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Climate change impact on the freshwater balance of quasi-closed lagoons in the North-Western Black Sea coast

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ABSTRACT

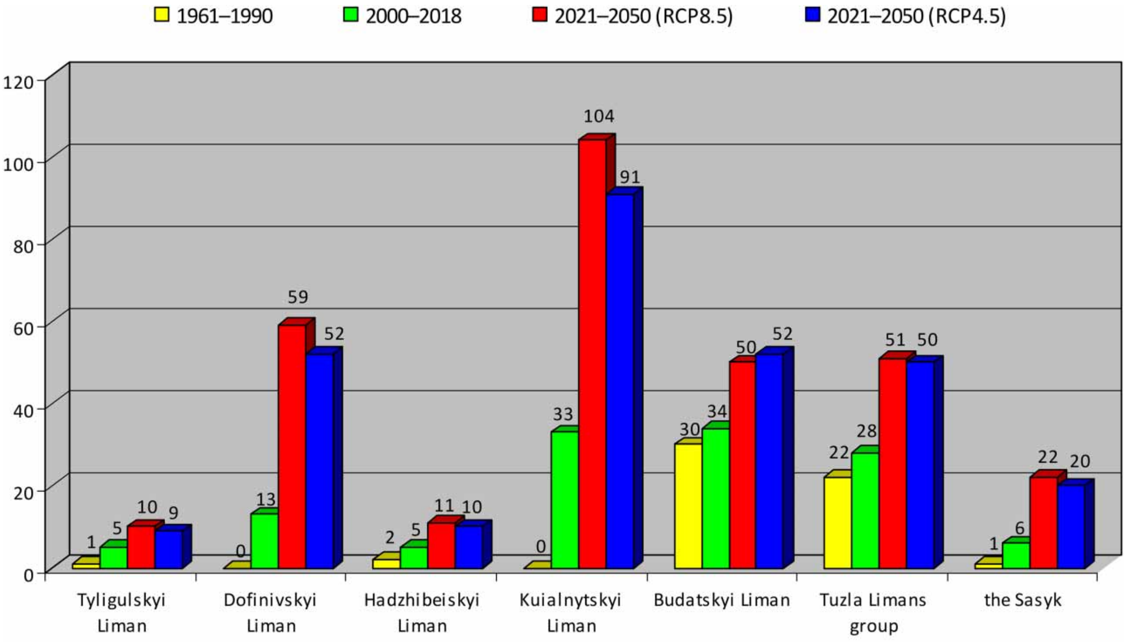
We studied the impact of regional climate changes that have occurred and are expected in the near future on the freshwater balance of quasi-closed lagoons in the North-Western Black Sea region. These lagoons do not have a permanent connection with the sea but are episodically connected to it by artificial channels, straits, or other hydraulic facilities. We used the value of the deficit in their annual freshwater balance as an indicator of vulnerability to climate change for each lagoon. The changes in the multi-year averages of climatic parameters in the North-Western Black Sea region, which determine the components of the water balance and its annual deficit in lagoons, were assessed by observations at hydrometeorological sites and outcomes of the EURO-CORDEX Project for the RCP4.5 and RCP8.5 scenarios. We have found that regional climate changes are resulting in the increasing deficit of annual freshwater balance for all quasi-closed lagoons in the North-Western Black Sea region. Also, climate change can result in excessive shallowing, salinization, and even the complete disappearance of some lagoons due to the lack of or insufficient water exchange with the sea.

Key words: climate change, freshwater balance, quasi-closed lagoons, North-Western Black Sea coast, water shortage

HIGHLIGHTS

- The annual mean temperature is significantly changing in the 21st century.
- Annual mean evaporation from lagoons in 2021–2050 compared to 1961–1990 will increase by 29–56%.
- Kuialnytskyi Liman will be most vulnerable to regional climate changes and can dry up completely.
- The hydro-ecological regime of quasi-closed lagoons will worsen due to water shortage.

GRAPHICAL ABSTRACT



Percentage shortage of the annual fresh water balance as related to the annual mean water volume in the quasi-closed lagoons on the North-Western Black Sea coast

1. INTRODUCTION

There are 17 main lagoons located along the coast at the North-Western part of the Black Sea between the mouths of the Danube and Dnieper rivers (Figure 1). They can be divided into two groups: open ones, with a free exchange of water with the open sea, and so-called 'quasi-closed' ones. The second group consists of the lagoons essentially isolated from the sea and intermittently connected to the sea by artificial channels, straits, or other hydraulic facilities. This group contains 'closed' and 'episodically closed' ('semi-closed' and 'episodically connected to the sea') types of lagoons by the classification adopted in Ukraine (Rozengurt 1974; Zaitsev *et al.* 2006; Tuchkovenko & Gopchenko 2011).

