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Application of bank protection structures for regulation of channel processes in the lower reaches of the Shu River

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ABSTRACT

The article presents the application of bank protection structures for regulating channel processes in the lower reaches of the Shu River under conditions of high hydrological variability. The analysis is based on long-term hydrological observations conducted at the Tashutkul (Tasotkel) hydrological station over the period 1967–2022. A statistical assessment of annual maximum and mean discharges, including measures of variability, skewness, and exceedance probability, revealed the occurrence of rare but extreme flood events that significantly influence channel deformation and bank erosion in reaches composed of sandy–gravel alluvial deposits. A probabilistic hydrological analysis was applied to justify the design hydraulic loads acting on river training structures. Based on the identified hydrological and morphological risks, an improved prefabricated modular floating bank protection spur was developed for river engineering and channel regulation. The proposed structure provides adjustable permeability, promotes flow energy dissipation, and reduces local scour intensity under different flow conditions. The obtained results may be applied in the design and operation of adaptive bank protection structures for the lower reaches of the Shu River and other rivers characterized by pronounced channel instability and hydrological variability.

Keywords: bank protection spur; erosion protection; river channel regulation; polyethylene beams; hydraulic structure; prefabricated modular structure; flood regulation; hydrological variability; discharge exceedance probability.

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Introduction

Erosion of riverbanks and changes in river channels under the influence of natural and anthropogenic factors represent one of the pressing issues in hydraulic engineering and environmental protection [[1], [2]]. Bank washout, soil collapse, and alterations in river course pose threats to infrastructure, agricultural lands, settlements, and aquatic ecosystems [3]. Under conditions of floods, high water events, and sudden water level fluctuations, traditional bank protection structures, such as levees, embankments, and concrete constructions, often prove insufficiently effective, and their construction requires significant time, financial, and material resources [[4], [5]].

The relevance of this research is driven by the high variability of runoff in Central Asia, frequent floods, and anthropogenic river regulation, which create significant risks to the safety of hydraulic structures and the stability of riverbank zones [[1], [3], [5], [6]]. Modern approaches to the design and construction of bank protection structures include the use of modular and permeable constructions capable of adapting to changing hydrological conditions, reducing flow velocity in the near-bank zone, and decreasing the intensity of erosion [[7], [8], [9]].

When addressing the durability and reliability of hydraulic and land-reclamation structures, particular attention is paid to improving design, implementing new, more environmentally friendly and cost-effective bank protection technology structures, and developing methods for their hydraulic justification [[10], [11]]. Such structures are characterized by good construction qualities, relative simplicity of installation, and cost efficiency; they integrate harmoniously into the bank zone of any water body and reliably protect it from negative natural and anthropogenic impacts. They can be used both for permanent bank protection and for emergency interventions in critical situations [[8], [12]].

The Zhambyl region is classified as a medium-risk area due to the potential occurrence of floods in the region. A preliminary assessment of flood-prone areas in the country is based on data from RSE «Kazhydromet», including snow reserves, precipitation, autumn soil moisture, soil freezing depth, and river ice conditions. In the event of floods, water may pose a threat to settlements in the Moyynkum, Sarysu, Zhambyl, Shu, Merken, Talas, Korday, Ryskulov, Baizak, and Zhualyn districts. Flooding during the flood-prone period and in the residential area of Tekturmas in Taraz is characteristic [2].

Some flood-related emergencies in the Zhambyl region, reported on regional websites of the Republic of Kazakhstan, in chronological order, include:

- March 27, 2017: Due to increased snowmelt in the mountainous area and higher inflow into the Ters-Ashybulaq Reservoir, there was a risk of washout of the roadway of the «Western Europe–Western China» highway in the Zhambyl district. Additionally, 15 dacha plots and 1 residential house in a dacha settlement, as well as areas in the village of Baiterek, were at risk of flooding. Water levels rose up to 25 centimeters.
- April 2017: In the Talas district, flooding from Lake Akkol caused inundation of the local «Akkol–Usharal» road.
- February 2018: Heavy rainfall, rapid snowmelt, and half-meter soil freezing led to the formation of hillside runoff, resulting in the flooding of 30 yards in three settlements in the Turar Ryskulov district.
- May 20, 2021: Due to heavy rainfall, yard areas in the villages of Ornek, Mamai-Kayindy, and Akyrtobe of the Ryskulov district were flooded. In total, 11 yard areas were flooded, with water levels ranging from 10 to 30 centimeters. Additionally, a local automobile bridge at the entrance to the village of Salimbay in the Ornek rural district was partially damaged.
- February 2023: Due to a sudden warming in the region and its foothill areas, intense snowmelt caused flooding in 11 settlements across four rural districts and in Taraz. Emergency response efforts to combat flooding in the villages of Merken, Tyskulov, Shu, and Zhualyn districts continued for four days.
- July 7, 2024: In the city of Zhanatas, Sarysu district, heavy rainfall caused the formation and passage of hillside runoff along Bayseitova, Ayapova, Yeseeva, Kurmangazy, and Klochkova streets. According to the akimat, more than 200 yard areas and 21 houses located in the foothill area were flooded as a result of the emergency.

The flood period can be complicated by a sudden rise in air temperature, which, in turn, can lead to intensive snowmelt in mountainous areas. The examples considered illustrate the types of natural disasters and enormous losses caused by spring floods on rivers. The only solution is timely preparation to prevent natural catastrophes and mitigate their consequences.

During potential flood periods, particular attention should be paid to existing hydraulic structures in the region (Figure 1). In the Zhambyl region, there are 142 hydraulic structures in operation: 84 reservoirs, 2 dams, 11 hydroelectric complexes, and 44 ponds. These structures are owned by the state, municipal authorities, and private entities.

Figure 1 - Tashutkul Dam with the Right-Bank and Left-Bank Regulators

Analysis shows that hydraulic structures in the region require special attention during the flood-prone period. In the Zhambyl region, there are 142 hydraulic structures in operation: 84 reservoirs, 2 dams, 11 hydraulic complexes, and 44 ponds, which are owned by the state, municipal authorities, and private entities [[1], [3]]. Thus, the relevance of this study lies in the need for a comprehensive assessment of hydrological conditions affecting river channels and bank erosion, as well as in the justification for the use of adaptive bank protection structures capable of effectively regulating channel processes and safeguarding coastal areas.

Experimental part

The methodological basis of this study is a comprehensive statistical analysis of long-term series of annual maximum discharges of the Shu River at the «Tashutkul» hydrological station for the period 1967–2022. The primary aim of the analysis is to determine the statistical characteristics of runoff distribution, assess its variability, identify extreme values, and construct theoretical and empirical exceedance probability curves, which are essential for the design of hydraulic structures and water resources planning.

The calculation of runoff module coefficients, reflecting the ratio of the actual annual discharge to the long-term mean discharge, is expressed as:

$$k_i = Q_i / Q_{mean} \tag{1}$$

The empirical exceedance probability for each discharge value in the ranked series of observations is determined as:

$$\mathrm{P} = \frac{m}{n+1} * 100\% \tag{2}$$

The correctness of the calculations is verified using the following conditions:

$\sum K_i \approx n; \sum (K_i - 1) \approx 0$, with a maximum allowable error of 0.3–0.5%.

