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MODELING OF TRANSBOUNDARY ILE-BALKHASH RIVER BASIN IN CENTRAL ASIA

Abstract. This article presents an overview of the Ile-Balkhash river basin modeling and its use for analyzing and forecasting of water resources and natural-economic demands for water. The model allows by defining possible scenarios, to test sensitivity of water supply system and its influence on environment and economy of the Ile-Balkhash river basin. The computer model results allow decision-making authorities to define optimized water management scenario. This study is mainly focuses on the implementation of a simulated dynamic-stochastic model of the water supply system of Balkhash Lake basin (Republic of Kazakhstan). Model simulations supplemented with uncertainty analysis and assessment of stochastic properties, using the Monte Carlo method. The model implemented in an object-oriented C# programming language. This manuscript presents the results of created water balance simulation algorithm of the Ile-Balkhash river basin. Developed and implemented water supply scenarios. Designed statistical assessment module of the model. Created results visualization block.

Keywords: water management, river basing modeling, environment, water recourses, hydrology, water supply, mathematical and computer modeling, dynamic-stochastic model.

1. Introduction. River basins are important for water use by various, often competing, and users. Thus, careful long-term use of water resources requires planning and management. Socio-economical activities depending on water availability (e.g., agricultural, ecologic, industrial or energy demands) are preferentially organized and coordinated within the entire river basin [1]. River basins are the fundamental natural systems of many hydrologic phenomena[2].River basin management and the organization of water resources management at the river basin level is a focus areas for policy-oriented research and technical advisory activities [3]. Water management generally focuses on an integrated basin system, including water supply, water demand, and intermediate components. In arid and semi-arid river basins, irrigation is the dominant water use, and there careful management plays a critical role [4].

The Ile-Balkhash river basin (140,000 km^2) is located in the southeastern part of the Republic of Kazakhstan and adjoining territories of China (Figure 1). The basin includes the Almaty region, the south-eastern part of the Karaganda region, the south-western part of the East Kazakhstan region, east of Zhambyl region (all Republic of Kazakhstan), as well as the north-western part of the province of Xinjiang in the People's Republic of China. The main watercourse of Ile-Balkhash river basin is Ile River, which measures approximately 1440 km, and which is the largest fresh water inflow to Balkhash Lake, the downstream end of the closed drainage basin. The Ile River provides about 80% of the inflow of fresh river water to the lake. Therefore, the level and water quality (salinity) of the lake, and ecological state and desertification of the region, are largely depending on the discharge of the Ile River [5].

In Central Asia, the sources of many transboundary rivers (e.g., Ile, Syrdarya, Chu, Talas rivers)are located in mountainous terrains where discharge is regulated by a cascade of reservoirs for various purposes (e.g., energy production, water consumption and flood risk management), which sometimes are competing with uses (e.g., agricultural production) in downstream countries (e.g., the Syrdarya basin in Central Asia). In these cases, the issues of river basin management are international, and policy solutions require regional collaboration between different countries [6].

