Sustainable development and protection of water resources in the irrigated land of the Ile river delta, Kazakhstan

Final Report

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Sustainable development and protection of water resources in the irrigated land of the Ily river delta, Kazakhstan

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Executive Summary

Many years of excessive irrigation and massive exploitation of local water resources in the Akdalinsky sand dune terrain of the Ily river basin have caused considerable deterioration of soil and water in the area. Extensive flood irrigation over sandy soils, leading to leaching of nutrients from the root zone, soil swamping, alkalization and secondary salinization, have resulted in pollution of surface and underground water, associated with significant decreases in crop yield and quality of life of the local population. This project allowed quantitative characterization of the complex hydrological and hydrochemical features in the Akdalinsky agricultural land. Based on this characterization, recommendations were drawn up to decrease the negative impacts of anthropogenic activities on the soil and water environment in the cultivated sand dunes area. The approach used for this study was based on analyses and integration of field data, and detailed numerical simulations of different agricultural production and water management strategies.

The innovative aspects of the project lie in further development of the methodology to determine appropriate ecological water demand for irrigation in drylands. We demonstrate that crop pattern changes will reduce the water consumption for irrigation and return flow of drainage water to the Ily River. Results indicate that increasing the area of rice fields will further lead to land swamping and deteriorating hydro-ecological conditions. Leachate of polluted water from the irrigated area returns into the Ily River via seepage and surface drainage, affecting the water quality of the Ily delta. Alternatively, decreasing the proportion of rice fields in the area will lead to lowering of the groundwater level to 3-5 m below surface and secondary salinization of a significant part of this land. Application of models to simulate different water management scenarios enabled us to find the optimal relation between areas of rice and other crops. For example, keeping an area of 4200-4500 ha for rice fields out of 15,200 ha in the Bakhbakhty region is the most rational solution for this region.

The results of this research have been used for planning water and agricultural activities in the region in the framework of a project for reconstructing irrigation and drainage systems. Specifically, the GIS-based database and developed model of hydrological and hydrochemical conditions are being included as part of the automated information system for monitoring ecological conditions in the study area. The Kazakhstan Institute of Hydrogeology and Hydrophysics (IHH) participates in transfer of the developed technology and training of water authority professionals. The model will enable estimation of the efficiency of planned activities regarding reconstruction of the Akdalinsky irrigation system, in order to predict their effect on conditions in the study area for different crop rotation scenarios.

As a result of this project, the computing facilities in the Laboratory of Modeling and Hydrodynamics of the IHH were strengthened. The Kazakh researchers were trained in using the Groundwater Modeling System, geo-information system MapInfo and database management system FOXPRO.

Research Objectives

In many parts of the world, significant portions of irrigated land are subject to degradation, salinization and contamination, making irrigation unsustainable (Scherr and Yadav, 1996). Due to excessive irrigation and consequent rising groundwater levels, the installation of expensive drainage systems is required, increasing the cost of crop production. This also induces the problem of disposal of drainage effluent, which is usually loaded with salts and, when thrown into the river, contaminates the river downstream. The problem is therefore how to use water more efficiently in order to prevent environmental damage and to get a better return for the cost of supplied water (D. Hillel, in "Fresh Water resources in Arid Lands", 1997).

The conditions of water and soil resources in Kazakhstan are in many ways determined by the influence of past water-related technological development and agricultural activities. During the Soviet period, Kazakhstan implemented many poorly designed and constructed land reclamation projects, associated with the diversion of water from far basins. The processes of environmental deterioration can be observed in the Ily-Balkhash region, where a big industrial-agricultural complex was established over sand dune terrain based on water diversion from the Ily river. A total area of 30,000 ha were irrigated for growing rice, wheat, corn, tobacco, sugar beet, vegetables and fruit. Previous research revealed that many years of excessive irrigation and unsustainable exploitation of local water resources in the Akdalinsky land of the Ily River basin caused considerable deterioration of soil and water, including leaching of nutrients from the root zone, soil swamping, alkalization and secondary salinization, and pollution of surface and underground water (Vesselov *et al.*, 1996a,b). Observations show significant levels of pesticides and biogenic contaminants in drainage water. The latter is recharged back into the Ily and Karatal Rivers, which, despite their poor water quality, are used by the local downstream population for domestic purposes. A decrease in discharge of the rivers in the basin was detected, together with a lowering of the water level in the Balkhash Lake. Desertification features have been observed during the last 15 years over the entire area, associated with qualitative and quantitative changes in groundwater, which is the central component of the ecological system. Therefore, an assessment of rational strategies for exploitation of water resources and prevention of contamination of the soil and water environment is a primary task. Investigation of these problems can be done by developing a physical and hydrochemical database and by applying mathematical model analyses. For example, applying a global water and food analysis model (Cai, 2004) demonstrated that there is little hope of resolving the conflict between agricultural water demand and ecological water demand in the Yellow River Basin.

The aim of this research was quantitative elaboration of a complex of hydrological features in order to decrease the negative effects of anthropogenic activities on the soil and water environment in the agricultural area of the Ily River basin. This is based on: 1) Assessing the extent of pollution and salinization of surface and underground water; 2) Adapting and implementing models for predicting the path and rates of pollutant migration and for simulating scenarios under various types of water resources exploitation; 3) Analyzing the results of hydrological simulations to determine measures for decreasing the risks of environmental pollution; 4) Assessing suitable scenarios for sustainable development of water resources in the study area.

The innovative aspects of the project involve further development of the methodology to determine appropriate ecological water demand for irrigation in drylands. The aim was to examine how changes in crop pattern will affect the water consumption for irrigation and return flow of drainage water to the Ily River. The results of simulations for different agricultural and water

application scenarios will help planners in protecting the local environment and establishing sustainable cultivation in this area. The "Jetisuss" hydrogeological-reclamation expedition by the Kazakhstan Ministry of Agriculture has started using the results of this research. This organization is responsible for water management in the area, participating in activities concerning re-design and reconstruction of the Akdalinsky irrigation system. The staff of this expedition helped in organizing field trips by Kazakhstan and Israeli investigators to the research site, and supplied data from field observations.

Methods and Results

The approach used for this study is based on analysis and integration of field data, and detailed numerical simulations of different agricultural production and water management strategies.

Hydrogeochemical conditions

The study area is sand dune terrain located in the southeastern part of Kazakhstan (Figure 1a). It is a flat closed depression resulting from intensive deformation during the Alpine time, and filled by alluvial-prolluvial sediments. The aquifers in the plain part of the basin, in the lake-alluvial deposits and the recent deposits of Middle and Upper Quaternary age, are composed of sand, loamy sand, and loam. Their thickness is 50-70 m near Lake Balkhash and up to 240 m in the deepest part of the depression near Bakanass. The depth of groundwater is 5-7 m along river valleys and between sand ridges and 15-18 m on the sand ridge areas. Groundwater chemical composition is predominantly of bicarbonate calcium and sodium sulfate type; TDS varies from 0.5 to 1.6 g/l. Aquifers of the upper horizon are interconnected hydraulically; the general direction of groundwater flow is from the south-east to the north-west towards Lake Balkhash. Groundwater in sand massifs is recharged by infiltration of surface water (mainly rivers), surface infiltration in periods of precipitation and underground inflow from mountain regions. In the foothills of the northern Balkhash zone, to the north of the Balkhash Lake, groundwater is recharged mainly from infiltration of winter and spring precipitation. Climate in the Lake Balkhash basin is continental, characterized by large daily and annual variations of air temperature, and high levels of solar radiation. Mean annual temperature is about 2 to 5 °C in the plains and -5 to -10 °C on the foothills. Mean air temperature during the coldest month (January) is -16 °C in the northern part and –5 °C in the southern part of the plain territory. Mean air temperature during the hottest month (July) is about 20-25 °C. Distribution of precipitation over the basin is very variable: about 150 mm falls on the coast of Lake Balkhash and 200-250 mm in the southern and northern Balkhash zones.

The central part of this area is the Akdalinsky irrigation system, located on the right side of the Ily River (Figure 1b) between the Taukum and Sary-Ishikotrau Sands. It includes the irrigated lands of Bakhbakhty, Tasmuran and Bakanass, with a total surface area of 30,000 ha. In the past, most of these lands were used for rice growing (45-54%). Crop rotation also includes alfalfa, corn, barley and wheat. Actual irrigation norms for rice in 2001 were 53,000 m^3/ha. Water from the Ily River with a TDS of 0.2-0.7 g/L is transported through the Tasmuran and Bakanass main canals and used for irrigation. Shallow (0.5-1.0 m deep) open drains connected to the open on-farm collectors (2-3 m deep) represent the drainage system. Drainage water from the irrigated lands is dumped into the Ily River through Main Collectors. This water has a high concentration of sulfate (190-210 mg/L), nitrate (0.5-2.1 mg/l), ammonia (up to 0.25 mg/l) and nitrite (up to 0.07 mg/L).

To assess hydrogeochemical conditions in the study area we collected hydrogeological and hydrochemical information on the area from previous investigations. This included meteorological data, lithological profiles for different cross-sections (62 well logs), groundwater level observations and geochemical information (296 wells). Data on water levels and chemical composition of surface water (including the Ily River, irrigation channels, and drained water in collectors) was collected.

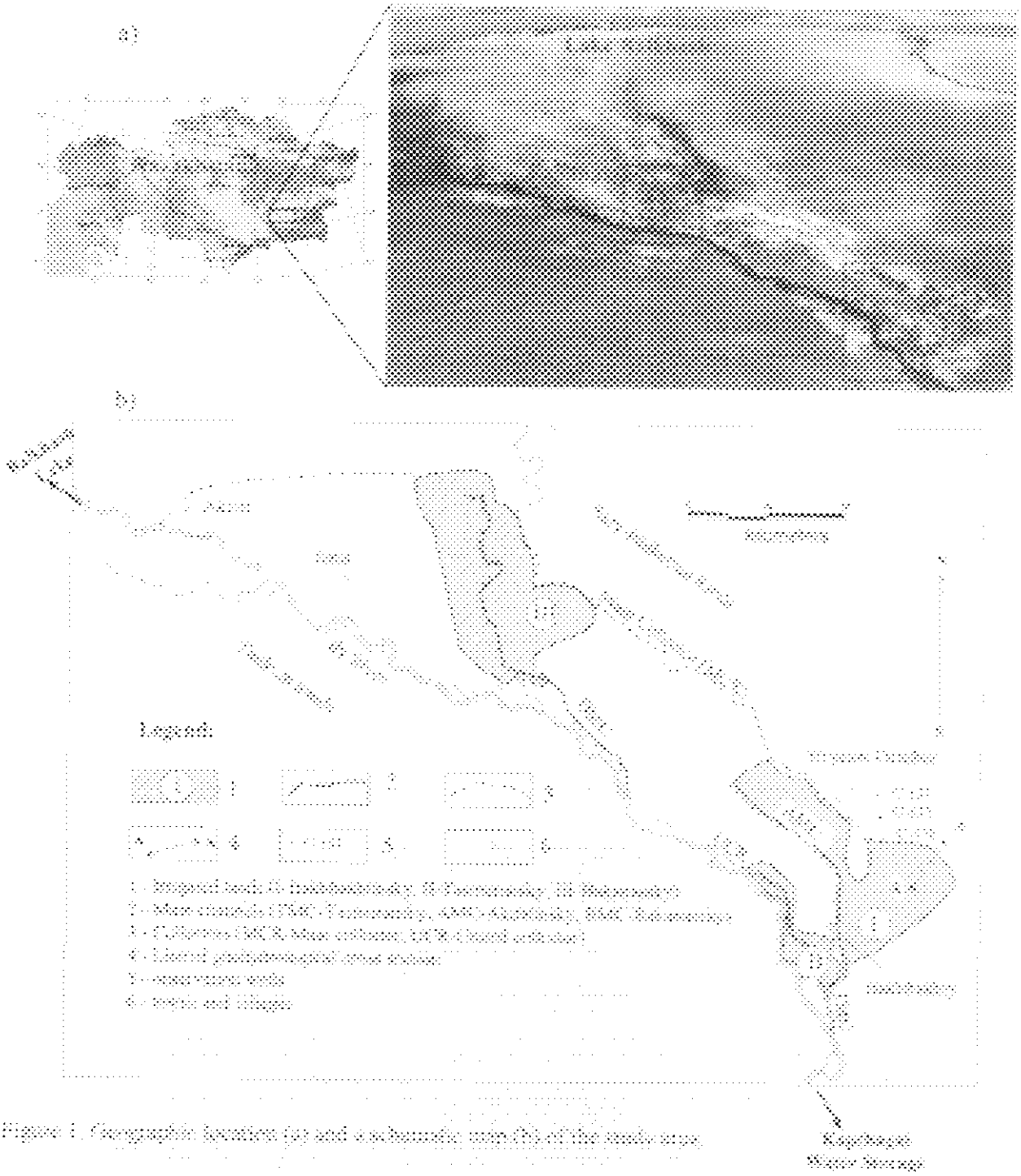


Figure 1. Geographic location (a) and a schematic map (b) of the study area.

Maps and reports concerning topography, geology, spatial hydrogeological parameters, major aquifers and water bearing units, drainage system schemes and agricultural crop rotation schemes were acquired. Taking into account the considerable volume of such information and the need for its analysis, a computerized database was developed using FoxPro 6.0 for data processing and producing maps. This included electronic tables of groundwater levels and chemical composition. Existing maps were digitized and stored into GIS: agricultural fields, land surface topography, hydrogeological parameters (estimated hydraulic conductivities and thickness of

major lithological units), well locations, and maps of irrigation and drainage systems were all stored.

