International Congress on Environmental
Modelling and Software

2nd International Congress on Environmental
Modelling and Software - Osnabrück, Germany -
June 2004

Jul 1st, 12:00 AM

Application of a GIS-based Simulation Tool to Analyze and Communicate Uncertainties in Future Water Availability in the Amudarya River Delta

Maja Schlüter

Nadja Rüger

Follow this and additional works at: https://scholarsarchive.byu.edu/iemssconference

Application of a GIS-based Simulation Tool to Analyze and Communicate Uncertainties in Future Water Availability in the Amudarya River Delta

Maja Schlüter[a] & Nadja Rüger[b]

[a] Institute of Environmental Systems Research, University of Osnabrück, 49069 Osnabrück, Germany, mschluet@usf.uni-osnabrueck.de

[b] Centre for Environmental Research, Dep. of Ecological Modelling, PF 500135, 04301 Leipzig, Germany

Abstract: Simulation and decision support tools facilitate a process of reasoning about potential future development paths of a system, e.g. a river system, under alternative management strategies. Joint scenario development and analysis with river basin authorities and stakeholders can inform and structure discussions on management goals and major uncertainties affecting river basin management in future. Tools can support the determination of strategies that balance water allocation between multiple users, such as irrigation and the environment, and measures to cope with uncertainties. The GIS-based simulation tool TUGAI has been developed to facilitate exploration of alternative water management strategies for the degraded Amudarya river delta and to analyze their ecological implications. It combines a multi-objective water allocation model with simple models of landscape dynamics and a fuzzy based assessment of habitat changes for riverine Tugai forests. The Tugai forests serve as an indicator of the ecological state of the delta region under a given water management scenario. In this contribution different sources of uncertainties in water availability for the Amudarya delta will be determined and the ecological implications of water supply uncertainty analyzed using the TUGAI tool. Scenario analysis provides an assessment of the range and magnitude of the impact of those uncertainties on the ecological situation in the delta. Uncertainties inherent in system understanding and representation that influence model outcomes are presented and discussed in view of their role in the impact assessment. The application of simple simulation tools that integrate the up to date available knowledge of the system for identification of the type and range of relevant uncertainties affecting river basin management and their perception with managers and stakeholders, for analysis and discussion of their potential impacts and development of cooping strategies will be discussed.

Keywords: integrated models; ecological impact assessment; Amudarya delta; uncertainty; scenario analysis

1. INTRODUCTION

Simulation and decision support tools facilitate a process of reasoning about potential future development paths of a system, e.g. a river system, under alternative management strategies. Integrated models that formalize the up to date available knowledge and clarify important cause-effect relationships can help to communicate the complexity of the water management situation. The use of simulation tools in workshop settings with river basin authorities and stakeholders can support identification of major uncertainties affecting river basin management in future. Analyses of "what-if" scenarios provide an assessment of the impacts of those uncertainties on the human and natural system as a basis for the development of cooping strategies. Scenario analysis is central to climate change impact assessment, but is not widely used in water resource assessment so far [IPCC, 2001].

Most decisions in river basin management have to be made under uncertainty. Uncertainty is defined as the impossibility of having all necessary information, knowledge and predictive capacity about a situation and its future development to describe and have full confidence in all possible outcomes of a decision. For analysis sources of uncertainty are identified and given a probability based on experience, knowledge or intuitive feelings. Potential impacts of those uncertainties can then be explored by scenario analysis.

There are different sources of uncertainty in a river basin management context. Uncertainty can be caused by a lack of knowledge on the functioning of the system which is reflected in system representations. It can also originate from factors external to a given river management situation, such as socio-economic changes or global change [see e.g. Pahl-Wostl 1998, Carter 2001] or human decision making. There are many techniques to estimate uncertainties, especially those caused by insufficient system understanding and representation, but often scenario analysis testing a range of plausible futures remains the only possible means [Carter 2001].

This paper presents the application of the integrated simulation tool TUGAI, which has been developed for ecological impact assessment in the Amudarya river delta, to determine and analyse management uncertainties in the river basin. As an example, scenario analysis of changes to the inflow to the delta is used to assess the potential impact of those water supply uncertainties on the ecological state of the delta. Uncertainty in inflow can be caused by a variety of factors, many of which are not reducible for water mangers in the delta region, such as political decisions, land use changes upstream, or climate change. The potential and limits of applying the tool to analyze and discuss those uncertainties with water managers and stakeholders will be discussed.

