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Analysis of Water Use and Allocation for the Khorezm Region in Uzbekistan Based on an Integrated Economic-Hydrologic Water Management Model

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Abstract

Water availability and an effective and sustainable management of water resources is an important factor in social and economic development. This applies notably for the case study area. The highly arid area Khorezm is situated in the Central Asian Republic of Uzbekistan and the Amu Darya delta region. Due to historical and recent expansion of irrigation projects the region is highly dependant on water for irrigation purposes. But inefficient water consumption and management result in drastic ecological, social, and economical problems like rise of soil and water salinity, water scarcity, declining yields, health problems and rising groundwater levels. This development and an increasing competition among water users within the region and between up- and downstream areas along the river calls for a more efficient water allocation and management approach.

In this presented study an integrated economic-hydrologic water management model for Khorezm region is developed with the main objective to determine different water users and water using patterns according to physical and agronomical basics and to find out strategies for a more efficient allocation and management of water resources that also allows the analysis of alternative water policy scenarios. The water allocation model is programmed in GAMS (General Algebraic Modeling System) and is made of a system of non-linear differential equations. The development of such a framework of analysis can be a step to integrate different disciplines (natural sciences, economics, social sciences) to find out a better water management including efficient, equitable, and environmentally sustainable water allocation mechanisms for the study area.

Keywords: Integrated hydrologic-economic model, irrigation, optimization model, Uzbekistan, GAMS, water allocation

Introduction

The region Khorezm, situated in the Central Asian Republic of Uzbekistan, is one of the numerous examples of irrevocable, inefficient water consumption and management mainly for irrigation. Agrarian economic tendency based on irrigated agricultural development resulted and still results in drastic ecological, social, and economical problems.

To reduce unsustainability and negative effects of water use to local and national ecosystem and population, one factor is a more efficient water allocation and water use and a more efficient, sustainable water resources management. The project „Economic and Ecological Restructuring of Water and Land Use in the Region Khorezm (Uzbekistan), a Pilot Project in Development

Research“[1] has been initialized which takes into account a holistic economic-environmental approach to improve the current situation with the development of effective and ecologically sustainable concepts for landscape and water use restructuring.
In the following introduced study a regional analysis for different spatial resolutions of water allocation, use and effects of alternative water management strategies and policies to hydrologic cycles, plant growth, yields, cropping areas and farmers is carried out for the Khorezm Region. The main objectives of the study will be the detection and determination of water supply and demand and as a consequence thereof the water availability and water use patterns in the region of Khorezm. Based on agronomic, hydrologic and climatologic fundamentals and calculations, economic consequences of alternative more effective water uses, management and allocations shall be determined and analyzed.
Research hypotheses that arise from given situation for the research will be following:

- The complex interdisciplinary relationships between hydrology, agronomy, and socio-economy can only be effectual acquired and manifested within an integrated modeling tool.
- With modified cropping pattern and reduced cropping areas but improved management and efficiency it should be possible to reduce environmental damages but to obtain and enhance production levels.
- Measures like taxes, subsidies, permits, and rights should have positive influence on more effective water use, allocation and ecology.

Regional Conditions and case study area

Khorezm is situated in the north-western part of Uzbekistan at the lower reaches of the Amu Darya River. Its total area is around 6300 square kilometers. The climate is continental, with moderately cold winters and dry hot summers.
The population of the Province region’s population exceeds 1.2 million, with about 80% living in the outlying areas. The Province is divided into 10 administrative districts. The Khorezm Oasis is a highly irrigated Region with lots of primary and secondary channels. The Amu Darya provides irrigation water to some 231.000 ha of land in Khorezm (from which more than 12% are with highly salinization degree). The region contributes to 15% of the national Uzbekistan river water withdrawals. The water withdrawal for agriculture is estimated at 94% of the whole regional water withdrawals.

Figure 1 : Central Asia, Uzbekistan, and Khorezm Region, based on UN map no. 3777

[1] Center for Development Research, University of Bonn, Germany in collaboration with: State Al Khorezmi University, Urgench, Uzbekistan; United Nations Educational, Scientific and Cultural Organization; German Remote Sensing Data Center; Institute for Atmospheric Environmental Research, Germany