To complete the existing database with hydrochemical information concerning environmental tracers and stable isotopes, additional water samples were collected in May (65 samples) and August 2003 (56 samples). Location of sampling boreholes in Bakhbakty and Bakanass areas is presented in Figures 1A and 2A (Appendix 1), respectively. The samples were analyzed for their pH, EC, TDS, concentrations of the major elements: Cl, SO_4, Br, NO_3, HCO_3, Na, K, Ca, Mg, PO_4, stable isotopes (Tables 1A, 2A in Appendix 2), and trace elements such as: Al, B, Ba, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, Pb, Se, Si, Sn, Sr, Ti, V, Zn, Li, Ag, As, Sb, and Hg (concentrations of trace elements are quite small, and therefore not presented in this report). The total dissolved solids (TDS) in the collected samples at the Bakhbakhty part of the irrigation system ranged from 218 to 2028 mg/l and the mean value was 695 mg/l. The TDS in the samples, collected at the Bakanass part of the irrigation system, ranged from 166 to 969 mg/l and the mean value was 505 mg/l. Most of the water samples were characterized by relatively high concentrations of up to 1008 and 450 mg/l sulphate; 360 and 545 mg/l hydrocarbonate; and 34 and 51 mg/l nitrate, in the Bakhbakhty and Bakanass regions, respectively. One water sample collected from well # 592 in the Bakanass region exhibited very high salinity (TDS = 3124 mg/l), which is probably due to high contents of dissolved minerals at that location. Comparing pre-irrigation (May 2203) and post-irrigation (August, 2003) water samples, we noted a general trend of decreasing TDS, Cl, Ca, Mg, PO_4 and HCO_3 concentrations in groundwater, probably due to leaching of salts by irrigation and drainage. Concentrations of SO_4, NO_3, and K increased due to application of fertilizers. The content of Na and the pH of the groundwater also increased.

Cluster and Principal Component Analyses of groundwater hydrographs and hydrochemistry

Hydrogeological and chemical data were used to characterize the effects of irrigation on hydrogeochemical conditions in the study area using statistical methods. SPSS cluster analysis was performed on the spatial distribution of hydrochemical data to specify the extent of aquifer heterogeneity. This allowed the delineation of hydrological sub-regions with homogeneous properties (water bodies) in order to assess further major flow patterns, sources of groundwater contamination and hydraulic parameters. Results are presented in Figure 2. The TDS concentration was the major factor affecting cluster analysis, indicating a pseudo-linear correlation among all the dissolved minerals. Water samples with low TDS (200-400 mg/l) and chemical composition close to that of irrigation water (Ily River) belong to a cluster located in the irrigated fields and close to the irrigation canals. Clusters with TDS of 600-1000 mg/l and 1200-1800 mg/l include water samples collected in boreholes located in the peripheral parts of the irrigated land, in non-irrigated areas and close to drainage collectors. We note that in the pre-irrigation period (May 2003) more clusters were delineated; however, after the end of irrigation, distribution of concentration became more uniform indicating a heavy irrigation effect on groundwater chemistry. Relative uniformity of concentrations and geographical overlapping of water bodies made it impossible to use the original compartmental modeling approach (Adar *et al.*, 1988a,b) for quantitative identification of recharge sources and hydraulic parameters. Analysis of the chemical data indicates that in the study area, groundwater chemistry obeys quasi-steady state conditions. In other words, introducing Ily water into irrigation channels and starting intensive irrigation in mid-May significantly changed groundwater levels and chemistry. Massive infiltration from rice fields and un-paved irrigation channels leaches salts, fertilizers and herbicides into the shallow groundwater, part of which is drained into collectors flowing back into the Ily River (Figure 1b).

Figure 2. Clusters of wells with similar concentrations of major ions for (a) Bakanas and (b) Bakhbakty parts of the Akdalinsk irrigation system, for the beginning (May) and end (August) of the 2003 irrigation season.

Elevated groundwater, due to massive irrigation during the hot summer season, induces evaporation, which increases topsoil salinization in the surrounding area. After harvesting crops in September-October, hydrological and hydrochemical conditions return to a state close to that observed before irrigation, producing a so-called seasonal oscillating pattern. However, the general hydrological conditions prevail all year long in elevated groundwater.

Principal Component Analysis (PCA), which is commonly used to reveal patterns in data sets (Moon et al., 2004 Winter et al., 2000), provided insights into the characteristics of groundwater in the Akdalinsky agricultural land of the Ily River basin. In this study 41 observation wells were classified into hydrograph types with similar variations. Wells exhibiting similar water table fluctuation characteristics were clustered, and the characteristic fluctuation curves, which are component scores for each PC (PC1 and PC2), were determined as representatives of each type. Varimax rotation using the Kaiser normalization method (Kaiser, 1958) was applied to classify total variables (i.e. groundwater fluctuation curves) into groups that showed similar characteristics. The procedure maximizes the factor loading variance in each vector, under the constraint that the factors remain orthogonal. Table 3A (Appendix 2) shows the factor loading values of wells for each component. The patterns of water table fluctuations in the Akdalinsky region reflect the land use pattern for agricultural crop production. The factor loading in Table 3A indicates that groundwater wells from irrigated croplands were mostly associated with PC1. The factor loading values emphasized in bold indicate associated loading groups. About 60% of the total observed wells were associated with PC1. Around 80% of the groundwater wells associated with PC1 were from irrigated cropland. Among the irrigated cropland, rice and alfalfa were the major contributors in the PC1 factor loading: rice accounted for 36%, alfalfa for 20% and unspecified crops for the rest of the loading. 40% of the total observed wells were associated with the PC2 factor loading. More than 40% of the factor loading associated with PC2 came from land that is not used for crop production. Among the cropland associated with PC2, alfalfa accounted for approximately 30% and unspecified crops for another 30% of the total factor loading. The results indicate that the dominant mode of variation in the groundwater water table is a pattern of irrigation effect, which is mostly described by the excessive water demand of the rice irrigation system.

Time series analysis of component scores indicated that most component functions can be best described with the rising and falling pattern of the groundwater hydrographs. The component scores and ground water table fluctuations associated with PC1 (1999-2002) for C-126 and C-594 are plotted in Figure 3. The loading of the variable for station W126 was the highest onto PC1 (0.925), followed by C-594 (0.902). As principal component loading becomes closer to 1, the shape of the pair of principal component scores and water table fluctuations becomes similar. The groundwater hydrographs and PC scores for the two representative wells associated with PC1 illustrate a rising water table trend during the irrigation period (May-August). Since no crop was allocated for C-126, the rising water table for the well is probably described by infiltration of water from an adjacent irrigation field, or by horizontal flow of water from the influence of poor drainage network. C-594 comes from the rice field, which is one of the representative wells of the PC1 factor loading (0.902). Similarly, Figure 4 shows principal component scores and groundwater table fluctuations (1999-2002) for C-60 (0.888) and C-129 (0.803), associated with PC2. The groundwater hydrographs and PC scores for the two representative wells associated with PC2 illustrate a falling of the water table for the years 2001 and 2002 during the irrigation period (May-August). C-60 (0.888) comes from an alfalfa field, whereas no crop was allocated for C-129 (0.807). Seasonal (irrigation effect) groundwater fluctuations for the years 2001 and 2002 were decreased compared to 1999 and 2000, which can be described by a decrease in irrigated areas and a changing crop pattern.

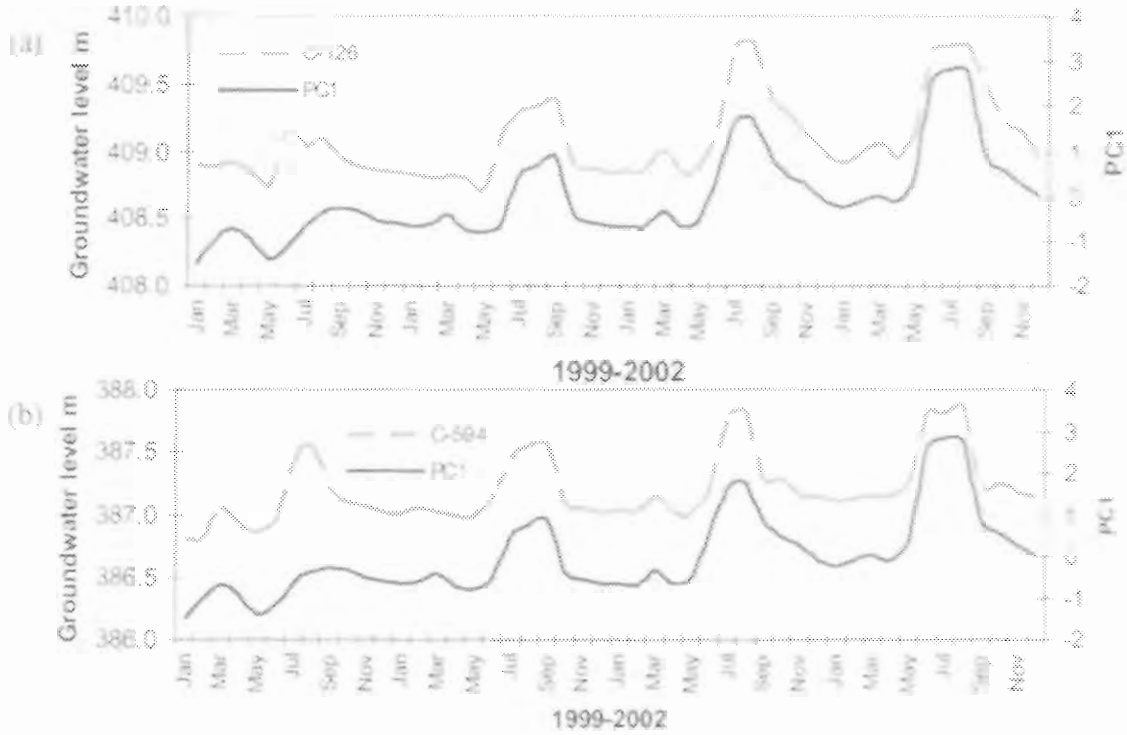


Figure 3. Component scores and groundwater levels associated with PC1:
a) well C-126; b) well C-594.

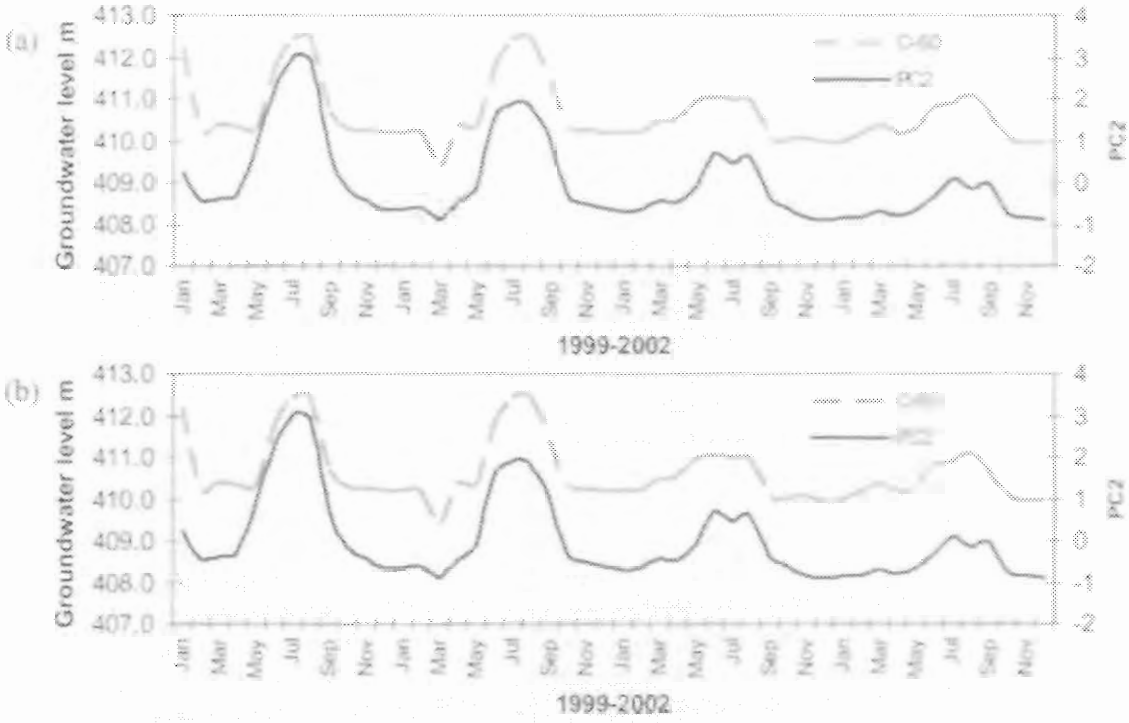


Figure 4. Component scores and groundwater levels associated with PC2:
a) well C-60; b) well C-129.

In 2002, the area occupied by rice fields in the Bakhbakhty part of the Akdalinsk region was 4165 ha compared to 7202 ha in 1988 (Vesselov et al., 2005). Results from the MODFLOW simulations indicate that decreasing this area will lead to a lowering of the groundwater level. Temporal structure analysis of water table fluctuations along with PC factor loading indicates that rising groundwater in the area is mainly associated with excess irrigation water

The groundwater geochemistry data were also subjected to evaluation via PC analysis to investigate agricultural impact on groundwater. The analysis generated 4 factors, which together account for ~90% and ~86% of the total variances for the pre- and post-irrigation period, respectively.

For the pre-irrigation period, the first factor loading accounts for ~50% of variation and is characterized by high positive loading for EC, Cl, SO_4, Na, Ca and Mg. The second factor, accounting for ~20% of the total variance, is mainly associated with very high positive loading of HCO_3 and $CaCO_3$. Perfect correlation was also observed between HCO_3 and $CaCO_3$. The third factor, accounting for ~10.5% of total variance, is associated with PO_4 and K. The fourth factor accounts for ~9.5% of the total variation and is mainly associated with the high loading for NO_3 and negative high loading for pH.

