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MODELING OF EROSION AND DESIGN OF STRUCTURES FOR STRENGTHENING THE WESTERN BUG RIVER BANKS

***A. A. Volchak*[1], *S. I. Parfomuk*[2], *N. N. Sheshko*[3], *N. N. Shpendik*[4], *S. V. Sidak*[5], *M. F. Kukharevich*[6]**

[1] *Doctor of Geographical Sciences, Professor, Professor of the Department of Environmental Management, Brest State Technical University, Brest, Belarus, e-mail: volchak@tut.by*

[2] *Candidate of Technical Sciences, Associate Professor, Head of the Department of Mathematics and Informatics, Brest State Technical University, Brest, Belarus, e-mail: parfom@mail.ru*

[3] *Candidate of Technical Sciences, Associate Professor, Associate Professor of the Department of Environmental Management, Head of the Research Department, Brest State Technical University, Brest, Belarus, e-mail: optimum@tut.by*

[4] *Candidate of Geographical Sciences, 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 Mathematics and Informatics, Brest State Technical University, Brest, Belarus, e-mail: harchik-sveta@mail.ru*

[6] *Teacher-intern of the Department of Environmental Management, Brest State Technical University, Brest, Belarus, e-mail: kukharevichmikhail@gmail.com*

Abstract

The Western Bug River is a transboundary river in Eastern Europe. The average long-term water discharge in the studied section is 80.2 m^3/s, and the spring flood with 1% probability is 818 m^3/s. Retrospective analyses of aerial photography data for the period from 2004 to 2022 allowed us to establish the average annual bank movement rate, which was 0.85 m/year. A digital relief model of the catchment area was created and a detailed channel model was constructed, which is based on the use of low-water and Navier-Stokes equations. The calculations were carried out using the server computing equipment of BrSTU and allowed us to build a picture of the spatial and temporal patterns of the free surface levels of the flow, as well as the velocity field. The total spatial and temporal resolution of the model is 371,000 cells with 100–200 time intervals at 10–20 vertical grid layers. To implement the program, a programming language was selected that ensures efficient calculations and convenient interaction with the existing MIKE 3 environment. As a result, Python/C++ was chosen, providing flexibility and high performance. The river sections exposed to the risk of erosion are identified, namely the coastal and coastal zone along the right bank in the area of the bend, both before and after it. The second section belongs to the floodplain zone, the flooding of which occurs during the spring flood corresponding to the maximum convergence of the meanders of the channel. The velocities obtained as a result of modeling do not exceed 2 m/s in the channel part. Areas at risk of erosion are highlighted. In the channel part, bank stabilization is recommended in the form of rock fill or stone paving. For the floodplain part near two meanders, it is necessary to provide for stabilization in the form of rock fill with a connecting structure for the passage of flood waters.

Keywords: river, runoff, modeling, erosion, meandering, fastening.

МОДЕЛИРОВАНИЕ РАЗМЫВА И ПРОЕКТИРОВАНИЕ СООРУЖЕНИЙ ДЛЯ УКРЕПЛЕНИЯ БЕРЕГОВ РЕКИ ЗАПАДНЫЙ БУГ

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

Реферат

Река Западный Буг – трансграничная река в Восточной Европе. Средний многолетний расход воды в исследуемом створе составляет 80,2 м^3/с, а весеннего половодья 1 % обеспеченности – 818 м^3/с. Ретроспективный анализ данных аэрофотосъемки за период с 2004 по 2022 гг. позволил установить среднегодовую скорость перемещения береговой линии, которая составила 0,85 м/год. Создана цифровая модель рельефа местности водосбора и построена детальная модель русла, которая основана на использовании уравнений малой воды и Навье-Стокса. Расчеты проводились с применением серверного вычислительного оборудования БрГТУ и позволили построить картину пространственного временных закономерностей уровней свободной поверхности потока, а также поля скоростей. Общее пространственно-временное разрешение модели 371000 ячеек с 100–200 временными интервалами при 10–20 слоях вертикальной сетки. Для реализации программы выбран язык программирования, обеспечивающий эффективные вычисления и удобное взаимодействие с существующей средой MIKE 3. В результате выбора был сделан в пользу Python/C++, обеспечивающего гибкость и высокую производительность. Выделены участки реки, подверженные риску размыва, а именно прибрежная и береговая зона по правому берегу в районе излучины как перед ней, так и после нее. Второй участок относится к пойменной зоне, затопление которой происходит в период весеннего половодья соответствующий максимальному сближению меандр русла. Полученные в результате моделирования скорости не превышают 2 м/с в русловой части. Выделены участки подверженные риску размыва. В русловой части крепление берегов рекомендуется в виде каменной наброски или каменного мощения. Для пойменной части вблизи двух меандр необходимо предусмотреть крепление в виде каменной наброски с устройством сопрягающего сооружения для пропуска паводковых вод.

Ключевые слова: река, сток, моделирование, размыв, меандрирование, крепление.

Introduction

The Western Bug River is a transboundary river in Eastern Europe, flowing through the territory of Ukraine, Belarus and Poland. It originates in the Podolsk Upland and flows through Ukraine, then along the border of Belarus and Poland and flows into the Zegrze Reservoir, and then into the Vistula River. The total length of the river is 772 km, on the territory of Belarus – 154 km. In the upper and lower reaches, the river valley is clearly defined and does not exceed 2–3 km in width, the floodplain is intermittent, with numerous oxbow lakes. In the middle section, the valley of the Western Bug widens to 3–4 km and has a wide, low, swampy floodplain. The river bed is winding throughout its entire length. It gradually widens from 10–20 m in the upper reaches to 50–75 m in the lower reaches, sometimes up to 200–300 m. The banks are mostly flat and swampy, covered with forest in some areas [1, 2].

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Currently, a hydrological gauging station operates on the Western Bug River in the village of Novoselki, as well as on the tributaries of the Mukhavets and Lesnaya Rivers. Observations have been conducted since 1975. The Western Bug River is characterized by mixed feeding with a predominance of groundwater, which is caused by the low thickness of the snow cover and the predominance of easily permeable soils. The average annual water flow on the border of Ukraine and Belarus is 50 m^3/s, when leaving Belarus – 100 m^3/s [3, 4].

