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Assessment of River Water Inflow into the Sasyk Estuary-Reservoir According to RCP4.5 and RCP8.5 Climate Change Scenarios for 2021-2050

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Abstract. The paper relevancy is determined by the need to substantiate the feasibility of restoring the ecosystem of the Sasyk estuary after its transformation into a reservoir (1978) and the unsuccessful desalination by the Danube waters for irrigation purposes. The paper is aimed at assessment of the possible inflow of fresh water to the Sasyk estuary from the Kohylnyk and Sarata rivers and their role in the formation of fresh water balance in the first half of the 21st century according to the climate change scenarios RCP4.5 and RCP8.5. The main calculation method is the 'climate-runoff' model, which uses meteorological data as input data. Estimates of freshwater inflow into the estuary-reservoir are provided for various calculation periods: before 1989 (before the beginning of significant climate change in the North-Western Black Sea Region); in the period of 1989-2018 according to the hydrometeorological observations; in 2021-2050, according to the averaged data from 14 runs of scenarios RCP4.5 and RCP8.5 under the EVRO-CORDEX project. Estimates of the average long-term values of freshwater inflow in natural conditions and the conditions transformed by water management activity were obtained for each calculation period. It is found that owing to changes in the regional climate for the period of 2021-2050, the total inflow of freshwater from rivers to the estuary in natural conditions will decrease by 23.5 % (by RCP4.5) and by 38.5 % (by RCP8.5) in comparison with the reference period (before 1989). Taking into account the impact of artificial reservoirs, the reduction in the river runoff will be 52.1 % (by RCP4.5) and 64.7 % (by RCP8.5). It is defined, that in case of renaturalization of the Sasyk reservoir into the estuary and the water inflow cut-off from the Danube river, the changes in climatic conditions expected in the first half of the 21st century, combined with water management activity, will result in the increased deficit of annual freshwater balance of the Sasyk reservoir up to 62 % under the RCP4.5 scenario and up to 75 % under the RCP8.5 scenario compared to the period before the emergence of climate change (before 1989). This change must be considered in scientific substantiation of the project on a reversion of the Sasyk Reservoir to the original status of the estuary to ensure such conditions of water exchange with the sea (for compensation of the water balance deficit), which will prevent the long-term trend of salinization.

Keywords: Sasyk estuary, water balance, freshwater inflow, climate change scenarios

Оцінка припливу річкових вод в лиман-водосховище Сасик за кліматичними сценаріями RCP4.5 та RCP8.5 на період 2021-2050 рр.

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Анотація. Актуальність роботи обумовлена необхідністю обгрунтування доцільності відновлення екосистеми морського лиману Сасик після перетворення його на водосховище (1978) та невдалого опріснення дунайськими водами в іригаційних цілях. Мета роботи полягає в оцінці можливого припливу прісних вод до лиману Сасик від річок Когільник і Сарата та їх ролі у формуванні прісного водного балансу в першій половині XXI сторіччя за кліматичними сценаріями RCP4.5 та RCP8.5. Основним методом розрахунків є модель "клімат-стік", яка використовує на вході метеорологічні дані. Оцінки припливу прісних вод до лиману-водосховища надані для різних розрахункових періодів: до 1989 р. (до початку значущих змін клімату на території Північно-Західного Причорномор'я); у період 1989-2018 рр. за даними гідрометеорологічних спостережень; у 2021-2050 рр. за осередненими даними 14 симуляцій сценаріїв RCP4.5 та RCP8.5 проекту EVRO-CORDEX. Оцінки середніх багаторічних величин притоку прісних вод в природних та перетворених водогосподарською діяльністю (побутових) умовах отримані для кожного розрахункового періоду. Установлено, що за рахунок змін регіонального клімату у період 2021-2050 рр., сумарний приплив прісних вод від річок до лиману у природних умовах зменшиться на 23,5 % (за RCP4.5) та на 38,5 % (за RCP8.5) у порівнянні із базовим (до 1989 р.) періодом. При урахуванні впливу штучних водойм зменшення стоку річок буде становити 52,1 % (за RCP4.5) та на 64,7 % (за RCP8.5). Визначено, що у разі ренатуралізації водосховища Сасик в морський лиман та припинення надходження до нього вод р. Дунай, зміни кліматичних умов, які очікуються у першій

половині XXI ст., у поєднанні із водогосподарською діяльністю, призведуть до зростання дефіциту річного прісного водного балансу водосховища Сасик до 62 % за сценарієм RCP4.5 та до 75 % за сценарієм RCP8.5 порівняно з періодом до прояву змін клімату (до 1989 р.). Ці зміни необхідно враховувати при науковому обґрунтуванні проекту повернення водосховища Сасик до первинного статусу морського лиману для забезпечення таких умов водообміну з морем (з метою компенсації дефіциту водного балансу), які унеможливлять виникнення багаторічної тенденції засолення його вод.