For the post-irrigation period, the first loading factor accounts for ~46% of variation and is characterized by high positive loading for Ca, Mg, SO_4, and moderate loading of PO_4 and K. Significant correlation over 0.6 was found between SO_4, Ca, Mg, and PO_4, suggesting that these variables are strongly influenced by fertilizers. The second factor, accounting for ~19.5% of the total variance, is mainly associated with very high positive loading of Na, Cl, EC and moderate loading of SO_4. High correlation was also observed among Na, Cl, and EC. The third factor, accounting for ~11% of total variance, is associated with high loading of HCO_3 and $CaCO_3$. Significant correlation was also observed between HCO_3 and $CaCO_3$. Previous research shows that the concentration of bicarbonate and calcium is practically constant along the Kaskelen River (Vesselov et al., 1996a), which is a main source tributary of the Ily River. The fourth factor accounts for ~9% of total variation, and is mainly associated with high loading for NO_3 and negative moderate loading for pH. Factor 4 is mostly associated with nitrogen fertilizers. Since large amounts of fertilizer such as urea and commercial composites have been applied for a long time under oxic conditions, the main component of fertilizers, NH_4, is oxidized to NO_3 by nitrification. When an NH_4^+ ion changes to NO_3^- through the nitrification process, H^+ is produced as a by-product. Therefore, NO_3 is enriched and pH is decreased in groundwater (Bohlke, 2002).

The isotopic compositions of collected groundwater samples were used to further assess the impact of agriculture on ecological conditions in the study area. The general meteoric relationship between oxygen-18 and hydrogen-2 has been described by the global meteoric water line, GMWL (Craig, 1961) with the equation $\delta D = 8\delta^{18}O + 10$. In the absence of primary data on isotopes in precipitation over the study area we used IAEA, WMO (2001) data from the two closest stations: Kabul, Afghanistan and Wulumuqi, China (Figure 5). The straight line $\delta D - \delta^{18}O$ for the precipitation data for Kabul is obtained by linear regression and is described by $\delta D = 7.98\delta^{18}O + 16$ (R^2=0.97), while that for Wulmuqi is described by $\delta D = 7.18\delta^{18}O + 2.13$ (R^2=0.99), i.e. the slopes of the regression lines for both precipitation data sets are similar to the GMWL. Assuming that rains in Kabul are more representative of the precipitation over the study area, one can infer that the isotopic signature of precipitation is modified by evaporation before groundwater recharge.

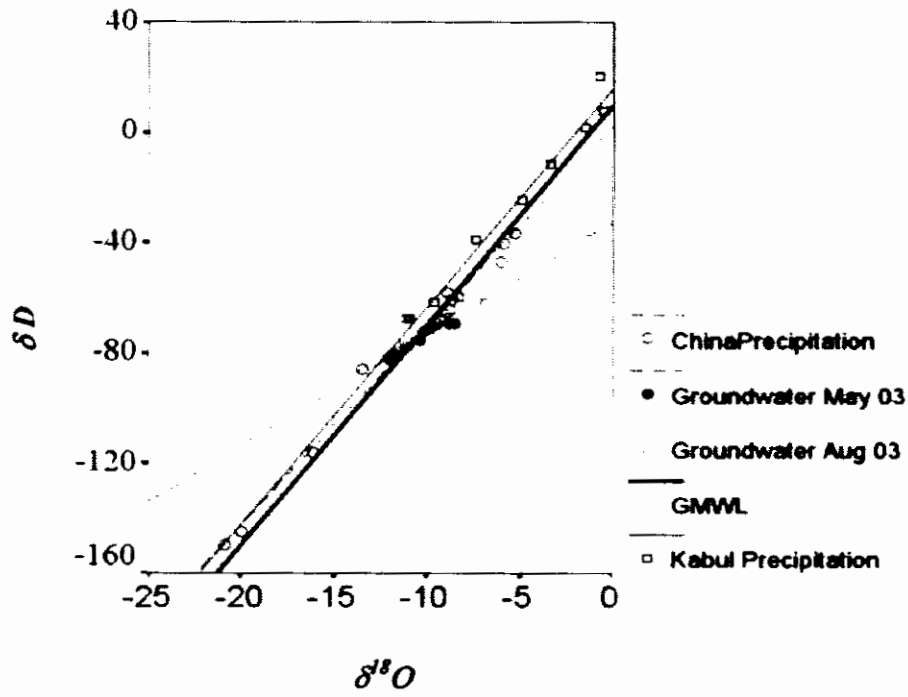


Figure 5. $\delta D - \delta^{18}O$ relationships for the precipitation data from Kabul (Afganistan), Wulmuqui (China), and for the Bakhbakhty groundwater samples in May and August 2003

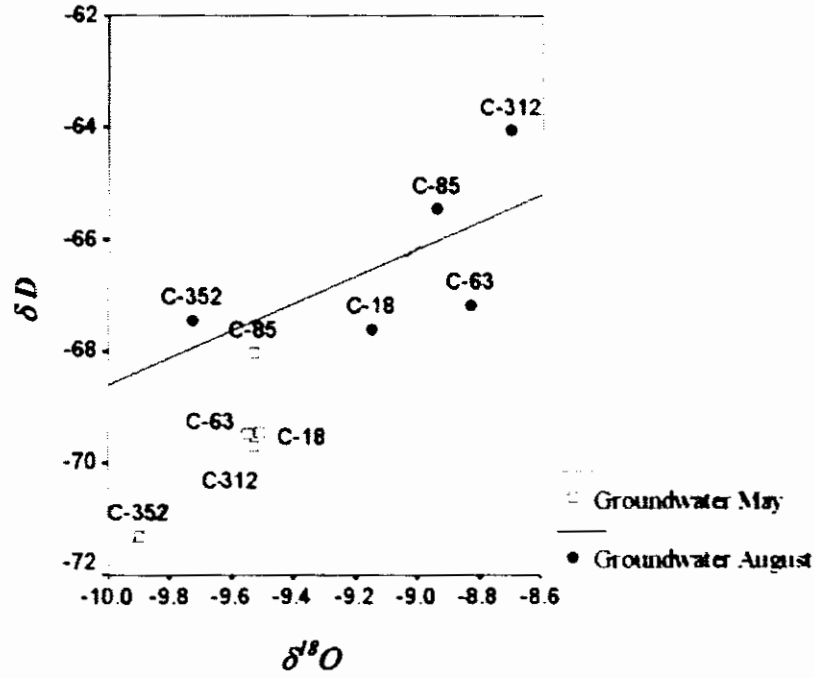


Figure 6. The $\delta D - \delta^{18}O$ relationship for selected Bakhbakhty groundwater wells in May and August 2003.

The $\delta^{18}O$ values of the Bakhbakhty groundwater samples ranged from –8.49 to –11.99 in May 2003, and from –6.88 to –11.36 in August 2003, while the δD values ranged from -68.03 to –82.41 in May and from -61.86 to –79.18 in August 2003. Although most of the $\delta^{18}O$ and δD samples showed an evaporative enrichment of δ values after the irrigation period, the observation wells located within open water bodies such as irrigation canals, flooded areas and drainage canals were not considered when assessing irrigation impact on groundwater, and $\delta D - \delta^{18}O$ straight lines were plotted for the selected observation wells located from the agricultural land (Figure 6). For May 2003 the straight line in Figure 6 is described by $\delta D = 5.75\delta^{18}O - 14.41$, and for August 2003 it is described by $\delta D = 2.43\delta^{18}O - 44.25$. The stable isotope data indicate that groundwater collected in May 2003 and in August 2003 differ not only in their values but also markedly in their deuterium excess values. The low average 'd-excess' values: ~-14.4 for May, and ~ -44.30 for August, 2003; would suggest that there is significant evaporation from rainwater and further evaporation from surface water (rice checks or irrigation canals), leaving the residual groundwater with lower values of 'd-excess'.

High nitrate levels are associated with enriched $\delta^{18}O$ values, clearly indicating that significant quantities of evaporated (isotopically enriched) irrigation water infiltrate along with fertilizer nitrate to the groundwater system. The post-irrigation (August 2003) nitrate levels were higher in all the observation wells than the pre-irrigation nitrate levels (May 2003), similarly enriched $\delta^{18}O$ values were observed for the post-irrigation period. The illustrated different $\delta^{18}O - NO_3$ trends suggest isotopically distinct, non-point source origins, which vary spatially and temporally, due to different degrees of evaporation recharge and amounts of fertilizer applied. However the positive $\delta^{18}O - NO_3$ relationship indicates clearly infiltration of isotopically enriched, evaporated irrigation water along with fertilizer nitrate to the groundwater aquifer.

Remote sensing analysis of the study area

Two LANDSAT images (Figure 2A, Appendix 1) for May 26, 1990 and May 13, 2000 were processed to assess the impact of irrigation on the hydro-ecological conditions of the Akdalinsky irrigation system and neighboring territory. Digital maps and photos of the settlements, water bodies, plants, agricultural fields, irrigated lands and topographic maps (1:200000) were utilized for decoding satellite images. A pretreatment procedure was carried out to obtain reliable relations between biophysical surface parameters and values of brightness: radiometric classification, atmospheric correction, and geometric correction. A number of ground control points (GCPs) were selected from the topographic maps for geometric correction and transformed to the Transverse Mercator coordinate system adopted in Kazakhstan. The methodological device ERDAS IMAGINE for image classification – supervised classification - was used for analyzing the satellite images. The classification is a grading process (classification by classes) of image elements (pixels) to produce a final number of classes on the basis of attribute values (DN - digital numbers). If a pixel satisfies some classification conditions, it defines a class corresponding to these conditions (ERDAS Field Guide; ERDAS, Inc., Atlanta, GA). Small standard plots (signatures) and single pixels were chosen in the satellite images corresponding to the following 8 major classes observed at the land surface: 1) agricultural fields, 2) clay desert, 3) takyr, 4) dense natural vegetation, 5) salty crust (Solonchaks), 6) sandy desert with Saksaul type of vegetation, 7) vegetated sands, and 8) water bodies and rice fields. The results were tested through accuracy assessment by calculating the error matrix that compares the relationships between ground-truth

data (reference data) and classified results category-by-category. The overall accuracy of the final maps was good (75%) in 1990, and very good (89%) in 2000. Maps of supervised classification of the study area are presented in Figures 3A-6A (Appendix 1). Digital analysis of these results revealed that during a period from 1990 till 2000 the area of rice fields decreased while groundwater level still remained close to the soil surface. This led to an increase in soil salinization, a decrease in vegetation area and desertification of the irrigated area and neighboring lands. During the 10-year period 1990-2000, the area of vegetated sands decreased from 3944 km^2 to 3714 km^2, dense natural vegetation (bushes) decreased from 545 km^2 to 138 km^2, salty crust (Solonchaks) increased from 7 km^2 to 447 km^2, sandy desert with Saksauls increased from 66 km^2 to 579 km^2, and takyrs and clay desert decreased from 80 km^2 to 46 km^2. The area of water bodies was smaller in 2000 (83 km^2) than in 1990 (265 km^2), mainly because the rice fields were not yet flooded by May 13, 2000.

The main drainage collector also significantly affects the environment. Inspection of the collector relief profile revealed that the altitude of its bottom and the water level in the collector at many locations are higher than the groundwater level of the surrounding area. Therefore, drainage water of high salinity flows from Bakhbakhty to Bakanass and on to the Ily River. Infiltration of this water along the collector leads to salinization of the surrounding territory.

Modeling of agricultural land use and water management scenarios

The above analyses of hydrogeochemical conditions prove that unsustainable exploitation of the Akdalinsky agricultural lands has a negative impact on the environment: raising groundwater levels, soil degradation, salinization and desertification. This is mainly caused by growing rice, which requires large irrigation norms and has a low efficiency of irrigation and drainage systems. A rational policy for sustainable land exploitation can be assessed by simulations of related processes with mathematical models.

We started simulations for different scenarios of irrigation and water exploitation with a one-dimensional model of water flow and solute transport in the unsaturated-saturated zone (numerical code WASTR3 was developed by A. Yakirevich). The following data were introduced into the model: lithological profiles, hydrological and hydrochemical parameters of different layers, crop rotations, transpiration, evaporation, precipitation, irrigation requirement and water application, initial distribution of water content, solute (TDS) concentration, groundwater levels, parameters of irrigation and drainage systems, TDS concentration in rainfall and irrigation water. Simulations were performed for the 8-year crop rotation period. Growing crops were rice, alfalfa, beet, barley, and corn. The following scenarios of water exploitation and land use were considered:

1. Rice as a major crop occupying 62.5 % of irrigated area (Soviet era policy);
2. Rice growing is reduced to 37.5 % of irrigated area (current policy);
3. Rice growing is terminated completely and replaced by other crops with higher water efficiency.

The annual volume of water applied for irrigation depends on the type of crop and on the specific climatic conditions. Mean annual irrigation norms were 24,000, 17,000 and 5,800 m^3/ha for scenarios 1, 2 and 3, respectively.

