ГЕОЭКОЛОГИЯ

UDC 556.16(476.1)

ENVIRONMENTAL PROBLEMS CAUSED BY THE EXTRACTION OF NON-METALLIC BUILDING MATERIALS FROM RIVERBEDS

A. A. Volchak[1], S. I. Parfomuk[2], N. N. Sheshko[3], N. N. Shpendik[4], D. N. Dashkevich[5], S. V. Sidak[6], M. F. Kukharevich[7], I. N. Rozumets[8]

[1] Doctor of Geographical Sciences, Professor, Professor of the Department of Environmental Engineering, Brest State Technical University, Brest, Belarus, e-mail: volchak@tut.by
[2] Ph.D in Engineering, Associate Professor, Head of the Department of Informatics and Applied Mathematics, Brest State Technical University, Brest, Belarus, e-mail: parfom@mail.ru
[3] Ph.D in Engineering, Associate Professor, Head of the head of the Research Department, Brest State Technical University, Brest, Belarus, e-mail: optimum@tut.by
[4] Ph.D in Engineering, Associate Professor, Associate Professor of the Department of Heat and Gas Supply and Ventilation, Brest State Technical University, Brest, Belarus, e-mail: shpendik@tut.by
[5] Senior Lecturer of the Department of Environmental Engineering, Brest State Technical University, Brest, Belarus, e-mail: dionis1303@mail.ru
[6] Assistant of the Department of Informatics and Applied Mathematics, Brest State Technical University, Brest, Belarus, e-mail: harchik-sveta@mail.ru
[7] Postgraduate student, Brest State Technical University, Brest, Belarus, e-mail: kukharevichmikhail@gmail.com
[8] Postgraduate student, Brest State Technical University, Brest, Belarus, e-mail: ivan.rozumets@bk.ru

Abstract

Extraction of non-metallic building materials from rivers can lead to negative consequences, such as disruption of the structure of the river bed, change in the balance of sediment intake. It can also lead to the undermining of the fish food supply, destroy spawning grounds, and reduce the ability of the river to self-purification. Data for the section of the Pripyat River at the Lubansky Bridge for the period from 1978 to 2018 were used. To study the impact on the river ecosystem of the planned work on the extraction of non-metallic building materials, an approach was used to determine the ecological runoff when a natural speed regime is formed, which ensures the natural functioning of the ecosystem. Digital models of the bottom relief in 2021 and 2022 showed a positive trend in the formation of sediments in the studied area. The volume of possible material intake was established, which amounted to 33122.5 m^3. At the same time, the estimated volume of sediment formation within this site is 11034 m^3 per year, then it is possible to carry out work on the intake of non-metallic building materials on the studied section of the river no more than once every three years.

Keywords: non-metallic building materials, mining, the Pripyat River riverbed, ecological runoff.

ЭКОЛОГИЧЕСКИЕ ПРОБЛЕМЫ, ВЫЗВАННЫЕ ДОБЫЧЕЙ НЕРУДНЫХ СТРОИТЕЛЬНЫХ МАТЕРИАЛОВ ИЗ РУСЕЛ РЕК

А. А. Волчек, С. И. Парфомук, Н. Н. Шешко, Н. Н. Шпендик, Д. Н. Дашкевич, С. В. Сидак, М. Ф. Кухаревич, И.Н. Розумец

Реферат

Добыча нерудных строительных материалов из рек может привести к негативным последствиям, таким как нарушение структуры русла реки, изменение баланса поступления наносов. Это также может привести к подрыву кормовой базы рыб, уничтожению нерестилищ и снижению способности реки к самоочищению. Р работе использованы данные по участку реки Припять у Любанского моста за период с 1978 по 2018 год. Для изучения влияния на речную экосистему планируемых работ по добыче нерудных строительных материалов использован подход по определению экологического стока при формировании естественного скоростного режима, обеспечивающего естественное функционирование экосистемы. Цифровые модели рельефа дна в 2021 и 2022 годах показали положительную тенденцию в формировании отложений на исследуемом участке. Был установлен объем возможного забора материала, который составил 33122,5 м^3. В то же время расчетный объем образования наносов в пределах этого участка составляет 11034 м^3 в год, поэтому проведение работ по забору нерудных строительных материалов на исследуемом участке реки возможно не чаще одного раза в три года.

Ключевые слова: нерудные строительные материалы, добыча, русло Средней Припяти, экологический сток.

