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THE IMPACT OF CLIMATE CHANGE ON EVAPORATION FROM THE RESERVOIRS OF THE SOUTHERN BUG BASIN

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Abstract. *The article deals with the issue of assessing the level of flow regulation of the Southern Bug River Basin within Khmelnytskyi and Vinnytskyi regions. The Southern Bug River Basin is one of the most regulated river basins in Ukraine, with 17 % of reservoirs and 20 % of ponds of the total number in Ukraine. Many of them are in extremely poor condition. Overgrowth, siltation, and bank degradation in many small reservoirs have led to a significant reduction in their volume, an increase in the area of shallow water, disrupted soil nutrition, and caused intensive development of higher aquatic vegetation. Studies have shown that water losses to evaporation in the reservoirs of this basin amount to 25,6 % of their total volume, or 50,2 % of the useful volume. At the ponds, losses are much higher and amount to 66,7 % of their total volume. In general, evaporation losses in the Southern Bug River (up to the border with Kirovohradskyi region) amount to 17,6 % of its average annual value over the long-term observation period. A significant increase in evaporation from the water surface has been observed in recent decades, due to an increase in air temperature during the growing season. While in the very low-water years of the last century, evaporation losses of the Southern Bug amounted to 38,3 % of the annual runoff, in 2020 they reached almost 70 %. The greatest increase in evaporation is observed in the summer months, due to an increase in daily maximum air temperatures and the number of days with average daily air temperatures above 30 °C. To solve the problem of conservation and efficient use of water resources, it is necessary to introduce a comprehensive system of organizational and technical measures, including optimization of the number of reservoirs in river basins, taking into account the level of flow regulation and economic needs; increasing the volume of functioning reservoirs by clearing their l*
Keywords*: anthropogenic load, evaporation, reservoir, flow regulation, precipitation, river basin, ponds*

Relevance of the research. Ukraine belongs to the countries with insufficient water resources, which necessitates intensive regulation of surface runoff. According to the UN economic criterion for sufficient water supply, there should be at least 1700 m^3 of water per person per year, and in Ukraine, per capita water supply is about 1200 m^3[1]. In the southern and eastern regions of Ukraine, reservoirs are practically the only source of guaranteed supply of drinking water for the population, as well as for the needs of municipal, agricultural, and industrial sectors for fresh water. Ukraine ranks second in Europe in terms of the number of reservoirs, after Spain. In total, there are 1054 reservoirs and 49444 ponds in the country, with a total area of 2891 km^2 [2, 3]. Reservoirs are used depending on the economic specialization of the region, in particular for runoff regulation and flood control, water supply, irrigation, fish farming, hydropower, and recreation. Flow regulation in the basins of small rivers can reach 70 %, and in the south – all 100 %, which causes significant irreversible losses of water resources and environmental problems caused by deterioration of water quality, channel deformations, intensification of eutrophication processes, flooding, etc.

Ukraine's reservoirs play an important role in providing water resources, but a significant part of them is in a very poor condition. Overgrowth, siltation, and bank degradation in many small water bodies have led to a significant reduction in their volume, an increase in the area of shallow water, disrupted soil nutrition, and caused intensive development of higher aquatic vegetation in warmed and fertile shallow areas. The increase in nutrient inputs, which are the source of nutrition for bacteria and aquatic vegetation, led to the "blooming" of water as a result of the development of blue-green algae.

Chemical, bacteriological, and biological pollution is a common occurrence in reservoirs and ponds, especially those built on small rivers and without a balance holder. Pollution of water bodies makes it impossible to use them as sources of water resources. The technical condition of hydraulic structures on these reservoirs is also unsatisfactory, which often makes it impossible to ensure the necessary flow regulation and environmental releases and discharges into the lower reaches. Many of the reservoirs have lost their economic significance and are only water intakes for local surface runoff and additional evaporators of water. Therefore, the problem of rational use of water resources in Ukraine is extremely relevant.

