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HYDROLOGICAL-STENOBIONTIC METHOD FOR DETERMINING ENVIRONMENTAL FLOWS FROM RESERVOIR

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In the practice of using river resources accumulated in reservoirs, there is a typical problem of unreasonably large water intake for industrial-household needs to the detriment of the aquatic ecosystem. An important tool for balancing these links is to provide environmental flows based on a comprehensive analysis of river functioning patterns. And in terms of a progressing negative impact of reservoirs on the integrity of river ecosystems, the choice of indicator hydrobiota for the calculation of environmental flows should be considered insufficiently substantiated. The solution of this problem, by filling the appropriate methodological niche, allowed substantiating the hydrological-stenobiontic method for determining environmental flows. The developed solutions are based on the minimum possible values of tolerance of aquatic ecosystems stenobionts to water velocity. Five groups of macrozoobenthos represent relevant target organisms. The hydrological calculations presented in the paper are based on the data of daily water flow rate for 80 years and the results of field studies of the river channel depth in the low water period. On this basis, it was determined that for lowland parts of rivers, the flow velocity in the tailwater of reservoirs should be at least 0.2 m/s. Comparison of the curve of the average monthly water velocity dynamics of 95 % runoff availability with the minimum corresponding requirements of stenobionts allowed determining the most threatening period of the year for the aquatic ecosystem – summer low water. For a reservoir in the lowland parts of the river, based on the developed method, the calculations substantiate an increase in the minimum volume of environmental flows by 40 % relative to the current one. It is also estimated that the average annual and average second volumes of environmental flows should be about 38 % of the respective river runoff. The obtained results are close to those found on rivers in China, Iran and the United States in the framework of a comprehensive analysis of hydrological, hydraulic and hydrobiological parameters of the aquatic ecosystem

Keywords: environmental flow, river channel reservoir, flow velocity, tailwater of reservoir, requirements of aquatic organisms

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1. Introduction

Water level and water flow rate are one of the most important water management characteristics of rivers, especially in water-deficient regions. Accordingly, the more stable these indicators are during the year, the better. In the practice of water use, this condition is implemented with the help of reservoirs, often without taking into account the seasonality of the high and low water periods. For example, some experts in the hydropower industry operate with the idea (in the context of increasing the volume of the river channel reservoir) that a flooded floodplain is a normal natural phenomenon [1]. However, it is not mentioned that this is typical for one or two months of the year, during floods. The natural dynamics of waters are not taken into account.

River damming is a global practice and usually performs several functions: energy, irrigation and water supply. However, with the construction of any river channel reservoir, the defining parameter of any hydroecosystem – continuity of river flow – is practically leveled [2]. While flow velocity affects the formation of some important "economic" indicators of the aquatic ecosystem: productivity, biodiversity, quality of water resources [3, 4].

The difficulty of finding a compromise in creating reservoirs to provide household and industrial water needs and environmental flows into the lower reaches is explained by the consumer approach to the river ecosystem. This problem is common all over the world, causing the degradation of biodiversity, physical and chemical parameters of water, disrupting the sustainable flow of ecosystem services. The creation of a large cascade of reservoirs on the Colorado River, for example, has exacerbated the scarcity of freshwater resources in the arid zone, rather than solved the problem [5].

One of the obligatory compromises is environmental flows to the tailwater of river channel reservoirs. However, their establishment is currently carried out by several methods. And each state independently institutionalizes regulations of the corresponding calculations.

Methods for determining the volume of environmental flows are focused either on specific river parameters (hydrology, hydraulics, biota, anthropogenic capacity, etc.), or a combination thereof. But the minimum functional requirements of aquatic organisms to flow (water) velocity and their ecological features of survival remain underestimated. This is especially important in terms of significant niches in information about fundamental aspects of aquatic biology, when the ecological processes that support aquatic ecosystems are insufficiently studied [6]. In addition, threats to river integrity are increasing due to rising water intakes, disturbance of river basins and climate change.

Currently, there are about 58 thousand large and 16 million small reservoirs in the world, which retain 20 % of river freshwater runoff [7]. As a result, the transformation of aquatic ecosystems downstream and upstream has similar, if not greater, scales. Therefore, the complexity and validity of methods for determining environmental flows are important to ensure balanced water use in river basins and minimize the negative impact of reservoirs on aquatic ecosystems.

2. Literature review and problem statement

In the practice of water use, several methods of calculating environmental flows have become widely used:

1) hydrological (according to the long-term supply curve; by the Tennant (or Montana) method [8, 9]). It is based on the observation data of river water flow over some time and statistical analysis methods [6];

2) hydraulic (for example, according to the wetted perimeter of the channel);

3) modeling of the physical habitat (Physical Habitat Simulation System (PHABSIM)) within incremental (Instream Flow Incremental Method (IFIM)). A detailed, simulated analysis is performed both for water amount and for the suitability of the river's physical habitat for the target biota [10], which is fish [11];

4) response of the aquatic ecosystem to its transformation (Downstream Response to Imposed Flow Transformations (DRIFT)). Factors of hydrology, hydraulics, water quality, geomorphology, hydrobiota are taken into account [12]. DRIFT is an example of holistic (complex) methods (Environmental Flow Management Plan Method, Building Block Methodology, etc.) aimed at providing the water needs of the entire river ecosystem [6].

According to [13], relatively fast hydrological and hydraulic methods are the most inaccurate in practice. And methods that take into account the biota response take 1–5 years to obtain reliable results.

There are opposing views. According to the conclusions [14], hydraulic and hydrological modeling methods provide the most comprehensive approach to flood and low flow period forecasting. But in this case, when the priority is a resource view of the river, it is impossible to predict the productivity of the aquatic ecosystem and its recreational status.

In the case of PHABSIM, there are opinions [15, 16] on the complexity of the practical application of this method to establish a river flow regime in order to achieve environmental goals in the basin.

Therefore, holistic methods have become widespread in the practice of substantiating the volume of environmental flows. The practical sense of their application is to determine the regime of river runoff, which supports the existence of all species, not just one or several [6], mainly fish. In addition, the water regime should be as close as possible to natural.