Introduction

Extraction of sand, gravel, pebbles and their mixtures from riverbeds and floodplains, their delivery to consumers is one of the components of the activities of river ports, shipping companies. In addition, the development of non-metallic building materials (NBM) is carried out by numerous construction organizations with powerful mining facilities, which requires coordination of the work of these organizations by environmental authorities and scientific justification of production volumes. The problem is compounded by the fact that, in an effort to reduce the costs of mining NBM, they try to locate their production sites near cities where working resources are concentrated. This approach is accompanied by disruption of water intakes and water outlets, erosion of bridge supports and crossings of oil and gas pipelines, affects the stability of port hydraulic structures, and contributes to the deterioration of navigable conditions in the quarry area. The negative consequences are especially acute on rivers with low water consumption in the low-water mark. This problem is acute in many regions of the world and is widely studied by specialists [1-6].

A number of works by Russian scientists are devoted to various aspects of assessing the consequences of the extraction of NBM from riverbeds. Thus, in [7], methods for calculating the subsidence of the water level due to large-scale mining of NBM are considered in detail, a comparative analysis of models for calculating changes in hydraulic and hydrochemical parameters in zero-, one-, two- and three-dimensional formulation is given. The authors present the main advantages and disadvantages of a large number of software products (HEC-RAS, MIKE, SMS, Delft3D-Flow, etc.) used in solving problems related to the assessment of the consequences of large-scale mining of petroleum products. In the article [8], a hydrodynamic model of the Vyatka River was developed, which made it possible to assess possible changes for both the high-speed and level regime of a water body due to the extraction of NBM for various limiting hydrological conditions. The mechanisms of formation and distribution of pollution of the river are investigated. Vyatka and the results of model calculations when washing floodplain water bodies. Based on the combination of the one-dimensional hydrodynamic model HEC-RAS v.4.1 for the primary assessment and the two-dimensional model SMS v.11.1 for the final calculations, the channel deformations were estimated under standard conditions of the hydrological regime of the Kama and Votkinsk reservoirs in [9].

The method of maintaining the stability of the riverbed during the extraction of non-metallic building materials is described in detail, the task is achieved by eliminating the reshaping of the runoff structure and preserving the equally waste planned jets along the width of the riverbed [10]. In [11], an assessment of the state of the riverbed was given and a forecast of channel deformations was made based on the analysis of the dynamics of changes in the main parameters of bends, taking into account the safety of navigation, a conclusion was made about the possibility of extraction of sand and gravel rocks. The article [12] describes in detail the natural and anthropogenic deformations of the Oka riverbed in the Ryazan region. The investigated section of the riverbed is more than 100 km. With the beginning of the extraction of NBM in 1973-2003, the volume of the riverbed increases, flowing differently at different times on different sections of the river.

The researchers note that the extraction of sand and gravel in rivers is the main cause of their degradation, especially when the natural solid sediment runoff in the river is disrupted by hydraulic engineering. With uncontrolled extraction of NBM in many rivers, meandering may decrease, the bank's collapse, and the geometry of the channels may be disrupted. In addition, such activities usually cause denudation and coarsening of the bottom, destruction of spawning grounds, erosion of hydraulic structures and destruction of bridges, as well as a decrease in solid runoff into the delta. Special attention is paid to modeling the extraction of sand and gravel from riverbeds and floodplains [13-14].

Thus, when designing the extraction of NBM from channel quarries, it is extremely necessary to take into account that their extraction makes more significant changes to the hydraulics of the river runoff and channel processes than dredging operations carried out to improve navigable conditions when the soil only moves in the riverbed.

The purpose of this work is the ecological justification of the possible removal of NBM from the riverbed. The Pripyat River in its middle course was chosen as a model river.

Materials and methods

The Pripyat River is the largest navigable right tributary of the Dnieper with a length of 775 km and a catchment area of 114.3 thousand km^2. In the studied alignment, the width of the river is 50-60 m, the bottom is sandy and sandy–muddy, and the average slope of the river is 0.08 m/km. The food is mixed, with a predominance of snow. The water regime is characterized by a long spring flood: from the first decade of March, at most in mid–April, the recession drags on for 3 - 3.5 months. The summer short-term rainfall is interrupted by rain floods and an almost annual autumn rise in the water level. Spring accounts for 60-65% of the annual runoff, the water rises to 3.5 m, accompanied by extensive spills. The color of the water is determined by the predominance of peat-bog soils in the river basin.

On the Pripyat River, in the area between the Pinsk City and the Lubansky Bridge, it is planned to mine NBM (Fig. 1).

The granulometric composition of the bottom sediments of the Pripyat River was determined by the sieve method by employees of the technological laboratory of the branch "Central Laboratory" of the Republican Unitary Enterprise "Scientific and Production Center for Geology according to soil samples from the riverbed selected by employees of the Applied Ecology sector of the Laboratory of Geodynamics and Paleogeography of the Institute of Nature Management of the National Academy of Sciences of Belarus (Table 1).

