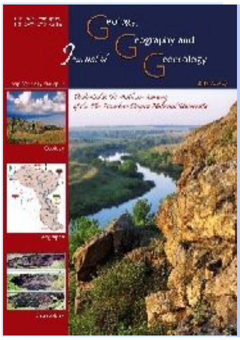

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GIS-based Assessment of the Assimilative Capacity of Rivers in Dnipropetrovsk Region

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Abstract. The objective of this paper is to identify the level of changes in the ecological status of surface reservoirs of Dnipropetrovsk region under the impact of anthropogenic factors and to find a rationale for the limit loads on aquatic ecosystems, based on a quantitative assessment of their assimilative capacity values using GIS-technologies.To characterize and evaluate economic activity in the river basins of Dnipropetrovsk region, the data of state statistical reporting by the form of 2-TP "Water resources management" of the State Agency for Water Resources of Ukraine were used. Parameters characterizing the assimilative capacity of water bodies were determined by taking into consideration the perennial average values of river runoff resources of the priority watercourses of Dnipropetrovsk region in the years with varying degrees of supply: with an average (50%), a low (75%) and a very low (95%) river water content. The main indicators characterizing the assimilative capacity of the water bodies of Dnipropetrovsk region are actual and necessary multiplicity of wastewater dilution, the limit to assimilative capacity of surface reservoirs, index of assimilative capacity utilization of river runoff resources of varying degrees of supply. A classification that characterizes the level of assimilative capacity utilization for water bodies is proposed. The level of assimilative capacity utilization of the Dnipro River in the reservoir areas, regardless of the degree of river runoff supply, is estimated as “allowable” . At 95% degree of river runoff supply, the level of assimilative capacity utilization of the Oril and Vovcha Rivers is characterized as “moderate”, the Samara River (after the confluence with the Vovcha River) as “high” and the Ingulets River with tributary the Saksagan River, and the Samara River (before confluence with the Vovcha River) as “very high”. It should be noted that irrespective of the level of river runoff supply, the index of assimilative capacity utilization of the Samara River (before its confluence with the Vovcha River) exceeds the limit value by 19-115 times. For the spatial analysis of hydrological parameters and visualizion of the data in the form of thematic maps, the geoinformation system “Rivers of Dnipropetrovsk region” was developed on the basis of the ESRI ArcGIS Desktop10 software package. Using the geoprocessing tools, on the basis of hydrological indices of 7 priority watercourses for each of the 22 administrative-territorial districts of Dnipropetrovsk region, the main indicators characterizing the assimilative capacity of water resources were calculated and ranked. The use of indicators characterizing the assimilative capacity of river runoff resources allows us to identify the threshold levels of anthropogenic transformation of aquatic ecosystems, develop and implement environmental measures to improve the ecological status and ensure environmental safety of surface reservoirs.

Key words: assimilative capacity,multiplicity of wastewater dilution, index of assimilative capacity utilization, river runoff, self-purification of water reservoirs

Оценка ассимиляционной емкости рек Днепропетровской области с использованием геоинформационных технологий

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Анотація. Проведено аналіз забору річкової води й скиду стічних вод у поверхневі водойми Дніпропетровщини. Визначено величини фактичної та необхідної для самоочищення кратності розведення стічних вод різної категорії якості річковими водами. Встановлено значення граничної асиміляційної ємності ресурсів річкового стоку Дніпропетровської області різного ступеня забезпеченості. Розраховано значення індексу використання асиміляційної ємності ресурсів річкового стоку різного ступеня забезпеченості. Запропоновано класифікацію, що характеризує рівень використання асиміляційної ємності водних об’єктів. Встановлено, що рівень використання асиміляційної ємності річки Дніпро на ділянці водоймищ незалежно від рівня забезпеченості річковим стоком, оцінюється як "припустимий". При 95%-вому ступені забезпеченості річковим стоком рівень використання асиміляційної ємності річок Оріль і Вовча характеризується як "помірний", р. Самари (після впадіння в неї р. Вовча) – "високий" та річок Інгулець з припливом Саксагань і Самара (до впадіння в неї р. Вовча) – "надзвичайно високий". За результатами розрахунків на основі програмного комплексу ESRI ArcGi Desktop10 розроблено геоінформаційну систему "Річки Дніпропетровської області". Визначено питомі показники, що характеризують асиміляційну ємність водних ресурсів у дуже маловодні роки за адміністративно-територіальними районами області.

Ключові слова: асиміляційна ємність, кратність розведення стічних вод, індекс використання асиміляційної ємності, забезпеченість річковим стоком, самоочищення водойм

Introduction. Intensive economic activity in the river basins of Dnipropetrovsk region significantly affects the quantitative and qualitative indicators of water resources and their ecological status. The overwhelming majority of Dnipropetrovsk region's rivers are degraded, as a result of an excessive anthropogenic load, prevailing over the capacity of water bodies for self-purification and self-repair. This, in turn, is exacerbated by the low level of water supply of the region. The resources of local river runoff are very small and amount to 450 m^3 per 1 inhabitant (Regional report on the state of the environment in Dnipropetrovsk region in 2016, 2017).

Small and medium-sized rivers experience anthropogenic impact more acutely than large ones, due to their small water content , and as a rule, the worst purification of wastewater dischargedinto them . The river beds accept the main technogenic load from water-users. Today, human economic activity has led to a crisis situation in the small and medium-sized rivers of Dnipropetrovsk region, which to a large extent determine the overall state of the DniproRiver. The largest tributaries of the Dnipro are the rivers Oril, Samara with the tributary of Vovcha and the Ingulets with the tributary of Saksagan. These rivers are the main sources of water supply in Dnipropetrovsk region, so far as they have a constant water flow. To ensure of the ecological safety of surface reservoirs, it is necessary that the paces of water resources use caused by natural processes and anthropogenic impact correspond to the paces of resumption (restoration) of aquatic ecosystems within the framework of balanced water use.