Study of hydromorphological parameters associated with changes in the river bank. The study of the Western Bug River was carried out within the framework of the State Scientific and Technical Program "Nature Management and Environmental Risks" on the assignment "To assess changes in hydromorphological, hydrological and hydrochemical indicators of the Western Bug River and to develop measures to reduce their negative consequences". During which it was established that significant changes in the coastline occur from the right (Belarusian) bank due to the nature of the river flow from south to north and the direction of the Coriolis force vector [5, 6].

The Western Bug River is a water body with a high risk of flooding due to spring floods and rain floods, which can result in significant flooding of coastal areas, including border infrastructure, agricultural lands and objects, residential and other buildings.

The main factors that lead to the shift of the fairway of the Western Bug River are: abrasion (erosion) of the banks, breakthrough of meanders, multi-branching (formation of shoals and islands). The maximum established displacement was 470 m. As a result of previous studies, 36 sections of the Western Bug River with a significant (more than 100 m) displacement of the river fairway over a 35-year period (1981–2016) were identified. 198 sections with multiple branches and 93 sections with right bank abrasion were identified. The amount of right bank abrasion at 255 sections was 3.665 km^2. Natural hydromorphological changes in the Western Bug River led to both right bank abrasion (channel displacement to the right) and right bank accumulation (channel displacement to the left). The amount of right bank accumulation at 252 sections was 4.137 km^2. Despite the fact that the overall balance of right bank abrasion and accumulation is positive for Belarus along the entire transboundary section of the Western Bug River (+47.2 ha), it should be noted the intense prevailing abrasion of the right bank on the "upper section" of the river.

Western Bug from the state border "Belarus – Ukraine" to the settlement Domachevo, as well as a number of individual sections with intense abrasion of the right bank (more than 3 ha) on the "middle section" from the settlement Domachevo to the city of Brest and the "lower section" from the city of Brest to the settlement Krynki [7, 8].

The purpose of the work was to provide a hydrological justification for the implementation of channel-regulating and bank protection measures in connection with the ongoing coastal erosion processes on the border sections of the Western Bug River.

Materials and methods

Estimated hydrological parameters

The observation period for the maximum water levels of the spring flood on the Western Bug River at the Novoselki section and on the Lesnaya River at the Tyukhinichi section is 35 years from 1988 to 2022. To identify the features of fluctuations in the maximum water levels of the spring flood on the Western Bug and Lesnaya Rivers, difference integral curves were constructed for 1988–2022, which show that the period under study includes intervals of decrease and increase in the maximum water levels of the spring flood, and since the beginning of the 20th century it has been in a positive phase – an upward trend, and only in recent years have the maximum water levels begun to decrease.

The results of calculations to determine the maximum water levels of the spring flood with a probability of 1, 3, 5 and 10 % along the Western Bug River at the Novoselki section are presented in Table 1, which were performed using the Hydrolog-2 software package [9–12].

Table 1 – Maximum water levels of spring floods with 1, 3, 5 and 10 % probability of the river Western Bug – Novoselki

Parameter	Water level, cm	Absolute level of BS, m
$H_P = 1\,\%$	556	124.56
$H_P = 3\,\%$	504	124.04
$H_P = 5\,\%$	479	123.79
$H_P = 10\,\%$	442	123.42

In classical approaches to hydrology, the provided values of levels are determined on the basis of data from hydrometric gauging stations located above and below the section under study. However, in this case, the Western Bug River, being a border river, does not have hydrometric gauging stations upstream and downstream of the study area. Transfer of levels of different probability is possible only on the basis of observation data from two observation points, both of which are located downstream, namely, a gauging station on the Lesnaya River in the settlement of Tyukhinichi and a gauging station on the studied Western Bug River in the settlement of Novoselki. In this case, we have, on the one hand, a gauging station on the studied river at a considerable distance, and on the other hand, a gauging station on a river of a lower order much closer downstream, but at the same time having different hydraulic conditions for the formation of levels and discharges. In conditions of limited observation data, observation data from both gauging stations were used simultaneously. Three approaches were used to calculate the calculated slopes: average annual level, level in the calculated month and level on the date of measurements. The level on the date of measurements should be discussed separately. Based on the data of one-time hydrometric studies, the actual levels in the section of the object on the Western Bug River were determined. One-time data allowed us to calculate the slopes during the period of work, which provided the possibility of verifying the results.

The transfer of levels was made on the basis of the calculated values of hydraulic slopes corresponding to the high-water period, taking into account the assumption of similar hydraulic conditions for the rivers Western Bug and Lesnaya in the high-water period. The averaged results for two calculation points are presented in Table 2.

Table 2 – Maximum water levels of spring floods with 1, 3, 5 and 10 % probability of the Western Bug River – the section under study

Parameter	Absolute level of BS, m
$H_P = 1\,\%$	130.87
$H_P = 3\,\%$	130.52
$H_P = 5\,\%$	130.34
$H_P = 10\,\%$	130.08

To transfer the average levels, we used data from natural (one-time measurements) and data from observations of the water level at the Novoselki station, assuming that on the date of measurements the levels in the studied section corresponded to the long-term level (126.40). The calculated levels in the studied section are presented in Table 3.

Table 3 – Average annual water levels of the river. Western Bug – Novoselki

Parameter	Absolute level of BS, m
$H_P = 25\,\%$	126.78
$H_P = 50\,\%$	126.58
$H_P = 75\,\%$	126.44

Due to the lack of hydrological observation data on water flow along the Western Bug River in the studied section, we used various alternative methods for determining the main hydrological parameters and obtained the following values of average annual water flow (Table 4).

Table 4 – Average annual water flow of the Western Bug River in the studied section

Parameter	Q, m^3/s
$Q_P = 5\,\%$	154
$Q_P = 10\,\%$	133
$Q_P = 25\,\%$	106
$Q_P = 50\,\%$	80.2
$Q_P = 75\,\%$	58.6
$Q_P = 90\,\%$	45.9
$Q_P = 95\,\%$	35.6

Analysis of the Western Bug riverbed transformation

Geoinformation systems are widely used in modern science. For the retrospective analysis of the spatial displacement of the studied section of the Western Bug river bed, remote sensing data in the form of visible range images from 2004 to 2022 were used. The collected raster data were spatially referenced in the flat coordinate system Pulkovo_1942_CS63_Zone_C1. A database of the spatial position of the right bank of the river was formed in the form of linear vector objects (Figure 1) [13].