Table 1 – Granulometric composition of the soil of the Pripyat River on the territory of the Pinsk district

Watercourse	Granulometric composition, %						
Fraction size, mm	0.80	0.63	0.315	0.25	0.10	0.071	riverbed
The Upper Pripyat River	21.4	12.7	40.3	10.3	15.1	0.2	0.0
The Pripyat River	0.4	0.5	16.2	17.0	62.2	2.9	0.8

Due to the fact that regular hydrological observations are conducted by the Hydro meteorological Service of the Republic of Belarus on the Pripyat River at the Lubansky Bridge, in the immediate vicinity of the NBM mining site, the determination of the calculated hydrological characteristics was carried out directly from the observation data, taking into account the requirements set out in [15-16]. In this work, data from hydrometric observations for the period from 1978 to 2018, i.e. 41 years, are used, which is sufficient to obtain objective statistical hydrological characteristics along the Pripyat River in the Lubansky Bridge alignment.

Figure 1 – Location of the investigated area

The missing data in the series of observations were restored using analog rivers using the software package "Hydrolog - 2" [17].

The ecological runoff was determined according to the methodology described in detail in [18-19]. Ecological runoff is the amount of water that must remain in the river to ensure the conditions for the existence of hydrobionts while maintaining its necessary quality. In this case, floodplain ecosystems are preserved, and the river remains an element of the landscape. Thus, the ecological runoff ensures the quantitative and qualitative condition of the water body in the most low-water period of the year. The existing approaches to determining the ecological runoff regulate only the minimum value of the river runoff. At the same time, there is no definition of ecological runoff for various security conditions. The most objective way to determine the ecological runoff, taking into account the intra-annual distribution, is the method of increasing security, therefore it is used in this work.

Riverbed processes in rivers are continuous and constantly changing depending on the hydrological regime, which mainly depends on the hydrodynamic action of flowing water, which has mechanical energy and is able to perform work on the erosion of the channel and floodplain, transfer and accumulation of sediments. When sediments are deposited, the area of the live section of the stream decreases, and, consequently, the runoff velocity and its transporting capacity increase, which stops the sediment deposition process. Depending on the distribution of runoff velocities in some areas, suspended sediments may turn into bottom sediments or vice versa.

Thus, the deformations of the channel, which are the result of a violation of the dynamic equilibrium between the transporting capacity of the stream and its saturation with sediments, tend to create a constant runoff of sediment along the length of the stream. It follows from this that the violation of the constancy of sediment runoff along the length causes erosion in some areas, and accumulation in others, which, ultimately, should lead to the restoration of the disturbed equilibrium of the constancy of sediment runoff along the length of the stream [20-21].

For the studied area, surveys of the bottom relief were carried out in 2021 and 2022 during the spring flood by means of a sonar multipath echo sounder. The measurement database is a file with the values of coordinates in a flat system and the bottom marks for individual measured points. Data processing was carried out using the author's design tools in the ArcGIS environment using a number of models for terrain analysis. As a result of processing the survey data presented by Dneprobugvodput, digital models of the bottom relief of the riverbed section were obtained. Using the COMSOL Multiphysics software package, we modeled the water runoff in the studied channel of the Pripyat River.

https://doi.org/10.36773/1818-1112-2023-130-1-113-117

The Computational Fluid Dynamics module was used for numerical modeling, which presents a set of RANS turbulence models (models based on Reynolds-averaged Navier-Stokes equations) implemented in the corresponding hydrodynamic interfaces [22-25].

In accordance with the current legislation on the protection of fish stocks and their habitats in natural conditions, the planned works should be assessed for damage caused to the watercourse and the amount of compensation payments for the harmful effects on it [26]. Compensation payments for a specific object of the animal world (in this case, fish) are calculated separately for each impact zone, followed by summation of the results.

According to the fisheries classification, the river belongs to the water bodies of the first category, for which the norm of allowable catch of fish from one hectare of fishing grounds is 32.4 kg per year. The total biomass of fish per unit area, taking into account the coefficient of recalculation of the fishing stock into the total biomass equal to 1.49, is determined by the dependence

$$B = S_{PC} \cdot C_{FS} \cdot C_B \,, \qquad (1)$$

where B is the total biomass of fish per unit area, kg / ha; S_{PC} is the standard of permissible catch of fish, kg / ha; C_{FS} is the coefficient of conversion of the standard of permissible catch of fish into the commercial fish stock; C_B is the coefficient of conversion of the commercial fish stock into the total biomass.