The result of technogenic impact on rivers is the loss of capacity of aquatic ecosystems for natural self-purification and self-restoration, that is, to cause a decrease in their assimilative capacity (Cairns Jr., 1999; Fallah-Mehdipour, 2015). Assimilative capacity (potential) of an ecosystem is an indicator of the maximum dynamic capacity of the amount of pollutants which can be accumulated, destroyed, transformed and transferred beyond the volume of the ecosystem without disturbing its normal activity (Izrael, Tsyban, 1989).

One method used to normalize the ecological state of aquatic ecosystems is assessment their ability to purify themselves by calculating the assimilative capacity for each water body or part of its water area (Glasoe, Steiner, Budd, Young, 1990; Hoang Ngos, Tran Quang, 2012; Hernandez, Uddameri, 2013). Thus, the use of indicators characterizing the assimilative capacity of river runoff resources allows us to identify the threshold levels of anthropogenic transformation of aquatic ecosystems, develop and implement environmental measures to improve the ecological status and ensure environmental safety of surface reservoirs.

The objective of the paper is to identify the level of change in the ecological status of surface reservoirs of Dnipropetrovsk region under the impact of anthropogenic factors and to find a rationale for the limit loads on aquatic ecosystems, based on the quantitative assessment of their assimilative capacity values using GIS-technologies.

Materials and methods of research. To characterize and evaluate economic activity in Dnipropetrovsk region's river basins, the data of state statistical reporting by the form of 2-TP "Water resources management" of the State Agency for Water Resources of Ukraine were used. To determine the limit assimilative capacity of water bodies, we used perennial average values of river runoff resources of the priority watercourses of Dnipropetrovsk region in the years with varying degrees of supply: with an average (50%), a low (75%) and a very low (95%) river water content.

As the main water bodies, for which the indicators characterizing their assimilative capacity were calculated, the largest watercourses of Dnipropetrovsk region were selected:

1 – the InguletsRiver, including its tributary the SaksaganRiver;

2 – the Dnipro River, site I (the area of the Dniprodzerzhinsk-Dnipro reservoirs);

3 – the OrilRiver;

4 – the Samara River, site I (before the confluence with the Vovcha River);

5 – the Samara River, site II (after the confluence with the Vovcha River);

6 – the VovchaRiver;

7 – the Dnipro River, site II (the area of the Dnipro-Kakhovka reservoirs).

Assimilative capacity of water bodies was assessed using the following groups of indicators:

1. Basic:

– total wastewater discharge into surface water bodies, mln. m^3;

– amount of wastewater discharged into water bodies as normatively clean (without purification), mln. m^3;

– amount of wastewater discharged into water bodies as normatively purified, mln. m^3;

– amount of wastewater discharged into water bodies as contaminated or insufficiently purified, mln. m^3;

– volume of river runoff the varying degrees of supply (in the years with an average, a low, a very low river water content), mln. m^3.

2. Estimated:

– value of necessary multiplicity of wastewater dilution discharged into surface reservoirs, conv. units;

– value of limit assimilative capacity of the water body that accepts discharged wastewater, mln. m^3;

– index of assimilative capacity utilization of the water body, conv. units.

The main criterion of assimilative potential of the water body is the multiplicity of wastewater dilution.

The indicator of necessary multiplicity dilution of wastewater volume in the water body volume is a universal characteristic (Farhadian, Bozorg Haddad, Seifollahi-Aghmiuni, Loáiciga, 2014; Monfared, Darmian, Snyder, Azizyan, Pirzadeh, Moghaddam, 2017). It shows by how many times the water volume that takes part in river runoff dilution increases relative to the primary discharged wastewater volume.

Depending on the ratio of the discharged wastewater volume and the water body volume, taking into account the intensity of dilution and self-cleaning processes occurring in it, various amounts of wastewater can be discharged into each water body for a certain time. At the same time, the limit volume of wastewater that can be discharged into a water body without violating sanitary requirements is conditioned by a certain dependence relative to water quality standards.

The natural self-cleaning ability of water bodies and watercourses is very low. A self-cleaning process occurs only if the wastewater is discharged into the surface reservoirs completely purified, and in a water body they have been diluted with river water in a ratio of 1:12-15. If, in water bodies and watercourses, wastewater is discharged in a large volume, and all the more so contaminated (or insufficiently purified), the stable natural balance of aquatic ecosystems is gradually lost, their normal functioning is disturbed, which makes these rivers unsuitable for use.

According to the recommendation of (Koronkevich, 1990), the multiplicity of dilution of conditionally pure water should be 1:3, purified household wastewaste – 1:5, unpurified – 1:20, purified industrial wastewaters – 1:15, unpurified – 1:50, for drains from urban territories – 1:3, from agricultural fields – 1:1. These values of the multiplicity of wastewater dilution were accepted as the basis for calculations.

For a more detailed study of the assimilative capacity of surface water bodies, various approaches and methods are used (Lee, Wen, 1996; Watson, Wyss, Booth, Sousa, 2012; Chiejine, Igboanugo, Ezemonye, 2016). Geoinformation technologies are the most important modern tool for analyzing data related to natural objects, which allow not only visualization of actual and forecasted situations on maps, but also generate new data and patterns. For example, the solution of tasks on the rational use and restoration of water resources can be carried out using automated GIS-zoning of study area (Rational Use and Recovery of Water Resources, 2016). For the assessment of levels of assimilative capacity utilization the rivers of Dnipropetrovsk region and visualization of data in the form of thematic maps, the geoinformation system “Rivers of Dnipropetrovsk region” was developed on the basis of the ESRI ArcGIS Desktop10 software package. To calculate and rank the indicators characterizing the assimilative capacity of water bodies, on the basis of hydrological indices of the seven priority rivers, geoprocessing tools such as overlay / identity were used for the administrative-territorial districts of Dnipropetrovsk region.