Using the methodology developed by the authors and described in detail in [14, 15], the shift in the position of the channel and the transformation of sinuosity were analyzed. In addition, the developed spatial model of the channel was used as a basis for the research. The results of digital information processing are presented in Figure 2–4.

Figure 1 – Vector object “bed edge”

Figure 2 – Analysis of displacements of the coastline of a section of the river bed (2004–2022)

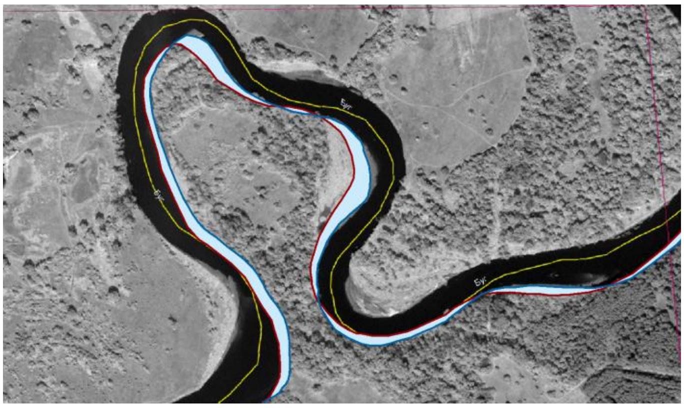

Figure 3 – Analysis of displacements of the coastline of a section of the river bed (2004–2022)

Figure 4 – Analysis of the displacement of the coastline of the river bed section (2012–2022)

Thus, the conducted analysis allowed us to record the change in the coastline over time in the studied area, which indicates the advisability of carrying out bank protection works in order to prevent the erosion of the coast by the current and, as a consequence, the formation of a new channel [16].

To process the remote sensing data, the indicator of the speed of the coastline movement process was used, which is the ratio of the right/left areas formed by the intersection of the vector object of the coastline at the initial and final moment of time, to the length of the studied section of the river and the time of these processes. Thus, the following results were obtained, presented in Table 5.

Table 5 – Calculation of the transformation rate of the Western Bug River bank

Time period, years	Sum of right areas, m^2	Sum of left areas, m^2	Section length, m	Velocity of transformation in the form of blur, m/year	Velocity of transformation in the form of deposits, m/year
2004–2012	17372.16	12611.67	2400	0.90	0.66
2012–2022	20951.33	7166.72	2485	0.84	0.29
2004–2022	36723.95	18178.84	2400	0.85	0.42

As can be seen from this table, the rate of these processes for individual time intervals differs slightly; primarily this concerns the rate of formation of a new coastline due to deposits. However, the erosion process, which is comparable for both time intervals, is of considerable interest from the point of view of predicting the occurrence of negative consequences. In further studies, the rate of spatial deformation of the coastline was adopted as 0.85 m/year.

Digital models of the river section relief development

GIS support ArcGis and its ArcToolbox toolkit, as well as tools of the MIKE 3 hydraulic modeling environment [17–19].

The following raster layers of various scales were used as cartographic bases:

- raster topographic maps;
- raster map of the Open street maps web service;

- raster images of remote sensing of the earth (maps.googleapis.com; Bing.map, etc.);
- data of geodetic surveys provided by the customer;
- data of echo sounding surveys of the river depth within the study area provided by the customer.

The data from the usgs.gov portal were used as the initial digital relief map for calculating the river catchment area in the calculation section. Within the study area, 30 raster data on the elevation marks of the terrain are available, with a resolution of one arc minute [20]. The resolution of the digital elevation model was 30 m by 38 m. Using the algorithms of the ArcGIS application, the catchment area of the Western Bug River in the studied section was calculated, which was 24865501221 m^2.

An irregular grid with a customizable cell size was used as the basis for the channel model. Thus, for the channel zone within the echolocation survey data, the maximum grid size was no more than 50 m^2, for the channel zone – 70 m^2, for the floodplain part – 400 m^2. To form the general boundaries of the model area, arcs with specified arc parameters were drawn.

General description of the water mass movement hydrodynamic model

Low water equations are a system of hydrodynamic equations adapted for modeling water flows in shallow water conditions. In the context of this work, low water equations play a key role in providing accurate and efficient modeling of water mass motion in river systems and coastal zones. The Navier-Stokes equations are the complete hydrodynamic equations describing fluid motion. In the context of hydrodynamic modeling for aquatic systems, they are written as [21, 22, 23]:

$$\frac{\partial \boldsymbol{u}}{\partial \boldsymbol{t}} + (\boldsymbol{u} \cdot \boldsymbol{\nabla})\boldsymbol{u} = -\frac{\boldsymbol{1}}{\boldsymbol{\rho}}\boldsymbol{\nabla p} + \boldsymbol{g} + v\boldsymbol{\nabla}^2\boldsymbol{u}\,; \tag{1}$$

$$\boldsymbol{\nabla} \cdot \boldsymbol{u} = \boldsymbol{0}\,, \tag{2}$$

where $\boldsymbol{h}$ – the velocity vector, $\boldsymbol{u}$ – the velocity vector, $\boldsymbol{\rho}$ – the fluid density, $\boldsymbol{p}$ – the pressure, $\boldsymbol{g}$ – the acceleration of gravity, $\boldsymbol{v}$ – the kinematic viscosity.

Low water equations are a simplified version of the Navier-Stokes equations used in shallow waters. The main difference is that low water equations take into account the vertical pressure distribution, making them more suitable for modeling river and coastal flows.