Results and discussion

Data on the quantitative characteristics of the runoff of the Pripyat River – the Lubansky Bridge by month and year are presented in Table 2. According to Table 2, 41% of the annual runoff accounts for the spring period, winter runoff accounts for 21% of the annual runoff, the summer-autumn season accounts for 38% of the annual runoff.

Table 2 – The main hydrological characteristics of the runoff of the Pripyat River – the Lubansky Bridge

Parameter	Month												Year
	1	2	3	4	5	6	7	8	9	10	11	12	
Q, m³/s	62.6	72.9	108	144	98.2	64.6	52.9	47.1	45.5	51.0	58.5	59.9	71.2
C_v	0.44	0.50	0.50	0.44	0.33	0.37	0.45	0.53	0.56	0.51	0.53	0.48	0.27

The average long-term value of the minimum annual runoff of 95% of the probability of exceeding the Pripyat River at the Lubansky Bridge alignment is 46.7 m³/s. Fig. 2 shows the results of calculating the minimum average monthly runoff of 95% of the probability of excess (security), taking into account the intra-annual distribution of runoff.

The size of the ecological runoff of the Pripyat River at the Lubansky Bridge is accepted as 75% of the minimum monthly runoff of 95% security and is 9.90 m³/s. When using the security transfer method, the ecological runoff of the Pripyat River has a 95% probability of exceeding, according to the hydrological calculations carried out, 39.0 m³/s. The obtained results formed the basis for calculating the runoff rate of water corresponding to the ecological runoff, taking into account the intra-annual distribution of runoff and existing before the start of the planned works in the Pripyat River riverbed (Table 3).

Based on the available data on river runoff and mathematical modeling, the average monthly and average annual values of solid runoff, including the runoff of suspended and entrained sediments, presented in Table 4, are determined.

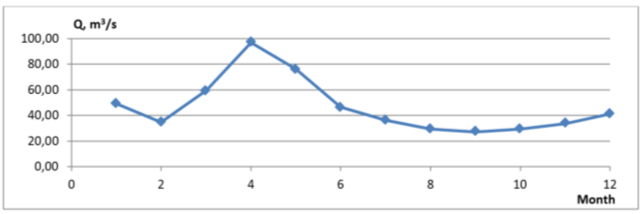

Figure 2 – Minimum average monthly runoff of 95% security, taking into account the intra-annual distribution of the runoff of the Pripyat River – the Lyubansky Bridge

Table 3 – Water runoff rates corresponding to the ecological runoff 95% probability of excess (security) taking into account the intra-annual distribution, m/s

Slot	Ecological runoff (75% of the minimum monthly runoff of 95 % security)	Ecological runoff (security transfer)
1	0.11	0.42
2	0.09	0.36
3	0.10	0.38
4	0.11	0.42
5	0.08	0.31
6	0.08	0.33
7	0.08	0.31
8	0.08	0.32
9	0.09	0.34
10	0.10	0.38
11	0.09	0.35
12	0.09	0.34
Minimum	**0.08**	**0.31**

Table 4 – Solid runoff of the Pripyat River – the Lubansky Bridge taking into account intra-annual distribution, m³/month (year)

Months												Year
1	2	3	4	5	6	7	8	9	10	11	12	
Suspended sediment runoff												
3288	2329	3970	6479	5093	3101	2415	1966	1805	1974	2243	2760	37423
Runoff of entrained sediments												
546	490	1449	3165	1915	630	435	215	254	352	321	248	10020
Solid runoff												
3834	2819	5419	9644	7008	3731	2850	2181	2059	2326	2564	3008	47443

The analysis of changes in the channel bottom marks in the studied area showed that the main channel processes are observed in the area below the bridge and the bend area near the left bank (Fig. 3). Thus, it can be assumed that these areas actively form channel-forming processes; therefore it is not rational to involve them in any anthropogenic activities. In quantitative terms, the ratio of sediment volume as of 2021 and 2022 has a positive balance, which is presumably due to an increase in meanders in the direction of the road with improved pavement.