The group of quasi-closed lagoons includes the Sasyk (transformed into a reservoir but currently planned for renaturalization), Tuzla Limans group (Shagany, Alibei, Burnas), Budatskyi (or Shabolatskyi) Liman, Hadzhibeiskyi Liman, Kuialnytskyi Liman, Dofinivskyi (or Velykyi Adzhalytskyi) Liman, and Tyligulskyi Liman. Currently, these lagoons do not have a permanent connection with the Black Sea and are separated from the sea by sand and shell isthmuses from a few hundred meters to 4 km in width. In the past, natural breaks in the isthmuses could periodically occur. However, such events have almost not been observed during the last years due to an anthropogenic transformation at the isthmuses. More details about the lagoons from this group are provided in the next section.

In recent decades, starting from the late 1980s, significant changes in climate and water resources in Ukraine have been observed (Grebin 2010). In the North-Western Black Sea coast, these changes are revealed by increasing climate aridity and, correspondingly, decreasing freshwater inflow to the coastal lagoons from their catchment basins (Tuchkovenko & Loboda 2014; Loboda & Bozhok 2015).

Climate change significantly affects coastal lagoons (Newton *et al.* 2018). Ecosystems of quasi-closed lagoons and other coastal areas (e.g., Kamil *et al.* 2021) are exceptionally sensitive and vulnerable to climate change. Due to the increase in air temperature resulting in the increasing evaporation and decrease in the freshwater inflow from the catchment, a significant shortage of the annual freshwater balance is registered in such kinds of lagoons. If this deficit will not be compensated, there is a long-term tendency to the decreasing water volume in the lagoons, their shallowing and, as a result, increasing

Figure 1 | Lagoons in the North-Western Black Sea region: 1 – the Sasyk, 2 – Dzhantsheiskyi Liman, 3 – the Malyi Sasyk, 4 – the Shagany, 5 – the Alibei, 6 – the Burnas, 7 – Budatskyi Liman, 8 – Dnistrovskyi Liman, 9 – Sukhyi Liman, 10 – Hadzhibeiskyi Liman, 11 – Kuialnytskyi Liman, 12 – Dofinivskyi Liman, 13 – Grygorivskyi Liman, 14 – Tyligulskyi Liman, 15 – the Tuzly, 16 – Berezanskyi Liman, 17 – Dniprovsko-Buzkyi Liman. White squares indicate the location of meteorological and hydrometeorological stations.

salinity and deterioration of water quality – increasing concentration of biogenic and polluting substances, deterioration of the oxygen regime, etc. – for traditional types of nature use (Tuchkovenko & Tuchkovenko 2018).

In recent decades, many researchers have paid great attention to studying the impact of climate change on the hydrology and ecology of coastal lagoons due to their robust sensitivity and vulnerability to these changes (e.g., Lloret *et al.* 2008; Lopes *et al.* 2019; Stefanova *et al.* 2020; Rodrigues *et al.* 2021; da Costa *et al.* 2022). Since the interactions between local anthropogenic influences and regional climate changes are very complex, it is necessary to estimate the joint anthropogenic and climate change impact on the hydro-ecological parameters of lagoonal water. The problems of lagoon management in conditions of climate change and anthropogenic impact have been considered by La Jeunesse *et al.* (2015); Stefanova *et al.* (2020), Dias *et al.* (2021); Lonsdale *et al.* (2022), and many others.

The current study hypotheses that the regional climate change during the recent decades has been resulting in the strengthening shortage of the annual freshwater balance for the quasi-closed lagoons in the North-Western Black Sea region. The magnitude of this shortage expressed as a percentage of the average annual water volume can be considered an indicator of vulnerability to climate change for each lagoon studied.

The aim of this paper is to assess quantitatively the impact of regional climate changes that have occurred and are expected in the near future on the freshwater balance of quasi-closed lagoons in the North-Western Black Sea region.