2. WATER MANAGEMENT IN THE AMUDARYA RIVER DELTA

The Amudarya delta is located in the semi-arid Turan lowlands of Central Asia in Uzbekistan and Turkmenistan (Figure 1). It is characterized by low precipitation (<100mm/year) and a strong continental climate. Runoff of the Amudarya river is almost exclusively formed by glacier and snowmelt in the Hindukush and Pamir mountain ranges in the upstream countries Tajikistan and Afghanistan.

Figure 1: Location of the Amudarya river delta in Central Asia (delta area in rectangle)

Natural runoff has severely been altered by the expansion of irrigated agriculture to cultivate cotton mainly during Soviet times. The delta area is most severely impacted by changes to the hydrological regime. Many of the once vast riverine forests and reed areas have disappeared with considerable effects on local biodiversity and the human population. In the past years, growing concerns of the basin countries and the international community have initiated efforts to accept the environment as another user of river water.

Uncertainty in future water availability is one driver that increasingly pressures river managers in the Amudarya basin. Current water management strategies of the three former Soviet Union basin countries (Tajikistan, Turkmenistan, Uzbekistan) are based on Soviet allocation quotas. The resources are redistributed on a yearly basis according to expected water availability and short term development goals of the basin countries, excluding Afghanistan. Predictions on water availability are mainly based on experience. Uncertainties that might affect river runoff especially in the downstream areas in the short and in the long term are only marginally taken into account. This predictive approach to water management is the current "norm" in water management in many basins. It uses the understanding of the system to predict future states and gears its management response to achieve the desired future outcome [Clark, 2002].

In the Amudarya basin uncertainty in future water availability arises from political and economic developments in the basin countries, such as changes in land and water use or an increase in water intake by Afghanistan, as well as natural variation in water availability (short term) or impacts of global change (long term). Some examples of sources of uncertainty are given in Table 1.

Table1: Examples of sources of uncertainty in future water availability in the Amudarya delta

Sources of Uncertainty	
System understanding/knowledge	**External Conditions and Developments**
Representation of the complex river system	Climate Change/ Climate variability
Predictions of water availability	Human decision making
Measurement errors (Data uncertainty)	Political and socio-economic changes
Missing knowledge on cause-effect relationships	Changes in water intake by Afghanistan

New integrated strategies that balance water needs of agriculture and other water users will have to be capable to cope with increasing variability and decreasing predictability in water availability.

3. THE TUGAI SIMULATION TOOL

The TUGAI tool has been developed to facilitate a first quick assessment of the ecological effects of changes in the spatio-temporal water distribution in the delta of the Amudarya river. The aim of the tool is to foster understanding of interrelationships between human action and the state of the local environment, to initiate a goal finding process for ecological rehabilitation and a search for new, integrative strategies of water management. It can support the determination of water management strategies that balance water allocations between multiple users, including the environment.
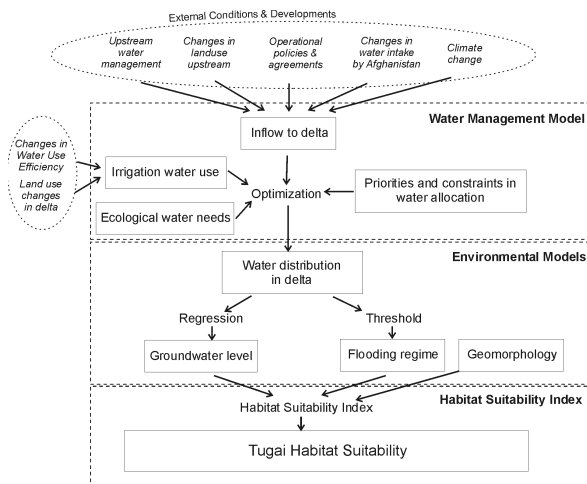

Figure 2: Flow chart of the Tugai tool with the three modules and their linkages. Dotted circles show measures or developments that can be expressed and analysed via scenarios.

