ISSN 2518-170X (Online)
ISSN 2224-5278 (Print)

NEWS OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES

№6
2025

ISSN 2518-170X (Online)
ISSN 2224-5278 (Print)

CENTRAL ASIAN ACADEMIC
RESEARCH CENTER

N E W S
OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES

6 (474)

NOVEMBER – DECEMBER 2025

THE JOURNAL WAS FOUNDED IN 1940

PUBLISHED 6 TIMES A YEAR

ALMATY, 2025

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News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Owner: «Central Asian Academic Research Center» LLP (Almaty).
The certificate of registration of a periodical printed publication in the Committee of information of the Ministry of Information and Communications of the Republic of Kazakhstan Nº KZ50VPY00121155, issued on 05.06.2025
Thematic scope: *geology, hydrogeology, geography, mining and chemical technologies of oil, gas and metals*
Periodicity: 6 times a year.
http://www.geolog-technical.kz/index.php/en/

«ҚР ҰҒА» РҚБ Хабарлары. Геология және техникалық ғылымдар сериясы».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Меншіктеуші: «Орталық Азия академиялық ғылыми орталығы» ЖШС (Алматы қ.).
Қазақстан Республикасының Ақпарат және коммуникациялар министрлігінің Ақпарат комитетінде 05.06.2025 ж. берілген № KZ50VPY00121155 мерзімдік басылым тіркеуіне қойылу туралы куәлік.
Тақырыптық бағыты: *Геология, гидрогеология, география, тау-кен ісі, мұнай, газ және металдардың химиялық технологиялары*
Мерзімділігі: жылына 6 рет.
http://www.geolog-technical.kz/index.php/en/

«Известия РОО «НАН РК». Серия геологии и технических наук».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Собственник: ТОО «Центрально-азиатский академический научный центр» (г. Алматы).
Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и коммуникаций и Республики Казахстан № KZ50VPY00121155, выданное 05.06.2025 г.
Тематическая направленность: *геология, гидрогеология, география, горное дело и химические технологии нефти, газа и металлов*
Периодичность: 6 раз в год.
http://www.geolog-technical.kz/index.php/en/

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OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224–5278
Volume 6. Number 474 (2025), 151–167

https://doi.org/10.32014/2025.2518-170X.577

UDC 556.01:504.4.062.2

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DYNAMIC-STOCHASTIC MODEL OF SUSTAINABLE WATER RESOURCES MANAGEMENT IN KAZAKHSTAN

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Abstract. Water resource systems are characterized by numerous uncertainties that cause significant variability in water distribution, particularly in watersheds with sizeable irrigation areas, diverse water users, and multiple water sources. The purpose of this study is to develop an integrated methodological approach for identifying and assessing extreme water-resource situations that lead to major socio-economic and environmental consequences. To achieve this, a dynamic–stochastic approach is applied to describe the temporal evolution of water management systems under random and unpredictable external factors. The proposed dynamic–stochastic model integrates hydrological, environmental, and economic components into a unified mathematical programming framework aimed at maximising economic benefits across different water-using sectors. This makes it possible to analyse combined environmental–economic issues within a consistent modelling environment. The results include the development of innovative simulation software for transboundary river-basin modelling capable of simulating

and evaluating a broad range of hydro-economic parameters and generating comprehensive water-supply scenarios. The novelty of the work lies in the creation of a modelling tool and methodological framework that have not previously been applied to the study of complex river basins. The model was validated and tested using the Ile–Balkhash River Basin, selected due to its hydrological complexity and high sensitivity to climatic and anthropogenic pressures. The tests revealed the strengths and weaknesses of the system, demonstrated the adequacy of model responses to external impacts, and confirmed the applicability of the methodology for further analysis and forecasting in other river basins.

Keywords: river basin modeling, Ile–Balkhash Basin, Balkhash Lake, hydro-economic modeling, simulation software

Contribution statement: *M. Leman – modeling, manuscript writing; I. Malkovskiy – conceptualization, methodology; L. Toleubaeva – concept development; A. Tairov – data analysis, A. Aldiyarova – data collection.*

Data Availability: *All study data are included in the article.*

Acknowledgments: *This study was a state granted and carried out under the Government scientific program «Water Resources Management of Kazakhstan River basins». The authors wish to acknowledge the Institute of Geography and Water Security for providing equipment, facilities and financial support.*

Research funding information: *The research is fully funded by the Government grant for Institute of Geography and Water Safety, Almaty, Kazakhstan.*