Results and their analysis. The main river of hydrographic networkofDnepropetrovsk region is the DniproRiver, which is represented by a cascade of reservoirs across the region territory: Dniprodzerzhinskoye, Dniprovskoye and Kakhovskoye. The total length of the DniproRiver within the region is 261 km, including 66 km within the Dniprodzerzhinskoye, 94 km within Dniprovskoye and 101 km within Kakhovskoye reservoirs.

In general, the hydrographic network of the Dnipro River basin within the region (Fig.1) is represented by 291 rivers, over 10 km long (of which 9 rivers are medium-sized), 101 reservoirs, 3,292 ponds and 1,129 lakes.

Currently, the water resources of Dnipropetrovsk region are intensively used for various needs. There are practically no rivers with a natural hydrological regime that has not been affected by economic activity. Most rivers are affected by the discharge of contaminated and/or insufficiently treated wastewater discharged by industrial, agricultural and communal enterprises directly into water bodies.

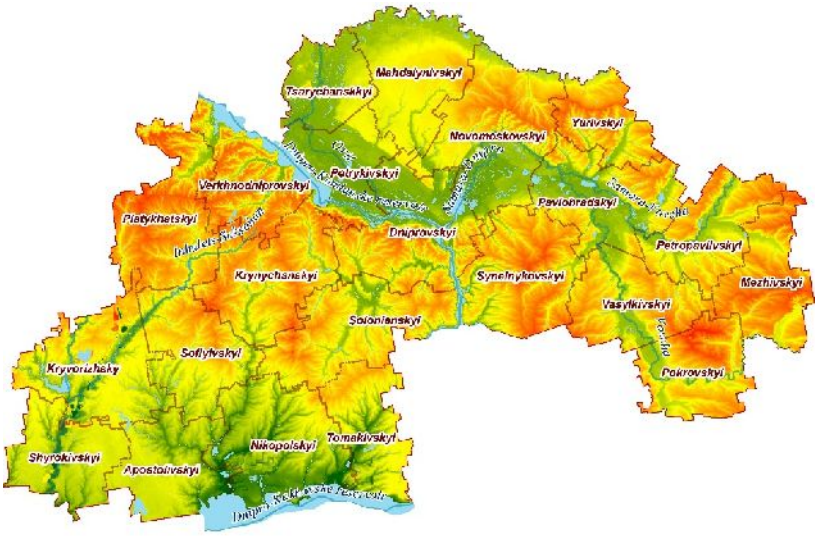


Fig. 1 Hydrographic network of Dnipropetrovsk region

The most important factors that affect the quantitative and qualitative indicators of water resources are the water intake from surface reservoirs and wastewater discharge of various quality categories.

Data about water intake from the considered surface reservoirs and the wastewater discharge of various quality categories in 2016 are provided in Table. 1.

Table 1 The values of water intake from surface reservoirs and wastewater discharge of various quality categories into water bodies of Dnipropetrovsk region

Sequence number of water body	Total water intake V_{intake}, mln. m^3	Total discharge V_{dis}, mln. m^3	Categories of wastewater discharged into surface reservoirs					
			Normatively clean without purification		Normatively purified		Contaminated (including insufficiently purified)	
			Discharge V_{NCWC}, mln. m^3	Share of total discharge K_{NCWC}	Discharge V_{NP}, mln. m^3	Share of total discharge K_{NP}	Discharge V_C, mln. m^3	Share of total discharge K_C
1. InguletsRiver	31.47	24.89	8.04	0.32	6.00	0.24	10.85	0.44
2.DniproRiver, site I	999.90	730.50	524.73	0.723	16.11	0.02	189.66	0.26
3.OrilRiver	7.06	5.00	0.44	0.09	-	-	4.56	0.91
4.SamaraRiver, site I	6.90	18.65	-	-	1.57	0.08	17.08	0.92
5.SamaraRiver, site II	11.18	27.25	1.63	0.06	23.45	0.86	2.16	0.08
6.VovchaRiver	33.99	2.59	-	-	1.05	0.41	1.54	0.59
7.DniproRiver, a site II	2261.59	878.88	715.50	0.81	99.20	0.11	64.18	0.07
Total:	3352.09	1687.76	1250.34	0.74	147.38	0.09	290.03	0.17

Most wastewater enters into surface reservoirs of Dnipropetrovsk region as contaminated or insufficiently purified. In the Oril and Samara rivers (before the confluence with the VovchaRiver), wastewater is completely discharged without purification. They account for 91% and 92% of the total wastewater discharge, respectively. Almost half the unpurified wastewater (44%) is discharged into the Ingulets River. The VovchaRiver collects 60% of the total discharge of contaminated wastewater. The remaining 40% of wastewater is discharged into the water body after purification. A significant amount of normatively purified wastewater (86% of the total discharge) enters the SamaraRiver after the confluence with the VovchaRiver.

Normally, in the structure of wastewater disposal in water bodies of Dnipropetrovsk region, normatively clean waters (without purification) predominate, which make up 74% of the total discharge. A significant part of normatively clean waters (72% and 81%) is discharged to the DniproRiver in the areas of reservoirs.

The share of normatively purified wastewater discharged into the surface reservoirs of the region makes up 9% of the total discharge, and contaminated including insufficiently purified – 17%. The percentage of wastewater discharged into water bodies of Dnipropetrovsk region after purification is rather low, which indicates a lack of interest of enterprises-water users in the implementation of environmental measures, including the installation of treatment facilities.

The level of river runoff use and the quality of water (or the intensity of contaminated wastewater entry into water ecosystems) over a certain period of time can be considered as integral indicators that determine the degree of anthropogenic load. The quality of water will depend on the volume of the water body. In this case, the anthropogenic load on water bodies is characterized by the coefficient of river runoff use K_{RRU}(Jacyk, Kanash, Stashuket al., 2007), which is estimated as the ratio of water intake from surface reservoirs (water intake coefficient) and the volume of discharged wastewater of various quality category to the value of river runoff at varying degrees of supply, that is,

$$K_{RRU} = \frac{V_{intake}}{V_{RR}} = \frac{V_{dis}}{V_{RR}}, \quad (1)$$

where V_{RR} is the volume of river runoff at varying degrees of supply for the main watercourses of Driproopetrovsk region, which is given in Table 2.

