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Assessment and forecast of hydropower potential of the Vistula basin rivers (within Ukraine)

Abstract: The article assesses and forecasts the hydropower potential of the rivers of the Vistula River basin within Ukraine. According to the proposed methodological approaches, the value of the total hydropower potential (THP) for 18 rivers of the studied basin, the length of which exceeds 10 km, has been established. It has been revealed that the total THP of the studied rivers is 56548 kW, which is 1.2% of the total hydropower potential of all rivers of Ukraine. The forecast of the THP for the rivers of the Vistula River basin was made considering the long-term variability of river water flow. For this purpose, according to the methods of mathematical statistics (difference integral curves, autocorrelation, spectral analysis), water cycles and their components – high-water and low-water phases were allocated. The ratio between the average annual water flow (the water flow series in the vast majority was 60-70 years) and the water flow into the high-water and low-water phases showed that the ratio was about 1.45. The calculated forecast THP corresponds to the forecast indicators of water flow into the high-water and low-water phases. During the period of the high-water phase, it is expected that the THP within the Vistula River basin within Ukraine will increase by an average of 15.1% compared to the THP calculated based on the average annual water flow for a multi-year period. The total value of the THP in the low-water phase will decrease by 20.4%. The results obtained regarding the assessment of the THP of the rivers of the Vistula River basin within Ukraine and their forecast changes in different phases of water flow can be used in the design and placement of hydropower facilities, taking into account all environmental and technological requirements for their construction.
Keywords: rivers of the Vistula River basin within Ukraine, total hydropower potential (THP), stochastic patterns, high-water and low-water phases of water flow, forecast estimates.

1. Introduction

Modern scientific research considers several categories of hydropower potential of rivers, namely general (theoretical hydropower potential is the total theoretical sum of the river runoff energy), environmentally permissible hydropower potential, technically possible hydropower potential and hydropower potential available for development (economically justified hydropower potential) (Kudri, 2020; Hydropower potential of rivers of Ukraine 2018; Obodovskyi et al., 2016; Obodovskyi et al., 2019a).

The most generalized assessment of the natural energy resource of the river is given by the total hydropower potential (THP), which is calculated from the river source to the mouth (the first structure is assigned at the place of the river source). At the same time, the correct allocation of individual sections on the river, for which calculations are made, is significant. Their number should not be significant. In general, for medium rivers, it should be in the range from 6 to 12, and for large and small, respectively, about twice as large or smaller (Palamarchuk 2001). For mountain rivers, the number of sections can be doubled. Water flow for each section of the river is taken as an average annual value in the initial and final formations, and their calculation is carried out, for the most part, for years with 50 % security. In general, the total capacity of all sections that can potentially be used for energy is estimated for the river. Therefore, taking into account the objectivity and reliability of the assessment of the THP, in our opinion and, according to a number of authors (Tsependa, 2009; Rudko and Konsevich, 1998; Badenko et al., 2013; Gogoase Nistoran et al., 2017; Hoes, et al., 2017), the most correct and objective results are given by the method of divisional accounting of the establishment of the THP.

Determining the hydropower potential of rivers is an urgent issue both from a scientific and practical point of view. The growth in the cost of traditional energy resources and their exhaustiveness prompts an increase in the share of alternative renewable energy sources. This natural resource of watercourses, the value of which is quite variable, depending on the periods of water flow of the river, makes it possible to assess the possibility of its use for the hydropower needs of the region. At the same time, the calculation and forecast of the total hydropower potential for transboundary river facilities is of some interest. For these rivers, according to the EU WFD (EU Water Framework Directive…, 2006), the use of hydropower potential for the purpose of hydropower production should not reduce the overall ecological condition of the river below good. These prerequisites prompted us to investigate the magnitude of the hydropower potential of the rivers of the Vistula River basin within Ukraine and predict its changes in the future depending on changes in their water flow.

2. Initial research data

The basin of the Vistula River, according to hydrographic zoning, on the territory of Ukraine has a catchment area of 12.9 thousand km^2 (Grebin et al., 2013). It is represented by two sub-basins – the Western Bug and the San (Fig. 1).