Author contribution: *This manuscript describes original work never realized and is not under consideration by any other journal. All authors approved the manuscript and this submission, and all authors made substantial contributions and declare no interest conflict.*

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ҚАЗАҚСТАННЫҢ СУ РЕСУРСТАРЫН ТҰРАҚТЫ БАСҚАРУДЫҢ ДИНАМИКАЛЫҚ-СТОХАСТИКАЛЫҚ МОДЕЛІ

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Аннотация. Су ресурстары жүйесі көптеген белгісіз факторларға байланысты динамикалық сипатқа ие, бұл әсіресе көптеген су көздері мен пайдаланушылары бар суару аймақтарда судың таралуын күрделендіреді. Зерттеудің мақсаты — су ресурстарын басқарудағы ең маңызды әлеуметтік-экономикалық және экологиялық салдарлары бар төтенше жағдайларды анықтау және бағалау үшін интеграциялық әдістемені әзірлеу. Осы мақсатқа жету үшін динамикалық-стохастикалық тәсіл қолданылады, ол кездейсоқ және алдын ала болжалмайтын факторлардың әсерін есепке алып, су ресурстарын басқару жүйесінің уақыт бойынша өзгеруін сипаттауға мүмкіндік береді. Динамикалық-стохастикалық модель су ресурстары мен экономикалық компоненттерді біріктіріп, әртүрлі салалардағы суды пайдалану арқылы экономикалық пайданы барынша арттыруға бағытталған математикалық бағдарламалау құрылымын қамтамасыз етеді. Бұл тәсіл біріктірілген экологиялық-экономикалық мәселелерді шешуге мүмкіндік береді. Зерттеу нәтижесінде трансшекаралық бассейндерді имитациялық модельдеу үшін инновациялық бағдарламалық қамтамасыз ету әзірленді, ол гидроэкономикалық параметрлерді бағалап, өзен бассейндерін сумен қамтамасыз етудің кешенді сценарийлерін жасауға мүмкіндік береді. Жаңалығы — бұрын-соңды Қазақстанда жасалмаған стохастикалық және экономикалық элементтерді интеграциялаудың жаңа тәсілін қолдану. Модель бастапқыда Орта Азиядағы ең ірі су қоймасы Балқаш көлін қамтитын Іле-Балқаш өзенінің алабында тексерілді. Алаптың гидрологиялық күрделілігі мен табиғи-климаттық және антропогендік әсерлерге жоғары сезімталдығы зерттеуге негіз болды. Сынақ нәтижелері модельдің сыртқы әсерлерге жауап беру дұрыстығын бағалауға, жүйенің күшті және әлсіз жақтарын анықтауға, сондай-ақ әдістеменің басқа трансшекаралық алаптарда қолданылуына мүмкіндік берді.

Түйін сөздер: өзен алабын моделдеу, динамикалық-стохастикалық модель, Балқаш көлі, имитациялық бағдарламалық қамтамасыз ету, гидроэкономикалық талдау, Орталық Азия

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ДИНАМИКО-СТОХАСТИЧЕСКАЯ МОДЕЛЬ УСТОЙЧИВОГО УПРАВЛЕНИЯ ВОДНЫМИ РЕСУРСАМИ КАЗАХСТАНА

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Аннотация. Системы водных ресурсов характеризуются высоким уровнем неопределённости, что обуславливает динамический характер распределения водных ресурсов, особенно в бассейнах с развитой ирригационной инфраструктурой, множественными источниками и разнородными категориями водопользователей. Цель исследования — разработать интегрированный подход и методику для выявления и оценки экстремальных водоресурсных ситуаций, оказывающих существенное социально-экономическое и экологическое воздействие. Для достижения цели применяется динамико-стохастический подход, позволяющий учитывать влияние непредсказуемых факторов и описывать эволюцию водохозяйственных процессов во времени. Разработанная динамико-стохастическая модель объединяет водные и экономические компоненты в единую математико-программную конструкцию, ориентированную на максимизацию экономической отдачи от использования водных ресурсов при соблюдении экологических ограничений. Такой подход обеспечивает возможность решения комплексных эколого-экономических задач в рамках единой модели. Результатом исследования стало создание программного обеспечения для имитационного моделирования трансграничных речных бассейнов, позволяющего оценивать широкий спектр гидроэкономических параметров и формировать различные сценарии водоснабжения. Научная новизна работы заключается в разработке метода интеграции стохастических

процессов и экономических элементов, ранее не применявшегося в Казахстане для моделирования сложных водохозяйственных систем. Модель была апробирована на бассейне Иле-Балхаш — одной из наиболее сложных и уязвимых водных систем Центральной Азии. Проведённые тесты позволили оценить корректность реакций модели на изменения внешних условий, определить сильные и слабые стороны моделируемой системы и подтвердить применимость предложенной методики для анализа других трансграничных речных бассейнов.

