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DEVELOPMENT OF A METHODOLOGY FOR AN INTEGRATED ASSESSMENT OF THE VOLUME OF MAXIMUM PERMISSIBLE WITHDRAWAL OF RIVER AND ECOLOGICAL FLOW

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KEY WORDS

water resources, river basin, irrevocable withdrawal of flow, environmental flow, quadratic equation, methodology.

ABSTRACT

Distinctive features of the modern approach to solving the problem of assessing the maximum permissible withdrawal of river flow and the release of environmental flow include consideration of the nature and scale of water resource use and their impact on the natural environment, as well as an assessment of their effects on ecology, the economy, and society within river basin catchment areas. *The aim* of the study is to develop a methodological approach to assessing the maximum permissible withdrawal of river flow and the release of environmental flow, taking into account geo-ecological constraints. *Materials and methods***.** The research methodology includes two approaches to substantiating the volumes of these quantities, based on the development of mathematical models of hydrological–ecological and economic activity of river basin catchment areas. The study used statistical data from government agencies of the Republic of Kazakhstan and the Kyrgyz Republic. *Results***.** General principles, criteria, parameters, and methods for regulating the maximum permissible withdrawal of river flow and the release of environmental flow are proposed, based on modeling natural and anthropogenic processes in river basins. An algorithm for approbation within the framework of calculating standards of permissible impact for specific river basins is presented. *Conclusions***.** The use of mathematical models makes it possible to carry out a more in-depth hydrological, ecological, and economic justification, contributing to the improvement of the socio-ecological situation within river basin catchment areas.

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1. INTRODUCTION

River basins are key natural systems that form the spatial basis for population distribution and natural resource management. Their significance is expressed through the interaction of ecological, economic, and social functions that determine environmental quality and human well-being. The uniqueness of river basin catchments results from their formation under highly dynamic hydrological and climatic conditions and their development in accordance with the law of geographical zonation. This necessitates regulation of their functioning, including the assessment of permissible irreversible water withdrawal and the establishment of environmental flow to support ecosystem conservation and restoration.

The conducted analysis of studies devoted to the problem of standardization of activities and environmental services of river basins, as well as consideration of the concept of «irrigation capacity of a river» in the works of A.N. Kostyakov and V.A. Kutergin [1], K.I. Shavva [2], L.M. Rex [3], I.M. Panasenko, A.K. Zaurbekov and T.I. Narbaev [4], A.K. Zaurbekov [5], M.G. Golchenko and E.A. Stelmakh [6], showed that there are no special, generally accepted algorithms for assessing, analyzing and forecasting the water resource potential of catchment areas of river

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basins. This indicates the need to develop mathematical tools based on predictive models that are highly accurate.

The most important element of environmental regulation of the activities and environmental services of river basin catchments is the concept of «ecologically acceptable withdrawal of water resources», reflected in the works of D. Ya. Ratkovich [7], A. V. Yatsyk [8], B. V. Fashchevsky [9], V. S. Kovalevsky [10], I. P. Aidarov, E. V. Venetsianov and D. Ya. Ratkovich [11]. These studies are based on integral parameters reflecting the relationships between components and general patterns of development of natural systems.

One of the fundamental areas of assessing the activities and environmental services of river catchments is the approach based on the law of tolerance by W. Shelford [12], which was developed in the works: «Survival Diagram» by R. Ricklefs [13], «Diagram of bioproductivity of floodplain meadow grass stand and reproduction of fish stocks» by M.Zh. Burlibaev [14], «Diagram of the life cycle of a river basin» by Zh.S. Mustafayev, L.Zh. Mustafayeva, K.B. Koybagarova and K.Zh. Mustafayev [15], as well as «Graph of the dependence of the ecological and economic activity of a natural system on the intensity of use of natural resources» by Zh.S. Mustafayev and K.Zh. Mustafayev [16]. The specified models, which have the form of irregularly shaped ellipsoids with limited domains of definition of functions depending on the intensity of natural and natural - technogenic processes, can be used to develop a theoretical and methodological basis for assessing the maximum permissible level of water resource use and establishing the value of environmental flow.

Various principles, methods, and techniques for calculating the maximum permissible withdrawal of river flow and the release of environmental flow do not provide a single, aggregated algorithm.

To assess the ecologically acceptable irrevocable withdrawal of river flow in river basins, V.G. Dubinina developed the «Methodological principles of environmental regulation of irrevocable withdrawal of river flow and establishment of environmental flow (release)» [17], based on the analysis of hydrological time series characterizing the optimal, normal and critical conditions for the functioning of aquatic and near-water (mainly floodplain) ecosystems:

$$VPIWRF_i = VRCSAF_i - HMVR_i \rightarrow$$
$$PIWRF_i = VPIWRF_i \cdot (NFVDA_i \ /AANFVDP_i), \quad (1)$$

where $VPIWRF_i$ is the average long-term volume of permissible irrevocable withdrawal of river flow; $VRCSAF_i$ is the volume of flow corresponding to the critical state of aquatic ecosystems; $HMVR_i$ is the historically minimum volume of flow in a series of observations or the flow of the year with 99% probability; $PIWRF_i$ - permissible irrevocable withdrawal of river flow in years of varying availability; $NFVDA_i$ - natural flow of a year with varying probability; $ALTNFVDA_i$ - average long-term natural flow in years with varying probability.

A weakness of the methodological approach to regulating irreversible withdrawal of river flow and the release of environmental flow is that it is mainly based on analyzing relationships between characteristics of the hydrological regime (critical flow, historically minimum flow, hydrological flow of various exceedance probabilities) and biological indicators, while the ecological state of river basins is not explicitly taken into account.