The Ukrainian part of the sub-basin of the Western Bug River has a catchment area of 10.4 thousand km^2. Its largest tributaries are the rivers Poltva, Rata and Luga. The catchments of the Poltva and Luga are completely located within Ukraine, and the Rata originates in the territory of the Podkarpackie Voivodeship of Poland. All the studied rivers of this catchment are plain. Here, 14 rivers were included to calculate the total hydropower potential (THP), on which 90 homogeneous sections were allocated. On the other hand, in the Ukrainian part of the sub-basin, the San River has an area of 2.5 thousand km^2 (Fig. 1). Most of the rivers of its catchment area can also be attributed to plains. Only the San River originates on the northern slopes of the Ukrainian Carpathians, where it has signs of a mountain river. The largest tributaries of the San within Ukraine are the rivers Vyshnia and Zavadivka (Lyubachivka). Both rivers are right tributaries of the San, originating on the territory of Ukraine and flowing into the main river on the territory of Poland. Within this sub-basin, 4 rivers were worked with the allocation of 35 sections on them, on which the THP was calculated.

It should be noted that the main criteria for choosing such sections are the presence of a homogeneous slope on the section, or a significant lateral inflow that changes the hydraulic conditions of the river.

Thus, in the Vistula River basin within Ukraine, the study of the total hydropower potential of its watercourses was carried out according to the assessment of the hydropower capacity of 18 rivers, the length of which exceeds 10 km. The total number of assessed areas on these rivers was 125.

The initial hydrological information for the entire study was hydrometric data of observations of water flows at hydrological stations from the beginning of observations to 2020 inclusive. There are 10 of them in the studied basin (Fig. 1). The duration of observations of water runoff in most of them (90 %) is 60-70 years.