Introduction

The urgency of providing estimates of freshwater inflows into the Sasyk estuary based on climate change scenarios in the 21st century is determined by the directions of the Strategy (IPCC, 2014) to reduce the climate change effects and consequences. This study is related to the existence of risks of the loss of biodiversity and the ecosystem functions and services of the Sasyk water body in the case of its renaturalization into the estuary owing to the reduced freshwater inflow in modern climate conditions and those expected in the 21st century. In the order of the President of Ukraine of 30 September 2019 on 'Sustainable Development Goals of Ukraine for the period up to 2030', "protection and restoration of terrestrial ecosystems and facilitation of their sustainable management…" in paragraph 15 is identified as one of the goals. The main task of this study is to substantiate the feasibility of restoration of the functioning of the Sasyk water body as an estuary, which in the last century for irrigation purposes was converted into a reservoir by separating it from the sea and desalination with the Danube waters. However, satisfactory water mineralization has not been obtained and now it functions as a freshwater ecosystem with low water quality (Tuchkovenko, 2011; Lozovitskyi, 2013; Lyashenko and Zorina-Sakharova, 2016). At present, fishery is the main consumer of ecosystem services.

The research object includes changes in the freshwater inflow from the rivers Kohylnyk and Sarata to the Sasyk reservoir (estuary) depending on climatic conditions and water management activities. The subject of research is the assessment of possible changes in the inflow of freshwater from the rivers Kohylnyk and Sarata into the lake under the climatic conditions of the first half of the 21st century.

The paper is aimed at an assessment of the possible inflow of freshwater to the Sasyk (estuary-reservoir) from the rivers Kohylnyk and Sarata and their role in formation of the freshwater balance of the estuary in the first half of the 21st century under RCP4.5 and RCP8.5 climate change scenarios.

Description of the Object

Historically, the Sasyk estuary was formed in the sea-flooded valley of the Kohylnyk and Sarata rivers

and belonged to the closed estuaries at the North-Western Black Sea Region; these estuaries were separated from the sea by isthmuses and spits without permanent channels. The water area of the estuary is a pear-shaped, elongated from north to south, and about 29 km long. The average depth of the estuary reached 1.7 m. The estuary width varied from 3 km to 12 km. The length of the natural sand bar was 14 km, the width – 150-250 m. Water exchange with the sea occurred periodically during the outbreak of the sandbar due to natural factors (storms, and changes in water levels in the estuary and the sea). Mineralization of the Sasyk estuary waters from the late 19th to the first half of the 20th century ranged 12-28 g per dm³, with the maximum values during periods of isolation of the estuary from the sea (Lyashenko and Zorina-Sakharova, 2016). Since 1958, when the estuary was connected to the sea through the Kundutska Prorva ('deep hole'), water mineralization varied from 2 g per dm³ in the upper reaches of the estuary, to which the Kohylnyk and Sarata rivers flow, to 18 g per dm³ in the water zones adjacent to the sandbar. On the coast of the estuary, there was a mud hospital.

In 1978, the Sasyk estuary was artificially separated from the sea by a dam through widening and strengthening the sandbar along which the highway now runs. The main purpose of this construction activity was to create a relatively deep freshwater reservoir on the flat terrain. Salt water was pumped from the estuary into the sea. Fresh water was supplied from the Danube River to the southern part of the estuary via the Danube-Sasyk Canal, 13.5 km long. Thus, the estuary was turned into an artificial lake.

After filling-up with fresh water, the reservoir should have been used for irrigation of agricultural lands at the Danube-Dniester interstream area. Water intake into the main canal of the Danube-Dniester irrigation system was performed in the north of the reservoir (Vyshnevskyi, 2000), whereto the rivers Kohylnyk and Sarata flow (Fig. 1). However, during the last two decades of the past century, a complete desalination of the reservoir did not occur owing to a number of miscalculations in the project. The water quality in the estuary currently remains unsatisfactory: a high mineralization of water is maintained, and the maximum permissible concentrations of chlorides, sulphates, heavy metals, phenols and pesticides
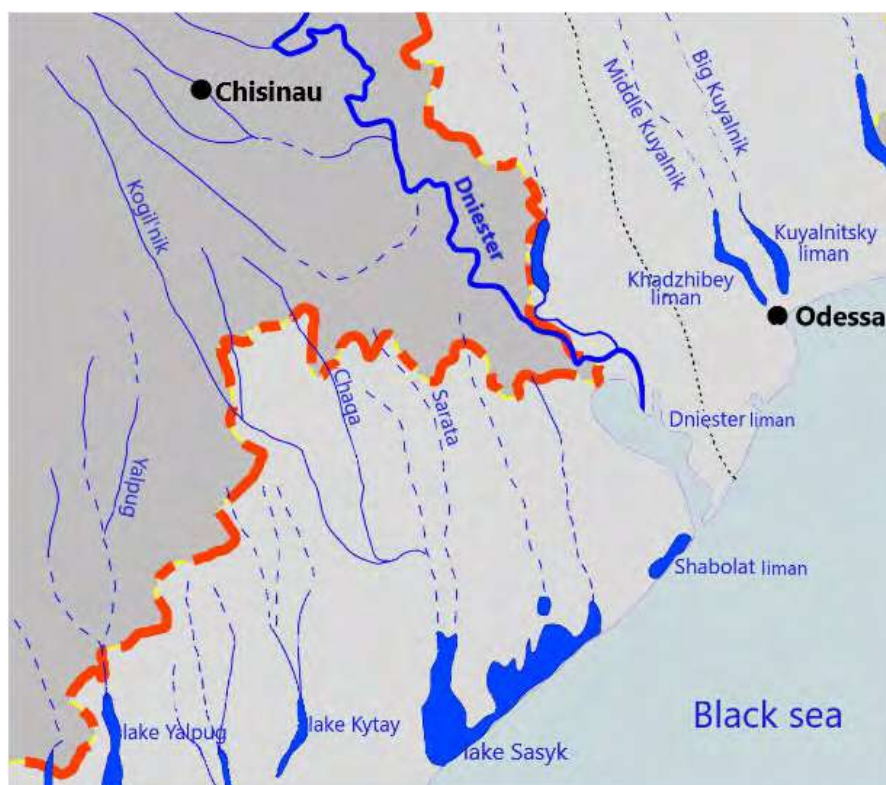
Fig. 1. A schematic map of the geographical location of the Sasyk estuary and its tributaries

