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CHANGE OF THE HORYN RIVER BASIN WATER BALANCE UNDER THE WARMER CLIMATE

Warmer climate caused a large complex of effects that appeared in every link of the global hydrological cycle. In most cases, these changes have a non-linear nature and occur with different intensity in hydrological and meteorological systems. Therefore, it is important to study such processes together, which will allow simultaneous detection of their mutual effects. The water balance method, when all components are calculated in the same dimensions (mm), and then compared with each other, is best suited for solving such a problem.

The increase in air temperature by 1,2°C caused significant changes in the overall structure of the Horyn River basin water balance: an increase in the expenditure parts uncertainty for the water balance components for the modern period 1991-2020. The closure error increase occurs mainly due to the cost part and its main component of total evaporation. According to Mali Vykorovychi hydrological gauge notes a decrease in the annual precipitation by 18 mm, river runoff by 21 mm, and an increase in total evaporation by 35 mm in absolute values. In the 1961-1990 according to the calculation of climatic water balance, the moisture accumulation prevailed over its utilization almost in 5 times but now, due to the increase in air temperature, their ratio has almost leveled off. Today river water regime almost moved from the excessively moistened to sufficiently moistened, and there are trends indicating the moisture consumption processes dominance in the basin over its accumulation.

Keywords: *water balance, climate warming, water runoff, the Horyn River.*

Introduction. The concept of water balance makes it possible to carry out an integrated assessment of the totality of physical processes occurring within river catchments. These processes include all stages of the water passage through individual links of the hydrological cycle with corresponding changes in its aggregate state. Thus, in this paper we will analyze both separately the components of the water balance, in particular precipitation, evaporation and runoff, as well as their mutual influence within a multi-year period. The relevance of this approach is confirmed by the recommendations [8] which indicate the use of water balances will provide a comprehensive study and management of water resources in the medium term.

The water balance is an effective tool for studying climate change. According to the latest report of the Intergovernmental Panel on Climate Change [2], for the time being there are clearly recorded changes in the atmosphere, hydrosphere and biosphere associated with an increase in the concentration of carbon dioxide to levels that have not been observed over the past two million years. This caused a sharp increase in air temperature due to both the general cyclical fluctuations of dry and wet periods in nature and human activity. In turn, the increase in air temperature caused changes in regional access to water resources [10]. These changes are highly uncertain – from an increase in the level of aridity [30,35], in particular, a seasonal decrease in water availability is predicted in most parts of Europe, with the exception of the north-eastern regions – to the appearance of extreme hydrological situations with a high level of flooding of territories and other negative consequences [2, 6, 33]. Overall, modern climate models indicate potential changes in the intensity of precipitation, an increase in the number of local floods and high risks of droughts.

All the trends described above are quite relevant for the territory of Ukraine. In our country, a comprehensive study of the hydrological regime of rivers through the equations of water balance, including the basin of the Horyn River, limited to the classic paper by Kahanera, [26] as well as a reference book [28] and therefore needs significant clarifications and adaptation to the current level of scientific developments.

For this purpose, using the example of different river basins, we are trying to introduce a balance approach and identify some general patterns of the development of hydrological processes. Using the evidence of the Western Bug River basin [11] an increase in the amount of total evaporation and an increase in the closure errors in the expenditure part of the water balance to the Kamianka Buzka gauge was recorded, after that, for the Upper Dniester basin according to the Kozhemiakin and Chornomorets [14], using various approaches, the total water balances for two periods were calculated separately for the mountainous and plain sections of the rivers; closure errors increase was again noted in a consumable part. To identify the causes of the described changes in water balances on the example of the Vorskla River [1] through the water equivalent of snow, a layer of snow nutrition in the incoming part of the water balance was calculated, which for the modern period decreased by 25 mm on average in the catchment area.

The selection of the Horyn River basin as the object of research for this work is conditional upon the fact that it is located in one of the most humid plain regions of Ukraine. As our previous experience shows, in order to identify and characterize local manifestations of global climate change, they can be traced more clearly in those regions that have both a higher amplitude of fluctuations in water content within the year, and higher absolute values of total precipitation. In such cases, the planned trends manifest themselves as contrastingly as possible.

To assess the development of the processes of precipitation and redistribution of moisture over time, two same duration periods were chosen, which makes it possible to correctly compare identical samples and representativeness of the conclusions obtained. The first period 1961-1990 corresponds to the climatological standard norm and in this work is called the standard reference period, while the second period 1991-2020, we will call it the “modern period” characterizes the modern water balance in the Horyn River basin.

According to World Meteorological Organization [32] recommendations «Climatological standard normals: Averages of climatological data computed for the following consecutive periods of 30 years» and the period from 1961 to 1990 has been retained as a standard reference period for long-term climate change assessments. Similar patterns are noted in the work [23] which state that: “The highest reductions of flow appear in the wetter northern basins”. The authors also point to a decrease in runoff and significant changes in its intra-annual distribution.

The objective of this study is to assess the already existing consequences that have been caused by climate change. Thus, it is based on the results of instrumental observations on a network of operating meteorological stations and hydrological gauges within the Horyn River basin and directly nearby. Precipitation and river runoff were determined from observational data, whereas evaporation was calculated using temperature and absolute humidity of the air by the Konstantinov [13] method. This method is based on the theory of turbulent diffusion and its main advantage is that it is based on the results of standard observations at meteorological stations, which ensures the availability of a sufficient amount of initial information during the entire calculation period. Accordingly, we can say that each component of the water balance is determined by independent methods.

Another important requirement for the correct calculation of the water balance is the selection of the starting point for the hydrological year. This is usually the base calculation period, which is a summer interval that contains closed periods of accumulation and consumption of water in the river basin [9]. The beginning of such a period of each year is individual. But, nevertheless, to simplify calculations mainly accepted the permanent boundaries of the hydrological year, which relate to the beginning of one of the months. For optimal determination of the beginning of the hydrological year in the Horyn River basin, we analyzed the precipitation distribution, according to which the wet period with a significant predominance of accumulation processes is conditionally stabilized in September, therefore we believe that the previous hydrological year ends in September. We also examined the dates of the snow cover appearance in the Horyn River basin for the period from 1961-2020, according to which the vast majority of cases occur in November, but in 5% they are recorded in October, which is an additional argument for electing the month of October for the beginning of the hydrological year, since the snow reserves formed at that time can theoretically take part in the formation of high water of the current hydrological year.

Study area and input data. The Horyn River basin is located mainly within the zone of mixed forests and this territory was generally characterized by a significant dominance of moisture intake over its evaporation in the standard reference period. Under such conditions, the hydrological regime of the river referred to excessively moistened territories and was characterized by a pronounced spring flood during which about 35% of the river flow took place. For the modern period, the share of spring flooding decreased by 5-8%.