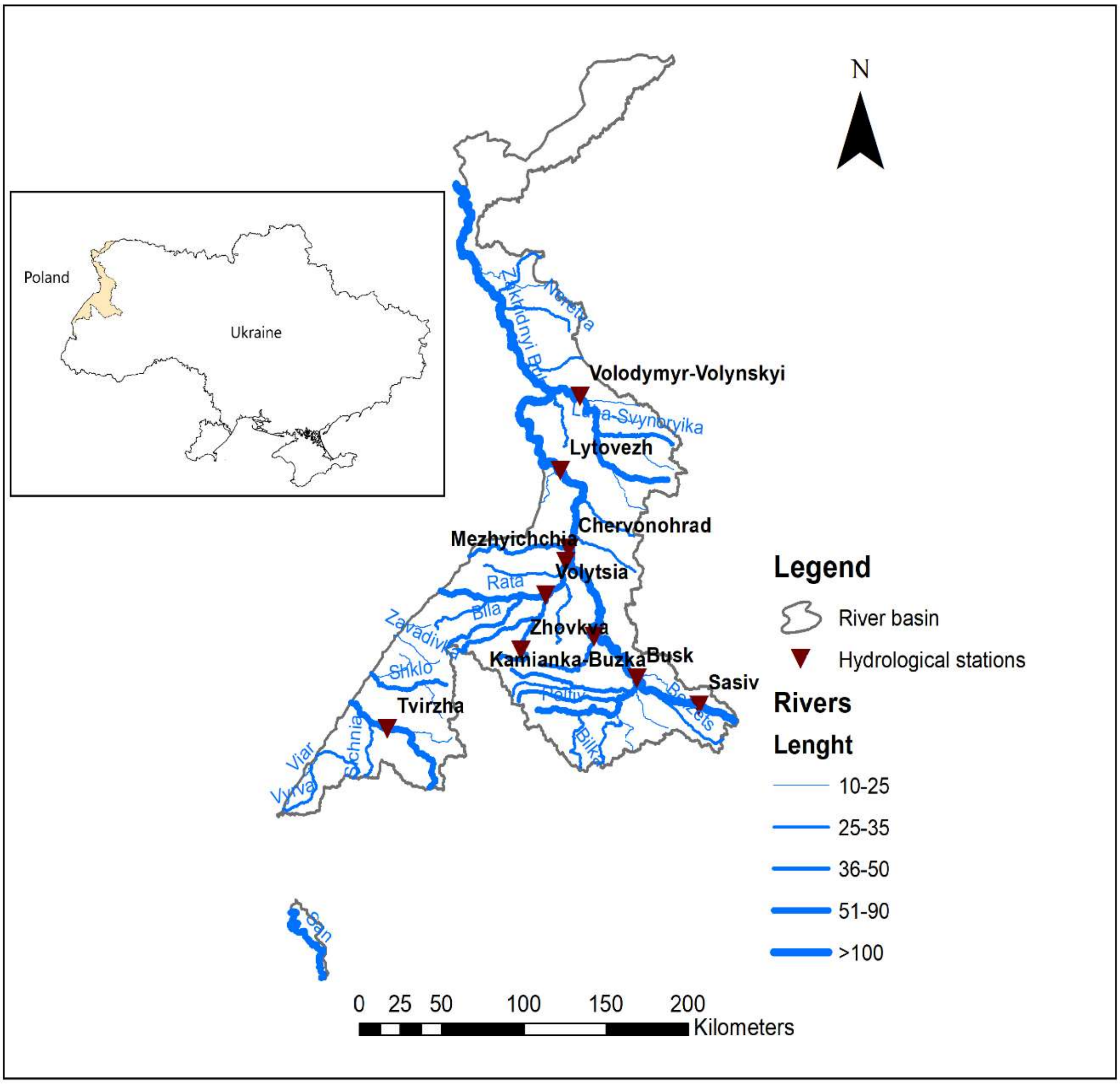

Figure 1. Hydrographic network and location of hydrological stations on the rivers of the Vistula River basin within Ukraine (Source: own work)

3. Characteristics and methods of research

3.1. General methodological provisions

In methodological terms, the total hydropower potential (THP) (N) (theoretical, natural, gross) of rivers can be defined as the arithmetic sum of potentials on the selected homogeneous sections of the river from the initial (initial) to the closing gates (linear method of assessment):

$$N = \sum_{i=1}^{n} N_i = \sum_{i=1}^{n} \left[g \left(\frac{Qn_i + Q\kappa_i}{2} \right) H_i \right], \quad (1)$$

where N - natural potential, kW (flow power in the calculated section of the river); i – the number of the river section; g - acceleration of the force of gravity, 9.81 m/s^2; Qn_i - average water flow, m^3/c{ at the beginning of the first section of the river; $Q\kappa_i$ - average water flow, m^3/s at the end of the first section of the river; *No* – the fall of the river on the first section of the river (Obodovskyi et al., 2016; Obodovskyi et al., 2019b; Obodovskyi et al., 2020).

For all homogeneous sections, morphometric characteristics such as distance from the mouth, length of the section (m), absolute elevation of the beginning and end of the section, slope on the section and area of the basin within the section are calculated (Korniienko et al., 2020).

To establish the water flow rates at the beginning and at the end of the first homogeneous section of the river, either the runoff data of the hydrological stations are used, or they are determined from the map of the spatial distribution of the water flow modules (Obodovskyi et al., 2020; River Runoff in Ukraine 2020; Lukianets et al., 2021). To determine from the map, the catchments of homogeneous areas are first outlined, the centers of these catchments are determined, for which the values of the modules of average flow are set, which are then converted through the areas of the specified areas into subdivision water flows.

For the resulting areas, the total hydropower potential is calculated. The total capacity of all sections is the total energy potential of the river and is defined as (2):

$$Ntot = N_1 + N2 + N3 + \dots N_n = \sum N_i, \quad (2)$$

where *N1, N2, N3* are the energy potentials of each of the sections.

It is also worth noting that for each section of the river, it is possible to determine the potential reserves of hydropower (E, kW/h) (3):

$$E = T \times g \times \left(\frac{Q_1+Q_2}{2}\right) \times (H_1 - H_2) \quad (3)$$

where T is the number of hours in a year, taken to be equal to 8760 (Avakyan et al., 1967, Hydropower, 1982).

As for the technological aspects of establishing the total hydropower potential of the rivers of the Vistula basin within Ukraine, the initial data are:

- Information on the relief. For this, methodological approaches are used, which are considered in the works (River Runoff in Ukraine 2020; Korniienko et al., 2020). At the same time, digital terrain models SRTM (Shuttle Radar Topography Mission) with a resolution of 30 m per pixel and electronic maps with a scale of 1:10,000 and 1:50,000 were used, from which you can take coordinates of sections and their heights (Global Data Explorer, http://gdex.cr.usgs.gov/gdex/).
- Information on water flows within hydrological stations and on selected sections of rivers (using a map of flow modules). For this purpose, methodological approaches are used, which are considered in the works (Obodovskyi etc. 2020; River Runoff in Ukraine, 2020; Lukianets et al., 2021).
- Slopes of rivers, which are determined based on their longitudinal profiles. They are built according to the elevations of topographic maps (scales of 1:10,000, 1:50,000 refined according to reference sources and remote sensing data (Hydropower Potential

Assessment, 2021).