Table 2. The volume of river runoff at varying degrees of supply for the main watercourses in Dnipropetrovsk region (Strelets, 1987)

Sequence number of water body	Supply the river runoff resources, mln. m^3, in the years with:		
	average river water content (50%)	low river water content (75%)	very low river water content (95%)
1. InguletsRiver	206	112	41
2.Dnipro River, site I	51100	42260	31670
3.OrilRiver	315	170	54
4.Samara River, site I	47	25	7,6
5.Samara River, site II	423	237	82
6.VovchaRiver	139	75	27
7.Dnipro River, site II	51100	42260	31670

The intensity characterization of anthropogenic load on water resources, depending on the cal-culated coefficient value of K_{RRU}, is given in Table 3.

Table 3. Estimated scale of anthropogenic load on water resources (Shiklomanov, 2008)

CoefficientvalueK_{RRU}	<10%	10-20%	20-40%	40-60%	>60
Intensity of anthropogenic load on water resources	low	moderate	high	very high	critically high

According to the "rule of one percent" (Reimers, 1990), aquatic ecosystems begin to lose their balance when fresh water is taken from water bodies and (or) contaminated wastewater is discharged, in the amount which exceeds 1% of river runoff value the varying degrees of supply.

It has been established (Jacyk, 2004) that when water resources are taken from surface reservoirs (wastewater discharge of various quality categories) in the volume of more than 10% of river runoff (K_{lim}<10%), the water body loses its capacity for self-purification.

The coefficient values of river runoff use the varying degrees of supply as a result of water intake from surface reservoirs in Dnipropetrovsk region and wastewater discharge of various quality categories are given in Table 4.

The water intake coefficient from the small and medium rivers of Dnipropetrovsk region in modern conditions reaches significant values. Thus, in the years with an average water content for the rivers Ingulets, Samara (before the confluence with the Vovcha River) and Vovcha River, it fluctuates within 15-25% of river runoff supply, which exceeds the limit permissible value by 1.5-2.5 times. In the years with very low water content, the values of water intake coefficient are even greater and makes up 77–126% of river runoff supply.

The most significant irrecoverable water costs are associated with excessive water intake for irrigation of agricultural lands, for watering vegetable gardens, garden areas, etc.

When calculating the coefficient of wastewater discharge into surface reservoirs of Dnipropetrovsk region, it is established that its values for the Ingulets and Samara Rivers not only exceed by 6 and 24.5 times, respectively, the limit permissible level of river runoff use in the years with a very low water content, but also for the Samara River (before the confluence with the Vovcha River) by 4 times more than the critical value of the coefficient (K_{CV}=60%).

Table 4. Results of calculating the coefficient values of river runoff use the varying degrees of supply for Dnipropetrovsk region

Sequence number of water body	The coefficient values of river runoff use (K_{RRU}), %					
	water intake coefficient in the years with:			coefficient of wastewater discharge in the years with:		
	average river water content (50%)	low river water content (75%)	very low river water content (95%)	average river water content (50%)	low river water content (75%)	very low river water content (95%)
1. InguletsRiver	15.3	28.1	76.8	12.1	22.2	60.7
2.DniproRiver, site I	2.0	2.4	3.2	1.4	1.7	2.3
3.OrilRiver	2.2	4.2	13.1	1.6	2.9	9.3
4.SamaraRiver, site I	14.7	27.6	90.8	39.7	74.6	245.4
5.SamaraRiver, site II	2.6	4.7	13.6	6.4	11.5	33.2
6.VovchaRiver	24.5	45.3	125.9	1.9	3.5	9.6
7.DniproRiver, site II	4.4	5.4	7.1	1.7	2.1	2.8

It is established that before the confluence of the VovchaRiver with the SamaraRiver, the volume of discharged contaminated and insufficiently purified wastewater, mainly mine waters, by 2.5 times exceeds the value of river runoff in the years with very low water content. This indicates that in the years with 95% level of river runoff supply, the Samara River in this area exists due to the discharged untreated wastewater. The river is practically unsuitable for any economic use and does not meet sanitary requirements (Kulikova, Pavlychenko, 2016).

Thus, excessive water intake from surface reservoirs and wastewater discharge leads to degradation of water bodies, loss of their ability to restore, deterioration of water supply conditions for the population living on the nearby area. Proceeding from this, to preserve the natural state of river ecosystems, it is expedient to control the specific load on water bodies.

Accounting the dilution capacity of the water body, which is based on hydrological data and its capacity for self-purification, allows us to determine the regime of wastewater discharge into the water basin and estimate the permissable amount of wastewater, that is, the critical ecological load. In this case, it takes into account the natural runoff of both the water body and wastewater.

The actual multiplicity of wastewater dilution of various quality categories (K_A) discharged into water bodies of Dniproopetrovsk region is determined by the formula:

$$K_A = \frac{V_{RR}}{V_{dis}}. \qquad (2)$$

The calculated coefficient values of K_A at varying degrees of river runoff supply are presented in Table 5.

Table 5. Results of calculating the multiplicity values of wastewater dilution discharged into surface reservoirs of Dnipropetrovsk region at varying degrees of river runoff supply

Sequence number of water body	Multiplicity of wastewater dilution of various quality categories:			
	actual (K_A) in the years with:			necessary (K_N)
	average river water content (50%)	low river water content (75%)	very low river water content (95%)	
1. InguletsRiver	8.3	4.5	1.7	1:26.381·V_{dis}
2.Dnipro River, site I	70.0	57.9	43.4	1:15.466·V_{dis}
3.OrilRiver	63.0	34.0	10.8	1:45.855·V_{dis}
4.Samara River, site I	2.5	1.3	0.4	1:47.057·V_{dis}
5.Samara River, site II	15.5	8.7	3.0	1:17.061·V_{dis}
6.VovchaRiver	53.6	28.9	10.4	1:35.794·V_{dis}
7.Dnipro River, site II	58.1	48.1	36.0	1:7.786·V_{dis}

Calculating the actual multiplicity values of wastewater dilution showed that, with the available wastewater volume discharge of various quality cat-egories, the Ingulets River, including its tributary the Saksagan River, and the Samara River do not have sufficient resources for dilution and self-purification processes. The worst situation is in years with very low river water content. At 95% level of river runoff supply of the SamaraRiver (before the confluence with the VolchyaRiver), the multiplicity value of wastewater dilution is 1:0.41, that is, the dilution process is not carried out.