Study area. The Horyn River is a typical plain river flowing through the territory of two countries, Ukraine and the Republic of Belarus (fig. 1). It is a second-order tributary of the Dnieper and the largest tributary of the Pripyat River. The Horyn River flows on three physical and geographical zones: zone of mixed forests, zone of broad-leaved forests and a small part in the forest-steppe zone. The river basin is located in two geomorphological areas: the upper part is located in the south on the Volyn-Podolsk upland, and the middle and lower parts in the north on the Polissya lowland [26].

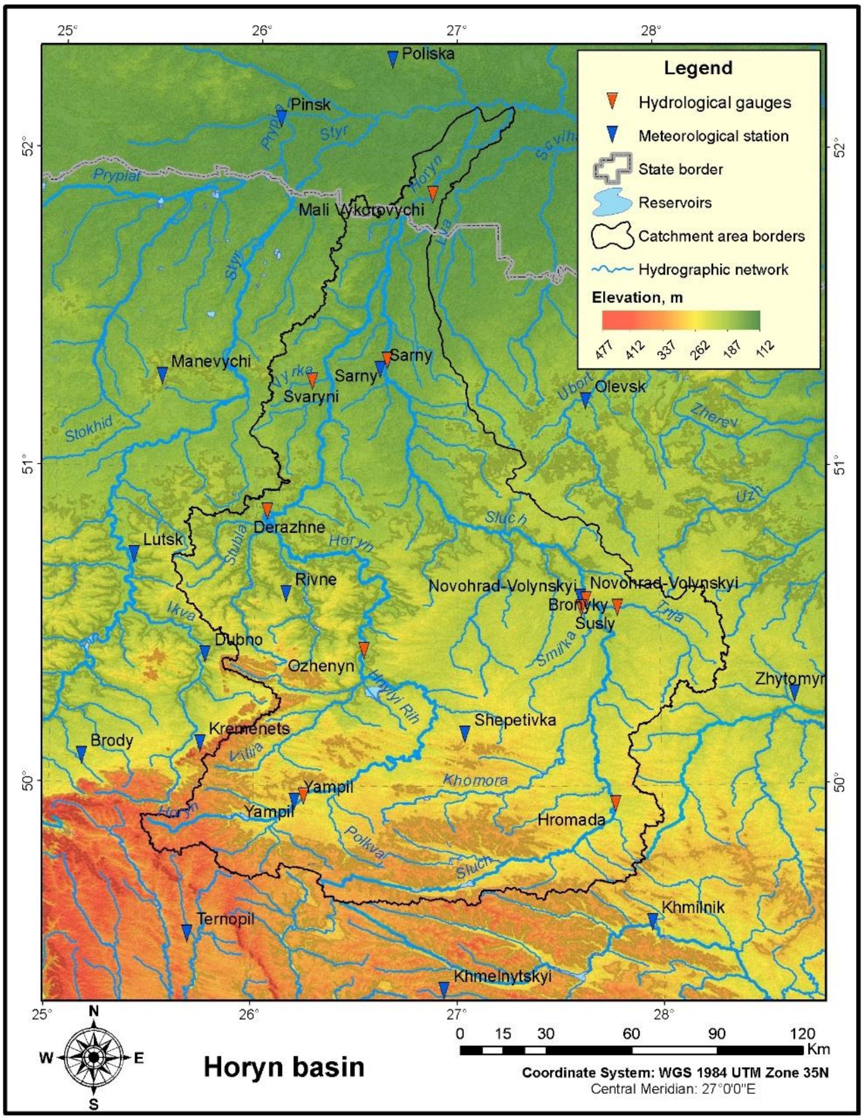

Fig. 1. **Physical and geographical location of the Horyn River basin**

The basin area is 27700 km2, the length is 659 km. The bed of the Horyn River is moderately meandering in the upper reaches, and in the middle and lower reaches it is strongly meandering. The width of the river to the mouth of the Polkva river is mainly 3-10 m, and below it is much more of 25-60 m. The river depths range from 0,3 to 2,5 m, and in some places exceeds 10 meters. The flow velocities on average are 0,3-0,5 m/sec. The bottom of the riverbed is mostly sandy, muddy on the stretch, and in some areas in the upper reaches the bottom of the riverbed is rocky. The overall slope is 0,33%. The largest tributary of the Horyn is the Sluch River, which flows into it north of the village of Velyun. According to our calculations, for the watershed of the hydrological gauge of Horyn – Mali Vykorovychi, which occupies about 97% of the entire territory of the Horyn River basin for the entire period of 1961-2020 selected for this work, the average annual air temperature is 7,7 °C, and the average annual precipitation is 635 mm. It ranges from 400-800 millimeters. During the warm period of the year (from April to October) more than half (about 70%) of the annual precipitation falls. The rainiest months are June and July. The daily maximum precipitation falls in the summer months and can reach 65 millimeters. The total flow of rivers is in the range of 105-145 mm/year. Its maximum values are observed in March and April, due to snow melting. The modern period is characterized by a decrease in the runoff of March and April by about 5 mm/month.

Datum dates estimation (inputs). Regular meteorological observations are carried out at separate points and characterize discrete manifestations of general meteorological processes. On the other hand, observations at hydrological gauges provide a general integral assessment of the totality of physical and geographical processes occurring within the entire above-placed river catchment. Thus, the contribution of each individual weather station to the total value of the meteorological characteristics (P, E) of the closure gates in the basin of the Horyn River is determined by the percentage of its coverage. In this regard, river reservoirs are divided by the Thyssen triangle system into separate zones of influence of each weather station. In proportion to the area of the obtained zones, meteorological characteristics are determined through the introduction of appropriate weighting coefficients.

Thataway the results of point meteorological observations were brought to the closing gates of hydrological gauges in this work. The calculation and value of the specified coefficients for rivers catchments of the Horyn River basin were presented in our previous publications [17, 18].

There are 15 meteorological stations in the basin of the Horyn River and in its close proximity, according to observations at which we collected data on temperature, absolute humidity (partial pressure of water vapor) and total precipitation. Also, nine hydrological gauges for which water balance components were calculated and its equation was compiled.

Using the weight coefficients, the amounts of precipitation, the average annual temperature and the absolute humidity of the air given to the corresponding hydrological gauges are calculated. A single observation period of 1961-2020 with a total duration of 60 years has been adopted for each of the hydrological gauges and meteorological stations. If there were omissions of observations, each of them was restored through the regression equation using analog points of the same characteristic.