in the water are exceeded. The waters of the Sasyk Reservoir are unsuitable both for drinking water supply, municipal and household consumption, and for irrigation. The water body ecosystem is characterized by such environmental problems as siltation, accumulation of contaminated suspended solids that come with the Danube water, accumulation and transformation of toxicants at all levels of the ecosystem, including hydrobionts; water-bloom with blue-green algae and, as a consequence, secondary pollution of the reservoir with organic compounds; accumulation of autochthonic organic matter, which is caused (along with the slow external water exchange) by the large volumes of nutrients coming from the Danube waters. These phenomena negatively affect fish farming, which developed intensively in the first decades of the reservoir's existence. In this regard, the administration of Odessa Oblast, upon the recommendation of research institutions of the National Academy of Sciences of Ukraine, decided to restore the ecosystem of the Sasyk estuary and rehabilitate the adjacent areas (2015). To implement such a solution, a scientific substantiation is needed. In this substantiation, it is important to assess the possible inflow of fresh water into the estuary from the rivers Kohylnyk and Sarata in the future, since the inflow of Danube water into it through the Danube-Sasyk canal will most likely be cut off owing to superfluous maintenance costs on the functioning of

the canal and greater pollution of the Danube water compared to the sea water.

Materials and methods

The data of meteorological observations (average long-term monthly values of precipitation and air temperatures for the period from the beginning of observations to 1989) for 24 meteorological stations located within the North-Western Black Sea Region and southern Moldova, the data of meteorological observations in the period of 1989-2018, and forecast values of meteorological characteristics in the period of 2021-2050, 14 ensemble-averaged climate model simulations according to RCP4.5 and RCP8.5 scenarios under the EURO-CORDEX project (Evans, 2011), were used in the paper. The use of ensemble-averaged data results from the assumption that, in the 'average statistical trajectory' for each of the scenarios, the systematic errors of individual models are compensated under averaging (Loboda and Kozlov, 2020).

The method of the determining the annual runoff parameters in natural conditions and the conditions disturbed by water management activity is based on the 'climate-runoff' model, which uses meteorological data and water use indices as the inputs (Loboda, 2005). The model consists of two parts. The first part simulates the natural (undisturbed by hydroeconomic activity) annual runoff, using

meteorological data as the input data. The theoretical basis of the modelling is the equation of water-heat balance for the catchment area in the modification of V.S. Mezentsev, adapted to the conditions of Ukraine (Kaczmarek, 1993). The results of applying this part of the model to the calculations of water resources in Ukraine according to global warming scenarios were released in international publications in the late 1990s (Snizhko et al., 2012). A similar balance approach, presented in the Turk model (Turk, 1954), is used by the Polish hydrologist Z. Kaczmarek (Kaczmarek, 1993) to make forecasts of the changes in annual runoff under conditions of warming in the EU. Scientists S. Snizhko and I. Kuprikov used this model in Ukraine (Snizhko et al., 2012).

The second part of the 'climate-runoff' model is designed to determine municipal (transformed by hydroeconomic activity) runoff. The equations of hydroeconomic balances of the catchment area, given in a probabilistic form, are the theoretical basis of this part (Loboda and Phan Van Chinnh, 2004).