Thus, due to excessive anthropogenic load, the resources of these rivers have completely lost their capacity for self-purification, since water bodies begin to experience the state of stress if the multiplicity of wastewater dilution with clean river water becomes lower than 1:10 (Reimers, 1990).

The actual multiplicity of wastewater dilution discharged into the remaining water bodies of Dnipropetrovsk region currently at least corresponds to the minimum that was previously taken to maintain the natural equilibrium of aquatic ecosystems (1:10).

Earlier, when the anthropogenic load on water bodies was insignificant, it was believed that to maintain the normal self-cleaning capacity of water basin, the multiplicity of wastewater dilution should be 1:10. However, today some wastewater requires more dilution with clean river water.

The most advanced treatment facilities provide for the purification of wastewater from organic pollutants by only 85-90%, and only in some cases – by 95%. Therefore, even after purification, it is necessary to dilute the treated wastewater with clean river water in a ratio by 1:6-12 and more for to ensure vital functions of aquatic ecosystems.

When calculating the necessary multiplicity of wastewater dilution (K_N) of various quality categories discharged into water bodies of Dnipropetrovsk region, the following ratios were adopted: for normatively clean waters (without purification) – 1:3, for normatively purified waters – 1:15, for contaminated (including insufficiently purified) – 1:50.

The necessary multiplicity value of wastewater dilution discharged into water bodies was determined by the formula:

$$K_N = \frac{3 \cdot V_{NCWC} + 15 \cdot V_{NP} + 50 \cdot V_C}{V_{dis}}. \quad (3)$$

The results of calculating the necessary multiplicity of wastewater dilution discharged into water bodies of Dnipropetrovsk region are shown in Table 5.

The calculated necessary multiplicity values of wastewater dilution allow us to determine how much the actual and theoretical values of this indicator really correspond to each other. At the present time, the actual multiplicity of wastewater dilution discharged into the Dnipro River on the reservoir areas, even in the years with a very low water content, exceeds the necessary values to ensure the normal functioning of reservoirs (by 2.8 times on the Dniprodzerzhinskoye – Dniprovskoye reservoirs and by 4.6 times – Dniprovskoye – Kakhovskoye reservoirs).

At wastewater discharge into the Oril, Vovcha and Samara Rivers (after the confluence with the Vovcha River), the actual multiplicity of wastewater dilution in the years with an average water content (50% level of river runoff supply) corresponds to the theoretically necessary value. At the same time, in the years with a very low water content, the coefficient values of K_F for all water bodies, except of the Dnipro River, is significantly lower than the necessary multiplicity of wastewater dilution.

Having determined the necessary multiplicity values of wastewater dilution K_N, we can find the value of limit assimilative capacity of the water body, which is expressed as the maximum amount of wastewater that can be discharged into the surface reservoir without violating its environmental sustainability.

The values of limit assimilative capacity of water bodies are defined as the ratio of the river runoff of varying degrees of supply to the previously calculated necessary multiplicity of wastewater dilution:

$$AC_{Lim} = \frac{V_{RR}}{K_N}, \text{ mln. m}^3. \quad (4)$$

The results of this calculation are presented in the Table 6.

Table 6. Calculation results of indicators characterizing the assimilative capacity of river runoff resources in Dnipropetrovsk region in the years with varying degrees of supply

Sequence number of water body	Limit assimilative capacity of water bodies (AC_{Lim}), mln. m^3, at the level of river runoff supply:			Reserve of river runoff resourcespotentially possible for use (V_{PPRR}), mln. m^3, at the level of supply:			The index of assimilative capacity of river runoff resources, conv. units, at the level of supply:		
	50%	75%	95%	50%	75%	95%	50%	75%	95%
1. InguletsRiver	7.81	4.25	1.55	-17.08	-20.64	-23.34	3.19	5.86	16.02
2.DniproRiver, site I	3303.92	2732.36	2047.66	2573.43	2001.87	1317.16	0.22	0.27	0.36
3.OrilRiver	6.87	3.71	1.18	1.87	-1.29	-3.82	0.73	1.35	4.24
4.SamaraRiver, site I	1.00	0.53	0.16	-17.65	-18.12	-18.49	18.67	35.12	115.12
5.SamaraRiver, site II	24.79	13.89	4.81	-2.45	-13.35	-22.44	1.10	1.96	5.67
6.VovchaRiver	3.88	2.10	0.75	1.29	-0.50	-1.84	0.67	1.24	3.44
7.DniproRiver, site II	6563.23	5427.83	4067.66	5684.35	4548.95	3188.78	0.13	0.16	0.22

As a result of calculation, limit values of assimilative capacity of the main watercourses of Dnipropetrovsk region are established, corresponding to the theoretical volume of wastewater that can be discharged into surface reservoirs without harm to water ecosystems. The basis of potential is the annual assimilative capacity of the Dnipro River, which is 2,000-6,500 mln. m^3 of wastewater.

Having determined the values of limit assimilative capacity of water bodies of Dnipropetrovsk region and the amount of water resources, which are being already in use and expressed by the actual volumes of wastewater discharge of various quality categories, it is possible to calculate the reserve values of river runoff resources potentially possible for use,

$$V_{\mathrm{PPRR}} = AC_{Lim} - V_{dis}, \text{ mln. m}^3. \quad (5)$$

The results of calculating the reserves of river runoff resources potentially possible for use in the years with varying degrees of supply in Dniproopetrovsk region are presented in Table 6.