A common poorly studied feature of hydrological-biotic methods (IFIM and holistic group) is that they do not take into account the peculiarities of ecological survival strategies of target (indicator) species of aquatic organisms. In particular, the sensitivity of eurybionts and stenobionts to hydrodynamic changes in the river, namely, the tolerance range of these changes. From the point of view of the ecosystem approach, this suggests the presence of an error in the known hydrological-biotic methods of calculating environmental flows.

According to [17], irrational and scientifically unreasonable use of water resources in river basins causes their degradation, reduces groundwater levels and worsens hydrobiological indicators. Thus, the application of morphological and ecological methods (based on ichthyofauna) of environmental flow calculation revealed that in the low flow period on the Liao River, the ratio of environmental flows to the average annual natural runoff is 5–13 % and 19–37 %, respectively. Obviously, using the peculiarities of the ecological functioning of the river biota to substantiate the volume of environmental flows is more "watery" than purely abiotic parameters. Despite the comprehensive approach, the analysis of the methodology of this study suggests the approximate accuracy of the results. This is due to the lack of "synthetic analysis" criteria. In particular, the procedure of comparing the water flow and wetness curves of the channel by "manually" determining the points of their function change needs additional substantiation.

In [18], in terms of substantiating environmental flows from the Guanting Reservoir on the Yongding River (China), the spawning velocity of fish was identified as a priority environmental goal in water management. This is especially true in the most critical period in the region, when much water is taken for irrigation. According to the obtained results, the minimum, average and ideal average annual environmental runoff for the Yongding River is $1.56 \cdot 10^8$ m^3, $5.97 \cdot 10^8$ m^3 and $11.02 \cdot 10^8$ m^3. These are approximately 7.19 %, 27.51 % and 50.78 % of natural river runoff, respectively. At the same time, during the periods of floods and biological reproduction in spring on the Yongding River, the needs of the economic complex should be within 20 % of runoff volume.

In [19], an attempt was made to combine the biosphere law of tolerance, the adaptation properties of aquatic organisms and the laws of the hydrological regime of the Wei River to calculate environmental flows. In particular, the Tennant method was improved by using the frequency of runoff in each month, rather than the average annual value of water flow. However, the author's conclusion is contradictory in that it is necessary to regulate the maximum water flow (to restrain the river), and not only environmental (often, the minimum necessary) flow. But this eliminates the ecosystem property of the river to self-purify by flood waters.

In fact, the range of maximum values of the monthly flow probability curve in other works [20] is also considered as the optimal environmental flow for a given month, which is fundamentally true according to the biosphere law of optimum.

Attention should be paid to the fact that many researchers, working with hydrological methods, do not take into account the factor of water evaporation from the reservoir, which affects the average second water flow. That is, at the point of runoff detention through the dam, water is not only accumulated, but also lost in the form of steam. This, in turn, causes a decrease in the average annual flow of water from the river, while other factors may remain unchanged. In this context, [20] concluded that the damming factor is more influential on river water content than climate change.

Noteworthy are the results of determining the volume of environmental flows from many channel dams in Iran, on the Zab River. Based on the use of hydrological, hydraulic and hydrobiological methods (indicator group – fish), it was found that to preserve the river ecosystem in the upper, middle and lower reaches, it is necessary to provide 35 %, 17 % and 18 % of the average annual runoff, respectively [21].

Environmental flow calculation programs or sites are also used in water management practice. However, these tools are either very simple [22] (only the cross-sectional area of the channel, water velocity (m/s) and water flow rate (m^3/s) are taken into account), or the result is based on expert opinion [23].

In general, the analysis of the practice of determining environmental flows showed that the issue of substantiation of the target biota and its requirements for the river flow velocity is insufficiently resolved.

According to [17], for most species of fish, the optimal river flow velocity during spawning is 0.3–0.4 m/s, and should be at least 0.15 m/s [24] to ensure minimal living activity (Table 1).

Table 1

Flow velocities (m/s) taken into account in fish ladder design [24]

Fish species	Threshold	Stimulating	Flushing
Sturgeon:			
adult fish	0.15...0.2	0.6...0.9	0.9...1.2
young	–	–	0.15...0.2
Salmon:			
adult fish	0.2...0.25	0.8...1.0	1.1...1.6
young	–	–	0.25...0.35
Ordinary fish:			
adult fish	0.15...0.2	0.5...0.7	0.9...1.2
young	–	–	0.15...0.25

However, a significant disadvantage of fish ladders is that these hydraulic structures are usually built in the form of steps. This form and dynamics of water flow are normal for salmon, but other fish species cannot overcome them [25], not to mention other aquatic organisms. In view of this, it may be assumed that insufficient elaboration of this methodological niche in the known hydrological-biotic methods for determining environmental flows lays down an error in the corresponding calculation results.

The fundamental river property, "fluidity", is crucial in the formation of the ecosystem. And hydrological-biotic methods for determining the volume of environmental flows emphasize the importance of taking into account river flow velocity [6]: either as a factor in forming the environment for hydrobiota, or as a tool for assessing complex changes in the aquatic ecosystem. However, the requirements of hydrobiota for the minimum numerical value of the flow velocity in the tailwater and lower reaches of the river after reservoirs and the justification for the choice of appropriate target (indicator) organisms remain insufficiently taken into account.

Since the most sensitive inhabitants are the first to respond to ecosystem changes [26, 27], it is important to determine the level of this sensitivity and, in fact, the ecological requirements of stenobionts for flow velocity.

The target group of organisms was selected among the representatives of macrozoobenthos: stoneflies (*Plecoptera*), mayflies (*Ephemeroptera*), caddisflies (*Trichoptera*), alderflies, dobsonflies and fishflies (*Megaloptera*), amphipods (*Amphipoda*).

Thus, the hydraulic requirements of macrozoobenthos are recognized as useful tools for managing aquatic ecosystems and assessing their integrity in terms of the dynamics of water flows, which is inherent for the river channel dam [28, 29]. In the United States, for example, aquatic invertebrates are used in 50 states to assess the biological health of streams and rivers [29].

Relevant studies of US rivers have revealed [30] that the lower the river velocity, the smaller the distance of mayflies movement (drift, migration). This conclusion is extremely important for environmental protection in the context of substantiating the possibility of organizing water intakes and domestic discharges on lowland parts of rivers. In such conditions, if the river velocity is not taken into account, the risk of death of a significant part of the food chain increases due to the inability to leave the contaminated area.