Based on the development and deepening of a concept well - known in the hydroecology of aquatic ecosystems, according to which changes in the structural and functional organization of river basins occur within the tolerance limits of the natural stage of hydrogenesis and do not undermine the ability of natural complexes to self - regulate, Zh.S. Mustafayev and K.Zh. Mustafayev formed a new direction in the field of assessing the environmental regulation of the activities and environmental services of river basin catchments. This direction is based on the principles of environmental and economic efficiency of the use of water and land resources, which is determined by the following formula [18]:

$$NRURRB_i = UVNRRBEA_i / PVNRRB_i \rightarrow$$
$$CESRB_i = EIOFNR_i / EIOFNR_i \rightarrow \rightarrow EAC_i = \int (NRURRB_i, CESRB_i) \rightarrow$$
$$CEEA_i = CEA_i \cdot NPVCEA_i + (1 - CEA_i) \cdot NVCEA_i \rightarrow$$
$$CEA_i = (1 - ESNSRB_i) \rightarrow \quad ESEESS_i = \int (EAC, CEEA_i) \rightarrow$$
$$CUWLRRB_i = \int (ESEESS_i, NRURRB_i) \rightarrow$$
$$MPIWWRRB_i = CUWLRRB_i \cdot AVWRRB_i \rightarrow$$
$$VEF_i = (1 - CUWLRRB_i) \cdot AVWRRB_i, \qquad (2)$$

where $NRURRB_i$ - coefficient of use of natural resources of river basins; $PVNRRB_i$ - potential volume of natural resources of river basins; $UVNRRBEA_i$ - the volume of natural resources of river basins used for economic activities; $CESRB_i$ - the coefficient of economic sustainability of river basins; $EIOFNR_i$ - economic income obtained from the use of natural resources; $EIOFNR_i$ - potential income obtained from the use of natural resources; EAC_i - economic activity coefficient; $CEEA_i$ - ecological - economic activity coefficient; $NPVCEA_i$ - maximum possible value of the economic activity coefficient; $NVCEA_i$ - minimum value of the economic activity coefficient; CEA_i - coefficient of ecological activity; $ESNSRB_i$ - ecological state of the natural system of river basins; $ESEESS_i$ − expected coefficient of ecological and economic sustainability; $CUWLRRB_i$ - coefficient of use of water and land resources of river basins; $AVWRRB_i$ - available volume of water resources of river basins; $MPIWWRRB_i$ - maximum permissible irrevocable withdrawal of water resources of river basins; VEF_i - volume of environmental flow.

These approaches are based on the principles of ecological and economic efficiency of water resource use; however, they do not consider the characteristics of river hydrological regimes.

The analysis indicates the need to improve the methodological approach to assessing the maximum permissible irreversible withdrawal of river flow and environmental flow releases by introducing mechanisms that take into account anthropogenic impacts on the hydro-ecological state of river basins.

The aim of the study is to develop a methodological approach to assessing the maximum permissible withdrawal of river flow and the release of environmental flow, based on hydrological, ecological, and economic characteristics of river basin catchment areas, making it possible to determine the tolerance threshold, the limits of permissible impact, and to establish the degree of reversibility of the changes that have occurred.

Object of the study. The object of the study is the catchment basin of the transboundary Shu River, formed by glaciers of the Kyrgyz Ala-Too and Terskey Ala-Too ranges on the territory of the Kyrgyz Republic, and the zone of channel losses located in the sands of the Moyynkum Desert on the territory of the Republic of Kazakhstan. The area of the Shu River basin catchment is 62,500 km², and the river length is 1,067 km. The basin covers mountainous, foothill, foothill–plain, and desert geographical zones [19…20].

2. MATERIALS AND METHODS

To form the research database of hydrological and hydrochemical characteristics of the Shu River, materials from the publications «Surface Water Resources…», «State Water Cadastre…», «Main Hydrological Characteristics…» (USSR), as well as «Long-Term Data on the Regime and Resources of Land Surface Waters…» of the Kyrgyz Republic and the Republic of Kazakhstan were used [19...20]. Data on demographic, agricultural, environmental, and industrial components were obtained from long-term materials of the National Statistical Committee of the Kyrgyz Republic and the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan [21]. Information on the territorial organization of water use was compiled based on reports on the activities of the Shu–Talas Basin Inspection for Regulation of Water Use and Protection of Water Resources of the Committee for Water Resources of the Ministry of Water Resources and Irrigation of the Republic of Kazakhstan and the Ministry of Water Resources, Agriculture, and Processing Industry of the Kyrgyz Republic for 1992…2024 [22]. Trend construction for the studied indicators was carried out by processing the corresponding time series in the Microsoft Excel software environment.

Among the approaches and methods proposed to solve the stated tasks aimed at assessing the volume of maximum permissible irreversible withdrawal of river flow and the magnitude of environmental flow release in river basins, the provisions of the materialist theory of scientific cognition were used as fundamental. The methodological basis of the study relies on the application of trend analysis methods, modeling of natural processes, as well as analysis and synthesis of information and statistical databases using trend equatio.

3. RESULTS AND DISCUSSION

Features of the methodological approach to assessing the volume of maximum permissible irreversible withdrawal of river flow and environmental flow release

River basin watersheds, which perform important environment-forming and ecological functions based on the use of water resources for economic activities aimed at improving human well-being, are subject to the Le-Chatelier-Brown principle only up to a certain level of natural resource management. When this level exceeds a critical threshold, irreversible processes begin to occur in the natural systems of river basins. To preserve the natural properties of river basins and their environment-forming functions, and therefore their ecological significance, it is necessary to regulate the permissible irreversible flow withdrawal and establish an environmental flow rate that ensures the maintenance of a certain type of ecological balance. This, in turn, is a prerequisite for preventing the degradation of aquatic and near-water ecosystems.

The complexity of developing methodological approaches to regulating permissible irrevocable withdrawals of river basin runoff and establishing environmental flow stems from the need to assess them within the context of a triad: ecology (ensuring the quality of the human habitat), economics (increasing the purchasing power of society), and society (improving the well-being of the population). Such an assessment should be based on long-term hydrological, environmental, and economic indicators characterizing the qualitative and quantitative state of the river basin catchment area [23].