Analysis of recent studies and publications. Extensive scientific research on the problem of conservation and rational use of water resources and assessment of the environmental impact of reservoirs has been conducted in Ukraine since the construction of the Dnipro reservoirs cascade. Papers [2–5] provide data on the quantitative assessment of water bodies in Ukraine within the main river basins and administrative units, as well as their main hydromorphological and technical characteristics. Based on long-term studies, the State Agency of Ukraine for Water Resources has developed the Rules for the Operation of Reservoirs of the Dnipro and Dniester Cascades to ensure effective flow regulation. For other water bodies, the territorial bodies of the State Agency of Ukraine for Water Resources have determined the procedure for establishing their operating regimes [6].

A large number of studies have been devoted to assessing the negative impact of artificial reservoirs on the ecological state of the natural environment, including flooding of territories, changes in the hydrological regime of rivers, activation of channel processes, changes in biodiversity and fish fauna, etc. [7–9]. A considerable amount of research is devoted to the deterioration of water quality, hydrochemical and hydrobiological regimes, eutrophication of water bodies, especially algal blooms [10, 11], as well as water balance studies, in particular, on runoff losses due to evaporation [12–15]. These studies point to the need to implement a comprehensive system of measures to improve the ecological status of water bodies and conserve and rationally use water resources, including improving flow control schemes by quantitatively optimizing ponds and reservoirs and reducing evaporation and filtration losses.

The aim of the study is to assess the level of runoff regulation of Ukrainian rivers and to substantiate promising measures to preserve water availability.

Research methods. The research was carried out on the basis of generally accepted methods of synthesis and analysis of long-term hydrometeorological observation data published in the materials of the State Water Cadastre and the Climate Cadastre of Ukraine, as well as literature on this issue.

Research results and their discussion. The Southern Bug River basin is one of the most heavily regulated river basins in Ukraine. It is home to 17 % of reservoirs and 20 % of ponds out of the total number of reservoirs in Ukraine. Table 1 shows the average annual evaporation from the surface of water bodies and its value as a percentage of the water volume in ponds and reservoirs for the Southern Bug section up to the border of Vinnytsia and Kirovohrad oblasts. In the calculations, the evaporation value of 650 mm was assumed, according to the corresponding map of the Climate Atlas of Ukraine. The analysis of the table shows that evaporation losses at the reservoirs amount to 25,6 % of their total volume, or 50,2 % of the useful volume. At ponds, losses are much higher and amount to 66,7 % of their total volume. This is due to the much shallower depths of small reservoirs and, accordingly, much larger water mirror areas per unit volume.

It should be noted that water losses due to evaporation from ponds and reservoirs within the Khmelnytsky section of the basin are higher than within the Vinnytsia region, due to the shallower depths of water bodies in Khmelnytsky. In total, evaporation losses within this section of the Southern Bug basin amount to 258,25 million m^3 on average per year, or 42,8 % of their total volume. In general, the total evaporation losses from the basin's water bodies (ponds and reservoirs) are 44 % higher than the useful volume of all reservoirs.

The average annual discharge of the Southern Bug River according to observations at the Pidhiria hydrological station located on the border of Kirovohradskyi and Mykolaivskyi regions is 56,2 m^3/s. In terms of the border of Vinnytskyi and Kirovohradskyi regionss, it is 46,6 m^3/s, and the average annual volume of the river flow is 1469,58 million m^3.

