions for scenarios of water allocation and ecological restoration.

Additionally, criteria need to be defined for acceptable model outputs (Kliskey et al 1999). In the case of this study outputs were considered acceptable where suitability ratings were "reasonable" considering knowledge of the ecology of the species and the actual distribution of Tugai forests.

Following is a short discussion of the applicability and potential improvements to the three modules in view of their use in the integrated tool. The models themselves were discussed in the respective chapters.

To enhance the predictive capabilities of the **water management model** AmuEPIC, a hydraulic model with an open channel routing routine should be developed and linked to the water management model and the GIS. This would improve the estimation of river stage and thus the prediction of groundwater levels and flooding events, but requires detailed data on channel properties. Alternatives for generating the water inflow to the delta, such as probabilistic approaches or precipitation- runoff modeling for the entire catchment, should be studied and tested.

The AmuEPIC model developed for the tool is fairly complex and can only be handled by a hydrologist who has understanding of the local situation and the basic principles of water allocation in the Amudarya river delta. Because the tool is intended primarily to study water allocation issues by water managers with respect to their ecological effects this is not seen as a serious drawback. Nevertheless hydrologists will have to be trained in the use of the water management model or knowledgeable people have to assist in scenario development. The complexity of the water management model was needed to account for the difficult water allocation task in the delta area.

Simulation of **groundwater table** and **flooding regime** have to be seen in the context of the ecological assessment they were planned for. They provide the dynamic landscape resulting from the selected spatio-temporal water distribution, that is the basis for evaluation of long term effects of water management measures. Because of their rough estimations, only relative assessment of model outcomes should be performed. They are not intended for quantitative predictions. It is doubtful that mechanistic models can be developed for groundwater flow or flooding regime in the Northern delta region without major data campaigns in the field and by remote sensing.

A better mapping of groundwater and flooding dynamics based on physically based approaches would enhance the possibility to study their effects on the ecosystems and to evaluate uncertainties and their effect on the outcome of the ecological assessment.

For **ecological assessment** Tugai forests were selected based on their indicator function for an ecosystem that is characteristic for a "healthy" state of the delta environment prior to degradation and that is valuable for the delta and its people. Development and assessment of alternative management scenarios is seen as a first step in determining restoration and management targets and fostering a discussion on values and services that should be protected. It also promotes a better understanding of potential outcomes of measures as well as conflicts of interest between involved parties.

First testing results indicate that there is a potential for increase of water discharge for environmental needs in the northern delta area, while, at the same time, providing irrigation and other water users with sufficient. The possibilities and implications of these results have to be discussed in view of the current situation and future development goals of the region. The tool might overestimate actual water availability to some extent, because the optimization algorithm is provided with more complete knowledge than the actual water manger in the field. The uncertainties the manager is confronted with became evident for example at the beginning of the year 2000 where water managers released large amounts of water to the delta area in January and February to protect the reservoirs expecting a high water year. In summer only little water arrived which led to a severe shortage. Losses might be underestimated, especially in a low water year, where much water is illegally withdrawn. Nevertheless these results point to the fact that water deficiency is to a large extent an organizational and management problem. In its official bulletin ICWC states that water expenses could be decreased by up to 20 km^3 per year by organizational and control measures alone (ICWC 1998), confirming these findings and the realism of the selected scenarios. Ecosystem rehabilitation could partially be achieved by better water distribution.

Floodplain inundation, which plays an essential role in sustaining former hydromorph ecosystems, is to a large extent determined by water management and timing of peak discharges in relation to irrigation schedules. Additional potential for ecosystem rehabilitation without any additional water costs lies in the management of flooding events. In the TUGAI tool newly designated flooded areas, be they semi-natural or artificial, can easily be included in the assessment as another management scenario.

Analysis of model results and their comparison with the real situation reveals many options for improvement of current water allocation strategies. Better forecasting of water availability is a major premise for better water allocation, next to demand side management, based on the real needs for agriculture and the environment. Water saving measures and changes in land use and cropping pattern, as they are envisioned by the basin countries and recommended by numerous international projects, will make additional water available. More transparent decision structures would enhance not only more efficient water use but also assessment and modeling for decision support.

For planning of actual restoration measures water demand of a site under given soil conditions, evaporation and water demands of the plants has to be determined. Potential and costs of artificial watering including costs of water have to be investigated using cost-benefit analysis. The tool allows for changes in the structure of the irrigation network, e.g. creation of a new canal to irrigate the respective site and allocation of the necessary water, but it does not have any facilities to calculate its cost. The costs included so far is the water that will be missing somewhere else and will lead to a worsening of the situation there.

9.2 Discussion of approach

Models based on the methodology of relative assessment have been used extensively and with success in ecosystem restoration projects such as e.g. the restoration of the Florida Everglades (DeAngelis et al. 1998, Curnutt et al. 2000). They facilitate extensive analysis of alternative management strategies even in situations where the knowledge on ecological details is not complete. In the given study for the Amudarya river delta, the approach was extended by attempting to facilitate a dynamic assessment of changing habitat conditions. The spatially - explicit species index models developed in the ATLSS approach (Curnutt et al. 2000) evaluate suitability of a given site for the selected species only for a given year, e.g. a wet year versus a dry year in comparison to a reference scenario. They do not consider the development of a site during the simulated time or its past history. The habitat suitability model developed for the aim of this study takes the past flooding regime into account as an information on the history of the site. The same accounts for the statistical groundwater model.

Static versus dynamic The objective to give the models dynamic characteristics has only been partially achieved. The habitat suitability evaluation is too strongly affected by annual variances in runoff. Incorporation of the history of a site into its evaluation in the TUGAI tool seems to go not far enough. Effects of single events, especially floods, should have less influence in favor of measures that evaluate the history of a given site. For habitat evaluation history of groundwater levels might also be taken into account, next to the flooding history. This should be tested in future. On the other hand such approaches are limited by the lack of understanding of the effects of past events on, for example, the species potential to survive a less suitable time period.

The strong influence of single events might be reduced by lowering the resolution of the habitat evaluation and increasing the influence of past events on the present day evaluation of a site. It was attempted to capture long term effects of proposed measures by calculating mean values of habitat indices over the modeled time period. Mean values reflect general outcomes of the simulated hydrological scenario over the entire simulation period. Through the aggregation important information on the temporal development is lost. Although, temporal aspects play a major role especially in scenarios where a gradual change in water availability is assumed.

Expert knowledge Similar to other ecological impact assessments on a landscape scale, this study tried to "address a problem that is extremely unstructured, highly uncertain and poorly understood by using "macroknowledge" "(Bojorquez-Tapia et al. 2002). Expert knowledge (= macroknowledge) is used to map ecosystem response to changes in environmental conditions, which is understood and documented mainly in a descriptive way. The environmental conditions on the other hand are best represented with mathematical and statistical approaches. This hybrid approach makes best possible use of a variety of information sources by selecting the approach that best fits the respective data. Such combined approaches translate a wide variety of information to a common language to assess ecological effects (Silvert 2000). Opposite to e.g. mathematical approaches that are constrained within a rather rigid modeling framework, they do not have to discard information because it does not fit the demands of the model. On the other hand there is no rigid framework for testing their results. The choice to use expert knowledge is also a concession to the fact that data and knowledge gaps are still too large to adequately represent causal relationships for the ecosystems or species in the delta. The application of process based approaches for landscape scale impact assessment for policy support will always be limited by the high data demand, uncertainties and the mostly small time frames for their development.

Interpretation of results The evaluation of outcomes of a habitat suitability index calculation is more open and the chances for false evaluation are reduced in comparison to other approaches such as species distribution models (Lischke 1998). It is more honest to rely on a habitat approach than on trying to predict species abundance and water use on a specific plot, which would suggest more control and deterministic knowledge on the developments then there realistically exist. Every approach has to be seen in the light of its possibilities and limitations. The simplicity of the environmental models of the tool permit an easy assessment of their limitations, sources of error and uncertainties.

A major contribution of the tool is its ability to structure a multi-objective policy making problem and provide a framework for analysis and discussion of the outcomes of various options. Aspects that are not taken into account in the models themselves, such as anthropogenic influences on the ecosystems or socio economic aspects, can enter the assessment through the scenario development. Realistic scenarios reflect the given external conditions. If a group of people with various backgrounds analyze the results a differentiated interpretation is possible that takes factors not explicitly included into the tool into account. In their study of three major US Ecosystem Management Initiatives (San Francisco Bay-Delta, Columbia River Basin and Florida Everglades) Roe and van Eeten (2002) found that joint scenario development exercises involving e.g. ecologists and hydrologists increased trust, focused, helped to find key issues and identified crucial gaps in modeling and research. A shared language and a better understanding of the system evolved.

Uncertainties Models should reflect the range of potential outcomes to possible decisions in order to give an estimation of the uncertainties of the results (Ewel 2001). Uncertainties propagate through the different models of the tool and influence model outcomes to varying degrees. Errors in river runoff and river stage estimation will for example affect the estimation of groundwater levels in the groundwater model. Their influence could be tested with statistical approaches. The range of realistic groundwater values would then be taken into account in the habitat suitability model. The effects of those uncertainties are alleviated in the current approach to some extent by the fuzzy methods used for evaluation of suitability of groundwater levels for Tugai forest habitat. Another potential solution to include uncertainty in scenario analysis would be the use of Bayesian decision analysis, which allows uncertainty about inputs and outcomes to be incorporated into the choice between different courses of actions (Harwood 2000).

Major uncertainties in data and model structure, their implications as well as possibilities for their reduction are discussed in the sections of the individual models (section 5 and 6).

The relative evaluation of the scenarios through the difference grids reduces the influence of uncertainties. It is assumed that variances are similar in management and reference scenarios. The initial values for groundwater simulation, on the other hand, directly affect groundwater estimation and assessment through the habitat index, which is especially critical around a depth of 0-3m. Initial values are taken from monitoring data and are assumed to be more or less correct.

Resolution Intact riverine landscapes are characterized by highly dynamic processes and continuous change, where catastrophic events play an important role (Jungwirth et al. 2002). Those dynamics are neglected in the given tool by operating on the monthly and annual scale. With respect to slowly developing Tugai ecosystems small scale changes might be less influential, although the impact of short term stresses like a drought or long inundation are not very well known. They might have a stronger effect on the viability of the trees than assumed in the index evaluation. More research is needed to clarify the effect of short term stresses.

Because of the reduction of the river network to the main river for the simulation of the groundwater table the direct effects of new canals or increase in discharge in a specific canal on groundwater levels cannot be assessed. As to the monthly resolution in the flood simulation small scale floods are omitted.