To analyze and evaluate the development features of hydrological processes in the catchment area of river basins, it is necessary to use a time hydrological series, expressed either by water flow (RWF_i) or by water volume (VRW_i), which is characterized by a trend that is a function of time and can serve as a basis for determining their statistical parameters.

The results of the analysis of the dynamics of hydrological processes within the catchment areas of river basins indicate that the average annual water flow (RWF_i) and runoff volume (VRW_i), considered as functions of time, have not only a stochastic component, but also a deterministic component, manifested in the form of multidirectional (positive and negative) trends:

$$RWF_i = \alpha \cdot SNY_i + b; \quad (3)$$

$$VRW_i = \alpha \cdot SNY_i + b; \quad (4)$$

$$RWF_i = -\alpha \cdot SNY_i + b; \quad (5)$$

$$VRW_i = -\alpha \cdot SNY_i + b, \quad (6)$$

where QP_i is the average annual water discharge in the river, m^3/s; α - is the regression coefficient showing the change in the result with a change in the time series by one unit; b - is the free parameter of the regression equation showing the minimum value of the time series; SNY_i - is the period number or the ordinal number of the year in the forecast period or an independent variable.

Based on the analysis of the relationships between the natural hydrological characteristics of the river, the minimum and maximum values of the average annual water flow (RWF_i) or runoff volume (VRW_i) are determined using the linear trend equations:

- if the linear trend equation is positive, then the minimum value of water flow (RWF_{mini}) or runoff volume (VRW_{mini}) will be equal to the free parameter of the regression equation (b), and their maximum value in the time interval in a given series is determined by the linear trend equation:

$$RWF_{maxi} = \alpha \cdot SNY_i + b; \quad (7)$$

$$VRW_{maxi} = \alpha \cdot SNY_i + b; \quad (8)$$

- if the linear trend equation is negative, then the maximum value of water flow (RWF_{maxi}) or runoff volume (VRW_{maxi}) will be equal to the free parameter of the regression equation (b), and their minimum values in the time interval in a given series are determined by the linear trend equation:

$$RWF_{maxi} = -\alpha \cdot SNY_i + b; \quad (9)$$

$$VRW_{maxi} = -\alpha \cdot SNY_i + b. \quad (10)$$

The historical maximum value of water flow ($HMWFV_i$) or runoff volume ($HMFVV_i$) is determined on the basis of an analysis of hydrological data for the time interval under consideration of the corresponding series of observations:

- the average arithmetic value of the average annual water flow ($AAWCV_i$) or runoff volume ($AAVAARV_i$) in a time interval in a given series is determined by the formula:

$$AAWCV_i = \sum_{i=1}^{N} RWF_i / N; \quad (11)$$

$$AAWCV_i = \sum_{i=1}^{N} VRW_i / N; \quad (12)$$

- the modular coefficient of average annual water consumption ($MCAAVC_i$) or runoff volume ($MCAARV_i$) is determined by the following mathematical expression:

$$MCAAVC_i = RWF_i / \ AAWCV_i; \quad (13)$$

$$MCAARV_i = VRW_i / AAWCV_i; \quad (14)$$

- the historically maximum value of water flow ($HMWFV_i$) or runoff volume ($HMFVV_i$) is determined using the maximum value of the modular coefficient of average annual water flow ($MCAAVC_{maxi}$) or runoff volume ($MCAARV_{maxi}$) according to the following formula:

$$HMWFV_i = MCAAVC_{maxi} \cdot AAWCV_i; \quad (15)$$

$$HMFVV_i = MCAARV_i \cdot AAWCV_i; \quad (16)$$

- the maximum and minimum values of the average annual water consumption coefficient and the volume of runoff are determined by the following mathematical expressions:

$$AAWCC_{maxi} = RWF_{maxi} / HMWFV_i; \quad (17)$$

$$AAWCC_{mini} = RWF_{mini} / HMWFV_i; \quad (18)$$

$$CAARV_{maxi} = VRW_{maxi} / HMFVV_i; \quad (19)$$

$$CAARV_{mini} = VRW_{mini} / HMFVV_i, \quad (20)$$

where $AAWCC_{maxi}$ and $CAARV_{maxi}$ - the maximum value of the average annual water flow rate and runoff volume; $AAWCC_{mini}$ and $CAARV_{min}$ - the minimum value of the coefficient of average annual water consumption and runoff volume.

The ecological state of a river basin's catchment area can be assessed based on the quality of atmospheric air and surface water, which are not only vital life - sustaining sources but also sensitive indicators of the well-being of the entire environment.

Various methods based on hydrochemical indicators are used as an integral indicator for assessing the quality of surface river waters and atmospheric air:

- water pollution index (WPI_i) [24] and air pollution index (API_i) [25], which are determined by the following formulas:

$$WPI_i = (1/n_i) \cdot \sum_{i=1}^{n} AACIW_i / MPCW_i; \quad (21)$$

$$API_i = (1/n_i) \cdot \sum_{i=1}^{n} AACIA_i / MPCA_i, \quad (22)$$

where n_i - is the number of substances polluting the atmosphere or surface river waters; $AACIA_i$ and $AACIW_i$ - average annual concentration $i$of the-th impurity in the air or in surface river waters; $MPCA_i$ and $MPCW_i$ - maximum permissible concentration i - impurities in the air or in surface river waters;

- the coefficient of maximum pollution of water ($WPIC_i$) and atmospheric air ($MAPC_i$), are determined by the following formulas [26]:

$$WPIC_i = WPI_i - 1 = [(1/n_i) \cdot \sum_{i=1}^{n} AACIW_i / MPCW_i] - 1; \quad (23)$$

$$MAPC_i = API_i - 1 = [(1/n_i) \cdot \sum_{i=1}^{n} AACIA_i / MPCA_i] - 1; \quad (24)$$