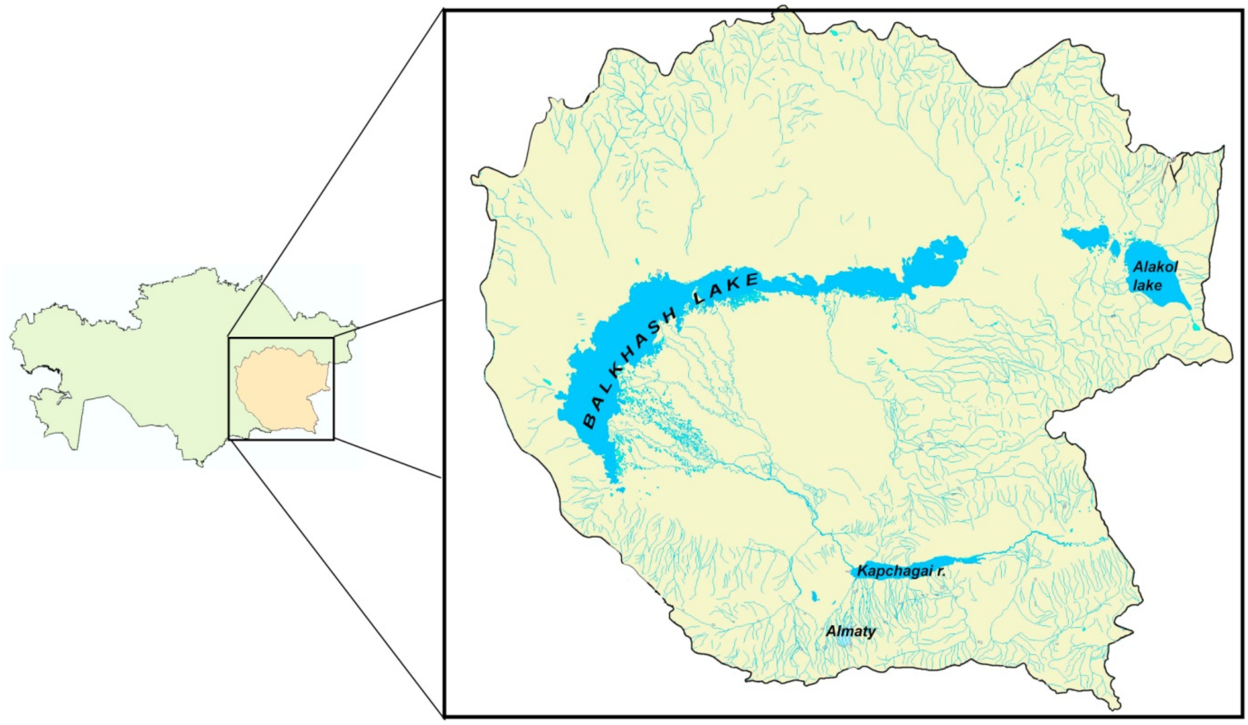

Figure 1 – Ile-Balkhash river basin

Complex system of interactions between different components makes river management on a basin scale challenging. A straightforward and effective tool for making economical and policy decisions is mathematical river basin modeling, which represents the relevant physical processes in the river basin and which can be used to predict the behavior of the basin under different (climatic) conditions or management scenarios. River basin models successfully deployed to aid in the determination of fair and equitable long-term water sharing agreements or short-term operational plans in transboundary basins [7].

In this study, a mathematical model combines the effects of management and use of surface and subsurface reservoir (supply) systems with effects of water extraction by irrigation forfarming. The model is designed as a tool to support decision-making on matters of National Water Complex (NWC), that include the development of water infrastructure, conservation and restoration of natural water bodies, the economic justification of water limits, and improving interstate water relations between Kazakhstan and China. Importantly, the model includes interactions between upstream and downstream water allocation,as well as a water users on local and regional scale management according to the planned water supply scenarios. In addition future water supply scenarios of the Republic of Kazakhstan (until 2030) were included – based on a previous study by Seversky and Malkovsky, 1998). This model-scenario thought as a planning exercise that examines the future with an expected to decrease due to intensive using of runoff in its Chinese part of the basin [8].

Methodology.

Design of the dynamic-stochastic model. The main goals of baseline scenario are to mitigate the impacts of upstream water usage on the Balkhash Lake Environment and to provide a tool to monitor the local supply-demand balance. This helps to increase agricultural productivity and industry, while preventing river channel degradation and impact on social and economic structures by water scarcity [9]. In Figure 2 the main components of Ile-Balkhash river basin are shown, including possible sources of water (groundwater and surface water), the water transport system and infrastructure (canals, piping network and reservoirs), extraction by water users(agricultural, municipal, and industrial), and a the output of the drainage system (surface and subsurface).

Computer simulation of Water Supply Systems (WSS)implemented by a set of mathematical tools, special computer programs and tricks replace the real object of study with a model that simulates impor-

