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ESTIMATION OF WATER LOSS FOR TOTAL EVAPORATION FROM THE SURFACE OF PONDS AND RESERVOIRS IN THE INGULETS RIVER BASIN

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Abstract. *The article considers the problem of water loss due to the evaporation from the surface of ponds and reservoirs under conditions of intense anthropogenic load and climate changes, focusing on the Ingulets river basin as an example of the one of the most regulated river systems in the steppe zone of Ukraine. Taking into account the growing shortage of water resources, especially after the explosion of the Kakhovka HPP, the relevance of studying evaporation from water surfaces of artificial reservoirs in the southern regions is increasing. Estimating water losses due to the evaporation from the surface of ponds and reservoirs in the Ingulets River basin is an important aspect of water resources management in the region. Available data on the areas of artificial water bodies and average evaporation rates were used to calculate total water losses. Based on a spatial analysis of over 1,200 water bodies in the Inhulets river basin, including an assessment of the areas and volumes of reservoirs and ponds, a quantitative assessment of water evaporation from their surface was carried out for 1961–1990 and 1991–2023. The research methodology is based on the processing of long term meteorological data from local weather stations, as well as the use of satellite and archival information from available sites. Climatic conditions in the studied region demonstrate a steady warming trend: over the past 30 years, the average annual temperature in the Ingulets river basin has increased by an average of 1,3 °C with slight decreases in precipitation over the studied period. It has been found that under modern conditions, evaporation can exceed the inflow from atmospheric precipitation, which turns artificial reservoirs into active factors in reducing the water balance of the Ingulets river basin. In 1991–2023, evaporation rates from the surface of water bodies increased by 13,7 % (107 mm) for the Znamyanka weather station, by 7,6 % (68 mm) for the Komisarivka weather station, and by 9,1 % (88 mm) for the Kryvyi Rih weather station. Particular attention is paid to assessing the water management efficiency of the functioning of such facilities in the context of environmental safety, hydrological stability, and adaptation to the climate changes. The obtained results are important for the development of regional water resources management strategies, improvement of methods for calculating water losses, and ecological and economic optimization of the water fund structure in small and medium-sized river basins.*

Key words: *Inhulets river basin, evaporation, climate change, artificial objects, ponds and reservoirs, water balance, water resources management*

Relevance of the research. Excessive regulation of river flow is one of the main water problems of Ukraine [p. 3, 1], which causes additional water losses due to evaporation, slowing down of water exchange and, as a result, the deterioration of water quality and degradation of riverbeds [p. 4, 1]. This is especially true for the Ingulets river basin, 80 % of the flow of which is regulated by artificial reservoirs [p. 69, 2].

On the one hand, the reservoirs and ponds of the Inhulets river contribute to the accumulation of Dnipro waters [2], which flow through the Dnipro-Inhulets Canal, providing an important water management function of technical and drinking water supply, irrigation, development of aquaculture, etc. On the other hand, these artificial reservoirs reduce river flow due to increased evaporation [2].

Therefore, evaporation is not a clear-cut problem, but becomes critical in cases where the volume of water losses approaches the volume of natural inflow, especially in regions with insufficient moisture availability. In the context of planning and operating water management systems, it is important to consider not only the volumes of useful water consumption, but also losses associated with evaporation [3].

Thus, a detailed study of the spatiotemporal patterns of evaporation in the Ingulets river basin, its relationship with climatic parameters and water use is relevant from both a scientific and an practical point of view.

Analysis of recent research and publications. Evaporation from water surface is a complex physical process, which depends on the surface temperature of air and water, wind direction and speed, depths of water bodies, aquatic vegetation, etc [4–9]. However, an estimate of evaporation losses with sufficient accuracy for practice can be obtained using data from relatively small evaporators and evaporation basins [10], using series of meteorological observations [11], including analogues [12].

Rudakov G.V., Gapich G.V. and Chushkina I.V. [13] determined the water loss due to evaporation from the water surface of the regulating basin on Petrykivka irrigation system (Tsarychanske MUVG) and proved that in August 2016, water losses due to evaporation from water surface exceeded water inflow with precipitation for the previous two months by more than 2,5 times. At that time, evaporation losses increased from 389,2 m^3 (RB-6) to 803,6 m^3 (RB-3), which was mostly caused by meteorological conditions. V.M. Korbutyak and D.V. Stefanyshyn [12] established that for a low-water year of 75 % water availability for the summer period (duration 92 days), a total of 391 mm, or 4,25 mm/day, evaporates from the water surface of the Basivkut reservoir (Rivne city). According to the V.G. Andreev, G.V. Gapich [14], the vast majority of small rivers in the steppe zone of Ukraine today do not meet the criteria of a natural water body, they are cascades of artificial evaporation ponds, have no hydraulic connection with each other, and lose water uselessly and irreversibly [p. 31, 15].

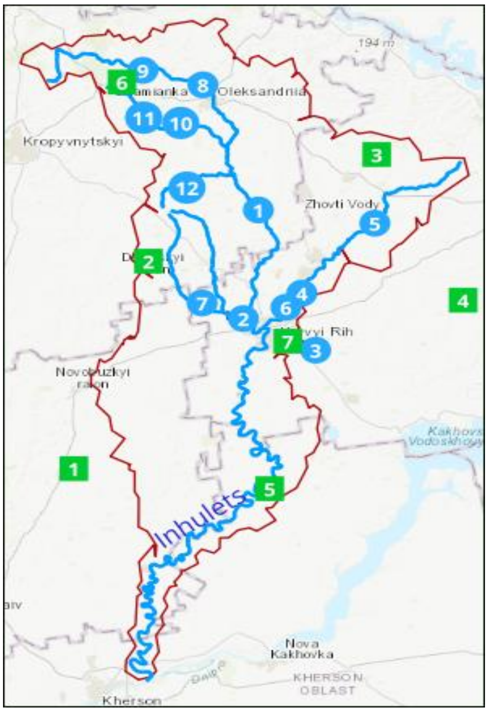
In [16] it is stated that the annual average volume of the Ingulets runflow at the Kryvyi Rih measurement point before the Saksagan river flows into it is approximately 240 million m³. To a large extent, this is water from the Dnipro river, supplied by the Dnipro-Inhulets canal from the Kremenchuk reservoir. In [16] it is indicated that approximately half of the river's flow is spent on irrigation, evaporation, and filtration. The minimum ecological flow for the Ingulets river is recommended by the flushing regulations and is up to 5,0 m^3/s [17]. Within the Inhulets river basin, two regions are distinguished by their geological structure: the northern part is within the Ukrainian Crystalline Shield, the southern part is in the Black Sea Depression [2]. As a result, groundwater flow in the Inhulets river basin is insignificant.

Andreev V.G. and Gapich G.V. state that for the stabilization and restoration of the hydrological and ecological state of small and medium-sized rivers of the steppe zone of Ukraine, the following are relevant [14]: assessment of the compliance of the existing number of ponds and small reservoirs in river basins with the requirements of the Water Code of Ukraine; ecological and economic justification of the feasibility of further operation for each individual reservoir and facility; development of regional programs for the elimination of ponds and reservoirs that do not perform their water management functions and create an ecological hazard to the functioning of the river ecosystem of the basin; further improvement of methodological approaches to assessing the level of ecological safety of water management facilities in small river basins.

The explosion of the Kakhovka hydroelectric power station dam on June 6, 2023 led to a large-scale environmental and humanitarian disaster in southern Ukraine [18]. There was a need to provide water to the affected regions [19]. In response, a large-scale project was implemented. "Ingulets-Pivdenne reservoir" waterway was built. It ensured the supply of 400 thousand cubic meters of water per day to the Southern reservoir, from where water is supplied to consumers through a purification system [20]. This became an additional load on the existing Inhulets river basin, since before the Kakhovka dam was blown up, water was supplied to the Pivdenne reservoir via the Dnipro-Kryvyi Rih canal from the Kakhovka reservoir.

The aim of the study is to assess water losses due to evaporation from the surface of ponds and reservoirs in the Ingulets river basin in the context of modern climate changes and intensive anthropogenic load. This study will contribute to increasing the accuracy of water management planning, in particular regarding the assessment of water supply, flow regulation, and optimization of the operation of artificial reservoirs in changing climatic conditions.