Calculations for the 'climate-runoff' model consist of the following stages. In the first stage, the zonal (climatic) runoff $\bar{Y}_C$ is defined by the isoline map. In the second stage, the natural $\bar{Y}_N$ or $\overline{W}_N$ (undisturbed by hydroeconomic activity) runoff is calculated. For rivers with a constant subterranean supply, natural and zonal runoff coincide. For small and medium-sized rivers, where there is a significant influence of the underlying surface, the coefficients of transition K_{trns} from zonal (climatic) to natural runoff are developed. These coefficients are identified depending on the average altitude (height) of a catchment area H_{trns}. In the third stage, the anthropogenic impact coefficients are calculated according to the data on the scale of hydroeconomic transformations and the climatic conditions. The calculated equations are realizations of the functions of anthropogenic impact. These functions are a generalization of the results of simulation stochastic modelling (Loboda and Gopchenko, 2006).

The 'climate-runoff' model was calibrated and tested on the data for many watersheds of diverse sizes located in various geographical zones of Ukraine. The advantage of the model is that it uses meteorological data at the input. Thus, the model can be applied both to the areas insufficiently studied in hydrological aspects and for making forecasts by climate change scenarios (Gopchenko and Loboda, 2001). The accuracy of identification of the average long-term values of annual climatic (zonal) runoff by the isoline map comprises ±10%.

The methods built on this model are included in the normative documents of the Republic of Moldova in the section on calculations of the annual runoff characteristics in the absence of observational data (ACDTRM, 2012). The 'climate-runoff' model is used for diagnostic calculations and forecasts of a runoff for the rivers, which supply the closed estuaries at the North-Western Black Sea Region, such as Tylihulskyi, Kuyalnytskyi and Khadzhybeiskyi (Tuchkovenko and Loboda, 2014; Loboda and Gopchenko, 2016; Loboda and Gryb, 2017).

To estimate the inflow of fresh water from rivers to the Sasyk estuary-reservoir, the following analytical functions (Gopchenko et al., 2014), which consider the effect of the main factors of water management transformations at the river catchment areas, were used. A coefficient of the influence of additional evaporation from the water surface of artificial reservoirs on the average long-term annual runoff $K'_{\bar{Y}}$ was calculated by the formula:

$$K'_{\bar{Y}} = e^{-\alpha_{\bar{Y}} f_R}, \qquad (1)$$

where f_R is the relative water surface area of artificial reservoirs, %; $\alpha_{\bar{Y}}$ is a coefficient that depends on the rate of annual natural runoff $\overline{Y}_N$.

To quantify the impact of irrigation from the Danube River, a coefficient of anthropogenic impact $K^n_{\bar{Y}}$ is defined by the following expression:

$$K^n_{\bar{Y}} = 1.0 + \alpha_{\bar{Y}} f_R + b_{\bar{Y}} v_0 + d_{\bar{Y}} \xi - m_{\bar{Y}} \eta, \qquad (2)$$

where f_R is the relative area of irrigated land in shares from the total catchment area; v_0 is a dimensionless parameter of the soil moisture level, average for the whole vegetation period, at which the development of the relevant crop is optimal (for the studied watersheds is equal to 0.9); ξ is a coefficient of return water from irrigated hydroeconomic areas, depending on their location in relation to the river course, which was set as equal to 1; η is an efficiency of the irrigation system, which was set as equal to 0.75; $\alpha_{\bar{Y}}, b_Y, d_Y, m_Y$ are coefficients that depend on the average long-term runoff $\overline{Y}_N$.

For the North-Western Black Sea Region, the accumulation of surface water in a large number of artificial reservoirs, most of which dry up almost every year, is of great importance.

The coefficient $K_{\bar{Y},F}$ characterizes the losses by filling artificial reservoirs with water and is defined as the ratio:

$$\frac{\overline{W}_N - \overline{W}_F}{\overline{W}_N} = \frac{\overline{W}_{MUN}}{\overline{W}_N} = K_{\bar{Y},F}, \qquad (3)$$

where $\overline{W}_N$ is the volume of natural runoff that enters the reservoirs or ponds at the catchment area;

$\overline{W}_F$ is the volume of filling; $K_{\overline{Y},F}$ is a coefficient of losses by filling of artificial reservoirs.

Calculations of the coefficient for the total impact of various anthropogenic factors $K_{\overline{Y},TOT}$ are performed:

when there are two factors indenified by the formula

$$K_{\overline{Y},TOT} = K_{\overline{Y}}' + K_{\overline{Y},F} - 1 \ , \qquad (4)$$

when there are three factors indenified by the formula

$$K_{\overline{Y},TOT} = K_{\overline{Y}}' + K_{\overline{Y},F} + K_{\overline{Y}}'' - 2 \ . \qquad (5)$$

The average long-term value of municipal runoff is identified by the formula

$$\overline{W}_{MUN} = K_{\overline{Y},TOT} \cdot \overline{W}_N \ , \qquad (6)$$

Where $\overline{W}_{MUN}$ is the volume of river runoff transformed by water management activity; $\overline{W}_N$ is the volume of natural runoff.