Thus, the average monthly values of water consumption in 1961 and 1963, for the Sluch-Hromada hydrological gauge, as well as the average monthly climatic indicators (precipitation, temperature, water vapor pressure) and for individual months of 1978, 1988, 1991 and 2001, for the meteorological stations Yampil, Zhytomyr and Khmilnyk were restored. The significance level is 5%, the correlation coefficient of temperature and humidity is averagely 0,98-0,99; average lunar precipitation and runoff layers 0,7-0,8. Based on the results of observations and calculated characteristics, which are given by the values of the corresponding weighting coefficients in the following sections of this work, maps of the components of the water balance, as well as the climatic water balance are constructed using the Thornthwaite method [29]. The maps obtained in this way were used exclusively to visualize changes in the structure of the water balance. They cannot be used as a basis for discrete evaluation of each individual characteristic.

Reliability of input data. Assessment of the source data reliability. The reliability of the Horyn River basin water balance calculating confirmed in the fact that its each one component determined independently. As well as by the fact that the errors in calculating the number of characteristics, with the exception of the flow of small rivers, are within acceptable limits at a significance level of 5%. Before calculating the water balances, the absolute (1) and relative (2) errors of each of their components were determined:

$$\sigma_a = \pm \frac{\sigma}{\sqrt{n}}, \qquad (1)$$

where σ_a – an average error of the arithmetic mean, σ – the mean square deviation, *n* – the number of terms of the series.

$$\sigma'_a = \pm \frac{C_v}{\sqrt{n}} * 100\%, \qquad (2)$$

where σ'_a-– a relative average error of the arithmetic mean, C_v – a coefficient of variation, *n* –is the number of terms of the series. It is worth noting here that evaporation was calculated based on averaged data for the basin, so the error was determined separately for each of its components, i.e., for temperature and absolute humidity of the air.

According to calculations of the table 1 all errors of the components of the water balance fall within the 95% confidence interval, with the exception of water runoff on the small rivers the Vyrka River, the Tnya River, the Smilka River and the upper reaches of the Sluch River. The absolute value of deviations is in the range of 6-8 mm, this is due to the fact that the flow of these rivers is small, sometimes it even stops completely, besides, it has decreased especially noticeably in recent years, so the errors on small rivers reach 7%.

Thus, the measurements of temperature, precipitation and humidity fully satisfy the requirements of representativeness required for such characteristics. Flow measurements in the Horyn River basin require the use of more sensitive methods for small river catchments. This has become especially relevant in recent years due to a decrease in the total amount of runoff and more intensive overgrowth of riverbeds

Table 1. **Error of the average value (σ_a) determination. Level of meaning 5%**

Parameter	*Horyn-Yampil*	*Horyn-Ozhenyn*	*Horyn-Derazhne*	*Horyn-Mali Vykorovychi*	*Vyrka-Svaryni*	*Sluch-Hromada*	*Sluch-Sarny*	*Tnya-Bronyky*	*Smilka-Susly*
Precipitation									
σ'_a, %	2,1	2,0	1,9	1,8	2,3	1,9	1,9	1,9	2,0
σ_a, mm	14	13	12	11	14	13	12	12	13
Runoff									
σ'_a, %	2,7	3,7	3,7	4,4	5,1	5,5	5,6	7,3	7,7
σ_a, mm	3,9	4,9	5,0	5,3	6,5	5,8	7,1	8,3	8,2
Temperature									
σ'_a, %	1,9	1,9	1,9	1,9	1,8	1,9	1,9	2,0	1,9
σ_a, ^{0}C	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
Absolute humidity									
σ'_a, %	0,6	0,7	0,6	0,6	0,7	0,6	0,6	0,6	0,6
σ_a, мbar	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1

Homogeneity. An important condition for conducting a statistical assessment of the initial information is its verification for uniformity, followed by the identification of certain deviations of stationary fluctuations of hydrological and meteorological processes. In this regard, according to the regulatory document SNiP 2.01.14-83 [22] adopted in Ukraine, standard parametric criteria for comparing Student arithmetic averages, comparing Fisher variance and nonparametric U-criterion for comparing inversions are mainly used. The significance level for accepting the null hypothesis is 5%. There are quite a lot of literary sources describing statistical methods, but the order of calculations in them is unchanged, in this work we used the textbook recommended in Ukraine [9] (table 2).

Climate warming in natural systems is primarily fixed through the thermal regime. This can explain the violation of the uniformity of variances by the parametric criterion U-test and the same violation by the nonparametric criterion t-test in the long-term series of observations of temperature and absolute humidity.

Table 2. **Homogeneity of the datum dates for counting water balance, periods 1961-1990 and 1991-2020.** Level of meaning 5% (ta=2,0016; Fa=1,85; 317-U-582)

Component	*Horyn-Yampil*	*Horyn-Ozhenyn*	*Horyn-Derazhne*	*Horyn-Mali Vykorovychi*	*Vyrka-Svaryni*	*Sluch – Hromada*	*Sluch-Sarny*	*Tnya-Bronyky*	*Smilka-Susly*
Precipitation									
t *	0,6	1,0	0,3	0,8	0,2	1,3	0,3	0,9	1,7
F **	1,7	1,6	1,9	1,9	1,4	1,6	1,1	1,7	1,4
U ***	405	380	417	395	317	364	439	376	323
Runoff									
t	1,1	2,1	2,5	2,0	0,2	3,9	1,4	1,5	0,98
F	1,4	1,2	1,5	1,2	1,5	1,5	1,7	1,2	1,1
U	517	552	565	561	451	685	376	557	520
Temperature									
t	4,9	4,9	4,9	4,9	4,6	4,7	5,0	5,4	5,1
F	1,05	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0
U	737	740	743	741	724	733	745	782	751
Absolute humidity									
t	4,3	5,1	4,6	4,5	4,9	4,6	4,2	2,9	3,9
F	1,3	1.3	1,2	1,1	1,1	1,3	0,9	1,1	1,1
U	702	741	721	710	743	724	703	656	692

Note. t* *- Student's t-test ,* ***F**** *- F-test,* ***U***** *- U-test*

Since these values determine the total evaporation by the Konstantinov method, we can also talk about the presence of a regional reaction of the Horyn River basin to global climate changes due to a violation of uniformity in the long-term dynamics of total evaporation (actual evapotranspiration AET). This does not allow to use a single calculation period to assess the main components of the water balance, which is an additional argument in favor of the approach we have applied with a comparison of two same duration periods.

As will be shown below, these changes manifest themselves in the form of an increase in the absolute values of total evaporation. Unlike evaporation, the long-term dynamics of precipitation and runoff in the Horyn River basin over the two selected periods so far corresponds to a normal distribution, i.e., it has not undergone irreversible changes. The exception is the distribution of runoff in the Sluch-Hromada basin, where the hydrological regime is influenced by 86 ponds and 6 reservoirs that are located within this catchment. In addition, the lack of accuracy of flow measurements within this hydrological gauge is also indicated by a close subcritical mean square error (table 1).