The results of simulations indicate that after one year of irrigation of rice fields the content of salts in the root zone is already drastically decreased and there is little change after that (Figure 7). TDS concentration in the root zone (0-0.7 m) after 8 years of irrigation was 0.009, 0.008 and

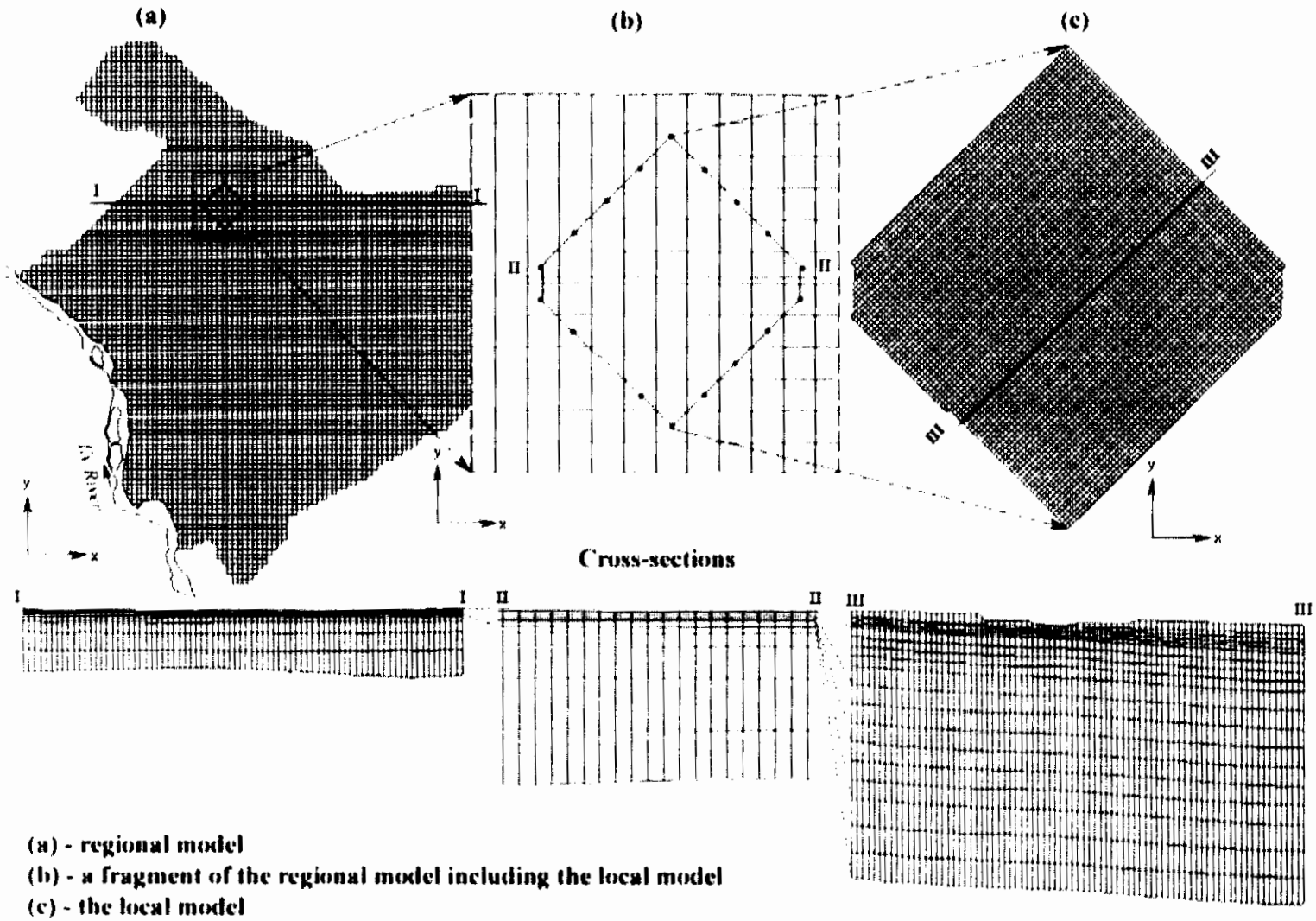
performed. Good agreement between measured and simulated groundwater levels was received. In most parts of the area the error did not exceed 0.5 m.

After solving the inverse problem, we performed *MODFLOW* simulations for three scenarios of water and land resources exploitation for the Bakhbakhty part of the Akdalinsk irrigation system: 1) rice fields with an area of 4165 ha; 2) rice fields with an area of 7202 ha; and 3) fields in which rice growing has been terminated completely. We assumed that during the long irrigation period (since 1967), the hydrological conditions have reached a quasi-steady-state, namely: oscillatory changes in groundwater level occur with a periodicity of one year. Therefore, simulations for the first and second scenarios were carried out for a one-year period. The crop field distribution schemes corresponding to the years 2002 and 1988 were considered. For the third scenario, irrigation norms were considerably smaller. This affects the groundwater dynamics and the quasi-steady-state conditions are no longer valid. Therefore, a forecast was made for a period of 20 years. This period corresponds to a time during which the groundwater mound was being dissipated (Vesselov et al., 1996b). Simulation results of groundwater depth from the surface are presented in Figures 7A-9A (Appendix 1), and simulation results of total water balance are presented in Tables 4A-6A (Appendix 2). The results indicate significant inefficient losses of water from the irrigation network and even from drainage collectors.

Propanid, Saturn, Ordram, HexaChloroCycloHexane (HCCH) and other pesticides have been used in the past for weed destruction during the rice crop rotation. Concentrations of pesticides in the drainage water increase sharply during dumping of water from rice fields (usually in the middle of June and in the middle of July). Input of these chemicals with respect to total contamination is relatively low, and the risk of direct poisoning of the population through drinking water nowadays is low. However, some species of fish and other low-level organisms (planktonic sources of fish food) can die as a result of the high toxicity of these chemicals to aquatic fauna. To assess the possible effect of pesticide application on groundwater quality, we used the results of observations made during 1980-1990 to perform simulations of pesticide transport in soil and groundwater.

As a first step, the mathematical model and numerical code *GLEAMS* (Groundwater Loading Effects on Agricultural Management Systems, Leonard et al., 1987) was applied. Application of the following pesticides was considered for simulations: Ordram, Bolero (Saturn), Propanil, Benzex (Benzene hexachloride) and DDT (the use of DDT was terminated at the end of the 1980s). The model takes into account dynamics of climatic factors, soil and hydrological parameters and agricultural aspects. Characteristic parameters of these pesticides were taken from the *GLEAMS* database. Simulations indicated that maximum concentrations of Bolero, Ordram and Propanil in groundwater reached 0.014, 80, and 0.2 μg/L, respectively, while the computed concentrations of Benzex and DDT in groundwater were close to zero. The observed concentrations of Benzex, Bolero and DDT in groundwater varied in the range of 0.003-0.14, 0.02-0.2 and 0.009-0.018 μg/L, respectively. Comparison of the simulated and observed concentrations led us to conclude that additional model calibration regarding pesticide parameters is needed, but that existing parameters are insufficient for this purpose. A considerable amount of the pesticides is being washed out with runoff water through open drainage canals. Simulated maximum removal of Bolero, Ordram, Benzex, Propanil and DDT with surface flow were up to 900, 1400, 25, 1600 and 160 g/Ha, respectively. This is an extremely important observation because the Ily River is not only the source of irrigation water but also an acceptor of the disposed runoff and drainage water.

More detailed simulations were carried out with a 3-D local model of pesticide transport. The local areal modeling domain is represented by a rectangular area located at the northern part of Bakhbakhty region (Figure 11).



(a) - regional model
(b) - a fragment of the regional model including the local model
(c) - the local model

Figure 11. Modeling domain for simulating pesticide transport.

The finite difference grid has 86 x 84 nodes (uniform grid increment is 20 m) in plain and 19 layers in depth (total simulated thickness was 25-27 m). The grid was constructed such that boundary nodes describe the configuration of irrigated fields and drainage canals. The boundary nodes of the local grid coincide with the nodes of the regional model grid (Figure 12). The first kind of boundary condition (hydraulic heads varying with time) was derived from the regional model solution and prescribed at the boundary nodes of the local grid. Drains and collectors, as well as evaporation from groundwater, were simulated by the third kind of boundary condition. Simulations were conducted for the irrigation period from May 10 to September 9. The crop rotation scheme corresponded to the one employed in 1988. Only one pesticide - Saturn (Bolero) - was considered. The processes of pesticide advective-dispersive transport and degradation were accounted for. Temporal variation of pesticide concentration in flooded rice fields was assigned as a boundary value for the first (from the land surface) model layer (Figure 13). The model was calibrated against observed water heads and measured distributions of pesticide in groundwater with depth. As a result, the values of effective porosity, hydraulic conductivity and dispersivity were determined.1 Consistent agreement between observed and simulated values of pesticide concentration was obtained.

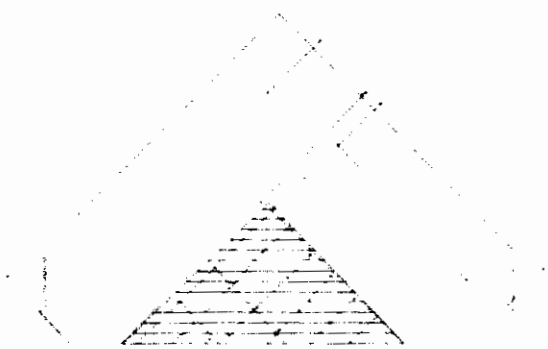


Figure 12. A scheme of drainage collectors and irrigation canals in the local model area.

Figure 13. Temporal variations in pesticide concentrations in rice field water.

A calibrated model was used to study the evolution of pesticide distribution in groundwater. Results of the simulation are presented in Figure 14 for different time intervals. We note that the pesticide plume reached maximum depths of 8-10 m. After about 55 days the plume dissipated and the concentration dropped to less than 2 ppb (maximum admissible concentration of pesticide concentration for fisheries). Drains and collectors intercepted most of the pesticides. The calculated maximum rate of pesticide removal by drains reached 0.09 g day ha (Figure 15).

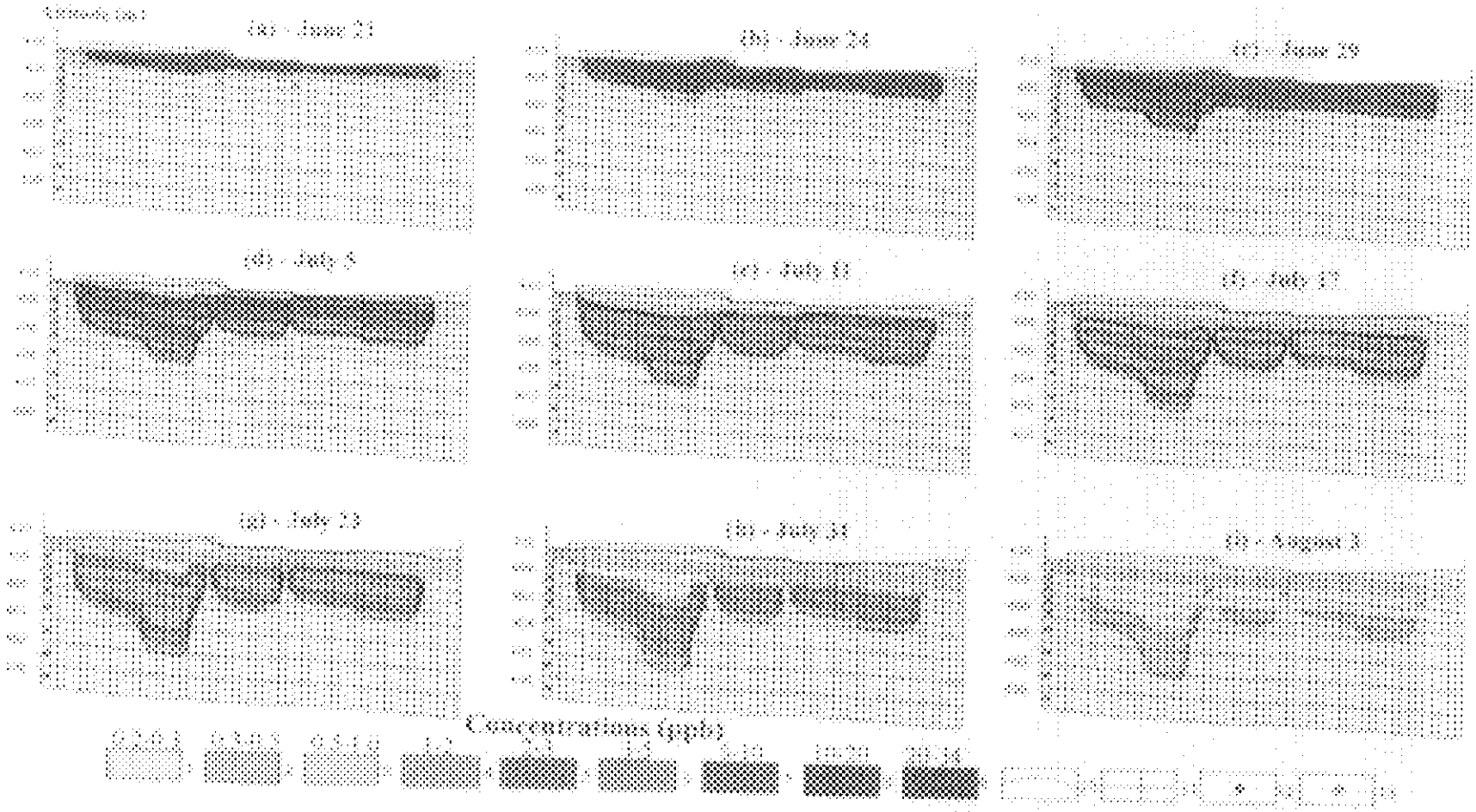


Figure 14. Simulation results of transport of the pesticide fluxes in a vertical cross-section under a rice field: (a)-(i) pesticide distribution at different points in time. 1-9 – concentrations (ppb), 10 – isoconcentration lines, 11 – finite difference grid, 12 – first boundary condition of prescribed head, 13 – drains