To define the contribution of freshwater inflow to the formation of the water regime at the Sasyk reservoir, in the case of its renaturalization to the initial status of the estuary, the fresh water balance equation was used. Precipitation on the water level of the reservoir and the inflow of freshwater from the catchment area of the estuary with the runoff of rivers are input components of the balance. Evaporation from the water surface of the estuary is the output component. The discrepancy of water balance is calculated by the equation:

$$\delta W = W_P + W_R - W_E \ , \qquad (7)$$

where δW is a discrepancy (deficit or surplus) of annual fresh water balance, million m³ per a year; W_P is a volume of precipitation that fell on the water surface of the estuary, million m³ per a year; W_R is a volume of water inflow to the estuary with a runoff of the Kohylnyk and Sarata rivers, million m³ per a year; W_E is a volume of water evaporated from the water surface of the estuary per a year, million m³ per a year.

Assessment of the annual layer of evaporation from the water surface of the estuary-reservoir at a first approximation was performed by means of the calculation formula (Ivanov, 1954), based on the data on long-term average monthly values of temperature and relative humidity:

$$E = 0.018(25 + T_a)^2(100 - R) , \qquad (8)$$

where E is an evaporation layer (mm per a month); T_a is a long-term average monthly air temperature (°C); R is a long-term value of the average monthly relative humidity (%).

Research results and discussion

The catchment area of the Kohylnyk River is 3910 km², and this of the Sarata River is 1250 km². The average altitudes of the catchments are 130 m and 100 m, respectively. The coefficients of transition from climatic to natural runoff is equal to 0.55 for the Kohylnyk River and 0.46 for the Sarata River.

Estimates of the freshwater inflow into the Sasyk reservoir under natural conditions of runoff formation were performed for diverse calculation periods. The period before 1989 is the baseline. In accordance with the research by V.V. Grebin, the year of 1989 was recognized as a crucial in the pattern of fluctuations in air temperatures over the flat terrain of Ukraine (Grebin, 2010). The period of 1989-2018 corresponds to the beginning of significant climate change. The period of 2021-2050 is considered for two climate change scenarios RCP4.5 and RCP8.5. Each of the scenarios includes 14 runs under the EVRO-CORDEX project. The ensemble-averaged data from simulations are used in the paper.

The prognosticated changes in the average long-term zonal runoff in the period of 2021-2050 according to the RCP4.5 and RCP8.5 climate scenarios (Fig. 2, Fig. 3) allowed us to conclude that there is a tendency to reduction in the water resources of rivers at the Danube-Dniester interfluve, including the Kohylnyk and Sarata rivers, in the future. If the reduction of water resources at these rivers in natural conditions of runoff formation owing to climate change has been only 8 % in the modern period (Table 1), in the coming decades it will reach 23.5 % (RCP4.5) or 38.5 % (RCP8.5).

Estimates of municipal runoff at various calculation intervals were provided using the anthropogenic impact coefficients calculated by equations (1-5). In the last century, the rivers Kohylnyk and Sarata were the part of the Danube-Dniester irrigation system (Lozovitskyi, 2010). The irrigation of agricultural areas with Danube water taken from the Sasyk Reservoir was the main factor in hydroeconomic activity. The coefficient of return water impact $K_{\overline{Y}}''$ was equal to 1.2 for the river Kohylnyk (the relative area of irrigation by Danube waters f_R was 1.3 % of the total catchment area), and 2.8 for the river Sarata (f_R = 6.2 %). The total coefficient of anthropogenic impact $K_{\overline{Y},TOT}$, including irrigation from local runoff and losses by additional evaporation, was 0.99 and 2.7 for each river, respectively. The significant water inflow from the courses of the Kohylnyk and Sarata rivers, owing to irrigation by the Danube waters, had negative features: these waters were mineralized and did not contribute
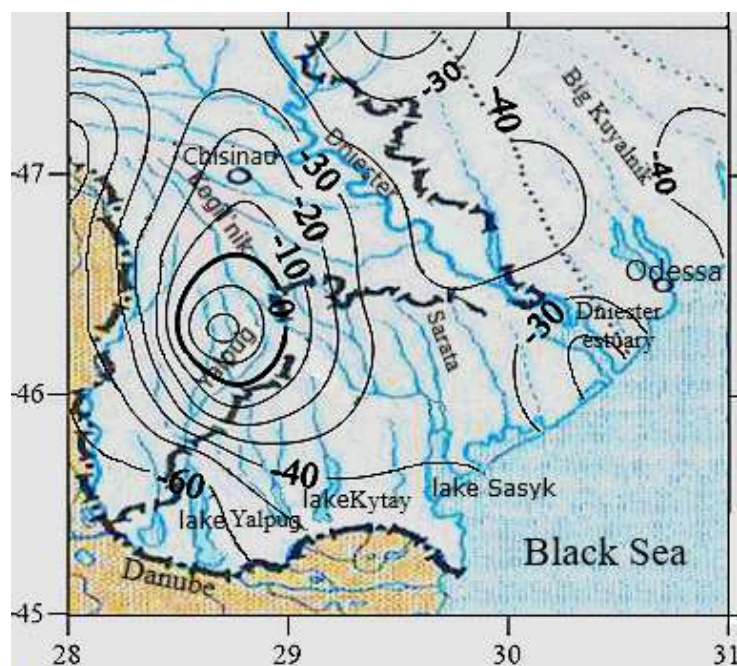
Fig. 2. Changes of the average long-term zonal annual runoff in the space (by the average statistical model of RCP4.5 pathway) for the period of 2021-2050, compared to the basic data before 1989.