In low water equations:

$$\frac{\partial \mathrm{h}}{\partial \boldsymbol{t}} + \frac{\partial(\boldsymbol{hu})}{\partial \boldsymbol{x}} + \frac{\partial(\boldsymbol{h}\mathrm{v})}{\partial \boldsymbol{y}} = \boldsymbol{P} - \boldsymbol{E} - \boldsymbol{R}\,; \tag{3}$$

$$\frac{\partial(\boldsymbol{hu})}{\partial \boldsymbol{t}} + \frac{\partial(\boldsymbol{hu}\mathrm{v})}{\partial \boldsymbol{y}} + \frac{\partial(\boldsymbol{hu}^2 + \frac{1}{2}\boldsymbol{gh}^2)}{\partial \boldsymbol{x}} = -\frac{\partial \boldsymbol{p}}{\partial \boldsymbol{x}} + \boldsymbol{Tbx}\,; \tag{4}$$

$$\frac{\partial(\boldsymbol{h}\mathrm{v})}{\partial \boldsymbol{t}} + \frac{\partial(\boldsymbol{hu}\mathrm{v})}{\partial \boldsymbol{x}} + \frac{\partial(\boldsymbol{h}\mathrm{v}^2 + \frac{1}{2}\boldsymbol{gh}^2)}{\partial \boldsymbol{y}} = -\frac{\partial \boldsymbol{p}}{\partial \boldsymbol{y}} + \boldsymbol{Tby}\,, \tag{5}$$

where $\boldsymbol{h}$ – the water depth, $\boldsymbol{u}$ and $\boldsymbol{v}$ – the horizontal and vertical velocity components, respectively, $\boldsymbol{P}$ – the moisture input, $\boldsymbol{E}$ – the evaporation, $\boldsymbol{R}$ – the runoff, $\boldsymbol{g}$ – the acceleration due to gravity, $\boldsymbol{Tbx}$ and $\boldsymbol{Tby}$ – the horizontal and vertical components of the frictional moment.

The choice of low-water equations is justified by the need to take into account the features of hydrodynamic processes in river systems and coastal zones. Low-water equations provide an adequate description of water movement at shallow depths, which is often encountered in these conditions [24]. A comparative analysis of the equations allows us to highlight their applicability in various modeling scenarios, and low-water equations become the preferred choice for this work, providing a balance between accuracy and computational efficiency in conditions of limited depths.

Development Methodology

The first stage of the program development was the definition of goals and objectives. This included defining the scope of the program, end users and expected results. The goal was to create a tool capable of simulating the movement of water masses in river systems with high accuracy.

After defining the goals, an analysis of available technologies and tools for program development was carried out.

The design of the program architecture included defining the data structure, choosing numerical analysis methods, and integration with the MIKE 3 interface. The program architecture ensured the efficient execution of numerical calculations and ease of implementation in the existing MIKE 3 environment [17, 18].

At the stage of implementing the mathematical model, algorithms based on low-water equations were written. The numerical methods used to solve differential equations ensure stability and accuracy of calculations. The integration of the program with MIKE 3 required interaction with the API and technical specifications of MIKE 3. This included the correct transfer of data between the program and the MIKE 3 platform, as well as ensuring compliance with MIKE 3 standards and requirements.

The program was tested on various test scenarios, including various hydrodynamic conditions and geographical features. Debugging included fixing identified errors and optimizing performance.

After completion of the development, the program was validated and calibrated. This stage included comparing the simulation results with real data and adjusting the model parameters to achieve optimal compliance with real conditions.

The entire development process is documented, including a description of the architecture, solution methods, and technical documentation on integration with MIKE 3. This ensured understanding and support of the program.

Implementation of the program

To implement the program, a programming language was selected that ensures efficient calculations and convenient interaction with the existing MIKE 3 environment. As a result, Python/C++ was chosen, providing flexibility and high performance [20].

To speed up development and ensure program stability, appropriate libraries and frameworks were used. This included libraries for numerical calculations, data processing and interaction with the MIKE 3 interface.

The program was developed taking into account a modular architecture that allows for easy support and further expansion. The modules included the main computing units, an interface for interaction with MIKE and components for processing input and output data.

The solution of the system of low-water equations was implemented using numerical methods. Suitable methods were selected for numerical integration and solving differential equations, ensuring stability and accuracy of calculations.

To successfully integrate the program with MIKE, interaction with the API was carried out. This included the transfer of hydrodynamic model data between the program and MIKE, as well as the management of modeling processes via the MIKE interface.

The program provides means for visualizing modeling results. This includes graphical display of water mass trajectories, changes in water depth, and other parameters, allowing users to visually evaluate the results.

The entire development process was accompanied by documentation, including technical documentation on the MIKE 3 API, user manuals, and installation instructions. This ensures transparency in using the program and facilitates the implementation process.

After successful completion of all testing and troubleshooting stages, the program is ready for the final stage of implementation.

Model parameters

The model parameters were adjusted based on calibration data in the form of the maximum spring flood flow of 50 % of the estimated probability.

The adjustment was carried out in the absence of the influence of the planned construction of protective dams.

The adjustment was carried out with the following parameters: the average annual flow of the Western Bug River in the studied section is 80.2 m^3/s, the mark in the inlet section is 126.58 m BS, the hydraulic slope is 0.122 ‰. Using these model parameters, the natural roughness of the river bed was adjusted.

The model took into account the effect of Coriolis acceleration, as well as the unevenness of the model grid.

Results and discussion

Analysis of research results

The calculations were carried out using the server computing equipment of BrSTU and allowed us to build a picture of the spatial and temporal patterns of the free surface levels of the flow, as well as the velocity field. The total spatial and temporal resolution of the model is 371,000 cells with 100–200 time intervals at 10–20 layers of the vertical grid. Thus, the maximum number of calculation cells is 1484 million and, accordingly, the same number of equations in the system. The adjustment was carried out by adjusting the parameters of the channel roughness, as well as the structure and parameters of the calculation grid. The number of time intervals was adjusted in order to achieve a steady state, as can be seen in Figure 5, as a rule, stabilization was observed at the 80–90 time step.

The overall simulation results for four design flow rates and levels are shown in Figures 6–8.