The object of research. The Ingulets river belongs to the middle size rivers and is a right tributary of the Dnipro, flowing through the Kirovohrad, Dnipropetrovsk, Mykolaiv and Kherson regions of Ukraine, with a length of approximately 549 km and a basin area of 14,870 km² (Fig. 1) [2].



– weather stations:
1. Bashtanska,
2. Dolynska,
3. Komisarivka,
4. Loskharivka,
5. Velyka Oleksandrivka,
6. Znamenka,
7. Kryvyi Rih

– reservoirs:
1. Iskrivske,
2. Karachunivske,
3. Pivdenne,
4. Kresovske,
5. Makartivske,
6. Saksaganske,
7. Khrystoforivske,
8. Oleksandriyske (Voynivske),
9. Dykivske,
10. Ivanivske,
11. Svitlopilske,
12. Verblyuzheske (Pogrebynske)

Fig. 1. Research object, Ingulets river basin

The Ingulets river basin contains a significant number of reservoirs and ponds and they play an important role in water supply, irrigation, and recreation. There are more than 1200 water bodies (ponds and reservoirs) in its basin [15, 21–25] (Table 1), which perform important water management functions, including ensuring the economic and drinking water supply of the cities of Kryvyi Rih and Zhovti Vody, receiving return waters of mining enterprises of Kryvyi Rih and supporting the Ingulets irrigation system [26, 27]. The river's regulation coefficient is 81 %, which indicates a significant impact of ponds and reservoirs on the hydrological regime of the river [27].

The climatic conditions of the Ingulets river basin are formed under the influence of a complex set of both general and local climate-forming factors [2]: solar radiation, air circulation, and the influence of the Earth surface. Precipitation for the entire basin is mainly associated with the activity of cyclones, to a lesser extent with the processes of intramass convection. During the year, about 450 mm of precipitation is recorded in the Ingulets river basin. The largest amount of precipitation is in June, the smallest is in February – March and September – October. Between periods of precipitation in the warm part of the year, long periods of drought are often observed.

There are several important reservoirs in the Ingulets river basin, such as Oleksandriyske (Voynivske), Iskrivske, and Karachunivske. Due to the water shortage in the Ingulets river basin, additional water is being supplied through the Dnipro-Ingulets canal along the riverbed to refill them for the local needs.

To calculate evaporation from the water surface [15, 21–25], the area of water bodies

1. Reservoirs and ponds in the Inhulets river basin

Kirovohrad region			Dnipropetrovsk region			Mykolaiv region			Kherson region		
quantity, pcs.	area, ha	volume, mln m^3	quantity, pcs.	area, ha	volume, mln m^3	quantity, pcs.	area, ha	volume, mln m^3	quantity, pcs.	area, ha	volume, mln m^3
reservoirs											
17	2646,0	81,8	4	6330,0	388,8	–	–	–	–	–	–
ponds											
502	4443,0	51,3	594	2787,0	39,9	22	234,0	2,6	94	546,7	8,8

in the Inhulets river basin and their volumes in the Kirovohrad, Dnipropetrovsk, Mykolaiv, and Kherson regions of Ukraine were determined (Table 1).

There are 1212 ponds in the Ingulets river basin (Table 1), which is 98 % of the total number of artificial water bodies; the area of the water surface in reservoirs is 8976 hectares (55 %), in ponds – 7230,0 hectares (45 %); the volume of water in the largest reservoirs – 573,2 million m^3 (86 %), in the ponds – 91,2 million m^3 (14 %). Evaporation from the surface of these reservoirs leads to water resources losses, which requires analysis.

Materials and research methods. According to the recommendations of the WMO (World Meteorological Organization) [28] and the IPCC (Intergovernmental Panel on Climate Change) [29], the current climate changes trends are assessed based on at least a 30-year period of continuous meteorological observations [30]. Typically, the base period for comparison is the period 1961–1990, which is considered as the climatic norm [30]. However, as new data sets accumulate annually, leading international expert groups for climate change assessments use other reference periods – 1981–2010 and 1991–2020 [30], since these periods also covered by the satellite data, along with the results of ground-based measurements at weather stations.

The used sources of meteorological data for the studied area of the Inhulets river basin are the archival data of meteorological observations [31] and the archives of the international Spanish meteorological site Globalclimatemonitor [32] from 1961 to 2023 period, and interpolated data according to the location of meteorological stations in the Inhulets river basin (Bashtanka, Velyka Oleksandrivka, Dolynska, Znamyanka, Komisarivka, Kryvyi Rih, Loskharivka) (Fig. 1).

In general, mathematical models used to calculate evaporation from water surface can be divided into aerodynamic models, energy balance models, water balance models, complex models, radiation-temperature models, temperature models, and models based on empirical formulae [33]. The Dalton's model is the predecessor of the mass transfer equation for estimating evaporation in open water bodies [33]. It is one of the most widely used model for calculating evaporation from a free water surface [33]. Observations of evaporation from water surface in Ukraine have significantly decreased compared to the 1950s – 1960s (36 observation points are equipped with DGI-3000 evaporators (previously there were 59), and 7 with evaporation basins (previously there were 14)) [4, 10]. Therefore, focusing on data from weather stations with existing evaporation basins or DGI-3000 evaporators, it is possible to obtain significant errors compared to using data on relative air humidity at weather stations in the Ingulets river basin. To quickly determine the water temperature for the Kakhovka reservoir, a graphical and analytical dependency on the average monthly air temperature was obtained [34]. It has been found [10] that the main factor in the current increase in evaporation is the increase in water temperature, which is accompanied by a significant increase in the partial pressure of saturated water vapor.

M.M. Ivanov found, O.R. Konstantinov developed and recommended [5] to use the connections of evaporation with the average monthly temperature and relative humidity of the air, as the most convenient for practical use, when determining evaporation from water surface, which do not require the introduction of additional corrections. Penman [7–9] proposed an equation for determining evaporation from water surface using the temperature at a height of 2 m.

So, evaporation from the surface of water bodies for specific months, seasons, and years is calculated using empirical formulae or graphs based on meteorological data (temperature and relative humidity, wind speed). Based on the above-mentioned, the evaporation rates from the surface of water bodies were determined using the formula refined by A.I. Shereshevsky [4]:

$$E = 0{,}37\, n\,(e_0 - e_{200})\,(1 + 0{,}14\, V_{200}) \quad (1)$$

where E is the evaporation (mm) per month;

$e_0 - e_{200}$ is the average monthly value of the difference between the elasticity of saturated water vapor (partial pressure of saturated water vapor) (mBar) and the elasticity (partial pressure of water vapor) of water vapor in the air (mBar) at a height of 200 cm;

V_{200} is the average monthly wind speed (m/s) at a height of 200 cm;

n is the number of days in a month.

The pressure of saturated water vapor is determined by the formula obtained by generalizing the tables of its dependence on temperature (Fig. 2, formula 2):

$$e_0 = 0{,}0436t^3 + 1{,}2442t^2 + 43{,}523t + 613{,}53,\ \text{Pa}, \quad (2)$$

where t is the air temperature, °C.