Taking into account the insufficient hydrological study of the rivers of the study area, a map of the isolines of the flow modules was used to determine the water flow rates in individual calculated areas (River Runoff in Ukraine, 2020; Lukianets et al., 2021), with the help of which the indicators of runoff modules for the selected areas were established. Taking into account the catchment areas of these areas, the runoff modules were converted into water flows, according to which their total hydropower potential was determined.

3.2. Forecast estimates of the THP

The following assumptions were used to create predictive estimates of the hydropower potential of rivers. Based on the provisions of the algorithm for establishing the hydropower potential of rivers (Obodovskyi et al., 2016; Obodovskyi et al., 2019a; Obodovskyi etc., 2020), the final step in assessing the total hydropower potential is to establish its changes. This step is extremely necessary when developing long-term plans for hydropower production. It allows you to estimate the magnitude and direction (increase or decrease in potential) of probable changes in the hydropower capacity of watercourses under the influence of fluctuations in water flow, which, in turn, are due to current and future climate changes.

The mathematical structure of the formula of hydropower potential (1) consists of two values (acceleration of free fall - g and hydraulic head - ΔH), which in each individual case practically do not change in time and the value of water flow (Q), which is marked by certain variability, in the long-term period of time. Thus, in order to predict changes in the total hydropower potential, it is necessary to first of all, to perform forecasting for the future changes in water flow. For such a forecast assessment of water variability, a study of the observed long-term fluctuations in river water flow according to the data of the Kamianka Buzka hydrological station, which is located on the Western Bug River, was previously conducted. For this purpose, methods of mathematical statistics, autocorrelation and spectral analysis, and difference integral curves are comprehensively applied to stock series. It has been established that the average annual water flow of the studied rivers of the Vistula basin has observed periods of water flow cycles within 29±2 years. The groupings of low-water years are 10±2 years, and the high-water phases last 17±2 years (Obodovskyi et al., 2020; Lukianets et al., 2021). In recent years, there has been a transition from a low-water to a high-water phase. It is this cyclical trend in the time series of the average annual water flow for the rivers of the studied basin that is the basis for forecast estimates of hydropower potential, taking into account the variability of water flow in the future.

Therefore, modern changes in the hydropower potential can take place only on the basis of changes in the water flow of rivers, namely water flow. If we consider the water flow due to water flow for a multi-year period as a flow rate, then its variability is insignificant. But in periods of different water flow (high water and low water), it has a more significant difference (Lukianets et al., 2021). Therefore, the average water flows for the low-water and high-water phases of the studied rivers were used as the main prerequisites for forecast estimates of hydropower potential. It should also be noted that the assessment of fluctuations in water flow by phases of water flow gives results based on a certain cyclical nature of climate changes and the characteristics of runoff associated with them by time dynamics, which are the main factors in establishing and forecasting the hydropower potential of rivers.

4. Results

4.1. Indicators of THP.

Table. 1 presents the results of calculations of the total hydropower potential of the studied rivers of the Vistula River basin within Ukraine, which in general is 56,548 kW (56.55 MW), or this corresponds to hydropower - 495360480 kW/h (496360.5 MW/h).

Table 1. Distribution of indicators of the total energy potential (*N*) of rivers in the Vistula River basin within Ukraine

№	River	Flows into	N, kW (E, kW/h)	% of the N of the Vistula River basin (within Ukraine)
1	San	Vistula	11 822 (103560720)	20.9
2	Western Bug	Vistula	31 656 (277306560)	56.0
3	Vyshnia	San	1 244 (10897440)	2.20
4	Shklo	San	1 087 (9522120)	1.91
5	Solotva	Liubachuvky	223 (1953480)	0.40
6	Belzets	Western Bug	488 (4274880)	0.86
7	Peltiv	Western Bug	2 612 (22881120)	4.62
8	Slotvyna	Western Bug	79 (692040)	0.14
9	Kamianka	Western Bug	161 (1410360)	0.28
10	Rata	Western Bug	4 248 (37212480)	7.51
11	Solokiia	Western Bug	611 (5352360)	1.08
12	Bilostok	Western Bug	223 (1953480)	0.39
13	Stasivka	Western Bug	152 (1331520)	0.27
14	Varenzhanka	Western Bug	127 (1112520)	0.23
15	Studzianka	Western Bug	142 (1243920)	0.25
16	Luha	Western Bug	1433 (12553080)	2.54
17	Bez nazvy	Western Bug	112 (981120)	0.20
18	Neretva	Western Bug	128 (1121280)	0.23
		The total basin	56 548 (495360480)	100.00