Limitations The empirical models used for the environmental assessment in this study sacrifice generality for realism and precision (Guisan & Zimmermann 2000). The designed tool is only applicable for semi arid delta regions where Tugai forests are a dominant landscape element. But, it can easily be expanded to include other representative species or communities, if sufficient data on hydrology and ecology are available. A major advantage of habitat suitability models is their quick and easy development, using expert knowledge or data. However, they should be seen as hypothesis of species-habitat relationships and not interpreted as reliable predictions of species response (Ranci Ortigosa et al. 2000). Similar approaches using statistical relationships between species and environment have been used e.g. in the INFORM tool (see subsection 3.3.2), although on a significantly smaller spatio-temporal scale. For the aim to provide decision support for the Amudarya delta, model outcomes should be as realistic as possible.

A serious shortcoming of the given approach that has to be considered when interpreting model results is the lack of feedbacks between different components of the system. In habitat suitability evaluation for Tugai the effect of plant activities on site conditions is not considered. A Tugai forest existing on a site will significantly influence groundwater and soil conditions and enhance the suitability of the site. Index calculations performed with the tool assume sites that are not influenced by any vegetation or human action. Thus areas that are evaluated unsuitable because of high groundwater levels might still be of satisfying quality. This has to be solved by analyzing conditions at each site individually. The existence of Tugai at a site in this case would act like a buffer. For high groundwater levels at a site the index model represents the lower value of habitat suitability, which is a desired feature. The nature of the habitat assessment prohibits the incorporation of feedbacks, but tighter coupling of the hydrological components, surface and subsurface flow, would be possible. For a relative comparison of the effect of different scenarios on the ecological quality of the landscape this shortcoming is less significant.

By modeling species habitat, biotic factors and anthropogenic factors actually influencing species distribution are neglected. Although, human influences on a given site can easily be determined and their effects evaluated. For sites judged as highly suitable that are located close to a settlement, grazing through animals will lower its actual suitability. Since scenarios are developed assuming that general conditions including human influence do not change, this does not affect the comparison of different scenarios. Scenario results depict the potential suitability under non human disturbed conditions.

Conclusion The tool allows an assessment of effects of alternative scenarios on the ecological situation of the Northern delta with respect to terrestric environments. It cannot provide an exact quantitative prediction of future biotic group responses due to the chosen approach, uncertainties in the data, model assumptions and the neglect of other influences, as mentioned above. The state of the semi-natural ecosystems in the delta region is not only dependent on the chosen hydrological regime but to the same extent on human action such as logging, animal grazing and land management practices. The impact of people on the ecosystem depends not only on the ecological characteristics but to the same extent on socio-economic and demographic factors that motivate human action (Ewel 2001). Market forces that influence the stakeholders and affect the resource and the link between ecological productivity, economic productivity and social well being have to be better understood (Ewel 2001, Hanna 2001). The same accounts for the socio-economic, political/legal and cultural settings that, especially in the countries in transition in Central Asia, play a crucial role in priority setting and policy making. These considerations have to be included into the process of scenario development and analysis where they will seriously affect goal setting and planning.

The HSI evaluation method indicates the direction and necessity for more detailed research on conservation issues and water management in the delta region. The aim of this thesis was to start at a coarse level to see whether a simple but meaningful assessment is possible with limited means. It should be seen as a first step for a more comprehensive analysis and management support.

To effectively use the tool people have to be convinced by the results of the modeling and trust the methods. Those in turn have to be transparent and easy to transfer and explain. In a management culture that has relied many years on planning in state enforced five year plans, convincing will need some effort.

9.3 Data and knowledge gaps

Development of the modules and their integration into the tool revealed data and knowledge gaps for integrated assessment of resource management problems of different character. They concern question of the type of data, their quantity and quality, their spatial and temporal resolution, connectivity or interrelation of the data especially across disciplines, but also questions of the right approach to represent and integrate research findings of each discipline as well as their integration and the appropriate presentation for policy makers.

The principle lack of specific, reliable data of the physical and ecological systems of the Amudarya delta has been mentioned extensively before. Insufficient input data challenges almost every modeling study of real systems to varying degrees. For landscape oriented modeling the demand for spatially explicit representations significantly increases data needs. Large scale studies often have to work with simple estimations. Increasing availability of remote sensing data partially solves this problem. Overflights over the delta region would facilitate the creation of a more detailed digital elevation model (DEM). The resolution of the DEM is very important for the accuracy of the model (Hüsing 2002). There are remote sensing methods to improve the groundwater database.

Data Quality of monitoring data is another problem, which is especially acute in Central Asia, but whose dimensions are difficult to estimate. Data are in most cases not provided with metadata, which makes an assessment of their quality difficult. There are caveats with the allocation data in Central Asia, which make analysis difficult (Micklin 2000). For hydrology, e.g the two databases available (Hydrometservice and WARMIS) showed serious inconsistencies and missing data. Runoff values differed significantly. Those inconsistencies are mainly caused by different accounting systems and yearly changes in ICWC reporting practices (Micklin 2000). Quality even of official data is sometimes doubtful, which could be seen with river runoff data at Kyzyljar in 2002, where groundwater inflow was declared as river runoff. Data have to be carefully examined before use and, if possible, checked in the field. Their sources have to be known. Results of any modeling should be seen in the light of the high uncertainty in hydrological input data. Fuzzy methods or methods that use the statistical distribution of a variable or parameter could be applied to deal with data uncertainty in modeling.

As to the Aral Sea GIS and the vegetation database, both are in many cases incomplete and badly documented. It was attempted to determine origin of the data as good as possible. Joint field work helped to estimate quality and application range of the ecological data. Since the non-spatial database and the Aral Sea GIS were compiled by the same people they are not independent and cross checking between the two sources as carried out for some spatial data is not a true validation. Although, there were no other data available for an independent validation.

The non static nature of environmental data is another handicap. Most of the original GIS data is based on maps from the 1980s. This was probably the time where most serious degradation took place (Novikova 2001). They thus might picture a slightly different situation than there is in the delta today. For ecological evaluation only geomorphology was used directly from the Aral Sea GIS, which will not change in such short time frames. The delta landscape is constantly changing making it difficult to accurately represent its actual state.

Hydrological knowledge is often very detailed but in a resolution that is not applicable to larger scale questions or for integration into assessment tools. Interests of hydrologists and ecologists often lie on different temporal and spatial scales. Questions researched in hydrology are often not ecologically relevant and vice versa.

Expert knowledge is qualitative and strongly subjective. The context and method to acquire the knowledge can influence the results, since experts make associations with a given situation or experience which might vary from case to case. In the case of this study inconsistent classifications occurred, which have been clarified in additional interviews whenever possible.

Socio-economic aspects of policy making and resource management are often less well known than the physical and ecological dimensions. The linkage between the hydrological-ecological and economic and societal dimensions and their representation in a decision support tool is a major research task.

Knowledge of system dynamics More information does not necessarily increase the accuracy and realism of models. It is essential to determine which data at what spatial and temporal resolution are needed for a given problem. The prerequisite is thus a thorough understanding of the system, its bio-physical processes, the forcing powers and interrelationships between structures as well as processes to determine the data needed for their representation. It appeared that such functional understanding of ecosystems in the delta area is to some extent still missing. While the response of Tugai to changes in groundwater level are largely known, there is not much knowledge on the physiological effect of floods on the trees or critical values of groundwater salinity. The demand is greatest for comprehensive data, that provide information in relationship to other factors, such as biological data that have reference to the environmental settings they were taken in. Another serious shortcoming are temporary resolved data that help to understand dynamics of a species or community. Although there is a general understanding of the direction of community development under changing environmental conditions it is rather difficult to formalize this mostly qualitative knowledge into information that can support actions to prevent their development into undesired directions. Such ecological data are difficult to obtain and rare. Additionally, more sophisticated methods are needed to transfer ecological knowledge to management.

Ecosystem adaptation & human learning Degradation in the delta area has reached a very high degree, imposing doubt as to whether its ecosystems can be restored to a condition similar to former times. Novikova et al. (1998) note that partial restoration of the deltaic plains with watering induced transformations of opposing character, resulting some times in new formations of Tugai, but sometimes in their further degradation. Further research is need on how ecosystems as well as human systems react to unpredicted changes, such as short or long term disturbances. When dealing with ecological systems one has to take into account their resistance and adaptability as well as irreversibility. Little is still known on what causes an ecosystem to react in a specific way and what mechanisms it relies on to resist or adapt to changes. The thresholds after which an ecosystem cannot return to its initial state are often not known and the implications of irreversibility for ecosystem management unclear (Chavas 2000). Functional changes can often be prevented by a structural change, which is a behavior that is outside of the abilities of most models (Morall 2003). A possibility to deal with this is the use of models that allow for dynamical structural change (Joergensen 1999), e.g. by using genetic algorithms (Morall 2003).

Due to the uncertainty that is associated with a decision that is based on poor information, it has to be refined when more information becomes available (Chavas 2000). This process of learning can be enhanced by gathering of more information e.g. through adaptive management, but it will also to a large extent be provided by research. The incorporation of learning into management and policy support models will also create a new view onto long term resource management questions and issues of sustainability. Research on methods that facilitate incorporation of learning into decision support tools and their application to a real world problem would enhance understanding of feedbacks between policy measures and their effects (see e.g. Carpenter et al. 1999). Again, interactive scenario development can include many of these aspects through human involvement in scenario development.

Scales Model development on a landscape scale will always need to depend to some extent on up- and downscaling of parameters and processes in space and time. The validity of applying assumptions and methods across different scales is in many cases not well known. In this study these difficulties occur especially with the surface and subsurface water distribution. The more complex model systems become the more difficult scaling issues will be. For ecological assessment selection of the right temporal and spatial scales for evaluation as well as measures is a very difficult question which is actively being researched.

9.4 Water management alternatives and the ecological situation in the delta region

Changes to water management policies, although demanded by all involved parties, is a difficult issue because of the complex problems of the region. The present day situation has to be seen in the light of the past Soviet history of the region. Politics and water management where controlled by Moscow and determined on a basin wide scale. The same accounts for hydraulic constructions to facilitate irrigated agriculture. Reservoirs were built upstream in the mountains where evaporation is lowest, while their water was mainly used downstream in the irrigation areas of the plains. Hydropower production only played a minor role and was always second in priority for water use. With five independent nations this has changed today and conflicts of interest in water use are a common dispute between the states. After independence the five countries have realized the need for cooperation to allocate the transboundary water resources. Nevertheless the difficult task of reforming the old Soviet system of water quotas so that they reflect current water needs has not been tackled so far.