2. HYDROGRAPHIC DESCRIPTION OF QUASI-CLOSED LAGOONS IN THE NORTH-WESTERN BLACK SEA COAST

The Tyligulskyi Liman lagoon is a flooded valley of the Tyligul River and extends quasi-meridionally from north-northwest to south-southeast. Its length approximates 52 km, and its width varies from 0.2 to 5.4 km. Tyligulskyi Liman is separated from the sea by a natural sandy isthmus, which is 3.3–4 km wide and up to 6.6 km long. The southern and central parts of the lagoon divided by shallow water are basins of 10–16 m depth. The maximum depth in the southern part reaches 22.2 m. The Tyligul River flows into the northern part of the lagoon; this part is shallow with depths of less than 4 m.

In the late 1950s, the isthmus was breached by an artificial channel connecting the lagoon with the sea. The aims were (i) to provide entrance from the sea to the lagoon during the spring for Black Sea mullet and other species of salt-water fish as well as freshwater fish that are carried to the sea from the Dnieper-Bug estuary during the spring flood, and (ii) to control the water balance of the lagoon to stabilize its water level.

Over the past years, the southern, adjacent to the sea, part of the channel has become very shallow due to the transportation of sand from the sea. In 2012–2015, the depth here was only a few tens of centimeters. In the 21st century, the channel operated irregularly, for 25–40 days in the spring and autumn, when a few hundred of meters closest to the sea were cleared of sand sediments. In 2016, the reconstruction of the connecting channel was started but had not yet been fully completed.

The catchment area of Tyligulskyi Liman is 5,420 km^2. The following rivers flow into the lagoon: Tiligul (catchment area 3,550 km^2, length 173 km), Balaichuk (catchment area 586 km^2, length 52 km), Tsarega (catchment area 657 km^2, length 46 km), and Khutorska (catchment area 108 km^2, length 19 km). The surface lateral inflow of freshwater through temporary watercourses (gullies, ravines, etc.) into the lagoon is generated on an area of 349 km^2. The Tyligul River feeds most of the runoff – more than 85% – into Tyligulskyi Liman (Tuchkovenko & Loboda 2014).

The Kuialnytskyi Liman lagoon is located 2 km northwest of the Gulf of Odesa coast and is one of the oldest closed estuaries of the North-Western Black Sea coast. The lagoon is an extension of the Velykyi Kuialnyk River valley. The catchment area of Kuialnytskyi Liman is 2,250 km^2. Historically, the freshwater feeding in the lagoon was mainly from the Velikiy Kuyalnik River with a catchment area of 1,860 km^2 (82.7% of the lagoon catchment area) and a length of 150 km (Loboda & Gopchenko 2016). Also, freshwater can flow into the lagoon through the watercourses on its eastern shore (small rivers Dovboka, Kubanka, gullies Hildendorfska, Korsuntsivska).

Due to economic transformations in the lagoon catchment area and climate changes, its length decreased from 26 to 15.3 km, the water area from 52.0 to 26.7 km^2, the water volume from 68 to 11 10^6 m^3, and brine salinity increased from 108 to 300 ‰ in the period 2003–2014 (Loboda & Gopchenko 2016). To prevent Kuialnytskyi Liman from completely drying up, it filled with seawater from the Gulf of Odesa using a specially laid gravity pipeline starting at the end of 2014. The lagoon fills every year from December to April when the sea water temperature is less than 8 °C.

The average annual water level in the lagoon in 2014 was −6.62 m in BHS[1]. It rose to −6.17 m in 2018, and then, due to the extremely dry 2019–2020, it decreased to −6.49 m in 2020. According to water level fluctuations in the lagoon, its water volume changed from 29.7 10^6 m^3 in 2018 to 16.85 10^6 m^3 in 2020, and the water area from 45.52 to 34.18 km^2, respectively.

The maximum depth in the lagoon, determined during field research in the summer of 2009, was 1.8 m at the −6.42 m water level (Loboda & Gopchenko 2016).

The Hadzhibeiskyi Liman lagoon is a closed water body created due to the flooding of the mouth of the Malyi Kuialnyk River valley by seawater. Later, the lagoon was separated from the sea by a sandy isthmus, the width and length of which today are 4.5 and 5.0 km, respectively. The length of the lagoon is 40 km, the width is 0.5–3.5 km, and the catchment area is 2,700 km^2. The rivers Malyi Kuialnyk (catchment area 1,540 km^2, length 118 km) and Svynna (catchment area 772 km^2, length 54.1 km) flow into the estuary (Tuchkovenko & Kozlov 2017).