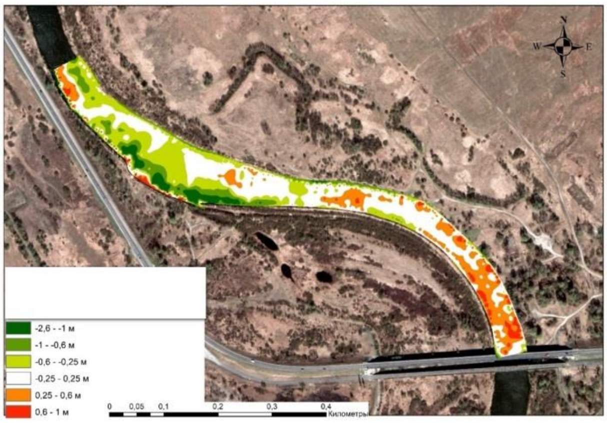

Figure 3 – Changes in the bottom relief for 1 year (from 2021 to 2022)

Taking into account the average long-term value of the runoff in the Pripyat River at the Lubansky Bridge alignment and the cross-sectional area in the places of the planned slots before and after the work on the extraction of NBM, we calculated the water runoff rates for 12 planned slots (Table 5).

Table 5 – Water runoff rates along 12 planned slots before and after the planned work on the extraction of NBM, m/s

Slot	Before the work on the extraction of NBM	After the planned works
1	0.76	0.54
2	0.65	0.46
…	…	…
12	0.62	0.47
Minimum	**0.56**	**0.32**

Comparing the data in Tables 3 and 5, it can be concluded that the water runoff rates for all 12 planned slots after the planned work on the extraction of NBM will be higher than the minimum water runoff rate corresponding to the ecological runoff of 95% of the probability of excess (security), equal to 0.31 m^3/s. Moreover, the latter value was obtained using the security transfer method and is, in a sense, an "upper estimate" of the water velocity of the ecological runoff. If we consider the water runoff velocity corresponding to the ecological runoff equal to 75% of the minimum monthly runoff of 95% security, then the minimum velocity in the slot 5 (0.32 m^3/s) is 4 times higher than the lowest rate of ecological runoff equal to 0.08 m^3/s.

Based on the preliminary placement of slots in the zones of the greatest bottom sediments and zones with the minimum intensity of channel processes, the approximate volume of possible NBM fences is calculated (Table 6).

Table 6 – Estimated volume of slots

Slot number	Area, m^2	Depth, m			Volume, m^3
		minimum	maximum	average	
1	320	1.83	3.05	2.57	821.22
2	320	2.20	2.82	2.65	847.16
…	…	…	…	…	…
52	320.5	1.78	1.81	1.80	575.54
53	320.5	1.80	1.88	1.82	582.51
				Total	**42424.27**

The average speed of water runoff through all planned slots after the planned works may decrease from 0.65 to 0.42 m^3/s, which will lead to the formation of bottom sediments with a volume of 11034 m^3/year.

The results obtained show that the planned works will not entail a violation of the ecological state of the Pripyat River. At the same time, the water runoff velocity in the river will be higher than with ecological runoff, and conditions for the existence of hydrobionts will be provided in the river while maintaining the necessary water quality.

During development, it is recommended to preserve gaps (10 m) for the formation of local distortions of the velocity field, which will contribute to more intensive sediment deposition. Taking into account the above, the layout of the slots is shown in Fig. 4. With this arrangement of slots, the volume of the recess will be 33122.5 m^3.

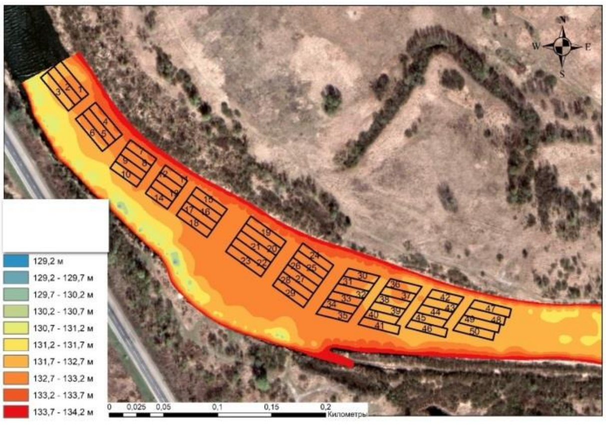

Figure 4 – Numbers and placement of slots taking into account technological gaps

The amount of damage was estimated using the method of compensation payments. Since, according to the fisheries classification, the river belongs to the water bodies of the first category, for which the norm of allowable catch of fish from 1 ha is 32.4 kg per year.

The average operational capacity of a dredger of the "ZS-28B" type is 450 tons/hour. The permissible time of soil removal is 140 hours of continuous operation of the dredger, that is, harmful effects on the watercourse will be carried out within 6 days.

The width of the zone of severe harmful effects is set at 1000 m, the zone of moderate harmful effects is 500 m. Taking into account the planned engineering and economic activities, the areas of harmful effects are calculated for 4 zones. The total areas of harmful effects are estimated:

- direct destruction zone – 1.65 ha;
- zone of severe harmful effects – 13.78 ha;
- zone of moderate harmful effects – 6.20 ha;
- zone of weak harmful effects – 6.20 ha.