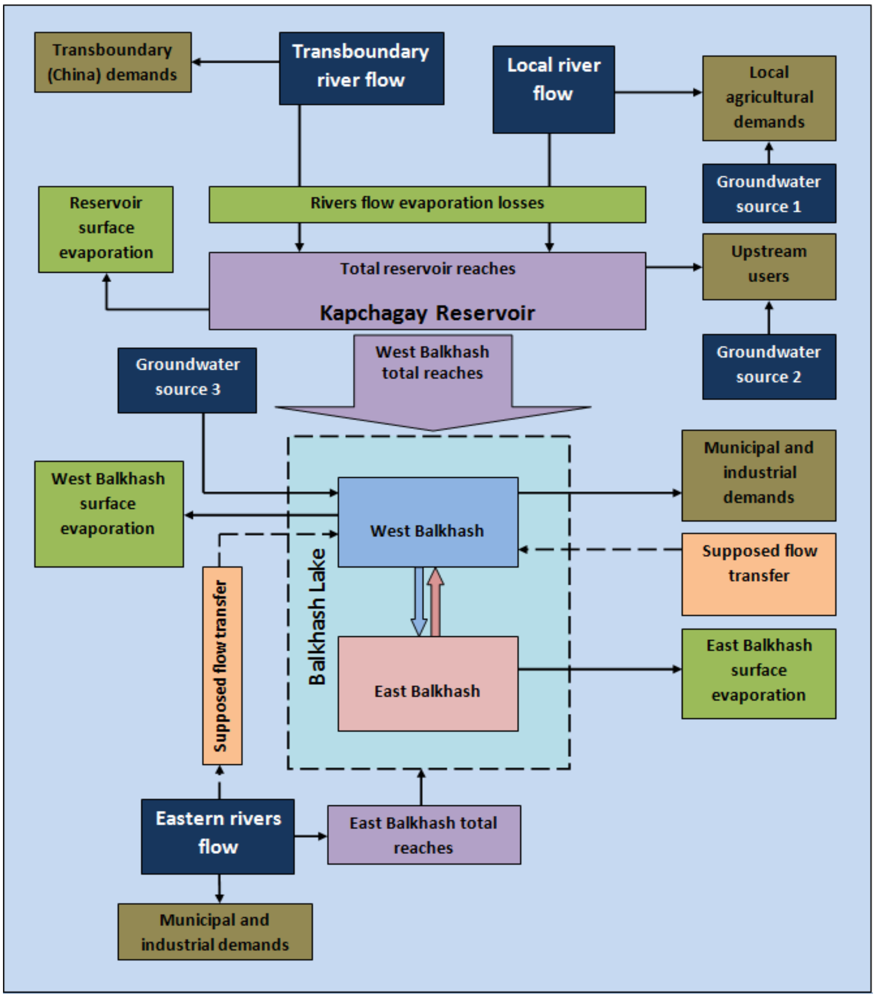

Figure 2 – Ile-Balkhashriver basin components of dynamic-stochastic model

tant processes and natural and human impacts on the water balance. A set of software tools and mathematical modeling techniques determines the specificity of the modeling system.

Developed software allows user to select a certain river basin, choose the scenario and generate a flow data of its main rivers, using the average flow data for long-term period, variation and modular run off coefficients. Further based on the specifics of the basin and region water demands (municipal, industrial, agricultural and environmental)the model simulates water balance according water users demands, taking into account river flow losses, reservoirs operation, Balkhash Lake surface evaporation and perspective water transfer. The objective of dynamic-stochastic model is to evaluate and future conditions of the river basin in terms of reducing transboundary flow of a long-term period (until 2050) under different scenario parameters. Further assessment of modeling undo different scenarios allows decision-making experts for effective water using and saving the environment.

For calibration purpose, model outputs compared with historical or measured outputs of the system (at gauging station) and the model parameters adjusted until the values predicted by the model agree, to a reasonable degree of accuracy, with the measured values.

Verification – an independent set of input data, i.e., different from that used in the calibration step, is used in the model and the model results are compared with measured outputs.

Development of a computer model, as well as data analysis, and the two-dimensional imaging performed with the use of modern means of creating and designing mathematical software. The model should meet the following requirements:

– Using object data and mathematical model;

– Processing large volumes of data;

– Visualize simulated results in a convenient form;

– Module structure of the program for effective update and upgrade software.

The set of functions and the process steps of created computer model corresponding to the logical and mathematical description of the Ile-Balkhash river basin, it includes the following procedures:

1. Development of a database, providing scenario analysis, operation and development of Water Supply Systems (WSS) for long-term period;
2. River flow modeling by random generating discharge using annual river flow and the flow variation coefficient;
3. Modeling of water demand dynamics of water users based on population, development of industries, agriculture and water supply standards;
4. Automatic modeling and simulation the results of water infrastructure reconstruction and (WSS) objects;
5. Modeling water forecast scenarios of (WSS), water scarcity and excess calculation for required time periods;
6. Scenario development assessment by hydrological risk and reliability criteria, of (WSS) characterizing the water scarcity and probability of system failures, using the "Wald's maximin criterion" and "Laplace criteria" (law of equal probabilities).
7. Data storage and modifying in a database. Visualization of the results in the form of graphs, curves and tables.

Referring to Figure 3 the algorithm scheme represents the implementation of the model simulation.