During Soviet times agriculture was completely restructured from efficient small scale enterprises to large, and often inefficient, collective farms. The agricultural and thus water management system grew under the principle of state ownership and tight control. Centralized management allowed little initiative on the local level. Planning is often compartmentalized and in many cases agencies collect and analyze data without much communication with other agencies (McKinney 1997). Information on costs and revenues of production are often not available to the farmers.

Many of the above named reasons are major sources of today's overuse of water resources and there are efforts to change them. Nevertheless water demands for the economy, especially irrigated agriculture, are continually growing. The states are in a situation today where all available fresh water resources are used. Northern Afghanistan will claim its fair share of the waters of the Amudarya river to develop irrigated agriculture in the north, which has been disfunctioning in many years of war. This will decrease the amount of water for Uzbekistan and Turkmenistan. The need for changes in landuse and agriculture is evident.

On the other hand there is realistic potential for significant water savings in agriculture. ICWC (1998) sees ineffective use of water resources mostly in agriculture as the main cause of the crisis and gives a potential of up to 30 km^3 that could be saved and diverted to the Aral Sea. About 15% of the irrigated land in the Aral Sea Basin is in extreme unsatisfactory condition. Taking these lands out of production would lead to significant water savings of approximately 15-20 km^3/year and more (UNEP 2002).

In reality it is at present doubtful whether the ecosystems will receive any of the access water, as long as the regions economy relies heavily on agriculture and needs all water resources to feed its population. River floodplain restoration takes place in the area of conflict between economic and socio-political demands and ecological targets (Jungwirth et al. 2002). Rehabilitation of the semi-natural ecosystems in the delta region would not be sustainable nor affordable or justifiable, would it not provide a source of income for the local population. The semi-natural ecosystems have always been part of the living basis of the local population. People will have to search for new sources to provide their income while securing their natural environment by rational rehabilitation and an extensive use, maybe different from that practiced today (e.g. ecotourism, hunting tourism, etc.). For the northern delta region, where the conditions for irrigated agriculture are unsatisfactory, sustainable land management might rather focus on animal husbandry, fish farming, ecotourism, hunting and alternative forms of agriculture using e.g. high saline drainage waters. Management and use of the remaining semi-natural ecosystems have to be seen in this context.

Restructuring of agriculture is a long term process, but solutions to improve the ecological situation have to be found at the same time. Given the scarcity of water resources, strategies have to be found that make best use of the resource. This includes multiple use of the water as well as best possible use of high water events. Saline drainage waters that originate from irrigation or flushing of the fields to leach out salt, can be reused for irrigation of salt resistant plants. Drainage waters are currently also used to provide water for delta lakes. Since reservoirs always receive water with high priority, terrestric ecosystems close to the reservoirs are most promising for restoration.

Results of scenario analysis and analysis of river discharge time series and water use in agriculture have shown that there is potential to use access water in high water years for ecosystem rehabilitation. Flood waters could be diverted to suitable areas instead of letting them flow to the dried out sea bottom of the Aral Sea. Using this additional water to flood existing Tugai forests would already have a positive effect on their condition and, with some support in form of watering, might facilitate their establishment in other places. A recent study in California has shown how stormwater management can improve water supply reliability and reduce environmental impact in another water stressed area (Wilkinson 2003). This confirms the possibilities of this aspect of water management, which should be further studied.

Treshkin (2001) proposes that a total of approx. 7.5km^3 annually are needed to flood the promising areas in the delta area for a period of 1-20 days from July to August for restoration. With proper water management this is feasible, as shown before, except for extreme low water years. A restoration strategy has to react flexible to the available water resources and allocate water to the sites with different priorities according to their current needs. The minimum amount of water needed to achieve the commonly agreed upon restoration goal, its timing and the length of potential drought periods for single forests have to be determined to develop an effective strategy.

10 Conclusion & Outlook

The GIS-based TUGAI tool presented in this work offers a simple, problem-oriented method to evaluate alternative water management strategies for the Amudarya river delta from an ecological perspective. It provides an interactive framework for comprehensive exploration of potential water management measures to improve the ecological situation in the northern delta area. Water management in the Aral Sea Basin today has the single objective to provide irrigated agriculture, by far the largest water user, with its water needs. Through the integration of an irrigation water allocation model with environmental models, multi-objective strategies for water allocation can be developed and assessed. The Tugai tool provides water managers and policy makers not only with a detailed model to determine optimal water management strategies serving multiple users, but also to directly assess the ecological effects of their choices. This is a first step towards a differentiated and integrated view on the complex problems in the Amudarya delta, where scarce water resources are a major factor determining future developments.

This study has investigated methods to integrate and formalize the available heterogeneous knowledge on landscape processes and interrelationships of the delta system to support policy decisions. Optimization, statistical, rule-based and fuzzy approaches were used to develop models that best represent the often incomplete or highly uncertain information. The integrated tool makes this knowledge easy accessible for policy development and decision making by non-experts. It became apparent that the understanding of ecosystem response to alterations of the environment is often too incomplete to derive policy recommendations indicating the risk and potential of given measures. Measures to quantify the effect of actions are difficult to determine because of the complex behavior and adaptability of ecological systems to change. Equilibrium based, static approaches are not suitable to map transient behavior, which in most real systems prevails. It was attempted to include dynamic aspects into static environmental models and assessment by taking the history of a site into account, but other important aspects of dynamic systems such as feedbacks are neglected. Here, further research would be very interesting.

In this thesis a detailed model of resource allocation was complemented by simple, qualitative models for the simulation and assessment of landscape dynamics. A procedure of relative assessment was chosen, because it provides a better means for comparison of scenarios, avoiding the temptation to interpret absolute values as certain predictions of future development. Scenario results indicate an optimal solution to the given management task, which can serve as a goal for the implementation of measures in reality. The strengths of this approach are the possibilities to find strategies that best suit the needs of agriculture and the environment. Potential conflicts with other water users and tradeoffs in the spatio-temporal distribution of the water resources can be assessed.

The realization of the tool in ArcView GIS proved to be a good method. Many users are familiar with a its graphical user interface and can thus be easily guided through a scenario run. In the water management model policy choices and general changes to water availability in the delta area can be expressed as alternative water supply and water allocation scenarios. Through simple interaction, the user submits the resulting landscape changes to an ecological assessment procedure and compares the results to a reference scenario. Changes in the ecological conditions under a given management scenario are directly visualized on color coded maps and ready for interpretation and analysis.

Future development of the delta region is to a large extent the results of policy choices in the Aral Sea Basin, Uzbekistan and the delta itself. The lack of common goals for resource and ecosystem management in the Amudarya delta in particular and the Aral Sea Basin in general, has impeded integrated measures and actions to improve the situation so far. Potential water and landuse strategies are constrained by uncertainties in future water availability, the demands of multiple users and political will. Scenario analysis with the tool helps to investigate tradeoffs and uncertainties and to assess their effects on the ecological conditions in the delta. Alternative options to deal with given uncertainties can be tested. A scenario with a decrease in water supply to the delta for example, has shown that a further decrease in water supply to the delta will have significant effects on the ecological state. However, what is even more important, scenario analysis will initiate a process of reasoning and search for measures to deal with the situation. The tool can be used in workshop settings involving policy makers, hydro-engineers, ecologists and local people, which will enhance discussions and create awareness for different views of the current situation and its desired future development. By facilitating discussion and assessment for a wide range of stakeholders, different views on the problem are considered.

Ecosystems in the northern delta region might not be restored and people rather brought to other places. The question whether ecosystem rehabilitation is desired and the necessary efforts can be undertaken or whether alternative uses or no use of the land are more appropriate, has to be solved by policy makers and the people. Alternative vegetation e.g. might be established on high saline soils and the bottom of former lakes might be rather used for grazing and fodder production. To answer such questions the potential of the delta region under current and proposed future water management have to be assessed. The assessment performed with the TUGAI tool gives an idea of the potential of the northern delta region for ecosystem rehabilitation using additional water in high water years or made available by water saving measures in agriculture. However, it can only assist in evaluating different options for policy decisions that have to be taken by the governments and people of the affected regions.

Awareness building is one of the major objectives of several current large scale projects (e.g. Aral Sea Basin Program (ASBP) 1998) and seen as an important measure to achieve water saving goals (ICWC 1998, ASBP 1998). In many cases people are not aware of the causal relationship between their own or state action in irrigated agriculture and the deterioration of their environment (ICWC 1998 and personal observation). The TUGAI tool will assist in creating awareness by confronting decision makers and stakeholders as well as planners and operators with the ecological implications of their judgments and policies. In the education of future water engineers and operational managers such an experience would increase sensitivity to the consequences of water construction and allocation plans.

The development of this prototype has to be seen in view of the fact that decisions on resources allocation have to be taken with incomplete knowledge today. The tool makes best possible use of the available information to facilitate scientific based policy making. A truly integrated view on water, land and ecosystem management issues in the Aral Sea Basin will need more research, especially on the socio-economic, political and legal boundary conditions and the development of additional and, in some parts more detailed, models. Research is necessary to facilitate the transfer of the gained knowledge on critical functional characteristics and processes to policy making.

Possible Extensions of the TUGAI tool The needs of the Tugai forest are only one aspect of the spectrum of ecosystem demands. To study tradeoffs in water allocation between different ecosystems of the delta the needs of ecosystems other than Tugai have to be assessed. In the case of the Amudarya delta aquatic ecosystems in lakes and canals represent another important ecological component of the delta system. Habitat suitability index models should be developed for aquatic animals, especially fish, and included in the assessment to account for tradeoffs in water allocation for restoration goals.

From the technical side the process-based modules of a future tool should be more tightly coupled. In fully integrated models each submodel has a set of drivers, state variables, flow variables and processes which are linked with each other, the state or flow variables of one submodel are used as driving variables of another (Antle et al. 2001). In this way important feedbacks would be incorporated and could be analyzed.

Performance measures for policy decisions in form of measurable objectives have to be defined. The determination of measures to value ecosystems and ecosystem services is an objective of research activities for wetland restoration in general. For realization every potential measure will be evaluated as to its costs and benefits. In the Amudarya delta a true estimation of the costs of any measure will only be possible when the water needed for their realization has a real price.

Potential applications of the tool in goal finding and policy making processes are all aimed at the primary goal of this thesis, to make scientific knowledge accessible and applicable for policy making. Future use of the tool in joint workshops in Central Asia can be a first test whether this approach is applicable and useful in the given situation and achieves the intended objectives. Given its usefulness and validity in addressing the needed problems, simple models for other ecosystems, for the socio-economic aspects and for hydrological prediction should be developed. Next to that it is necessary to study and take into account the currently ongoing assessment of alternative agricultural developments.