The US experience has also shown [29] that water intake of more than 85 % of river runoff, combined with increased water temperatures, reduces macrozoobenthos species diversity. At the same time, the most stress-sensitive species were the first to respond to changes and were displaced by more adapted ones to the deficit of runoff.

The expediency of involving ecological survival strategies of macrozoobenthos in the process of environmental flows substantiation is related to the fact that they: are sensitive to the stability of hydrological and hydraulic conditions [28, 29] and the presence of pollutants in water [31–33], occupy an important place in food chains [34], are economically and practically available [35], the life cycle involves a sedentary lifestyle [33, 35], have a wide distribution area [35].

The results of the analysis of the outlined target group of organism's sensitivity to flow velocity are given in Table 2.

Table 2

Requirements of stenobionts for river flow velocity

Stenobionts	Flow velocity
Mayflies (*Ephemeroptera*)	>0.2 m/s [36–38]
Stoneflies (*Plecoptera*)	>0.2 m/s [38–40]
Alderflies, dobsonflies and fishflies (*Megaloptera*)	>0.2 m/s [38]
Caddisflies (*Trichoptera*)	>0.2 m/s [38, 41, 42]
Amphipods (*Amphipoda*)	>0.1 m/s [43]

In contrast to the data in Table 2, in [26], for example, the minimum flow velocity for most representatives of macrozoobenthos (except amphipods) is determined to be 0.1 m/s, and the average (normal) is 0.6±0.1 m/s.

Comparing the data given in Table 1, 2, it is seen that the minimum requirements of macrozoobenthos for flow velocity are higher than for fish. The same aspect confirms their stenobiont features at least in the range of low river flow dynamics. Therefore, for ensuring the functional integrity of the aquatic ecosystem, in the process of substantiating the volume of environmental flows, it is logical to rely on the biological requirements and ecological features of benthic invertebrates.

The above also shows a practical need to integrate the ecological characteristics of stenobionts in the process of reservoir management.

3. The aim and objectives of the study

The aim of the study was to develop a hydrological-stenobiontic method for determining environmental flows, taking into account the functional requirements and environmental features of some representatives of macrozoobenthos to water flow velocity. This will increase the ecosystem objectivity of the volume of environmental flows from reservoirs, which will promote balanced water management in the upper and lower reaches of the river.

To achieve the aim, the following objectives were set:

– to substantiate the method of determining the volume of environmental flows, taking into account the hydrological and hydrobiological parameters of the aquatic ecosystem (on the Southern Bug River example);

– to assess the ecosystemness of current environmental flow volumes, based on the functional requirements of stenobionts to water flow velocity.

4. Materials and methods for determining the volume of environmental flows

The volume of environmental flows was determined by synthesizing hydrological, hydraulic and biological methods.

The river flow availability of the Southern Bug River was determined based on data from the Oleksandrivka hydrological post for 1936–2016 (taken from the Central Geophysical Observatory of Ukraine) and analysis of relevant information sources.

Environmental flows at the level of 17 m^3/s are regulated for the Oleksandrivsky Reservoir for today. However, methods of calculating and principles of substantiating this value cannot be found, because "Temporary rules of operation of the Oleksandrivsky Reservoir at the normal supported level of 16.0 m" is confidential information.

The essence of applying the biological part of the method was to determine the functional needs and ecological characteristics of aquatic organisms to the minimum flow velocity in the river. The indicators obtained within this framework are the result of the analysis of relevant information sources (Table 2).

The parameters of the width and slope of the river channel for calculating environmental flows by the hydraulic method were obtained using Google Earth software tools. The depth of the Southern Bug at the research point was determined in the field. It was decided to calculate the length of the wetted perimeter and the channel cross-sectional area based on the geometric method, by combining the figures of a triangle and half of an ellipse (Fig. 1). Solving such problems by the geometric method has shown its effectiveness in forecasting the quantity and quality of water resources [44].

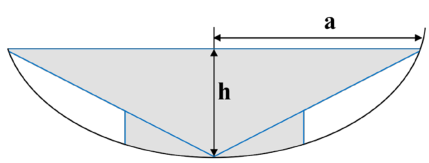

Fig. 1. Scheme of the river channel

In this case, the above scheme should be taken as a generalized schematic representation of the cross-section of the river channel.

The calculation of hydraulic parameters is based on the Chezy formula (1):

$$v = C \cdot \sqrt{R_h \cdot I}, \tag{1}$$

where C is the coefficient of friction resistance of water along the length of the channel (Chezy coefficient), which is an integral characteristic of resistance forces; R_h – hydraulic radius, m; I – hydraulic slope, m/m.

The hydraulic radius, the value of which, according to [45], for open watercourses should not exceed their depth, was determined by formula (2):

$$R_h = \frac{A}{P}, \tag{2}$$

where A is the cross-sectional area of the river, m^2; P – wetted perimeter, m.

The Chezy coefficient (C) was determined by the formulas of Pavlovsky N.N. (3), (4) (calculated values of the hydraulic radius R_h further did not exceed 3 m, which is methodologically correct):

$$C = \frac{1}{n} \cdot R_h^{\,y}, \tag{3}$$

$$y = 2.5\sqrt{n} - 0.13 - 0.75\sqrt{R_h}\left(\sqrt{n} - 1\right) \text{ at } R_h < 3-5 \text{ m}, \tag{4}$$

where n – channel roughness coefficient. According to [45], n=0.33 for the studied section of the Southern Bug river channel (Fig. 2).

Fig. 2. Layout of the studied section of the Southern Bug river channel (A: 47°41'39"N 31°15'39"E; B: 47°41'37"N 31°15'36"E)

The adequacy of the results was checked by comparing them with available published data on environmental flows into the reservoir tailwater and with the river runoff availability curve.

5. Results of determining environmental flows by hydrological and stenobiont indicators of the river

5. 1. Estimation of ecosystemness of modern environmental flow volumes

With the required amount of initial data, the cross-sectional area of the river channel and the wetted perimeter were calculated.