Based on the obtained values, the biased coefficients of variation $\left(\tilde{C}_v\right)$ and skewness $\left(\tilde{C}_s\right)$ are calculated:

$$\tilde{C}_v = \sqrt{\frac{\sum_{i=1}^{n}(K_i - 1)}{n-1}} \tag{3}$$

$$\tilde{\mathrm{C}}_s = \frac{\mathrm{n} \cdot \sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{K_i} - 1)^3}{(\mathrm{n}-1)\cdot(\mathrm{n}-2)\cdot\tilde{\mathrm{C}}_{\mathrm{v}}^3} \tag{4}$$

The adequacy of the observation series is assessed using relative errors:

$$\varepsilon_Q = \frac{C_v}{\sqrt{n}} \cdot 100\% \tag{5}$$

$$\varepsilon_{\mathrm{C_v}} = \sqrt{\frac{1+\mathrm{C}_{\mathrm{v}}^1}{2\cdot\mathrm{n}}} \cdot 100\% \tag{6}$$

The length of the observation series is considered sufficient for the determination of the mean annual discharge Q_{mean} and the biased coefficient of variation $\tilde{C}_v$, if $\varepsilon_Q \leq 5 - 10\%$, and $\varepsilon_{C_v} \leq 10 - 15\%$. hus, the observation series for the period 1967–2022 is regarded as sufficient for estimating the mean annual runoff Q_{mean} and the coefficient of variation.

To construct theoretical exceedance probability curves, the calculated coefficients of variation and skewness for the three-parameter gamma distribution and the binomial distribution are used, with coefficients $a_1, \ldots, a_6$ and $b_1, \ldots, b_6$ selected in accordance with the ratio *$C_s/C_v=2$* and the lag-1 autocorrelation coefficient *$r(1)=0.4$.* The autocorrelation between adjacent terms of the series is calculated using the following formula:

$$r(1) = \frac{\sum_{i=1}^{n-1}(Q_i - \bar{Q}_1)\cdot(Q_{i+1} - \bar{Q}_2)}{\sqrt{\sum_{i=1}^{n}(Q_i - \bar{Q}_1)^2 \cdot \sum_{i=1}^{n-1}(Q_{i+1} - \bar{Q}_2)^2}} \tag{7}$$

Results and Discussion

The results of the study are structured to consistently link the hydrological conditions of the Shu River with the engineering measures aimed at regulating channel processes and protecting riverbanks from erosion. First, the results of the statistical analysis of maximum river discharges are presented, which characterize the hydrological loads governing channel deformation and bank erosion in the lower reaches of the river. Second, based on the identified hydrological and channel-forming conditions, the applicability of a modular floating permeable groyne is substantiated as an adaptive bank protection structure.

1. Statistical Processing and Hydrological Assessment of Maximum Discharges. Analysis of the chronological series of maximum annual discharges of the Shu River at the Tashutkul hydrological station for the period 1967–2022 reveals significant fluctuations in runoff, indicating a high variability of the hydrological regime (Figure 2). During the analyzed period, the minimum maximum discharge was recorded in 1992 at 102 m^3/s, while the

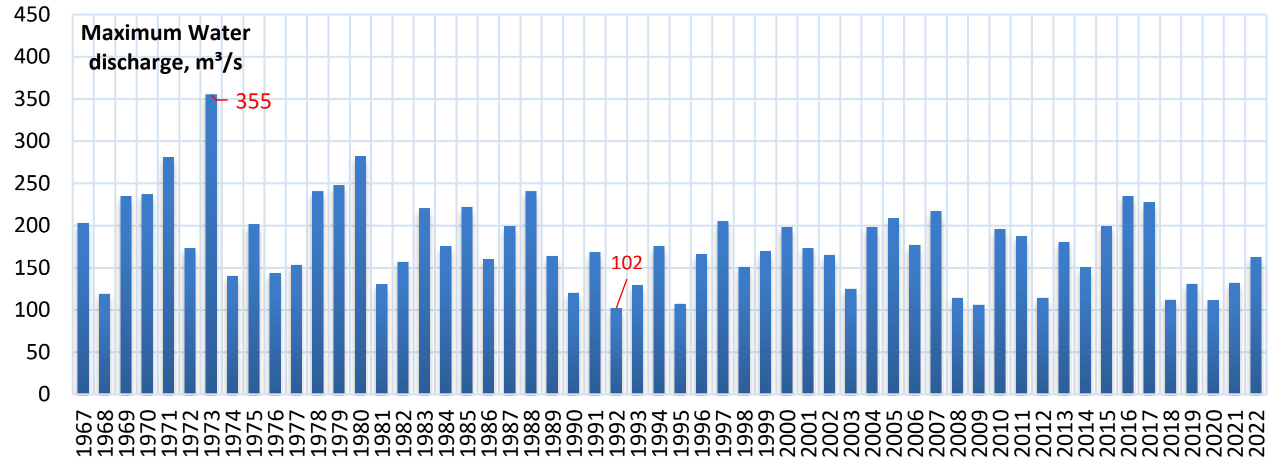


Figure 2 - Chronological series of annual maximum discharges of the Shu River at Tashutkul (1967–2022)

maximum occurred in 1973, reaching 355 m³/s, which is almost four times higher than the minimum value. This extreme reflects the impact of an exceptionally wet year and highlights the significant instability of runoff in the lower reaches of the river. Between 1967 and 1981, maximum discharges showed a stable increasing trend: starting at 203 m³/s in 1967, the values rose to 355 m³/s in 1973. From 1974 to 1981, relatively moderate and fluctuating values were observed (130–282 m³/s), which may be associated with alternating dry and wet periods.

Between 1982 and 1994, maximum discharges decreased, peaking at 240 m³/s in 1988 and reaching a minimum of 102 m³/s in 1992, indicating a prolonged dry period at the end of the 20th century. From 1995 to 2001, maximum discharges increased again, reaching 132 m³/s in 2005; after 2002, maximum discharge values remained high but exhibited pronounced variability (68–287 m³/s), reflecting changing climatic conditions and the influence of anthropogenic factors on the river's flow regime.

The high interannual variability of maximum discharges of the Shu River has important practical implications: it must be considered in the design and operation of hydraulic structures, planning of irrigation systems, flood preparedness, and water resource management. Analysis of extreme values allows for the assessment of the probability of rare but potentially hazardous hydrological events and enhances the reliability of engineering solutions.

To assess the homogeneity of the maximum annual discharges of the Shu River at the Tashutkul hydrological station for the period 1967–1994, the t and F statistical tests were applied. The series of maximum discharges was examined for systematic differences and stability of variance between data subseries.

The t-test showed that the calculated value of t was 1.4109, while the critical tabular value at a significance level of 0.05 is ±2.006. Since the calculated value falls within the critical interval ($-2.006 < 1.4109 < 2.006$), the hypothesis of equality of means is not rejected. This indicates that there are no statistically significant differences in the average maximum discharges between the subseries of the dataset.

The F-test allows for the assessment of equality of variances between two subseries. The calculated F value was 1.523, which is less than the tabular value $F = 1.96$ at a 0.05 significance level. This confirms that the variances of the subseries do not differ statistically.

The results of both statistical tests indicate the homogeneity of the series of maximum discharges of the Shu River at the Tashutkul hydrological station for the analyzed period. The practical significance of this homogeneity lies in the possibility of using the series for further hydrological analysis, construction of exceedance probability curves, calculation of extreme discharges, and the design of hydraulic structures without the need for adjustments. Stability of the statistical characteristics of the series ensures the reliability of engineering calculations and water management planning.