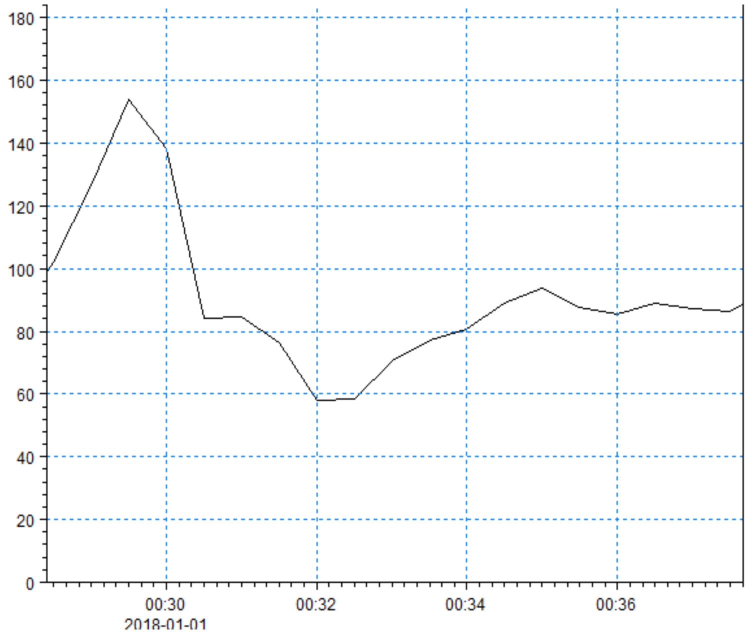

Figure 5 – Variability of flow rate in the design section over time

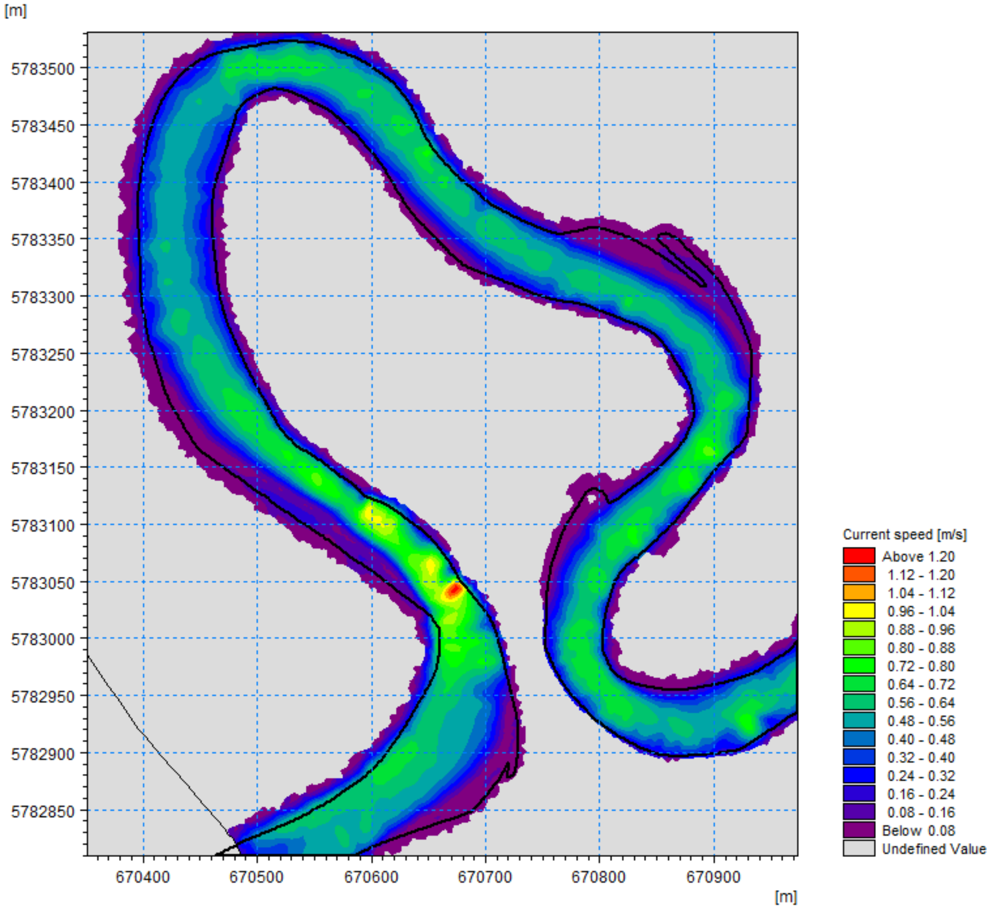

Figure 6 – Velocity field at an average annual flow rate of 25 % probability

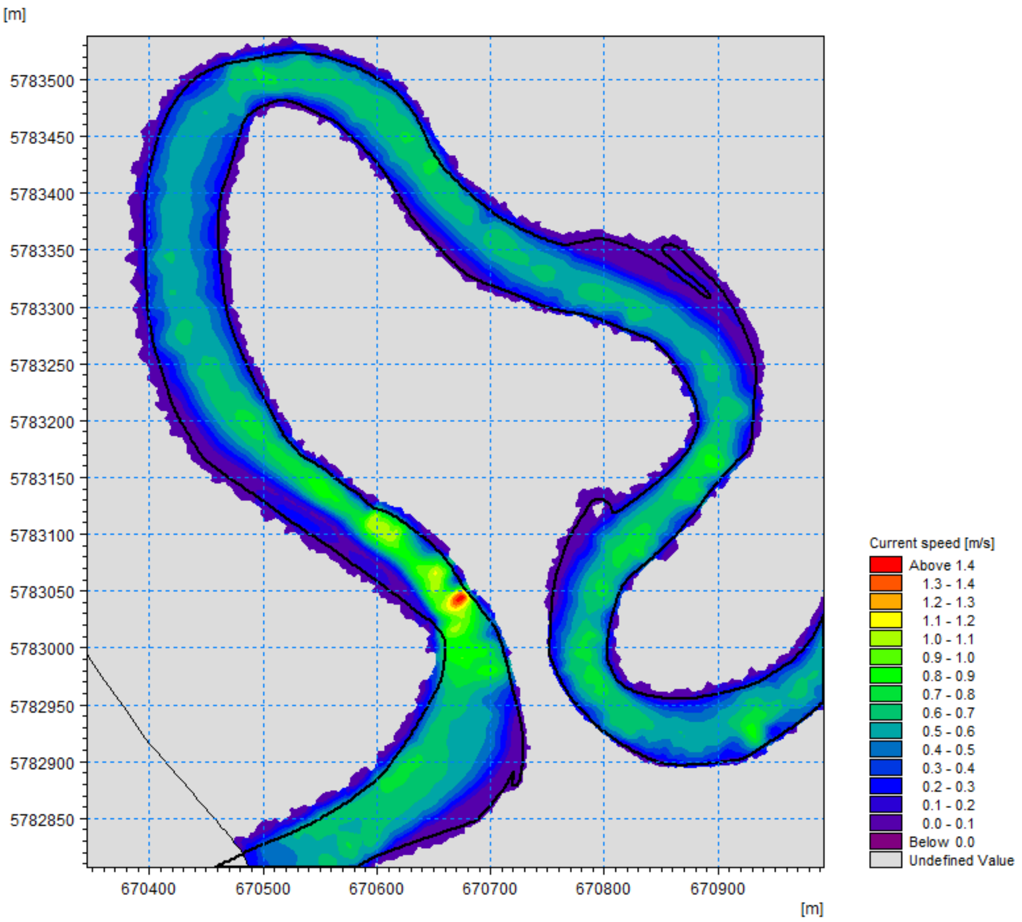

Figure 7 – Velocity field at an average annual flow rate of 50 % probability

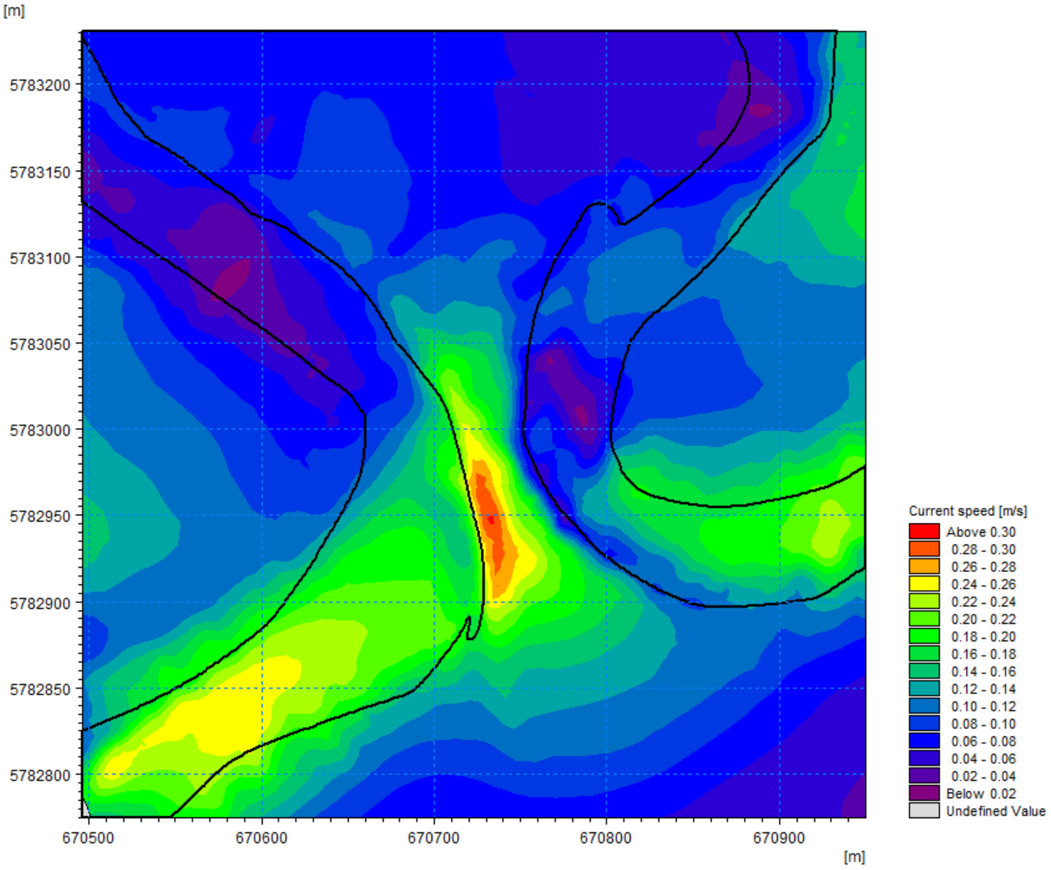

Figure 8 – Velocity field at spring flood flow rate of 10 % probability

Analyzing the obtained results, it is possible to identify areas at risk of erosion, namely the coastal/shore zone along the right bank in the area of the bend, both before and after it. The second section refers to the floodplain zone, the flooding of which occurs during the spring flood corresponding to the maximum convergence of the meanders of the channel. The velocities obtained as a result of modeling do not exceed 2 m/s in the channel part. The recommended method of support is rock fill or stone paving. For the floodplain part near two meanders, it is also necessary to provide for support in the form of rock fill with the device of a connecting structure for the passage of flood waters. The dimensions of the structure and the parameters of the support are determined by the project based on the actual geological conditions, resistance to erosion and the availability of applicable materials.

Coastal fortifications

The choice of the type of bank reinforcement is made subject to the conditions of technical feasibility and economic advantage; it is recommended to use building material available at the work site or in the immediate area. Technical feasibility consists in the fact that the strength of the bank reinforcement structure corresponds to the forces it must withstand. Engineer Fargues, famous for his works in France, established a direct relationship between the curvature of the