Ключевые слова: моделирование речных бассейнов, динамико-стохастическая модель, озеро Балхаш, имитационное моделирование, гидроэкономический анализ

1. Introduction. Water resources are the foundation of strategic economic and natural resources and then become the guarantee of global sustainable development. When insufficient water resources meet rising water consumption, over-withdrawal of water resources and associated ecological, environmental degradation would occur (Israilova et al., 2023). The planning of human activities involving rivers and their floodplains must consider certain hydrologic facts. One of these facts is that surface water flows and aquifer storage volumes vary over space and time (Daniel, 2017). An effective tool for research systems and its influences is numerical simulation modelling, where the influence of various factors is considered by setting the probabilistic characteristics of processes (probability distribution law). Water resources availability was particularly critical since the demands from multiple sectors were rapidly increasing in many regions of the past years (Li et al., 2009).

The manuscript introduces a novel method for simulating water supply system of Balkhash Lake in Central Asia, through numerical experiments utilizing mathematical models. These models accurately replicate the behavior of real objects over time periods. At the same time, the development and functioning of water bodies and water infrastructure is described by a set of algorithms that simulate the probabilistic process of formation of river flow resources and the dynamics of water demand of natural economic systems and administrative regions, as well as the rules of water regulation and water distribution. In the future, we should expect aggravation of the situation with water supply in the republic due to the reduction of river flow from the territory of neighbouring countries, as well as due to the climatically conditioned reduction of local flow (Medeu et. al., 2017).

The main objective is to provide decision-makers involved in planning the use and protection of water resources with a comprehensive suite of programs. These programs utilize modern technologies to generate the necessary data to support various water supply scenarios.

2. MATERIAL AND METHODS

2.1 Study area

Central Asia, primarily comprised of drylands (MEA, 2005), relies heavily on water to sustain its natural ecosystems, biodiversity, and various land use

activities. Along the rivers of Central Asia, the most productive and diverse ecosystems within these drylands are found (Tesch, 2020).

Balkhash Lake, a closed-basin lake located in arid part of Kazakhstan (Central Asia), ranks as the 15-th largest lake globally and the third largest in Asia (Mischke et. al, 2020). The lake the end part of the transboundary basin, the main river is the Ile, which originates from the People's Republic of China. The Ili River originates in the Tian Shan Mountains in the south and provides 78% of the flow. The Karatal River drains the Dzungar Alatau and delivers most of the remaining discharge 15% (Propastin, 2013). The river, a critical water source in southeastern Kazakhstan, sustains drinking water supplies, electricity generating and irrigates farmlands across seven regions. Transboundary river basins, such as the Ile-Balkhash, present additional complexities, as water must be managed across multiple political jurisdictions, each with its own interests and needs (Wolf et al., 1999, Kummu et al., 2010).

Balkhash Lake is a vital water body boasting a diverse aquatic flora and fauna, particularly notable for its varied wildlife. The lake's economic significance primarily stems from local fisheries and recreational resorts. The hydrological balance of Balkhash Lake is significantly affected by the climatic conditions in the upper reaches of its main tributary, the Ili River, and the resulting inflow into the lake (Petr, 1992, Propastin, 2013). Two parts of the lake are divided by the Saryesik Peninsula and that is why the water composition of the two parts is different. However, this unique lake might significantly shrink due to the intensification of agriculture, aggravating climate change, and the potential basin-wide impacts of China's Belt Road Initiative, according to the recent research of the University of Oxford (Tesse de Boer et al, 2021). The study area is illustrated in Figure 1.

Figure 1. The Balkhash Lake. Central Asia (adopted from MODIS, Terra satellite, 2024).

2.2. Materials and methodology

The methodology of the developed model is based on the implementation of various river basin structures, each characterized by distinct natural and economic features. This model was tested on a unique and complex river basin in Central Asia. The basin encompasses all types of water consumers and users, includes a reservoir, and Balkash Lake considering arid climate and river flow losses.