The tool combines an optimization model of water allocation (water management model) with simple GIS-based simulations of changes to major environmental variables (environmental models) and an ecological assessment of the environmental situation based on the habitat quality for characteristic riverine Tugai forests (Habitat Suitability Index) (see Figure 2). The Tugai forests are used as an indicator of the ecological situation in the delta area. Tugai are mainly poplar-willow forests that occur along rivers and in river deltas in arid regions in Central Asia. They can tolerate extreme temperatures, drought and moderate soil salinity, but their establishment and viability depends on floods and "reachable" groundwater levels. A habitat suitability index indicates the suitability of a site for establishment, survival and reproduction under the given environmental conditions. Based on the habitat needs of the dominant poplar species, groundwater level (distance of groundwater table from soil surface), flooding regime (flooding frequency, timing and duration) and geomorphology (classified into river bar, slope of river bar, floodplain or terrace, interfluve lowland,

lake depression), have been chosen as important environmental variables for habitat suitability. Scenarios reflecting changes in inflow to the delta region or policy decisions for water management measures in the delta itself can be developed and their implications for the ecological situation in the northern delta area (approximately 3000 km^2) assessed. The tool allows qualitative comparison of alternative strategies, tradeoffs in spatio-temporal water allocation und the ecological implications of water supply uncertainties using colour coded maps, tables and graphs.

Since the tool is based on assumptions concerning landscape dynamics and their impact on deltaic ecosystems, deficient knowledge, uncertain data and parameter values, its "forecasts" are themselves subject to uncertainty. The range of outcomes achieved as results of scenario analysis should be critically reviewed in view of the uncertainties associated with the impact assessment [Kwadijk & Rotmans 1995].

4. UNCERTAINTIES IN SYSTEM REPRESENTATION

In the following the three submodels of the TUGAI simulation tool are subject to a critical revision with respect to uncertainties in the representation of relevant processes and their impact on simulated habitat suitability for Tugai forests.

Water management model
The water management model uses a multi-criteria optimization algorithm to distribute the available inflow into the delta among the water users. The modelled water allocation necessarily differs from the real water distribution, because it optimizes the distribution in a deterministic way under "perfect knowledge" on future water availability. In reality however, management decisions are taken under high uncertainty. Nevertheless, given the complex river network and demands of the irrigation users, an optimization model appeared to be the best approach [see also Wardlaw and Barnes 1999]. Calibration of the objective weights of the multi-objective function was carried out by fitting model results to observed data to achieve the best representation of current water allocation practices to be used as a reference scenario. When interpreting model results, they have to be seen as "best achievable" water allocation under the given supply and demands. Validation and sensitivity analysis have shown that the model manages to allocate available water quantities in the desired way, although spatio-temporal distribution within individual months might differ from the observed. The model reacts to changes in allocation priorities as expected [Schlüter et al. 2004].

Environmental Models

A statistical approach is applied to predict the groundwater level at 12 wells across the delta area depending on mean annual river runoff and hydraulic gradient between the water level in the river and the well in the preceding year. Spatial interpolation between the wells is performed by triangulation. The main disadvantage of the statistical approach is that it is only valid within the range of values used to fit the regression equations. These limitations should be kept in mind when applying the tool, especially when defining future management scenarios that might create environmental conditions that go beyond these limits. Although, within the variable ranges dealt with in scenarios for the Amudarya river delta, the statistical approach is fully applicable.

The occurrence of floods is simulated using a rule-based approach. If a certain runoff threshold at the gauging station at the entrance to the northern delta is exceeded a flood occurs. The threshold was determined by analysis of historic runoff data and knowledge of years and months when floods had occurred [Schlüter et al. 2003]. This threshold certainly is a parameter the habitat suitability index will react sensitive to, because it determines how often floods occur (see 4.1 Example of scenario analysis). The flood extents were estimated based on satellite images of a large flood in 1998, assuming that all future floods will have the same extension. To some extent this approach can be justified by the existence of hydraulic structures (e.g. overflow dams) that assure that excess water is diverted into designated depressions. Nevertheless, the assumption of constant flooded area independent of the amount of water is certainly a strong limitation of the tool. Lack of time and data on channel geometry as well as a detailed digital elevation model for the flat territory made it impossible to construct a more realistic flood model. Here, future research and modelling can significantly improve the impact assessment. At the time being, those limitations have to be taken into account in the interpretation of results of scenario analyses.