Based on long-term observations of maximum annual discharges of the Shu River at the Tashutkul hydrological station for 1967–2022, statistical processing was performed using the method of moments. The objective of the analysis is to assess the distribution of extreme discharges, construct the exceedance probability curve, and determine design values for various water management tasks.

The series of maximum discharges exhibits high interannual variability. The calculated parameters are as follows: mean maximum discharge Q_{mean} =179.5 m³/s, coefficient of variation $\tilde{C}_v = 0.4$, reflecting substantial year-to-year fluctuations in maximum runoff; skewness coefficient $\tilde{C}_s = 0.9$, indicating a right-skewed distribution, i.e., the presence of individual years with extremely high discharges. The analysis shows that the river is subject to rare but powerful floods, with several high extreme years (e.g., 1973 - 355 m³/s, 1971 - 281 m³/s, 1980 - 280 m³/s) significantly influencing the mean value and shape of the distribution.

Using the module coefficients k_i , an empirical exceedance probability curve of maximum discharges was constructed. The curve was approximated using a three-parameter gamma distribution, allowing for the assessment of the hydrological reliability of extreme discharges. Comparison of the empirical and theoretical curves showed good agreement, confirming the reliability of the original observations, the correctness of the selected distribution model, and the suitability of the data for engineering design and water management planning.

Based on the constructed exceedance probability curve, design values of maximum discharge were determined for different exceedance probabilities: rare extreme events P ≤ 1 %): $Q_{0.1}$=415 m³/s; Q_1=332.6 m³/s; average conditions (P = 50%): Q_{50}=146 m³/s; minimum guaranteed extremes (P ≥ 95%): Q_{95}=68.97 m³/s. These values allow a quantitative assessment of the range of extreme maximum discharges and can be used for: the design of dams, reservoirs, and hydro complexes; calculation of channel and spillway capacities; and forecasting flood and high-water risks.

Assessment of interannual dependence of maximum discharges revealed a positive first-order autocorrelation *r(1)=0.4* in Figure 3. This indicates the inertia of the hydrological regime, where high or low maximum discharges tend to recur over several consecutive years. This feature is particularly important for long-term water management planning and forecasting of extreme floods. The method of moments confirmed the statistical reliability of the maximum discharge series: the variation and skewness indicators agree with empirical data, and the constructed theoretical exceedance probability curve allows the determination of design discharges for a wide range of probabilities.

After constructing the empirical exceedance probability curve of maximum discharges of the Shu River at the Tashutkul hydrological station, its correspondence with the theoretical curve was verified. The analysis showed that the empirical points generally agree well with the theoretical values, confirming the correctness of the calculated coefficients of variation and skewness of the series, as well as the reliability of the constructed empirical curve. This agreement demonstrates a strong correlation between observed and calculated discharges, providing a basis for water resources analysis, irrigation system planning, and assessment of risks associated with floods or water scarcity.

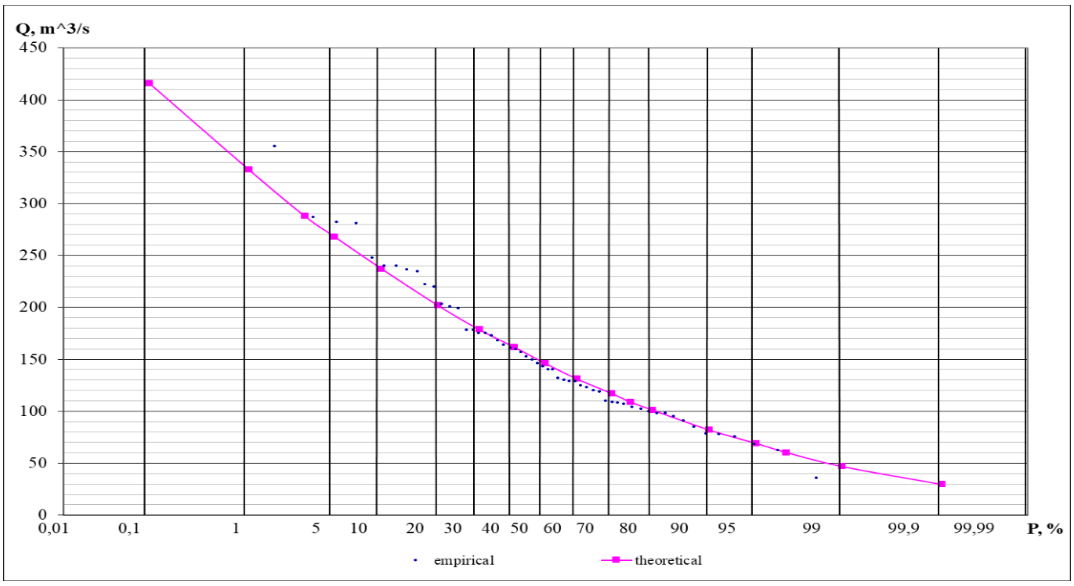


Figure 3 - Exceedance probability curve of annual maximum discharges of the Shu River

Table 1 - Theoretical exceedance probability curve values $C_v = 0.4$ and $C_s=2C_v$

Exceedance probability, *P* (%)	0.1	1	3	5	10	20	30	40	50
Modular coefficient, K_p	2.700	2.160	1.870	1.740	1.540	1.310	1.160	1.050	0.948
River discharge Q_p, m^3/s	415.7	332.6	287.9	267.9	237.1	201.7	178.6	161.7	146.0
Exceedance probability, *P* (%)	60	70	75	80	90	95	97	99	99.9
Modular coefficient, K_p	0.852	0.760	0.708	0.656	0.532	0.448	0.392	0.304	0.192
River discharge Q_p, m^3/s	131.17	117.01	109.00	101.00	81.91	68.97	60.35	46.80	29.56

The calculated ordinates of the exceedance probability curve and the corresponding maximum discharges for different exceedance probabilities are presented in Table 1.

The analysis of the hydrological regime of the Shu River confirms a pronounced interannual variability and significant asymmetry of maximum annual discharges, which indicates the presence of rare but powerful flood events exerting substantial influence on the statistical characteristics of runoff. Similar patterns have been identified for other river systems of Central Asia, where climate change and anthropogenic regulation intensify hydrological extremes and increase uncertainty in the estimation of design discharges [[1], [2], [3]]. Long-term observation series therefore remain a key prerequisite for reliable flood-frequency analysis and assessment of hydraulic structure reliability.

The obtained results demonstrate that, despite noticeable interannual fluctuations, the series of maximum annual discharges remains statistically homogeneous, which is consistent with conclusions reported in hydrological studies emphasizing the importance of multi-decadal datasets for engineering applications [[6], [7]]. The detected positive lag-1 autocorrelation indicates inertia in the hydrological regime, meaning that high-flow and low-flow conditions tend to persist over several consecutive years. Such behavior has been widely discussed in the context of flood risk assessment and should be explicitly considered when evaluating the safety margins of hydraulic engineering structures [[4], [10]]. The application of the method of moments and probabilistic exceedance curves based on the three-parameter gamma distribution proved effective for describing the distribution of extreme discharges. A good agreement between empirical and theoretical curves confirms the adequacy of the selected statistical model and supports its applicability for determining design discharges of various exceedance probabilities [13]. Similar probabilistic approaches have been successfully applied in climate impact assessments for river basins in Kazakhstan, demonstrating their robustness under conditions of increasing hydrological variability [[5], [14]].