The model's performance was evaluated using this representative and intricate river basin. Specific scenarios have been identified through analysis of both theoretical and applied results where it is inherently impossible to simultaneously maintain the key standard parameters of the Western Balkhash, water level and salinity. The prioritization of one parameter over another should be justified based on an evaluation of their individual impacts on the lake's various components. A preliminary assessment suggests that, in terms of creating the most favorable conditions for the population of the Balkhash region (including maintaining a suitable microclimate and preventing desertification and salt dispersion from the drying lake bed), the optimal approach is to maintain a high-water level in Balkhash (referred to as the «highly mineralized lake» option).

To restore and preserve the water supply functions of the lake, the most effective solution appears to be the establishment of a 'small fresh' lake. However, considering the interests of fisheries, whose productivity depends on both the lake level (water area) and water mineralization, an intermediate option seems to be more suitable. The conflicting nature of this situation naturally leads to the problem of multicriteria optimization regarding the lake's level and salinity, necessitating a compromise solution.

One of the fundamental aspects of the effectiveness of the considered alternatives to the state of the lake. Balkash is the duration of the process of establishing a new level and salinity regime. The dynamics of the average salinity values of the Western Balkhash is determined not only by the limiting (equilibrium) values of this indicator, but also by the initial conditions - the excess of the initial water salinity over the equilibrium state. In this case, the average salinity of flowing water bodies, tends, with constant elements of the water balance, to an equilibrium position according to an exponential law, i.e.:

$$m_4^{T+\Delta T} = M_4 + (m_4^T - M_4)\exp(-\frac{Q - P_3}{W_3} \cdot \Delta T), \quad (1)$$

where: m^T, $m^{T+\Delta T}$ – average values of water mineralization in Western Balkash at certain time T and $T+\Delta T$ (initial and final); M_4 – maximum (equilibrium) salinity of the western part of the lake; Q – average annual volume of river inflow into Western Balkhash; W_z and P_z – the volume of the western part of the lake and its "water consumption" at the accepted level.

The main factors determining the intensity of the process of self-regulation

of Balkash Lake level are the inflow and surface evaporation as well as the morphometric characteristics of its water body. The average levels dynamics of the Lake described by the following approximate formula:

$$Z_B^{T+\Delta T} = Z_B + (Z_B^T - Z_B)\exp(-\frac{\text{в}E^2}{R - P_3}\Delta T), \quad (2)$$

where: Z_B^T, $Z_B^{T+\Delta T}$ – Balkash Lake levels, respectively, at period T and $T+\Delta T$ (initial and final);

Z_B – gravity level of the lake, corresponding to the equality between the rate of inflow and the rate of visible evaporation;

R – annual river inflow rate;

E – norm of the annual evaporation from the water surface; RZ – water consumption rate of Balkash Lake at the accepted level;

в – parameter of the morphometric characteristics of the Lake Balkash within the possible amplitude of fluctuations in its level (b = 0.54).

According to Balkash Lake salinity research (Mischke, S., Zhang et al., 2020) for discrete values of river inflow, water exchange limitation coefficient and inflow salinity allows to draw the following conclusions:

The standard value of the limiting salinity of the lake (Mg = 1.6 g/l) without artificial regulation of its hydrological regime is ensured by river inflow with water mineralization (conservative salt content) of no more than 0.16 g/l (zero option). Each 0.1 g/l increase in inflow mineralization leads to an increase in the limiting salinity of the Lake by an average of 0.8 g/l.

2.3 The model description

Figures 2 and 3 shows the structure and parameters of the dynamic-stochastic model.

A logical and mathematical description of the model has been developed. It consists of the following modules:

–water demand dynamic model;

– stochastic model of available water resource potential;

– The water balance model of Balkash Lake whole and its western and eastern parts individually;

– the water balance model of the Balkash Lake.