During Soviet times the production of agricultural commodities particularly of cotton was expanded far into the country's dessert and marginal land with a sharp increase of irrigated area. One of the areas with the most intensive agricultural use is the Khorezm Region.
This resulted amongst others to an increase of environmental, social and economic problems like rise of soil and water salinity, water scarcity and competition, declining yields, health problems, rising groundwater level. Most prominent example for a resulting ecological crisis for downstream rivers and delta regions like Khorezm is the so called "Aral Sea Crisis".
After independency in1991, Uzbekistan's government tried to alter the Soviet-style command economy of central planning mainly with subsidies and controls on production and prices (CIA, 2005). But Uzbekistan still has retained many elements of Soviet economic planning. Economic policy remains under state control; the government has limited foreign direct investment, and little privatization has occurred aside from small enterprises (Curtis, 2004). Intended structural changes and imperative measures to protect environment didn't or just slowly occur because the state still continues to be a dominating influence in the economy and thus in environment. Additional growing population causes increased pressure on the environment and natural resources like the Amu Darya River in Uzbekistan (United Nations, 2001).

The average water use per hectare is up to 12000 m^3; for wheat, rice and cotton it is still around 5000, 30000, 12000 m^3 respectively (UNESCO, 2000; FAO, 1997). The main strategic crop in Khorezm region is still cotton which occupied more than 45% of all sown area in the period 1998-2001. Other basic crops in Khorezm are wheat and rice, potato, vegetables, melons, fruits and grapes. Cereal production, especially rice, has increased significantly during last several years.

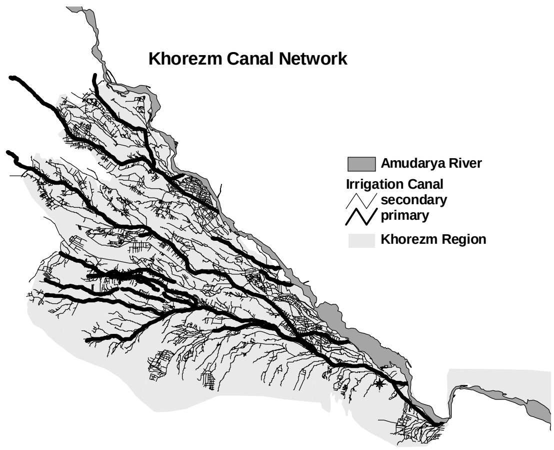

Figure 2: Canal Network of Khorezm

One of the central problems of the irrigation system seems to be its poor efficiency and maintenance. The average weighted efficiency of the irrigation network, which shows the water losses along the distance between the source and the irrigated field, is 63% (FAO, 1997). Due to the transition to a market economy there is a lack of economic incentives and financial resources to improve the irrigation system, and neither land-use nor water-use practices encourage efficiency in water use. At present collector-drainage water is not treated at all. The annual discharge of collector and drainage water goes directly into the rivers, evaporation ponds, natural salt lakes, or is reused for irrigation.

Methodology

Water Management Models/ Economic-Hydrologic Models

Sustainable and efficient management of water resources requires an interdisciplinary approach. Natural, economic and sociologic aspects have to correlate and must be incorporated into a model. There are two types of hydrologic-economic modeling techniques: simulation and optimization. Simulation models simulate water resources behavior in accordance with predefined set of rules governing water allocations and infrastructure operations while optimization models optimize and select allocations and infrastructure based on objective function and accompanying constraints (McKinney et al., 1999). Integrated hydrologic-economic models consist of a hydrologic and an economic system. The economic components are driven by the hydrologic and agronomic system that is based on physical parameters and principles while the hydrologic components and their operation is driven by socio-economic (and environmental) objectives.

Khorezm Water Management Model

The purposes of the study and the model are:

- the identification of strategies and policies for more efficient water allocation among users, agricultural development and water resources demand management in Khorezm
- the detection and determination of water supply and demand and as a consequence thereof the water availability and water use patterns in the region of Khorezm
- the evaluation of economic and environmental consequences (costs, benefits, tradeoffs and complementarities) of water uses in the region, water based or related constraints to agricultural and economic development
- the exploration of impacts of economic incentives such as water prices, irrigation investment; salinity control measures on crop pattern change, hydrology and water uses

The model comprises of:

- The hydrologic components (water flow and salinity transport and balances, Groundwater and drainage balances)
- Economic components (production and profit functions for different crops and water uses, costs, revenues, welfare, water prices, taxes…)
- Agronomic components (crop parameters, yields, soil characteristics…)
- Irrigation management (efficiencies)
- Institutional rules, policies and economic incentives (as scenario analyses)

Structure, components and modules of the model

The Amu Darya river water is distributed to the main irrigation canals in Khorezm. As the model is static, the water is exogenously given to the region and then distributed to the districts. Within the districts the water is distributed for industrial/municipal consumption and to the different agricultural demand sites where water is allocated to a series of crops and crop fields, according to their water requirements and profitability and according to different soil types. This surface water and the additional water of precipitation, drainage reused water and groundwater can be used for irrigation. Main part is consumed by the crops via evapotranspiration. The rest is percolated to downward layer and to groundwater, is drained and applied to evaporation ponds or is reused for irrigation. Due to high groundwater levels and the deliberately afflux of irrigation and drainage water within the canals the influence of groundwater and groundwater exchange (seepage losses, capillary rise) is included within the modeling framework.