1. Regulating the flow of the Southern Bug River up to the border with Kirovohradskyi region

Region	Number of reservoirs	Area of the river ha	Volume, million m^3		Evaporation	Evaporation losses	
						of total volume	of useful volume
			full	useful	Million m^3	%	%
Reservoirs							
Vinnytska	42	8604	269,0	117,0	55,93	20,8	47,8
Khmelnytska	24	5241	82,5	62,2	34,07	41,3	54,8
Total	66	13845	351,5	179,2	90,00	25,6	50,2
Rates in							
Vinnytska	3401	17614	182,0		114,49	62,9	
Khmelnytska	976	8271	70,4		53,76	76,4	
Total	4377	25885	252,4		168,25	66,7	
Total for the Southern Bug basin (up to the border of Kirovograd region)							
		39730	603,9		258,25	42,8	144,1

Since the average annual volume of evaporation from the reservoirs of the Southern Bug basin within Khmelnytskyi and Vinnytskyi regions is 258,25 million m^3, the loss of river flow due to evaporation is 17,57 %. The lowest average annual river discharge at the Pidhiria settlement in the last century was 25,7 m^3/s (1995), which corresponds to a discharge of 21,31 m^3/s at the region's border, or a runoff of 673,9 million m^3. Accordingly, evaporation from the reservoirs of the Southern Bug in the Khmelnytski and Vinnytskyi regions in the very low-water years of the last century reached 38,32 % of the annual river flow.

As noted above, the evaporation (Table 1) is calculated based on the average evaporation data shown on the zoned map of the Climate Atlas of Ukraine, which was built on the basis of the Climate Cadastre of Ukraine for 1961–1990 and, accordingly, does not take into account the climate changes observed in Ukraine in recent decades. Figure 1 shows the dynamics of the Southern Bug River flow based on observations at the Pidhiria hydrological post since 1927, which shows a sharp decrease in river flow since 2007. In 2020, the river flow was more than twice as low as the lowest flow recorded during the above observation period and amounted to 371,32 million m^3. Accordingly, evaporation from the reservoirs of the Southern Bug in the Khmelnytskyi and Vinnytskyi regions reached almost 70 % of the river's annual runoff.

An analysis of the intra-annual distribution of runoff (Fig. 2) for the periods before 2000 and 2000–2020 shows that the largest decrease in runoff was recorded during the spring flood and from July to September. In the first case, this is due not only to climate change, in particular a decrease in snow reserves in the basin, but also to flow regulation, since the volume of spring filling of reservoirs before the normal headwater level of reservoir depends on the level of their operation at the beginning of the flood. Due to climate change in recent decades, the level of pre-flood filling of reservoirs has decreased significantly. The decrease in runoff during the warm season is due to the maximum increase in daily maximum air temperatures, which have repeatedly reached historical highs in recent years.

The annual runoff volume is mainly determined by the difference between the amount of precipitation in the basin and evaporation, as well as the irrevocable volume of water withdrawals for economic use. An analysis of precipitation dynamics over a multi-year period (Fig. 3) shows a slight decrease in recent years, which cannot significantly affect a significant reduction in runoff. Accordingly, the sharp decline in river runoff was mainly due to an increase in evaporation, as the number of artificial reservoirs built in recent decades and, accordingly, additional flow regulation is insignificant.

The main reason for the increase in evaporation is air temperature. For example, the average annual air temperature in Kyiv has increased by almost 3 °C in recent decades [5]. Due to the high level of urbanization of the territory (heating networks, a large percentage of paved surfaces, and the level of gas and smoke emissions), this is much higher than in natural areas, where the temperature increase within Ukraine reaches 1–2 °C. In Vinnytsia, the average annual air temperature (modern climatic norm) increased by 1,2 °C between 1991 and 2020 compared to the period 1961–1990 (previous climatic norm) (Table 2). The highest temperature increase was observed in January and February, when evaporation is practically absent, and in the summer months, when evaporation is highest (Fig. 4).