Habitat Suitability Index

Groundwater level, flooding frequency, flooding timing, flooding duration and geomorphology at a given site are assigned separate suitability values which are then combined to a single value – the habitat suitability index. Both, important habitat variables and the response of habitat suitability to changes of the variables have been determined on the basis of expert knowledge, because available data proved to be not suitable for statistical analysis. To test uncertainty in the structure of the model two different methods have been compared: a multi-criteria evaluation and a fuzzy rule-based

system. Both use the same habitat variables, but combination to the composite index differs [Rüger 2002]. Results of the two methods are similar with slight differences in their qualitative behaviour. The outcomes of the fuzzy rule-based system are more sensitive to flood events and low groundwater tables are judged more severe than the in the multi-criteria evaluation. However, it is not possible to predict how the introduction of other potentially important habitat variables (e.g. soil salinity) would alter the outcome of the habitat model. Nevertheless, we believe that both indices represent the to date available ecological knowledge on habitat requirements of Tugai forest.

Expert evaluation and validation have shown that the simulation tool provides meaningful results despite the mentioned uncertainties in system understanding and representation. The tool has been tested with historic runoff data from the years 1991-1999. Results of habitat suitability for Tugai forest do not contradict the data on Tugai forest distribution [Rüger et al. 2004] and regional experts confirm the qualitative simulation results.

5. UNCERTAINTIES CAUSED BY POLITICAL AND ECONOMIC DEVELOPMENTS IN THE RIVER BASIN

The tool can be applied for scenario analysis with authorities and stakeholders in the Amudarya river basin to assess the implications of uncertainties in future water availability on the ecological situation in the delta. After identifying relevant uncertainties scenarios reflecting their expected impacts on the hydrological regime can be developed and analysed. This process guarantees that a wide range of views of relevant uncertainties among the stakeholders and priorities in policy making are represented in the analysis [Alcamo 2001].

5.1. Example of scenario analysis

A range of plausible scenarios reflecting a decrease in inflow to the delta from 1% up to 14 % of the inflow in the reference scenario has been developed to analyse the effect of further decrease in water supply on the riverine ecosystems. Inflow to the delta in the reference scenario is based on a 14- year characteristic runoff time series (monthly time steps) at the gauge at the entrance to the delta. A decrease in inflow of up to 14% is realistic since it reflects the maximum amount of water Afghanistan is entitled to withdraw from the Amudarya river. In the past 30 years Afghanistan has not been able to use this water because of war. Instead these resources are used for irrigation in the downstream countries Turkmenistan and Uzbekistan.

Figure 3 depicts the results of the scenario runs over a time period of 28 years (mean value). In all scenarios mean monthly inflow is reduced by the respective percentage, while irrigation water demands remain the same as in the reference scenario. It is expected that the ecological situation deteriorates in all scenarios because the water remaining after serving irrigation needs decreases.
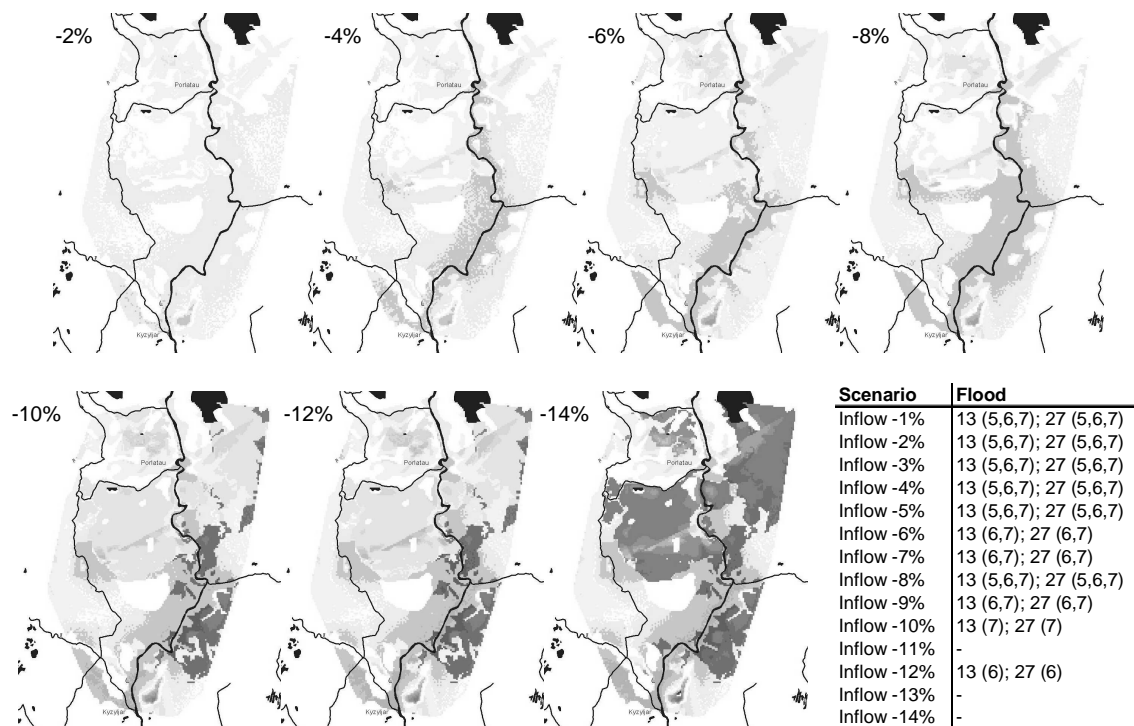