The cropping areas and yields are determined within the optimization model within set boundaries that represent historical cropping patterns and yields. Within the regional scale the general hydrologic operation system and the water allocation to districts is determined under the condition of maximizing profits for the single districts and for the whole region. For the water allocation at the sub-regional and district level efficiencies of the water distribution system and the groundwater and drainage system is taken into consideration. The allocation among crops and among different soil types is determined in dependency of soil parameters, cropping pattern and crop characteristics.

The demand of water is determined endogenously within the model by using empirical agronomic production functions. Water supply is determined through hydrologic water balances

and variables (surface water, groundwater balance, drainage water, soil water) in the region with extension to the irrigated crop fields at each of the irrigation demand sites.
Water demand and water supply are then integrated into an endogenous system; the valuation of revenues, gross margins, water values or marginal values for water uses is implemented in an economic objective function, which is constrained by hydrologic, agronomic, and institutional relations. Water institutions and organizations and their water related policies and future programs will also be included into the model. Those institutional regulations will be modeled as different scenarios.
The model consists of 10 districts. It is assumed that every single district consist of an evaporation pound and a groundwater tank. There also exist connections between the irrigation canal network and the drainage and groundwater system. The model considers 8 different crops (cotton, wheat, rice, other grain, alfalfa, vegetables, fruits, potatoes) and comprises of 3 main soil types (light, medium, heavy soils).
Salt concentrations for surface and subsurface water, groundwater and crop fields, drainage and return flow are calculated separately within the model and shall provide a basis for analyses e.g. whether the present irrigation system will be worsened in the future due to high salinity levels in irrigation water and soil salinity accumulation.
The model is performed in the modeling language of a General Algebraic Modeling System (GAMS) [Brooke et al., 1988], a system for programming mathematical problems. GAMS is used to allow for planned linkages with other models that are developed within the project. The temporal resolution amounts to a one year time horizon with 12 month modeling periods.

Data, Data Interpretation and Model parameters

The modeling framework required multidisciplinary data mainly on hydrology, climatology, agronomy, economy, sociology, and crop-, soil-, and groundwater-related parameters. This study uses data from other studies and projects, data collected within the project, secondary statistical data, experiment and empirically estimated data, data from literature and internet, official governmental scientific databases, and expert knowledge. Data contain different types of information like: time series and single measurements, spatial and non-spatial data, data on country-, district-, and field- level with high or low resolution, qualitative and quantitative data. Basis year is 2003 or e.g. for climatologic and groundwater analyses time series between 1990 till 2004 were used, if available.

Some Hydrologic-climatologic conditions and analyses:

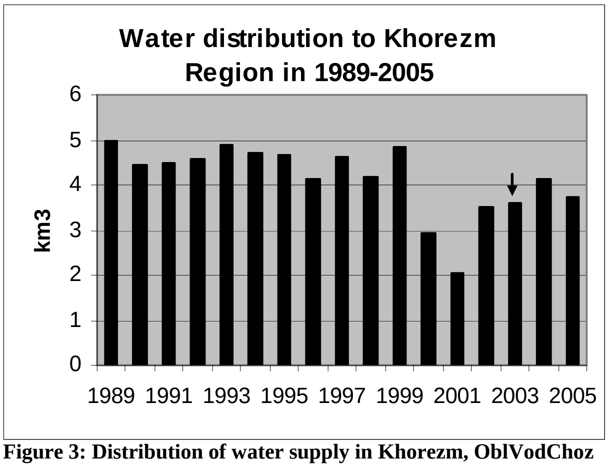

Figure 3: Distribution of water supply in Khorezm, OblVodChoz (2004), Upradik 2004, OblSelVodChos 2002, SIC ICWC 2005

Water distribution of 1989-2005 shows in 2000 and notably in 2001 particularly within the vegetation period really bad water supply conditions that influences yields, cropping areas and profits while ensuing years indeed denote an upwardly trend but don't approximate to the nineties. The model is based on data for year 2003 as this year seems to be a good medium water availability event. Monthly water supply by district is characterized by high water amounts within the main crop growth periods in June to September with a peak in August and July. A relatively high amount of water in nonvegetaion periods (Oct-March) is distributed mainly for soil leaching (Feb-March) and filling up the channel system (Jan-Feb). For this reason leaching is additionally separated within the model.