bank and the depth of the river near it, i.e. the degree of its erosion by the current. It should also be taken into account that the lower part of the bank slope in height from the base to the horizon of medium-low low water is constantly under water and is subject to the continuous eroding action of the river flow. The part of the slope from the horizon of medium-low low water to the horizon of the highest water is subject to the periodic eroding action of the flow, the destructive action of ice moving near the banks, the influence of atmospheric and ground water, in winter - the action of frost and, finally, is partially destroyed by trampling by animals and people. Above the horizon of the highest waters, the coast is exposed only to atmospheric waters and frost, and to trampling by animals and people. Particular attention should be paid to protecting the lower part of the slope from its base to the horizon of medium-low low waters, since the destruction of this part of the slope causes the collapse of the entire part located above. Part of the coastal slope from the last horizon to the horizon of the highest waters is first cut off and planned for a certain slope – from one and a half to three times, depending on the nature of the soil of which the coast consists. For weaker soils, a gentler slope is adopted. One or another type of coating is arranged along the planned slope, depending mainly on the magnitude of the spring flow speeds and the power of spring ice drift.

A distinction is made between active and passive coastal fortifications. The former significantly affect the structure of the flow in the coastal area, and the latter only protect the coastal slope from erosion. Coastal coverings can be continuous, securing the entire coastal slope from erosion, and strip covering separate parts of the river slope along the length from erosion.