At a height of 2 m (200 cm), the partial pressure of water vapor is found by formula 3, using the data on relative humidity [35].

$$e_{200} = \frac{e_0}{100} \quad (3)$$

where φ is the relative air humidity, %;

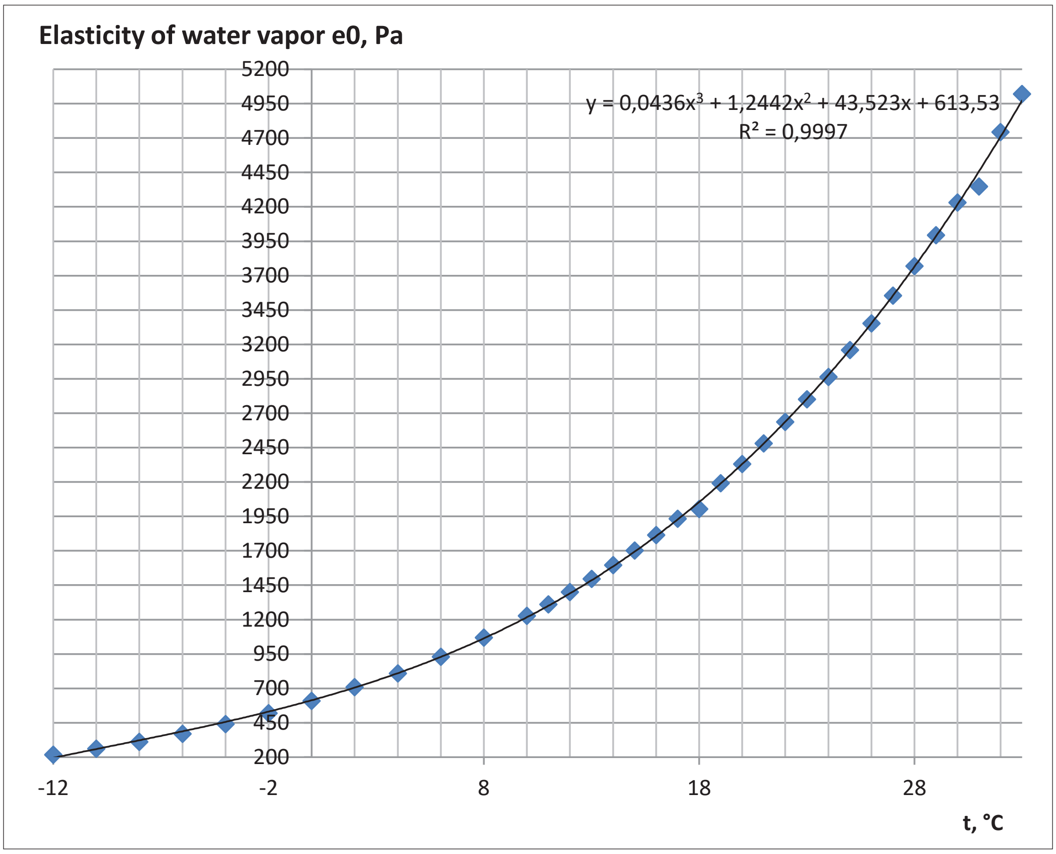


Fig. 2. Dependence of the elasticity of saturated vapor on air temperature (t, °C; e_0, Pa)

Relative air humidity and average monthly wind speed for the studied period are taken from the reference data [35], air temperature values are taken from meteorological archives [31, 32] for each of the weather stations of the Hydromet network located in the Inhulets river basin.

Research results.

Climate change in the Ingulets river basin. To characterize the climatic conditions in the Inhulets river basin over the past 63 years, data from 7 weather stations of the Ukrainian Hydrometeorological Center network were used: Bashtanka, Velyka Oleksandrivka, Dolynska, Znamenka, Komisarivka, Kryvyi Rih, Loskharivka.

The average annual air temperature in the Ingulets River basin in 1961–1990 was stable (average 8.6 °C), with minor fluctuations (Fig. 3). Data for the period of 1991–2023 confirm a sharp trend towards an increase in the average annual temperature to 9.9 °C, which is 1.3 °C more than the previous 1961–1990 period. This trend is especially noticeable after 2010. There are also significant increases in average monthly multi-year temperatures throughout the year – from 0.7 (April–May) to 2.0 (August) and 2.2 °C (January) (Fig. 4).

The average annual precipitation in the Ingulets river basin in 1961–1990 was 483.2 mm, and in 1991–2023 it decreased by almost 10 mm (473.1 mm). The distribution of precipitation during the year changed by season becoming more uneven.

Temperature changes and uneven precipitation have a very negative impact on the water regime of the Ingulets river and require further study and monitoring to promote the adaptation of this river to climate changes.

Calculation of evaporation from the surface of water bodies in the Ingulets river basin. To substantiate the elements of the balance model [36] when implementing integrated water resources management according to the basin principle, an important element is the determination of water loss for total evaporation from the surface of water bodies (ponds and reservoirs) in the Ingulets river basin.

To calculate evaporation from the surface of water bodies, detailed data on the areas of ponds and reservoirs are required (the authors have summarized these data in Table 2) as well as the local monthly climatic indicators of the region according to weather stations (Bashtanka, Velyka Oleksandrivka, Dolynska, Znamyanka, Komisarivka, Kryvyi Rih, Loskharivka).

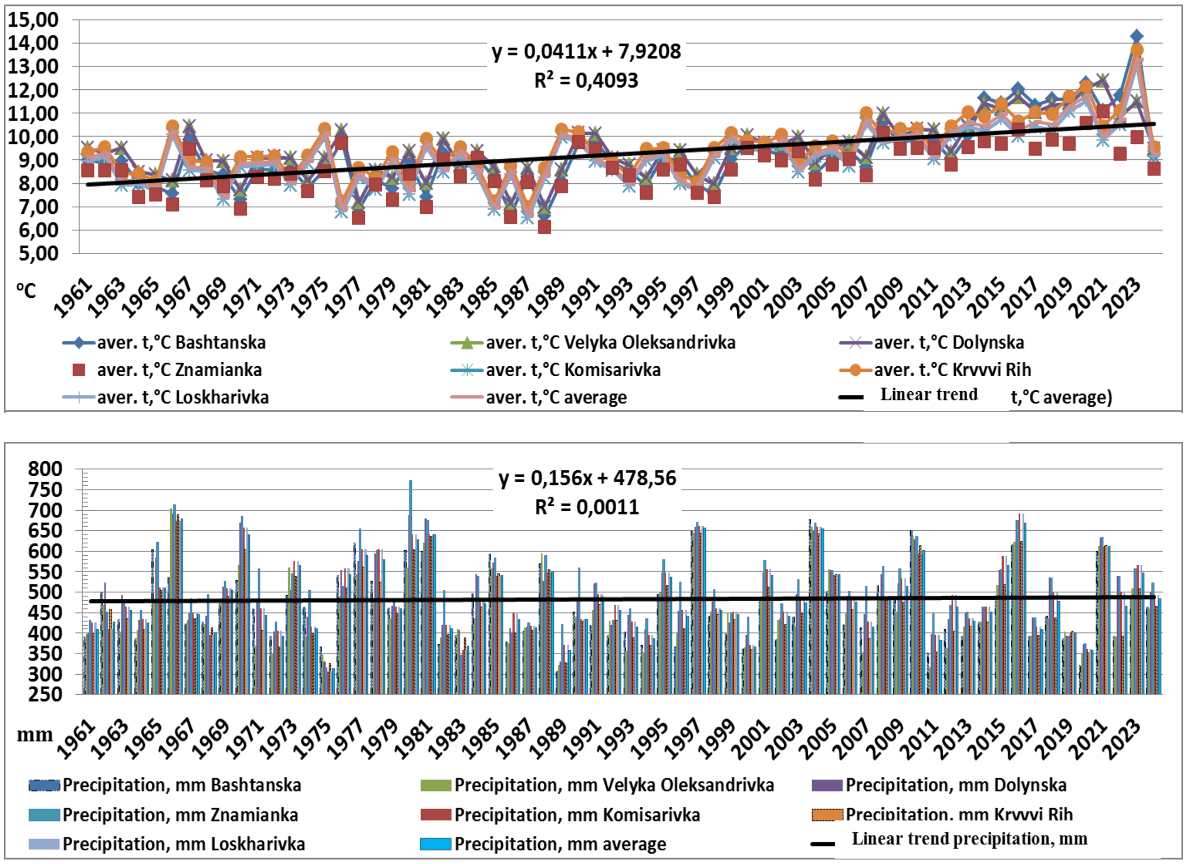


Fig. 3. Average annual dynamics of precipitation and temperature in the Ingulets river basin for the period 1961–2023