The obtained design discharges for low exceedance probabilities (P ≤ 1–5%) indicate that hydraulic loads during extreme flood years may significantly exceed the design parameters of existing hydraulic structures, many of which were constructed based on outdated hydrological norms. This conclusion is consistent with recent studies highlighting increased flood risks and the need to revise design criteria for hydraulic structures under changing climatic conditions [[1], [4], [11]].

2. Improved Prefabricated Modular Floating Bank Protection Spur. An effective method for diverting floodwaters and providing flood protection is the rapid construction of prefabricated, demountable river-regulating structures. Such structures are widely used not only in emergency response situations but also as permanent regulators of local channel deformations. The application of a system of permeable spurs makes it possible to modify the river flow regime, reduce unit discharge, and decrease near-bank flow velocities, thereby transforming a wandering channel into a stable meandering one [8].

The permeable bank protection spur proposed by V.D. Shuminsky [9] is known to reduce erosion of riverbanks and improve flow energy dissipation efficiency through regulation of the structure’s porosity coefficient. In hydraulic engineering practice, the «Movable Bank Protection Spur» [15] is also used, maintaining its operational performance under varying hydrological conditions. Traditionally, such structures are installed from the riverbank at a specific angle to the flow and consist of an abutment (root), a main body, and a head section, which is subjected to the most intensive erosive forces. However, rigid fixed structures have several disadvantages: during ice drift, they reduce the effective ice passage width and act as partial dams [[16], [17]]; moreover, under variable water levels and flow velocities, they require excessive height and material consumption, being designed based on extreme maximum hydrological conditions [[8], [12]].

A more advanced type is the floating bank protection spur [18], which is capable of operating in both solid and permeable flow regimes. Its structural disadvantages include the need for preparatory works involving the placement of reinforced concrete blocks in the lower part of the structure, the complexity of installing stoppers and embedded components, which reduces the speed of assembly, as well as the circular surface of the pipes used, which increases flow slip and reduces transverse roughness [[9], [16]].

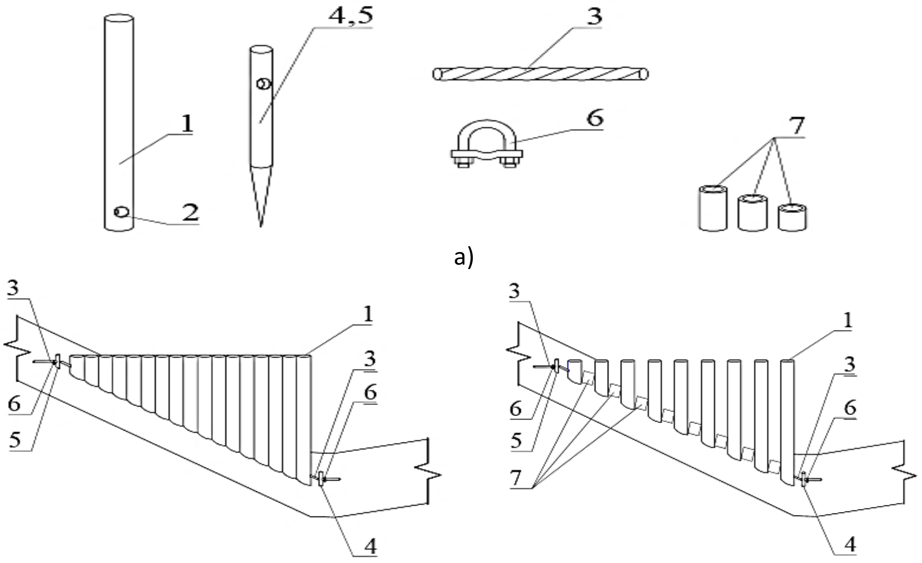
Based on an analysis of existing river-regulating and bank protection structures, as well as prefabricated floating bank protection spur systems, this paper presents the development of an improved prefabricated floating bank protection spur design that eliminates the identified shortcomings.

This is achieved through an improved prefabricated floating bank protection spur design, in which the upper part consists of hollow polyethylene beams with a cross-sectional size of 20 × 15 cm, hermetically sealed at the ends. The lower part of each beam is equipped with mounting holes through which the elements are installed onto a cable; one end of the cable is fixed to a driven metal stake using a fastening clamp or anchored, while the other end is secured to the bank after installation is completed. When operating in a permeable spur mode, polyethylene spacer bushings with the required degree of porosity are installed between the beams along the axis. The upper free part of the beams remains in a floating condition.

As a result of the improvement of the prefabricated floating bank protection spur, the upper part is replaced with polyethylene beams, while the lower part is freely mounted on a cable without a foundation base, which allows the structure's configuration to be adjusted depending on hydrological conditions and operating regimes.

An important advantage of the proposed spur is the ability to regulate its permeability through replaceable spacing elements. This enables flexible control of flow velocity, energy dissipation, and sediment transport downstream of the structure, ensuring effective performance under extreme flood events, medium discharges, and low-flow periods. Such adaptability significantly distinguishes the proposed design from traditional spurs and enhances its reliability under conditions of hydrological uncertainty [[15], [17]].

Overall, the integration of long-term flow analysis with adaptive engineering solutions provides a comprehensive approach to improving the reliability and safety of hydraulic structures. For transboundary river systems such as the Shu River, where climatic variability, upstream flow regulation, and increasing water resource demands jointly affect the hydrological regime, the combined application of probabilistic hydrological assessment and flexible bank protection structures is particularly well justified [[2], [11], [16], [18], [19], [20]].



a)

b) c)

a – Prefabricated elements of the improved modular floating bank protection spur: 1 – polyethylene beams, 2 – mounting holes, 3 – cable, 4,5 – metal stake, 6 – fastening clamp, 7 – polyethylene spacer bushings;
b, c – assembled solid and through versions of the improved modular floating bank protection spur.

Figure 4 - Improved modular floating bank protection spur

For the practical implementation of the proposed spur and the evaluation of its hydraulic performance, it is necessary to determine the principal structural and hydraulic parameters governing the interaction between the structure and the flow. The definition of the permeability coefficient follows the calculation methodology for combined permeable river training structures [21]. Owing to the different geometry of the proposed design, the original calculation relationships were adapted for a system of horizontally oriented polyethylene beams and adjustable spacer bushings.

The fundamental design parameter is the permeability (porosity) coefficient of the structure (P), defined as the ratio of the open (permeable) area of the structure to the total area of its frontal projection:

$$P = \frac{\omega_c}{\omega} = \frac{\omega_c}{\omega_b + \omega_c} \qquad (8)$$

where:

$$\omega_c = (d_1 + d_2 + \cdots + d_m) \cdot H \qquad (9)$$

$$\omega_b = (s_1 + s_2 + \cdots + s_n) \cdot H \qquad (10)$$

Here: $\omega_b, \omega_c, \omega$ - the areas occupied by the beams, the inter-beam openings, and the total frontal area of the structure, respectively, m^2; $s_1, s_2, \cdots, s_n$ - the frontal widths of the beams, m; $d_1, d_2, \cdots, d_m$ - the widths of the openings between the beams, which are adjustable through the length of the spacer bushings, m; n - the number of beams; m is the number of inter-beam openings $(m = n - 1)$; H - the design flow depth, m.