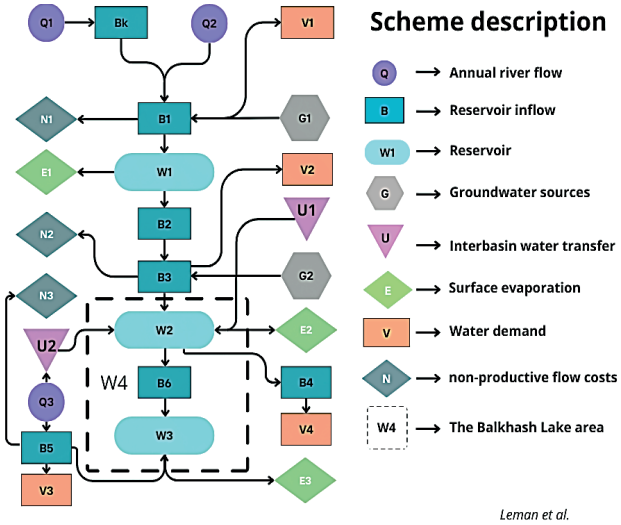

Figure 2. The structure of dynamic-stochastic model of Ili-Balkash River basin.

2.4 Programming and model implementation

Machine language, the fundamental language understood by computers, is essential for executing operations within computational models. The «model translation» process involves converting theoretical models into a computer-readable format using machine language. This translation is crucial for accurately simulating complex systems and ensuring the model's functionality (Lange and Sippel, 2020, Miller and Thompson, 2020).

Figure 3 illustrates the general operating diagram of the computer simulation model, outlining its main processes and stages of operation.

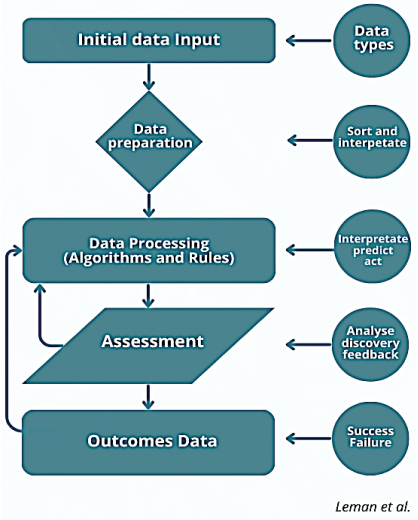

Figure 3. General scheme of operation of the computer simulation model.

The initial step is always to load the input and initial data into the software. The developed software package provides several different options for loading input and initial data.

The first is manual data entry by the operator, the second option is loading prepared data in the form of a script, considering the adjustment of the "operators" script parameters, and the third option is loading data in an automated form from the database.

The next stage of the simulation computer model is preparing the data in a form convenient for processing and loading it into the computer's RAM. Data for calculations is packaged into instances of special data types of collection classes, which allow more flexible work with groups of objects than in arrays. Memory is also used more efficiently; if the number of objects increases, memory is allocated dynamically. The main types of collections used are "Queue", "List", "Dictionary". These collections allow you to effectively work with heterogeneous data contained in model objects.

After preparing the data for calculation, the modeling process starts. The calculation process is carried out in a parallel thread, which allows calculations to be carried out simultaneously, in the background, regardless of further actions of the user and the operating system. Using an additional thread makes it possible to create animation of the calculation process, as well as the visualization process with the ability to slow down, pause and reverse.

The final stage of the computer simulation model is the analysis of the modeling result - processing data from the modeling process, preparing and filling out data tables, creating two-dimensional graphs, creating and preparing two-dimensional visualization interfaces.

The model being developed consists of several interconnected processes and modules.

In addition to these processes computer simulation model includes service modules designed for the interaction of the program with the user, operating system, and database. Figure 4 shows a diagram of the interaction of the main processes and modules.

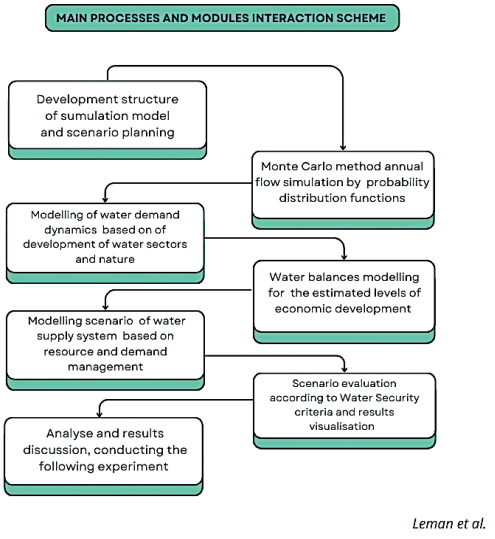

Figure 4. Scheme of interaction of main processes and modules.