It is established that the reserve of potentially useable river runoff resources is fully exhausted. This means that the wastewater amount of various quality categories entering into the water bodies in Dnipropetrovsk region is greater than the maximum possible amount of wastewater that can be discharged into the surface reservoir without violating its environmental sustainability. The exception is the Dnipro River in the reservoir areas, which has significant reserves of river runoff resources potentially possible for use .

In the years with an average water content, the tributaries of the Dnipro River, namely the Oril and Vovcha Rivers, have an insignificant reserve of river runoff resources potentially possible for use.

The index of assimilative capacity utilization of river runoff resources at varying degrees of supply was determined from the ratio:

$$I_{ACU} = \frac{V_{dis}}{AC_{Lim}}, \text{ conv. units.} \quad (6)$$

The results of calculating the index of assimilative capacity utilization of river runoff resources at varying degrees of supply in Dnipropetrovsk region are given in Table 6.

The level of assimilative capacity utilization of river runoff resources from the values of I_{ACU} obtained was estimated in accordance with the proposed classification and presented in Table 7.

Table 7. Estimated scale level of assimilative capacity utilization of river runoff resources

Ranges of index values I_{ACU}	≤1	1-5	5-10	>10
Level characterization of assimilative capacity utilization of river runoff resources	allowable	moderate	high	extremely high

According to the results of calculations, it is established that the level of assimilative capacity utilization of the Dnipro River on the reservoir areas, regardless of the degree of river runoff supply, is estimated as “allowable”. In the years with an average water content (50%), the level of assimilative capacity utilization of the Oril and Vovcha Rivers is estimated as “moderate”, the Samara River (after the confluence with the Vovcha River) and the Ingulets River with the Saksagan tributary – “moderate”.

At 95% level of river runoff supply, the I_{ACU} index for the considered water bodies, except for the Dnipro River, exceeds the limit value (I_{ACU}=1). At the same time, the level of assimilative capacity utilization of the Oril and Vovcha Rivers is character-ized as “moderate”, the Samara River (after the con-fluence with the Vovcha River) as “high” and the In-gulets River with tributary the Saksagan River, and the Samara River (before confluence with the Vovcha River) as “very high”. It should be noted that irrespective of the level of river runoff supply, the index of assimilative capacity utilization of $I_{\mathrm{ACU}}$for the Samara River (before the confluence with the Vovcha River) exceeds the limit value by 19-115 times.

Based on the results of calculations, thematic maps published in the form of the GIS “Rivers of Dnipropetrovsk region” in the ArcGIS-Online service were obtained (Fig. 2–4). Since in years with a very low water content in surface reservoirs, the demand for water has been increasing, and the sanitary and hygienic conditions of aquatic ecosystems have been deteriorating, the maps are developed for the period when the level of river runoff supply is 95%.