The half-area of the ellipse (S_1) and the area of the triangle (S_2) are determined by formulas (5) and (6), respectively:

$$S_1 = \frac{1}{2} \cdot \pi \cdot a \cdot h, \quad (5)$$

$$S_2 = \frac{1}{2} \cdot AB \cdot h, \quad (6)$$

where a – half the width of the river channel (Fig. 1) or large radius of the ellipse, a=47.5 m; h – depth (small radius), h=2 m; AB – width of the river (Fig. 2), AB=95 m.

The cross-sectional area of the river channel will be half the sum of S_1 and S_2 (7):

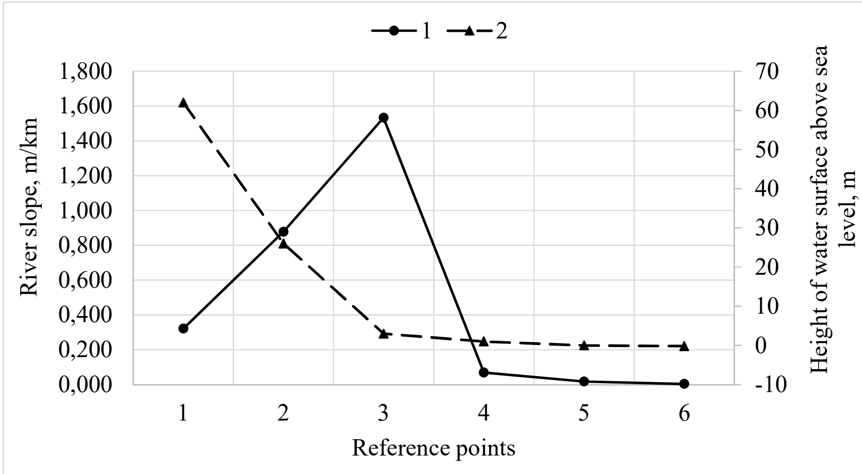

Fig. 4. Dynamics of the Southern Bug River slope (according to Table 4): 1 — slope; 2 — height of water surface above sea level

$$S_{rc} = 0{,}5 \cdot (S_1 + S_2). \quad (7)$$

To apply the Chezy formula, the last necessary component, the area of the wetted perimeter, is determined by the formulas (8)–(10).

$$P_{el} = 2 \cdot \pi \cdot \sqrt{\frac{a^2 + h^2}{2}}, \quad (8)$$

$$P_{tr} = d_1 + d_2, \quad (9)$$

$$P_{rc} = \frac{1}{2} \cdot (P_{el} + P_{tr}). \quad (10)$$

In the case of the riverbed perimeter by P_{el}, the value of 211.11 m is halved.

To facilitate the calculations for P_{tr}, a simplification is made in the form of d_1=d_2, assuming that the relief of a straight segment of the riverbed can be considered symmetric. At the same time, there is an awareness that the center of the channel, under the action of Coriolis forces, is shifted from the visual center. However, assume that this does not significantly affect the size of the wetted perimeter.

Thus, having obtained an isosceles triangle (Fig. 3), it is easy to determine the wetted perimeter (AB – river width).

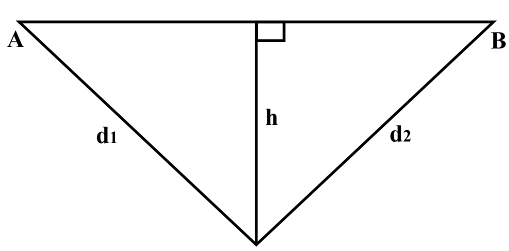

Fig. 3. Schematic shape of the river channel (second component)

Based on reference data [45], it was found that the Chezy coefficient is equal to 30.0. While its calculated value (C) is slightly different – 32.145.

According to empirical calculations, the slope of the river (I) in the study area is 0.57 m/km (between points 2 and 4) (Fig. 4).

According to the Chezy formula, it was found the flow velocity in this section of the river channel – v. The results of all calculations are summarized in Table 3.

Table 3

Results of calculations of hydrological and hydraulic parameters of the river channel

Parameter	Content	Result of calculation
S_1	Ellipse area	149.15 m^2
S_2	Triangle area	95 m^2
S_{rc}	Cross-sectional area of the river channel	122 m^2
v_0	Long-term average flow velocity based on the corresponding water flow rate	0.77 m/s
P_{el}	Wetted perimeter of the ellipse	105.55 m
P_{tr}	Wetted perimeter of the triangle	95 m
P_{rc}	Wetted perimeter of the river channel	101 m
R_h	Hydraulic radius	1.21 m
y	Dimensionless coefficient of Chezy formula (3)	0.31
C	Chezy coefficient	32.145
I	River slope	0.00057 m/m
v	Flow velocity according to Chezy formula	0.84 m/s

The obtained value of the cross-sectional area of the Southern Bug River within the village of Oleksandrivka (122 m^2) was compared with the long-term average daily water flow rate before the creation of the existing channel reservoir and dam of Oleksandrivka HPP (1936–1983; sample of 17,623 values). The average long-term water velocity (v_0) was 0.77 m/s.

The obtained value of v_0 does not differ much from the calculated v (at C=32.145) and is almost identical – 0.78 m/s (at C=30.0), which in general can be considered as confirmation of the correctness of the obtained results.

Comparing the value of the current environmental flows (17 m^3/s) with the calculated cross-sectional area (122 m^2), the flow velocity will be lower than the required minimum – 0.14 m/s.

The obtained value does not even satisfy the minimum required for limnophilous fish species (Table 1). Regarding the typical for the Southern Bug rheophilic and permeable ichthyofauna, hydrological conditions are generally unsatisfactory. The obtained value of the flow velocity allows assessing the current standard of environmental flows as non-ecosystem.

5. 2. Determination of the ecological volume of environmental flows according to hydrological and biotic indicators

According to [46], environmental flow characterizes the quantity, time and quality of freshwater flows, as well as the levels required to maintain aquatic ecosystems, which support human cultures, the economy, sustainable existence and well-being.

In some documents [47], environmental flows are classified into two types: natural (environmental flow) and ecological (ecological flow). The first is defined as the flow regime necessary to meet socio-cultural and environmental needs, i.e. taking into account human needs. And the second – as a flow needed to support the functions of the ecosystem affecting native species of fish and wildlife.