Issues of conservation and rehabilitation of the remaining Tugai forests in the delta area are receiving more attention. An upcoming project of the United Nations Developmental Program (UNDP) to be financed by the Global Environmental Facility (GEF) focuses on biodiversity conservation by restoring Tugai forest. At the same time the local population will be provided with services they can receive from a sustainable use of the forests or alternative compensations. The TUGAI tool will be used in the planning and implementation stage of the project to support discussions with stakeholders, especially concerning water allocation questions.

Various studies have shown that many of the current problems of the Aral Sea Basin in general and the Amudarya delta in particular are caused by ineffective management and use of the water resources. Even with growing population the region has enough water for the economy, humans and the environment. Better spatio-temporal water distribution based on scientific knowledge and experience would already bring improvement for the ecological situation with relatively small cost and effort. Scenario analysis with the TUGAI tool can be a first important contribution.

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A Annex

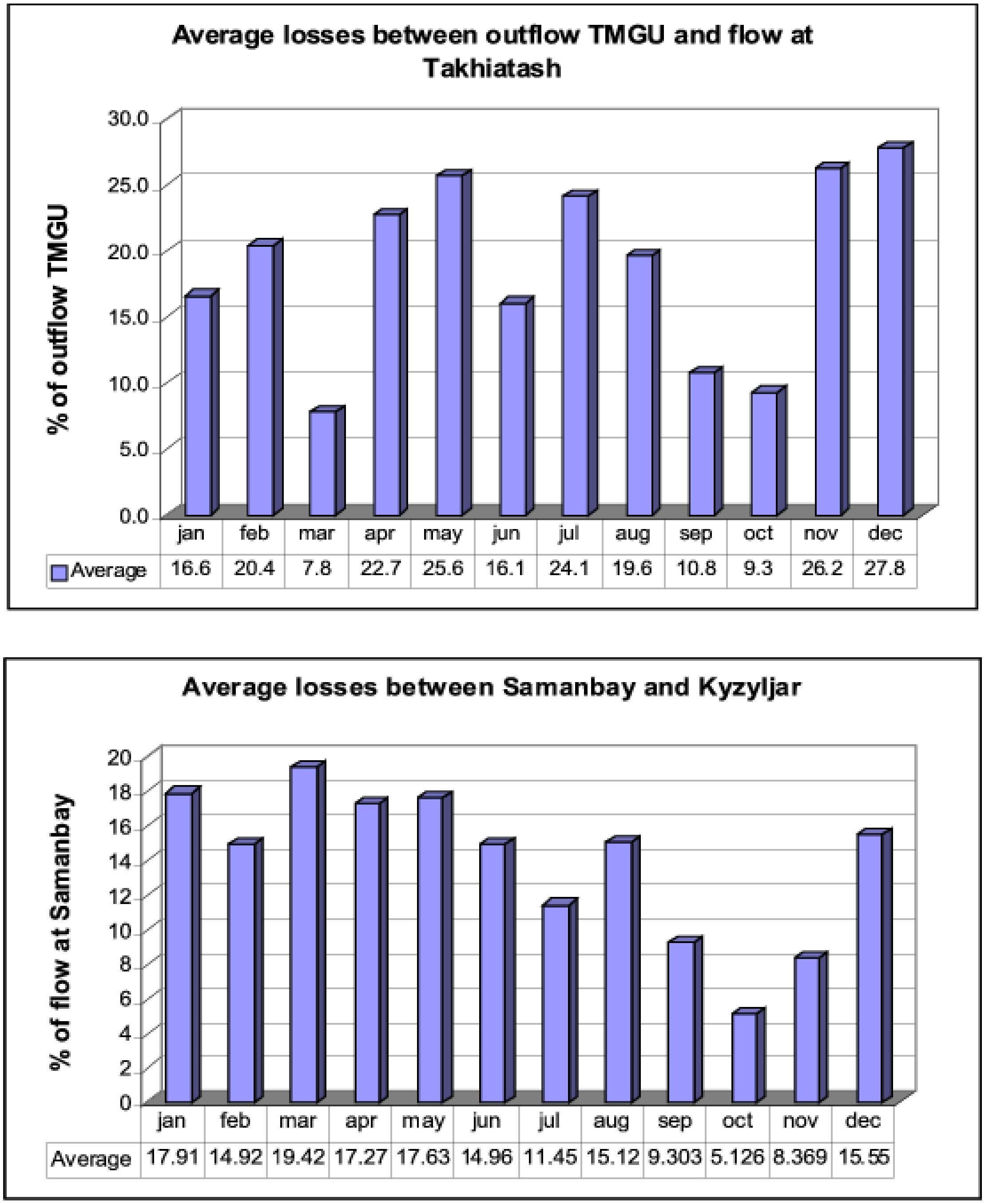
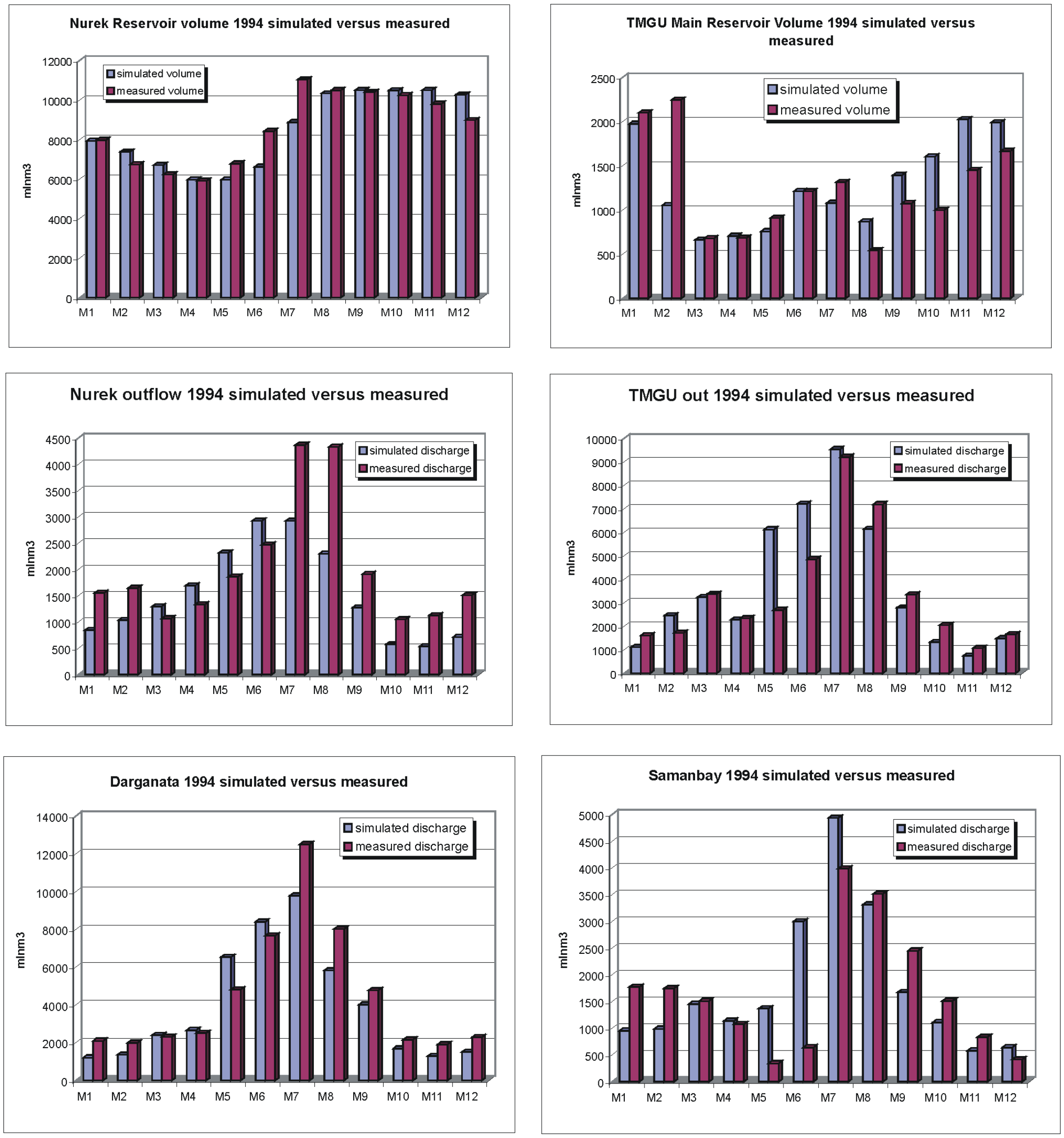


Figure 55: Mean monthly losses in the middle reach between TMGU and Takhiatish (dam close to the river station Samanbay) and Samanbay to Kyzyljar as they were included as input data for water losses in the river and delta model (AmuEPIC).



Nurek Reservoir volume 1994 simulated versus measured

TMGU Main Reservoir Volume 1994 simulated versus measured

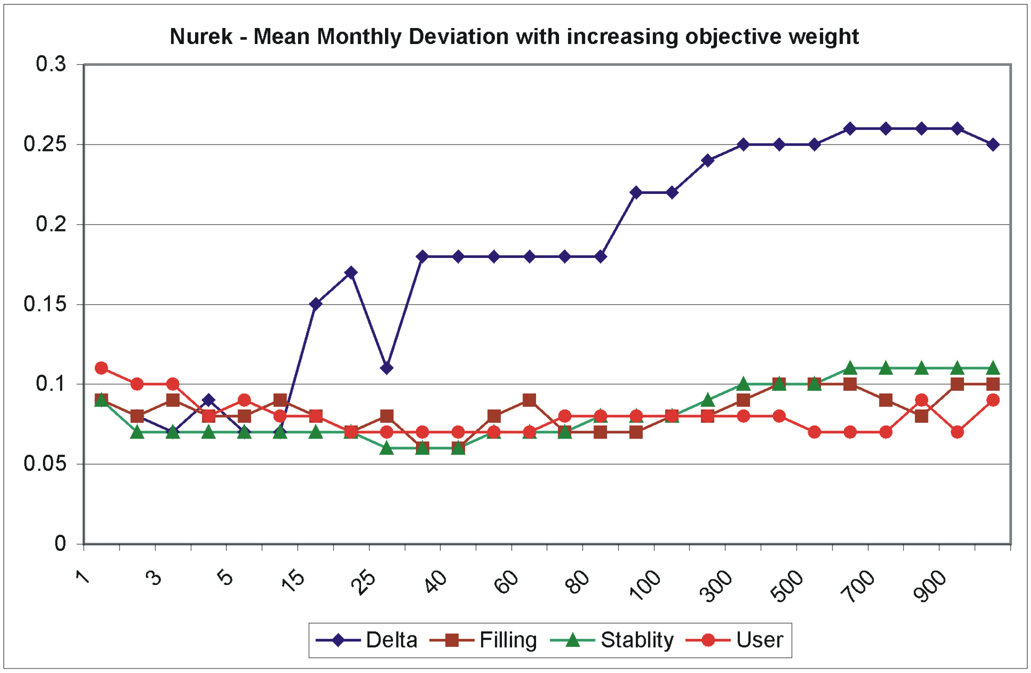
Nurek outflow 1994 simulated versus measured

TMGU out 1994 simulated versus measured

Darganata 1994 simulated versus measured

Samanbay 1994 simulated versus measured

Figure 56: Results of the calibration run for the high water year 1994. Figure show modeled and observed values for volumes of Nurek and Tyuyamuyun reservoir(above), mean monthly outflow for both reservoirs (middle) and river flow at the gaging stations Darganata (inflow to the delta) and Samanbay (northern delta).