These areas should be considered as areas that will not be able to produce fish products and offspring from it, throughout all the years of the reproductive ability of a part of the population.

In the Pripyat River on the territory of the Pinsk district, on an area of 1 hectare, an average of 1817 fish live in a fish herd. The expected damage to the type of engineering and economic activity planned in 2022 in the studied sections of the riverbed is estimated at 552 pieces of fish per 1 ha of the watercourse area. The coefficient of the status of the territory in the studied areas is equal to 1 for all fish species, except for the fish included in the "Red Book of the Republic of Belarus", for which the coefficient is equal to 3. The Pripyat of the planned works on the extraction of NBM in the territory of the Pinsk district of the Brest region, are estimated at 341 base values.

To increase the stability of the channel to the predicted planned high-altitude deformations, it is recommended to observe the following conditions directly during the development of the slots:

- the length of the slots cannot exceed the length of the existing channel formations created by the river in a multi-year section and during navigation in 2022, therefore, before the start of the planned work, it is necessary to clarify the placement and length of shallow sections of the channel;
- the width of the recess should not violate the stability of the coastal slopes – in the studied areas with a freely meandering type of channel process , it cannot be more than 0.5 of the width of the channel along the water cut of the inter-runoff rate of 50 % security;
- the depth of development is taken from the surface of the bottom of the watercourse and is the average thickness of the removed soil layer;
- the development of soil should begin from the lower section of the development and gradually move upstream against the current, which will allow the suspension formed during the work to be deposited in the developed slot;
- when carrying out the planned works, it is necessary to leave undeveloped bottom sections of the channel about 10 m long between the sequentially located slots for a local artificial basis of erosion;
- the slots should be placed at a distance of at least 5 m from the shore, which will minimize the sharp collapse of the shallow sections of the channel being developed and prevent the collapse of the coastal slopes.

In conditions of increasing anthropogenic impact on the riverbed process of the watercourse, in order to reduce the fall of the water level and the bottom of the riverbed by engineering methods of stabilization and recultivation of the natural regime of the Pripyat River, it is recommended to provide:

- creation of artificial local erosion bases below the planned NBM workings – flooded sheet pile walls, bottom thresholds;
- dumping on coastal slopes and into the bed of coarse-grained material;
- creation of artificial zones for the habitat of ichthyoid fauna, etc.

The timing of the work on the extraction of NBM should exclude periods of spawning migrations and fish spawning.

Conclusion

The determination of the natural hydrological regime of the Pripyat River is based on an assessment of the existing and projected ecological runoff, which ensures the functioning of the watercourse as an ecosystem. Carrying out work on the extraction of NBM causes changes in the channel parameter, which in turn leads to a change in the hydrological regime. Since the normal functioning of the watercourse is possible in the presence of

https://doi.org/10.36773/1818-1112-2023-130-1-113-117

ecological runoff in it, we performed a comparative assessment of the simulated ecological runoff of the Pripyat River in this area. The results obtained allow us to conclude that the planned work on the extraction of NBM will not entail a violation of the ecological state of the Pripyat River. At the same time, the water runoff velocity in the river will be higher than with ecological runoff, and conditions for the existence of hydrobionts will be provided in the river while maintaining the necessary water quality.

The simulation of the longitudinal runoff showed the redistribution of velocities within the slots and technological gaps. Changes in the velocity plot form sections with a runoff velocity of less than 0.3 m/s within the deepened part of the slot, and increased velocities (more than 0.9 m/s) at the sections of technological breaks. This structure of velocity redistribution increases the intensity of sediment deposition, and at the same time reduces the rate of transformation of the spatial position of the shoreline of the riverbed in relation to anthropogenic objects.

Digital models of the bottom relief in 2021 and 2022 showed a positive trend in the formation of sediments in the study area. Taking into account the current bottom relief and analytically established areas of potential extraction of non-metallic materials, the volume of possible material intake was established, which amounted to 33122.5 m^3. Since the estimated volume of sediment formation within this section is 11034 m^3/year, it is possible to carry out work on the intake of NBM on this section of the river no more than once every three years with mandatory repeated environmental assessment of hydraulic and hydrological processes.

The total compensation payments for the harmful effects on the ichthyoid fauna of the Pripyat River of the planned work on the extraction of NBM are estimated at 10924.47 rubles.