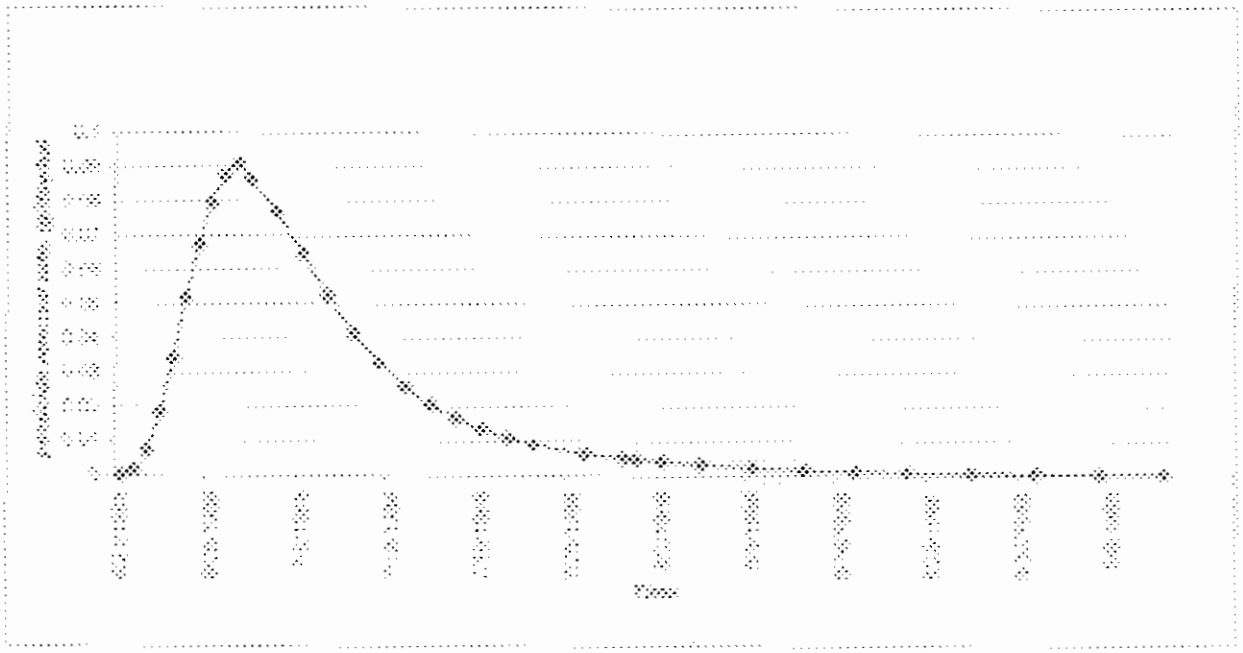


Figure 15. Simulated pesticide removal rate by drainage.

Conclusions

The results of field investigations and simulations with mathematical models in the study area led to the following conclusions and recommendations:

- The efficiency of the irrigation network (mainly unpaved canals) of the Akdalinsky land is very poor. Water losses from irrigation canals are large, leading to the development of close-to-swamping conditions. Therefore, reconstruction works are recommended to decrease water losses by infiltration from the transmitting canals.
- The performance of the drainage canals is not always efficient. Some collectors discharge water to the aquifer. Regular cleaning and deepening of drainage canals and collectors is recommended.
- In 2002, the area occupied by rice fields in the Bakhbakhty part of the Akdalinsk irrigation land was 4165 ha. Results of simulations indicate that, on one hand, increasing this area will lead to further swamping of the land; on the other hand, decreasing the proportion of rice fields will lead to lowering of the groundwater level to 3-5 m below surface. Taking into account the critical groundwater depth of about 3.75 m, and the high potential evaporation, this will lead to the secondary salinization of a significant part of this land. Keeping an area of rice fields of 4200-4500 ha is the most rational solution for this region.
- Most dangerous pollutants of surface and subsurface water in the study area are pesticides. Groundwater is polluted by pesticides leaching from the vadose zone during irrigation and by infiltration from imperfect drainage collectors. Simulation results indicate that pesticides are partly degraded, while the rest is removed from fields with surface and drainage water. This process depends mainly on pesticide characteristics and flooding regimes over the rice fields. To decrease pesticide concentration in overland water, the discharge of surface water from rice

fields must be minimized. The application of more degradable pesticides is recommended. The application of pesticides of DDT type must be prohibited.

- During the last few years, starting from the post-USSR period in 1993 and owing to the difficult financial situation facing agriculture in Kazakhstan, application of pesticides in the Akdalinsky irrigated land was practically stopped. Nowadays, economics and agriculture are recovering fast. Therefore, an increased application of fertilizers and pesticides is expected in order to increase the agricultural yield. As a result, the problem of ecological safety of the environment becomes more acute. Thus, additional efforts and investments must be made to improve monitoring of soil and water quality, including further development and application of mathematical models.
- The People's Republic of China plans to increase its water intake from the Ily River in near future. This will lead to a decrease in water discharge to Lake Balkhash and, probably, deterioration in the ecological condition of the area. Thus, existing water policy in this region will require tight regional management and cooperation. Using developed models, it will be possible to simulate consequences of water management policies and to predict hydrological and hydrochemical conditions in the Akdalinsky irrigated land. Actually, the models that were developed and used in this study are a prototype for an automated system of water resources regulation in the region.

List of participants

Israeli team: Dr. Alexander Yakirevich – PI, Dr. Eilon Adar – co-PI, Dr. Anil Mishra – Postdoc (Nepal), Irina Aidarov – M.Sc. student, Dr. Ludmila Katz – chemist, Natalia Bondarenko - technician.

Kazakhstan team: Prof. Vassily Vesselov – co-PI, Dr. Yuri Panichkin – co-PI, Dr. Nonna Zakharova – senior researcher, Dr. Ludmila Trushel – senior researcher, Dr. Tamara Vinnikova – senior researcher, Mrs. Oksana Miroshnichenko – Ph.D. student, Mr. Vladimir Ostanin – leading engineer, Mr. Alexander Engels – leading engineer.

Impact, Relevance, and Technology Transfer

The main results of this research were transferred to the Jetissus Hydrogeological-Reclamation expedition of the Water Resources Committee (under the Ministry of Agriculture of the Kazakhstan Republic). The expedition has started using the project's findings for planning water and agricultural activity in the region, within the framework of a project to reconstruct irrigation and drainage systems. Specifically, the GIS-based database and developed model of hydrological and hydrochemical conditions are being included as a part of the automated information system for monitoring ecological conditions in the study area. The Institute of Hydrogeology and Hydrophysics (IHH) of Kazakhstan participates in this technology transfer and training professionals of water authorities. Implementation will afford the possibility to estimate efficiency of planned activities regarding reconstruction of the Akdalinsky irrigation system, and to predict the effect of water management on conditions in the study area for different crop rotation scenarios.

As a result of this project, the computing facilities in the Laboratory of modeling and hydrodynamics at the IHH were improved. The Kazakh researchers were trained to use the Groundwater Modeling System (GMS 4.0), geoinformation system MapInfo and database management system FOXPRO. In the course of this project, Mrs. O. Miroshnichenko (IHH) prepared and defended the PhD thesis "Development and identification of the mathematical models of geofiltration using GIS-based technologies and expert approach". Mrs. I. Aidarov (BGU) is preparing her M.Sc. thesis entitled "Sustainable management of water resources in arid lands".

The results of this investigation will be presented as an illustrative example for a cycle of lectures entitled "Modeling of environmental-technogenic systems", by Dr. V. Yu. Panichkin of the National Kazakh Technical University.

It is expected that by the end of 2005 the main results of this project will be published on the Internet within the framework of the UNESCO project 27212604 KZH "Support and improvement of the national informational network in Kazakhstan as of the water resources of Aral and other regions with strained water balance".

Project Activities/Outputs:

1) *Meetings*

The first meeting took place in Sede-Boqer from November 20 to December 4, 2002. Dr. Yakirevich, Prof. Adar (BGU), Prof. Vesselov, and Dr. Panichkin (IHH) attended this meeting.

The second meeting took place in Kazakhstan (Almaty and Bakhbakty) during May 8-15, 2003. Dr. Yakirevich, Prof. Adar (BGU), Prof. Vesselov, Dr. Panichkin, Dr. Zakharova and Mrs. Miroshnichenko (IHH) attended this meeting.

The third meeting took place in Sede-Boqer during November 11-25, 2003. Dr. Yakirevich, Prof. Adar, Mrs. Aidarov (BGU), Prof. Vesselov, Dr. Panichkin, Dr. Zakharova and Mrs. Miroshnichenko (IHH) attended this meeting.

The fourth meeting took place in Kazakhstan (Almaty) during April 9-13, 2005. Dr. Yakirevich (BGU), Prof. Vesselov, Dr. Panichkin, Dr. Zakharova, Dr. Trushel and Mrs. Miroshnichenko (IHH) attended this meeting.

2) *Training*

Dr. Yu. Panichkin, Dr. N. Zakharova and Ph.D. student O. Miroshnichenko were trained in Israel during November 11-25, 2003. The purpose of the training was to learn to work with the Groundwater Modeling System (*GMS 4.0*) and to use models of groundwater flow and solute transport.

3) *List of publications*

Paper: Vesselov, V.V., Panichkin, V.Yu., Adar, E., Yakirevich, A., Zakharova, N.M., Miroshnichenko, O.L, Trushel, L.Yu. and Shakibaev, I.I. 2005. Geoinformation-mathematical modeling of hydrogeological conditions of the Akdalinsky irrigated land. Proc. of National Academy of Science of Kazakhstan, ser. Geology, 1, 2005, 86-95.

Poster: "Assessment of agricultural impact on groundwater in the Ily River basin, Kazakhstan" was presented at the International Conference on "Integrated Assessment of Water Resources and Global Change: A North-South Analysis", Bonn, Germany, 23-25 February 2005.

Project Productivity:

We believe that the project accomplished all of the proposed goals. The obtained results indicate good prospects for future applications of the developed methodology for sustainable management of water resources in the study area.

Future Work

The observed advantages obtained in this research project for the Akadalinsky cultivated area should be expanded to other similar areas with extensive agricultural development facing similar ecological features in Kazakhstan. It will be well worth conducting similar investigations in the Karatal irrigated land in order to plan activities to decrease environmental damage already observed in the local aquatic environment there. The area is located south of Balkhash Lake, and around 150 km from the Akdalinsky land to the west, near Ushtobe village. Rice, onions, sugar beet and alfalfa are grown on a total irrigated land area of 14,000 ha. Water from the Karatal River is used for irrigation. An inefficient irrigation system in place since 1929 has caused the land to be saturated and led to the development of swamping conditions, soil sodification, secondary salinization and contamination of surface and groundwater. Shallow water seepage in Ushtobe village has been monitored. About 50% of the land area is in poor condition (Vesselov *et al.*, 1996b) due to high groundwater levels and salinity. The main hazards to the environment are an increase in soil content in the upper soil layers and alkalization processes, especially in loamy soils. It was found that changing from rice to alfalfa led to a drastic increase in soil alkalinity. As a result, the negative effect of soil salinity on growing plants increased by 5-10 times. None of the existing theories can explain this phenomenon for the conditions of the irrigated lands of the Ily and Karatal rivers.

The objectives of the proposed research are as follows:

- Investigation of the unique (known to be different from the Akdalinsky region) processes of soil alkalization, sodification and salinization in the study area;
- Development and use of mathematical models to assess factors affecting soil degradation;
- Elaborating on measures to decrease deterioration of soil and water environments;
- Optimization of agricultural activity for sustainable exploitation of land and water resources.

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Appendix 1. Figures

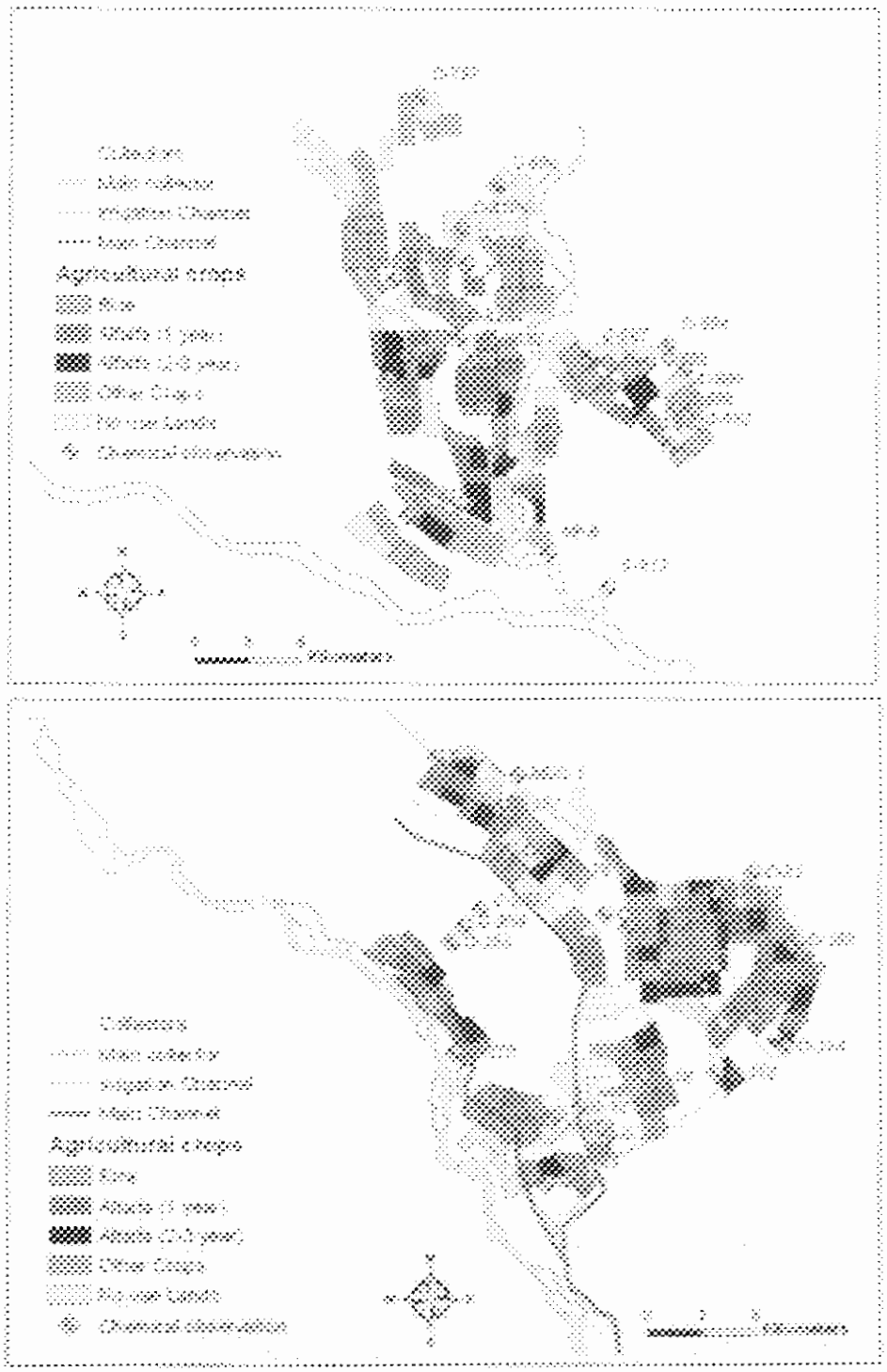

Figure 1A. Location of sampling points at the Bakanasa (a) and Bakhbakhty (b) areas