Calculations of coastal coverings include the following sections [25, 26]:

- assessment of the stability of the covering under the influence of the current;
- determination of the length and width of the covering;
- calculation of the size of the stone and the thickness of the concrete slabs in the above-water part of the structure;
- determination of the thickness of the stone ballast in the underwater part of the slope.

Coastal slopes and fortifications on them, first of all, need to be checked for resistance to the impact of the current velocity in the area of the fortified bank. To determine the current velocity in the alongshore stream, natural or calculated plans of the flow on the river section are constructed at the average low-water and average flood water flow. If the river floodplain on the section is flooded during the flood, then the level of the floodplain (low-water) edges is taken as the calculated high water level. Based on the data on the granulometric composition of the soil making up the coastal slope and on regulatory materials, permissible (non-erosive) current velocities at the calculated water levels are established. Depending on the composition of the soils making up the slope, in accordance with regulatory requirements, the permissible laying of the coastal slope during its fortification is also established. Comparison of actual current velocities with permissible ones allows us to estimate the stability of the coastal slope under the impact of the water flow on it, and, if necessary, select the appropriate coastal fortification. The length of the coastal slope reinforcement zone is established on the basis of compared and combined plans of the site for a long-term period and plans of the flow at characteristic water levels.

To determine the width of the reinforcement, the coastal slope is divided into four zones: I – above-water slope zone; II – wave run-up and wind surge zone; III – variable level zone; IV – underwater slope zone (below low water levels).

The width of the reinforcement in each zone and the size of the stone for reinforcing the above-water slope are determined by calculation. The lower boundary of the protected area, as a rule, is located in the zone of intersection of the plane of the slopes and slopes with their base. If maximum bottom velocities exceed permissible values of non-eroding bottom velocities, an anti-erosion apron in the form of a flexible mattress, rock fill, etc. must be provided in the design of the bank protection structure. The erosion depth must be established based on in-kind observations or determined on the basis of calculations.

In order to select the most effective type of bank protection structure for a specific section and correctly assign its parameters, it is necessary to carry out detailed hydrological studies of the river regime, the results of which must contain the following data:

- the length and sources of supply of the river, the area of its catchment basin;
- the width and depth of the channel flow, its slope;
- the nature of the banks and the type of channel process in the studied section of the river, an assessment of the nature of deep and planned deformations of the channel and floodplain;
- current velocities, discharge and river level marks during low water and floods, their recurrence and probability;
- characteristics of floods, their intensity and duration, the boundaries of flooding of the area;
- data on the height, length, period and occurrence of wind waves;
- duration of ice drifts, as well as data on the thickness and density of the ice cover.

Comparison and selection of optimal designs should be accompanied by appropriate technical and economic justifications, the development of which should take into account the degree of feasibility and effectiveness of design and construction solutions for various options. Technical and technological solutions for a specific option should contain assessments of the economic, social and environmental effects of its implementation.

Conclusion

Retrospective analysis of aerial photography data for the period from 2004 to 2022 based on the dynamics of spatial deformation of the river bed made it possible to establish the average annual rate of coastline displacement, which amounted to 0.85 m/year. Provided that the general cross-section of the channel and the established predicted displacement rate are preserved, the value of channel erosion in the vertical plane was determined (0.41 m/year).

Based on the results of in-kind studies and remote sensing, a digital model of the terrain of the Western Bug River catchment area in the studied section was created, and based on the data of geodetic surveys and echo sounding, a detailed model of the channel of the studied area was constructed. The average long-term water flow in the studied section of the Western Bug River was 80.2 m^3/s, and the spring flood of 1 % probability was 818 m^3/s. The determination of the calculated levels was carried out on the basis of the natural hydraulic slope.

The developed hydraulic model of the studied section of the channel is based on the use of two dependencies: the low-water equation and the Navier-Stokes equation. The method was selected based on the convergence data when calculating the coefficient matrix of the system of equations. The model included from 10 to 20 layers of the computational grid vertically. Sections at risk of erosion were identified, namely the coastal/shore zone along the right bank in the area of the bend, both before and after it. The second section refers to the floodplain zone corresponding to the maximum convergence of the meanders of the channel, the flooding of which occurs during the spring flood.

In the channel part, bank stabilization is recommended in the form of rock fill or stone paving, since the flow rates do not exceed 2 m/s. For the floodplain part near two meanders, it is necessary to provide for stabilization in the form of rock fill with a connecting structure for passing flood waters.