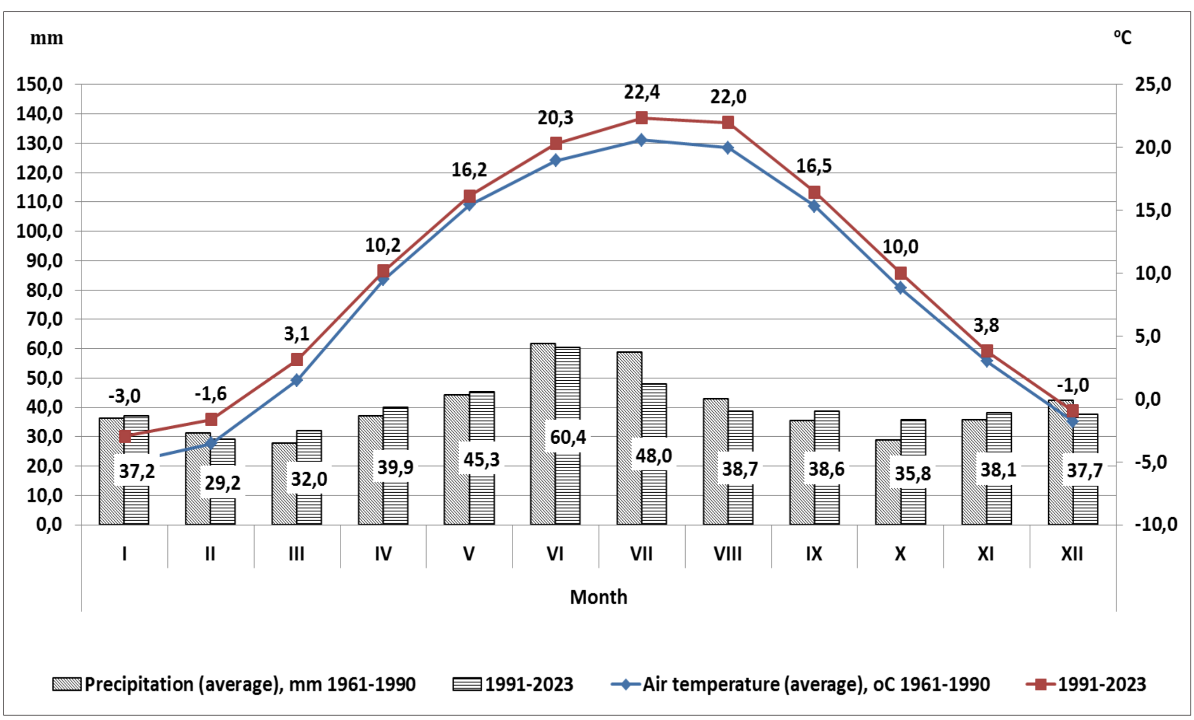


Fig. 4. Average monthly dynamics of precipitation and temperature in the Ingulets River basin for the following periods: 1961–1990 (norm), and 1991–2023

2. Calculation of evaporation from the surface of reservoirs with a volume of more than 10 million m³ and some smaller ones within the Ingulets River basin with a water surface area of more than 100 hectares

Name of reservoir, river (basin)	Location of the reservoir (settlement, region), weather station	Evaporation, mm		Area of reservoir, ha	Volume of reservoir		Evaporation, thousand m³	
		norm (1961–1990)	calculated (1991–2023)		total, mln m³	useful, mln m³	norm (1961–1990)	calculated (1991–2023)
Iskrivske, Ingulets river	vil. Iskrivka, Kirovohrad region (Znamyanka, Komisarivska)	841,0	928,0	1110,0	40,7	31,0	9335,1	10300,8
Karachunivske, Inhulets river	Kryvyi Rih, Dnipropetrovsk region (Kryvyi Rih)	972,0	1060,0	4480,0	308,5	288,5	43545,6	47488,0
Pivdenne, Bazavluk river	*Apostolivskyi, Dnipropetrovsk region (Kryvyi Rih)*	972,0	1060,0	1130,0	57,3	26,5	10983,6	11978,0
Kresivske, Saksagan river (Inhulets river, Dnipro river)	Kryvyi Rih, Dnipropetrovsk region (Kryvyi Rih)	972,0	1060,0	520,0	10,1	7,7	5054,4	5512,0
Makortivske, Saksagan river (Inhulets river)	vil. Makorty, Dnipropetrovsk region (Komisarivka)	898,0	966,0	1330,0	57,9	53,9	11943,4	12847,8
Saksaganske, Saksagan river (Inhulets river)	Kryvyi Rih (Kryvyi Rih)	972,0	1060,0	70,0	2,6	2,1	680,4	742,0
Khrystoforivske , Bokovenka river (Inhulets river)	vil. Khrystoforivka, Dnipropetrovsk region (Kryvyi Rih)	972,0	1060,0	120,0 (area of water surface 62,0)	4 design (1,5 actual)	No data	602,64	657,2
Oleksandriyske (Voynivske) Ingulets river	*Oleksandria, Kirovohrad region (Znameyanka)*	783,0	890,0	about 200,0	6,3	No data	1566,0	1780,0
Dykivske (Inhulets river)	*vil. Dykivka, Kirovohrad region (Znamyanka)*	783,0	890,0	194,0	3,58	3,24	1519,0	1726,6
Svitlopilsky Beshka river (Inhulets river)	*vil. Svitlopil Kirovohrad region (Znamyanka)*	783,0	890,0	188,0	3,80	2,80	1472,0	1673,2
Ivanivske Beshka river (Ingulets river)	*vil. Ivanivka Kirovohrad region (Znamyanka)*	783,0	890,0	125,0	3,20	3,20	978,8	1112,5
Pogrebnyakivske Verblyuzhka river (Ingulets river)	*vil. Verblyuzhka Kirovohrad region (Znameyanka)*	783,0	890,0	188,0	8,00	7,24	1472,0	1673,2

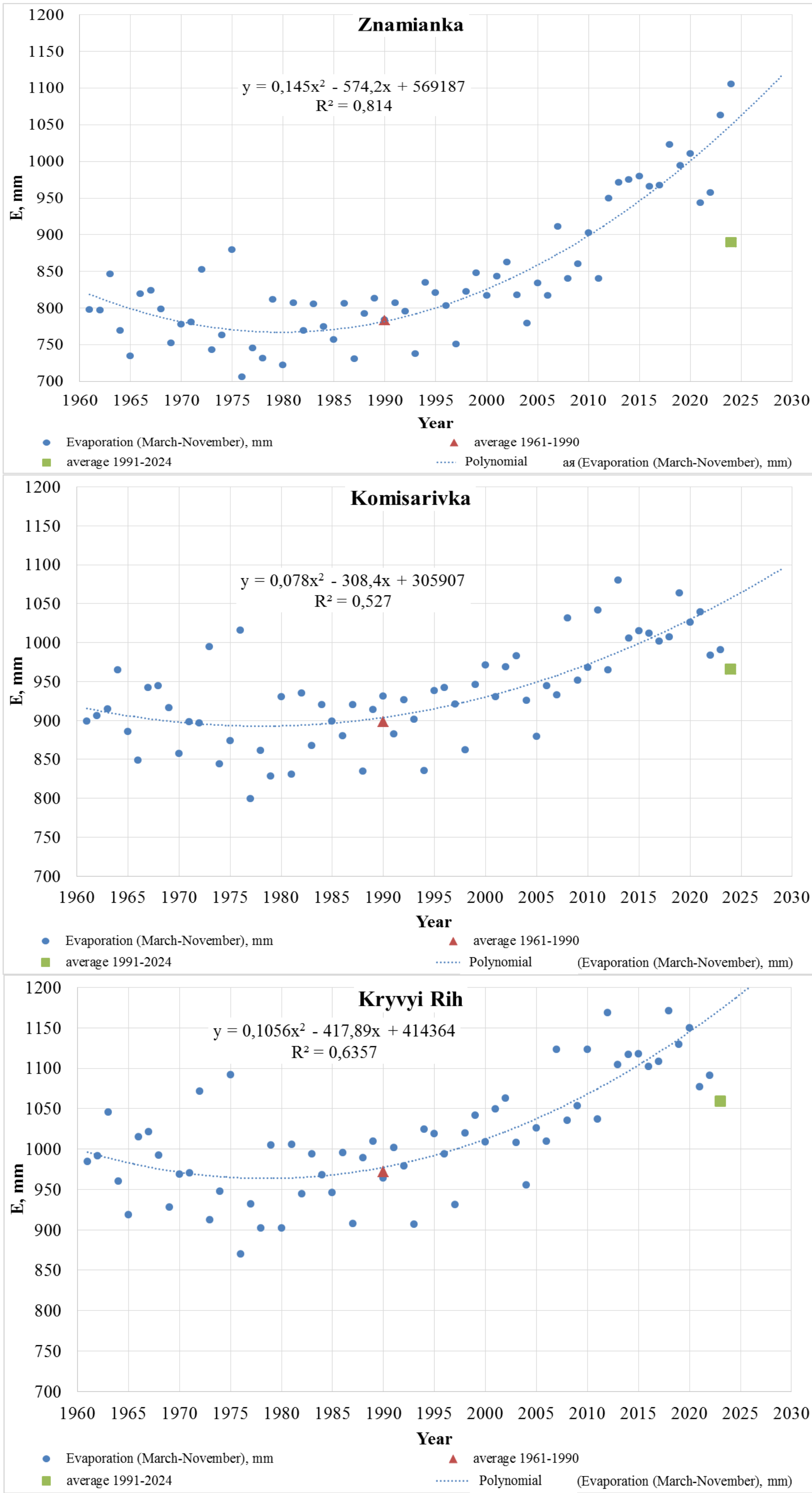


Fig. 5. Estimated evaporation for 1961–2023 period for the ice-free period (March–November) and average values for each of the two periods (1961–1990 and 1991–2023)