Methods. For the time being, there is a very wide range of approaches in the world to determine the elements of the water balance and closing its equation. It is calculated at the global, regional and local levels and one or another method of determining its components is selected depending on the scale of the research object. For instance, the research by Zhang et al. [36] states that authors used data of global water budget data sets from in situ, satellite, reanalysis, and land surface models. Each of these sources of information has a number of its own advantages and disadvantages. Indirect methods for determining the components of the water balance provide a very large array of initial information continuously distributed over the basin area and this is their main advantage, however, direct measurement on the ground, despite the fact that it describes processes only at certain points, gives results as close to reality as possible. Generally speaking, in situ measurements are better suited to the local instantaneous study of water budget components, it is needed for detailed validation of models, whereas remote sensing is better suited to providing global averages; in that sense, both approaches complement each other.

In this work, we use in situ data, but in the future, we plan to involve satellite data and reanalysis data in such calculations.

General information on water balance. General methodological recommendations regarding the calculation of water balances based on the results of in situ observations (in situ data) are presented mainly in [8, 33].

The water balance of the territory is a manifestation of the law of conservation and transformation of matter in relation to the process of water exchange of this territory with the atmosphere. The long-term water balance of the river basin is presented in the form of an equation (3).

$$\frac{dW}{dT} = P - E - R, \qquad \textbf{(3)}$$

where $\frac{dW}{dT}$ are changes in moisture reserves within the river basin over a certain period of time *T*; *P* is precipitation (rain and snowfall) coming to the surface of the basin; *E* is total evaporation from the surface of the basin; *R* is runoff from the basin of surface and groundwater (river water runoff).

Water balances are compiled for periods of different duration, for instance, in [36], the water balance equation has the form (4):

$$P - E - R - TWSC = 0, \qquad \textbf{(4)}$$

where *TWSC* - total water storage change.

The methodology and calculations for closing the balance on the Earth scale and beyond the basins of the largest rivers through terrestrial water storage (TWS) are given in Lehmann et al. [16]. The main advantage of calculating multi-year balances is the mutual compensation of changes in moisture reserves within the catchment area, since during the multi-year period they tend to zero ($\frac{dW}{dT} \to 0$) and then the water balance equation takes the form (5) in accordance with Galushhenko [9] as well as Rasmussen et al. [25].

$$P = E + R \pm \mu\,, \qquad \textbf{(5)}$$

where μ is a water balance closure, due mainly to the imperfection of the measurement processes of its components.

The ratios estimate within the climatic water balance in this work were carried out in accordance with the methodology given in the works [25, 29]. Precipitation and runoff, which are included in the resulting equation, are measured directly on the network of observation points, and the calculation of total evaporation in this work is carried out using the Konstantinov method, which belongs to the group of semi-empirical methods. This method is based on the dependence of the vertical gradients of temperature and humidity of the air on the same elements, but shifted in time, revealed by the author. Using a significant number of experimental observations and based on the turbulent diffusion equation for each individual month, Konstantinov [13] developed separate dependencies used through the introduction of inertia corrections into the corresponding characteristics. Corrections for inertia are removed from the corresponding monthly nomograms or, as in our case, from the calculation tables presented by Galushhenko [9].

Results. The main requirements for the correctness of calculating the water balance and bringing them to the average long-term value are mainly the determination of all its components by independent methods, as well as a satisfactory value of the resulting error. In the first case, as already noted above, the runoff and precipitation layers were calculated based on the results of instrumental observations at hydrological gauges and meteorological stations, and the total evaporation is determined separately through temperature and absolute humidity of the air.

Change in air temperature over two periods. Compared with the period of climatic norm, the air temperature in the basin of the Horyn River increased by 1,2°C. Within the catchment area, the distribution of the average annual air temperature repeats the general patterns characteristic of the entire flat territory of Ukraine. The main front of changes is directed mainly from the northwest to the southeast.

The overall temperature increase turned out to be quite heterogeneous in the intra-annual division. Thus, the average long-term temperature of January 2,2°C (2,1-2,6°C) and partly of

July 1,7°C increased the most in the basin of the Horyn River. These two months, together with the neighboring ones, form two conditional peaks of air temperature growth within its intra-annual distribution. In contrast to them, two periods were recorded with a relatively small (0,2-0,8°C) increase in air temperature – this is the interval from September to December inclusive and separately the month of May.

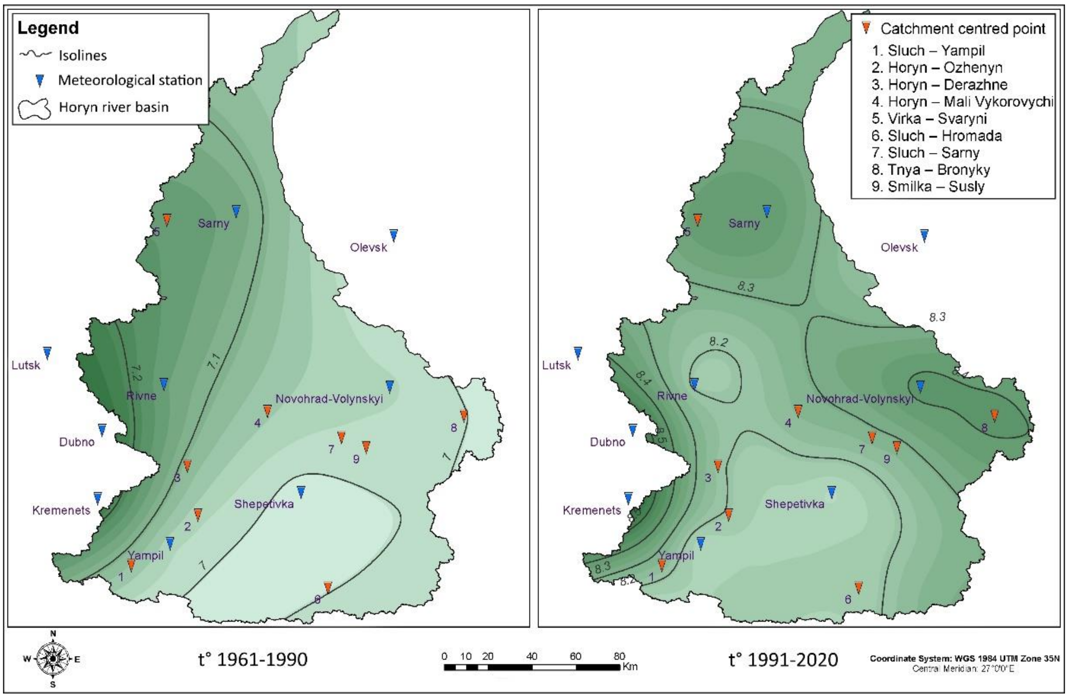

Fig. 2. **Change in the average annual air temperature over two periods**

<u>*Total evaporation.*</u> It is obvious that synchronously, before the change in air temperature, there were changes in the amount of total evaporation, which increased by 36 mm on average in the basin. In the internal annual context, evaporation increased the most in March (8 mm), also in July and August (6 mm), while a relatively significant increase in temperature and absolute humidity in January did not greatly increase the total evaporation from the snow surface (by only 3 mm) due to a small evaporation of the winter period under any conditions in general.