- the integral index of water pollution ($IWPI_i$) and atmospheric air ($IAPI_i$) is determined by the following mathematical expressions [27]:

$$IWPI_i = (1/N) \cdot \sum_{i=1}^{N} \{1 - exp[-(AACIW_i / MPCW_i)]\}; \quad (25)$$

$$IAPI_i = (1/N) \cdot \sum_{i=1}^{N} \{1 - exp[-(AACIA_i / MPCA_i)]\}. \quad (26)$$

To assess the degree of environmental pollution, one can use generalized indicators of pollution of atmospheric air and surface river waters in the form of a desirability function, which allows one to aggregate many factors into a single indicator based on the geometric mean equation, which is one of the classical Pythagorean means, and has the following form:

$$GIAWP_i = \sqrt{\Pi_{i=1}^{n} \ WPI_i \cdot \ API_i}; \quad (27)$$

$$GCMAWP_i = \sqrt{\Pi_{i=1}^{n} \ WPIC_i \cdot \ MAPC_i}; \quad (28)$$

$$GIIAWP_i = \sqrt{\Pi_{i=1}^{n} \ IWPI_i \cdot \ IAPI_i}, \quad (29)$$

where $GIAWP_i$ - generalized index of pollution of atmospheric air and surface river waters; $GCMAWP_i$ - generalized coefficient of maximum pollution of atmospheric air and surface river waters; $GIIAWP_i$ - generalized integral index of pollution of atmospheric air and surface river waters.

The ecological state of the catchment area of river basins ($ESRB_i$) can be approximately estimated by the relationship:

$$ESRB_i = 1 - \exp(-GIAWP_i) = 1 - \exp(-GCMAWP_i) = \\ = 1 - \exp(-GIIAWP_i). \quad (30)$$

To determine the design value of the ecological state of the territory of river basins, one can use the scale of integrated assessment of the danger of the ecological situation on human health (Table 1) [28].

Table 1

Quantitative assessment of the ecological situation of the natural environment

Index gradations	The nature of biological response	Danger level	$ESRB_i$
0	Death	Extremely dangerous	1.0 - 0.80
1	The presence of a disease in the body	Very dangerous	0.64 - 0.80
2	The presence of physiological diseases	Moderately dangerous	0.48 - 0.64
3	The presence of physiological and other changes	A little dangerous	0.32 - 0.48
4	The appearance of chemical substances in organs and tissues that do not cause any changes	Conditionally dangerous	0.16 - 0.32
5	No signs of adverse effects	Not dangerous	< 0.16

The selection of the design value of the ecological state of the territory of river basins is carried out on the basis of the materialistic theory of scientific knowledge, which considers socio - historical practice as the basis of knowledge and the criterion of truth, within the framework of the principles of equal, reasonable and fair use of natural resources, which are a component of the human habitat.

Based on the Gurvits stability criterion, it is possible to present a mathematical model of the design value of the coefficient of hydrological and ecological activity ($HEARB_i$) of the catchment area of river basins:

$$HEARB_i = (1 - ESRB_i) \cdot AAWCC_{maxi} + ESRB_i \cdot AAWCC_{mini}; \quad (31)$$

$$HEARB_i = (1 - ESRB_i) \cdot CAARV_{maxi} + ESRB_i \cdot CAARV_{mini}. \quad (32)$$

The economic activity of the catchment area of river basins, which are the spatial basis for human economic activity and are based on the use of their natural resources, is to a certain extent a function of the degree of use of water resources. According to the international statistics of the UN – Aquastat FAO [29], in order to assess the current state and efficiency of water resources use, it is recommended to use such general indicators for assessing water resource potential as the volume of withdrawal of renewable water resources ($VWRWR_i$) and the maximum possible gross product of the catchment area of river basins ($MPGDP_i$), environmental, economic and social damage during the use of water resources ($EESD_i$) and the expected gross product of the catchment area of river basins ($EGDP_i$).

Features of the methodological approach to assessing the volume of maximum permissible irreversible withdrawal of river flow and environmental flow release

Based on statistical data books of the Kirghiz SSR and the Kazakh SSR for 1945…1990, as well as the Kyrgyz Republic and the Republic of Kazakhstan for 1991…2024, and using the methodological approach to pricing in water use developed by A.T. Asanbaev, D.M. Mamatkanov, K.I. Shavva, A.K. Shapar [30], as well as S.R. Ibatullin, Zh.S. Mustafayev and K.B. Koybagarova [31], research databases were formed on the following indicators for the catchment area of the Chu River basin: the volume of withdrawal of renewable water resources ($VWRWR_i$), the maximum possible gross product of the catchment area of river basins ($MPGDP_i$), environmental, economic and social damage from the use of water resources ($EESD_i$) and the expected gross product of the catchment area of river basins ($EGDP_i$).

To assess the ecological status of the Chu River basin catchment area, the natural values of water management indicators were converted into a single scale of dimensionless numerical indicators:

- coefficient of withdrawal of renewable water resources ($CWRWR_i$):

$$CWRWR_i = VWRWR_i / VRWR_i, \quad (33)$$

where $VRWR_i$ - volume of renewable water resources;

- coefficient of the maximum possible gross product of the catchment area of river basins ($CMPGP_i$):

$$CMPGP_i = GPCARD_i / MPGDP_i, \quad (34)$$

where $GPCARD_i$ is the gross product of the catchment area of river basins;

- coefficient of environmental, economic and social damage ($CEESD_i$):

$$CEESD_i = EESD_i / \ MPGDP_i; \quad (35)$$

- coefficient of expected gross product of the catchment area of river basins ($EGPC_i$):

$$EGPC_i = (GPCARD_i - EESD_i)/MPGDP_i. \quad (36)$$

Based on the analysis and assessment of water management indicators in the Chu River basin catchment area for 1945…2024 and the extrapolation of long-term data, an applied economic activity model implemented in Microsoft Excel was developed to model water resource management. Graphs were constructed using the smallest rectangle method, based on a philosophical approach that ensures the transformation of quantitative changes into qualitative ones (Figure 1).