Fig. 3. Changes of the average long-term zonal annual runoff in the space (by the average statistical model of RCP8.5 pathway) for the period of 2021-2050, compared to the basic data before 1989.
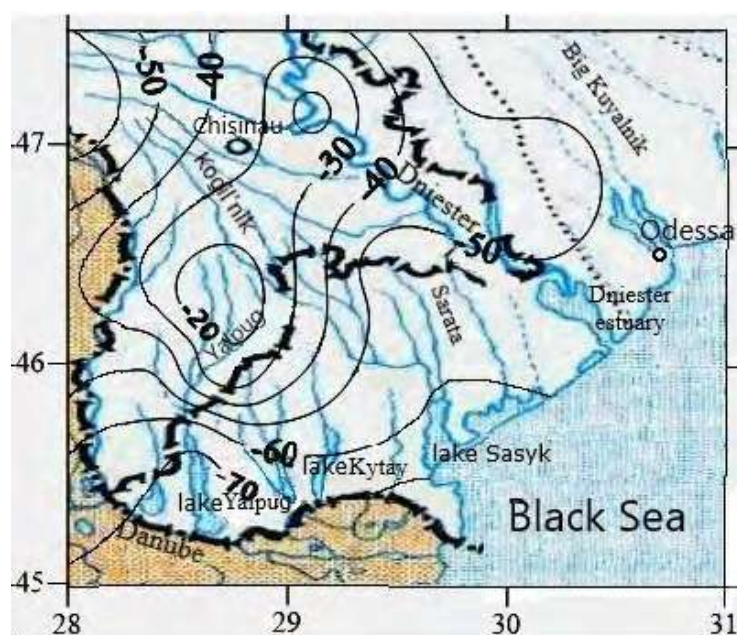
to desalination of the estuary (Bloshl et al., 2019).

In the modern period, there is virtually no irrigation of agricultural areas within the Kohylnyk and Sarata catchment areas with Danube waters. According to the Basin Administration for Water Resources of Rivers at the North-Western Black Sea Region and the Lower Danube, the water surface area at the Kohylnyk River catchment area makes up 0.866 thousand ha, the volume of artificial reservoirs is 11.43 million m³, and the relative water surface area is 0.22 %. At the catchment area of the Sarata River, the total

volume of artificial reservoirs equals to 3.89 million m³, and the relative water surface area is 0.33 %.

The results of identification of the volume of municipal runoff for RCP4.5 and RCP8.5 pathways are given in tables 2 and 3. Analysis of the dynamics of changes in river water inflow in the context of hydroeconomic transformations (Table 4, Fig. 4) showed that the presence of artificial reservoirs within catchment areas intensifies the reduction in water resources at the studied rivers and their capacity to provide the fresh water inflow into the reservoir.

Table 1. Estimates of the average long-term volumes of natural annual runoff, identified by the climate-runoff model, for various calculation periods

River	$\overline{W}_N$, million m³			
	Before 1989, a baseline period	1989-2018	2021-2050 RCP4.5	2021-2050 RCP8.5
Kohylnyk	58.2	53.6	45.1	36.6
Sarata	9.78	8.40	6.90	5.18
Total inflow	68.0	62.0	52.0	41.8
Changes in freshwater inflow, %	-	-8.82	-23.5	-38.5

Table 2. Assessment of the average long-term value of freshwater inflow in the period of 2021-2050 according to the scenario RCP4.5 in the runoff formation conditions disturbed by hydroeconomic activities

River	$\overline{W}_N$, million m³	Volume of artificial reservoirs, million m³	f_R, %	Coefficients of anthropogenic impact $K_{\overline{Y}}$ under various factors of hydroeconomic activity			$\overline{W}_{MUN}$, million m³
				$K_{\overline{Y},F}$	$K'_{\overline{Y}}$	$K_{\overline{Y},TOT}$	
Kohylnyk	43.9	11.4	0.22	0.74	0.95	0.69	30.3
Sarata	6.9	3.89	0.33	0.44	0.90	0.34	2.35
The total inflow							32.6

According to UN recommendations, a more than 50 % reduction in the average long-term annual runoff leads to the destruction of water resources, and a more than 75 % reduction – to their irreversible destruction. Under the development of climatic events by the RCP8.5 scenario while maintaining the current level of anthropogenic pressure, it is possible to lose the rivers Kohylnyk and Sarata as sources of freshwater supply to the Sasyk estuary-reservoir.