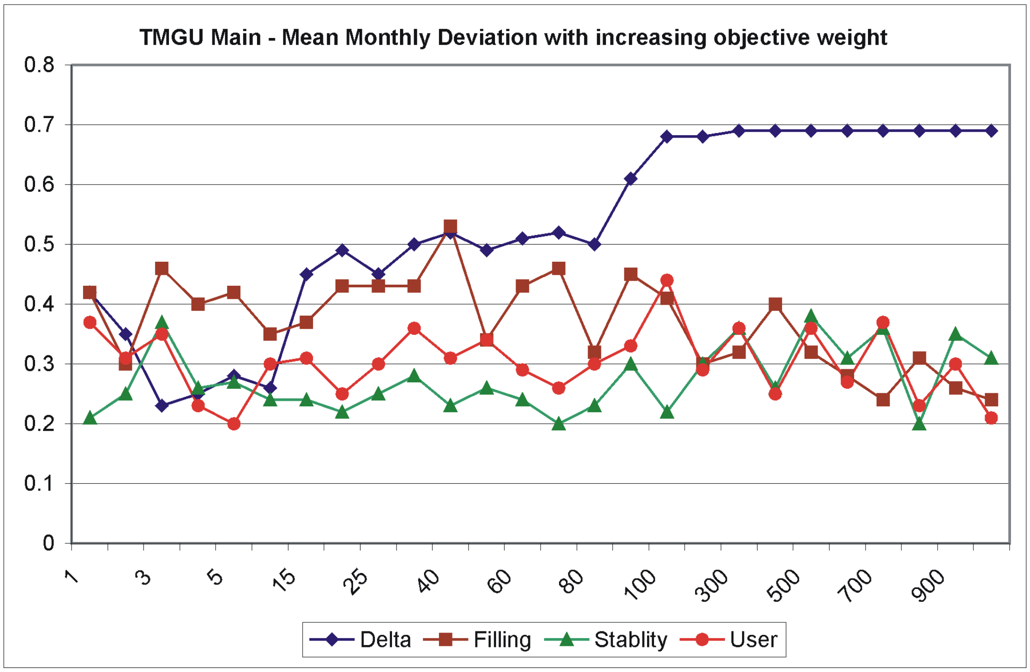
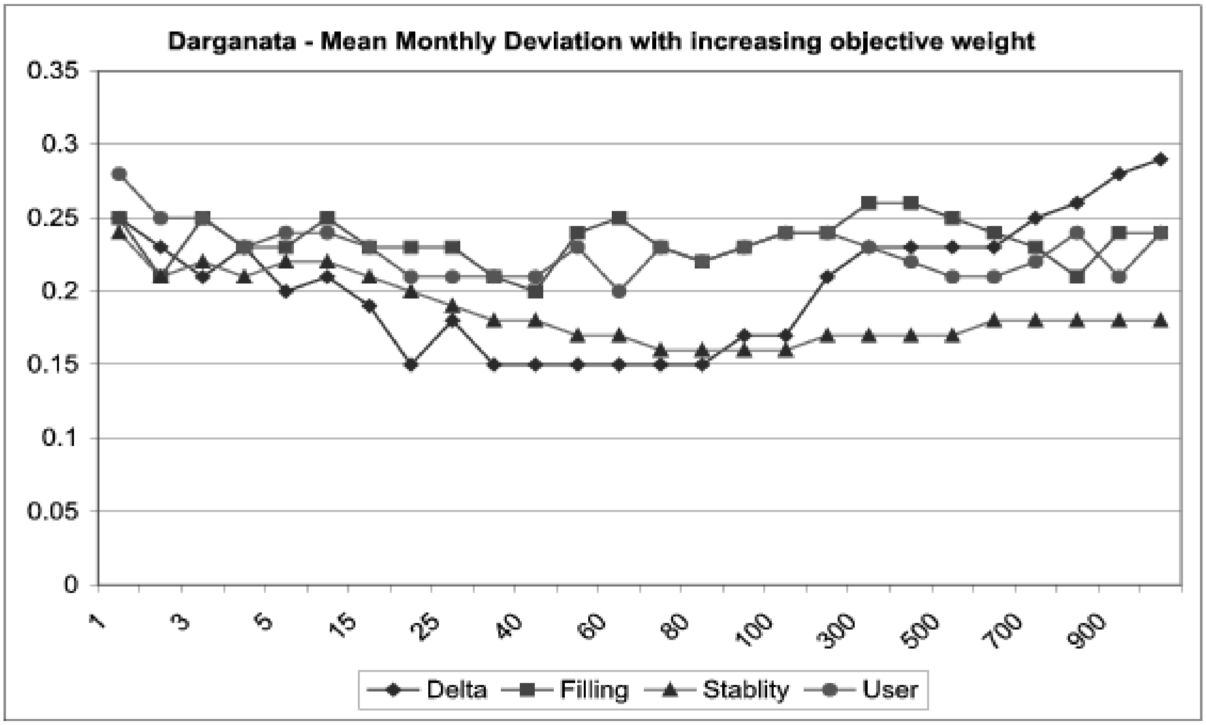


Figure 57: Results of the sensitivity analysis of the objective weights for end of the month monthly volumes of Nurek and TMGU reservoirs for the high water year 1994. On the x-axis increasing values for the objective weights are depicted, on the y - axis the relative deviance to the observed values is indicated.



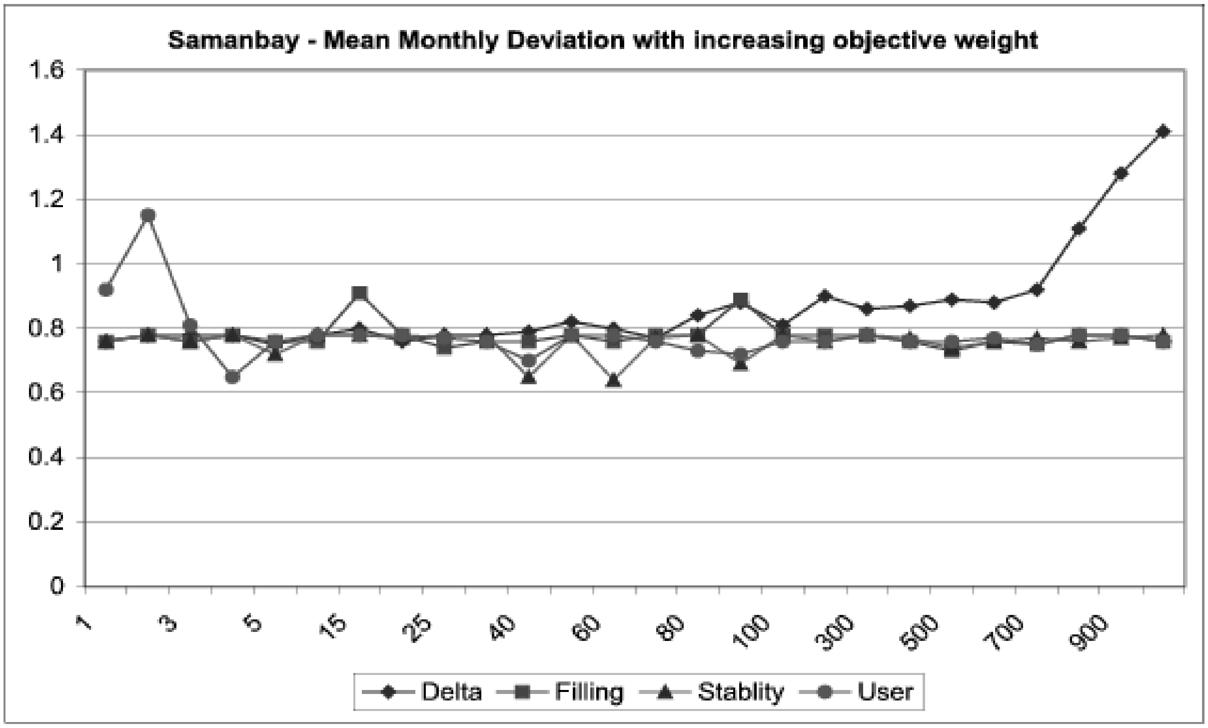


Figure 58: Results of the sensitivity analysis of the objective weights for mean monthly river flow at Darganata and Samanbay for the high water year 1994. On the x-axis increasing values for the objective weights are depicted. The y-axis shows the relative deviance from the observed values.