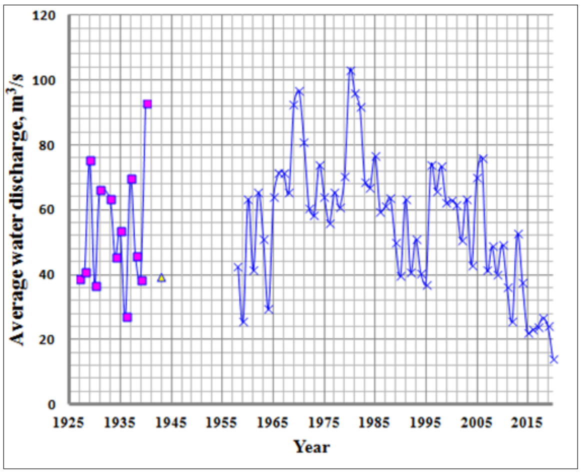


Fig. 1. Dynamics of the average annual runoff of the Southern Bug River – Pidhiria settlement

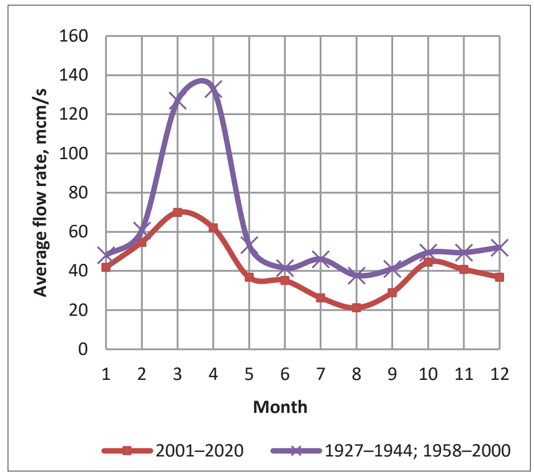


Fig. 2. Distribution of the average annual runoff of the Pivdennyi Buh River – Pidhiria settlement by months for different time intervals

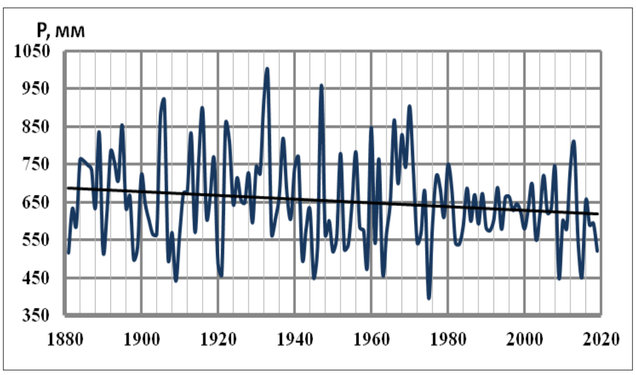


Fig. 3. Dynamics of precipitation in Kyiv over the entire observation period

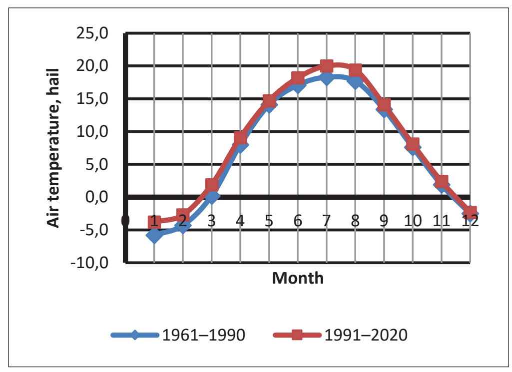


Fig. 4. Intra-annual distribution of air temperature, Vinnytsia city

2. Air temperature at the Vinnytsia weather station

Period	**Month**												
Years	1	2	3	4	5	6	7	8	9	10	11	12	Year
1961–1990	–5,8	–4,3	0,2	8,0	14,1	17,1	18,3	17,7	13,4	7,6	1,9	–2,5	7,1
1991–2020	–3,8	–2,7	1,9	9,1	14,7	18,2	20	19,4	14,1	8,1	2,4	–2,3	8,3

Fig. 5 shows the dynamics of evaporation from Kyiv reservoirs. To calculate evaporation, an approximate empirical method by A.M. Postnikov was used, based only on the dependence of evaporation on the sum of monthly air temperatures during the frost-free period. The formula was derived from instrumental measurements of evaporation and air temperature on the largest reservoirs of the former USSR. The calculations show a sharp increase in evaporation since 1997.