In any case, the concept of environmental flows includes the need to preserve aquatic ecosystems for the sustainable use of relevant services in the future by all water users (both man and nature).

Given the minimum requirements for the flow velocity of stenobionts (0.20 m/s) (Table 2), the value of the minimum environmental flow for the Oleksandrivsky Reservoir must be at least 24 m^3/s.

At the flow velocity of 0.29 m/s (obtained by the value of the river slope between points 2–4), the minimum environmental flow to the Oleksandrivsky Reservoir tailwater will be 35.38 m^3/s.

This value is 38 % of the average long-term water flow rate (94 m^3/s), which is comparable with the results [17, 18, 21] in terms of substantiation of the ecological volume of environmental flows.

It should be noted why the study adopted $S_{rc}=const$ for different water flow rates in the river. This is because the salt waters of the Bug estuary, in the absence of freshwater runoff, tend to rise 100–150 km upstream under the influence of southern winds. This is facilitated by the low values of the river slope from north to south: from 70 mm to 4 mm (Table 4). As a result, this causes salinization of waters, irrigation systems, changes in species diversity and deterioration of the sanitary-epidemiological situation in the lower reaches of the Southern Bug River in general [48].

The proposed approach ($S_{rc}=const$) allows expanding the geography of its application. Dynamic factors can be the width of the river and the reference point (according to Google Earth).

The obtained results of the non-compliance of the current standard at 17 m^3/s with ecosystem requirements for environmental flows (in terms of flow velocity and volume) are logically related to the processes of siltation, water quality deterioration and depletion of species biodiversity, which are typical for dammed lower reaches of the Southern Bug River [49–51].

Table 4

Southern Bug River slope in the part of middle and lower reaches

Reference points	Relevant settlement	Distance from the mouth, km	Height of the river surface above sea level, m	Slope, m/km
0	Savran	330	90	–
1	Pervomaisk	243	62	0.322
2	Yuzhnoukrainsk	202	26	0.878
3	Oleksandrivka	187	3	1.533
4	Voznesensk	158	1	0.069
5	Nova Odesa	103	0.01	0.018
6	Mykolaiv	49	–0.2	0.004
7	river mouth	0	–2	0.037

According to Fig. 5, comparing the conditions before and after the regulation of the river channel (1936–1983 and 1984–2016, respectively), threats to hydrobiota seem to be minimal under conditions of proper environmental flows.

However, the extreme danger for hydrobiota is the lack of environmental flows in the low water period (with the prioritization of industrial needs) or unreasonably low regulatory value. In particular, for winter and summer low water (Fig. 6). Using the calculations of river flow availability [50], the approximate values of water velocity during the year under current conditions of water use were determined.

According to Fig. 6, the risk of violation of the functional integrity of the ecosystem at the level of stenobionts (0.20 m/s) in a low-water year (95 % of runoff availability) is typical for the period from June to October: during the most productive phase of the river. The situation is similar for fish (0.15 m/s line). At the same time, six of the last ten years have been shallow.

Given the above, during the specified period of the year, priority in water supply should be given to the aquatic ecosystem to ensure the minimum required (environmental) flow velocities in the reservoir tailwater and river lower reaches.

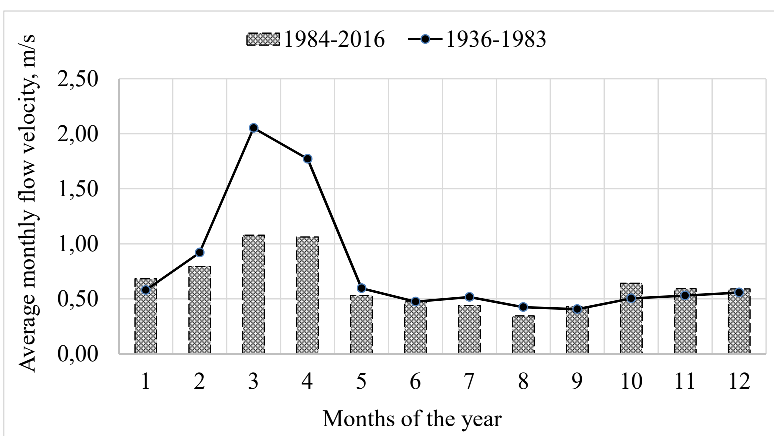

Fig. 5. Dynamics of average monthly flow velocity of the Southern Bug River based on average monthly water flow rate

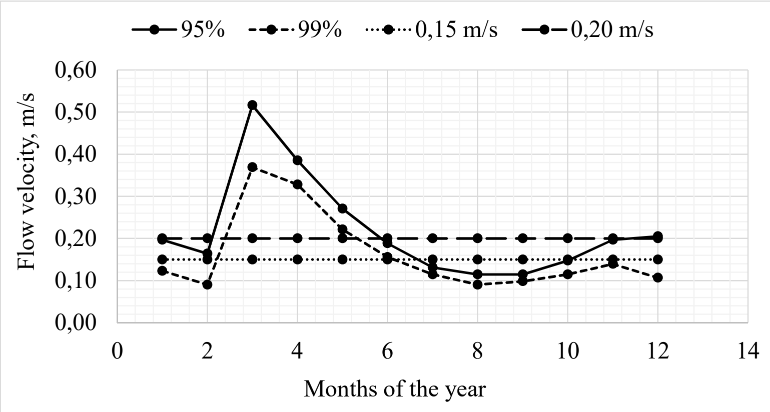

Fig. 6. Average flow velocities of the Southern Bug at different levels of flow availability in regulated conditions

6. Discussion of the results of the study of hydrological-stenobiontic content of environmental flows

Close values of the calculated water velocity by hydrological perennials (v_0=0.77) and hydraulic parameters of the river (v=0.84 at C=32.145 and v=0.78 at C=30.0) confirm the possibility of applying the geometric method [44] to determine the cross-sectional area of the river channel and the length of the wetted perimeter (Fig. 1–3). And, as a result, to involve them in the process of environmental flows substantiation.