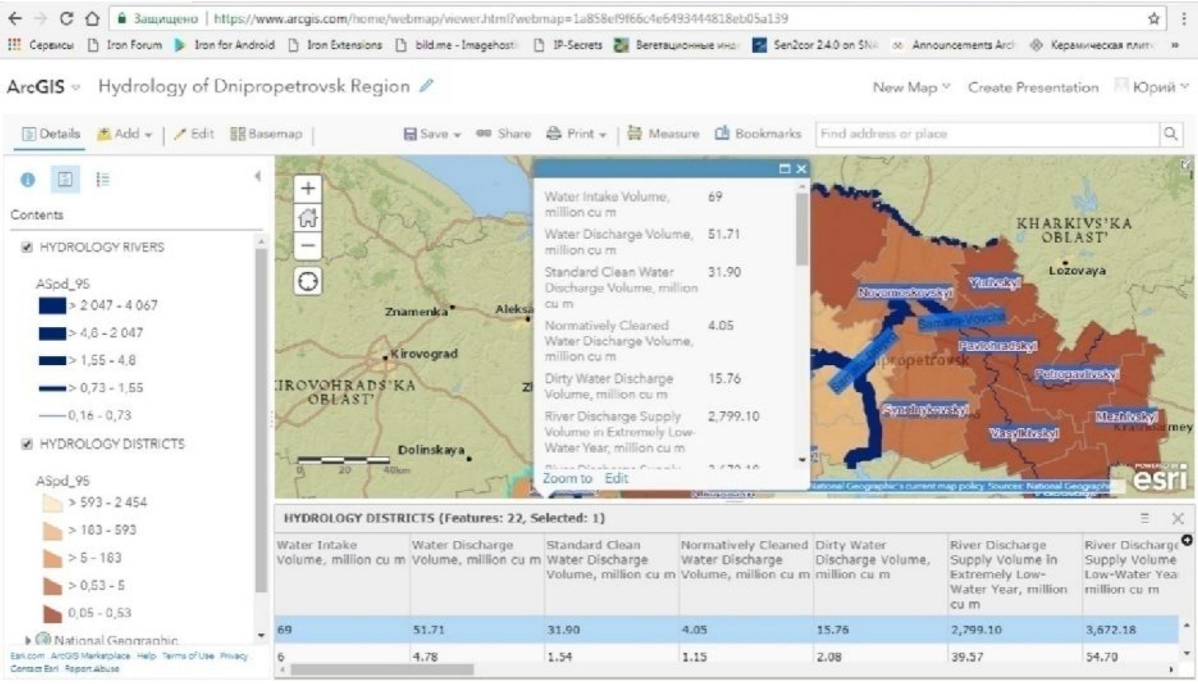
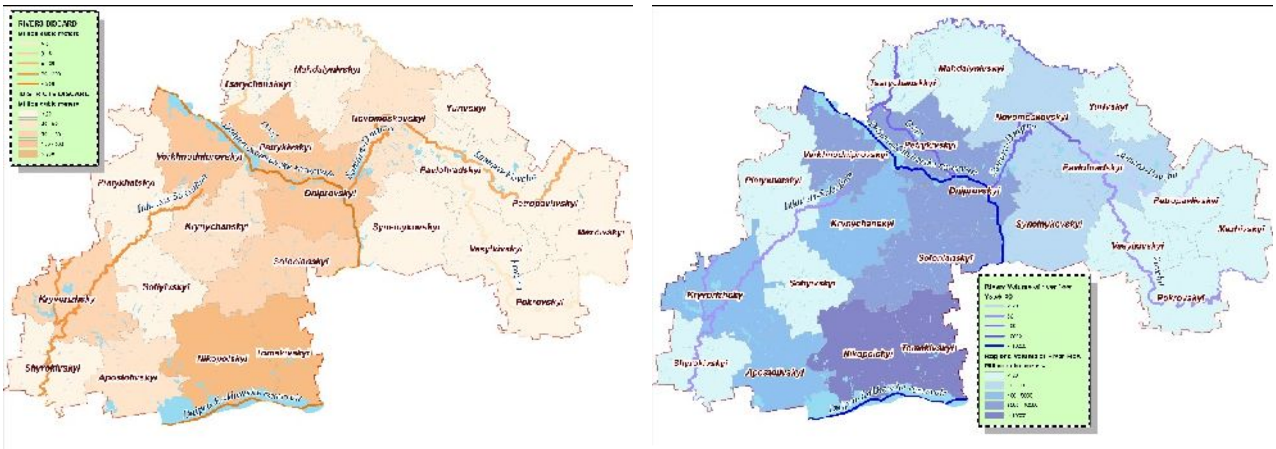
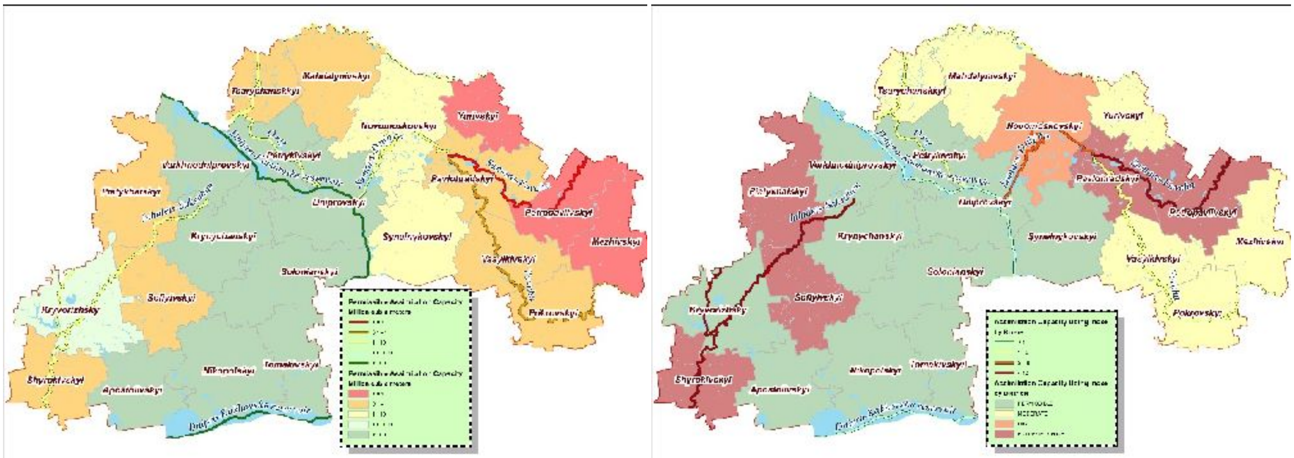


Fig. 2. Publication of the GIS "Rivers of Dnipropetrovsk region" in the ArcGIS-Online service



a) b)

Fig. 3. Distribution of total wastewater discharge (a) and river runoff supply in the years with a very low water content (b) over the area of Dnipropetrovsk region



a) b)

Fig. 4. Distribution of limit assimilative capacity (a) and index of assimilative capacity utilization of river runoff resources (b) in the years with a very low water content over the area of Dnipropetrovsk region

Using the geoprocessing tools, on the basis of the hydrological indices of 7 priority water-courses for each of the 22 administrative-territorial districts of Dnipropetrovsk region, the main indica-tors char-acterizing the assimilative capacity of water re-sources in the years with a very low river water content (95% level of river runoff supply) were calcu-lated and ranked per 1 inhabitant and unit area of a specific district. The results are pre-sented in Table 8.

Table 8 The main indicators characterizing the assimilative capacity of water resources in the years with a very low river water content over the area of Dnipropetrovsk region