Before the Kakhovka HPP dam was blown up, the Pivdenne and Zelenodolsk reservoirs were supplied with water from the Dnipro-Kryvyi Rih canal. After the Kakhovka HPP was blown up, an additional load was placed on the Inhulets river, associated with ensuring water use and evaporation from the surface of the Pivdenne reservoir, where water is supplied via a pipeline from Inhulets.

It was found that the closest to the reservoirs indicated in Table 2 are the weather stations Znamyanka, Komisarivka and Kryvyi Rih (Fig. 1). For these weather stations, based on monthly weather data for the ice-free period (March-November), evaporation was calculated for 1961–1990 and 1991–2023 periods using the above-described methodology.

For each periods of 1961–1990 and 1991–2023 average values of the evaporation rate from the surface of water bodies were calculated (Fig. 5).

As calculations show (Table 2, Fig. 5), in 1991–2023, evaporation rates from the surface of water bodies increased by 13,7 % (107 mm) for the Znamyanka weather station, by 7,6 % (68 mm) for the Komisarivka weather station, and by 9,1 % (88 mm) for the Kryvyi Rih weather station.

Approximate estimates of the volume of evaporation from the surface of reservoirs in the Ingulets river basin were obtained by multiplying the area by the average long-term rate of evaporation from the surface of these reservoirs. Calculations of evaporation for reservoirs with a volume of more than 10 million m³ and some smaller ones within the Ingulets river basin are given in Table 2.

It was determined that in 1991–2023 period the average evaporation from the surface of reservoirs in the Ingulets river basin was approximately 97,5 million m³/year, which is 9,35 % higher than the norm (1961–1990).

According to rough estimates, evaporation from the water surface of ponds in the Ingulets river basin may be 70,2 million m³/year, according to the area of their water surface given in Table 1 (7230 ha) and the average evaporation value for 1991–2023 (Fig. 5 – 972 mm), which is equivalent to evaporation from reservoirs. At the same time, the water volume of the ponds is 102,6 m³, which is almost 5 times less than the volume of the reservoirs.

Discussion of the results. Analysis of the average annual dynamics of precipitation and temperature in the Ingulets River basin for the period of 1961–2023 shows that there is a constant increase in temperature indicators (Fig. 3). The linear trend of temperature increase has an insufficiently high coefficient of determination ($R^2 = 0{,}41 < 0.5$). This indicates that there is a nonlinear trend of temperature increase over the past 63 years (Fig. 6).

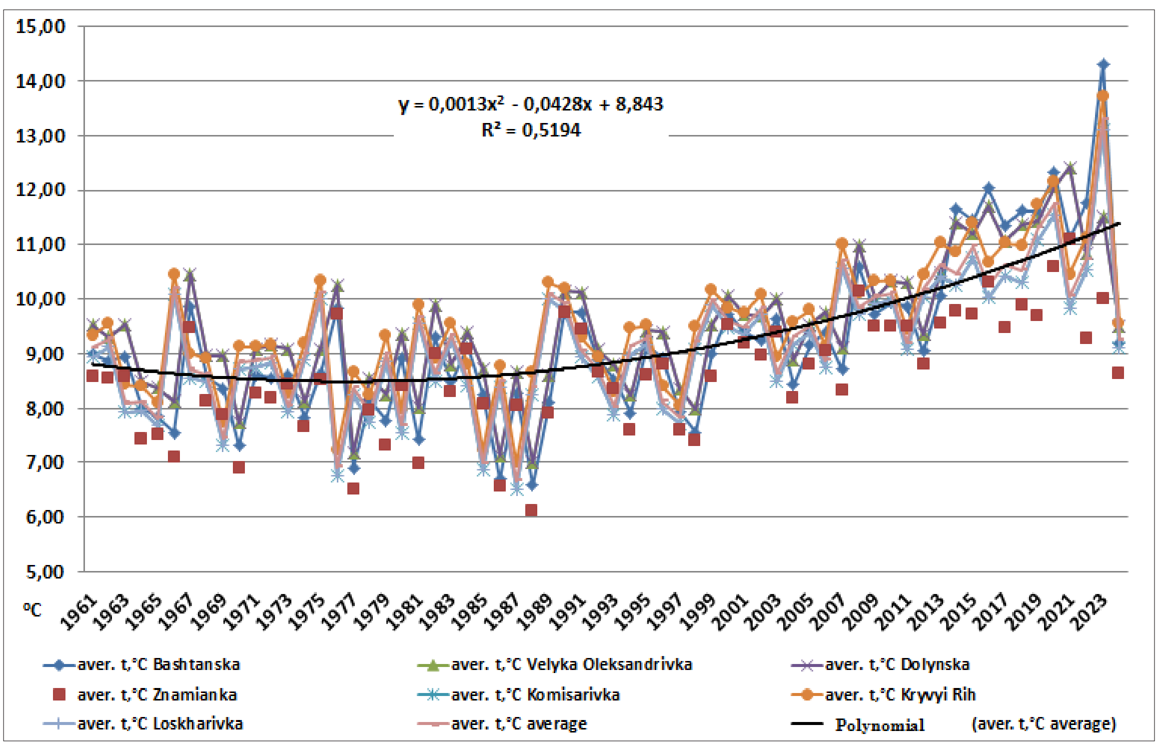


Fig. 6. Nonlinear trend of increase in average annual temperature in the Ingulets river basin

The difference between the average annual temperature values for 1961–1990 and 1991–2023 periods for weather stations in the Ingulets river basin (Fig. 7) indicates that the temperature increased by an average of 1,3 °C. In the southern part of the basin, this change is bigger, in the northern part – smaller (Fig. 1, Fig. 7).

Characterizing the dynamics of precipitation, it can be stated that the graphical analysis does not allow us to identify any long-term trend (R^2 = 0.001). The average long-term precipitation in the Ingulets river basin for 1961–2023 period remains at a stable level. The difference between the average annual precipitation values for 1961–1990 and 1991–2023 periods for each of the weather stations in the Ingulets River basin (Fig. 8) shows different trends in change. For example, the amount of precipitation at the Bashtanka weather station decreased by 19 mm. At the Komisarivka and Loskharivka in the northeastern part of the basin (Fig. 1) it increased by 8,5 mm (Fig. 8).

Trends in precipitation changes throughout the year (Fig. 4) show a decrease in their amount in the summer and an increase in the fall. In winter and spring, no clear trend of change is observed.

The obtained results of studies on the amount of evaporation from the surface of water bodies in the Ingulets river basin for the modern period are consistent with the normative multi-year values (Fig. 9) published on the portal "Nature of Ukraine" [37], which presents an evaporation map based on the climatic norm of 1961–1990 period. Comparison of the data obtained by the authors with cartographic norms (Table 3) showed minor deviations (up to 10 %), which confirms the correctness of the methodology and the reliability of the obtained results.