Similar to the trends in the intra-annual distribution of the water balance components (table 3) can be noted from the research of Dubois et al. [7]. It is referred about an increase in the number of days with temperatures above 0°C, which leads to a decrease in the amount of snow reserves and the depth of soil freezing. The consequences in our case are an increase in the inter-soil runoff of the winter season and a decrease in the runoff of the spring flood.

Table 3. **Water balance components for the Horyn River basin**

Hydrological gauge: Horyn-Mali Vykorovychi													
1961-1990	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	**Total**
P, *mm*	40	44	44	38	34	31	46	60	90	94	70	54	**644**
E, *mm*	37	24	10	4	8	19	59	78	86	79	67	47	**517**
R, *mm*	7	8	9	9	8	19	27	13	9	9	7	7	**130**
μ, *mm*	-3	12	25	25	18	-7	-39	-31	-5	5	-4	0	**-3**
1991-2020	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	**Total**
P, *mm*	41	41	41	35	35	37	38	62	79	95	64	57	**626**
E, *mm*	37	24	14	5	12	25	60	79	87	85	73	51	**552**
R, *mm*	6	6	7	9	10	17	18	10	8	7	6	5	**109**
μ, *mm*	-1	11	20	21	13	-6	-40	-27	-15	3	-15	2	**-36**

Precipitation amount. In parallel with the increase in total evaporation, there is a decrease in the annual amount of precipitation. In particular, an increase in annual evaporation by an average of 36 mm in the basin is accompanied by an almost commensurate decrease in precipitation by 24 mm. The reduction in precipitation is characterized by the greatest heterogeneity of the intra-annual distribution among all components of the water balance, since it has the highest amplitude of fluctuations. From their growth in February-March and September-October by 2-6 mm to a reduction in their number from November to January by an average of 3 mm, and also most of all in June by 11 mm.

River flow. This feature has a very significant effect on the formation of river flow. This is noticeable during the spring flood; we noted a similar pattern in the case of the Vorskla River [1]. Here it means that the increase in temperature and precipitation in February and March (1 - 6 mm) is accompanied by their predominant precipitation during this period in liquid form, due to which the runoff of the spring flood decreases, which can be estimated for April and May (2 - 10 mm) on small rivers the Tnya, the Smilka and the Vyrka, this period is limited mainly to April. In general, the increase in air temperature in the Horyn River basin caused a decrease in the total river flow by an average of 16 mm (21mm Horyn-Mali Vykorovychi).

Closure of the water balance equation. With regard to the water balance closure, it is worth noting that its value is allowed within 20% of the total precipitation, 10% is more acceptable, which is the case both in the Ukrainian recommendations [9] and in more modern works by Rodell et al. [27] and Dorigo et al. [5]. And the priority is always on the maximum reduction in the absolute value of the discrepancy. In this paper, two groups of water balances are actually calculated, according to the period of the climatic norm and the modern period. Calculations show that the average discrepancy of the standard reference period was 3%, whereas in the modern period it has grown to 7% in absolute value, this excess corresponds to a layer of 43 mm. The increase in the magnitude of the closure was also recorded by us for other river basins of the territory of Ukraine [1, 11, 14].

Changes in the structure of the water balance. To find out the reasons for the increase in the residual value, we will further consider the mutual effects of individual components of the water balance. Thus, on average, for the Horyn River basin, the annual precipitation of the modern period decreased by 24 mm (4%) compared to the period of the climatic norm, and the total evaporation increased by about the same 36 mm (7%). At the same time, river flow decreased by 16 mm (13%) I.e., at all hydrological gauges, without exception, there is an increase in the expenditure part (output) of the water balance, which cannot be compensated by a synchronous change in the revenue part (input) and automatically increases the total value of the balance discrepancy.

Similar changes in the structure of the water balance are described in paper [12], where the authors record a general trend towards a decrease in runoff in the water balance in the period from 1981 to 2011.

Climatic water balance. In order to find out how moisture is redistributed within the catchment area of the Horyn River, which largely determines changes in the structure of the modern water balance, we use such an approach as the dismemberment of moisture reserves of a certain territory by mutual redistribution of precipitation and total evaporation within the climatic water balance. The climatic water balance was introduced by Thornthwaite [29] as well as Muller and Grymes [20], initially for analyses of energy and moisture in the various regions.

The climatic water balance quite clearly describes the intra-annual redistribution of moisture within the river basin through the concept of water surplus and utilization/recharge (fig. 3). The general pattern of redistribution of moisture within the catchment area of the river is the dominance of one of the processes of surplus-utilization, which determines the hydrological regime of rivers. In the case of the Horyn River basin, precipitation prevails over evaporation for a long-term observation period. According to figure 3, we see how the humidification regime in the Horyn River basin has changed. The increase in air temperature caused a quantitative increase in the moisture layer, which goes to utilization, such a feature can be traced even visually. The process of increasing the value of utilization (by 22 mm on average in the basin and by 21 mm given by the Mali Vykorovychi gauge) is accompanied by a decrease in the water surplus layer (-65 mm on average in the basin and by -57 mm according to the Mali Vykorovychi gauge).

For the period 1961-1990, the Horyn River basin was characterized by a significant predominance of water surplus (134 mm on average in the basin or 131 mm in the Mali Vykorovychi) by almost 5 times over the utilization/recharge layer (27 mm and 28 mm, respectively). But in the modern period 1991-2020, almost the alignment of the surplus layers is observed (69 mm and 74 mm) utilization/recharge (49 mm and 49 mm). So, the increase in the average annual air temperature by 1,2°C radically, very dramatically changed the humidification regime of this river basin. It means that a 17% increase in temperature caused a 44% increase in the utilization/recharge layer and a corresponding decrease in the water surplus layer by 48%.