The geographical distribution of the total hydropower potential is shown in Fig. 2. It should be noted that these values of the total hydropower potential are rather insignificant in its distribution within Ukraine. Their share is only 1.2% of the total hydropower potential of all rivers of Ukraine.

According to Table 1 and Fig. 1 the value of the total energy potential varies from 79 kW (0.14%) to 31.656 kW (56.0%). In this context. rivers with the highest water flow also have the highest indicators of THP (*N*). These include such watercourses as the Western Bug. San. Ratu. Peltiv. Luga. Vyshnya and Shklo. which account for almost 88% of its total value. For these seven rivers of the basin. the indicators of energy potential are in the range of 1000-310000 kW and correspond to the potential possibilities of building small hydroelectric power plants on them. According to the classification scheme (Law of Ukraine…, 1998). for most sections of these rivers of the basin. the indicators of energy potential correspond to the possibilities of construction of mini hydroelectric power plants. When using the hydropower potential of rivers and their sections in the Vistula basin. it is worth paying attention to the conditions for the location of hydroelectric power plants considering all environmental and technological requirements for their construction. To implement this issue. it is necessary to take a sufficiently calibrated and comprehensively justified approach to the choice of sections where it is planned to equip hydropower facilities.

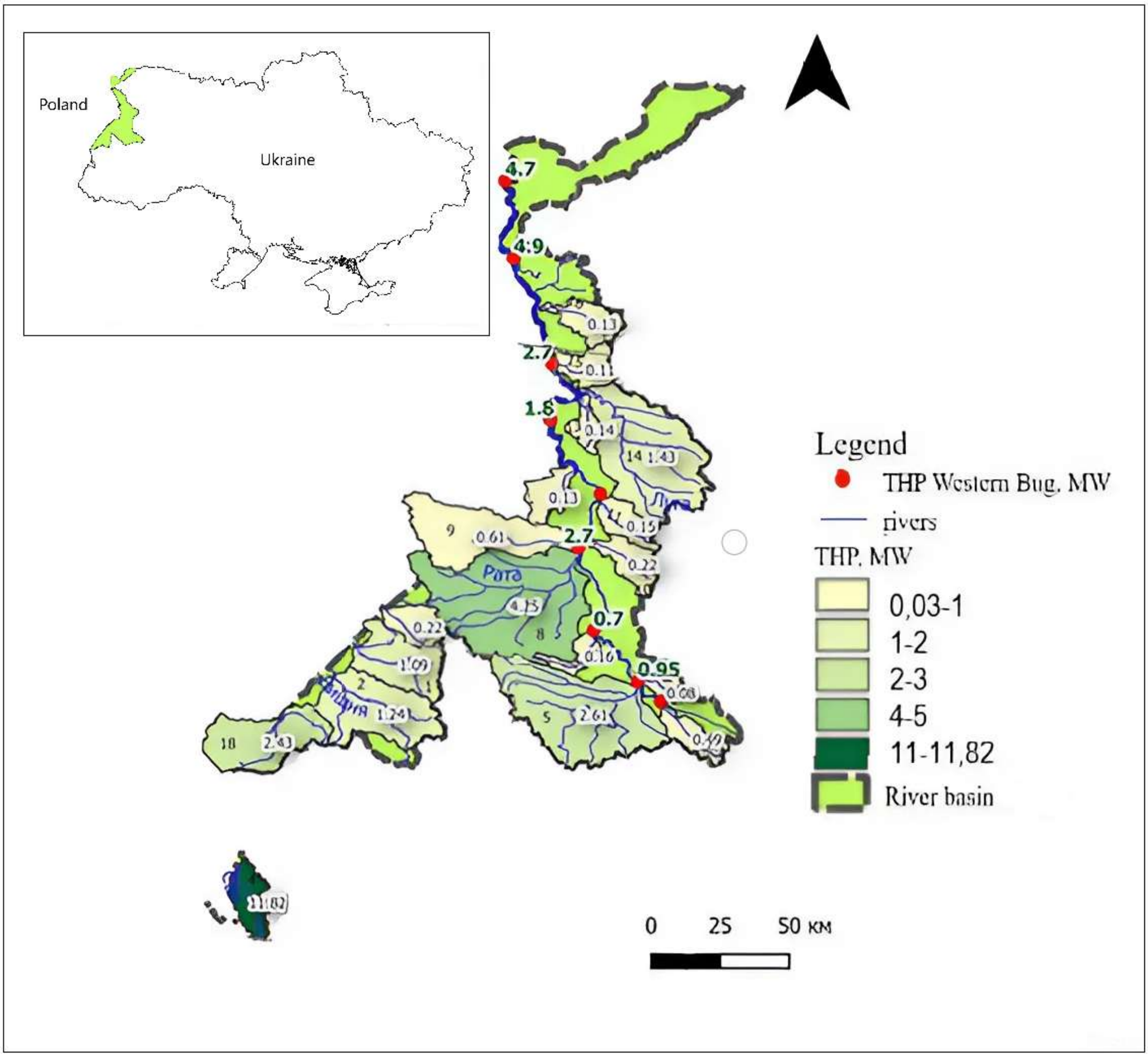

Figure 2. Map of the distribution of the THP (*N*) of the rivers of the Vistula River basin within Ukraine (Source: own work)