Regular monitoring of river runoff is lacking but it is known (Tuchkovenko & Kozlov 2017) that they are significantly regulated. At the end of the 1990s, the total number of ponds and reservoirs at the Malyi Kuialnyk River was 21 with a total volume of 7.72 10^6 m^3, and at the Svynna River it was 9 with a total volume of 7.02 10^6 m^3. Now, the water flow of the Svynna River is mostly retained by ponds at its mouth.

[1] Baltic Height System.

The anthropogenic factors are the inflow of return partially purified sewage water of Odesa city from the biological treatment station 'Pivnichna' (56.4 10^6 m^3 per year) and drainage water from sewage farm from pumping stations and sewage treatment facilities (20.2 10^6 m^3 per year). These factors define significantly the water level variability in the lagoon.

At the end of the 1960s, a hydraulic unit discharging water from the lagoon into the sea was put into operation. The unit has a main lock and a pumping station (capacity of 7.0 m/s) with a pressure pipeline and a water outlet to the sea. However, in recent years it has not functioned and, appropriately, restoring the possibility of emergency gravity discharge of water from the lagoon into the sea in case of an increase in the water level in the estuary to critical values through reconstructed channels is an urgent issue.

The Dofinivskyi Liman lagoon was created by the marine transgression into the valley of the Velykyi Adzhalyk River. In the past, the river length came up to 25–30 km, but currently, it has completely dried. The catchment area of Dofinivskyi Liman only is 50 km^2, and includes the basin of the Velykyi Adzhalyk River and Chorna Balka, which is about 110 km^2. Freshwater inflows into the lagoon (200–300 m^3/day) from the ponds located on the territory of the Oleksandrivka village and also flows over a dam separating the lagoon from the Oleksandrivka pond when it overflows (Tuchkovenko *et al.* 2008). Sokolov (2012) estimates the annual volume of surface runoff in the lagoon of 50% probability at 1.8 10^6 m^3. Tuchkovenko *et al.* (2008) estimate the same value at 3.03 10^6 m^3 but in a low-water year of 95% probability at 1.36 10^6 m^3.

Since 1998, the occasional connection of the lagoon with the sea is maintained artificially through a 250 m long pipeline with a pipe diameter of 920 mm, which goes into the sea at a depth of 3 m and in this part is 200 m long.

The Budatskyi (or Shabolatskyi)Liman lagoon is separated from the sea by a narrow isthmus 80–200 m wide, has a length of 17 km, an average width of 1.5 km, and a maximum width of 2.5 km. The average depth of the lagoon is 1.05 m, and the maximum is 2.25 m. Taking into account the reed bed in the eastern part of the lagoon, the water area is 31.5 km^2, and the water volume is 30.0 10^6 m^3 (Zaitsev *et al.* 2006; Shuiskyi & Vykhovanets 2011). The catchment area of the lagoon is 156 km^2.

Currently, Budatskyi Liman has connected to Dniestrovskyi Liman by two channels, which are open throughout the year. In spring and autumn, the lagoon is connected to the sea through a channel in the southwestern part of the isthmus near the village of Prymorske (Budaky). Sea water enters the estuary in spring and autumn through this channel and from the Dniestrovskyi Liman through the Bugaz channel during strong surge-driving winds. Small volumes of freshwater runoff can enter the estuary through gullies Akkembetska and near Prymorske (Burhaz 2018).

The Tuzla Limans group was created by the flooding of lowlands by the sea and subsequent separation from the sea by a sandy bar. There are three main ('primary') lagoons in the Tuzla Limans group – Shagany, Burnas, Alibei – and a few 'secondary' lagoons (Popova 2016). The Shagany, Burnas, and Alibei lagoons are connected by wide straits and separated from the sea by a single isthmus, so they are considered as a single lagoonal complex. The length of the isthmus separating the lagoons from the sea is 29 km and the width is from 60 to 400 m.

The state and use of the natural resources in the lagoons are conditioned by the presence of natural breakthroughs created in the isthmus by storms and artificial channels. From two to five channels constantly existed in the isthmus from 1953 to 1990, which ensured a steady and favorable fishing activities hydrological and hydrochemical regime.