For a structure with uniformly spaced beams of equal width (s) and openings of equal width (d), Equation (8) can be simplified as follows:

$$P = \frac{d}{s+d} \qquad (11)$$

The permeability coefficient is related to the channel blockage coefficient by the following relationship:

$$P = 1 - P_b \qquad (12)$$

Adaptation of the proposed structure to different hydrological conditions is achieved by varying the length of the spacer bushings. For a polyethylene beam with a frontal width of $s = 0.20$ m, an opening width of d=0.20 m is adopted under mean-flow conditions ($Q_{50\%}$), corresponding to a permeability coefficient of P=0.50. Under extreme flood conditions ($Q_{1\%}$), the opening width is increased to d=0.30 m, resulting in a permeability coefficient of P=0.60 and a corresponding reduction in the hydrodynamic load acting on the retaining cable.

The flow velocity immediately downstream of the proposed permeable spur (V_p) is determined using the velocity coefficient φ, based on the analytical relationships reported in [22] and their subsequent nonlinear approximation using experimental datasets presented in [21]:

$$V_p = \varphi \cdot V_1 = [1{,}2 \cdot P^{0{,}4} \cdot (1 - P)^{0{,}1}] \cdot V_1 \quad (13)$$

where: φ - the dimensionless velocity coefficient of the permeable barrier accounting for turbulent head losses; P - the dimensionless permeability (porosity) coefficient of the spur flow section, determined by the length of the spacer bushings; V_1 - the approach flow velocity of the Shu River during the design flood corresponding to $Q_{1\%}$, m/s. The permeability coefficient P is related to the structural blockage coefficient P_b by the relationship $P_b = 1 - P$.

The kinematic structure of flow deformation downstream of permeable elements has been comprehensively investigated in the monograph [21]. Based on the experimental jet-contraction curves and the relationships between the geometric characteristics of the deformation zones, the channel blockage ratio (n), and the installation angle of the structure (α) presented therein, the authors of the present study performed an analytical approximation of the experimental datasets using the least-squares method in Microsoft Excel. The resulting regression equation (13) represents a local empirical model and is applicable within the investigated permeability range of $0.2 \leq P \leq 0.6$, which, according to the experimental conditions reported in [21] and the relationship between the coefficients, corresponds to blockage coefficients of $0.4 \leq P_b \leq 0.8$.

Statistical analysis of the long-term observational series (1967–2022) at the reference Tashutkul hydrological station showed that, under extreme conditions corresponding to the centennial flood discharge $Q_{1\%}$, the design mean flow depth is H= 2.5 m, while the mean approach velocity is V_1 = 1.8 m/s. Under these conditions, the proposed floating structure provides controlled flow velocity reduction downstream of the barrier. In the baseline operating mode at a permeability coefficient P=0.50

(blockage coefficient P_b = 0.50), the flow velocity downstream of the structure V_p decreases to 1.55 m/s (a reduction of 14%), while the kinetic energy of the flow is dissipated by up to 26%. In the extreme flood operating mode (P = 0.60, corresponding to P_b = 0.40), the velocity downstream of the spur is 1.61 m/s (a reduction of 11%), and the kinetic energy of the surface flow layer is effectively dissipated by 20%, which minimizes the risk of bank deformation in reaches composed of sandy–gravel deposits with particle sizes d_i= 1.0÷2.5 mm.

Based on experimental studies presented in [21], it has been substantiated that the velocity distribution in the zone of intense turbulent mixing follows the universal self-similar Schlichting–Abramovich law. The classical physical foundations of this relationship for channel flows are described in detail in [23]:

$$\frac{u-u_*}{u_{max}-u_*} = (1-\eta^{1.5})^2 \tag{14}$$

where: u - the local longitudinal flow velocity at the considered point in the downstream reach, m/s; u_* - the velocity of the co-flow penetrating through the permeable gaps of the bushings, m/s; u_{max} - the maximum velocity at the boundary of the core of the main (transit) flow; η - the dimensionless relative vertical coordinate of the investigated cross-section.

This theoretical justification enables the application of the classical velocity distribution law for numerical assessment of flow kinematics downstream of the proposed spur, thereby preventing the formation of hazardous secondary (reverse and unstable) flow structures.

Based on the maximum hydrodynamic loading during the extreme flood event $Q_{1\%}$ at the Tashutkul hydrological station, the peak longitudinal tensile force (T) acting on the supporting cable system was determined. In accordance with the requirements of the regulatory document SP RK 3.04-107-2014 [24], the longitudinal component of the flow force (N_w, kN) was adapted to the geometry of the permeable barrier of the proposed floating structural model:

$$T = N_w = 0.59 \cdot (b \cdot h_1) \cdot {V_1}^2 \cdot P_b \tag{15}$$

where: T - the distributed hydrodynamic load on the supporting steel cable, kN/m; N_w - the distributed longitudinal component of the flow force acting on the structure, kN/m; 0.59 - the hydrodynamic coefficient according to SP RK 3.04-107-2014 [24]; b - the frontal width of the polyethylene beam (0.20 m); h_1 - the design flood depth at the Tashutkul hydrological station cross-section (2.5 m); V_1 - the approach flood-flow velocity (1.8 m/s), which governs the loading on the cable as it is induced by the incoming flow; P_b - the dimensionless blockage (channel constriction) coefficient of the spur formed by the beams according to [21].

Substitution of field hydrological parameters of the Shu River under emergency extreme flood conditions (V_1 = 1.8 m/s), with a frontal projection area of the beam ($b \cdot h_1$) = 0.5 m², and a blockage coefficient in extreme conditions P_b = 0.40 (corresponding to a permeability coefficient P = 0.60), yields a peak distributed load on the supporting cable of T = 0.382 kN/m (or 382.3 N/m). The obtained hydrodynamic load characterizes the force exerted by the flow on the supporting system of the structure and may be used for subsequent structural design and selection of the retaining cable parameters.

The quantitative design assessment of the static and dynamic stability of the floating element in the river flow was performed based on the balance of vertical forces. The distributed buoyant force (F_A), N/m, was determined using the following expression:

$$F_A = \rho_v \cdot g \cdot (a \cdot b) \tag{16}$$

where: ρ_v - the water density (1000 kg/m³); g - the gravitational acceleration (9.81 m/s²); a and b - the geometric dimensions of the cross-section of the polyethylene beam (0.15 × 0.20 m). Substitution of the structural parameters yields a buoyant force under full submergence of F_A = 294.3 N/m. Considering the distributed self-weight load of the polyethylene beams together with the supporting cable (F_b = 65.0 N/m), the net static buoyancy reserve of the structure amounts to 229.3 N/m.

To assess the dynamic stability of the proposed structure under flood conditions, the associated vertical (downward) hydrodynamic force (Q_w), arising from the pressure difference and tending to press the floating barrier toward the riverbed, was calculated. The computation was performed in accordance with the regulatory provisions of SP RK 3.04-107-2014 [24] using the following expression:

$$Q_w = 0.59 \cdot A_1 \cdot {V_1}^2 \cdot P_b \tag{17}$$

where: A_1 - the lateral submerged projected area (sail area) of the submerged element per unit length of the structure, taken as $a \cdot 1$ = 0.15 m²; V_1 -

the approach flood-flow velocity of the Shu River at the design discharge $Q_{1\%}$, (1.8 m/s); P_b - the dimensionless blockage coefficient of the spur.