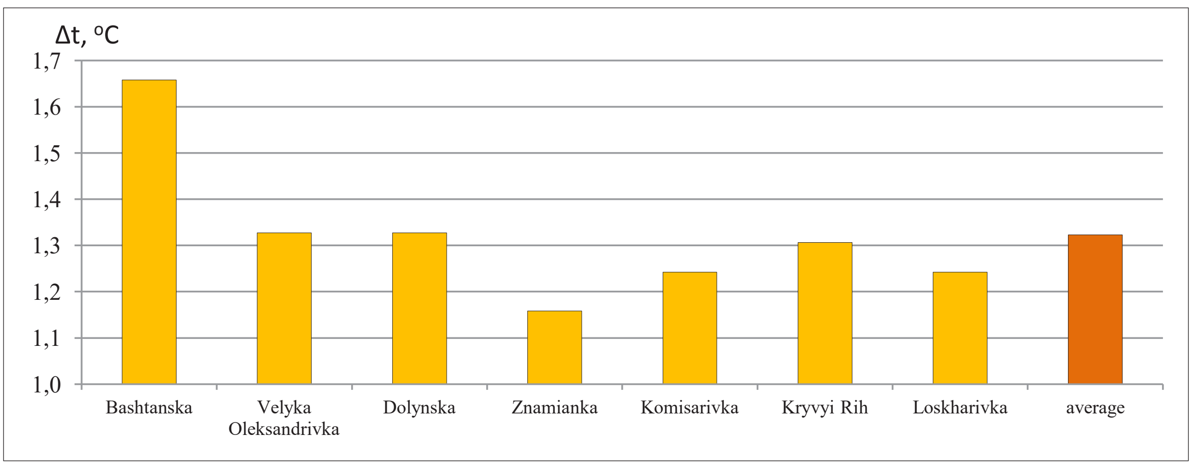


Fig. 7. Difference between average annual temperature values for 1961–1990 and 1991–2023 periods for weather stations of the Ingulets River basin

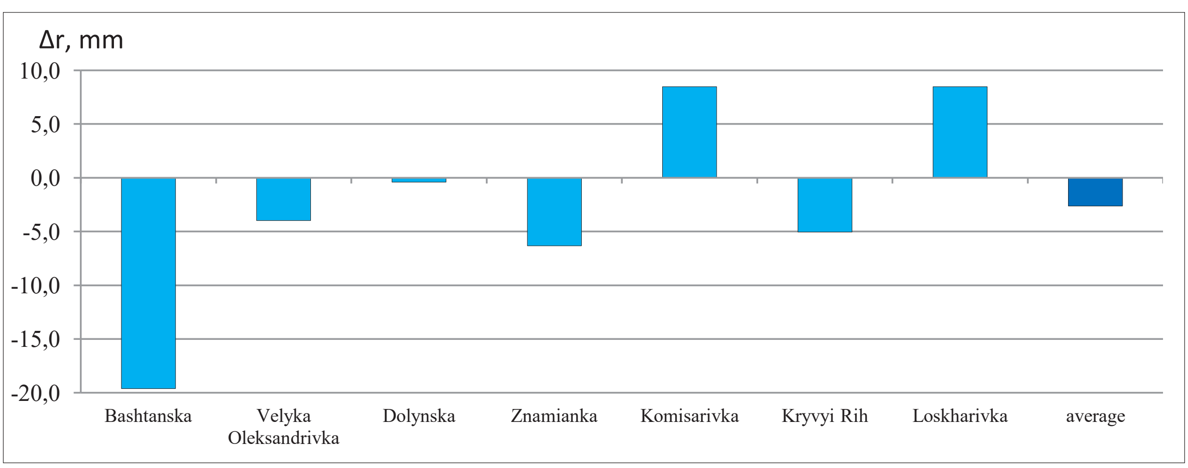


Fig. 8. Difference between average annual precipitation values for 1961–1990 and 1991–2023 periods for weather stations of the Ingulets river basin

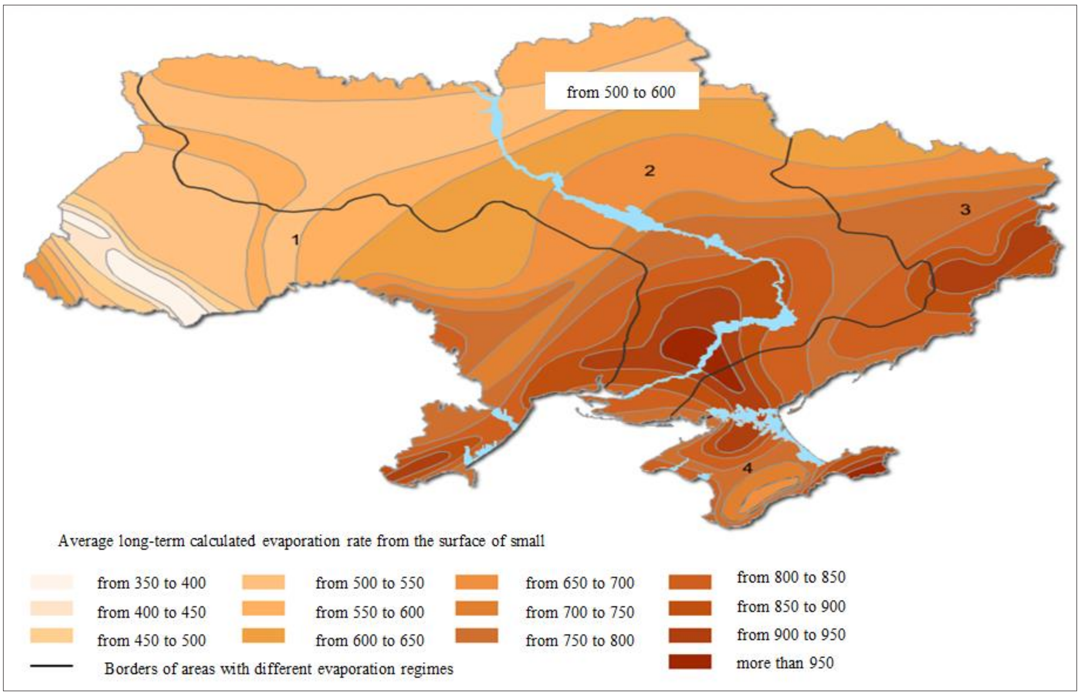


Fig. 9. Map of normative long-term values of evaporation from the surface of water bodies [37]

3. Comparison of evaporation standards for 1961–1990 period for reservoirs within the Ingulets river basin obtained from maps and calculated by the authors

Name of reservoir, river (basin)	Location of the reservoirs (settlement, region)	Evaporation rate (Fig. 9), mm	Evaporation rate (1961–1990 period), mm	Difference
Iskrivske, Ingulets river (Dnipro river)	vil. Iskrivka, Kirovohrad region (Znamyanka, Komisarivska)	750–800	841	+10…2 %
Karachunivske, Inhulets river (Dnipro river)	Kryvyi Rih, Dnipropetrovsk region (Kryvyi Rih)	900–950	972	+8…2 %
Pivdenne*, Bazavluk river (Dnipro river)	*Apostolivskyi, Dnipropetrovsk region (Kryvyi Rih)*	>950	972	≈2 %
Kresivske, Saksagan river (Inhulets river, Dnipro river)	Kryvyi Rih, Dnipropetrovsk region (Kryvyi Rih)	900–950	972	+8…2 %
Makortivske, Saksagan river (Inhulets river, Dnipro river)	vil. Makorty, Dnipropetrovsk region (Komisarivka)	850–900	898	+6…0 %
Saksaganske, Saksagan river (Inhulets river, Dnipro river)	Kryvyi Rih (Kryvyi Rih)	900–950	972	+8…2 %
Khrystoforivske , Bokovenka river (Inhulets river) [73]	vil. Khrystoforivka, Dnipro-petrovsk region (Kryvyi Rih)	900–950	972	+8…2 %
Oleksandriyske (Voynivske) Ingulets river (Dnipro river)	*Oleksandria, Kirovohrad region (Znameyanka)*	750–800	783	+4…–2 %
Dykivske (Inhulets river, Dnipro river)	*vil. Dykivka, Kirovohrad region (Znamyanka)*	750–800	783	+4…–2 %
Svitlopilsky Beshka river (Inhulets river, Dnipro river)	*vil. Svitlopil Kirovohrad region (Znamyanka)*	750–800	783	+4…–2 %
Ivanivske, Beshka river (Ingulets river, Dnipro river)	*vil. Ivanivka Kirovohrad region (Znamyanka)*	750–800	783	+4…–2 %
Pogrebnyakivske, Verblyuzhka river (Ingulets river, Dnipro river)	*vil. Verblyuzhka Kirovohrad region (Znameyanka)*	750–800	783	+4…–2 %

*After the Kakhovka Dam was blown up it is supplied with water from the Ingulets river.