In case of the renaturalization of the Sasyk estuary-reservoir and the restoration of its natural status as the estuary, the inflow of Danube water into the water body through the Danube-Sasyk canal will most likely be stopped, since this entails extra costs to ensure operation of the canal and the related hydraulic structures. Therefore, the annual freshwater balance of the estuary will be defined by the equation (7), i.e. without regard to the inflow of Danube waters. According to the results of calculations of its components (Table 5), in the first half of the 21st century there had already been an increase in the water balance deficit from – 9.7 million m³ per a year in the period until 1989 to – 35.2 million m³ per a year in the period of 2000-2018, and its further increase to 62.5 million m³ per year in the period of 2021-2050 is expected under the RCP4.5 scenario and to 74.2 million m³ per year under the RCP8.5 scenario.

It is important to notice that the results obtained are in good agreement with the research of other authors. The paper (Bloshl et al., 2019) shows that according to the data of 1960-2010 a decrease in water runoff comprising 5 % per decade is typical for the studied area. This is accounted for by the increased air temperatures in winter and their transition from negative to positive values. The forecasts of climate change in Ukraine according to 8 global models of the RCP8.5 scenario for the periods of 2041-2070 and 2071-2100 illustrate the continuation of the decreasing trends until the end of the 21st century. In the Danube-Dniester interfluve, the average long-term precipitation will fluctuate during the century within ±10 %. The average annual air temperature will rise up to 4 Celsius degrees in 2041-2070 and up to 5 Celsius degrees in 2071-2100 (Didovets et al., 2020). As a result of rising air temperature and subsequent rise in evaporation and reduction of fresh water inflow from the catchment area, in the Sasyk estuary-reservoir there will be an increase in the deficit of annual freshwater balance, which, according to the estimates given in the Table 5, will comprise 62 % in the period of 2021-2050 under the RCP4.5 scenario and 75 % under the RCP8.5 scenario, compared to the baseline period before 1989. If this deficit is not compensated, there is a long-term trend for reduction in the volume of estuaries, their shallowing and, as a consequence, there is an increase in salinity and deterioration of water quality (the increased concentrations of nutrients and pollutants, the deteriorated oxygen regime, etc.) for traditional types of nature management (Tuchkovenko and Loboda, 2017).

Table 3. Assessment of the average long-term value of freshwater inflow in the period of 2021-2050 according to the scenario RCP8.5 in the runoff formation conditions disturbed by hydroeconomic activities

River	$\overline{W}_N$, million m³	Volume of artificial reservoirs, million m³	f_R, %	Coefficients of anthropogenic impact $K_{\overline{Y}}$ under various factors of hydroeconomic activity			$\overline{W}_{MUN}$, million m³
				$K_{\overline{Y},F}$	$K'_{\overline{Y}}$	$K_{\overline{Y},TOT}$	
Kohylnyk	36.6	11.4	0.22	0.69	0.945	0,64	23,4
Sarata	5.18	3.89	0.33	0.24	0.88	0,12	0,622
The total inflow							24.0

Table 4. Estimates of the average long-term volumes of municipal annual runoff, identified according to the climate-runoff model, for various calculation periods

River	$\overline{W}_N$, million m³				
	Before 1989 with regard to donor irrigation	Until 1989 without regard to donor irrigation	1989-2018	2021-2050 RCP4.5	2021-2050 RCP8.5
Kohylnyk	57.6	44.2	39.7	30.3	23.4
Sarata	26.4	4.99	3.78	2.35	0.622
Total inflow	84.0	49.2	43.5	32.6	24.0

There are two ways to stabilize the hydrological and hydroecological regimes of 'closed' estuaries, to which the Sasyk belongs, in the context of climate change: (1) – restoration of the natural runoff of rivers that supply the estuary with fresh water; (2) – provision of water exchange of the estuary with the sea through artificial connecting canals ('sea-estuary' canals) with a delivery capacity that will ensure the necessary flushing of the estuary with seawater (Tuchkovenko and Loboda, 2017). Comparison of data on the volume of natural (Table 1) and municipal (Table 4) runoff of the Kohylnyk and Sarata rivers, expected in the period of 2021-2050, with the values of the deficit of fresh water balance of the estuary (Table 5) shows that the first way is not capable to solve the problem for the Sasyk estuary. When implementing the second way, it should be taken into consideration that the climate change, which occurred and is expected in
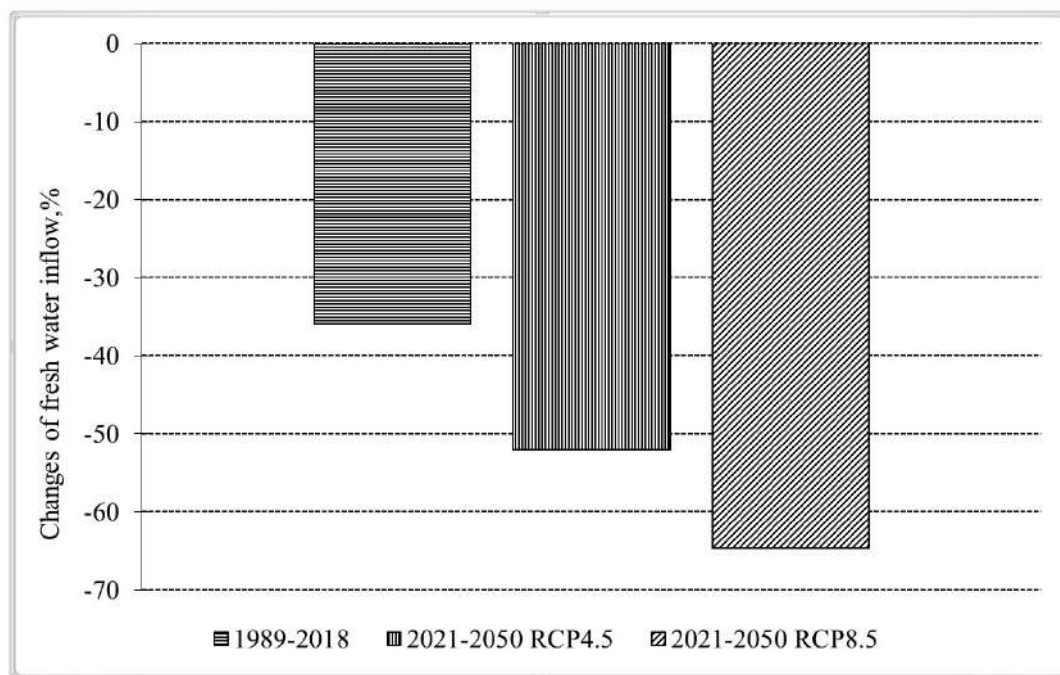