The obtained value of the hydrodynamic submerging force under the design permeability of the structure (P = 0.50, corresponding to a blockage coefficient P_b = 0.50) is:

$Q_w = 0.59 \cdot 0.15 \cdot (1.8)^2 \cdot (1 - 0.50) = 0.143$ kN/m or (143,4) N/m

A comparison between the dynamic submerging force and the net static buoyancy reserve shows that the restoring Archimedes forces exceed the destabilizing hydrodynamic forces by a factor of 1.6 (229.3/143.4 ≈ 1.6). This result indicates sufficient stability of the floating barrier and the maintenance of its stable operating position at the water surface even during the passage of a critical centennial flood with a 1% exceedance probability at the Tashutkul hydrometric station cross-section.

For a quantitative assessment of erosional channel processes beneath the proposed structure, the relationship of I.I. Levi for permeable systems was used to estimate the limiting depth of local scour H_{p} [[21], [25]]:

$$H_p = h_1 \cdot \left(\frac{V_p}{V_n}\right)^{1.2} \cdot {P_b}^{0,5} \qquad (18)$$

where: h_1 - the design flood depth at the Tashutkul hydrological station cross-section, m; V_p - the flow velocity immediately downstream of the permeable spur, m/s; V_n - the critical non-scouring velocity of the flow for the riverbed soils of the Shu River, m/s; P_b - the dimensionless blockage (constriction) coefficient of the structure formed by the beams.

The physical meaning of equation (18) lies in the modification of the classical erosional framework proposed by I.I. Levi through the introduction of a reducing dimensionless factor (${P_b}^{0,5}$). This coefficient accounts for the jet-like structure of the flow in the downstream reach and the reduction in unit discharge due to partial filtration of water through the regulated gaps between the spacer bushings of the proposed structure.

Downstream of the Tashutkul hydrological station, the riverbed of the Shu River consists of sandy–gravel alluvial deposits with a mean weighted sediment diameter of (d_i = 1.0–2.5) mm. For this type of soil and a flood depth of 2.5 m, the mean cross-sectional non-scouring velocity ranges from 0.85÷1.20 m/s. However, in the present study, the critical near-bed velocity corresponding to the initiation of sediment motion, equal to 0.55 m/s according to a verified methodology, was adopted as the design value of (V_n) in equation (18). Partial conveyance of flood discharge through the body of the proposed floating spur leads to a reduction in the calculated depth of the local scour hole at the structure head by 15–37% compared with solid prototype structures.

As shown in numerical hydrodynamic studies [26], localized flow velocities at the head of permeable spurs decrease due to nonlinear filtration processes. The proposed structure allows maintaining the permeability coefficient within the optimal range P = 0.50÷0.60 (corresponding to a blockage coefficient P_b = 0.50÷0.40). This ensures the «flattening» (spreading) of the near-bed vortex zone downstream of the barrier and increases the effective length of the protected riverbank to 4–10 times the length of the structure itself.

The sedimentation regime analysis within the spur cells was performed according to the regional methodology of «KRSU» for piedmont–plain conditions of the Shu River. The critical near-bed velocity at which transported sediments begin to deposit in the inter-spur space ($V_{i.s.}$, m/s) is determined using the relationship proposed by V.F. Talmaza [27], which has been thoroughly validated in studies of the Shu River [28]:

$$V_{i.s.} = 1{,}4 \cdot \frac{m-1{,}5}{m+1} \cdot \left(\frac{H_i}{d_i}\right)^{\frac{1}{m}} \cdot \sqrt{\frac{\gamma_n-\gamma_v}{\gamma_n} \cdot g \cdot d_i} \qquad (19)$$

where: m = 4 is the exponent describing the vertical velocity distribution for the considered reach; H - the design flood depth (2.5 m); d_i - the mean weighted diameter of sandy–gravel sediments (1.0–2.5 mm); γ_n and γ_v - the unit weights of bed sediments (26.5 kN/m³) and river water (10.0 kN/m³), respectively; g - the gravitational acceleration (9.81 m/s²).

Adjustment of the permeability of the proposed floating spur to the optimal range of 0.50÷0.60 (achieved through the selection of polyethylene spacer bushings) artificially reduces the local near-bank flood velocity V_p within the inter-spur zone to a level satisfying the sedimentation condition $V_p \leq V_{i.s.}$. This ensures stable and controlled accumulation of sandy–gravel material within the spur cells, prevents the formation of hazardous impinging flow conditions, and promotes natural aggradation and widening of the protected riverbank zone on the Kazakhstan side of the transboundary Shu River.

For an objective assessment of technical advancement and to substantiate the novelty of the

Table 2 – Comparative Assessment of the Hydraulic Performance of the Proposed and Prototype Bank Protection Spurs

Hydraulic and Structural Parameter	Floating Prototype (Rigid Sealed Pipes)	Proposed Modular Permeable Spur	Quantitative Assessment of Technical Advancement Based on Verification
Regulation of permeability (P)	Fixed (P ≤ 0.15)	Adjustable (P = 0.20÷0.60)	Adaptation to flood variability ranging from 50% to 1% exceedance probability in the Shu River
Flow velocity reduction coefficient (V_p/V_1)	Uncontrolled flow impingement and attachment	Reduction of flow velocity immediately downstream of the spur by 11–14%	Transformation of near-bank flow into a safe non-erosive regime ($V_p \leq V_{i.s.}$)
Degree of flow kinetic energy dissipation (E_k)	Intense local vortex formation at the head	Internal friction of split jets (energy dissipation of 20–45%)	Effective dissipation of kinetic energy within the permeable body of the spur
Local scour depth beneath the structure (H_p)	High (1,3 ÷1,5h_1)	Minimized (reduction of calculated scour depth by 32–37%)	Reduced risk of structural undermining; expansion of the protection zone up to 4–10 spur lengths (according to validated methodology [25])
Installation complexity and deployment rate	High (on-site welding and installation of heavy bed anchors required)	Low (modular assembly on a bank-mounted cable without heavy machinery)	High operational efficiency for emergency flood response conditions

claimed utility model, a comparative analysis of its characteristics with a baseline floating prototype made of rigid sealed pipes was conducted. The comparative evaluation, verified using external sources, is summarized in Table 2.

The implementation of the proposed engineering solution enables a transition from passive resistance to the dynamic impact of the river flow to active and controlled regulation of channel deformation processes. This makes the developed floating structure particularly suitable for bank protection in transboundary river basins (notably the Shu River), which are characterized by high variability of flood discharge and intensive anthropogenic flow regulation.

Conclusions

The study of channel processes in the lower reaches of the Shu River revealed pronounced interannual variability of river discharge, which intensifies bank erosion during extreme flood events. Based on long-term hydrological observations, design discharges corresponding to different exceedance probabilities were determined and used to justify the hydraulic loads acting on bank protection structures in accordance with the fundamental principles of hydrodynamics [23]. As an adaptive engineering solution, an improved prefabricated modular floating bank protection spur with adjustable permeability is proposed. Computational and theoretical analyses, together with a comparison with a conventional rigid prototype, confirmed its advantages in terms of structural stability, ease of installation, and overall hydraulic performance.

Based on the hydraulic justification of the structural parameters for the proposed spur at the Tashutkul hydrological station cross-section of the Shu River, the following conclusions were drawn:

1. It was established that varying the length of the polyethylene spacer bushings from 0.20 to 0.30 m allows the permeability coefficient of the structure to be adjusted within the range $0.50 \leq P \leq 0.60$, which, according to the relationship ($P_b = 1 - P$), corresponds to channel blockage coefficients of $0.40 \leq P_b \leq 0.50$. This enables the spur to adapt to both mean annual flow conditions ($Q_{50\%}$ = 146.0 m³/s) and extreme flood discharges ($Q_{1\%}$ = 332.6 m³/s).