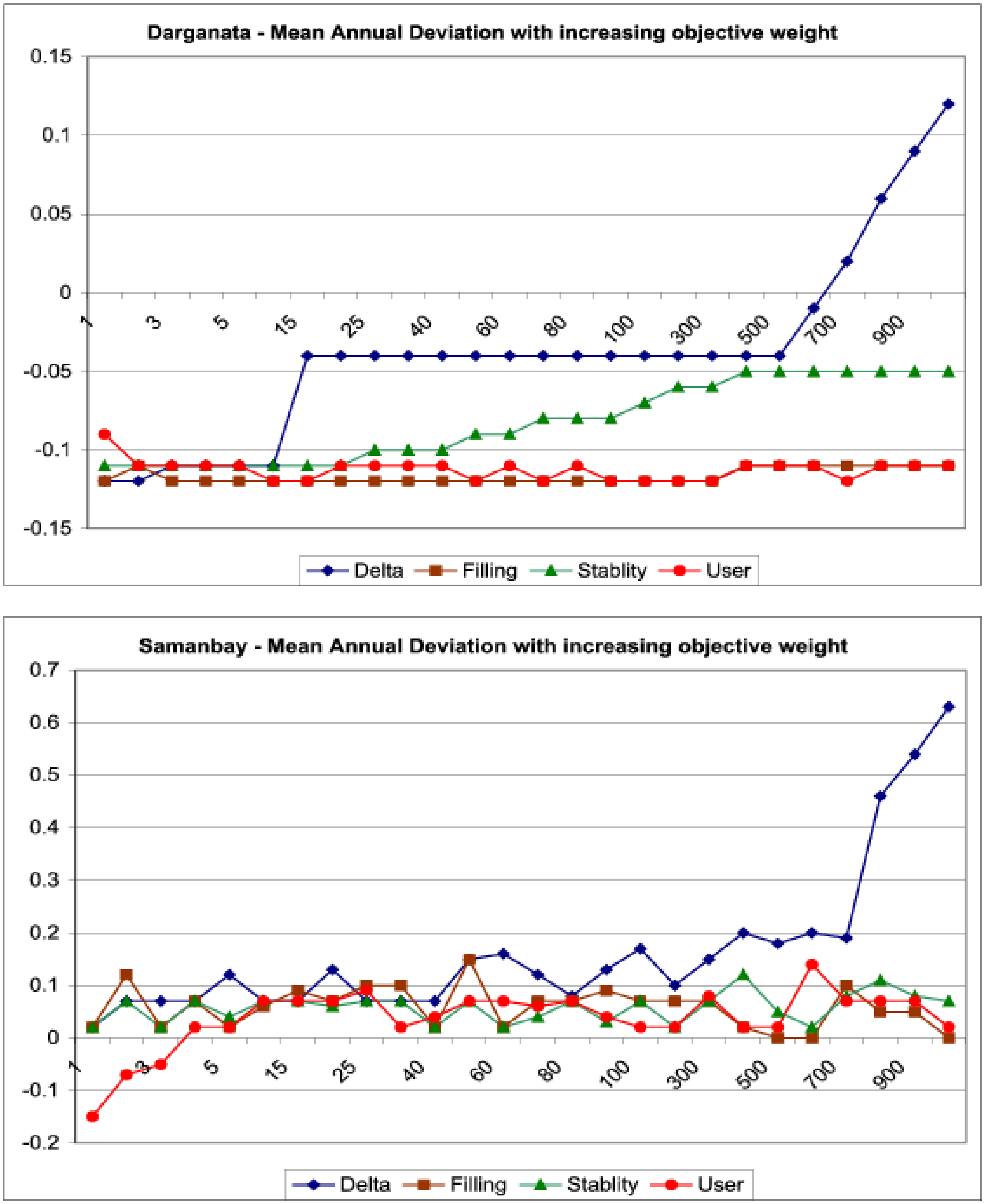
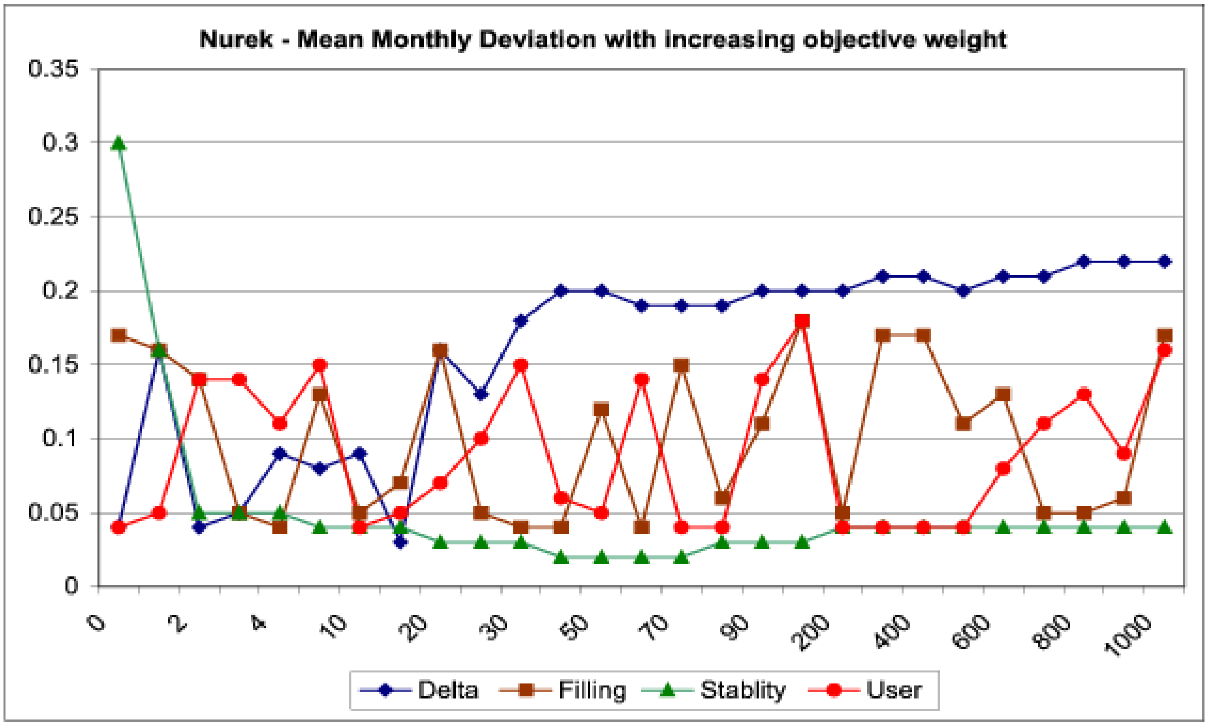


Figure 59: Results of the sensitivity analysis of the objective weights in the high water year 1994 for the mean annual flow at the gaging stations Darganata and Kyzyljar. The x axis depicts increasing values of the objective weights. The y- axis indicates the deviation from observed values.



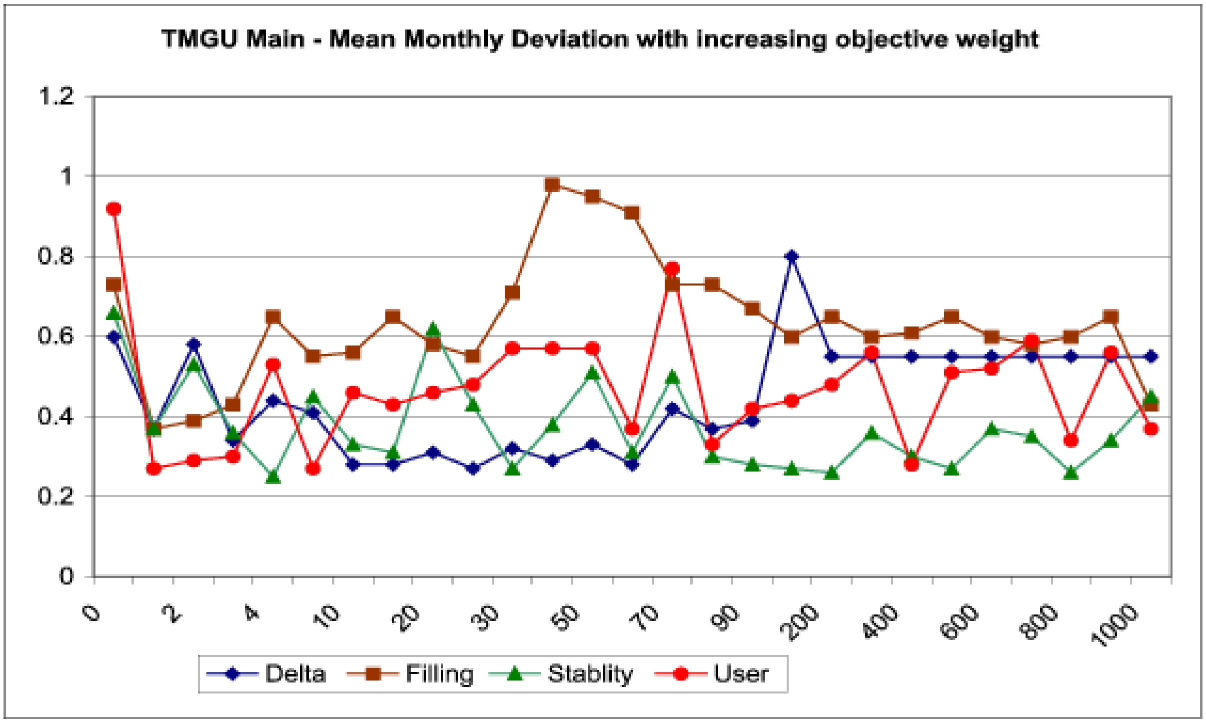
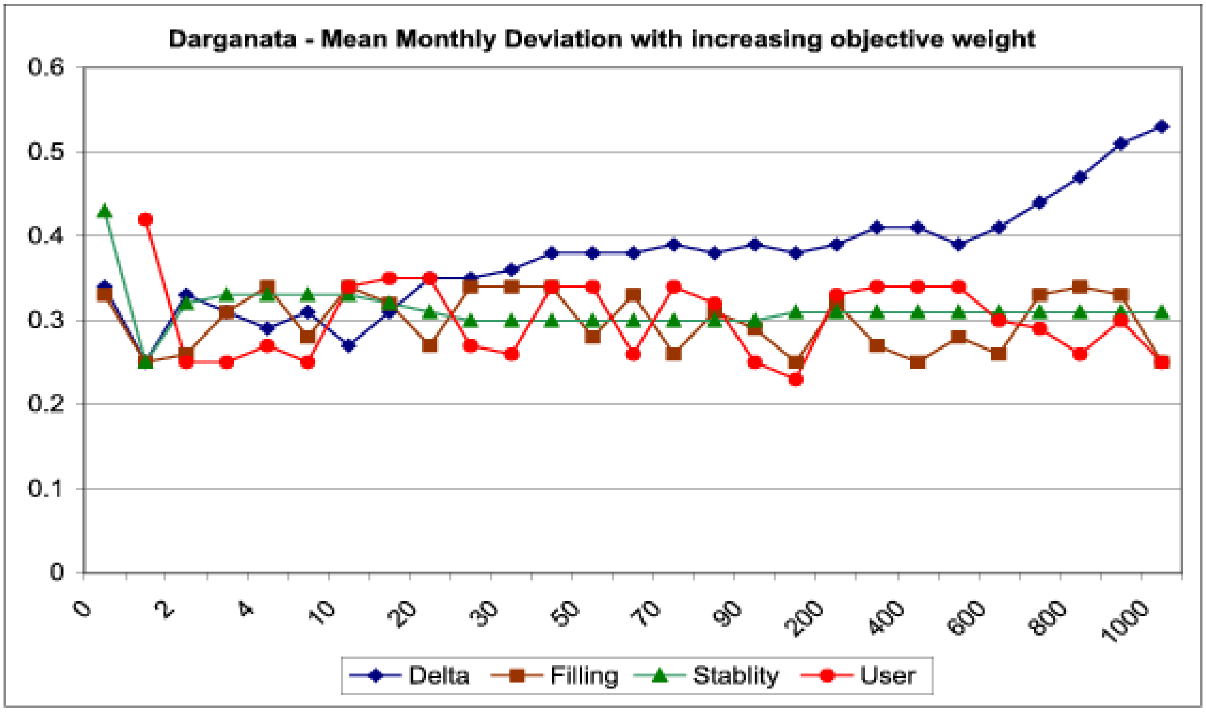


Figure 60: Results of the sensitivity analysis of the objective weights for end of the month monthly volumes of Nurek and TMGU reservoirs for the low water year 1997. On the x-axis increasing values for the objective weights are depicted, on the y - axis the relative deviance to the observed values is indicated.