From 2010 to 2015, the lagoonal complex was connected to the sea by a wide and deep breakthrough resulting from the erosion of the initially small, artificially created channel on the 24 km of the isthmus (Shagany Liman), and it was artificially closed in 2015. Since then, the connection of the lagoons with the sea has been maintained through an artificial fishing-and-launch channel created on the 2 km of the isthmus (Burnas Liman) with a design width of 15 m and a bottom mark of -1 m in BHS. This channel is in operation for several months in spring and autumn.

The catchment area of the Tuzla Limans group is 2,231 km^2. The main watercourses periodically feeding the lagoons with freshwater are Khadzhyder River (flowing into Alibei Liman) with a catchment area of 894 km^2 and Alkaliia River (flowing into Solone Lake and Burnas Liman) with a catchment area of 443 km^2.

The Sasyk reservoir had in the past natural water exchange with the adjacent part of the Black Sea (Zhebriyanska Bay) by breakthroughs periodically created in the sandy isthmus separating it from the sea. In 1978, under the construction of the first phase of the Danube-Dnieper irrigation system, the Sasyk Liman lagoon was separated from the sea by widening a 15-km isthmus and strengthening it with concrete elements, and the lagoon was connected to the Danube River by a lock canal.

However, the main goals of the project – to improve the potable and industrial water supplies and to bring the quality of water used for irrigation to the regulatory level – were not reached. The main reason was the unsatisfactory quality of the waters in the Sasyk reservoir. In general, the current state of its ecosystem can be defined as stressed and unstable, i.e., it has limited possibilities for self-regulation and is dependent mainly on external factors.

The runoff of 2 rivers – Kogylnyk and Sarata – flows into the northern part of the reservoir. Sarata has a length of 120 km and a catchment area of 1,250 km^2. Its riverbed is partially cleaned and straightened; locks regulate the water flow. The water from the river is used for industrial and agricultural water supply and irrigation. Kogylnyk is 243 km long and has a catchment area of 3,910 km^2 (Ivanova 2018; Loboda *et al.* 2021).

3. METHODS

The natural freshwater balance of the lagoon can be determined by the ratio of its main source and sink components. The first ones include atmospheric precipitation on the surface of the water body and water inflow from the catchment basin of the lagoon by rivers and other watercourses. The second one is the evaporation from the water surface of the lagoon. The groundwater inflow into the lagoons cannot be taken into account, since according to Timchenko (1990) even before the pronounced climate change it was less than 10% of other above-mentioned sources, which is the result of arid climate conditions in the North-Western Black Sea coast (Hylke *et al.* 2018). Therefore, the equation of the annual freshwater balance for a lagoon purely isolated from the sea can be written as follows:

$$\delta W = W_P + W_R - W_E \tag{1}$$

where δW is the residual – shortage or surplus – of the annual freshwater balance, W_P is the amount of atmospheric precipitation falling onto the water surface of the lagoon, W_R is the water volume inflowing into the lagoon from the catchment basin by watercourses, W_E is the amount of water evaporated from the surface of the lagoon. The water level in the lagoon is increasing in the case of positive δW and vice versa.

Regulation of the water level in the lagoon on a multi-year timescale is possible by establishing a natural (through breaks in their isthmuses) or artificial (through connecting channels or other water-conveying hydraulic facilities) water exchange with the sea. For this case, the water balance equation of the lagoon connected to the sea takes the following form:

$$W_P + W_R - W_E + \delta W_{\mathrm{SEA}} = 0 \tag{2}$$

where δW_{SEA} is the difference between water volumes outflowing from or inflowing into the lagoon during a year through natural and/or artificial waterways.

The amount W_E is mostly defined by potential evapotranspiration (PET). The technique of Ivanov (1954) is used to estimate PET by empirical relation:

$$\mathrm{PET} = 0.0018(25 + T)^2(100 - R) \tag{3}$$

where PET is in millimeters per month, T is the mean monthly temperature in °C, R is the mean monthly relative humidity in percent. Then, W_E can be easily determined, knowing the morphometric characteristics of the lagoon.

As indicators of vulnerability to climate change for each lagoon, the ratios expressed in percentages are used:

- between the residual of the annual freshwater balance and the total mean annual water volume W

$$I_{PRE} = \frac{W_P + W_R - W_E}{W} \cdot 100\% \tag{4}$$

- between the difference of annual precipitation and evaporation from the water surface (with constant water area) and the total mean annual water volume W

$$I_{PE} = \frac{W_P - W_E}{W} \cdot 100\% \tag{5}$$

The higher the value of the above indices means the greater the sensitivity of the lagoon to climate changes.