4.2. Forecast of the THP

For the rivers of the Vistula basin within the territory of Ukraine. a forecast of changes in their total hydropower potential was made. It was implemented according to the established stochastic regularities of long-term variability of river flow with the allocation of water flow cycles. the components of which are high-water and low-water phases (River Runoff in Ukraine. 2020; Lukianets et al., 2021).

For this purpose. first of all. approximations of the relationships between the average annual flow of river water for a long-term period and the average water flow into the high-water and low-water phases of water flow within the Vistula basin were established. which testified to their significant crowding of very high - $R^{2=}$ 0.996... 0.997 (Fig. 3).

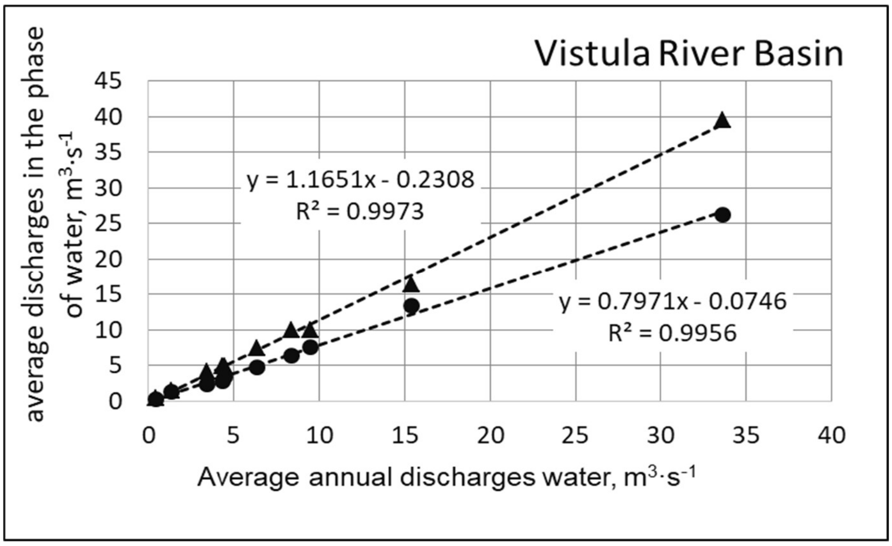

Figure 3. Connections between the average annual water flow for a multi-year period and the average annual water flow in the high-water and low-water phases of water flow within the Vistula River basin (Source: own work)

For all homogeneous sections of the studied rivers according to the regression equations. which are presented in Fig. 3. forecast water flows were established. which correspond to the high-water and low-water phases. And according to their values. the calculation of the THP of a certain area for a particular phase of water flow was carried out. According to the

Table 2 - Indicators of the total hydropower potential for the rivers of the Vistula River basin within Ukraine and its forecast values in the high-water and low-water phases of water