Scenario	Flood
Inflow -1%	13 (5,6,7); 27 (5,6,7)
Inflow -2%	13 (5,6,7); 27 (5,6,7)
Inflow -3%	13 (5,6,7); 27 (5,6,7)
Inflow -4%	13 (5,6,7); 27 (5,6,7)
Inflow -5%	13 (5,6,7); 27 (5,6,7)
Inflow -6%	13 (6,7); 27 (6,7)
Inflow -7%	13 (6,7); 27 (6,7)
Inflow -8%	13 (5,6,7); 27 (5,6,7)
Inflow -9%	13 (6,7); 27 (6,7)
Inflow -10%	13 (7); 27 (7)
Inflow -11%	-
Inflow -12%	13 (6); 27 (6)
Inflow -13%	-
Inflow -14%	-

Figure 3 Results of scenario analysis for a decrease in inflow of 2% to 14% of the inflow in the reference scenario over a time period of 28 years. The maps show the main river and major canals in the Northern delta region. Colour coding depicts the difference in mean habitat suitability between simulated and reference scenario over the entire simulation period. Dark grey indicates a decrease in habitat suitability, light grey an increase. The table lists the years and months (e.g. 5=Mai) when floods occur in the respective scenario.

.

Scenario analysis reveals a differentiated picture of the mean situation in the delta with areas where suitability has lowered and others where the situation for Tugai forests has improved. With a decrease of inflow by 2% the situation changes only insignificantly, thus indicating that the decrease in water availability has no severe ecological impact. In the scenarios with 4% to 8% less inflow habitat suitability for the Tugai forests visibly deteriorates along the river and on some river bars in the southern part of the study area. The area affected increases with decreasing inflow as expected, although differences to the reference are still small. The scenarios also show an increase in suitability in the northern former swampy part of the delta. This is caused by a lowering of the groundwater table to more suitable levels. Stakeholders and experts have to judge whether an establishment of forests in these regions would be feasible. In scenarios 10% and 12% there are areas in the southern part of the delta where suitability has significantly decreased. These are mainly formerly flooded areas, which now lack flooding. In the scenario of a decrease in inflow of 14% habitat suitability decreases in the entire delta with large areas strongly impacted. In this scenario no floods occur at all, a fact that strongly affects habitat suitability.

Floods in the 28 year reference scenario occur in year 13 (Mai, June, July) and in the same months of year 27 (Fig 2). Up to a decrease in inflow by 5% the flooding regime remains the same. Further decrease causes a shortening of the flooded period. The lack of one flooded month has no severe effect on suitability. With further decrease in inflow to the delta (Scenario 10% - 12%) the flood only occurs in July in year 13 and 27, which has a pronounced effect on habitat suitability as mentioned above.

The analysis shows that there are thresholds in the decrease of monthly inflow beyond which habitat quality lowers significantly, mainly due to changes in the flooding regime. As long as floods still occur at least for one month changes in habitat suitability show a spatially differentiated picture with some areas deteriorating others improving. This information can support the planning of specific measures to cope with the uncertainty in inflow by e.g. guaranteeing a certain flow into a selected area. Although, when planning rehabilita-

tion measures other factors than those accounted for in the TUGAI tool will also have to be considered, such as soil salinity or closeness of the site to human settlements. Joint scenario development and analysis with local stakeholders can point to human factors that are not explicitly taken into account in the models. The experience of the local stakeholders with their environmental system adds important aspects to the analysis that have not and often cannot be included in the simulation tool.