The water balance components for the modern period of 2000–2018 are estimated by the available data of monthly mean air temperature, air relative humidity and precipitation at meteorological (Sarata, Odesa, Serbka, Ochakiv) and coastal hydrometeorological stations (Pivdennyi, Bilgorod-Dnistrovskyi) located at the Ukrainian coast of the north-western part of the Black Sea.

To determine the past climate-induced changes, the water balance components are compared to the estimated by reference period 1961–1990. As it has been noted that significant changes in the climate and water resources in Ukraine began at the end of the 1980s, the meteorological and hydrological parameters from 1961 to 1990 are really the reference ones to recognize change climatic effects.

The near-future climatic conditions are determined for the period 2021–2050 by the outcomes of the EURO-CORDEX Project (Jacob *et al.* 2014) for two scenarios – RCP4.5 and RCP8.5 (Moss *et al.* 2010). Single simulation – regional model CLMcom-CCLM4-8-17 combined with global model MPI-ESM-LR – was selected from the ensemble of 14 runs by different regional climate models using the procedure described by Khokhlov *et al.* (2021); outcomes from this simulation correspond in the best way to the ensemble mean values. The monthly mean values of meteorological parameters by this simulation in grid points closest to the lagoons are then used to determine the future climate-induced changes in the water balance components.

Observational data on the runoff of rivers and other watercourses feeding the lagoons in the North-Western Black Sea coast are lacking or insufficient for a reliable quantitative assessment of their changes due to the combined influence of natural and anthropogenic factors. The 'climate-runoff' model (Gopchenko & Loboda 2005; Loboda *et al.* 2005) is therefore used to determine the inflow of freshwater to the lagoons under different climatic conditions. This model allows for obtaining estimates for the parameters of natural and domestic (transformed by water management) river runoff by meteorological information and the economic activity at a river. The model consists of a few successive computational blocks: climate – climatic (zonal) runoff – underlying surface – natural runoff – water management activity – domestic runoff. The river runoffs in the periods 1961–1990 and 2000–2018 were preliminarily calculated by the observations at meteorological stations of the Dniester-Southern Bug and Danube-Dniester interfluves; for the near-future period 2021–2050, the outcomes of the EURO-CORDEX Project were used as described in the previous paragraph (Loboda *et al.* 2019).

Table 1 shows morphometric characteristics of the quasi-closed lagoons on the North-Western Black Sea coast. The water areas of the lagoons were updated to the conditions of 2020 using satellite images of Google Earth tools. The water volumes were estimated using the information about their average depth available in the references. It was also supposed that there are no intra-annual changes in the water volume and the water area of lagoons.

4. RESULTS

Table 2 contains the climatic parameters for the modern period and the near future compared to the reference period.

This table shows that the stations along the western coast of the north-western part of the Black Sea (Odesa, Bilgorod-Dnistrovskyi, Sarata) are featuring by slightly increasing annual precipitation in the modern period compared to the reference one

Table 1 | Morphometric characteristics of quasi-closed lagoons on the North-Western Black Sea coast used to calculate the components of their freshwater balance

Lagoon	Water volume, 10^6 m^3	Water area, km^2	Mean depth, m	Water height, m in BHS	Reference
Tyligulskyi Liman	693.0	128.9	5.40	−0.4	Tuchkovenko & Loboda (2014)
Dofinivskyi Liman	4.5	6.1	0.74	−0.1	Zaitsev *et al.* (2006); Sokolov (2012)
Hadzhibeiskyi Liman	729.0	114.0	6.40	1.4	Tuchkovenko & Kozlov (2017)
Kuialnytskyi Liman	28.3	45.0	0.63	−6.2	[a]
Budatskyi Liman	31.5	30.0	1.05	−0.4	Zaitsev *et al.* (2006)
Tuzla Limans group	236.0	196.7	1.20	−0.3	Rozengurt (1974); Popova (2016)
The Sasyk	414.3	197.3	2.10	0	[b]

[a]Unpublished study at the Odessa State Environmental University (2016).
[b]Unpublished study at the Ukrainian Scientific Center of Ecology of the Sea (2008).

and their expected decrease in the near future. On the contrary, some increase in annual precipitation is expected in 2021–2050 on the northern coast (Serbka and Pivdennyi) compared to the modern period.