The most effective tool for systemic analysis of economic processes in the catchment area of river basins can be special mathematical models in the form of a second - order polynomial equation (quadratic equation), which reflect the relationships between their structural and dynamic variables (Figure 1):

- the coefficient of the maximum possible gross product of the catchment area of river basins ($CMPGP_i$), as a function of the coefficient of extraction of renewable water resources ($CWRWR_i$), initially increases with a fairly high intensity up to a certain limit, after which it slows down as the quality of natural resources decreases and, is described by the following equation:

$$CMPGP_i = -1{,}4972 \cdot {CWRWR_i}^2 + 2{,}4349 \cdot CWRWR_i + 0{,}0013, \quad R^2 = 0{,}9909; \quad (37)$$

- the coefficient of ecological - economic - social damage ($CEESD_i$), as a function of the coefficient of extraction of renewable water resources ($CWRWR_i$), at the beginning at the limit of tolerance it grows very slowly, and after which it grows sharply with a sufficiently high intensity depending on the quality of the environment and natural resources defined in the spatial-temporal limits and is described by the following equation:

$$CEESD_i = 1{,}0{,}524 \cdot CWRWR_i^{\,2} - 0{,}2643 \cdot CWRWR_i + 0{,}0238, \quad R^2 = 0{,}9946; \tag{38}$$

- the coefficient of the expected gross product of the catchment area of river basins ($EGPC_i$), as a function of the coefficient of extraction of renewable water resources ($CWRWR_i$), according to the Le-Chatelier-Brown law, initially increases to a certain limit, after which a period of decline occurs within certain spatial-temporal limits and is described by the following equation:

$$EGPC_i = -2{,}5501 \cdot CWRWR_i^{\,2} + 2{,}6992 \cdot CWRWR_i - 0{,}0225, \quad R^2 = 0{,}9980; \tag{39}$$

- the theoretical curve of well-being of the economic situation ($TWBCES_i$), as a function of the coefficient of extraction of renewable water resources ($CWRWR_i$), which has an irregular ellipsoid shape, which is a modification of the density graph in the form of a Gaussian curve [32], the «survival diagram» of R. Ricklefs [33], the homeostatic curve of B. Fashchevsky [34] and the law of tolerance of W. Shelford [12] and is described by the following equation:

$$TWBCES_i = -2{,}9988 \cdot CWRWR_i^{\,2} + 3{,}0070 \cdot CWRWR_i + 0{,}0421, \quad R^2 = 0{,}9744. \tag{40}$$

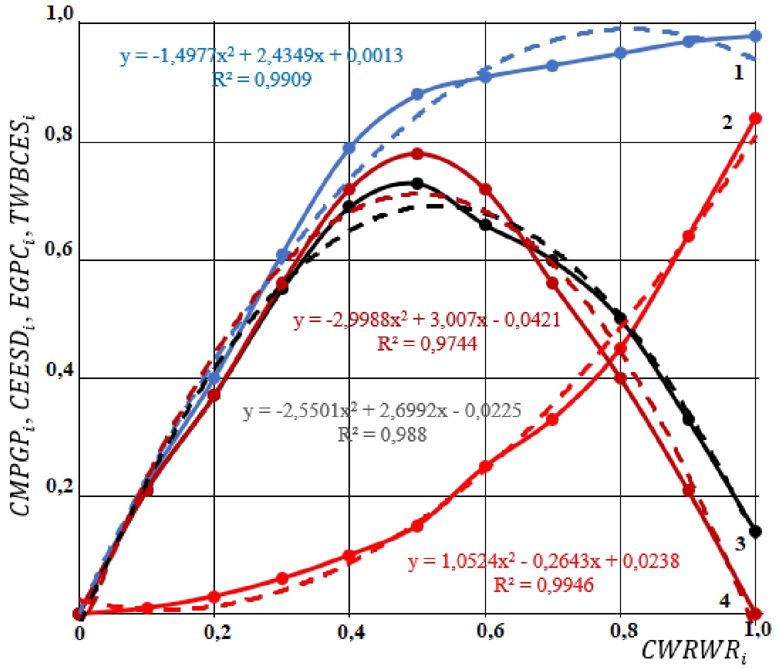

Figure 1. Applied model of economic activity of the catchment area of the Chu River basin (1 - coefficient of the maximum possible gross product of the catchment area of the river basins ($CMPGP_i$); 2 - coefficient of environmental, economic and social damage ($CEESD_i$); 3 - coefficient of the expected gross product of the catchment area of the river basins ($EGPC_i$); 4 - theoretical curve of well-being of the economic situation ($TWBCES_i$).

The coefficient of hydrological-ecological activity ($HEARB_i$) and the coefficient of expected gross product ($EGPC_i$) or economic activity ($EARB_i = EGPC_i$) of the catchment area of river basins are specific values that allow them to be determined by calculations based on official statistical data using a detailed structured procedure that allows, based on the contribution of each indicator, to determine the coefficient of maximum permissible withdrawal of renewable water resources ($CMPWRWR_i$) for human economic activity: $CMPWRWR_i = f(HEARB_i, EARB_i)$.

Thus, the mathematical model of the coefficient of maximum permissible withdrawal of renewable water resources ($CMPWRWR_i$) allows us not only to obtain an equation for determining the volume of maximum permissible withdrawal of renewable water resources ($MPWVRWR_i$), but also for the volume of environmental flow (VEF_i):

$$MPWVRWR_i = CMPWRWR_i \cdot VRWR_i; \qquad (41)$$

$$VEF_i = (1 - CMPWRWR_i) \cdot VRWR_i = EFVC_i \cdot VRWR_i, \qquad (42)$$

The mathematical model of the coefficient of maximum permissible withdrawal of renewable water resources ($CMPWRWR_i$) is extremely complex and requires the use of graphical - analytical and analytical solution methods.