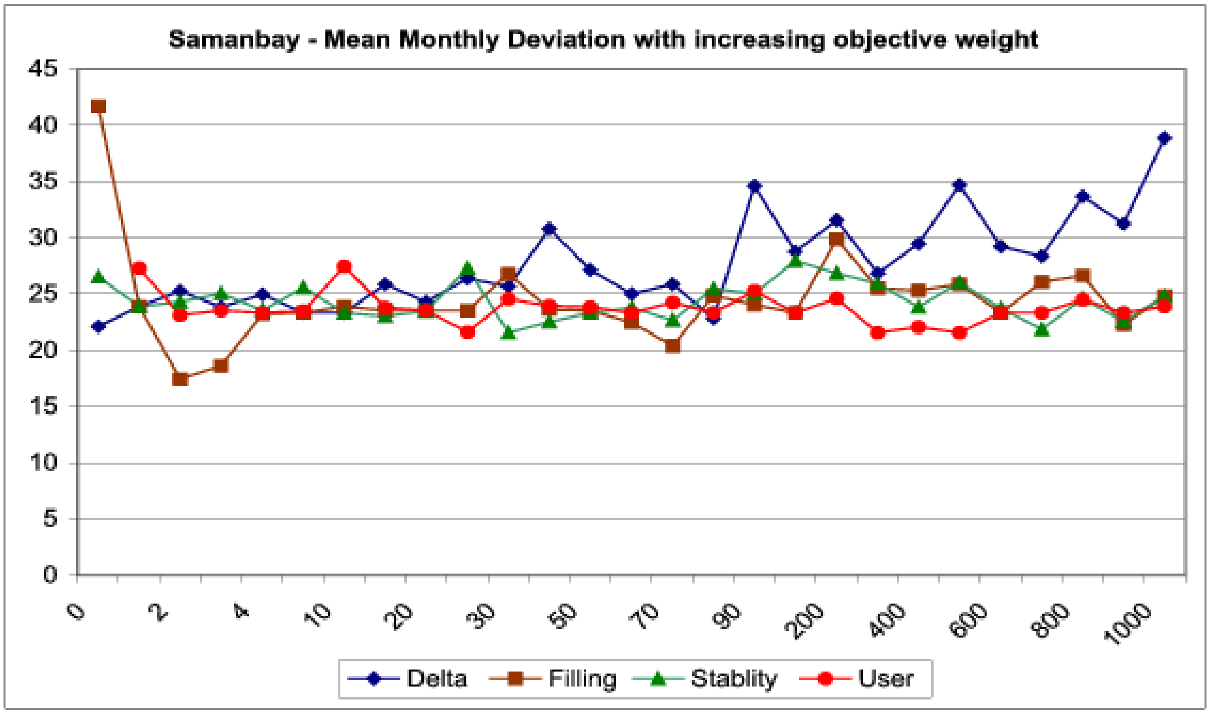
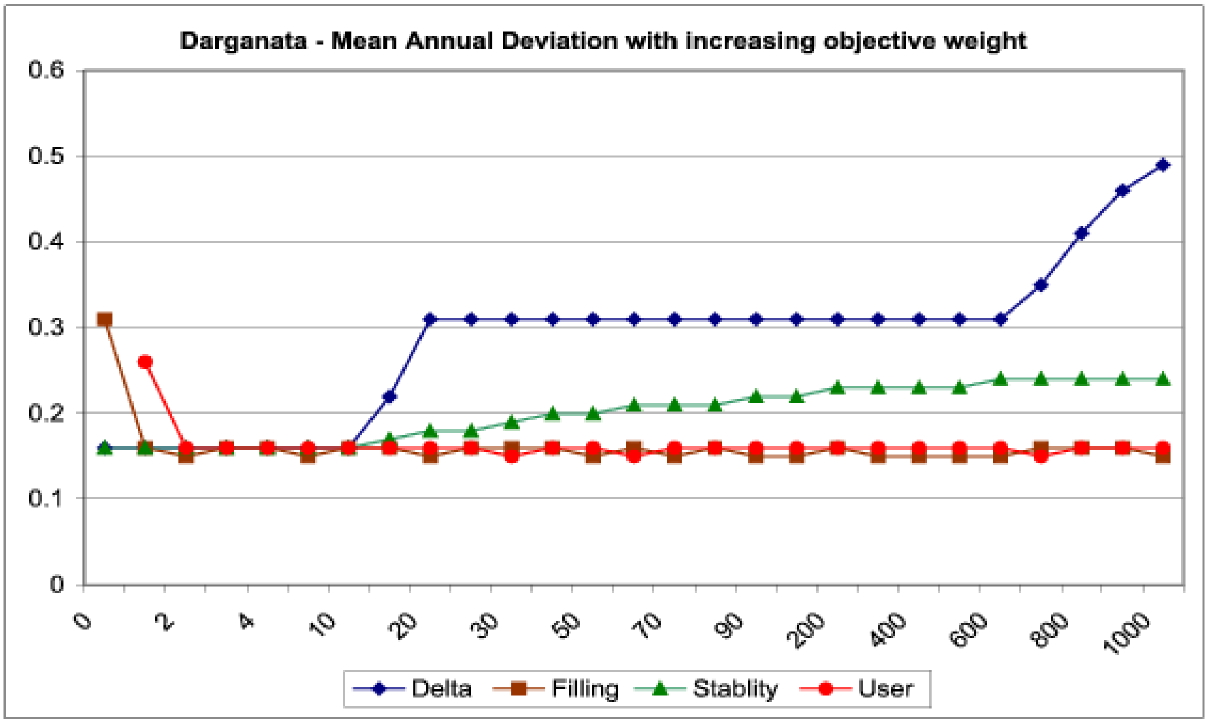


Figure 61: Results of the sensitivity analysis of the objective weights for mean monthly river flow at Darganata and Samanbay for the low water year 1997. On the x-axis increasing values for the objective weights are depicted. The y-axis shows the relative deviance from the observed values.



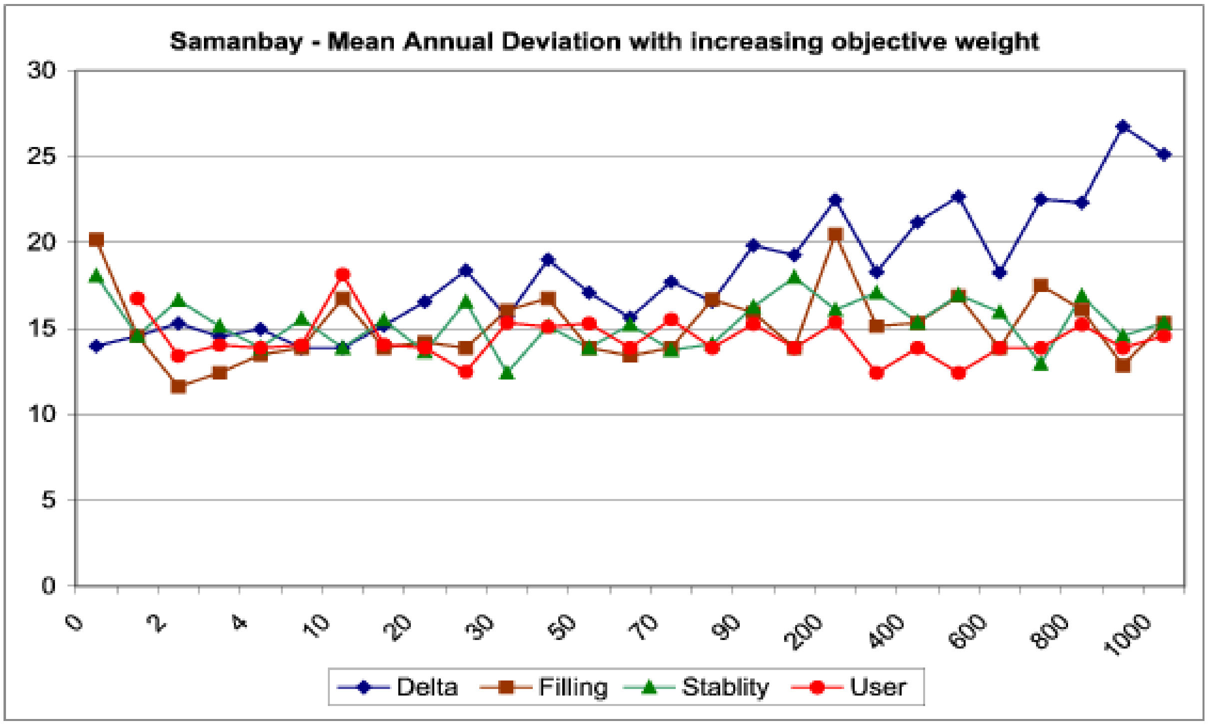


Figure 62: Results of the sensitivity analysis of the objective weights in the low water year 1997 for the mean annual flow at the gaging stations Darganata and Kyzyljar. The x axis depicts increasing values of the objective weights. The y- axis indicates the deviation from observed values.