A gradual increase in air temperature can be noted during the 21st century compared to the reference period – the annual mean temperature in 2000–2018 is 1.1–1.5 °C (10–14%) higher and expected in 2021–2050 will be 2.3–3.6 °C (23–36%) higher than in 1961–1990. Also, annual mean relative humidity in 2000–2018 does not differ significantly from values for 1961–1990, but in 2021–2050 it will decrease by 10–16% compared to the modern conditions.

The annual mean evaporation from the water surface has been increasing since the beginning of the 21st century by 13–15% along the northern coast of the north-western part of the Black Sea and by 7–9% along the western coast as compared to the reference period. The table shows two different values – the first does consider substantial changes in annual mean relative humidity in the near future, and the second does not – which is defined by the significant increase in the air relative humidity in the future but not in the past. Byrne & O'Gorman (2016) have argued that the relative humidity over the land can decrease due to global warming. Only the absence of its significant decrease in the past observations (see Table 2) raises doubts in contrast with the data, e.g., Cséplő *et al.* (2022), that is probably due to the proximity to the sea surface. Therefore, both values – with and without considering substantial changes in annual mean relative humidity – are considered in this article. So, the annual mean evaporation from the lagoonal water surface in 2021–2050 will increase by 11–20% due to only increasing air temperature. If the expected changes in both air temperature and relative humidity are considered, the annual mean evaporation will increase by 29–56% compared to the current condition.

Table 3 contains the estimates of the annual freshwater balance for the lagoons in the reference period, modern period, and the near future. The water volume W_R inflowing into the lagoons from the catchment basin by rivers and other watercourses, if water management activity is persisting at the current level, will decrease by 52% under the climatic conditions of the RCP4.5 scenario and by 68% under the RCP8.5 scenario in 2021–2050 compared to 1961–1990. Note that river runoff in the modern period has already decreased by 44% on average due to both decreasing runoff during spring floods and increasing evaporation from the catchment area in the warm half of the year (e.g., Loboda & Bozhok 2015; Ovcharuk *et al.* 2020).

Table 2 | Climatic parameters in some sites at the North-Western Black Sea coast

Climatic parameter	Site	1961–1990	2000–2018	2021–2050 (RCP8.5)	2021–2050 (RCP4.5)
Annual precipitation (mm)	Ochakiv	417	425	n/a	n/a
	Pivdennyi	n/a	441	461	466
	Serbka	460	449	461	461
	Odesa	464	485	454	450
	Bilgorod-Dnistrovskyi	433	459	440	420
	Sarata	482	488	412	428
Annual mean temperature (°C)	Ochakiv	10.0	11.1	n/a	n/a
	Pivdennyi	n/a	11.3	12.2	12.0
	Serbka	9.4	10.7	11.8	12.5
	Odesa	10.1	11.5	12.4	12.6
	Bilgorod-Dnistrovskyi	10.6	12.1	13.3	13.6
	Sarata	10.1	11.5	13.5	13.7
Annual mean relative humidity (%)	Ochakiv	79	75	n/a	n/a
	Pivdennyi	n/a	n/a	64.4	64.3
	Serbka	73	72	64.9	64.8
	Odesa	76	75	63.0	63.0
	Bilgorod-Dnistrovskyi	77	n/a	65.8	65.8
	Sarata	76	76	64.9	64.6
Annual mean evaporation (mm)[a]	Ochakiv	761	856	n/a	n/a
	Pivdennyi	n/a	857	1,117/892	1,117/894
	Serbka	855	968	1,114/1,008	1,120/1,007
	Odesa	752	862	1,173/898	1,175/900
	Bilgorod-Dnistrovskyi	748	815	964/829	970/832
	Sarata	768	824	1,025/889	1,033/890

[a]For the near future, the data were calculated with/without considering substantial changes in annual mean relative humidity as compared to 2000–2018.