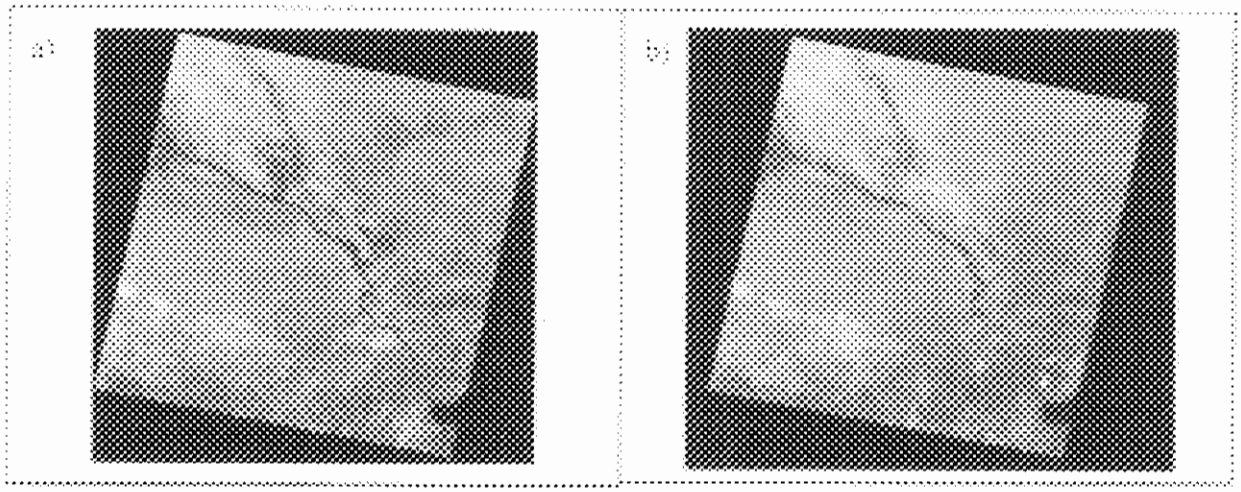

Figure 2A. The LANDSAT images of the study area: a) May 26, 1990, and b) May 13, 2000

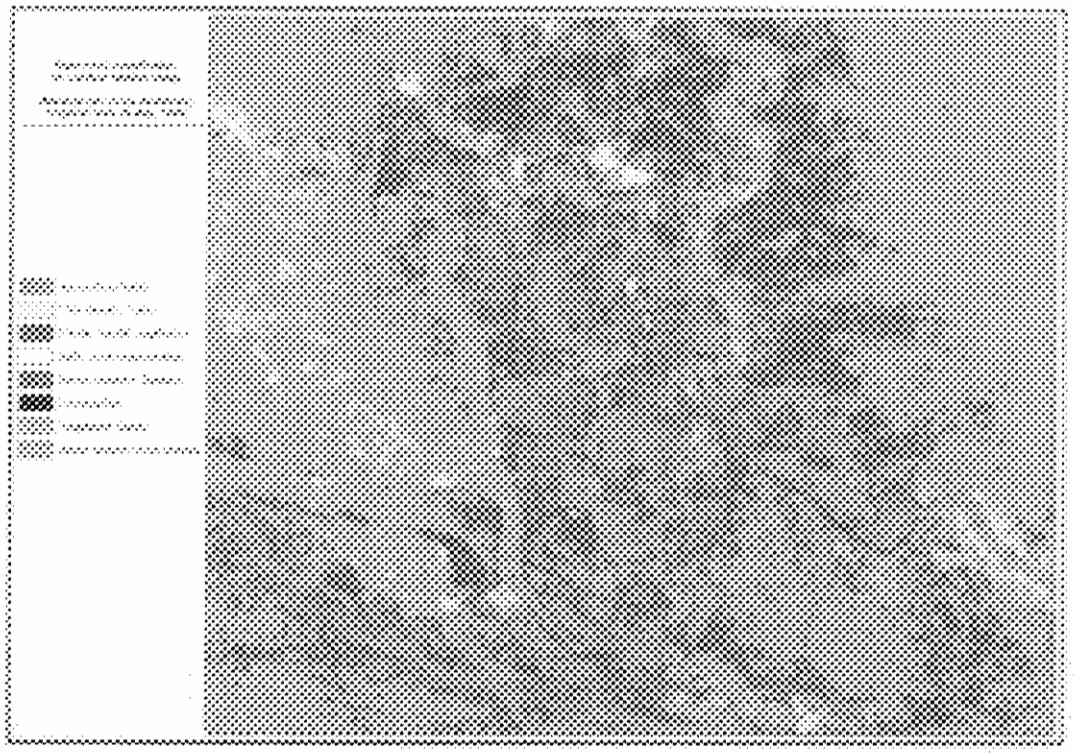

Figure 3A. Results of supervised classification in the Bakanass part of Akdalinsky area (26 May, 1990)

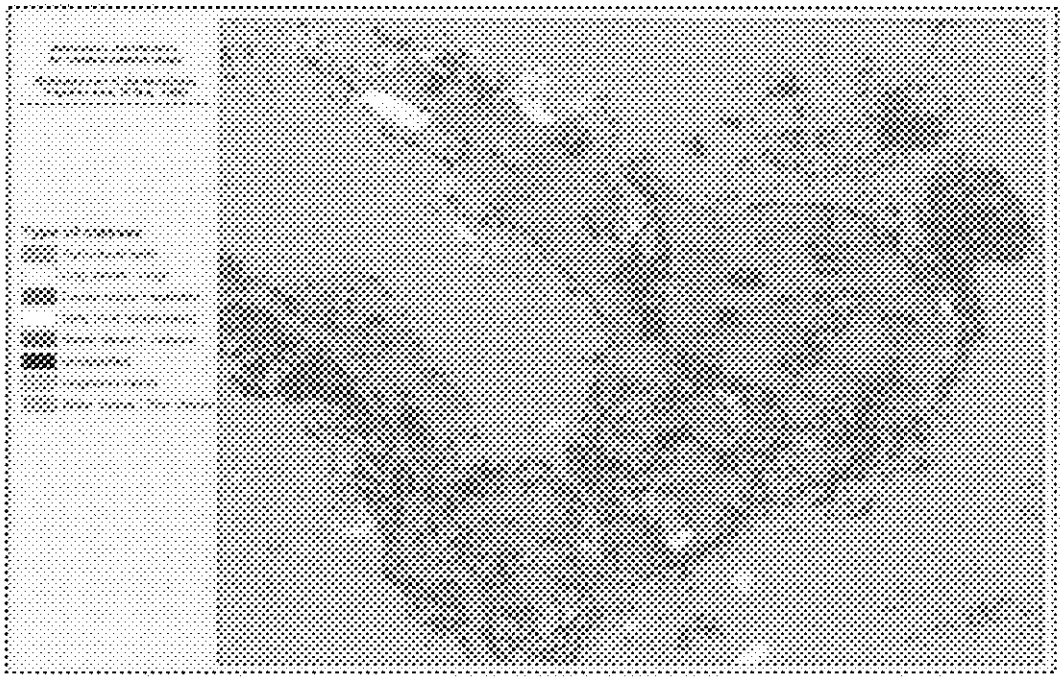

Figure 4A. Results of supervised classification in the Bakhbakhty part of Akdalinsky area (26 May, 1990)

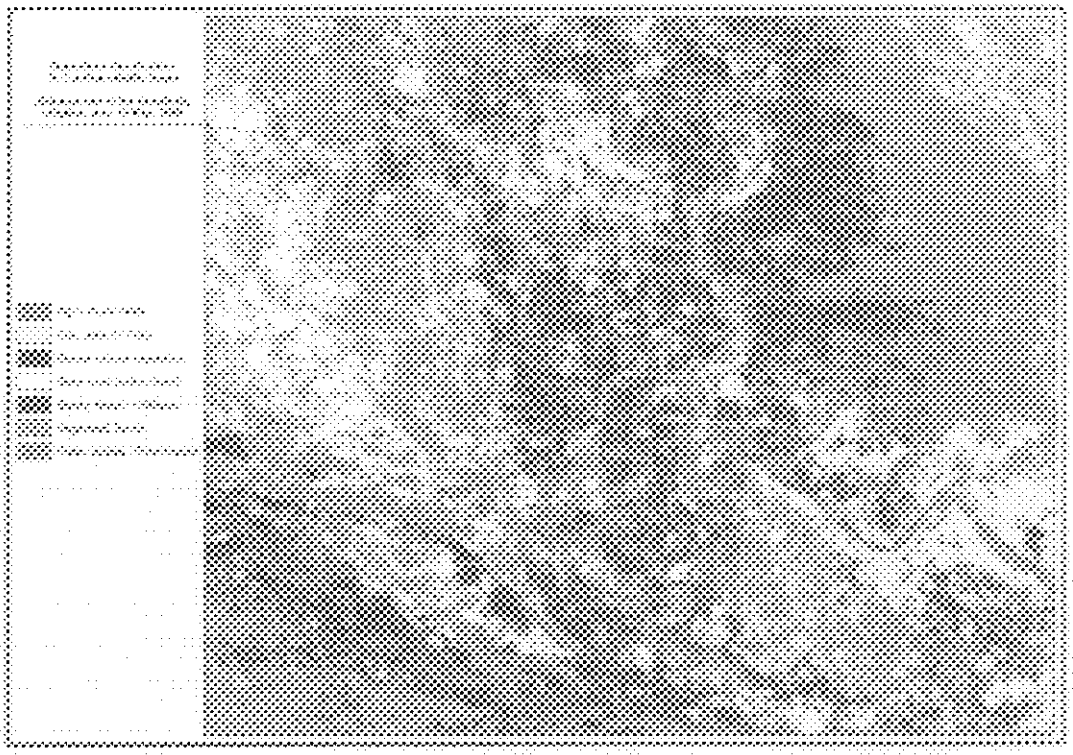

Figure 5A. Results of supervised classification in the Bakanass part of Akdalinsky area (13 May, 2000)

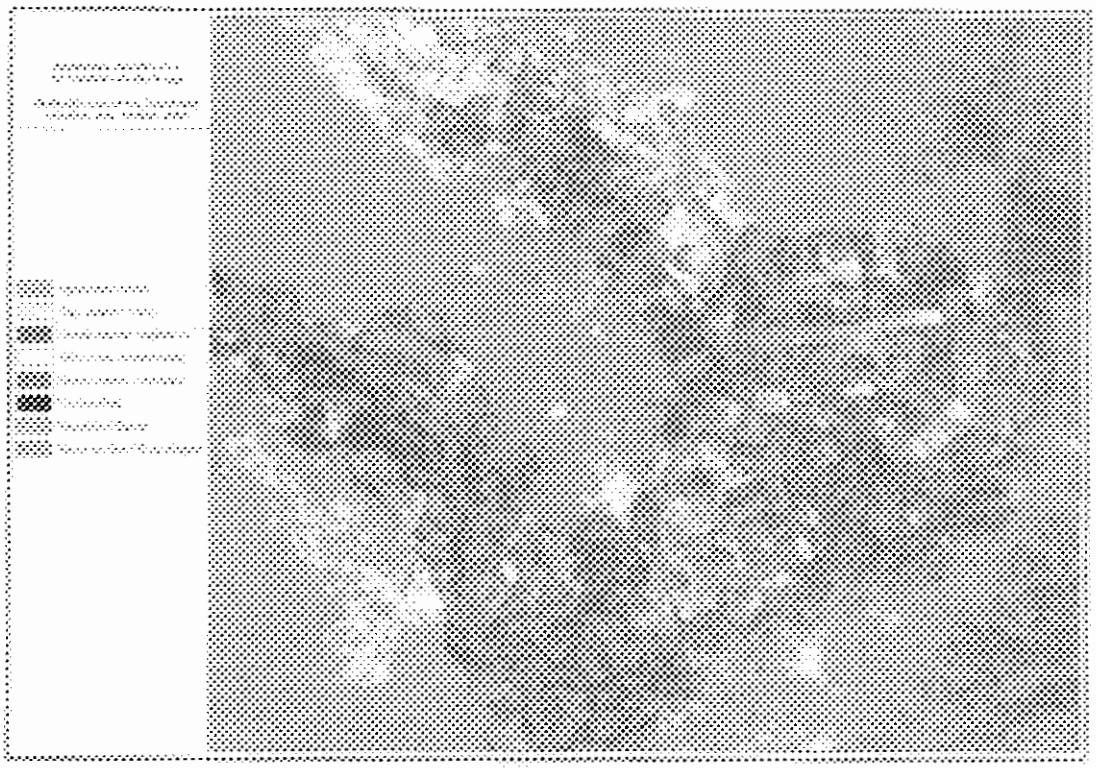

Figure 6A. Results of supervised classification in the Bakhbakhty part of Akdalinsky area (13 May, 2000)

Figure 7A. Simulated groundwater depth (m) in the Rakhbakhty area for scenario 1.
(a) – May 15, 2002; (b) – July 15, 2002; (c) – September 10, 2002;
(d) – January 20, 2003; (e) – May 3, 2003.