Quantitative evaluation of the hydraulic performance showed that, at the baseline permeability coefficient P = 0.50, the proposed structure reduces the approach flood-flow velocity by 14% (from 1.80 to 1.55 m/s) and dissipates up to 26% of the flow kinetic energy. Under the extreme operating condition (P = 0.60), the flow velocity immediately downstream of the spur is reduced to 1.61 m/s, corresponding to a 20% reduction in the kinetic energy of the surface flow layer.

Partial conveyance of flood discharge through the permeable body of the spur reduces the intensity of local scour at the spur head by 15–37% compared with impermeable prototype structures. Redistribution of the flow structure increases the effective length of the protected riverbank to approximately 4–10 times the length of the structure itself.

Reducing the local near-bank velocity within the inter-spur zone to the condition ($V_p \leq V_{i.s.}$) creates favorable hydraulic conditions for the stable deposition of sandy–gravel sediments, prevents the formation of hazardous bank-attached currents, and promotes the natural accretion of the protected riverbank.

The calculated peak distributed hydrodynamic load acting on the supporting system is T = 382.3 N/m. At the same time, the net static buoyancy reserve of the polyethylene beams (229.3 N/m) exceeds the dynamic submerging force of the flow (143.4 N/m) by a factor of 1.6, thereby ensuring the stability of the floating structure. The calculated hydrodynamic load characterizes the force exerted by the flow on the supporting system and may be used for the subsequent structural design and selection of the retaining steel cable.

The obtained results confirm the potential of the proposed improved prefabricated modular floating permeable bank protection spur for river engineering applications, including bank protection and channel regulation in rivers characterized by high hydrological variability and intensive anthropogenic flow regulation.

Conflicts of interest. On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Шу өзенінің төменгі ағысындағы арналық процестерді реттеу үшін жағалауды қорғау құрылымдарын қолдану

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ТҮЙІНДЕМЕ

Мақалада гидрологиялық режимнің жоғары өзгергіштігі жағдайында Шу өзенінің төменгі ағысындағы арналық процестерді реттеу үшін жағалауды қорғау құрылыстарын қолдану мәселелері қарастырылған. Зерттеу 1967–2022 жылдар аралығында Ташуткөл (Тасөткел) гидробекетінде жүргізілген көпжылдық гидрологиялық бақылаулар деректеріне негізделген. Жылдық ең жоғары және орташа су шығындарына, олардың өзгергіштігіне, асимметриясына және қамтамасыз етілуіне жүргізілген статистикалық талдау сирек кездесетін, бірақ арнаның деформациясы мен құмды-қиыршықтасты шөгінділерден құралған жағалаулардың шайылуына елеулі әсер ететін экстремалды су тасқыны оқиғаларының бар екенін көрсетті. Арнаны реттейтін құрылыстарға әсер ететін есептік гидравликалық жүктемелерді негіздеу үшін ағындының ықтималдық талдауы қолданылды. Анықталған гидрологиялық және морфологиялық қауіптер негізінде инженерлік қорғау мен арналық процестерді реттеуге арналған жетілдірілген құрастырмалы-жиналмалы қалқымалы жағалауды қорғау шпорасының конструкциясы ұсынылды. Ұсынылған конструкция өткізгіштік дәрежесін реттеуге, ағын энергиясын бәсеңдетуге және әртүрлі ағыс режимдерінде жергілікті шайылу қарқындылығын төмендетуге мүмкіндік береді. Алынған нәтижелер Шу өзенінің төменгі ағысында және арналық процестері мен гидрологиялық режимі айқын тұрақсыз өзге де өзендерде бейімделгіш жағалауды қорғау құрылыстарын жобалау мен пайдалануда қолданылуы мүмкін.

Түйін сөздер: жағалауды қорғау шпорасы, шайылудан қорғау, арнаны реттеу, полиэтилен арқалықтары, гидротехникалық құрылыс, құрастырмалы-жиналмалы конструкциясы, су тасқынын реттеу, гидрологиялық өзгермелілік, су шығынының қамтамасыз етілуі.

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Применение берегозащитных сооружений для регулирования русловых процессов реки Шу в нижнем течении

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АННОТАЦИЯ

В статье рассмотрено применение берегозащитных сооружений для регулирования русловых процессов в нижнем течении реки Шу в условиях высокой изменчивости гидрологического режима. Анализ выполнен на основе многолетних гидрологических наблюдений на гидропосту Ташуткуль (Тасоткель) за период 1967–2022 гг. Статистическая оценка максимальных и средних годовых расходов воды, включая показатели изменчивости, асимметрии и обеспеченности, выявила наличие редких, но экстремальных паводковых событий, существенно влияющих на деформацию русла и размыв берегов, сложенных песчано-гравелистыми отложениями. Для обоснования расчетных гидравлических нагрузок, действующих на руслорегулирующие сооружения, применен вероятностный анализ стока. На основе выявленных гидрологических и морфологических рисков предложена усовершенствованная сборно-разборная конструкция плавающей берегозащитной шпоры, предназначенная для инженерной защиты и регулирования русловых процессов. Конструкция позволяет регулировать проницаемость, обеспечивать рассеивание энергии потока и снижать интенсивность размыва при различных режимах течения. Полученные результаты могут быть использованы при проектировании и эксплуатации адаптивных берегозащитных сооружений в нижнем течении реки Шу и на аналогичных реках с выраженной русловой и гидрологической нестабильностью.

Ключевые слова: берегозащитная шпора, защита от размыва, регулирование русел, полиэтиленовые брусья, гидротехническое сооружение, сборно-разборная конструкция, регулирование паводков, гидрологическая изменчивость, обеспеченность расходов.

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References

[1] Didovets I, Lobanova A, Krysanova V, Menz C, Babagalieva Z, Nurbatsina A, Hattermann F. Central Asian Rivers under Climate Change: Impacts assessment in eight representative catchments. Journal of Hydrology: Regional Studies. 2021; 34:100779. https://doi.org/10.1016/j.ejrh.2021.100779

[2] Kaliyeva K, Punys P, Zhaparkulova Y. The impact of climate change on hydrological regime of the transboundary River Shu Basin (Kazakhstan–Kyrgyzstan): forecast for 2050. Water. 2021; 13(20):2800. https://doi.org/10.3390/w13202800

[3] Issaldayeva S, Alimkulov S, Raimbekova Z, Bekseitova R, Karatayev M. The climatic and river runoff trends in Central Asia: The case of Zhetysu Alatau region, the south-eastern part of Kazakhstan. Heliyon. 2023; 9(7):e17897. https://doi.org/10.1016/j.heliyon.2023.e17897

[4] Kundzewicz ZW, Kanae S, Seneviratne SI. Flood risk and climate change: global and regional perspectives. Hydrological Sciences Journal. 2014; 59(1):1-28. https://doi.org/10.1080/02626667.2013.857411

[5] Chen F, Yuan Y, Trouet V, Büntgen U, Esper J, Chen F, Zhang H. Ecological and societal effects of Central Asian streamflow variation over the past eight centuries. Climate and Atmospheric Science. 2022; 5(1):27. https://doi.org/10.1038/s41612-022-00239-5

[6] Yue S, Pilon P, Phinney BOB. Canadian streamflow trend detection: impacts of serial and cross-correlation. Hydrological Sciences Journal. 2003;48(1):51-63. https://doi.org/10.1623/hysj.48.1.51.43478

[7] Hamed KH. Trend detection in hydrologic data: The Mann–Kendall trend test under the scaling hypothesis. Journal of hydrology. 2008;349(3-4):350-363. https://doi.org/10.1016/j.jhydrol.2007.11.009

[8] Giupponi C, Gain AK. Integrated water resources management (IWRM) for climate change adaptation. Regional

Environmental Change. 2017;17(7):1865-1867. https://doi.org/10.1007/s10113-017-1173-x

[9] SU1070257A1 Russia. Skvozna beregozashchitna shpora [Permeable bank protection spur]. Shuminsky VD. Patent of the USSR. 1982. (in Russ.).