Fig. 6a shows a graph of the dependence of daily evaporation from the water surface on air temperature, which is based on field data measured in DGI-300 evaporators [15]. The analysis of the graph shows that evaporation increases proportionally with increasing air temperature only up to a temperature of 16 °C, when the increase in evaporation for each degree of temperature increase ranges from 0 to 0,3 °C (Fig. 6b) With further increase in temperature (T), the increase in evaporation (P) increases according to a polygonal dependence (Fig. 7), approximated by Eq:

$$P = 0.0115T^2 - 0.0559T + 0.5333 \qquad (1)$$

In the temperature range from 17 to 40 °C, the evaporation increase varies from 0,3 to 0,9 mm for each degree of increase in daily temperature (Table 3).

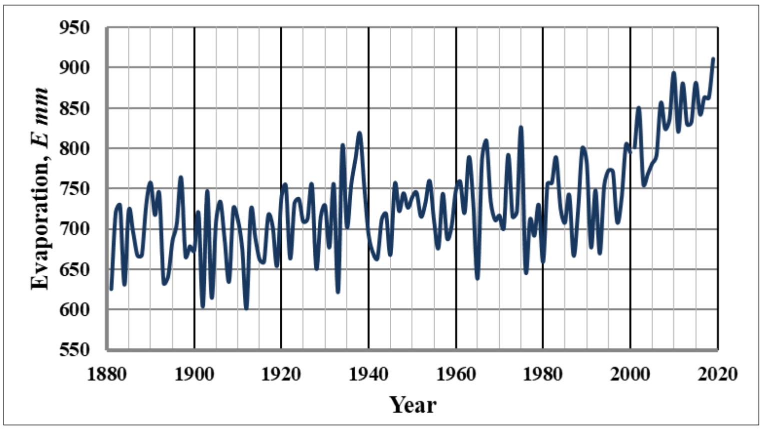
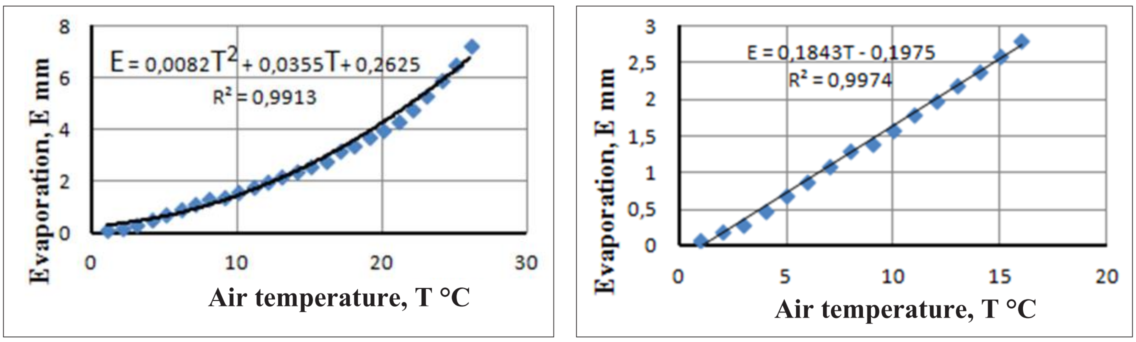


Fig. 5. Estimated evaporation from the water surface of Kyiv reservoirs since 1881



a) b)

Fig. 6. Dependence of evaporation on air temperature:
a) polygonal dependence; b) linear dependence in the low temperature range.