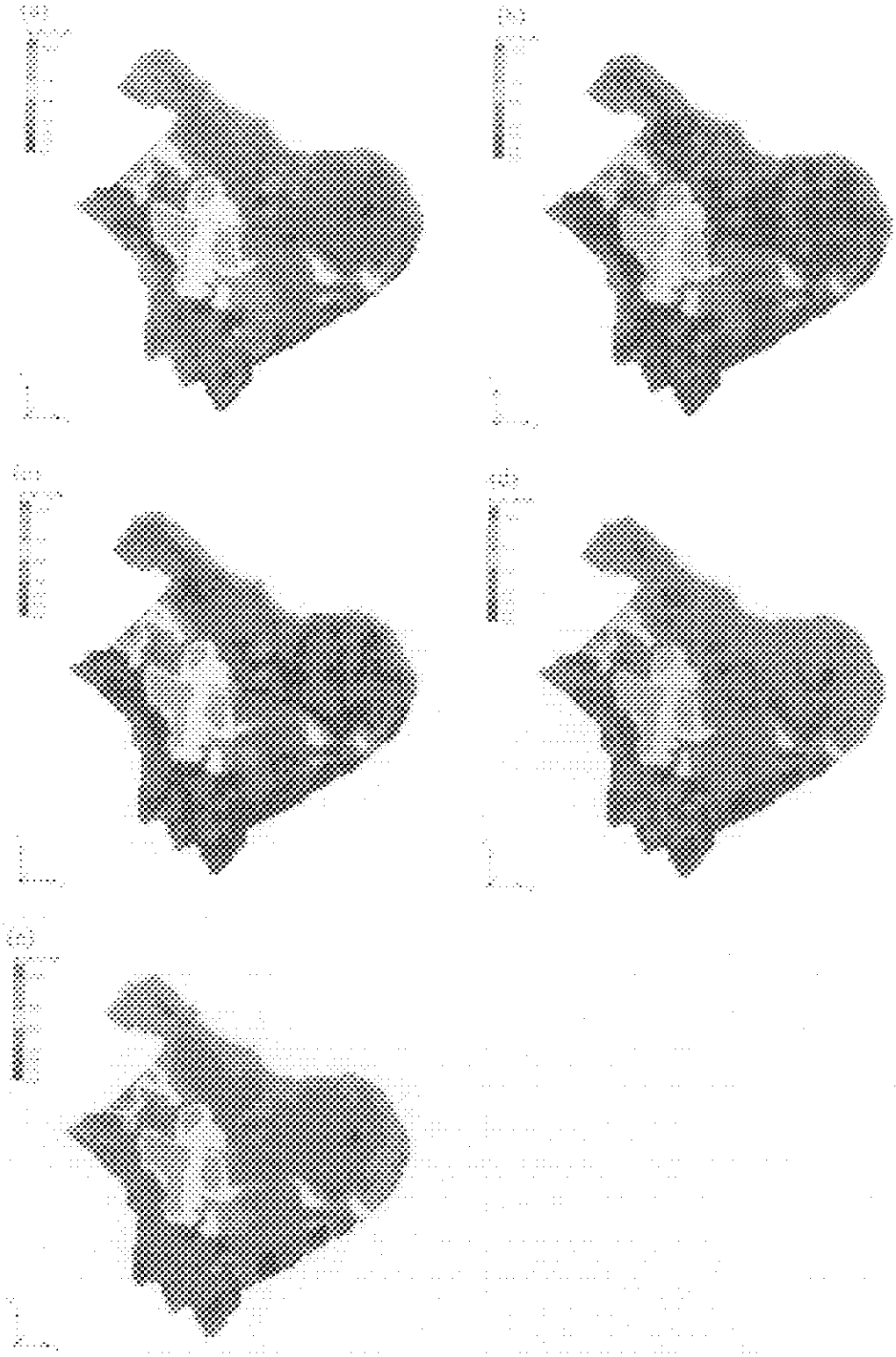

Figure 8A. Simulated groundwater depth (m) in the Bakhtiakhty area for scenario 2: (a) – May 15, 1988; (b) – July 15, 1988; (c) – September 10, 1988; (d) – January 20, 1989; (e) – May 1, 1989

Figure 9A. Simulated groundwater depth (m) in the Bakhbakhty area for scenario 3 in years (a) –2004, (b) –2006, (c) –2008, (d) –2013, (e) –2023.

Appendix 2. Tables

Table 1A. Chemical analyses of water samples collected at the Bakhbakhty part of the Akdalinsky irrigation system

Borehole	Date	pH	TDS	Cl	SO4	NO3	HCO3	Na	K	Ca	Mg	PO4	^{18}O	^{2}H
			mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	‰	‰
K-614	*May03*	7.46	323.05	11.80	16.20	1.94	216.00	38.80	3.58	16.52	18.00	0.21		
(10)	*Aug03*	7.88	278.40	40.01	4.23	3.16	185.00	38.60	4.26	17.40	19.20	0.75		
K-614	*May03*	7.13	381.69	21.60	49.50	0.84	211.00	52.50	9.66	16.30	19.70	0.59		
(20)	*Aug03*	7.58	307.84	37.20	6.25	13.20	220.00	52.40	11.30	13.90	19.10	0.74		
K-614	*May03*	7.64	179.31	15.84	9.09	0.00	110.00	25.30	2.44	8.71	7.93	0.32		
(50)	*Aug03*	7.75	140.16	17.70	2.69	0.82	98.60	26.80	2.54	5.70	7.06	0.24		
K-614	*May03*													
(70)	*Aug03*	7.17	231.68	24.20	4.25	8.15	165.00	25.63	4.37	13.40	18.10	1.65		
C-81	*May03*	7.61	485.42	30.52	94.32	0.00	240.00	38.43	6.55	50.10	25.50	0.89		
	Aug03	7.55	368.00	47.20	98.50	5.44	146.00	41.74	26.92	15.20	28.10	1.52	-10.58	-73.64
C-125	*May03*	7.39	1203.03	145.00	570.00	2.82	150.00	165.00	4.61	122.00	43.60	1.87		
	Aug03	7.44	1096.32	126.00	360.00	62.70	290.00	155.00	15.10	115.00	44.90	6.59		
C-122	*May03*	7.67	1378.29	148.00	580.00	4.68	260.00	189.00	7.51	117.00	72.10	2.20		
	Aug03	7.84	1047.04	112.00	375.00	5.54	310.00	172.00	5.47	89.60	48.50	1.46		
C-79	*May03*	7.64	418.36	25.44	47.85	0.76	235.00	36.42	2.99	42.30	27.60	0.62		
	Aug03	7.37	313.60	36.20	32.30	28.40	180.00	48.40	5.91	15.20	22.30	0.53		
C-370	*May03*	7.76	218.29	29.72	1.64	0.00	130.00	27.60	2.13	16.50	10.70	0.10		
	Aug03	7.58	163.20	18.40	3.56	5.13	120.00	33.18	3.15	11.05	6.98	0.16		
C-185	*May03*	7.87	387.89	28.38	1.78	0.00	258.00	44.30	5.23	28.00	22.20	0.31		
	Aug03	7.67	305.28	30.20	4.97	4.66	230.00	52.10	7.61	13.35	20.90	0.23		
C-253	*May03*	7.75	387.30	95.60	58.50	0.58	125.00	61.02	7.12	16.50	22.20	0.91		
	Aug03	7.85	297.60	41.30	25.90	3.15	180.00	54.50	6.42	9.13	18.20	0.45		
C-254	*May03*	7.76	296.78	40.78	13.30	0.74	156.00	48.60	18.90	8.81	8.91	0.37	-11.99	-82.41
	Aug03	7.90	238.08	15.90	1.32	2.46	195.00	50.50	18.50	9.25	7.38	0.13	-11.36	-79.18
C-255	*May03*	7.31	238.02	40.94	2.92	0.00	130.00	27.10	8.86	16.10	12.10	0.02	-11.21	-77.13
	Aug03	7.30	187.52	16.30	2.07	25.46	120.00	35.53	11.90	15.10	2.47	0.24	-11.93	-80.95
C-17V	*May03*	6.32	1339.40	96.50	825.00	18.20	43.50	95.50	8.20	180.00	72.50	3.14	-10.40	-75.63
	Aug03	6.92	1210.88	41.50	740.00	12.80	121.39	85.60	6.28	182.45	50.46	2.30	-9.67	-69.93
C-334	*May03*	7.56	1425.20	45.30	890.00	0.00	118.00	93.10	21.80	147.00	110.00	5.75	-10.13	-72.32
	Aug03	7.85	1382.40	51.70	975.00	4.34	60.39	85.00	20.05	248.55	69.70	3.25	-8.82	-65.85
C-312	*May03*	6.82	476.92	61.40	72.50	0.00	210.00	95.30	3.40	15.62	18.70	0.55	-9.53	-69.71
	Aug03	7.53	344.32	21.80	76.83	1.69	165.00	73.50	4.46	20.80	11.28	0.33	-8.70	-64.05

Borehole	Date	pH	TDS mg/l	Cl mg/l	SO4 mg/l	NO3 mg/l	HCO3 mg/l	Na mg/l	K mg/l	Ca mg/l	Mg mg/l	PO4 mg/l	^{18}O ‰	^{2}H ‰
C-60	*May03*	7.39	700.86	49.80	151.00	7.30	325.00	52.50	8.16	51.50	55.60	6.26		
	Aug03	7.45	901.76	35.80	165.00	1.89	580.00	95.80	14.96	68.80	69.60	1.05	-7.57	-62.41
C-365	*May03*	7.89	549.95	64.10	32.30	0.60	298.00	127.00	3.00	10.75	14.20	0.62		
	Aug03	8.70	448.00	60.50	14.36	1.68	210.00	135.00	3.24	3.57	3.86	0.28	-9.08	-67.84
C-367	*May03*	7.43	402.11	29.50	62.50	1.26	205.00	26.40	4.15	56.50	16.80	1.30		
	Aug03	7.38	393.60	26.42	3.16	0.92	310.00	29.85	5.79	50.38	23.07	0.14		
C-12	*May03*	7.01	622.76	54.30	37.00	20.51	360.00	36.50	7.95	75.50	31.00	0.17		
	Aug03	7.73	268.80	17.50	36.75	21.20	165.00	69.80	7.26	9.50	6.43	0.35		
C-23	*May03*	7.03	1933.13	305.00	1008.00	4.25	39.60	350.00	12.95	150.00	60.50	2.83	-8.78	-69.13
	Aug03	6.75	1824.00	305.00	880.00	15.60	82.35	445.00	17.46	68.50	42.50	3.15	-8.74	-67.44
C-378	*May03*	6.12	555.37	130.00	229.00	0.00	24.40	44.40	4.74	95.70	25.40	1.73		
	Aug03	7.14	618.88	85.40	188.00	1.54	174.00	74.50	9.51	62.50	42.90	0.95		
C-63	*May03*	7.97	340.45	28.50	29.50	0.47	192.00	24.30	4.46	36.20	19.40	5.62	-9.55	-69.46
	Aug03	7.95	236.16	19.21	8.62	2.33	165.00	51.35	7.75	16.02	4.04	0.58	-8.83	-67.17
C-360	*May03*	8.73	445.39	25.70	72.50	0.58	190.00	61.60	10.80	11.40	34.22	0.79	-8.49	-64.25
	Aug03	8.86	391.68	22.60	125.00	0.77	120.00	69.25	13.56	6.31	29.35	0.55		
C-362	*May03*	7.28	807.76	66.20	143.00	0.46	360.00	52.60	27.90	102.00	55.60	25.13		
	Aug03	7.38	712.96	32.75	42.87	1.90	480.00	48.30	9.43	70.10	47.90	1.65		
C-18	*May03*	7.42	403.32	36.50	18.10	4.48	235.00	51.50	4.04	32.50	21.20	0.99	-9.51	-69.44
	Aug03	7.57	310.00	44.50	10.20	2.98	225.00	32.40	6.11	35.60	22.30	0.35	-9.15	-67.61
C-92	*May03*	7.77	436.18	34.50	112.00	0.58	168.00	47.30	6.72	38.36	27.60	1.12		
	Aug03	8.05	271.36	31.01	68.80	0.96	126.00	62.50	9.94	9.55	9.01	0.19		
C-P-157	*May03*	8.22	350.51	21.50	26.40	0.74	194.00	25.50	5.60	36.60	20.40	0.57		
	Aug03	7.79	216.32	24.60	2.55	0.52	165.31	38.50	5.84	12.30	12.20	0.10	-6.88	-61.86
C-85	*May03*	7.68	528.68	25.20	135.00	7.52	225.00	23.60	8.30	66.50	35.60	1.96	-9.53	-68.03
	Aug03	7.63	467.20	25.42	124.00	8.03	250.00	55.20	18.80	46.50	28.40	0.63	-8.94	-65.45
C-P-78	*May03*	7.67	421.73	30.60	54.30	1.34	225.00	47.50	3.94	34.40	23.60	1.05		
	Aug03	7.80	224.00	10.31	15.95	3.08	180.00	61.20	5.76	5.88	5.02	0.09		-57.55
C-352	*May03*	7.03	384.54	27.60	22.20	1.68	230.00	36.50	8.93	33.45	22.92	1.26	-9.90	-71.30
	Aug03	7.78	256.64	11.43	24.30	3.82	195.00	43.20	15.50	12.56	13.50	0.19	-9.73	-67.44
AMK	*May03*													
	Aug03	7.87	355.0	20.60	74.50	3.79	165.00	23.10	2.31	49.20	16.90	0.57	-10.28	-72.60
Ily River	*May03*	7.72	393.5	26.40	89.00	3.18	176.00	26.4	2.25	52.9	17.4	0.38	-10.61	-74.34
	Aug03													
MDC	*May03*	7.38	1025.39	73.50	414.00	0.78	262.00	95.40	6.71	115.00	58.00	1.36	-9.18	-69.61
	Aug03	7.99	1105.28	67.30	570.00	0.00	254.00	172.00	7.75	99.45	50.30	1.42	-8.83	-64.20