Water consumption of southern agricultural crops is increasing and will continue to increase due to the air temperatures rising [38], which is accompanied by an increased evaporation from the water surface of ponds and reservoirs [11] and is confirmed by trend analysis (Fig. 5). This, in accordance with global trends [11, 39], will lead to an increase in the demand for water resources in the Ingulets river basin.

As the average annual flow of the Ingulets river is about 0,3 km³, and water losses due to evaporation can reach up to 0,165 km³ per year, this means that they account for more than 50 % of the river's flow.

Taking into account the expected increase in the load on the surface water resources of the basin (Fig. 5), it is necessary to implement scientifically based management solutions [14], in particular, attracting additional volumes of water from the Dnipro river through the Dnipro–Inhulets canal.

According to research results, the evaporation rate from the surface of the basin's water bodies for the period 1991–2023 increased by an average of 10 % compared to the climatic norm of 1961–1990 period, which is a consequence of climate changes. Evaporation from ponds, as shown above, is proportional to losses from the surface of reservoirs. This will contribute to the increase in the deficit of water resources in the Ingulets river basin and will become a limiting factor for the development of irrigation. In order to increase the accumulation of water in existing artificial reservoirs, it is advisable to clean and deepen them, and to develop catchment and coastal areas.

Prospects for further research. The obtained results have practical significance and can be used to develop adaptation measures in response to climate changes, improve methods for assessing water losses caused by the evaporation, and develop effective water resource management strategies in river basins. It is important to take into account modern challenges, in particular, climate stress – the combined impact of long-term increases in air temperature, changes in precipitation patterns, increased frequency and duration of droughts, as well as anthropogenic stress – that is, man-made changes in the hydrological regime through the flow regulation, water abstraction, pollution, and transformation of natural ecosystems. Further research should be aimed at a comprehensive assessment of these factors to substantiate scenarios for sustainable water use under climate changes.

Conclusions. The results of the research show that the climatic conditions in the studied region confirm a steady warming trend: over the past 33 years, the average annual temperature in the Ingulets river basin has increased by an average of 1,3 °C. At the same time, water losses due to evaporation from the water surface of reservoirs and ponds in the Ingulets river basin are significant and are increasingly having an impact on the regional water balance. This is especially relevant in the context of the growing shortage of water resources associated with climate changes and infrastructure losses. The evaporation rate from the surface of ponds and reservoirs for the period 1991–2023 in the Ingulets river basin increased by an average of 10 % compared to the evaporation rate in 1961–1990 period.

The analysis confirms the dominance of artificial reservoirs (ponds and reservoirs) in the hydrological regime of the Ingulets river basin, which causes a change in natural flow (water losses due to evaporation reach approximately 0.165 km³ per year), the transformation of rivers into cascades of isolated reservoirs.

The obtained results can be used to develop programs for climate changes adaptation and form regional strategies for water resources management, in particular in emergency situations similar to the disaster caused by the destruction of the Kakhovka HPP dam.

References

1. Materialy naukovo-praktychnoyi konferentsiyi "Pryroda i voda" [Materials of the scientific and practical conference "Nature and Water]. (2018). Pryroda i voda: Naukovo-praktychna konferentsiya. Dnipro: DDAEU, 3–4 Retrieved from: https://dspace.dsau.dp.ua/bitstream/123456789/1460/1/Природа_і_вода.pdf [in Ukrainian]

2. Khil'chevs'kyy, V.K., Kravchyns'kyy, R.L., & Chunar'ov, O.V. (2012). Hidrokhimichnyy rezhym ta yakist' vody Inhul'tsya v umovakh tekhnohenezu [Hydrochemical regime and water quality of Ingulets in conditions of technogenesis]. Kyiv: Nika-Tsentr, 180. Retrieved from: https://geo.knu.ua/wp-content/uploads/2025/01/hilchevskyj-vk.-ta-in._gidrohim.-rezhym-ingulczya.pdf [in Ukrainian]

3. Zhao, G., Gao, H., & Kao, S. C. (2021). The implications of future climate change on the blue water footprint of hydropower in the contiguous US. *Environmental Research Letters*, 16 (3), 034003. DOI 10.1088/1748-9326/abd78d.

4. Shereshevs'kyy, A.I., & Synyts'ka L.K. (2003). Rozrakhunkove vyparovuvannya z vodnoyi poverkhni na terytoriyi Ukrayiny [Estimated evaporation from the water surface on the territory of Ukraine]. *Naukovi Pratsi UkrNDHMI*, 252, 11–26 [in Ukrainian]

5. Hryb, O.M. (2014). Otsinka vyparovuvannya z vodnoyi poverkhni v rayoni Tylihul's'koho lymanu [Estimation of evaporation from water surfaces in the Tiligul estuary area]. *Visnyk Odes'koho derzhavnoho ekolohichnoho universytetu*, 17, 173–184. Retrieved from: http://nbuv.gov.ua/UJRN/Vodeu_2014_17_21 [in Ukrainian]

6. Béchet, Q., Sialve, B., Steyer, J. P., Shilton, A., & Guieysse, B. (2018). Comparative assessment of evaporation models in algal ponds. *Algal Research*, 35, 283–291.

7. Jensen M.E. (2010). Estimating evaporation from water surfaces. In *CSU/ARS Evapotranspiration Workshop, Fort Collins, CO*, 1–27. Retrieved from: https://www.researchgate.net/publication/265749992_Estimating_evaporation_from_water_surfaces.

8. Penman, H.L. (1948). Natural evaporation from open water, bare soil and grass. *Proc. Roy. Soc. London*, 120–146.

9. Penman, H.L. 1963. Vegetation and hydrology. *Tech. Comm.*, 53. Commonwealth Bureau of Soils, Harpenden, England. 125 p.

10. Vyshnevs'kyy, V. (2022). Vplyv zminy klimatu na vyparovuvannya z poverkhni vody v Ukrayini [The impact of climate change on evaporation from water surfaces in Ukraine]. *Zhurnal heolohiyi, heohrafiyi ta heoekolohiyi*, 31 (1), 163–170. Retrieved from: https://doi.org/https://doi.org/10.15421/112216 [in Ukrainian]

11. Zhou, Y., Dong, J., Cui, Y., Zhou, S., Li, Z., Wang, X., & Xiao, X. (2022). Rapid surface water expansion due to increasing artificial reservoirs and aquaculture ponds in North China Plain. *Journal of Hydrology*, 608, 127637. Retrieved from: https://doi.org/10.1016/j.jhydrol.2022.127637.

12. Korbutyak, V. M., & Stefanyshyn, D. V. (2018) Transformatsiyi minimal'noho stoku r. Sluch ta yikh vplyv na Novohrad-Volyns'ke vodoskhovyshche yak ob″yekt mistsevoyi krytychnoyi infrastruktury [Transformations of the minimum flow of the Sluch River and their impact on the Novograd-Volynske reservoir as an object of local critical infrastructure]. *Matematychne modelyuvannya v ekonomitsi*, 4, 70–81. Retrieved from: http://nbuv.gov.ua/UJRN/mmve_2018_4_8 [in Ukrainian]

13. Rudakov, L.M., Hapich, H.V., & Chushkina, I.V. (2017). Vyznachennya vtrat vody na vyparovuvannya z vodnoyi poverkhni rehulyuyuchykh baseyniv zroshuval'nykh merezh [Determination of water losses due to evaporation from the water surface of regulating basins of irrigation networks]. Vdoskonalennya hidrotekhnichnykh system ta vodohospodars'kykh tekhnolohiy. Materialy mizhnar. nauk.-prakt. konferentsiyi. Kherson: Vyd-vo PP "LT – Ofis", 176–179. Retrieved from: http://dspace.dsau.dp.ua/jspui/handle/123456789/1442 [in Ukrainian].