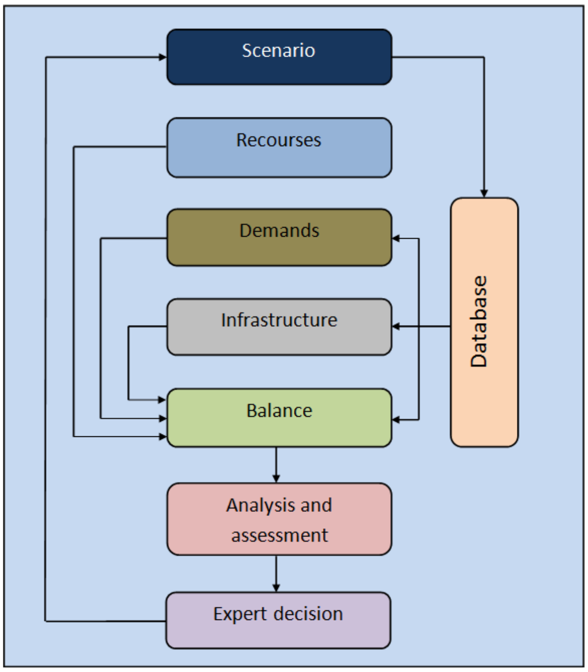

Figure 3 – Simulation algorithm of computer model

The computer model is an effective tool for the assessment and analysis of the Ile-Balkhash river basin. This mathematical software has a module structure with a certain algorithm and links between modules. Each module of program contains a specific data type, performs specific functions and applicable program interface[10].

The database operations module loading certain scenario data from the database load and prepare data for computer model. The main components of database formed based on the characteristics of Ile-Balkhash river basin. The database contains hydrological stations actual discharge data and other river basin characteristics such as reservoir operation parameters and its evaporation rates, river flow losses and water supply demands.

The scenario operations module allows creating, modifying and saving the water-using scenario.

Water balance and mathematical operations module contains average annual flow data of the main rivers and its tributaries. It calculates annual water balance of Ile-Balkhash river basin including in flows, Kapchagay reservoir operations, Balkhash Lake evaporation rivers flow losses, groundwater storages, water demands based on a 35-year period. This module also contains supposed water transfer data inside and between the basins.

The statistical assessment module estimates the data processing by hydrological risk and reliability criteria (Wald's maximin criterion and Laplace criteria).

Interface module allows the user to interact with the software to perform hydrological calculations for analyzing the system.

The simulation results block includes three modules by the types of displaying the simulated results: Table form data presentation module, graphs form data presentation module and 2-dimension visualization module. These modules display calculated data in user-friendly form for further analysis. The Figure 4 shows modular structure of the computer model and interaction between them.

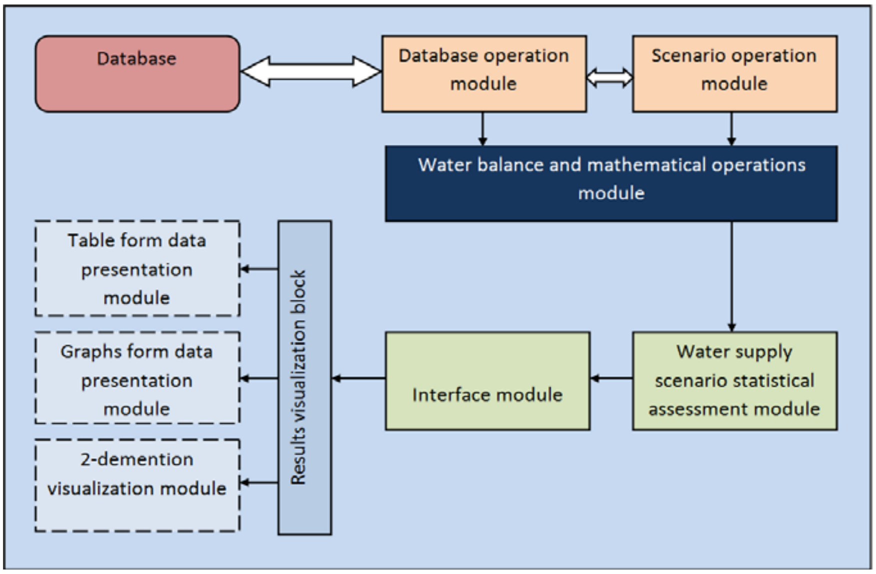

Figure 4 – The modules interaction scheme

Validation and verification of the model.

Validation and verification are two of the most important steps in any simulation study [11]. Verification is the process of ensuring that the model design (conceptual model) has been transformed into a computer model with sufficient accuracy; Validation is the process of ensuring that the model is sufficiently accurate for the purpose at hand [12]. A successful Verification and Validation project cannot be realized unless you have a solid management approach [13]. The scheme development model steps are shown in Figure 5.