The essence of the graph - analytical method for determining the coefficient of maximum permissible withdrawal of renewable water resources ($CMPWRWR_i$), which are a function of economic activity ($EARB_i$) and hydrological-ecological activity ($HEARB_i$) of the catchment area of river basins, is as follows. Initially, when constructing graphs in one Cartesian system, one should first construct a graph of the complex function of ecological activity ($EARB_i$), which has a bell - shaped form and is approximated by a quadratic equation:

$$EGPC_i = EARB_i = -2{,}5501 \cdot CWRWR_i^{\,2} + 2{,}6992 \cdot CWRWR_i - 0{,}0225. \qquad (43)$$

Next, it is necessary to construct a graph of the hydrological-ecological activity function ($HEARB_i$) having the following form: $HEARB_i = (1 - ESRB_i) \cdot AAWCC_{maxi} + ESRB_i \cdot AAWCC_{mini}$or $HEARB_i = (1 - ESRB_i) \cdot CAARV_{maxi} + ESRB_i \cdot CAARV_{mini}$, which, depending on the level of adopted ecological - economic - social decisions, will move along the ordinate axis, intersecting the bell - shaped form of the economic activity function in two places, dividing them into different areas (Figure 2).

In this case, the abscissas of the intersection points of the bell - shaped curves A $(EARB_i, CWRWR_i)$will B $(EARB_i, CWRWR_i)$be the roots of the quadratic equation $EARB_i = -2{,}5501 \cdot CWRWR_i^{\,2} + 2{,}6992 \cdot CWRWR_i - 0{,}0225$, where the maximum value of the coefficient of withdrawal of renewable water resources ($CWRWR_{maxi}$) will be equal to the coefficient of maximum permissible withdrawal of renewable water resources ($CMPWRWR_i$).

The analytical method for determining the coefficient of maximum permissible withdrawal of renewable water resources ($CMPWRWR_i$) is based on the classical approach to solving a three - term quadratic equation based on the root formula and Vieta's theorem.

Based on the joint solution of the functions of the coefficient of hydrological-ecological activity ($HEARB_i$) and ecological activity ($EARB_i$)using the root formula, it is possible to determine the coefficient of maximum permissible withdrawal of renewable water resources ($CMPWRWR_i$).

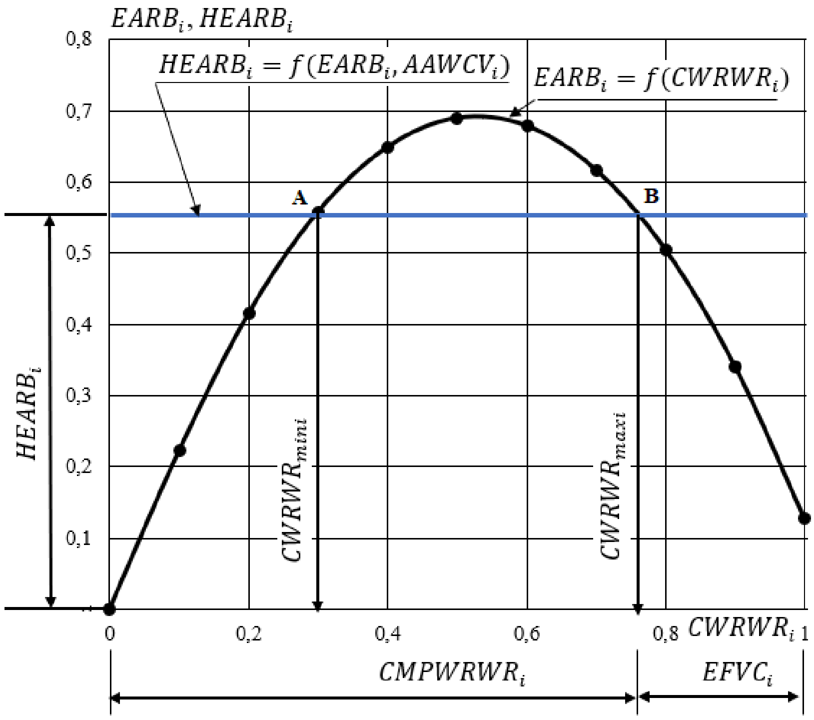

Figure 2. Graphical - analytical determination of the coefficient of maximum permissible withdrawal of renewable water resources ($CMPWRWR_i$) and the volume of environmental flow ($EFVC_i$)

The starting point for establishing the coefficient of maximum permissible withdrawal of renewable water resources ($CMPWRWR_i$) is the design value of the coefficient of hydrological and ecological activity ($HEARB_i$) adopted on the basis of the strategy and tactics of environmental protection activities in the catchment area of river basins, which is numerically equal to the coefficient of ecological activity ($EARB_i$). In this case, the basic three - term quadratic equation $Y = a \cdot X^2 + b \cdot X + c$ in a particular case has the following form: $EGPC_i = EARB_i = -2{,}5501 \cdot {CWRWR_i}^2 + 2{,}6992 \cdot CWRWR_i - 0{,}0225$ with constant coefficients a = - 2.5501, b = 2.6992, c = - 0.0225 and $Y = EGPC_i = EARB_i = HEARB_i$= 0.5500.