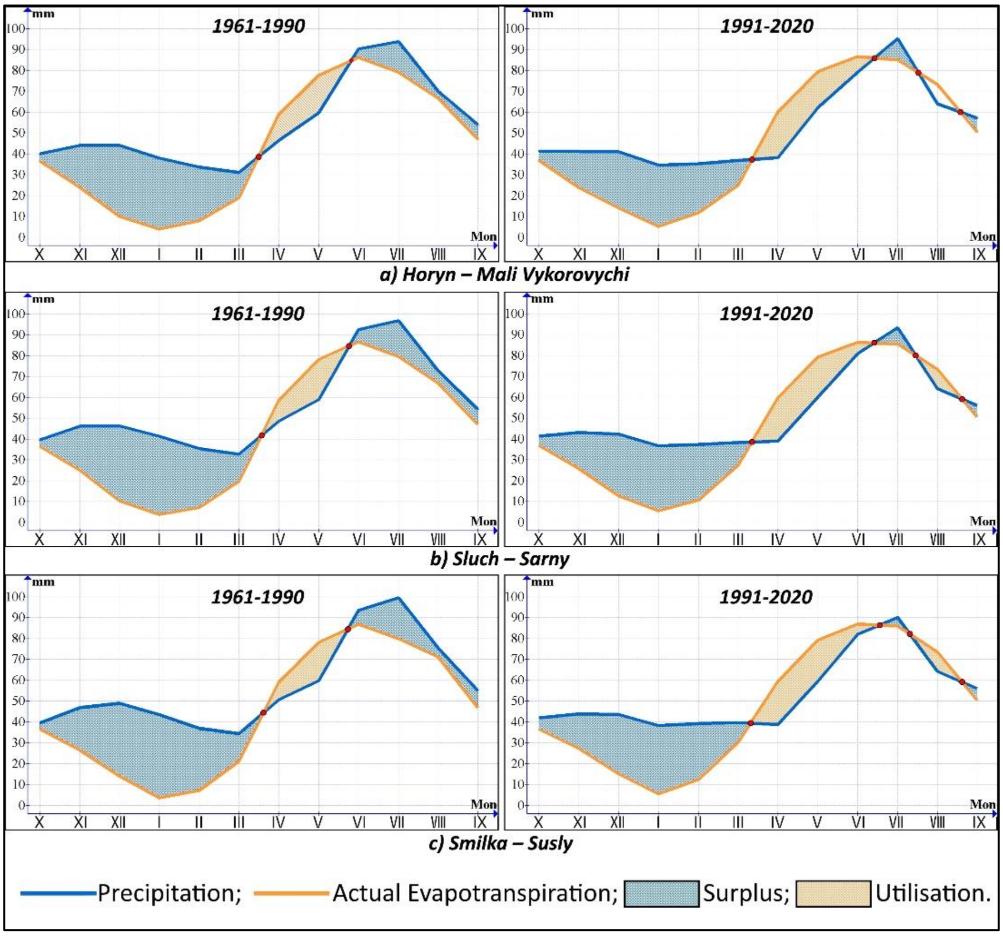

Fig. 3. **Intra-annual distribution of the ratio of water surplus and utilization of individual catchments of the Horyn basin**

Changes in the humidification/disposal regime in the territory of the Horyn River basin for two characteristic periods can be traced in figure 4.

The standard reference period was characterized by more intensive changes in the water surplus and utilization/recharge layers over the territory of the Horyn River basin. These changes in general outline the course of annual isotherms (figure 4) with a corresponding increase in absolute values, both air temperature and moisture reserves from the northwest to the southeast. The spatial distribution of utilization/recharge has the opposite character – a decrease in the absolute value in the same direction.

In the modern period, there is a tendency to equalize spatial changes in the layers of water surplus and utilization/recharge over the territory of the Horyn River catchment area. This is accompanied by a decrease in the total amplitude of oscillations of both characteristics, which has decreased in the modern period by one and a half to two times.

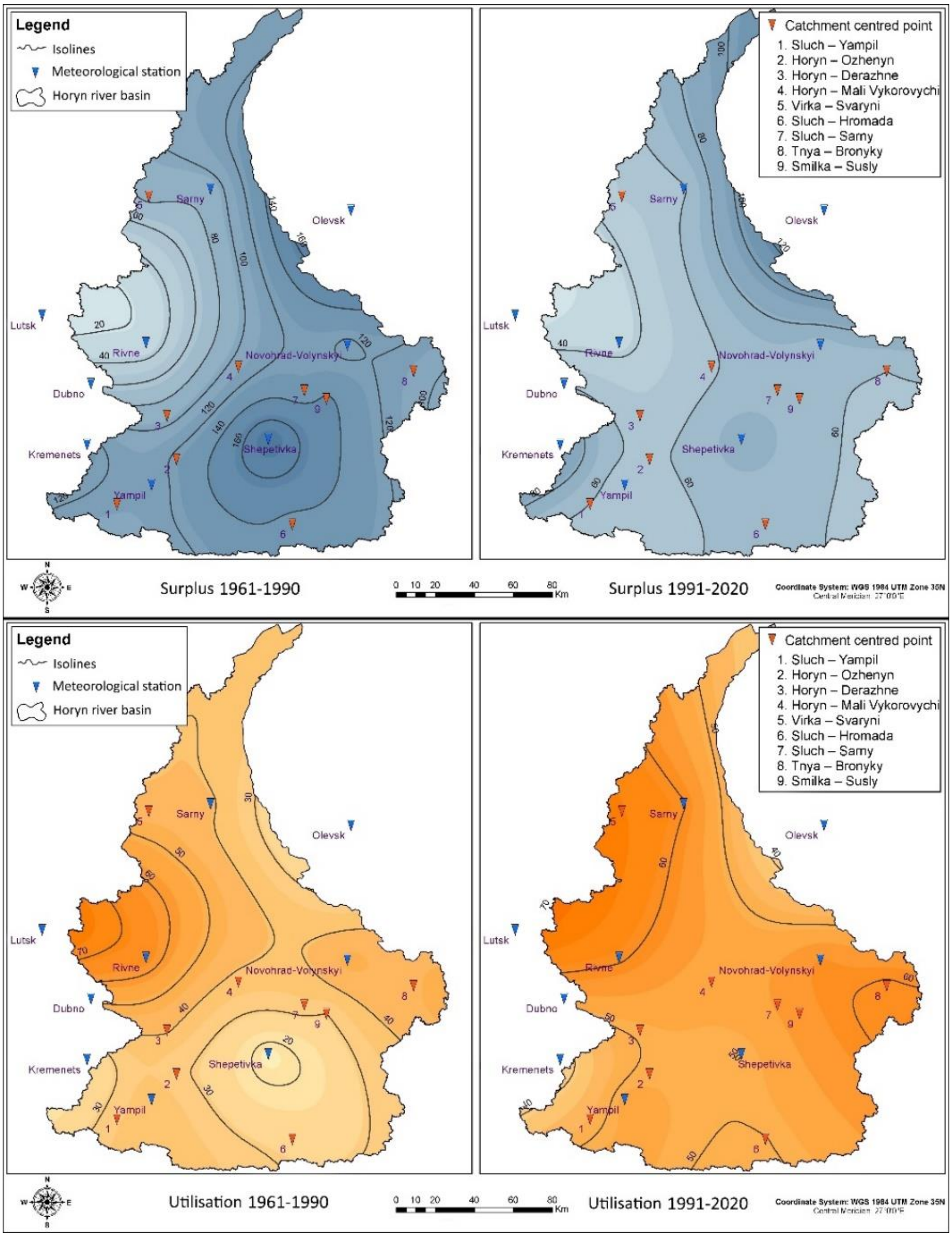

Fig. 4. **Spatial distribution of the ratio of water surplus and utilization/recharge of individual catchments of the Horyn basin**