References

1. Mikel Calle, Petteri Alho, Gerardo Benito, Channel dynamics and geomorphic resilience in an ephemeral Mediterranean river affected by gravel mining, Geomorphology, Volume 285, 2017, Pages 333-346, ISSN 0169-555X, https://doi.org/10.1016/j.geomorph.2017.02.026.
2. Thomas Dépret, Clément Virmoux, Emmanuèle Gautier, Hervé Piégay, Mariya Doncheva, Brian Plaisant, Sirine Ghamgui, Evan Mesmin, Ségolène Saulnier-Copard, Lucile de Milleville, Julien Cavero, Pablo Hamadouche, Lowland gravel-bed river recovery through former mining reaches, the key role of sand, Geomorphology, Volume 373, 2021, 107493, ISSN 0169-555X, https://doi.org/10.1016/j.geomorph.2020.107493.
3. Ramesh Murlidhar Bhatawdekar, Trilok Nath Singh, Edy Tonnizam Mohamad, Rajesh Jha, Danial Jahed Armagahni, Dayang Zulaika Abang Hasbollah, Chapter 17 - Best river sand mining practices vis-a-vis alternative sand making methods for sustainability, Editor(s): Thendiyath Roshni, Pijush Samui, Dieu Tien Bui, Dookie Kim, Rahman Khatibi, Risk, Reliability and Sustainable Remediation in the Field of Civil and Environmental Engineering, Elsevier, 2022, Pages 285-313, ISBN 9780323856980, https://doi.org/10.1016/B978-0-323-85698-0.00007-1.
4. E. S. Rentier, L. H. Cammeraat, The environmental impacts of river sand mining, Science of The Total Environment, Volume 838, Part 1, 2022, 155877, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2022.155877.
5. B.R.V. Susheel Kumar, Muhammad Faiz Bin Zainuddin, Dato Chengong Hock Soon, Ramesh Murlidhar Bhatawdekar, Chapter 18 - Learning lessons from river sand mining practices in India and Malaysia for sustainability, Editor(s): Thendiyath Roshni, Pijush Samui, Dieu Tien Bui, Dookie Kim, Rahman Khatibi, Risk, Reliability and Sustainable Remediation in the Field of Civil and Environmental Engineering, Elsevier, 2022, Pages 315-331, ISBN 9780323856980, https://doi.org/10.1016/B978-0-323-85698-0.00002-2.
6. Duncan Wishart, Jeff Warburton, Louise Bracken, Gravel extraction and planform change in a wandering gravel-bed river: The River Wear, Northern England, Geomorphology, Volume 94, Issues 1–2, 2008, Pages 131-152, ISSN 0169-555X, https://doi.org/10.1016/j.geomorph.2007.05.003.
7. Lepihin, A. P. K probleme ocenki posledstvij krupnomasshtabnoj dobychi nerudnyh stroitel'nyh materialov na poverhnostnye vodnye ob"ekty / A. P. Lepihin, T. P. Lyubimova, S. A. Lepeshkin, A. A. Tiunov, Ya. N. Parshakova, D. I. Perepelica // Vodnoe hozyajstvo Rossii. – 2014. – №3. – S. 108–119.
8. Lepihin, A. P. Gidrodinamicheskoe modelirovanie reki Vyatki v srednem techenii: postanovka zadachi, rezul'taty raschetov / A. P. Lepihin, T. P. Lyubimova, Yu. S. Lyahin, A. A. Tiunov, A. V. Bogomolov, D. I. Perepelica, Ya. N. Parshakova // Vodnoe hozyajstvo Rossii. – 2013. – №3. – S. 16–32.
9. Perepelica, D.I. Ocenka deformacij rusla reki Kamy i razrabotka rekomendacij po reglamentacii dobychi nerudnyh stroitel'nyh materialov v predelah nizhnego b'efa Kamskoj GES / D. I. Perepelica, A. P. Lepihin, S. A. Lepeshkin, A. A. Tiunov // Vodnoe hozyajstvo Rossii. – 2018. – №6. – S. 39–48.
10. Kuz'min A. I., Turkin V. N., Tkachyov P. S. Sposob sohraneniya ustojchivosti rusla pri dobyche nerudnyh stroitel'nyh materialov // Omskij nauchnyj vestnik. – 2009. – №. 1 (84). – S. 85-86.
11. Sitnov A. N., SHestova M. V., Voronina Yu. E. Prognoz ruslovyh deformacij i osobennosti razrabotki pojmennyh kar'erov nerudnyh stroitel'nyh materialov v meandriruyushchih ruslah rek s uchetom bezopasnyh uslovij sudohodstva (na primere r. Belaya) //Nauchnye problemy vodnogo transporta. – 2020. – №. 65. – S. 179-188.