Then, the three - term quadratic equation for determining the coefficient of maximum permissible withdrawal of renewable water resources ($CMPWRWR_i$) will take the following form:

$$HEARB_i = a \cdot {CWRWR_i}^2 + b \cdot CWRWR_i + c \quad \rightarrow$$
$$a \cdot {CWRWR_i}^2 + b \cdot CWRWR_i - (c + HEARB_i) = 0 \rightarrow$$
$$a \cdot [CWRWR_i + (b/2 \cdot a)]^2 - \{[b^2 - 4 \cdot a \cdot (c + HEARB_i)]/4 \cdot a\} \rightarrow$$
$$a \cdot [CWRWR_i + (b/2 \cdot a)]^2 = \{[b^2 - 4 \cdot a \cdot (c + HEARB_i)]/4 \cdot a\} \rightarrow$$
$$[CWRWR_i + (b/2 \cdot a)]^2 = \{[b^2 - 4 \cdot a \cdot (c + HEARB_i)]/4 \cdot a^2\}. \qquad (44)$$

Since the left side of the last expression is non - negative, then in order for the equation to have roots, it is necessary and sufficient that the right side is also non - negative, and this is possible only in the case when the number $D = [b^2 - 4 \cdot a \cdot (c + HEARB_i)]$, the so - called discriminant of a quadratic equation, is greater than or equal to zero, then the quadratic equation will take the following form:

$$CWRWR_i + (b/2 \cdot a) = \pm\sqrt{\{[b^2 - 4 \cdot a \cdot (c + HEARB_i)]/4 \cdot a^2\}} \rightarrow$$

$$CWRWR_i = -(b/2\cdot a) \pm \sqrt{\{[b^2 - 4\cdot a\cdot (c + HEARB_i)]/4\cdot a^2\}} \rightarrow$$
$$CWRWR_i = -(b/2\cdot a) \pm \sqrt{[b^2 - 4\cdot a\cdot (c + HEARB_i)]}/2\cdot a \rightarrow$$
$$CWRWR_i = \{-b \pm \sqrt{[b^2 - 4\cdot a\cdot (c + HEARB_i)]}\}/2\cdot a \rightarrow$$
$$D = \sqrt{[b^2 - 4\cdot a\cdot (c + HEARB_i)]} \rightarrow$$
$$CWRWR_i = \left(-b \pm \sqrt{D}\right)/\ 2\cdot a. \quad (45)$$

Thus, equation (35) as an equation for the coefficient of economic and ecological activity of the catchment area of river basins ($EGPC_i = EARB_i$) reflects the following properties:

- $CWRWR_{si} = -b/2\cdot a = -2{,}6992/2\cdot(-2{,}5501) = 0{,}5292$ – the axis of symmetry of the bell - shaped curves characterizing the economic and environmental activity of the catchment area of river basins (Figures 2);

$$EGPC_i = EARB_i = (4\cdot a\cdot c - b^2)/4\cdot a =$$
$$=[4\cdot(-2{,}5501)\cdot(-0.0225) - 2{,}6992^2]/4\cdot(-2{,}5501) =$$
$$= (0{,}2295 - 7{,}2857)/(-10{,}2004) = 0{,}692$$

- the top of the bell - shaped curves characterizing the economic and environmental activity of the catchment area of river basins (Figure 2);

- $D = \sqrt{[b^2 - 4\cdot a\cdot (c + HEARB_i)]} = \sqrt{2{,}6992^2 - 4\cdot 1{,}4599} = \sqrt{2{,}6992^2 - 4\cdot 1{,}4599} = \sqrt{7{,}2857 - 5{,}8397} = \sqrt{1{,}4460} = 1{,}2025$ – discriminant of a quadratic equation characterizing the economic and environmental activity of the catchment area of river basins;

- the abscissa of the intersection points of the bell - shaped curves, characterizing the ecological and economic activity of the catchment area of the river basins with the axis $CWRWR_i$ is the root of a square trinomial:

$CWRWR_{mini} = (-b + \sqrt{D})/2\cdot a = (-2{,}6992 + 1{,}2005)/(-5{,}1002) = 0{,}2935$ and $CWRWR_{maxi} = (-b - \sqrt{D})/2\cdot a = (-2{,}6992 - 1{,}2005)/(-5{,}1002) = 0{,}7646$ (Figure 2).

Therefore, the maximum permissible volume of water resource withdrawal from river basins will be the maximum value of the abscissa according to the points of intersection of the Pythagorean bell-shaped watershed curves, which represent the economic activity ($CWRWR_{maxi}$), characterizing the irreversible ecological period, then the environmental flow ($EFVC_i$) will be equal to: $EFVC_i$ =1 - $CWRWR_{maxi}$= 1 – 0, 7646 =0,2354.

To determine an integrated assessment of the maximum permissible withdrawal of renewable water resources in river basin catchment areas, a system of indicator metrics has been developed, presented as mathematical models of hydrological, ecological, and economic activity coefficients. Each coefficient characterizes a specific aspect of the quantitative or qualitative state of the natural environment surrounding humans and can be used to manage environmental safety and rational nature management.

The key features of the proposed relationship between the hydrological-ecological and economic activity coefficient ($HEARB_i, EARB$) and the extraction of renewable water resources ($CWRWR_i$) are that, for minor impacts on the water intake area of river basins, its response is disproportionately small (due to adaptation); then, the impact is proportional to the impact; and finally, for very strong impacts that destroy the natural system of river basins, their further increase has little effect on the degradation process. The proposed methodology for assessing the maximum permissible withdrawal of renewable river flow and the magnitude of environmental flow release within river basin catchment areas is based on a developed mathematical model of economic activity described by a logistic curve in the form of a quadratic equation, as well as on a model of hydrological and ecological activity represented by a system of multiparameter linear equations. These models reflect the laws, principles, rules, and hypotheses of environmental management science and are consistent with the requirements of existing regulatory documents governing environmental quality standards.

4. CONCLUSION

The proposed methodology for assessing the maximum permissible withdrawal of renewable water resources and environmental flow within river basin catchment areas is distinguished by its basis in that it is based on a developed mathematical model of economic activity, described by a logistic curve in the form of a quadratic equation, and hydrological and ecological activity, represented by a system of multiparameter linear equations reflecting the laws, principles, rules, and hypotheses of environmental science, as well as current regulatory documents on environmental performance standards.