Discussion. The water balance as a mechanism for studying local impacts on river basins of global climate change makes it possible to identify the mutual influences of its components. But the volume of such impacts cannot be estimated solely because of the water balance equation. Therefore, it is very important to supplement the calculations by calculating the surplus/utilization/recharge layers according to the scheme described by Thornthwaite [29] and Muller and Grymes [20] water budget analysis. This paper does not consider such a characteristic as Potential Evaporation (PE), since it is not included in the equation itself, and also for the conditions of the river basins of the Ukrainian Polissya, to which the Horyn River belongs, the ratio of the amount of heat spent on evaporation of precipitation to the radiation balance of the underlying surface according to Lipinsky et al. [3] is 0,8-1,0. This indicates that the value of Potential Evaporation (PE) in this basin is close to the value of Actual Evaporation

(AE), which we are considering in detail. In accordance with the Thornthwaite-Mather scheme [20, 29], we used only processes related to precipitation changes – total evaporation. Although, as the results of our calculations show, after leveling the surplus/utilization layers to 69 mm and 49 mm on average in the basin or 74 mm and 49 mm in the gauge, Mali Vykorovychi calculations of moisture deficiency (D) can become a rather promising direction for further research of this river basin.

Usually, when using Thornthwaite-Mather water budget analysis, Actual Evacuation (AE) is calculated using the same method. Thus, e.g., it was in the work Nugroho et al. [21]. However, in this paper, Actual Evacuation (AE) is calculated not according to the recommendations of Thornthwaite, but according to the Konstantinov method. Similarly, in research of Wescoat Jr. [31], Actual Evacuation (AE) is calculated using The Penman-Monteith equation. In our opinion, the advantage of the Konstantinov method over Thornthwaite is the absence of precipitation in the calculation scheme for determining AE. So, Thornthwaite [29] defines AE using the difference (P-RE), whereas Konstantinov through independent characteristics of temperature and partial pressure. The use of independent characteristics is an important prerequisite for calculating the water balances of rivers. The inability to use The Penman-Monteith equation is due to the absence for us today of the entire set of in suit data since 1961. And the task of this work was precisely the assessment of the components of the water balance for the same period by the same methods.

The climatic water balance, together with its other advantages, is a very visual method of assessing the effects of climate change. However, to date we have found only research by Cowell and Urban [4] in which it is compared over two periods. Although in this research, the second period is modeled for the entire XXI century. But we have both periods of observation of real data.

Thus, the use of the climatic water balance is possible with a combination of different methods of calculation, or even measurement of PE and AE, and in our opinion is an important promising method for studying climate change at the local and regional levels. For instance, in the work of Xu et al. an increase in evaporation in the Shule River Basin has been demonstrated [34]. The authors cite 13,4 mm/10 years for the period 1957-2010. In our case, this is 12 mm/10 years – the general trends of the influence of climate change on evaporation are similar, but the intensity of these processes depends on the region of the study. Let us note that an additional factor in the growth of the total evaporation is the duration of the growing season: in direct proportion. But an increase in evaporation leads to periods of increased runoff deficit [7]. In turn, additional effects occur when "Runoff-deficit exacerbation compared to precipitation deficit during droughts is a common feature of basins across Europe" [19]. A balance modeling using by SWAT+ [24] demonstrates that a decrease in precipitation and river runoff and an increase in evaporation in each of the RCP (representative concentration pathways) scenarios.

Less unambiguous conclusions regarding changes in the components of the water balance are given in the work of Kurkute et al. [15]. Using the example of the Mackenzie River and the Saskatchewan River, the authors show that the distribution of precipitation and runoff is largely adjusted by the influence of local factors (the Saskatchewan River). But at the same time, as in other cases, there is an increase in evaporation.

To compare the changes in the humidification regime of the Horyn River basin over two characteristic periods, we calculated the difference (delta) of the surplus and utilization layers (figure 5).

Changes in the humidification regime are characterized by fairly clear two opposite trends: a decrease in moisture reserves is accompanied by an increase in moisture utilization. At the same time, the decrease in moisture reserves in the Horyn-Mali Vykorovyhi closure is 57 mm, and the growth of the utilization layer is only 21 mm. The patterns we found indicate that an increase in air temperature in the Horyn River basin is accompanied by a decrease in moisture intake within 36 mm. The reasons for this phenomenon require further study, however, it can already be assumed that an increase in air temperature increases the ability of the atmosphere to retain moisture due to an increase in the value of water holding capacity and for the latitude of the Horyn River basin, this value should be within 30 mm.