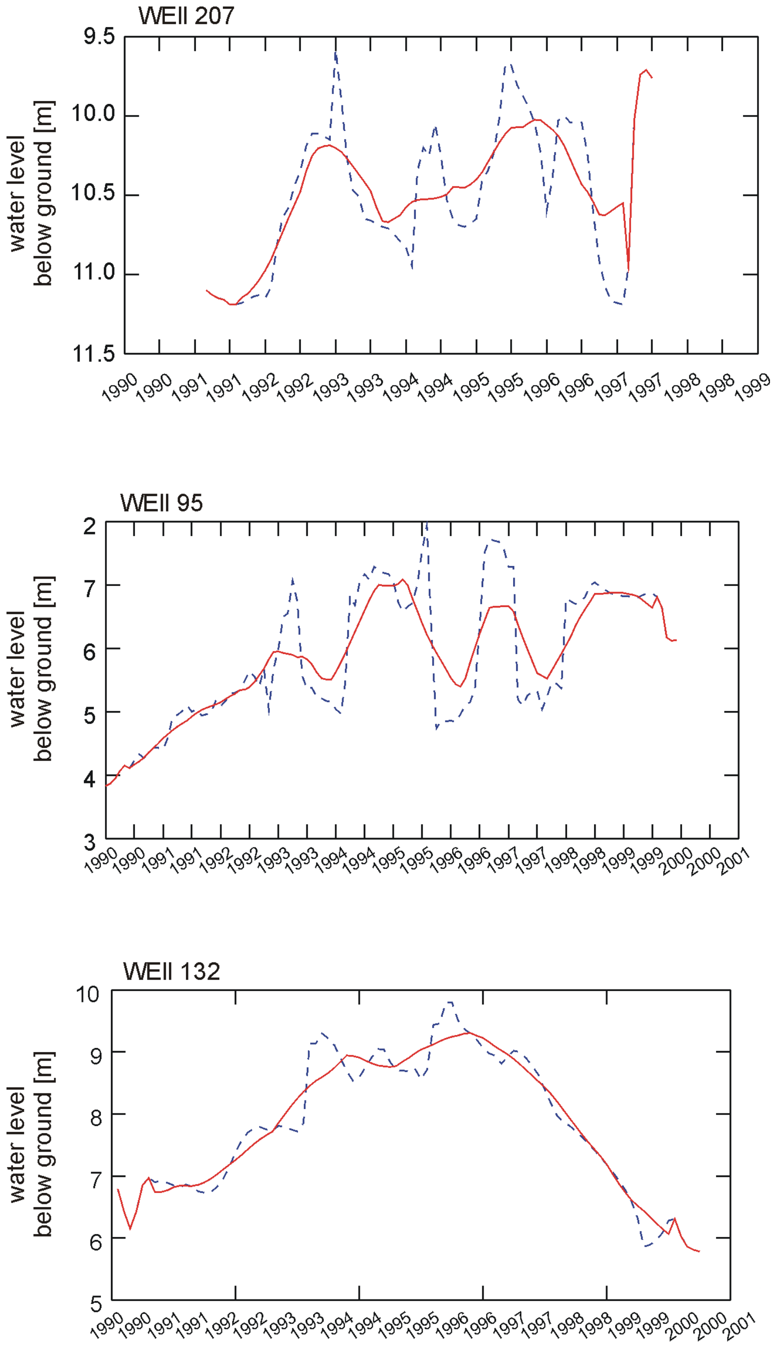
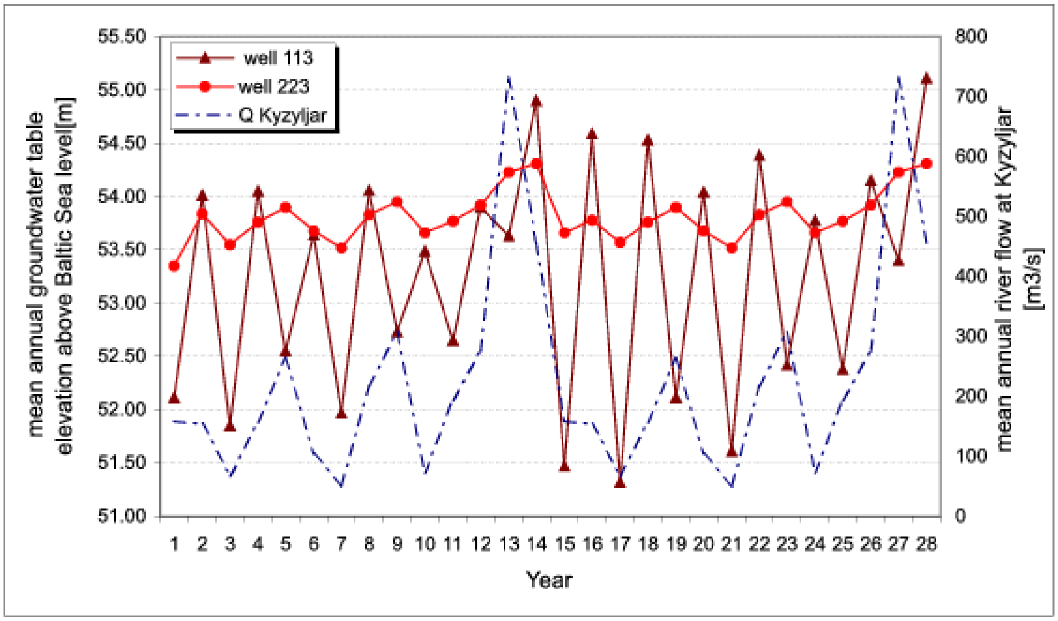


Figure 63: Smoothed series of wells No 207, 95 and 132 (mean, 12).



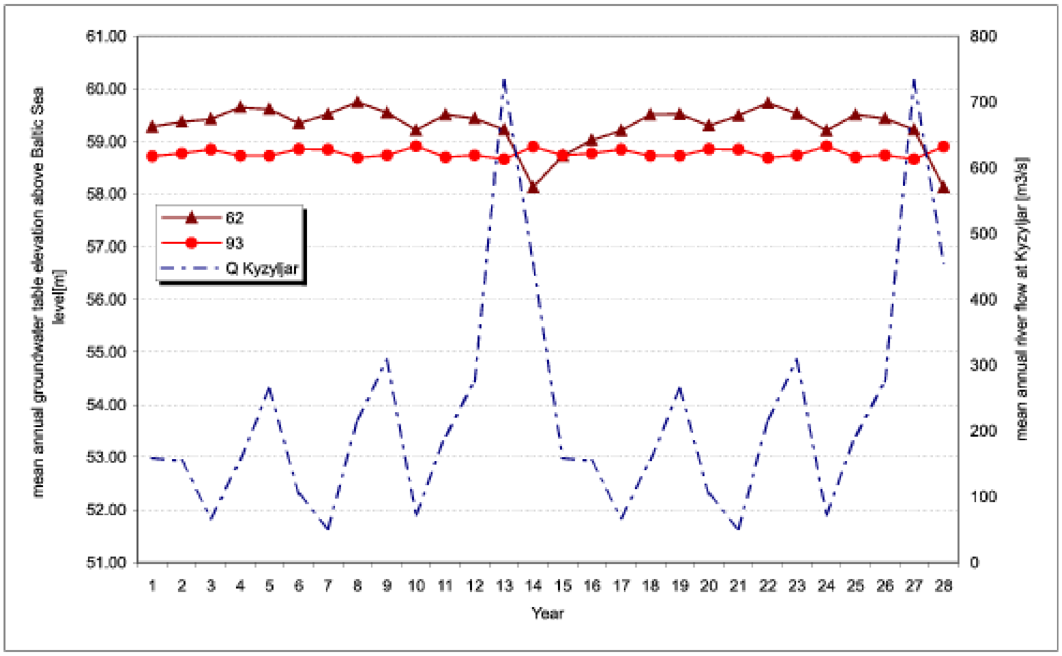


Figure 64: Goundwater levels above sea level in individual wells of the BAU scenario run.

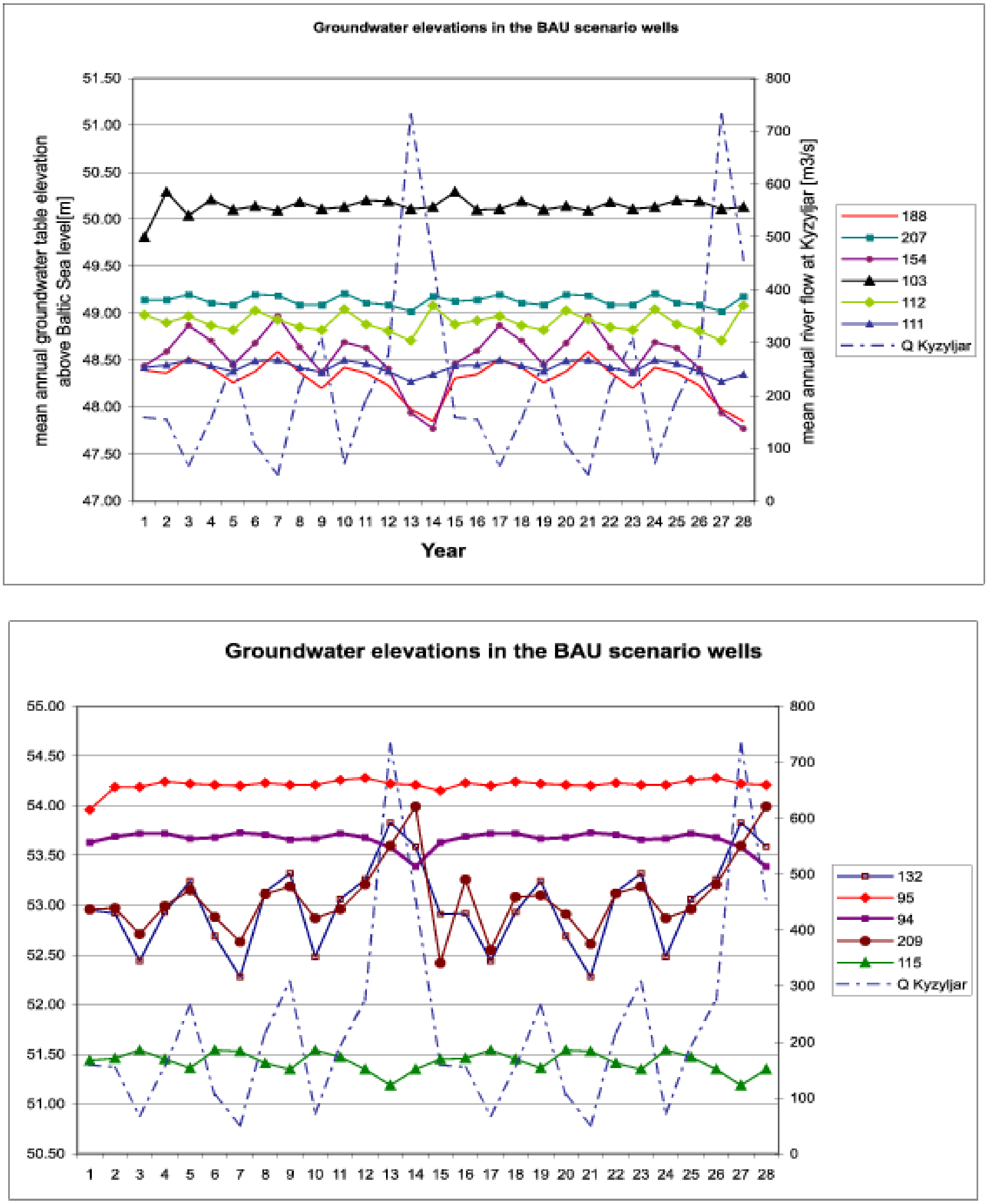


Figure 65: Goundwater levels above sea level in individual wells of the BAU scenario run.

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