[10] Rakhimova M, Liu T, Bissenbayeva S, Mukanov Y, Gafforov KS, Bekpergenova Z, Gulakhmadov A. Assessment of the Impacts of Climate Change and Human Activities on Runoff Using Climate Elasticity Method and General Circulation Model (GCM) in the Buqtyrma River Basin, Kazakhstan. Sustainability. 2020; 12(12):4968. https://doi.org/10.3390/su12124968

[11] Tazhiyev S, Murtazin Y, Rakhimova V, Rakhmetov I, Adenova D, Koshpanova K, Sotnikov Y, Abdizhalel M, Akylbayeva A, Yerezhep D. Applied Hydrogeological Assessment and GIS-Based Modeling of Transboundary Aquifers in the Shu River Basin. Water. 2025; 17(16):2476. https://doi.org/10.3390/w17162476

[12] Yapiyev V, Ongdas N, Saidaliyeva Z, Zhiyenbek A, Smogulova T, Baigaliyeva M, Prikaziuk E. Baseline information and regionalization of the large river basins of Kazakhstan. Frontiers in Water. 2025; 7:1601671. https://doi.org/10.3389/frwa.2025.1601671

[13] Bolatova A, Krysanova V, Lobanova A, Bolatov K. Assessment of climate change impacts for two tributary basins of the Irtysh River in Kazakhstan. Climate Research. 2023; 91:159-174. https://doi.org/10.3354/cr01726

[14] Tursunova A, Nurbatsina A, Salavatova Z, Huthoff F. Sustainability Challenges in Kazakhstan’s River Systems: Assessing Climate-Induced Hydrological Changes. Sustainability. 2025; 17(8):3405. https://doi.org/10.3390/su17083405

[15] RU2730607C1 Russia. Podvizhnaya beregozashchitnaya shpora [Movable bank protection spur]. Kupchikova NV. Patent of the Russian Federation. 2020. (in Russ.).

[16] Yerzhanova NK, Sennikov MN, Transgranichnoe sotrudnichestvo v sfere upravleniya riskami pavodkov [Transboundary Cooperation in Flood Risk Management], Mezhdunarodnaya nauchno-prakticheskaya konferentsiya «Teoreticheskie i prikladnie problemi geografii» [International Scientific and Practical Conference «Theoretical and Applied Problems of Geography»], Astana, 20 May. L.N. Gumilyov Eurasian National University. 2024, 244-248. (in Russ.).

[17] US20240279892A1 USA. River training structure, system comprising river training structure, and method for training a river. Jan SR. US international patent application. 2021.

[18] KZ27570 Kazakhstan. Sborno-razbornaya konstruktsiya plavayushchei beregozashchitnoi shpori [Prefabricated modular floating bank protection spur]. Bakbergenov NN, Musin Zh. Patent of the Kazakhstan. 2013. (in Russ.).

[19] Sennikov MN, Yerzhanova NK, Sovershenstvovanie upravleniya transgranichnimi vodnimi resursami po Shu-Talasskomu basseinu Respubliki Kazakhstan [Improving the management of transboundary water resources in the Shu-Talas basin of the Republic of Kazakhstan], Materiali Mezhdunarodnoi konferentsii SVO VEKTsA «Problemi upravleniya rechnimi basseinami v usloviyakh izmeneniya klimata» [Proceedings of the International Conference of the North-Eastern European Central Asian Region «Problems of River Basin Management in the Context of Climate Change»], Tashkent, 18-19 May, 2017. NITs MKVK. 2017, 208. (in Russ.).

[20] Sennikov MN, Yerzhanova NK, Prognoznoe povishenie vodoobespechennosti po regulirovaniyu vodnimi resursami Zhambilskoi oblasti [Projected Increase in Water Availability for Water Resources Regulation in Zhambyl Oblast], Mezhdunarodnaya nauchno-prakticheskaya konferentsiya Innovatsionnie i prakticheskie resheniya uskorennogo vosstanovleniya produktivnosti degradirovannikh oroshaemikh zemel KazNIIVKh [International Scientific and Practical Conference Innovative and Practical Solutions for Accelerated Restoration of Degraded Irrigated Land Productivity], Taraz, 20 May, 2022. KazNIIVH. 2022, 68-72. (in Russ.).

[21] Khalimbetov AB, Bakiev MR, Khudaiberganov HA, Sovershenstvovanie konstrukcii i metodov rascheta kombinirovanny`x damb na predgorny`x uchastkax rekax [Improvement of the design and calculation methods of combined dams on foothill river sections]: monograph. Tashkent: NIU TIIIMSKH. 2022, 100. (in Russian).

[22] Ambartsumyan GA, K voprosu gidromekhanicheskogo rascheta skvoznoi shpory s gidravlicheskim barerom [On the problem of hydromechanical design of a permeable spur with a hydraulic barrier] Izvestiya Akademii nauk Armyanskoi SSR. Seriya tekhnicheskikh nauk. Gidravlika, gidrotekhnika. – 1968. – T. XXI, № 5. – p. 32–37 (in Russ.).

[23] Levi II, Dinamika ruslovykh potokov [Dynamics of channel flows]. 2-e izd., pererab. i dop. Leningrad: Gosenergoizdat. 1957, 223.

[24] SP RK 3.04-107-2014, Nagruzki i vozdeistviya na gidrotekhnicheskie sooruzheniya (volnovye, ledovye i ot sudov) [Loads and impacts on hydraulic structures (wave, ice and ship loads). Astana: Committee for Construction]. Astana: Komitet po delam stroitel'stva, ZHKKh i upravleniya zemel'nymi resursami MNE RK. 2015.

[25] Levi I I. Dvizheniya rechnykh potokov v nizhnikh biefakh gidrotekhnicheskikh sooruzheniy [Movements of river flows in downstream reaches of hydraulic structures]. M.-L.: Gosenergoizdat. 1955, 256.

[26] Mikhasek AA, Malyugin NR. Vliyanie fil'tratsii v tele aktivnogo beregozaschitnogo sooruzheniya na kharakteristiki obtekayushchego potoka [Influence of filtration through the body of an active bank protection structure on the characteristics of the surrounding flow]. Gradostroitel'stvo i arkhitektura. 2019; 9(3):92–98. https://doi.org/10.17673/Vestnik.2019.03.12

[27] Talmaza V F. Nekotorye osobennosti dvizheniya vlekomykh nanosov na rekakh gorno-predgornoi zony [ome features of bedload sediment transport in rivers of mountainous and foothill regions]. Dinamika i termika rek. Moscow: Stroiizdat. 1973.

[28] Rustembek uulu Abdinazar, Meyman uulu Bektur. Rezul'taty model'nykh issledovanii regulyatsionnykh sooruzhenii na uchastke reki Chu [Results of physical model studies of river training structures on the Shu River reach]. Vestnik KRSU. 2018; 18(8):134–137.