Fig. 4. Changes in the average long-term inflow of fresh water from the Kohylnyk and Sarata rivers into the Sasyk estuary-reservoir under various climatic conditions compared to the baseline period (before 1989)

Table 5. Estimates of the components of the annual freshwater balance of the Sasyk estuary and its deficit for various calculation periods

Item №	Calculation period	W_P, million m³ per a year	W_R, million m³ per a year	W_E, million m³ per a year	δW, million m³ per a year
1	Before 1989	99.3	49.2	158.2	-9.7
2	2000-2018	100.5	34.0	169.7	-35.2
3	2021-2050 RCP4.5 pathway	88.2	32.6	183.3	-62.5
4	2021-2050 RCP8.5 pathway	84.9	24.0	183.1	-74.2

the 21st century, in particular a significant increase in the freshwater balance deficit of the water body, leads to a completely different hydrological situation than that observed before the transformation of the Sasyk estuary into a freshwater reservoir in the seventies of the 20th century. The issue of ensuring the delivery capacity of the 'sea-estuary' artificial canal (canals), which will provide not only compensation for the deficit of freshwater balance of the estuary by seawater, but also the required speed of its flushing, takes on particular relevance. Methodical approaches to finding solution for this problem are considered in (Kushnir and Tuchkovenko, 2020).

Conclusions

1. According to the 'climate-runoff' model developed by OSENU (Odessa State Environmental University), the estimates of freshwater inflow from the Kohylnyk and Sarata rivers to the Sasyk estuary are provided. The current and potential inflows are defined for various climatic conditions and for various factors of hydroeconiomic activity (irrigation due to local runoff, irrigation due to the donor river, losses by additional evaporation from the water surface of artificial water bodies, losses by filling of artificial reservoirs). The meteorological data (average monthly precipitation and air temperatures according to both observational data and climate change scenarios) and information on the scale of water management transformations at the catchment areas are the input to the model. Based on the application of the 'climate-runoff' model, the average long-term parameters of natural and municipal runoff of the Kohylnyk and Sarata rivers are identified for diverse calculation periods, which correspond to certain climatic conditions and predominant factors of hydroeconiomic activity.

2. It is found that in the period of 2021-2050,

owing to the expected changes in the regional climate, the total inflow of freshwater from rivers to the estuary-reservoir will decrease by 23.5 % (according to the scenario RCP4.5) and by 38.5 % (according to the RCP8.5 pathway) compared to the baseline period (before 1989). By virtue of the total impact of artificial reservoirs and regional climate change, the total inflow of freshwater from rivers to the reservoir will decrease by 52.1 % (according to RCP4.5) and by 64.7 % (according to RCP8.5) compared to the baseline period of natural runoff (before 1989).

3. It is defined that in case of renaturalization of the Sasyk Lake into the estuary and the water inflow cut-off from the Danube River, the changes in climatic conditions expected in the first half of the 21st century, combined with water management activity, will result in the increased deficit of annual freshwater balance of the Sasyk reservoir up to 62 % under the RCP4.5 scenario and up to 75 % under the RCP8.5 scenario compared to the period before the emergence of climate change (before 1989). This change must be considered in scientific substantiation of the project on a reversion of the Sasyk Reservoir to the original status of the estuary to ensure such conditions of water exchange with the sea (with the aim of compensation of the water balance deficit), which will prevent the long-term trend of salinization of its waters.

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