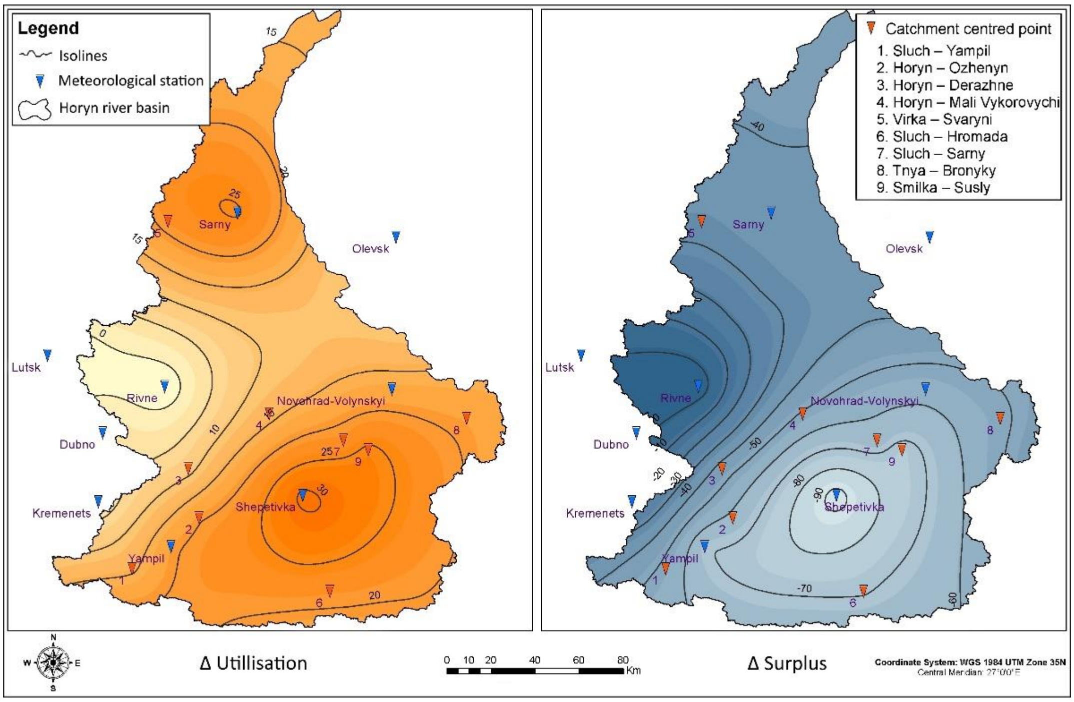

Fig. 5. **Difference between the surplus and utilization layers over two characteristic periods**

Conclusions. The increase in air temperature causes the following changes in the overall structure of the water balance of the Horyn River basin. In general, in the period 1961-1990, the catchment area belonged to the zone of excessive moisture. It was characterized by the predominance of precipitation over evaporation. However, in the period 1991-2020, the proportion of precipitation and evaporation almost leveled off. The humidification regime of the modern period of the rivers of the Horyn River basin is characterized by a transition from excessive to sufficient. The changes in the input and output parts of the water balance described above do not fully compensate for each other. If the average value of moisture utilization in the Horyn River basin has increased, then the opposite value of moisture replenishment has decreased. If we take the Horyn-Mali Vykorovychi closure line, the ratio will be 21 mm by 57 mm, in other words, on average, the proportion across the basin will remain the same. Such a pattern indicates that in the second period there is a significant decrease in the amount of moisture entering the river basin and this decrease is on average 43 mm.

The water balance of the Horyn River basin according to the data of the Horyn - Mali Vykorovychi blocking hydrological gauge in the modern period is characterized by a general decrease in the annual precipitation by 18 mm, an increase in total evaporation by 35 mm, a decrease in river runoff by 21 mm and, as a consequence, an increase in the total value of the equation closure due to a sharp decrease in the water surplus layer.

The results we have obtained were not obvious, especially if we consider each component separately. Thus, a comprehensive assessment of local manifestations of global climate change through changes in water balance ratios is a promising direction of research.

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Зміна водного балансу басейну річки Горинь в умовах потепління клімату

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Потепління клімату обумовило великий комплекс наслідків, що проявилися у кожній ланці глобального гідрологічного циклу. У більшості випадків ці зміни мають нелінійний характер та проходять з різною інтенсивністю у гідрологічних та метеорологічних системах. Тому, на нашу думку, дуже важливо вивчати такі процеси разом, що дозволить одночасно виявляти їх взаємні впливи. Для вирішення подібного завдання найкраще підходить метод водного балансу, коли всі складові обчислюються в одних і тих же розмірностях (мм), а потім порівнюються між собою.

Зростання температури повітря з періоду 1961-1990 до 1991-2020 на 1.2°C обумовлює значні зміни в загальній структурі водного балансу басейну річки Горинь. В першу чергу це зростання невизначеності у витратних частинах кожного з обчислених водних балансів для сучасного період 1991-2020. Збільшення нев'язки відбувається переважно за рахунок витратної частини й головної її складової - сумарного випаровування. Невизначеність підтверджується порушенням однорідності за параметричним критерієм t-test (Критерій Стьюдента) рядів температури та абсолютної вологості повітря. У абсолютних значеннях за даними замикального гідрологічного посту Малі Викоровичі можна простежити зниженням річної суми опадів на 18 мм, річкового стоку води на 21 мм та зростанням сумарного випаровування на 35 мм.

Більш чітко локальні прояви глобальних змін клімату можна побачити, якщо оцінювати воднобалансові співвідношення в межах кліматичного балансу. Тут фіксується зміна пропорції накопичення вологи (S) – виснаження/ відновлення (U/R) від 131 мм (S) – 28 мм (U/R) для 1961-1990 до 74 мм (S) 49 мм (U/R) для 1991-2020. Тобто якщо у період кліматологічної стандартно норми накопичення вологи переважало над її виснаженням майже у 5 разів, то зараз, через зростання температури повітря, їх співвідношення практично вирівнялося. Це призвело до того, що нині водний режим річки із категорії надмірно зволожених може перейти у категорію достатньо зволожених і намічені тенденції свідчать про можливий початок домінування процесів виснаження вологи у басейні над її накопиченням.

***Ключові слова:** зміни клімату; водний баланс; стік води; річка Горинь*

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АВТОМАТИЗОВАНА СИСТЕМА «ICE-AUTUMN» ДЛЯ ДОВГОСТРОКОВОГО ПРОГНОЗУВАННЯ ДАТ ПОЯВИ ЛЬОДОВИХ ЯВИЩ ТА ВСТАНОВЛЕННЯ ЛЬОДОСТАВУ НА ВОДОСХОВИЩАХ ДНІПРОВСЬКОГО КАСКАДУ

Довгострокове прогнозування дат появи льодових явищ і встановлення льодоставу на водосховищах Дніпровського каскаду має важливе, перш за все, практичне значення, оскільки на його основі планується робота гідроенергетики, судноплавства, рибного, комунального господарств, тощо. У сучасному світі забезпечення споживачів прогнозною гідрологічною продукцією відбувається за допомогою різноманітних автоматизованих комп'ютерних комплексів і систем, які мають зручний інтерфейс для користувача. Такий підхід набув широкого використання і в Україні. Так, в Українському гідрометеорологічному центрі (УкрГМЦ) використовуються автоматизовані прогнозно-моделювальні комплекси, які дозволяють виконувати коротко- і довгострокове прогнозування перебігу стоку води під час повені на річках України. Разом з цим, автоматизована система прогнозування строків настання основних фаз льодового режиму річок і водосховищ України була створена тільки для короткострокового прогнозування. Отже, у роботі вперше створено автоматизовану систему «Ice-Autumn» для довгострокового прогнозування дат появи льодових явищ і встановлення льодоставу на водосховищах Дніпровського каскаду, для якої програмне забезпечення написане на мовах програмування C# та C++ у середовищі Visual Studio 2022 Community Edition у вигляді Windows форм та консольних додатків. Основою