№	River	THP for a multi-year period. kW	% of basin THP	THP – high-water phase. kW	THP – low-water phase. kW
1	San	11822	20.9	13607	9410
2	Western Bug	31656	56.0	36436	25198
3	Vyshnia	1244	2.20	1432	990
4	Shklo	1087	1.91	1251	865
5	Solotva	223	0.40	257	178
6	Belzets	488	0.86	562	388
7	Peltiv	2612	4.62	3006	2079
8	Slotvyna	79	0.14	91	63
9	Kamianka	161	0.28	185	128
10	Rata	4248	7.51	4889	3381
11	Solokiia	611	1.08	703	486
12	Bilostok	223	0.39	257	178
13	Stasivka	152	0.27	175	121
14	Varenzhanka	127	0.23	146	101
15	Studzianka	142	0.25	163	113
16	Luha	1433	2.54	1649	1141
17	Bez nazvy	112	0.20	129	89
18	Neretva	128	0.23	147	102
	The total basin	**56548**	**100**	**65087**	**45013**

indicators of the sections. the THP of the river was established in the high-water and low-water phases of water flow.

The values of the projected changes in the THP in different phases of water flow for individual rivers of the Vistula basin within Ukraine are presented in Table 2. According to the expected estimates of long-term fluctuations in water flow during the period of the high-water phase. an increase in the THP is predicted on average for the rivers of the Vistula basin within Ukraine and will probably amount to 65087 kW. The total value of the THP in the low-water phase is likely to be 45013 kW. Table 3 presents the changes in the high-water and low-water phases of water flow in % for a multi-year period (Table 3).

Analyzing Table 3. it can be stated that. in general. for the rivers of the Vistula River basin within Ukraine in the high-water phase of water flow. the forecast indicators of hydropower potential. on average. will increase by 15.1% relative to the total THP. in the low-water phase. respectively. will decrease by 20.4%.

Table 3. Forecast indicators of the total hydropower potential of the Vistula River basin within Ukraine in the high-water and low-water phases of water

Name of the river basin	THP for a multi-year period. kW	THP – high-water phase		THP – low water phase	
		Forecast THP. kW	% change in terms of THP over a multi-year period	Forecast THP. kW	% change in terms of THP over a multi-year period
Vistula River basin	56548	65087	15.1	45013	-20.4

5. Conclusions

The area of the studied basin is 12.9 thousand km2. It is represented by two sub-basins – the Western Bug (10.4 thousand km2) and the San (2.5 thousand km). It was carried out according to the assessment of the hydropower capacity of 18 rivers. the length of which exceeds 10 km.

According to the proposed methodological approaches. the value of the THP of the rivers of the Vistula River basin within Ukraine was calculated. which is 56.548 kW. The specified value of the THP is rather insignificant in its distribution within Ukraine. its share is only 1.2%. If we analyze the THP of the Vistula Basin within Ukraine. the largest values are inherent in the Western Bug River – 31.656 kW. which is 56.0% of the basin THP and the San River – 20.9% (11.822 kW).

The basis for the forecast estimates of the RFP for the rivers of the Vistula River basin was the established stochastic regularities of long-term variability of river flow. The study of the cyclical trend made it possible to distinguish the cycles of water flow. high-water and low-water phases. which are components of the cycles. The level of approximation of the relationships between the average annual water flow for a long-term period and the average annual water flow in the high-water and low-water phases of water flow is R2 = 0.996... 0.997. The average ratio between the flow of water of rivers in the high-water and low-water phases was about 1.45. The calculation of the forecast THP for the rivers of the Vistula River basin corresponds to the defined indicators of water flow of the high-water and low-water phases. Therefore. in the result. during the period of the high-water phase within the river basin of the Vistula. an increase in the THP is predicted by an average of 15.1% compared to the THP for the multi-year period and will amount to 65.087 kW. In the low-water phase. the total value of the THP will decrease by 20.4% and will probably amount to 45.013 kW. These percentage values can also be used to forecast the indicators of the THP of individual rivers of the Vistula River basin.

The results obtained regarding the assessment of the THP of rivers in the Vistula basin area and their forecast changes in different phases of water flow can be used in the design and placement of hydropower facilities. considering all environmental and technological requirements for their construction. Also. considering the transboundary nature of the studied basin. we hope that the results obtained will be useful for Polish colleague's researchers and designers.

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