Administrative-territorial district of Dnipropetrovsk region	Total wastewater discharge, m^3		River runoff supply, m^3		Multiplicity of wastewater dilution		Limit assimilative capac-ity of river runoff, m^3		tive ca-pacity utilization of river runoff
	e r 1 M	n h a	e r 1 M	i n h a b	c t u a	e s s	e r 1 M	i n h a b	
Apostolivskyi	0.0302	726.8	1.086	26168.38	36.0	7.8	0.1395	3360.98	0.22
Dniprovskyi	0.1218	2551.5	5.180	108480.73	42.5	15.6	0.3331	6975.21	0.37
Krynychanskyi	0.0237	1144.0	0.990	47737.80	41.8	15.9	0.0623	3005.78	0.38
Kryvorizhsky	0.0296	1153.4	0.967	37672.62	32.7	18.3	0.0529	2061.44	0.56
Mahdalynivskyi	0.0009	45.2	0.010	494.45	10.8	45.9	0.0002	12.06	4.2
Mezhivskyi	0.0002	8.6	0.002	90.18	10.4	35.8	0.0001	4.29	3.41
Nikopolskyi	0.2519	13190.1	9.075	475281.01	36.0	7.8	1.1655	61038.99	0.22
Novomoskovskyi	0.0099	273.4	0.032	889.05	3.2	17.9	0.0018	50.07	5.5
Pavlohradskyi	0.0080	450.8	0.013	737.97	1.6	38.2	0.0003	18.18	23.33
Petropavlivskyi	0.0082	396.5	0.003	161.69	0.4	47.1	0.0001	3.85	115.51
Petrykivskyi	0.1570	6572.4	6.776	283734.87	43.2	15.6	0.4332	18138.96	0.36
Piatykhatskyi	0.0018	67.2	0.003	109.77	1.6	26.4	0.0001	4.48	16.16
Pokrovskyi	0.0008	29.2	0.009	303.69	10.4	35.8	0.0002	8.76	3.44
Shyrokivskyi	0.0039	178.8	0.006	294.26	1.6	26.4	0.0002	11.17	16.04
Sofiyivskyi	0.0023	143.8	0.004	236.49	1.6	26.4	0.0001	9.27	16.05
Solonianskyi	0.0752	3396.4	3.261	147275.62	43.4	15.5	0.2108	9522.32	0.36
Synelnykovskyi	0.0011	50.2	0.049	2123.95	43.4	15.5	0.0031	137.37	0.37
Tomakivskyi	0.2552	12627.8	9.197	455083.01	36.0	7.8	1.1812	58444.43	0.22
Tsarychanskyi	0.0014	48.6	0.016	526.71	10.8	45.9	0.0003	11.21	4.23
Vasylkivskyi	0.0005	21.8	0.006	243.04	10.4	35.8	0.0002	6.23	3.21
Verkhnodniprovskyi	0.1401	3498.7	6.048	151037.28	43.2	15.5	0.3898	9735.65	0.36
Yurivskyi	0.0002	15.4	0.003	176.80	10.8	45.9	0.0001	7.69	3.99

The greatest amount of wastewater is dis-charged into surface reservoirs of Nikopolskyi, Tomakivskyi, Dniprovskyi, Verkhnodniprovskyi, Petrykivskyi and Solonianskyi districts. In accord-ance with (Ulzetueva, Gomboev, Zhamyanov, Mo-lotov, 2015), the intensity of anthropogenic load on the water bodies of these areas in terms of total wastewater discharge is estimated as “extremely high” (more than 100 mln. m^3 per year). In six dis-tricts of Dnipropetrovsk region (Kryvorizhsky, Krynychanskyi, Apostolivskyi, Novomoskovskyi, Pavlohradskyi and Petropavlivskyi), the intensity of anthropogenic load on water bodies is estimated as “high” (the volume of discharged wastewater is within $10<V_{dis}<100$ mln. m^3 per year), in three dis-tricts (Vasylkivskyi, Yurivskyi and Mezhivskyi) it is estimated as “low”. In other districts, the intensi-ty is characterized as “average”.

The most river runoff supply in years with very low water content was in 9 districts of Dnipro-petrovsk region (41% of the territory). In the most cases, the Dnipro River flows through these dis-tricts.

In ten districts of Dnipropetrovsk region (45.5% of the territory), the actual multiplicity of wastewater dilution discharged into surface reservoirs exceeded the necessary value by 1.8–4.6 times. This indicates that water bodies located in a given territory have a certain reserve of river runoff resources potentially possible for use.

Water bodies located on the territory of other areas (54.5% of the area of the region) do not have sufficient resources for wastewater dilution and self-purification processes. The actual multiplicity values of wastewater dilution do not correspond (much lower) than calculated values of necessary multiplicity of wastewater dilution. At the same time, in six districts of the region, the actual multiplicity values of wastewater dilution corresponds to the minimum ratio (1:10) necessary to maintain the natural capaity of water bodies for restoration.

In ten administrative-territorial districts of Dnipropetrovsk region (45.5% of the territory), the level of assimilative capacity utilization of river runoff in the years with a very low water content is estimated as “allowable”, in six (27.3%) as “moderate”, in one region (4.6%) as “high” and five districts (22.7%) as “extremely high”. The worst situation with assimilative capacity utilization of river runoff resources is in Piatykhatskyi, Shyrokivskyi, Sofiyivskyi, Pavlohradskyi and Petropavlivskyi districts. The index of assimilative capacity utilization of water bodies located in these territories exceeds the limit value (I_{ACU}=1) by 16-116 times.

Conclusions. 1. Rational use of water resources of small and medium-sized rivers is one of the complex and urgent problems in the water economy and management.Intake of river runoff resources, discharge of return waters into the watercourses, and various types of human activity in the river basin territories cause a decrease in the water capacity of the basins.

2. Loss of the capacity for self-purification, due to prolonged and excessive discharge of contaminated or insufficiently purified wastewater, will inevitably lead to contamination of aquatic ecosystems. The use of such water by the population for household, drinking or cultural and other purposes can lead to negative consequences for human health.

3. The limit assimilative capacity of the considered water bodies is in most cases exceeded. Therefore, one of the main tasks of sustainable water-use is to regularize the tempo of contaminated wastewater discharge toward the calculated value of assimilative capacity of aquatic ecosystems, the value of which will increase as the increase stable boundaries of anthropogenic load exceed.

4. The problem of rational use and protection of rivers should be solved in a comprehensive, systemic manner, taking into account the mutual influence of all factors, processes and components of the geographic network, as well as the impact of economic and other anthropogenic activities. In industrialized areas and in zones of intensive agricultural production (irrigation, animal husbandry), the purity of water resources, prevention of the discharge of contaminated or insufficiently purified wastewater into small water bodies are crucial in the problem of pollution of small and medium rivers. One of the main directions of work towards water resources protection is the complete purification of the wastewater formed, the implementation of new (low-water, non-water and non-waste) technological processes in industrial production, the transition to closed (in-line) water supply cycles, when the purified wastewater is not discharged but is utilized multifold in technological processes. Recycling and re-sequential water supply systems will make it possible to completely eliminate wastewater discharge into surface reservoirs, and use of fresh water to replenish irreversible losses.

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