The analysis and assessment of the regulation of maximum permissible irreversible withdrawal of river flow and environmental flow release in the basin of the transboundary Shu River showed that they are based on indicators of the territorial organization of water use, grounded in the fundamental principles of environmental management. At the same time, the catchment area is considered not only as a spatial basis of the natural environment surrounding humans, but also as a tool for managing economic activity within the framework of the sustainable development triad: ecology (ensuring the quality of the human living environment), economy (increasing the level of economic development and purchasing power of society), and society (improving the well-being of the population).

Updating the methodological provisions предусматривает consideration of climatic, hydrological, hydrochemical, and water management changes under conditions of global climate change, as well as their impact on the values of maximum permissible river flow withdrawal and environmental flow release. This is aimed at ensuring sustainable conditions for the development and functioning of river basin ecosystems that perform important environment-forming and ecological functions.

DATA AVAILABILITY

The data used in this study were obtained by the authors from the following sources: data from Hydrological Yearbooks («Resources...» and the State Water Cadastre), as well as materials from state statistical collections.

AUTHORS' CONTRIBUTION

Conceptualization – ZhM; resources - KM; formal analysis – KM ; methodology - ZhM; software - KM; supervision - ZhM; visualization – KM; writing -original draft preparation – ZhM; writing—review and editing - KM .

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ӨЗЕН АҒЫНЫ МЕН ЭКОЛОГИЯЛЫҚ АҒЫННЫҢ ЕҢ ЖОҒАРЫ РҰҚСАТ ЕТІЛГЕН АЛУ КӨЛЕМІН КЕШЕНДІ БАҒАЛАУ ӘДІСТЕМЕСІН ӘЗІРЛЕУ

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ТҮЙІН СӨЗДЕР

су ресурстары, өзен алабы, ағынның қайтымсыз тартылуы, экологиялық ағын, квадрат теңдеу, әдіснама.

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АБСТРАКТ

Өзен ағынының шектілген-мүмкіншілік шегін және экологиялық ағынының шамасын бағалау мәселесін шешуге арналған қазіргі кездегі замуани тәсілдің айрықша ерекшеліктері, ол су ағынын пайдалану сипаты мен ауқымының табиғи ортаға әсерін, сондай-ақ олардың өзеннің су жинау алқабтарының аймақтарындағы экологияға, экономикаға және әлеуметтік жағдайына әсерін бағалау болып табылады. *Зерттеудің мақсаты* - геоэкологиялық шектеулердің талаптарын ескере отырып, өзен ағынының шектілген-мүмкіншілік шегін және экологиялық ағынының шамасын бағалаудың әдіснамалық тәсілін әзірлеу. *Зерттеу мәліметтері мен әдістері*. Зерттеу әдіснамасы өзен алқабының су жинау аймақтарының гидрологиялық, экологиялық және экономикалық белсенділігінің математикалық модельдерін әзірлеуге негізделген осы мәндердің көрсеткіштерін негіздеудің екі тәсілін қамтиды. Жұмыста Қазақстан Республикасы мен Қырғыз Республикасының мемлекеттік ұйымдарының статистикалық деректері пайдаланылды. *Нәтижесі.* Өзен алабының табиғи және техногендік жүргілерінің модельдерін құруға негізделген өзен ағынының шектілген-мүмкіншілік шегін және экологиялық ағынының шамасын реттеудің жалпы қағидасы, сынақтық көрсеткіштері және мөлшерлеудің әдістері ұсынылған. Нақты өзен алабтары үшін шектілген-мүмкіншілік шегін және экологиялық ағынының шамасын бағалаудың есептеудің шеңберінде тексерудің алгоритмі ұсынылған. *Қорытынды*. Математикалық модельдерді пайдалану гидрологиялық, экологиялық және экономикалық тұрғыдан тереңірек негіздеуге мүмкіндік береді, бұл өзеннің сужинау аймақтарындағы әлеуметтік-экологиялық жағдайды жақсартуға ықпал етеді.

РАЗРАБОТКА МЕТОДОЛОГИИ ИНТЕГРАЛЬНОГО ОЦЕНИВАНИЯ ОБЪЕМА ПРЕДЕЛЬНО-ДОПУСТИМОГО ИЗЪЯТИЯ РЕЧНОГО И ПРОПУСКА ЭКОЛОГИЧЕСКОГО СТОКА

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КЛЮЧЕВЫЕ СЛОВА

водные ресурсы, речной бассейн, безвозвратное изъятие стока, экологический сток, квадратное уравнение, методология.

АБСТРАКТ

Отличительными чертами современного подхода к решению задачи оценки предельно допустимого изъятия речного стока и попуска экологического стока являются учет влияния характера и масштабов использования водных ресурсов на природную среду, а также оценка их воздействия на экологию, экономику и социум на территории водосборов речных бассейнов. *Цель исследования* заключается в разработке методического подхода к оценке предельно допустимого изъятия речного стока и попуска экологического стока с учетом

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требований геоэкологических ограничений. *Материалы и методы исследования*. Методология исследования включает два подхода к обоснованию объемов указанных величин, основанных на разработке математических моделей гидролого-экологической и экономической активности территорий водосборов речных бассейнов. В работе использовались статистические данные государственных организаций Республики Казахстан и Кыргызской Республики. *Результаты.* Предложены общие принципы, критерии, параметры и методы нормирования предельно допустимого изъятия речного стока и попуска экологического стока, базирующиеся на моделировании природных и антропогенных процессов в речных бассейнах. Приведен алгоритм апробации в рамках расчетов нормативов допустимого воздействия для конкретных речных бассейнов. *Выводы*. Использование математических моделей позволяет провести более углубленное гидролого-эколого-экономическое обоснование, способствующее улучшению социально-экологической обстановки на территории водосборов речных бассейнов.