Despite the fact that the relevant methods can be used independently of each other, as confirmed by international practice, they are not able to provide an ecosystem justification for environmental flows without taking into account the hydrobiological component. After all, the latter largely determines not only the minimum volume of discharges from reservoirs, but also the parameters of water velocity in the river channel. The linear dynamics of the flow becomes even more important because it prevents, due to the creation of a certain level of turbulence, the uniform heating of the entire water column in the river and its deoxygenation.

Comparison of the curves of hydrological runoff availability and the minimum functional requirements of hydrobiota (representatives of macrozoobenthos and fish) to the water velocity (Fig. 6) shows insufficient environmental justification of environmental flows in modern reservoir management practice. Whereas the calculations show that the situation can be improved by replacing the indicator biota: from fish – to some representatives of macrozoobenthos, which are stenobionts by the factor of ecological features of life.

In the context of the study, another point needs to be taken into account: despite the presence of some volume of water in the river channel that corresponds to the environmental flow, it is necessary to ensure the minimum environmental dynamics of the flow. The outlined situation can be typical for lowland parts of rivers that flow into a more watery river or sea (estuarine mouth type). As a result, with a slight slope of the river, the water level can raise upstream: the volume of water is constant, but the flow is almost absent. According to the data of Tables 1, 2, the conditions for normal functioning of hydrobiota are practically leveled. We consider it possible to apply the developed method for other rivers, where there is no support of estuarine waters, taking into account the dependence of the river cross-sectional area on water flow rate.

The issue of the volumes of environmental flows depending on the season and phases of the river ecosystem, including spawning and flooding, requires a separate thorough study. After all, with the help of maximum water flow rate, the channel is naturally cleaned, and the fish receives a "signal" about the optimal conditions for mating. Given the above, there is a need to study the seasonal change of indicator biota in the future: for example, on rheophilic fish species. In the case of the Southern Bug, for example, limiting the environmental flow to only 38 % of the river runoff in the third and fourth months of the year (flood season), the flow velocity in the current regulated conditions (Fig. 5) will be lower than the "stimulating" one (Table 1) – about 0.4 m/s. While, from a hydrobiological point of view, we can consider the corresponding values of the flow velocity of 0.78 m/s for March and 0.68 m/s for April in the version with an unregulated channel quite satisfactory.

However, for those regions where climate aridization is observed, the phase of the summer low water on the river, which falls on the period of active increase of biomass in the aquatic ecosystem, deserves priority attention. After all, during the flood period, the probability of providing environmental flow velocities in the reservoir tailwater and, respectively, river lower reaches, can be considered quite high.

In contrast to [11, 17, 18, 21], where the hydrobiological component of environmental flows is based on the requirements of ichthyofauna to the volume and velocity of water flow, the proposed method allows optimizing the management process, first of all, through crisis low water situation on the river. It corresponds to the low water period: water intake remains constant or increases when the river runoff reaches minimum values. The advantage of macrozoobenthos, in contrast to fish, in addition to a narrower ecological valence to flow velocity, is its lower mobility. And with the deterioration of water resources, in the absence or unreasonably low volume of environmental flows, this link in the food chain can significantly degrade in biomass and diversity. This, in particular, allows using environmental features and functional requirements of benthic invertebrates in the process of substantiation of environmental flows from reservoirs.

7. Conclusions

1. The hydrological-stenobiontic method for determining environmental flows is proposed, taking into account the ecological valence of aquatic organisms to changes in river flow dynamics. The main indicator group of organisms is macrozoobenthos stenobionts. Unlike ichthyofauna, benthic invertebrates are more demanding on water velocity, which allowed justifying the importance of determining and taking into account its ecological values in the reservoir tailwater and river lower reaches. For lowland parts of rivers, this value should be at least 0.2 m/s, which is the lower limit of the tolerance zone of stenobionts to this factor.

2. The calculations of the minimum environmental flow volume for the reservoir, situated in the lowland parts of the river, based on the proposed solutions, allowed justifying the increase of the minimum environmental flow volume by 40 % relative to the current one. The average annual and average second volumes of environmental flows should be about 38 % of the corresponding river runoff.