For many software programs, probabilistic models are a useful asset in modeling statistical behavior, such that coverage testing is possible by automating test-case selection, execution and evaluation (Marinescu et. al, 2015)

Developing the structure of a simulation model and planning scenarios for the development of a water basin includes a key point in creating the structure of a simulation model considering the characteristics of the water basin (Dolbeshkin et. al., 2017). Planning and developing scenarios for the water supply system means designing and creating a database where data on water resource dynamics, changing water demand, calculated water balance data, etc. can be displayed and stored. The input parameter represents a system of assumptions about the dynamics of water resources and changes in water demand. The result of this process is the functional and chorological structure of the simulation mathematical model.

An appropriate database is essential for accurate model functionality. The time structure is divided into stages, with a large model step: retrospective until 2023, perspective 2025-2050. The software architecture is a client-server application, which is a prevalent model in network computing. This architecture minimizes software compatibility issues with user computers, as the server handles most processing tasks and ensures consistent functionality across different platforms (Rizwan et al., 2018). This configuration facilitates real-time collaboration among multiple experts, thereby increasing the system's efficiency and ability to expand. The server part of the programme is implemented using the Python programming language, the Django framework, and the SQLite DBMS. The client part of the programme is implemented using JavaScript, the Leaflet library, and ChartJS.

The software main components: database, administration module, dynamic-stochastic model, scheme map module and their functionality described in Figure 5.

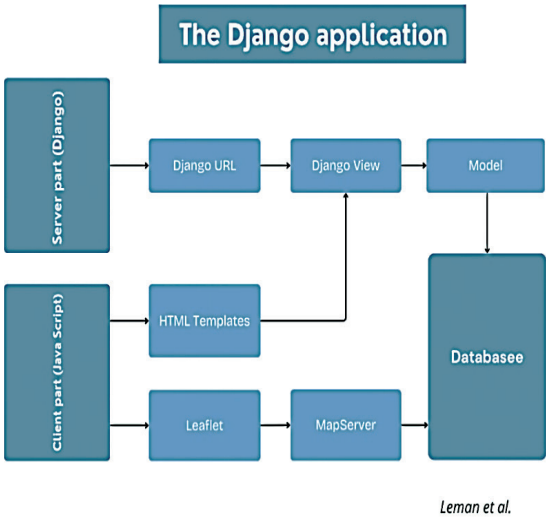

Figure 5. The Django application scheme.

Database. A data storage structure and models were developed based on the collection of hydrological data, water quality data of the Ili-Balkash basin, and water demand for the population and economic sectors of the basin. Developed database allows users to store and process data and model parameters in the form of scripts. The client part of the application operates using a data structure based on JSON, which is used to exchange data.

The Administration Module provides essential additional functionality for working with scripts, quick editing outside the computer model, and using JSON editors for debugging the script. The SQLite database management system also functions optimally thanks to this module. The functionality allows update and edit the application content, create user accounts and control access to the software package – whether that's mass or private.

The software implementation of the dynamic-stochastic model ensures that all stages of the modelling process are completed correctly and on time.

The software is a set of functions and subroutines in the Python programming language, that ensure all stages of the modeling process:

– Reading and loading script parameters from the database;

– Formation of series of random numbers of runoff according to specified coefficients of variation and flow rates;

– Water balance model of the Ili-Balkash river basin;

– Evaluation model by specified criteria;

– Display and visualization data in the form of maps, graphs, charts and tabular data.

The Scheme and map module are a visualization tool for the Balkash Lake basin components, including: basin map and borders, layers, river and administrative araes, large rivers, reservoirs, as well as a background (Google Maps, OpenStreetMap). For these layers, it is possible to dynamically change the display for more convenient analysis.

3. VALIDATION AND VERIFICATION

The object database is established based on the unique characteristics of the region's water economy, including its environmental conditions, territorial and sectoral structure, primary water resources of the WHB, and the water demand of various economic sectors (Smith & Jones, 2018; Anderson et al., 2020).

The results of the implemented model were rigorously validated and verified through both manual numerical calculations and advanced statistical analyses. The validation process involved comparing model outputs with observed data from historical water usage and resource availability, ensuring the model's ability to accurately replicate real-world conditions (Brown et al., 2019). Verification, on the other hand, was conducted by testing the model under various scenarios and stress conditions to ensure robustness and reliability, figure 7.