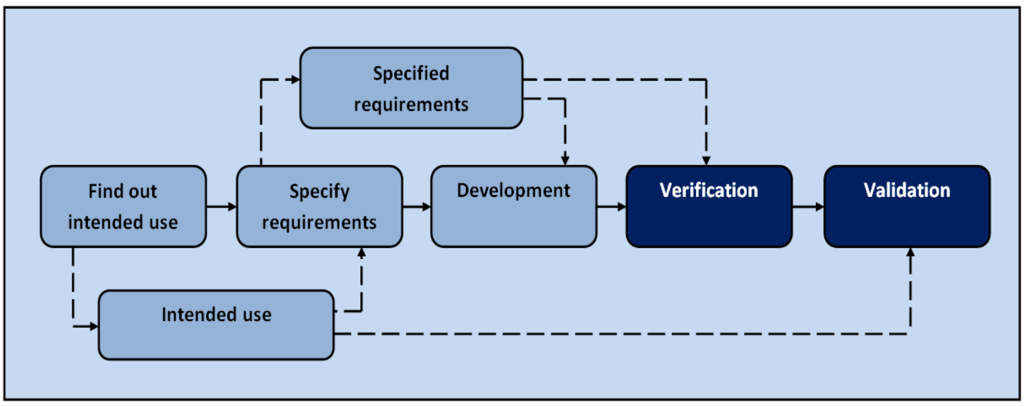

Figure 5 – Model Validation and Verification scheme

Ile-Balkhash river basin model calibrated for 20 years period (1992–2011). Model accuracy surveyed through a validation data period. Initials conditions of simulation experiments on validation stage were determined by processing historical data over the period. Adjusted two major parameters: Ile River losses dynamics and Balkhash Lake level dynamics for a 20 years period as it shows figures 6 and 7. Then the program estimates the scenarios, according to the *water supply reliability* and *hydrological risk criteria* as well as operates the reservoir states conditions. The program displays a window (Figure 8), that shows the results of statistical evaluation of water supply scenarios according to the known formulas.

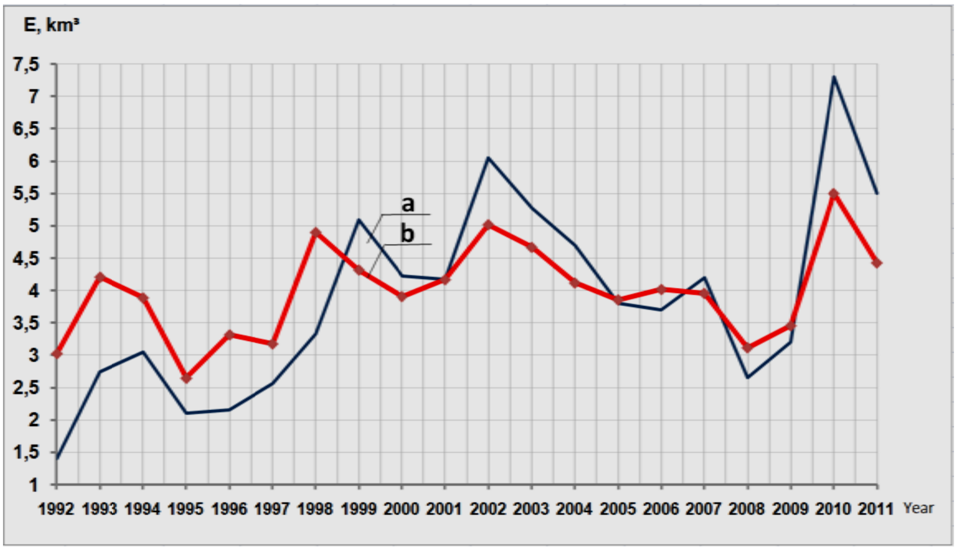

Figure 6 – Ile River losses (downstream, Kapchagay reservoir): a – actual data; b – simulated data