Considering different water use per hectare within the single district a relatively uniformly distributed scheme arises. The average water consumption range between 15200-18700 m^3 per hectare. In Gurlan mainly cotton and rice were cultivated. Remaining districts far away the river (Khiva, Yangiarik) show higher water consumption per hectare due to high water losses within the irrigation canal system. Whereas canal network for Urgench, Khanka and Yangibazar is well extended and close to the Amu Darya River.

Some Agronomic-economic conditions:

Since there exist different types of soil classifications within the datasets the study refers to the so called hydromodule zones, a differentiation of soil types in dependency on soil texture and groundwater table. Light soils were indicated as sandy and sandy-loamy soils (clay fraction under 35%), medium soils as light and moderately textured loamy soils, and heavy soils as heavy loamy and loamy soils, with homogeneous and heterogeneous texture and a clay fraction of min. 45% SoyuzNIHI UzASHI, 1992. In dependency of soil types essential factors like soil moisture, hydraulic conductivity, and storage capacity define soil water balance and finally crop growth and yields.

Actual crop yields serve as standard of comparison for with GAMS modeled relative yield values. Only if it is possible to correctly calculate those yield and according to them actual yields, further calculations on gross margins and other economic scenarios can be executed.

Analysis, Validation, Sensitivity

The validation testing comprises measuring how well a model serves its intended purposes. Here validation by construct and/or by result can be done. Validation by construct signifies techniques that are employed in a model construction motivated by real world observations (functions, modules of software and equations, values); to assure the model was build properly. Validation by results refers to procedures wherein the results of the models are compared ex post with corresponding real observations (McCarl, Apland, 1986). Validation of applied functions and procedures is included, the model is based on a successfully applied model for the Syr Darya River basin in Central Asia (Cai, 1999), calculation of evapotranspiration and yield and resultant objective function are based on FAO recommended and widely used Crop water production model (Allen et al., 1998). For this required plant specific parameters are taken from in Uzbekistan defined and measured parameters. They finally were crosschecked with worldwide collected literature data to obtain that data and boundaries are composed in given limits. All other equations are based on experiments and well established theory[2]; soil parameters and their boundaries are based on field measurements and are additionally crosschecked with literature information[3]. Sensitivity analyses can not characterized within the framework of this paper, for further information see Schieder (forthcoming).

The validation of results can be done for irrigated areas, yields, relative yields, actual evapotranspiration, soil moisture, effective precipitation, efficiencies. Data for groundwater and other hydraulic values like deep percolation and groundwater extraction, water supply to districts, fields and crops, cropping prices (variable costs) are difficult to access and mostly also depend on estimates but should be located within a realistic range.

Positive modeling, Zero scenario:

For validation and first analyses a positive model is assembled. It is conducted to test the models consistency with reality. A positive model analyses of “what is” unlike normative models that

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[2] Groundwater tank model based on Bear, 1977; Groundwater extraction based on Eagleson 1978, effective rainfall via USDA, 1969

[3] soil moisture, groundwater table, permeability...Scheffer, Schachtschabel (1998); pumping capacity Sokolov (1999)

analyses of “what should be”[4]. Therefore all relevant input parameters as water supply, cropping areas and yields are fixed and were taken from actual data observations in 2003. This method shall be used to point out if the outcomes with underlying applied formulas and data for water balances and crop production processes stand in a realistic range. In further steps the fixation will be abolished little by little to crosscheck all parameters and to obtain finally a free and validated optimization model.

The determination of Actual Evapotranspiration is one of the most important factors within this model as crop growth, soil moisture and soil water balance, yields and according to them agricultural profit and benefits form a chain of causation. Monthly actual evapotranspiration (ETa) is determined for all 10 districts, 8 crops, and 3 soil types. ETa ranges between 340 (wheat) to 1055 (rice) mm, with an average of 680 mm per year[5]. Due to high water consumption and type of irrigation mainly rice has a really huge evapotranspiration rate. Winter wheat, as it grown in winter and spring denotes the slightest evapotranspiration as can be seen in the following figures. Differences between crops are relatively high due to crop specific properties like crop development stages, plant height, leaf area, ground coverage and water management (Allen et al., 1998). Also differences of ETa between soil types are not negligible, there are determined by soil characteristics like humidity, storage capacity, porosity, matrix potential. Compared with other studies the range of Eta in 2003 in Khorezm matches very well. Conrad et al. (2004) stated a calculated evapotranspiration for the summer season of zero to more than 1000 mm, with an average of approx. 600-900 mm. Forkutsa (2006) calculated ETa values on her fields in Khiva between 160-640 mm (average of 450) in 2003.