References

1. Volchek, A. A. Vodnye resursy Brestskoj oblasti / A. A. Volchek, M. Ju. Kalinin. – Minsk : Izdatel'skij centr BGU, 2002. – 436 s.
2. Loginov, V. F. Vodnyj balans rechnyh vodosborov Belarusi / V. F. Loginov, A. A. Volchek. – Minsk : Tonpik, 2006. – 160 s.
3. Proekt Plana upravlenija bassejnom r. Zapadnyj Bug. – Minsk, 2016. – 54 s.
4. Ocenka izmenenija gidromorfologicheskih, gidrologicheskih i gidrohimicheskih pokazatelej reki Zapadnyj Bug i meroprijatija po snizheniju ih negativnyh posledstvij / V. N. Korneev, E. E. Petlickij, K. S. Titov, I. A. Bulak // Vestnik Brestskogo gosudarstvennogo tehnicheskogo universiteta. – 2021. – № 1 (124). – S. 90–95. – DOI: 10.36773/1818-1212-2021-124-1-90-95.
5. Pen'kovskaja, A. M. Vlijanie gidromorfologicheskih izmenenij v rechnoj seti na jeko-logicheskij status vodnyh ob'ektov bassejna reki Zapadnyj Bug / A. M. Pen'kovskaja, E. N. Popova, I. A. Bulak // Vestnik Brestskogo gosudar-stvennogo tehnicheskogo universiteta. Serija: Vodohozjajstvennoe stroitel'stvo, teplojenergetika i geojekologija. – 2016. – № 2. – S. 24–29.
6. Pen'kovskaja, A. M. Jekologicheskoe sostojanie poverhnostnyh vodnyh ob#ektov, vodoho-zjajstvennye problemy i meroprijatija, napravlennye na ih reshenie v bassejne reki Zapadnyj Bug / A. M. Pen'kovskaja, E. N. Popova. – Minsk : CNIIKIVR, 2015. – S. 226–228.
7. Mihnevich, Je. I. Ustojchivost' beregov vodohranilishh pri formirovanii profilja dinamicheskogo ravnovesija v nesvjaznyh gruntah / Je. I. Mihnevich, V. E. Levkevich // Melioracija. – 2016. – № 4 (78). – S. 18–23.
8. Volchek, An. A. Zatoplenija na territorii Belarusi / An. A. Volchek // Vestnik Brestskogo gosudarstvennogo tehnicheskogo universiteta. Serija: Vodohozjajstvennoe stroitel'stvo, teplojenergetika i geojekologija. – 2017. – № 2. – S. 39–53.
9. Volchek, A. A. Paket prikladnykh programm dlya opredeleniya raschetnykh kharak-teristik rechnogo stoka / A. A. Volchek, S. I. Parfomuk // Vesnik Paleskaga dzhzyarzhaýnaga universiteta. Seryya pryrodaznaýchykh navuk. – 2009. – №1. – S. 22–30.
10. Volchek, A. A. Gidrologicheskie raschety : ucheb.-metod. posobie // A. A. Volchek, P. S. Lopuh, An.A. Volchek. – Minsk : BGU, 2019. – 316 s.
11. Zheljaznjakov, G. V. Tochnost' gidrologicheskih izmerenij i raschetov / G. V. Zheljaznjakov, B. B. Danilevich. – L. : Gidrometeorologicheskoe izd-vo, 1966. – 240 s.
12. Raschetnye gidrologicheskie harakteristiki. Porjadok opredelenija. Tehnicheskij kodeks ustanovivshejsja praktiki : TKP 45-3.04-168-2009(02250). – Minsk : RUP «Strojtehnorm», 2010. – 55 s.
13. Volchek, A. A. Geoinformacionnaja sistema gidrograficheskoj seti vodosbora r. Zapadnyj Bug / A. A. Volchek, V. Sobolevski, N. N. Sheshko // Vestnik Brestskogo gosudarstvennogo tehnicheskogo universiteta. Serija: Vodohozjajstvennoe stroitel'stvo i teplojenergetika. – 2009. – № 2. – S. 2–8.
14. Volchek, A. A. Transformacija gidrograficheskoj seti malyh rek vodosbora r. Pripjat' v predelah prirodno-territorial'nogo kompleksa nacional'nogo parka «Pripjatskij» / A. A. Volchek, O. P. Meshik, N. N. Sheshko // Pryrodnae asjaroddze Palessja: zb. navuk. prac / Paleski agrarna-jekalagichny instytut NAN Belarusi; rjedkal. M. V. Mihal'chuk (gal. rjed.) [i insh.]. – Brjest; Al'ternativa, 2014. – Vyp. 7. – S. 11–14.
15. Volchek, A. A. Uchet razovyh gidrometricheskih izmerenij pri opredelenii osnovnyh gidrologicheskih harakteristik i parametrov rusla / A. A. Volchek, N. N. Sheshko // Saharovskie chtenija 2011 goda: jekologicheskie problemy XXI veka : materialy 11-j mezhdunar. nauch. konf., 19–20 maja 2011 g., g. Minsk, Respublika Belarus' / pod red. S. P. Kundasa, S. S. Poznjaka. – Minsk : MGJeU im. A. D. Saharova, 2011. – S. 237–238.
16. Makarevich, A. A. Rechnoj stok i ruslovye processy : posobie / A. A. Makarevich, A. E. Jarotov. – Minsk : BGU, 2019 – 115 s.
17. Flow Model FM – Hydrodynamic Module Scientific Documentation // DHI. MIKE 3. – URL: https://www.mikepoweredbydhi.com/products (date of access: 30.07.2024).
18. Sediment Transport Module ST – Scientific Documentation // DHI. MIKE 3. – URL: https://www.mikepoweredbydhi.com (date of access: 01.07.2024).
19. Kurushin, A. A. Reshenie mul'tifizicheskih SVCh zadach s pomoshh'ju SAPR COMSOL / Kurushin. – M. : «One-Book», 2016. – 376 s.
20. Kosicin, D. Ju. Jazyk programmirovanija Python: ucheb.-metod. posobie / D. Ju. Kosicin. – Minsk : BGU, 2019. – 136 s.
21. Aleksandrov, D. V. Vvedenie v gidrodinamiku: ucheb. posobie / D. V. Aleksandrov, A. Ju. Zubarev, L. Ju. Iskakova. – Ekaterinburg : Izd-vo Ural. un-ta, 2012. – 112 s.
22. Komp'juternoe modelirovanie processov perenosa i deformacij v sploshnyh sredah: Uchebnoe posobie / V. E. Ankudinov, D. D. Afljatunova, M. D. Krivilev, G. A. Gordeev. – 1-e izdanie. – Izhevsk : Izd-vo «Udmurtskij universitet», 2014. – 108 s.
23. Kolesnichenko, V. I. Vvedenie v mehaniku neszhimaemoj zhidkosti: ucheb. posobie / V. I. Kolesnichenko, A. N. Sharifulin. – Perm' : Izd-vo Perm. nac. issled. politehn. un-ta, 2019. – 127 s.
24. Kalugin, A. S. Matematicheskoe modelirovanie dvizhenija pavodochnoj volny pri ispol'zovanii ishodnoj informacii razlichnoj detal'nosti / A. S. Kalugin, I. N. Krylenko // Vodnoe hozjajstvo Rossii. – 2014. – №3. – S. 138–145.
25. Melezh, T. A. Inzhenerno–geologicheskaja ocenka jekzodinamicheskih rezhimov doliny reki Pripjat' i prilegajushhih territorij / T. A. Melezh, A. I. Pavlovskij // Vestnik VGU. Serija: Geologija. – 2015. – № 3 – S. 122–124.
26. Mihnevich, Je. I. Propusknaja sposobnost' rusel reguliruemyh rek i vodootvodjashhih kanalov / Je. I. Mihnevich // Prirodnaja sreda Poles'ja: osobennosti i perspektivy razvitija: sb. nauch. tr. Vyp. 1: v 2 t. – Brest : Al'ternativa, 2008. – T. 2. Vodnye resursy Poles'ja. – S. 38–41.

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