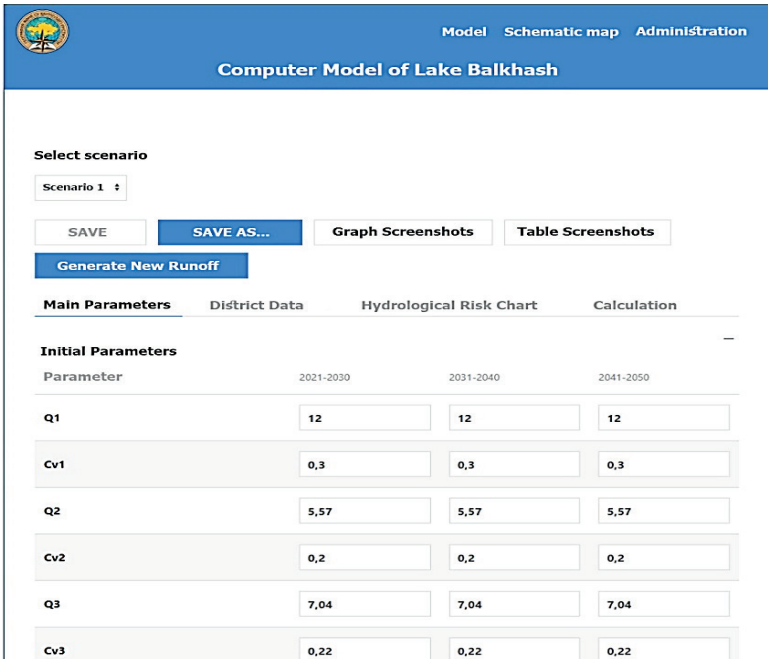

Figure 7. The primary operating window for inputting initial data.

The statistical methods employed in these analyses include regression analysis, Monte Carlo simulations, and sensitivity analysis. These techniques help in understanding the degree of correlation between the modeled outcomes and actual observations, as well as in assessing the model's responsiveness to changes in input parameters (Lee and Kim, 2021). This comprehensive approach to validation and verification provides confidence in the model's utility for simulating the water dynamics and demand within the WHB (watershed basin).

4. RESULTS AND DISCUSSION

The results obtained during processing of the input parameters of the model demonstrate the feasibility of rapidly and efficiently calculating substantial quantities of data over extended periods, while simultaneously acquiring the requisite data for subsequent analysis and forecasting of the water management complex. Additionally, the model allows for the generation of an unlimited number of scenarios for the development of a future water supply strategy, contingent on the availability of water in a given year, the economic and ecological circumstances within the river basin, or the administrative districts and provinces of the country. Analyzing the modeled data helps in understanding the impact of economic growth, industrial demands, and population changes on water resources (Pahl-Wostl et al., 2007).

The model applied to the Ili-Balkash River basin addresses the key mater managing issues:

• Creating a various water management scenario for decision-makers and policies;

• Considers a possible hydrological risk;

• Assesses the system for water supply reliability and stress.

As a result, the model is volume instrument for forecast and basin planning, being an effective tool for optimal water management in agriculture, industries and future environment planning. It assesses the availability, reliability of water resources and identifies potential shortages. The primary operating window for inputting initial data shown on the figure 8.

Analyzing transboundary inflows and local water sources, the model can predict areas and periods of water scarcity, aiding in effective water resource planning and management (Vörösmarty et al., 2000).

Figures 4 shows results visualization modules, which are present calculated data of hydrological risk and demand criteria. In this instance, the criteria for the reliability of the water supply to the system have been selected. Furthermore, the block illustrates all water users and considers their priority for water access in accordance with the selected management scenario and displays the status of Lake Balkash at the time selected by the colour.