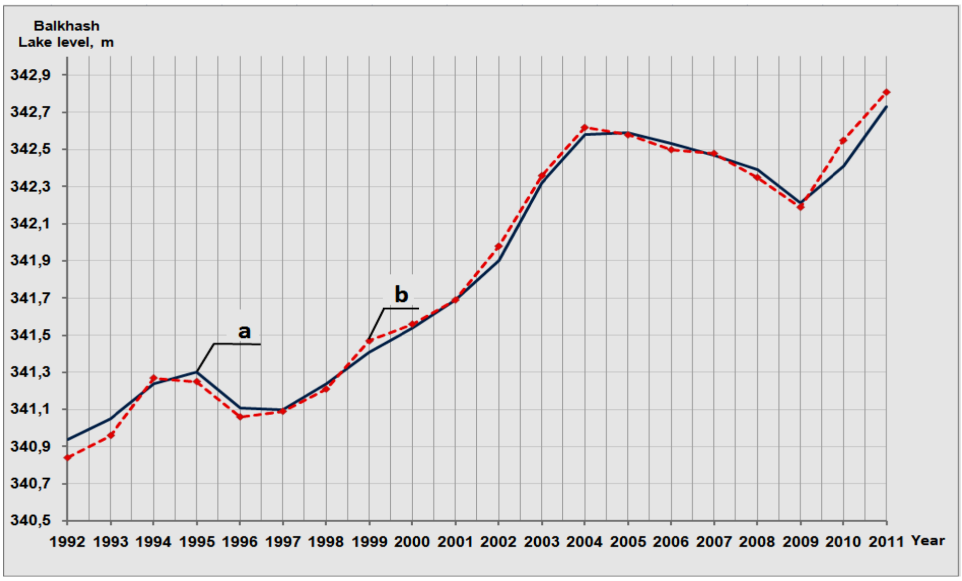

Figure 7 – Balkhash Lake levels: a – actual data; b – simulated data

Statistical evaluation of water supply scenarios.

1. Water supply reliability criteria – the probability (expectation) of water demands satisfaction by the relative number of uninterrupted years:

$$P_i = 1 - \frac{n_i}{N} \quad (1)$$

where N – number of years of the settlement period; n – number of cases when water supply less than demands, Q^T.

2. Hydrological risk criteria – relative value water supply interruptions (water supply shortages),the quantity of which is calculates as:

$$\overline{R_i} = \frac{1}{N}\sum_{T=1}^{N}(1-\frac{Q_i^T}{Q_i}) \quad (2)$$

"Laplace criteria" (law of equal probabilities).

$$R_i^{"} = \max(1-\frac{Q_i^T}{Q_i}) \quad (3)$$

"Wald's maximin criterion" – is a non-probabilistic decision-making model according to which decisions are ranked based on their worst-case outcomes.
where Q_i and Q_i^T – declared (guaranteed) and the actual value of the water supply delivered forthe i-th component; N – the duration in years of the period.

The figure 8 shows the statistical assessment module. This window displays assessment criteria and Balkhash Lake hydrological risk probability. This proves that the model accurately respond to all system changes.

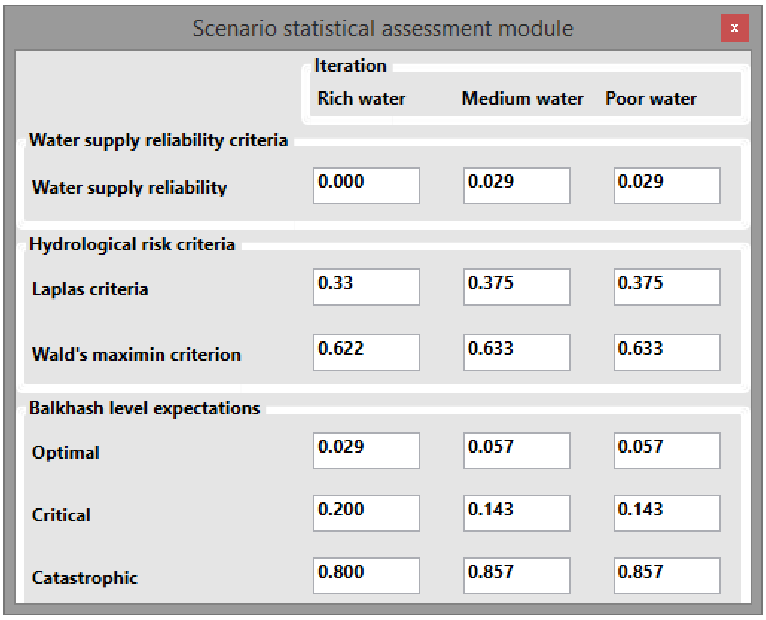

Figure 8 – Scenario statistical assessment program module

Balkhash Lake has different limnological conditions its south-western part has a salinity of <2 g·L^{-1} whereas the salinity of the eastern basin is ~4 g·L^{-1} [14]. Balkhash Lake ecosystem sustainability is required to provide optimal salinity regime, which depends on the Ile River inflow and a two-way flow between western and eastern parts of the lake [15]. The parameters program software displays as graphs as it shown in figure 9.

For analyzing and forecasting the program allows displaying all simulated parameters of the river basin such as Ile delta regime, Balkhash Lake inflows, level changes, Kapchagay reservoir operations, and water supply demands for agriculture, industry, municipal and environmental.

The software displays a two-dimensional interactive visualization of the river basin, which displays water balance, objects interaction and system changes for the simulated period (2016-2050).This interactive visualization allows user to analyze and optimize the necessary parameters of Ile-Balkhash river basin and clearly show the effects of the development according to the accepted scenario. By choosing the required scenario, which implies reducing transboundary flow and water consumption priority “Environment” or “water user“ priority, we can see the influence on the Lake Balkhash environment or water supply deficits.