References

1. Landau, Yu., Chornomorov, A. (2020). Pivdennyi Buh: yak polipshyty vodozabezpechennia Mykolaivshchyny. Uriadovyi kurier. Available at: https://ukurier.gov.ua/uk/articles/pivdennij-bug-yak-polipshiti-vodozabezpechennya-mi/
2. Panasyuk, I. V., Tomil'tseva, A. I., Zub, L. M. (2020). Basic approaches to preparing of operating rules for lowland reservoirs of small HPPs in terns of compliance with environmental requirements. Hidroenerhetyka Ukrainy, 3-4, 52–57. Available at: https://uhe.gov.ua/sites/default/files/2020-12/15.pdf
3. Rytwinski, T., Taylor, J. J., Bennett, J. R., Smokorowski, K. E., Cooke, S. J. (2017). What are the impacts of flow regime changes on fish productivity in temperate regions? A systematic map protocol. Environmental Evidence, 6 (1). doi: https://doi.org/10.1186/s13750-017-0093-z
4. Zeiringer, B., Seliger, C., Greimel, F., Schmutz, S. (2018). River Hydrology, Flow Alteration, and Environmental Flow. Riverine Ecosystem Management, 67–89. doi: https://doi.org/10.1007/978-3-319-73250-3_4
5. Winton, R. S., Calamita, E., Wehrli, B. (2019). Reviews and syntheses: Dams, water quality and tropical reservoir stratification. Biogeosciences, 16 (8), 1657–1671. doi: https://doi.org/10.5194/bg-16-1657-2019
6. Arthington, A. H., Tharme, R. E., Brizga, S. O., Pusey, B.J., Kennard, M. J. (2003). Environmental flow assessment with emphasis on holistic methodologies. Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries. Volume II. Sustaining Livelihoods and Biodiversity in the New Millennium. Available at: http://www.fao.org/3/ad526e/ad526e07.htm#bm07
7. Mulligan, M., van Soesbergen, A., Sáenz, L. (2020). GOODD, a global dataset of more than 38,000 georeferenced dams. Scientific Data, 7 (1). doi: https://doi.org/10.1038/s41597-020-0362-5
8. Tennant, D. L. (1976). Instream flow regimens for fish, wildlife, recreation and related environmental resources. Fisheries, 1 (4), 6–10. doi: https://doi.org/10.1577/1548-8446(1976)001<0006:IFRFFW>2.0.CO;2
9. Yang, F., Xia, Z., Yu, L., Guo, L. (2012). Calculation and Analysis of the Instream Ecological Flow for the Irtysh River. Procedia Engineering, 28, 438–441. doi: https://doi.org/10.1016/j.proeng.2012.01.747
10. Stalnaker, C., Lamb, B. L., Henriksen, J., Bovee, K., Bartholow, J. (1995). Instream flow incremental methodology. A primer for IFIM. Biological Report No. 29. National Biological Service, 45. Available at: https://books.google.com.ua/books?id=rEyGMq8TJOcC&printsec=frontcover&hl=ru&source=gbs_ge_summary_r&cad=0#v=onepage&q&f=false
11. Physical Habitat Simulation (PHABSIM) Software for Windows. U.S. Geological Survey. Available at: https://www.usgs.gov/software/physical-habitat-simulation-phabsim-software-windows
12. DRIFT. Available at: https://www.drift-eflows.com/about-drift/
13. Davis, R., Hirji, R. (2003). Water resources and environment technical note C.2. Washington. Available at: https://iwlearn.net/resolveuid/7d6ea185fd753130f6558a39950d746b
14. Reil, A., Skoulikaris, Ch., Alexandridis, T. K., Roub, R. (2018). Evaluation of riverbed representation methods for one-dimensional flood hydraulics model. Journal of Flood Risk Management, 11 (2), 169–179. doi: https://doi.org/10.1111/jfr3.12304
15. Ekologicheskie popuski (2003). Publikatsii Treningovogo tsentra MKVK. Vypusk 1. Tashkent. Available at: http://www.cawater-info.net/library/rus/01_eco.pdf
16. King, J. M., Tharme, R. E. (1994). Assessment of the Instream Flow Incremental Methodology, and initial development of alternative instream flow methodologies for South Africa. Water Research Commission, Report No. 295/1/94. Available at: http://www.wrc.org.za/wp-content/uploads/mdocs/295-1-941.pdf
17. Minjian, C., Gaoxu, W., Huali, F., Liqun, W. (2012). The Calculation of River Ecological Flow for the Liao Basin in China. Procedia Engineering, 28, 715–722. doi: https://doi.org/10.1016/j.proeng.2012.01.796
18. Sun, T., Yang, Z.-F. (2005). Calculation of environmental flows in river reaches based on ecological objectives. Huan Jing Ke Xue, 26 (5), 43–48. Available at: https://pubmed.ncbi.nlm.nih.gov/16366468/
19. Huang, S., Chang, J., Huang, Q., Wang, Y., Chen, Y. (2014). Calculation of the Instream Ecological Flow of the Wei River Based on Hydrological Variation. Journal of Applied Mathematics, 2014, 1–9. doi: https://doi.org/10.1155/2014/127067
20. Tan, G., Yi, R., Chang, J., Shu, C., Yin, Z., Han, S. et. al. (2018). A new method for calculating ecological flow: Distribution flow method. AIP Advances, 8 (4), 045118. doi: https://doi.org/10.1063/1.5022048
21. Abdi, R., Yasi, M. (2015). Evaluation of environmental flow requirements using eco-hydrologic–hydraulic methods in perennial rivers. Water Science and Technology, 72 (3), 354–363. doi: https://doi.org/10.2166/wst.2015.200
22. Global Environmental Flow Calculator. Available at: http://naturalresources-centralasia.org/assets/files/VALUES/ValuES_Method_Profile_Global_Flow_Calculator_EN.pdf
23. IWMI Environmental Flow Calculators. Available at: https://www.iwmi.cgiar.org/resources/data-and-tools/models-and-software/environmental-flow-calculators/
24. Vasil'ev, Yu. S., Hrisanov, N. I. (1991). Ekologiya ispol'zovaniya vozobnovlyayuschihsya energoistochnikov. Leningrad: Izdatel'stvo Leningradskogo universiteta, 343.
25. Jansson, R. (2006). The effect of dams on biodiversity. Dams under Debate. Swedish Research Council Formas, 77–84. Available at: https://www.researchgate.net/publication/265914243_The_effect_of_dams_on_biodiversity
26. Chunyan, Q., Yong, Z., Haiyan, Y., Beixin, W. (2013). Concordance among different aquatic insect assemblages and the relative role of spatial and environmental variables. Biodiversity Science, 21 (3), 326–333. doi: https://doi.org/10.3724/sp.j.1003.2013.08223
27. Bezsonov, Y., Andreev, V., Smyrnov, V. (2016). Assessment of safety index for water ecological system. Eastern-European Journal of Enterprise Technologies, 6 (10 (84)), 24–34. doi: https://doi.org/10.15587/1729-4061.2016.86170