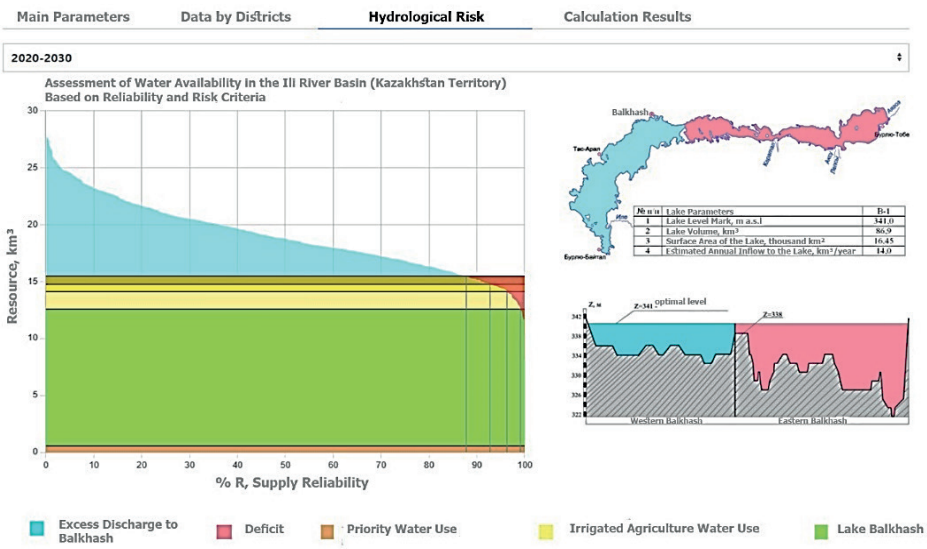

Figure 8. Assessment visualization module by reliability and hydrological risk criteria.

The model shows water availability assessment in the Ile-Balkhash river basin (Kazakhstan's part) for the chosen period (2020-2030; 2031-2040; 2041-2050) based on reliability and hydrological risk criteria. The panels present graphs of resource allocation across reliability levels (P, %) probability of deficit or surplus of river flow and other various components, including Balkhash Lake level, inflow volume, priority of water use by economics, and regional water resources.

The also panels include a Maps visualisation block, (illustrated in Figure 9) and cross-sectional diagrams showing water level dynamics and critical indicators, providing a comprehensive visualization of the modeled scenarios for future water management. The results of the modeling, based on the selected scenarios, are presented within the framework of the mathematical software complex.

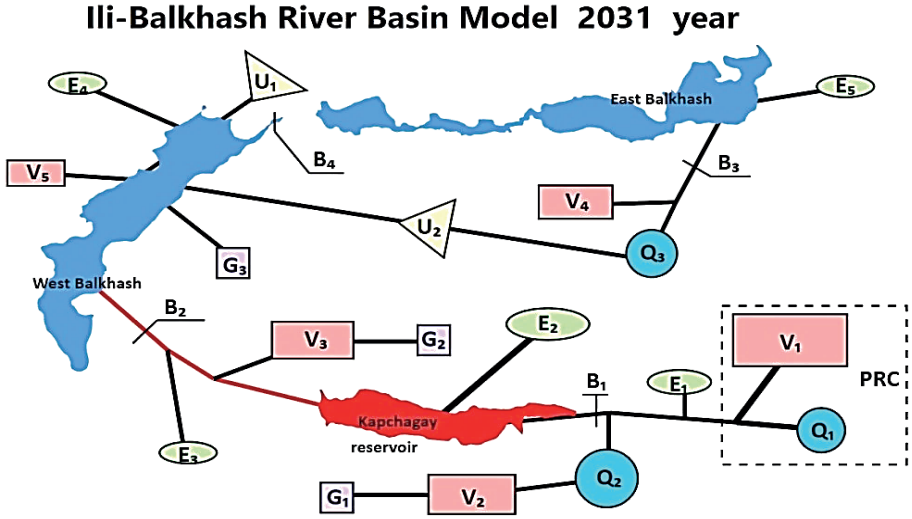

Figure 9. The scheme module window of the Ile-Balkhash basin.

5. CONCLUSION

The developed dynamic-stochastic model of water resources management, tested using the Ile-Balkhash basin as a case study, demonstrated a high degree of reliability and stability in assessing water availability within the transboundary basin.

The temporal structure of the model, organized into forecast stages for the years 2030, 2040, and 2050, made it possible to identify the characteristics and dynamics of long-term changes in water resources.

Calculations based on reliability criteria and hydrological risk confirmed the applicability of the proposed approach for analyzing water management scenarios under conditions of uncertainty.

The technical implementation of the server component using Python, the Django framework, and the SQLite DBMS provided a stable computational environment and the potential for further scaling of the developed tool.

The conducted tests made it possible to identify the strengths and weaknesses of the modeled system, assess the adequacy of its response to external impacts, and confirm the applicability of the proposed dynamic-stochastic modelling methodology for further research and scenario forecasting in other river basins, including transboundary ones.

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ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Ответственный редактор *А. Ботанқызы*
Редакторы: *Д.С. Аленов, Т. Апендиев*
Верстка на компьютере: *Г.Д. Жадырановой*

Подписано в печать 15.12.2025.
Формат 70x90$^{1}/_{16}$. 20,5 п.л.
Заказ 6.

«Central Asian Academic Research Center» LLP
Алматы, Қонаев к-сі, 142