AMK – Akdalinsk Main Canal, MDC – Main Drainage Collector

Table 2A. Chemical analyses of water samples (mg/l) collected at the Bakanass part of the Akdalinsky irrigation system

Borehole	Date	pH	TDS	Cl	SO4	NO3	HCO3	Na	K	Ca	Mg	PO4	^{18}O	^{2}H
			mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	‰	‰
C-617	*May03*	8.09	838.78	97.78	138.00	0.00	386.00	103.00	11.10	48.80	54.10	1.34		
	Aug03	7.95	544.00	58.73	85.40	8.37	310.00	92.10	11.20	19.80	37.20	0.43		
K-602(70)	*May03*	6.64	233.87	46.18	12.08	1.98	106.00	32.30	7.05	18.76	9.52	0.18		
	Aug03	7.41	191.36	9.64	1.15	19.80	126.00	39.50	8.37	8.86	5.08	0.07		
C-603	*May03*	8.47	444.33	39.54	49.73	0.00	239.00	27.50	3.22	41.60	42.10	1.22		
	Aug03	8.02	383.36	29.20	16.29	1.81	305.00	39.70	7.46	25.20	36.40	0.14		
K-613(20)	*May03*													
	Aug03	7.53	328.96	18.40	2.45	19.50	253.15	35.50	23.50	25.50	18.10	0.11		
K-613(50)	*May03*													
	Aug03	7.46	171.52	8.52	1.62	3.09	156.00	18.60	5.63	19.30	11.45	0.07		
K-613(70)	*May03*	7.26	272.39	29.14	10.56	1.94	160.00	26.30	6.05	24.50	13.90	5.39		
	Aug03	6.78	224.64	12.10	4.75	19.50	158.60	25.80	21.20	20.50	10.09	4.75		
C-600	*May03*	7.40	796.29	94.36	59.61	0.66	415.00	162.00	7.90	21.50	33.90	2.19		
	Aug03	8.05	631.04	42.60	60.48	17.50	440.00	164.00	8.22	10.49	25.39	0.29		
C-815	*May03*	7.37	413.28	37.72	91.16	1.26	177.00	45.60	3.34	22.70	34.50	0.59		
	Aug03	7.98	342.40	34.50	31.80	0.32	236.00	42.04	4.24	20.70	30.11	0.12		
C-797	*May03*	7.57	296.72	45.60	10.52	50.74	115.00	32.50	2.76	26.50	13.10	0.28		
	Aug03	8.05	275.20	29.52	39.56	0.72	165.00	84.50	2.42	5.38	3.02	0.11		
C-592	*May03*	9.75	3124.24	604.00	450.00	0.68	740.00	669.00	104.00	169.00	76.00	2.55		
	Aug03	10.74	3168.00	480.00	1010.00	1.95	0.00	960.00	105.00	0.68	10.11	2.42		
C-594	*May03*	7.77	824.99	140.00	88.50	5.36	360.00	165.00	6.73	21.20	38.20	0.72		
	Aug03	8.05	636.16	106.00	99.20	5.47	290.00	166.00	6.40	10.35	25.04	0.33		
C-598	*May03*	8.27	873.60	82.52	210.00	1.20	285.00	152.00	3.28	35.40	65.80	1.76		
	Aug03	9.00	610.56	34.58	230.00	21.70	136.00	162.00	3.94	7.42	25.78	0.67		
C-607	*May03*	7.66	669.20	55.62	95.68	0.00	349.00	95.40	5.46	17.80	49.50	0.88		
	Aug03	7.89	441.60	37.10	77.90	10.40	260.00	85.50	7.34	7.70	34.23	0.27		
C-810V	*May03*	8.51	607.62	45.58	102.00	0.00	254.00	43.10	3.64	88.50	31.80	2.27		
	Aug03	7.93	479.36	26.20	110.00	0.00	280.00	44.54	3.27	46.50	32.11	0.30		
C-562	*May03*	0.00	448.89	41.20	104.00	0.72	188.00	35.50	1.97	36.20	41.30	0.32		
	Aug03	7.95	344.96	31.20	62.30	3.55	195.00	46.30	5.10	24.50	24.50	0.01		
C-647A	*May03*	7.57	449.89	46.24	72.56	0.00	215.00	24.60	2.75	66.60	20.30	0.47		
	Aug03	7.47	140.16	8.86	13.50	6.63	108.00	29.40	4.66	11.94	3.75	0.16		
C-819	*May03*	7.87	572.21	41.22	71.54	0.00	310.00	49.60	4.09	55.90	32.20	0.71		
	Aug03	7.72	446.72	27.39	83.01	6.53	275.00	76.50	7.34	29.41	25.80	0.41		
Bakanass Main Canal	*May03*	7.57	421.92	30.1	96.51	0.00	186.00	29.20	2.30	56.30	18.20	0.41	-10.24	-70.74
	Aug03													

Table 3A. PCA component loading for the groundwater monitoring stations

Number	Wells	PC1	PC2	Land use	Region
1	C-126	**0.925**	0.238	No crop	Bakhbakhty
2	C-594	**0.902**	0.332	Rice	Bakanass
3	C-608	**0.889**	0.280	Rice	Bakanass
4	C-370	**0.837**	0.412	Rice	Tasmuran
5	C-607	**0.824**	0.438	Rice	Bakanass
6	C-49	**0.817**	0.432	Alfa-Alfa	Bakhbakhty
7	C-336	**0.802**	0.437	Rice	Tasmuran
8	C-651	**0.798**	0.365	Alfa-Alfa	Bakanass
9	K613(100)	**0.796**	0.436	No crop	Bakanass
10	K613(10)	**0.778**	0.381	No crop	Bakanass
11	C-376	**0.778**	0.410	Rice	Bakhbakhty
12	K614(20)	**0.769**	0.437	Other crop	Tasmuran
13	C-819	**0.769**	0.557	Other crop	Bakanass
14	C-617	**0.765**	0.534	Rice	Bakanass
15	C-810	**0.742**	0.593	Other crop	Bakanass
16	C-600	**0.732**	0.581	Rice	Bakanass
17	K602	**0.730**	0.288	Other crop	Bakanass
18	K614(50)	**0.718**	0.586	Other crop	Tasmuran
19	C-308	**0.708**	0.592	Alfa-Alfa	Tasmuran
20	C-659	**0.702**	0.617	Other crop	Bakanass
21	C-806	**0.702**	0.560	No crop	Bakanass
22	C-18	**0.690**	0.609	Rice	Bakhbakhty
23	C-367	0.674	**0.679**	Other crop	Bakhbakhty
24	C-592	**0.668**	0.453	No crop	Bakanass
25	K614(70)	**0.663**	0.500	Other crop	Tasmuran
26	C-829	0.659	**0.713**	No crop	Bakanass
27	C-647	0.651	**0.733**	Alfa-Alfa	Bakanass
28	C-362	**0.641**	0.573	Alfa-Alfa	Bakhbakhty
29	C-815	0.605	**0.724**	No crop	Bakanas
30	C-21	0.604	**0.768**	Rice	Tasmuran
31	C-828	0.603	**0.734**	No crop	Bakanass
32	C-332	0.601	**0.630**	No crop	Bakhbakhty
33	C-P78	0.587	**0.743**	Alfa-Alfa	Bakhbakhty
34	C-352	0.569	**0.720**	Alfa-Alfa	Bakhbakhty
35	C-603	0.551	**0.657**	Other crop	Bakanass
36	C-100	0.547	**0.787**	No crop	Bakhbakhty
37	C-797	0.539	**0.764**	No crop	Bakanass
38	C-129	0.500	**0.807**	No crop	Bakhbakhty
39	C-598	0.279	**0.803**	Other crop	Bakanass
40	C-357	0.253	**0.905**	Other crop	Bakhbakhty
41	C-60	0.111	**0.888**	Alfa-Alfa	Bakhbakhty

Extraction method: Principal component analysis. Rotation method: Varimax using Kaiser normalization.

Table 4A. Groundwater balance components (m^3 day) in the Bakhbakhty part of the Akdalinsk irrigation system. Simulation scenario 1: area of rice fields is 4165 ha.

	Water balance components	Steady-state	Transient conditions				
	Date:	1967	15 05 2002	15 07 2002	09 09 2002	20 01 2003	03 05 2003
Inflow components	Rainfall infiltration	1600	9100	15300	6300	6300	6300
	Infiltration of melted snow	42700	42700	42700	42700	42700	42700
	Irrigation canal losses	61300	1883462	1216278	952407	-	-
	Infiltration from rice fields	-	1710500	819860	760760	-	-
	Decrease of storage	-	-	-	-	610671	442730
	Losses from collectors	-	128980	128000	79290	-	-
	Inflow along boundaries	30590	948700	490000	322950	87084	51900
	Sum	**136190**	4714342	2712138	2164407	746755	543630
Outflow components	Groundwater evaporation	94880	323266	411268	437509	303898	260504
	Discharge to collectors	-	651900	903520	1073240	297730	160640
	Discharge to irrigation canals	-	144510	144000	144000	-	-
	Outflow to Ily river	2492	300	830	1318	1560	1560
	Increase of storage	-	3261748	1026464	206173	-	-
	Outflow along boundaries	38804	337400	223460	297832	140840	118440
	Sum	**136176**	4719124	2709542	2160072	744028	541144
	Imbalance (%)	0.01	-0.101	0.095	0.20	0.36	0.45

Table 5A. Groundwater balance components (m^3 day) in the Bakhbakhty part of the Akdalinsk irrigation system. Simulation scenario 2: area of rice fields is 7202 ha.

	Water balance components	Steady-state	Transient conditions				
	Date:	1967	15 05 1988	15 07 1988	09 09 1988	20 01 1989	03 05 1989
Inflow components	Rainfall infiltration	1600	9100	15300	6300	6300	6300
	Infiltration of melted snow	42700	42700	42700	42700	42700	42700
	Irrigation canal losses	61300	1870780	1198164	936990	-	-
	Infiltration from rice fields	-	2603200	1431800	1321100	-	-
	Decrease of storage	-	-	-	-	691089	485257
	Losses from collectors	-	111690	102570	70897	-	-
	Inflow along boundaries	30590	873480	446300	303440	86254	50920
	Sum	136190	5501850	3236834	2681427	826343	585177
Outflow components	Groundwater evaporation	94880	362565	459626	484405	322556	273538
	Discharge to collectors		904780	1363010	1567080	345280	180780
	Discharge to irrigation canals		138220	136560	141540	-	-
	Outflow to Ily river	2492	694	1157	1552	1691	1656
	Increase of storage		3748571	1031073	157180	-	-
	Outflow along boundaries	38804	356046	245333	331248	156949	129444
	Sum	136176	5510876	3236759	2683005	826476	585418
	Imbalance (%)	0.01	-0.16	0.002	-0.058	-0.016	-0.041

Table 6A. Groundwater balance components (m^3/day) in the Bakhbakhty part of the Akdalinsk irrigation system. Simulation scenario 3: no rice fields.

	Water balance components	Transient conditions				
	Date:	2004	2006	2008	2013	2023
Inflow components	Rainfall infiltration	6300	6300	6300	6300	6300
	Infiltration of melted snow	42700	42700	42700	42700	42700
	Irrigation canal losses	-	-	-	-	-
	Infiltration from rice fields	-	-	-	-	-
	Decrease of storage	226882	136826	104700	51226	30264
	Losses from collectors	-	-	-	-	-
	Inflow along boundaries	34801	34801	34801	30171	30576
	Sum	310683	220627	188502	130397	109841
Outflow components	Groundwater evaporation	187385	127492	100763	74363	61276
	Discharge to collectors	54380	25512	20237	15950	13182
	Discharge to irrigation canals	-	-	-	-	-
	Outflow to Ily river	1568	1534	1506	1457	1423
	Increase of storage	-	-	-		
	Outflow along boundaries	69773	69773	69773	42827	38900
	Sum	313106	224311	192279	134597	114781
	Imbalance (%)	-0.77	-1.66	-2.0	-3.22	-4.5