28. Dolédec, S., Lamouroux, N., Fuchs, U., Mérigoux, S. (2007). Modelling the hydraulic preferences of benthic macroinvertebrates in small European streams. Freshwater Biology, 52 (1), 145–164. doi: https://doi.org/10.1111/j.1365-2427.2006.01663.x
29. Holt, E. A., Miller, S. W. (2010). Bioindicators: Using Organisms to Measure Environmental Impacts. Nature Education Knowledge, 3 (10), 8. Available at: https://www.nature.com/scitable/knowledge/library/bioindicators-using-organisms-to-measure-environmental-impacts-16821310/
30. Hoover, T. M., Richardson, J. S. (2009). Does water velocity influence optimal escape behaviors in stream insects? Behavioral Ecology, 21 (2), 242–249. doi: https://doi.org/10.1093/beheco/arp182
31. Vilenica, M., Mičetić Stanković, V., Sartori, M., Kučinić, M., Mihaljević, Z. (2017). Environmental factors affecting mayfly assemblages in tufa-depositing habitats of the Dinaric Karst. Knowledge & Management of Aquatic Ecosystems, 418, 14. doi: https://doi.org/10.1051/kmae/2017005
32. Jacobus, L. M., Macadam, C. R., Sartori, M. (2019). Mayflies (Ephemeroptera) and Their Contributions to Ecosystem Services. Insects, 10 (6), 170. doi: https://doi.org/10.3390/insects10060170
33. Bouchard, R. W. Jr. (2004). Guide to aquatic macroinvertebrates of the Upper Midwest. Water Resources Center, University of Minnesota, 208. Available at: https://dep.wv.gov/WWE/getinvolved/sos/Documents/Benthic/UMW/Ephemeroptera.pdf
34. Aquatic Benthic Macroinvertebrates As Water Quality Indicators. Available at: https://www.wpwa.org/documents/education/Biological%20sampling.pdf
35. Bubnov, A. G. et. al.; Grinevich, V. I. (Ed.) (2007). Biotestoviy analiz – integral'niy metod otsenki kachestva obektov okruzhayuschey sredy. Ivanovo, 112.
36. Garbe, J., Beevers, L., Pender, G. (2016). The interaction of low flow conditions and spawning brown trout (Salmo trutta) habitat availability. Ecological Engineering, 88, 53–63. doi: https://doi.org/10.1016/j.ecoleng.2015.12.011
37. Life in freshwater stream - Mayfly Nymphs (2014). Available at: http://ifieldstudy.net/sns/outstanding_reports/2014/files/team25.pdf
38. Hall, T. J. (1980). Influence of wing dam notching on aquatic macroinvertebrates in Pool 13, upper Mississippi River: the prenotching study. Wisconsin, 168. Available at: https://apps.dtic.mil/sti/pdfs/ADA096633.pdf
39. Marden, J. H., Thomas, M. A. (2003). Rowing locomotion by a stonefly that possesses the ancestral pterygote condition of co-occurring wings and abdominal gills. Biological Journal of the Linnean Society, 79 (2), 341–349. doi: https://doi.org/10.1046/j.1095-8312.2003.00192.x
40. Khazeyeva, L. A. (2007). Description of the larva of a stonefly from the family Chloroperlidae, genus Chloroperla Newman, 1836 of the northern slopes of the Central Caucasus region. Questions of Aquatic Entomology of Russia and Adjacent Lands: Third All-Russia Symposium on Amphibiotic and Aquatic Insects. Voronezh, 356–358. Available at: https://www.zin.ru/animalia/coleoptera/pdf/third_all_russia_symposium.pdf
41. Collier, K. (1993). Flow preferences of aquatic invertebrates in the Tongariro River (Part 2 of 5). Wellington. Available at: https://www.doc.govt.nz/globalassets/documents/science-and-technical/sr60a.pdf
42. De Brouwer, J. H. F., Besse-Lototskaya, A. A., ter Braak, C. J. F., Kraak, M. H. S., Verdonschot, P. F. M. (2016). Flow velocity tolerance of lowland stream caddisfly larvae (Trichoptera). Aquatic Sciences, 79 (3), 419–425. doi: https://doi.org/10.1007/s00027-016-0507-y
43. Franken, R., Batten, S., Beijer, J., Gardeniers, J., Scheffer, M., Peeters, E. (2006). Effects of interstitial refugia and current velocity on growth of the amphipod Gammarus pulexLinnaeus. Journal of the North American Benthological Society, 25 (3), 656–663. doi: https://doi.org/10.1899/0887-3593(2006)25[656:eoirac]2.0.co;2
44. Han, J., Lee, D., Lee, S., Chung, S.-W., Kim, S., Park, M. et. al. (2019). Evaluation of the Effect of Channel Geometry on Streamflow and Water Quality Modeling and Modification of Channel Geometry Module in SWAT: A Case Study of the Andong Dam Watershed. Water, 11 (4), 718. doi: https://doi.org/10.3390/w11040718
45. Kiselev, P. G. (Ed.) (1972). Spravochnik po gidravlicheskim raschetam. Moscow: «Energiya», 312.
46. Arthington, A. H., Bhaduri, A., Bunn, S. E., Jackson, S. E., Tharme, R. E., Tickner, D. et. al. (2018). The Brisbane Declaration and Global Action Agenda on Environmental Flows (2018). Frontiers in Environmental Science, 6. doi: https://doi.org/10.3389/fenvs.2018.00045
47. Guidelines for Determination of Environmental Flows (e-flows) for Development Projects that Result in Impounding of Water in Streams/ Rivers (2018). Central Environmental Authority. Ministry of Mahaweli Development and Environmental. Available at: http://203.115.26.10/2018/EIA_PUB/e-flow.pdf
48. Vodohospodarska sytuatsiya v baseini richky Pivdennyi Buh u 2017 rotsi. Available at: https://mk-vodres.davr.gov.ua/node/1148
49. Bezsonov, Ye. M.; Malovanyi, M. S. (Ed.) (2020). Ekoloho-ekonomichni naslidky vid ruslovykh vodoskhovyshch: vitchyznianyi ta mizhnarodnyi dosvid. Rozdil 1 «Ekolohichni aspekty zberezhennia bioriznomanittia, monitorynh, audyt, systemnyi analiz ta otsinka ryzyku, vidnovliuvalni dzherela enerhiyi». Collective monograph «Sustainable Development: Environmental Protection. Energy Saving. Sustainable Environmental Management». Lviv, 184–214. doi: https://doi.org/10.23939/book.ecocongress.2020
50. Khilchevskyi, V. K., Chunarov, O. V., Romas, M. I. et. al.; Khilchevskyi, V. K. (Ed.) (2009). Vodni resursy ta yakist richkovykh vod baseinu Pivdennoho Buhu. Kyiv: Nika tsentr, 184. Available at: https://www.researchgate.net/profile/Valentyn_Khilchevskyi/publication/316822383_Water_resources_and_quality_of_river_waters_of_basin_of_South_Bug_Vodni_resursi_ta_akist_rickovih_vod_basejnu_Pivdennogo_Bugu/links/591291e2a6fdcc963e7cf258/Water-resources-and-quality-of-river-waters-of-basin-of-South-Bug-Vodni-resursi-ta-akist-rickovih-vod-basejnu-Pivdennogo-Bugu.pdf
51. Lyashenko, A., Slepnev, O., Makovsky, V., Sytnyk, Y., Grigorenko, T. (2018). Macrozoobenthos of water objects affected by the South-Ukrainian electric power-producing complex. Fisheries Science of Ukraine, 2, 43–58. doi: https://doi.org/10.15407/fsu2018.02.043