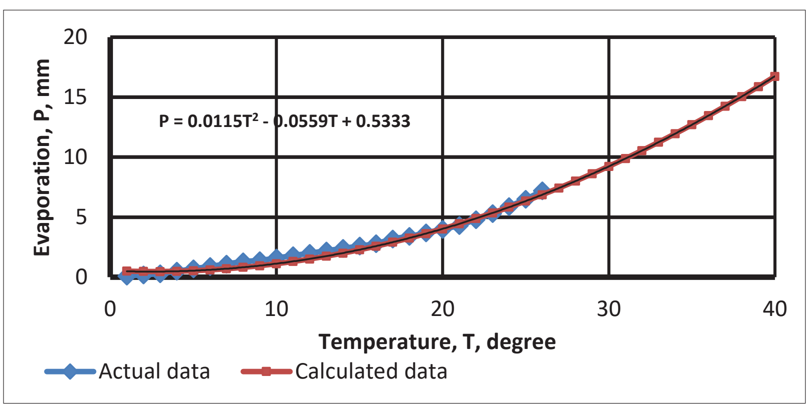


Fig. 7. Dependence of evaporation on air temperature

These results show that the evaporation rate is not proportional to the increase in air temperature, but increases sharply at its maximum values, especially when the temperature exceeds 30 °C. The last two decades have been characterized not only by an increase in the average annual temperature, but also by a sharp increase in average daily temperatures in the summer months. In these years, most of the historical temperature maximums were exceeded. Thus, while in Kyiv from 1971 to 2006 there were an average of 9 days with temperatures above 30 °C, from 2007 to 2020 the number of such days per year increased to an average of 24 (Fig. 9). In 2010, there were 44 days with temperatures above 30 °C [15].

3. Dependence of daily evaporation from the water surface on air temperature in Ukraine

Temperature, °C	Evaporation, P, mm	Evaporation increase by 1 ^{0}C, (ΔP/1 °C)	Temperature, °C	Evaporation, P, mm	Evaporation increase by 1 ^{0}C, (ΔP/1 °C)	Temperature, °C	Evaporation, P, mm	Increase in evaporation by 1 $^{(0)}$C, (ΔP/1 °C)
1	0,5	0,0	15	2,3	0,3	28	8,0	0,6
2	0,5	0,0	16	2,6	0,3	29	8,6	0,6
3	0,5	0,0	17	2,9	0,3	30	9,2	0,6
4	0,5	0,0	18	3,3	0,3	31	9,9	0,6
5	0,5	0,0	19	3,6	0,4	32	10,6	0,7
6	0,6	0,1	20	4,0	0,4	33	11,2	0,7
7	0,7	0,1	21	4,4	0,4	34	12,0	0,7
8	0,8	0,1	22	4,9	0,4	35	12,7	0,7
9	1,0	0,1	23	5,3	0,5	36	13,5	0,8
10	1,1	0,2	24	5,8	0,5	37	14,2	0,8
11	1,3	0,2	25	6,3	0,5	38	15,1	0,8
12	1,5	0,2	26	6,9	0,5	39	15,9	0,8
13	1,7	0,2	27	7,4	0,6	40	16,7	0,9
14	2,0	0,3						

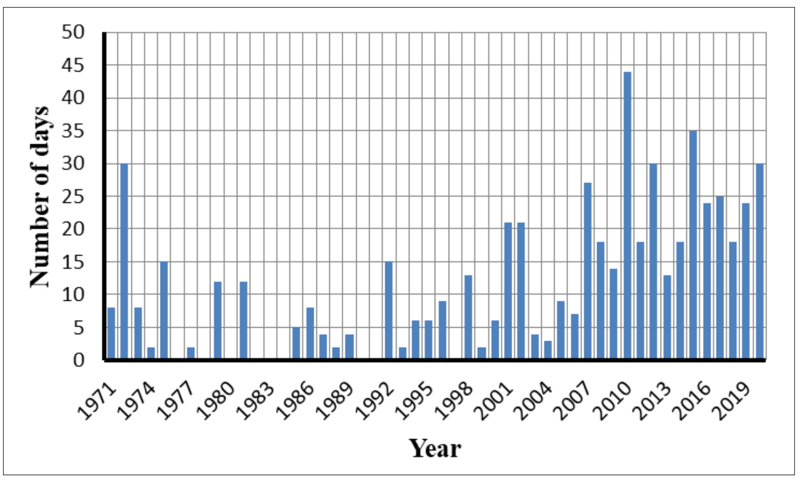


Fig. 8. Number of days with average daily temperature above 30° C, Kyiv

The calculations based on the formula for the dependence of daily evaporation on temperature showed that in the period from 1991 to 2020, the average annual evaporation increased by 81 mm compared to the period 1961–1991, and in July and August, monthly evaporation increased by 20 mm.