6.   CONCLUSIONS

Application of simple simulation tools, such as the TUGAI tool presented here, for scenario development and analysis with river basin authorities and stakeholders facilitates discussions on major uncertainties that will affect river basin management in future. It can help to identify relevant uncertainties and to assess their implications from the point of view of the stakeholders. Different views might arise between various groups in the initial assessment and the interpretation of model results. These activities raise awareness and can support an ongoing process of determining goals and decision making [Pahl-Wostl 1998].

The aim of the TUGAI tool is to facilitate such a process of analysis and decision making among authorities and stakeholders for the development of future water management strategies in the Amudarya river delta. Scenario outcomes reveal tendencies and magnitude of changes to the ecological condition in the delta that might result from changes to the hydrological regime. In order to provide scenario results real time in a workshop setting as input for discussions the tool has to be kept simple. Although uncertainties in model outcomes have been assessed and quantified as far as possible, a final judgment on the range of uncertainties inherent in the impact assessment versus the magnitude of expected future changes caused by external factors remains difficult. We believe that the tool is a good representation of the currently available knowledge and is simple enough that the user can understand its dynamics and inherent uncertainties. It is crucial that uncertainties are evaluated at each stage of the impact assessment and that assumptions used in the representation of the system are clearly communicated [Carter 2001]. A dialogue with local experts which have large informal knowledge about ecological processes in the study area is important for further validation. In the given example the key role of floods is visible. The results can initiate discussions on the necessary measures to guarantee minimum amount of floods to maintain the forests and create awareness among those res-

ponsible for water allocation to the ecological effects of their measures. They might also catalyse a discussion on the appropriateness of the assumptions on the role of floods. Such interactive processes can also support specification of future research and data needs of a specific situation.

7.   REFERENCES

Alcamo, J., Scenarios as tools for international environmental assessments. *Env. Issue Rep.,* 24, European Environment Agency, 2001.

Carter, T.R., Uncertainties in Assessing the Impacts of Regional Climate Change. In: M. B. India & D.L. Bonillo (eds.) *Detecting and Modelling Regional Climate Change*, Springer, Berlin, Germany, 441-469, 2001.

Clark, M. J., Dealing With Uncertainty: Adaptive Approaches to Sustainable River Management. *Aquatic Conservation -Marine and Freshwater Ecosystems,* 4, 347-363, 2002.

IPCC Report, Hydrology and Water Resources. Implications of Climate Change for Water Management Policy. *Climate Change 2001. Working Group II.* http://www.grida.no/climate/ipcc_tar/wg2/188.htm, 2001.

Kwadijk, J., Rotmans, J., The impact of climate change on the river Rhine–a scenario study. *Climate Change,* 30(4), 397-425, 1995

Pahl-Wostl, C., Jaeger C.C., Rayner S., Schär, C., van Asselt, M., Imboden, D. Vckovski, A. Regional Integrated Assessment and the Problem of Indeterminacy. In: P. Cebon, U. Dahinden, H. Davies, D.M. Imboden, . C.C. Jaeger (eds). *Views from the Alps. Regional Perspectives on Climate Change.* MIT Press, Cambridge, 435-497, 1998.

Rüger, N., Habitat suitability for *Populus euphratica* in the Northern Amudarya delta – a fuzzy approach. *Beiträge des Instituts für Umweltsystemforschung.* 26. , 2002. http://www.usf.uni-osnabrueck.de/usf/beitraege/index.en.html

Rüger N., Schlüter M., Matthies M. A fuzzy habitat suitability index for *Populus euphratica* in the Northern Amudarya delta. Submitted to Ecological Modelling, 2004.

Schlüter M., Savitsky A.G., Rüger N., Lieth H., Simulation der großräumigen Grundwasser- und Überflutungsdynamik in einem degradierten Flussdelta als Basis für eine ökologische Bewertung alternativer Wassermanagementstrategien. In: J Strobl, T Blaschke, G Griesebner (eds) *Angewandte Geogr. Informationsverarbeitung XV. Beiträge zum AGIT-Symposium Salzburg 2003*, Wichmann, Heidelberg, 437-443, 2003.

Schlüter M., Savitsky A.G., McKinney D.C., Lieth H.. Optimizing long-term water allocation in the Amudarya river delta - A water management model for ecological impact assessment. *Environmental Modelling and Software*, in press 2004.

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