12. Berkovich K. M., Zlotina L. V., Turykin L. A. Prirodno-antropogennye deformacii rusla Oki v rajone Ryazani //Geomorfologiya. – 2009. – №. 2. – S. 26-32.
13. Abedin Mohammad-Hosseinpour, José-Luis Molina, Ebrahim Jabbari, Interaction between gravel mining pits and river curvature on maximum scour depth through 2D hydraulic modelling, Journal of Hydrology, Volume 604, 2022, 127245, ISSN 0022-1694, https://doi.org/10.1016/j.jhydrol.2021.127245.
14. Wujuan Zhai, Jiyong Ding, Xiaowei An, Zhuofu Wang, An optimization model of sand and gravel mining quantity considering healthy ecosystem in Yangtze River, China, Journal of Cleaner Production, Volume 242, 2020, 118385, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2019.118385.
15. Raschetnye gidrologicheskie harakteristiki. Poryadok opredeleniya : TKP 45-3.04-168-2009 (02250). – Mn.: Strojtekhnorm, 2010. – 55 s.
16. Volchek, A. A. Gidrologicheskie raschety: uchebnoe posobie / A. A. Volchek. – Moskva: KNORUS, 2021. – 418 s.
17. Volchek, A. A. Paket prikladnyh programm dlya opredeleniya raschetnyh harakteristik rechnogo stoka // A. A. Volchek, S. I. Parfomuk / Vesnik Paleskaga dzhzyarzhaýnaga universiteta. Seryya pryrodaznaýchyh navuk. – 2009. – №1. – S. 22–30.
18. Volchek, A. A. Ocenka ekologicheskogo stoka reki Yasel'da v stvore vodohranilishcha «Selec» / A. A. Volchek, N. N. Sheshko // Sovremennye problemy ochistki stochnyh vod i ohrany resursov poverhnostnyh vod v prigranich'e: materialy mezhdunar. iauch.-prakt. konf. (Brest, 24-25 sentyabrya 2015 goda) / gl. red. N.V. Mihal'chuk. – Brest: Al'ternativa, 2015. – S. 12–22.
19. Volchek, A. A. Ocenka vliyaniya rybhoza «Selec» na stok reki Yasel'da / A. A. Volchek, S. I. Parfomuk, N. N. Sheshko, N. N. Shpendik, D. N. Dashkevich, S. V. Sidak, M. F. Kuharevich // Vestnik Brestskogo gosudarstvennogo tekhnicheskogo universiteta. – 2022. – № 1 (127): Geoekologiya. – S. 83–85.
20. Mihnevich, E. I. Levkevich, V. E. Ustojchivost' beregov vodohranilishch pri formirovanii profilya dinamicheskogo ravnovesiya v nesvyaznyh gruntah // Melioraciya. – 2016. – №4(78) – S 18–23.
21. Mihnevich, E. I. Propusknaya sposobnost' rusel reguliruemyh rek i vodootvodyashchih kanalov / E. I. Mihnevich // Prirodnaya sreda Poles'ya: osobennosti i perspektivy razvitiya: sb. nauch. tr. Vyp. 1: v 2 t. – T. 2. Vodnye resursy Poles'ya. – Brest : Al'ternativa, 2008. – S. 38–41.
22. Volchek, A. A. Inzhenernaya gidrologiya i regulirovanie stoka. Gidrologicheskie i vodohozyajstvennye raschety. Uchebnoe posobie / A. A. Volchek, An. A. Volchek, V. K. Kursakov. – Gorki: Belorusskaya gosudarstvennaya sel'skohozyajstvennaya akademiya, 2013. – 315 s.
23. Kurushin A. A. Reshenie mul'tifizicheskih SVCH zadach s pomoshch'yu SAPR COMSOL – M.: «One-Book», 2016. – 376 s.
24. Oficial'nyj sajt ComsolMultiphysics. [Elektronnyj resurs]. Rezhim dostupa: http://www.comsol.com/, svobodnyj.
25. Oshovskij, V.V. Ispol'zovanie komp'yuternyh sistem konechno-elementnogo analiza dlya modelirovaniya gidrodinamicheskih processov / Oshovskij V. V., Ohrimenko D. I., Sysoev A. Yu. // Naukovi praci DonNTU. Cepiya: Himiya i himichnatekhnologiya, 2010. – Vip. 15(163). – S. 163–173.
26. Postanovlenie Soveta Ministrov Respubliki Belarus' ot 7 fevralya 2008 g. № 168 «Ob utverzhdenii Polozheniya o poryadke opredeleniya razmera kompensacionnyh vyplat i ih osushchestvleniya».

Received 10.01.2023, revised 16.02.2023, accepted 17.02.2023