Conclusions. The increase in the intensity of evaporation from the water surface in recent decades has caused a significant decrease in water resources in Ukraine, which is primarily due to excessive losses of runoff due to evaporation from the surface of ponds and reservoirs, a significant part of which is in poor environmental condition and has a low level of use efficiency. Water losses by evaporation from the reservoirs of the Southern Bug basin within Khmelnytsky and Vinnytsia oblasts can reach 70 % of the total annual runoff in very dry years. To solve the problem of conservation and efficient use of water resources, it is necessary to implement a comprehensive system of organizational and technical measures, including: optimization of the number of reservoirs in river basins, taking into account the level of flow regulation and economic needs; increasing the volume of functioning reservoirs by clearing their beds (taking into account hydrogeological conditions); elimination of shallow reservoirs or reduction of the area of their shallow areas; restoration of water sources; clearing of water sources in their upper reaches.

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ВПЛИВ КЛІМАТИЧНИХ ЗМІН НА ВИПАРУВАННЯ З ВОДОЙМ БАСЕЙНУ ПІВДЕННОГО БУГУ

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Анотація. *Висвітлено питання щодо оцінки рівня зарегулювання стоку річок басейну Південного Бугу в межах Хмельницької та Вінницької областей. Басейн Південного Бугу є одним з найбільш зарегульованих річкових басейнів України, де знаходиться 17 % водосховищ і 20 % ставків від їх загальної кількості в Україні. Значна їх частина знаходиться у вкрай незадовільному стані. Заростання, замулення, деградація берегів на багатьох малих водоймах призвели до значного зменшення їхнього об'єму, збільшення площі мілководь, порушили умови грунтового живлення та спричинили інтенсивний розвиток вищої водної рослинності. Виконані дослідження показали, що на водосховищах зазначеного басейну втрати води на випарування становлять 25,6 % від їх повного сумарного об'єму, або 50,2 % від корисного. На ставках втрати значно вищі і становлять 66,7 % їхнього сумарного об'єму. У цілому втрати стоку Південного Бугу на випарування (до межі з Кіровоградською областю) становлять 17,6 % від його середньорічного значення за багаторічний період спостережень. Значне зростання випарування з водної поверхні спостерігається в останні десятиліття, що обумовлено підвищенням температури повітря у вегетаційний період. Якщо у дуже маловодні роки минулого століття втрати на випарування Південного Бугу становили 38,3 % річного стоку, то у 2020 році вони сягнули майже 70 %. Найбільше зростання випарування спостерігається в літні місяці, що зумовлено зростанням добових максимумів температур повітря та кількості днів з середньодобовими температурами повітря понад 30 °С. Для вирішення проблеми збереження й ефективного використання водних ресурсів необхідне впровадження комплексної системи організаційних і технічних заходів, що включають оптимізацію чисельності водойм у басейнах річок з врахуванням рівня зарегулювання стоку та господарських потреб; збільшення об'єму функціонуючих водойм за рахунок розчищення їх ложа; ліквідацію мілких водойм, або зменшення площі їх мілководних ділянок; відновлення природних джерел живлення водойм; забезпечення нормальних умов роботи регулювальних споруд у відповідності з правилами їх експлуатації, а також впровадження системи заходів щодо покращення екологічного стану водойм.*

Ключові слова: *антропогенне навантаження, випарування, водосховище, зарегулювання стоку, опади, річковий басейн, ставки*