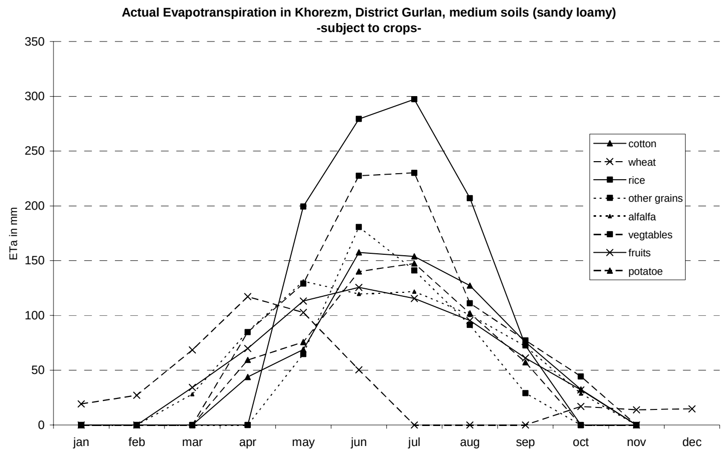

Figure 4: Actual Evapotranspiration (ETa)

Groundwater in Khorezm is in general relatively shallow. Due to leaching in Feb-April and because of intensive irrigation within the summer months the groundwater table converges towards surface. This shallow groundwater is desired by farmers and to some extent consciously manipulated (water afflux in canals); since subsurface water can be reached and used by crop roots, and represents a storage

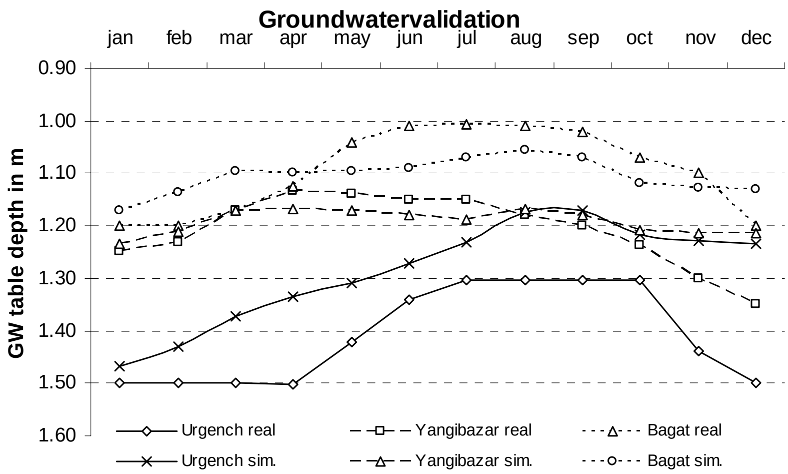

Figure 5: Groundwatersimulation

[4] that will be done later

[5] reference year is 2003

in times of water shortages. As can be seen in figure above the groundwater simulation matches well with “real” groundwater data for those districts.

Gross margins for considered agricultural crops are determined via production function. For costs all variable costs for seed, fertilizer, machinery and labor are included. Crop selling prices are based on farmer interviews, market analyses and modeling[6,7,8]. Together with the calculation of relative yields (subject to actual evapotranspiration) it is now possible to determine economic parameters like gross margins for main agricultural crops per district, value of water, marginal value, gross revenue or costs of goods sold:

Table 1: Some Economic Indicators for Khorezm Region in 2003

		Khasarasp	*Khanka*	*Urgench*	*Yangibazar*	*Gurlan*	*Bagat*	*Yangiarik*	*Khiva*	*Khushkupir*	*Shavat*	*Khorezm total*
Gross margin in M US $	*with water price*	7.435	7.031	5.832	2.663	8.103	3.593	4.857	3.709	0.958	3.588	47.769
	without water price	8.007	7.626	6.479	3.167	8.846	4.089	5.287	4.179	1.634	4.181	53.495
Gross margin, US$/ha		314	263	242	129	309	178	307	193	35	134	207
Cropped area in ha		23715	26720	24070	20610	26220	20160	15821	19221	27290	26710	230537
Revenue in M US $		16.31	15.64	14.29	9.93	18.26	10.42	10.58	9.87	9.46	12.07	126.82
Variable planting costs, M US$		8.30	8.01	7.81	6.76	9.41	6.33	5.30	5.69	7.82	7.89	73.33
water costs, M US$		1.24	1.26	1.38	1.05	1.58	1.10	0.98	1.02	1.54	1.33	12.46
total water applied, M m3		411.8	418.5	458.5	350.9	526.6	366.1	326.6	338.6	513.5	443.6	4154.7
Value of water US $/m3	*with water price*	0.018	0.017	0.013	0.008	0.015	0.010	0.015	0.011	0.002	0.008	0.011
	without water price	0.019	0.018	0.014	0.009	0.017	0.011	0.016	0.012	0.003	0.009	0.013

Gross Margins are a relationship of revenue and costs and serve as an indicator of profitability of crops as well as of districts. In Table 1 also a differentiation between Gross margins with and without water pricing is classified. An assumed water price of 0.003 US$ per cubic meter for surface water is used. As can be seen those water pricing has an influence of approximately 11% on gross margins. Another interesting point is the distribution of Gross margins on single crops. As in Table 2 exemplified mainly cotton and alfalfa have a negative value. This means even without introduction of water pricing, costs for those crops exceed revenues. For alfalfa this can be explained by utilization within another production process of animal feeding. So alfalfa is mainly used within the farms and not for selling. For cotton the still existent system of state orders and guaranteed selling prices have negative effects on gross margins. Herewith it must be mentioned that depending on farmer’s cotton growing orders pesticides, machinery and seed will be provided and do not reflect real marked prices. Despite significant favorable crop growing prices in 2003 it was not worthwhile for farmers to grow cotton mainly because of compared with world market lower selling prices. On the other hand a certain quantity of cotton will be bought by government to guaranteed prices.

[6] Per farm survey within the framework of his dissertation acquired: N. Djanibekov (forthcoming)
[7] Bobojonov (2004)
[8] For rice, potato and vegetables the prices vary a little by district

Table 2: Gross margin per crop in M US$

	cotton	wheat	rice	other grain	alfalfa	vegetable	fruit	potato
Khasarasp	-0.52	0.50	6.54	0.02	-0.22	1.10	0.01	0.01
Khanka	-0.27	0.48	4.85	0.02	-0.27	1.93	0.05	0.23
Urgench	-0.78	0.64	4.93	0.05	-0.21	1.00	0.18	0.02
Yangibazar	-0.89	0.36	3.02	0.01	-0.21	0.44	-0.14	0.09
Gurlan	-1.63	0.32	8.34	0.06	-0.36	1.08	0.15	0.15
Bagat	-0.63	0.56	3.05	0.02	-0.29	0.78	0.02	0.09
Yangiarik	-0.44	0.32	3.68	0.03	-0.16	1.23	0.06	0.14
Khiva	-0.13	0.20	1.04	0.01	-0.15	2.44	0.06	0.26
Kushkupir	-1.37	0.51	1.72	0.04	-0.51	0.52	-0.02	0.08
Shavat	-0.67	0.44	2.14	0.02	-0.29	1.20	0.28	0.47
Khorezm total	-0.73	0.43	3.93	0.03	-0.27	1.17	0.07	0.15

Conclusions

The research develops a modeling system to analyze and appropriate more efficient water allocation and sustainable water resources management on a regional scale for Khorezm Oblast in Uzbekistan. Crop water demands as the basis of profits from agriculture shall be secured trough stable and flexible water supply.

The main advantage of the model is its flexibility in respect to integrate several aspects of social-economical-hydrological-ecological aspects in an endogenous system and due to this account for the interdisciplinary nature of water resource problems. By dint of the model it is possible to analyze e.g. effects of institutional directives to economical incentives and prohibitions on ecology and hydrology and vice versa impacts of hydrological dispensation on economy.

First results and validations within the positive model show a functioning operative stable running model that now will be expanded for salinity mechanisms, sensitivity analyses and upgrading of the real optimization model and its economic and hydrologic analyses. The model is build up in a way to afford further considerations on a river basin scale or just for a more detailed spatial scale for e.g. district level. It also can serve as one part of a decision support system. It also should be possible to expand the model into a Node-Link-Network for analyzing dynamic processes.

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