14. Andreev, V. H., & Hapich, H.V. (2020). Vplyv budivnytstva stavkiv i vodoskhovyshch na ekolohichnu bezpeku baseyniv malykh richok stepovoyi zony Ukrayiny (na prykladi Dnipropetrovs'koyi oblasti) [The impact of the construction of ponds and reservoirs on the ecological safety of small river basins of the steppe zone of Ukraine (on the example of the Dnipropetrovsk region)]. *Melioratsiya i vodne hospodarstvo*, 1, 158–166. Retrieved from: http://nbuv.gov.ua/UJRN/Mivg_2020_1_18 [in Ukrainian].

15. Hrebin', V.V., Khil'chevs'kyy, V.K., Stashuk, V.A., Chunar'ov, O.V., & Yaroshevych, O.YE. (2014). Vodnyy fond Ukrayiny: Shtuchni vodoymy – vodoskhovyshcha i stavky: Dovidnyk [Water Fund of Ukraine: Artificial Water Reservoirs – Reservoirs and Ponds: Handbook]. Kyiv: "Inter-pres LTD" [in Ukrainian].

16. Stashuk, V.A., Morozov, V.V., & Ladyky, M.M. (2010). Melioratsiya vody i ahrolandshaftiv v baseyni r. Inhulets': Monohrafiya [Land Reclamation of Water and Agricultural Landscapes in the Ingulets River Basin: Monograph]. Kherson: Vyd-vo "Aylant" [in Ukrainian].

17. Rehlament promyvannya rusla ta ekolohichnoho ozdorovlennya r. Inhulets' u 2019 rotsi (Al'ternatyvnyy variant) [Regulations for the washing of the riverbed and ecological improvement of the Ingulets River in 2019 (Alternative version)]. (2019). Kyiv: PrAT "Ukrvodproekt" [in Ukrainian].

18. Shumilova, O., Sukhodolov, A., Osadcha, N., Oreshchenko, A., Constantinescu, G., Afanasyev, S., & Grossart, H. P. (2025). *Environmental effects of the Kakhovka Dam destruction by warfare in Ukraine. Science*, 387 (6739), 1181–1186. DOI: 10.1126/science.adn8655.

19. Cabinet of Ministers of Ukraine. (2024). Derzhavna tsil'ova prohrama kompleksnoho vodozabezpechennya terytoriy, yaki zaznaly vplyvu voyennykh diy, na period do 2030 roku Derzhavna tsil'ova prohrama [State Target Program for Comprehensive Water Supply of Territories Affected by Military

Actions for the Period Until 2030 State Target Program]. Kyiv: State Agency of Water Resources of Ukraine. Retrieved from: https://davr.gov.ua › fls18 › watersupplyprogram [in Ukrainian].

20. Murashko, A. (2024). Pidryv Kakhovs'koyi HES: budivnytstvo mahistral'noho vodohonu "Inhulets' – Pivdenne vodoskhovyshche" zaversheno [Kahovka blown up: construction of the Ingulets – Pivdenne Reservoir water main completed]. Ukrainian National News. Retrieved from: https://unn.ua/news/pidryv-kakhovskoi-hes-budivnytstvo-mahistralnoho-vodohonu-inhulets-pivdenne-vodoskhovyshche-zaversheno [in Ukrainian].

21. Palamarchuk, M.M., & Zakorchevna, N.B. (2006). Vodnyy fond Ukrayiny: Dovidkovyy posibnyk [The Water Fund of Ukraine: Reference Manual]. 2-e vyd. [2nd ed.]. Kyiv: Nika-Tsentr. 320 [in Ukrainian].

22. Cabinet of Ministers of Ukraine. (2024). Plan upravlinnya richkovym baseynom Dnipra [Dnieper River Basin Management Plan]. State Agency of Water Resources of Ukraine. Retrieved from: https://davr.gov.ua/fls18/PURBDnipro.pdf [in Ukrainian].

23. Derzhavnyy vodnyy kadastr: oblik poverkhnevykh vodnykh ob'yektiv [State Water Cadastre: Accounting for Surface Water Bodies]. www.geoportal.davr.gov.ua Retrieved from: https://geoportal.davr.gov.ua/#arraysSurfaceWatersSidebar [in Ukrainian]

24. Monitorynh ta ekolohichna otsinka vodnykh resursiv Ukrayiny [Monitoring and ecological assessment of water resources of Ukraine]. www.monitoring.davr.gov.ua Retrieved from: http://monitoring.davr.gov.ua/EcoWaterMon/GDKMap/Index.

25. Kryvul'chenko, A.I., Fomenko, R.P., & Naumenko, N.V. (1999). Fond vodoskhovyshch Kirovohrads'koyi oblasti, holovni osoblyvosti ta zakonomirnosti poshyrennya [Reservoir Fund of Kirovohrad Region, Main Features and Distribution Patterns]. Regional geographical studies: Scientific news. Kirovohr[in Ukrainian]ad: Regional Research Center of V. Vynnychenko Kyiv State Pedagogical University, 26–35.

26. Kovalchuk, V., Kovalchuk, P., Yatsyuk, M., Kovalenko, R., Demchuk, O., & Balykhina, H. (2020). System model of integrated management of the water resources of the Ingulets River by a basin principal. *Land Reclamation and Water Management*, (1), 37–48. DOI: https://doi.org/10.31073/mivg202001-219 [in Ukrainian].

27. Khil'chevs'kyy, V.K. Inhulets'. Velyka ukrayins'ka entsyklopediya [Great Ukrainian Encyclopedia]. www.vue.gov.ua. Retrieved from: https://vue.gov.ua/Інгулець. [in Ukrainian]

28. World Meteorological Organization (WMO). www.wmo.int. Retrieved from: https://wmo.int

29. Intergovernmental Panel on Climate Change (IPCC). www.ipcc.ch. Retrieved from: https://www.ipcc.ch

30. Metodychni rekomendatsiyi shchodo vrakhuvannya klimatychnoho komponenta pid chas zdiysnennya otsinky vplyvu na dovkillya [Methodological recommendations for taking into account the climate component when assessing the impact on the environment]. (2024). Kyiv: Ministry of Environmental Protection and Natural Resources of Ukraine. Retrieved from: https://mepr.gov.ua/wp-content/uploads/2024/10/1382nd2.docx [in Ukrainian]

31. Freemeteo. www. freemeteo.com.ua. Retrieved from: freemeteo.com.ua

32. Mizhnarodnyy ispans'kyy meteosayt Globalclimatemonitor [International Spanish weather website Globalclimatemonitor]. Retrieved from: https://www.globalclimatemonitor.org [in Ukrainian].

33. Zhang, S., Chen J., Du, Q., Xue, J., Yang, X. (2024). Energy conversion for water surface evaporation in evaporation ponds with different depths and improvement of Dalton model. *Journal of Hydrology*, Vol. 644, 132094. https://doi.org/10.1016/j.jhydrol.2024.132094.

34. Obukhov, Ye. V. (2014). Uzahal'nennya zalezhnostey mizh hidrometeorolohichnymy kharakterystykamy v rayoni Kakhovs'koho vodoskhovyshcha dlya vyznachennya vyparovuvannya z yoho vodnoyi poverkhni [Generalization of dependencies between hydrometeorological characteristics in the area of the Kakhovka reservoir to determine evaporation from its water surface]. *Ukrayins'kyy hidrometeorolohichnyy zhurnal*, 15, 141–148. Retrieved from: http://nbuv.gov.ua/UJRN/Uggj_2014_15_22 [in Ukrainian].

35. Klimatychnyy kadastr Ukrayiny (2006). Derzhavna hidrometeorolohichna sluzhba UkrNDHMI. Tsentral'na heofizychna observatoriya [in Ukrainian].

36. Koval'chuk, V.P., Yatsyuk, M.V., Nechay, O.M., Balykhina, H.A. (2025). Stsenarnyy analiz i porivnyannya variantiv utylizatsiyi shakhtnykh vod zi stavkiv-nakopychuvachiv. [Scenario analysis and comparison of options for disposal of mine water from storage ponds.]. Zbirnyk tez XIII Mizhnarodnoyi naukovo-praktychnoyi konferentsiyi "Voda dlya maybutn'oho: upravlinnya,