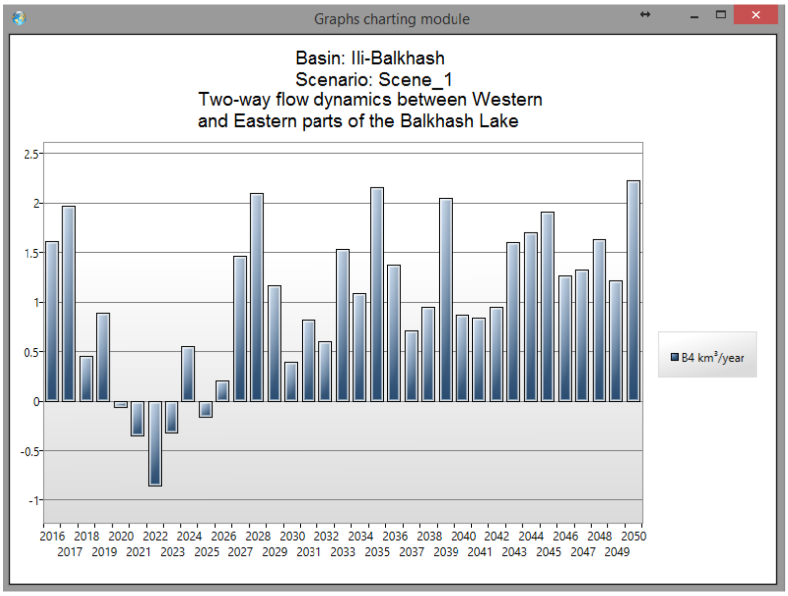

Figure 9 – Two-way flow dynamics between Western and Eastern parts of the Balkhash Lake

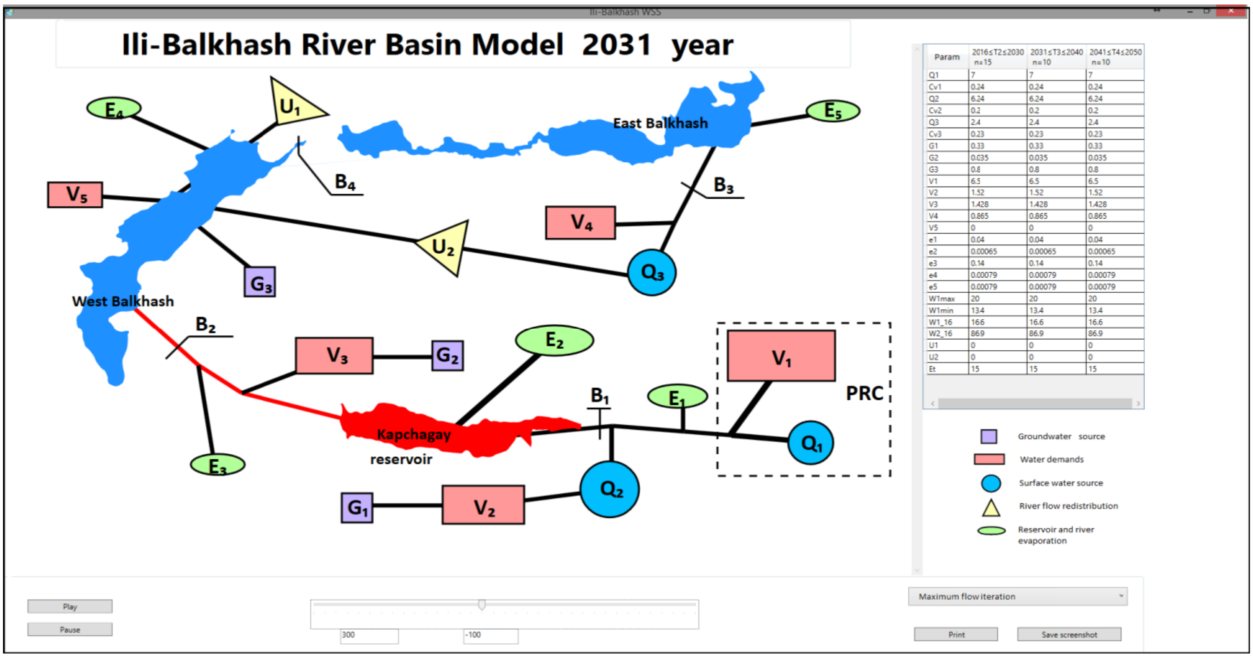

Figure 10 – Ile-Balkhash river basin two-dimensional interactive visualization

Conclusions. Submitted mathematical and software package improves efficiency of water management of the Ile-Balkhash river basin as well as an opportunity for assessment and forecasting in the management of Transboundary Rivers. Computer modeling of river basin allows making policy decisions, according the analysis of simulated data.

The values of the input parameters based on actual data, expert hypotheses or a preliminary analysis. The sensitivity of the results evaluated through a series of iterations. The model accuracy surveyed through a validation period (1992–2011). Model performance for 20-years validation period evaluated suing most reliable actual data: downstream reservoir flow and Balkhash Lake level dynamics. Hydrological simulation model of Ile-Balkhash river basin created in object-oriented programming language C#. The developed mathematical software package includes a set of modules: graphical interface, mathematical functions, interactive analysis, and interaction with the operating system. The model has a two-dimensional visualization of the simulation process, based on schematic symbols of objects, their interaction and parameters. Performing calculations of the model confirmed its functionality and reliability of results obtained in a wide range of input parameters, proved the effectiveness of simulation calculations for water predictive assessment of possible scenarios of river basin and Balkhash Lake hydro-ecological regime assessment. The numerous iterations function helps to reduce the impact of accidental inaccuracy of the model.

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ОРТАЛЫҚ АЗИЯДАҒЫ ТРАНСШЕКАРАЛЫҚ ІЛЕ-БАЛҚАШ ӨЗЕНІ БАССЕЙНІНІҢ МОДЕЛДЕУ

Аннотация. Ұсынылған мақала Іле-Балқаш трансшекаралық өзен алабының математикалық компьютер үлгілеуі. Негізгі құралы ретінде үлгілеуді пайдалану автоматизациялау үшін және су шаруашылық есептеулерді оңтайландыру, су теңдестік алаптарын үлгілеу, және де суға деген табиғи-экономикалық қажеттілігің ескере отыра трансшекаралық ағынды жағдайында су қорына болжау және талдау. Үлгілеу сценарийлерін анықтауға, сумен қамтамасыздандыру жүйесінің сезімталын тексеру және де аймақтын экономикасы және қоршаған ортаға оның әсерін анықтауға мүмкіндік береді. Осы зерттеулерде негізгі назар Балқаш көлі алабын сумен қамтамасыздандыру жүйесінің динамика-стохастикалық үлгеуің жүзеге асыру. Үлгілеу құбылмалық талдаумен және Монте-Карло әдісін пайдалана стохастикалық қасиеттерін бағалаумен толықтырылған. Үлгілеу С# бағдарлама нысанды-бағдарлану тілінде жүзеге асырылған. Іле-Балқаш алабының су теңдестік үлгілеу алгоритмі өңделген. Сумен қамтамасыздандыру сценарийлері еңгізілген және өңделген. Статистикалық бағалау модулі өңделген. Үлгілеу нәтижелерінің көзбен шолу блогі өңделген.

Түйін сөздер: су қорларын басқару, өзен алаптарын үлгілеу, қоршаған орта, су қорлары, гидрология, сумен қамтамасыздандыру, математикалық компьютерлік үлгілеу, динамика-стохастикалық үлгілеу.

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МОДЕЛИРОВАНИЕ ИЛЕ-БАЛКАШСКОГО ТРАНСГРАНИЧНОГО БАССЕЙНА В ЦЕНТРАЛЬНОЙ АЗИИ

Аннотация. Статья представляет математическую компьютерную модель Иле-Балкашского трансграничного речного бассейна. Использование моделирования как основного инструмента для автоматизации и оптимизации водохозяйственных расчетов, моделирование бассейновых водных балансов, а также анализа и прогноза водных ресурсов в условиях трансграничности стока с учетом природно-экономических потребностей в воде. Модель позволяет определить возможные сценарии, проверить чувствительность системы водообеспечения и ее влияние на окружающую среду, и экономику региона. Основное внимание в этом исследовании уделяется реализации моделируемой динамико-стохастической модели системы водообеспечения бассейна озера Балкаш. Моделирование модели дополняется анализом неопределенности и оценкой стохастических свойств с использованием метода Монте-Карло. Модель реализована в объектно-ориентированном языке программирования C#. Разработан алгоритм моделирования водного баланса Иле-Балкашского бассейна. Разработаны и внедрены сценарии водообеспечения. Разработан модуль статистической оценки. Блок визуализации результатов моделирования.

Ключевые слова: управление водными ресурсами, моделирование речных бассейнов, окружающая среда, водные ресурсы, гидрология, водообеспечение, математическая компьютерная модель, динамико-стохастическая модель.

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