Table 3 | Estimates of annual freshwater balance (in million m^3/year) for the quasi-closed lagoons in different periods

Period	Lagoon	W_P	W_R	W_E[a]	δW[a]
1961–1990	Tyligulskyi Liman	60.3	38.8	−104.1	−5.0
	Dofinivskyi Liman	2.8	3.0	−4.7	1.1
	Hadzhibeiskyi Liman	52.9	14.9	−85.7	−17.9
	Kuialnytskyi Liman	20.9	13.2	−33.8	0.3
	Budatskyi Liman	13.0	0.0	−22.4	−9.4
	Tuzla Limans group	94.8	3.1	−151.1	−53.2
	The Sasyk	91.0	49.1	−145.1	−5.0
2000–2018	Tyligulskyi Liman	57.3	25.3	−117.5	−34.9
	Dofinivskyi Liman	2.8	1.8	−5.2	−0.6
	Hadzhibeiskyi Liman	55.3	6.5	−98.3	−36.5
	Kuialnytskyi Liman	21.8	7.5	−38.8	−9.5
	Budatskyi Liman	13.8	0.0	−24.5	−10.7
	Tuzla Limans group	96.0	1.1	−162.1	−65.0
	The Sasyk	92.2	37.4	−155.7	−26.1
2021–2050 (RCP8.5)	Tyligulskyi Liman	59.4	13.3	−143.8/−128.9	−71.1/−56.2
	Dofinivskyi Liman	2.8	1.5	−7.0/−5.5	−2.7/−1.2
	Hadzhibeiskyi Liman	51.8	5.3	−133.7/−102.4	−76.6/−45.3
	Kuialnytskyi Liman	20.4	3.2	−52.9/−40.4	−29.3/−16.8
	Budatskyi Liman	13.2	0.0	−28.9/−27.9	−15.7/−14.7
	Tuzla Limans group	81.0	0.0	−201.6/−174.8	−120.6/−93.8
	The Sasyk	77.9	24.0	−193.7/−168.0	−91.8/−66.1
2021–2050 (RCP4.5)	Tyligulskyi Liman	59.8	21.5	−144.1/−128.8	−62.8/−47.5
	Dofinivskyi Liman	2.8	1.9	−7.0/−5.5	−2.3/−0.8
	Hadzhibeiskyi Liman	51.3	6.5	−134.0/−102.6	−76.2/−44.8
	Kuialnytskyi Liman	20.3	6.8	−52.9/−40.5	−25.8/−13.4
	Budatskyi Liman	12.6	0.0	−29.1/−25.0	−16.5/−12.4
	Tuzla Limans group	84.2	0.2	−203.2/−175.1	−118.8/−90.7
	The Sasyk	80.9	32.6	−195.2/−168.2	−81.7/−54.7

[a]For the near future, the data were calculated with/without considering substantial changes in annual mean relative humidity as compared to 2000–2018.

Moreover, Loboda & Gryb (2017) showed that the consequences of water management activity are intensifying under global warming.

Table 3 and Figure 2 show that the negative annual freshwater balance for most quasi-closed lagoons before the climate changes, i.e., until the early 1990s, did not exceed a few percent of their water volume except for the Tuzla Liman group and the Budatskyi Liman. Note that this was not a significant problem for the latter if considering the possible inflow of the desalinated water from the Dnistrovskyi Liman lagoon by artificial channels in the reed bed (see Section 2). The freshwater shortage deepened in the first decades of the 21st century for all quasi-closed lagoons. These changes were especially noticeable for Kuialnytskyi Liman, where an annual deficit has reached 33% of the total water volume of the lagoon, and for Dofinivskyi Liman – up to 13%. For the Tuzla Liman group, the shortage increased from 22% in the reference period to 25% in the modern period, for Tyligulskyi Liman – from 0.7 to 5.0%, and for the Sasyk reservoir – from 1.2 to 6,3%.

In the near future, the deficit of the annual freshwater balance will significantly increase if considering the relative humidity of the air. So, for Kuialnytskyi Liman, the annual shortage will reach 91–104% of the total volume of its water (here and below smaller value corresponds to the RCP4.5 scenario and the larger one – to the RCP8.5); for Dofinivskyi Liman – 52–59%, for the Sasyk reservoir – 20–22%, and it will be about 50% for Budatskyi Liman and the Tuzla Liman group (top panel in Figure 2). On the other hand, the deficit of the annual freshwater balance will be significantly less if assuming no significant changes in air humidity in 2021–2050 compared to 2000–2018 (middle panel in Figure 2). The shortages will be 47–59% of the total volume of water for Kuialnytskyi Liman, 39–47% for Budatskyi Liman, 38–40% for the Tuzla Liman group, 18–25% for Dofinivskyi Liman, and 13–16% for the Sasyk reservoir.

Table 3 also discovers an interesting detail – the water volume inflowing into the lagoon from the catchment basin by rivers and other watercourses (W_R) will define the difference between the values of the annual freshwater balance for the RCP4.5

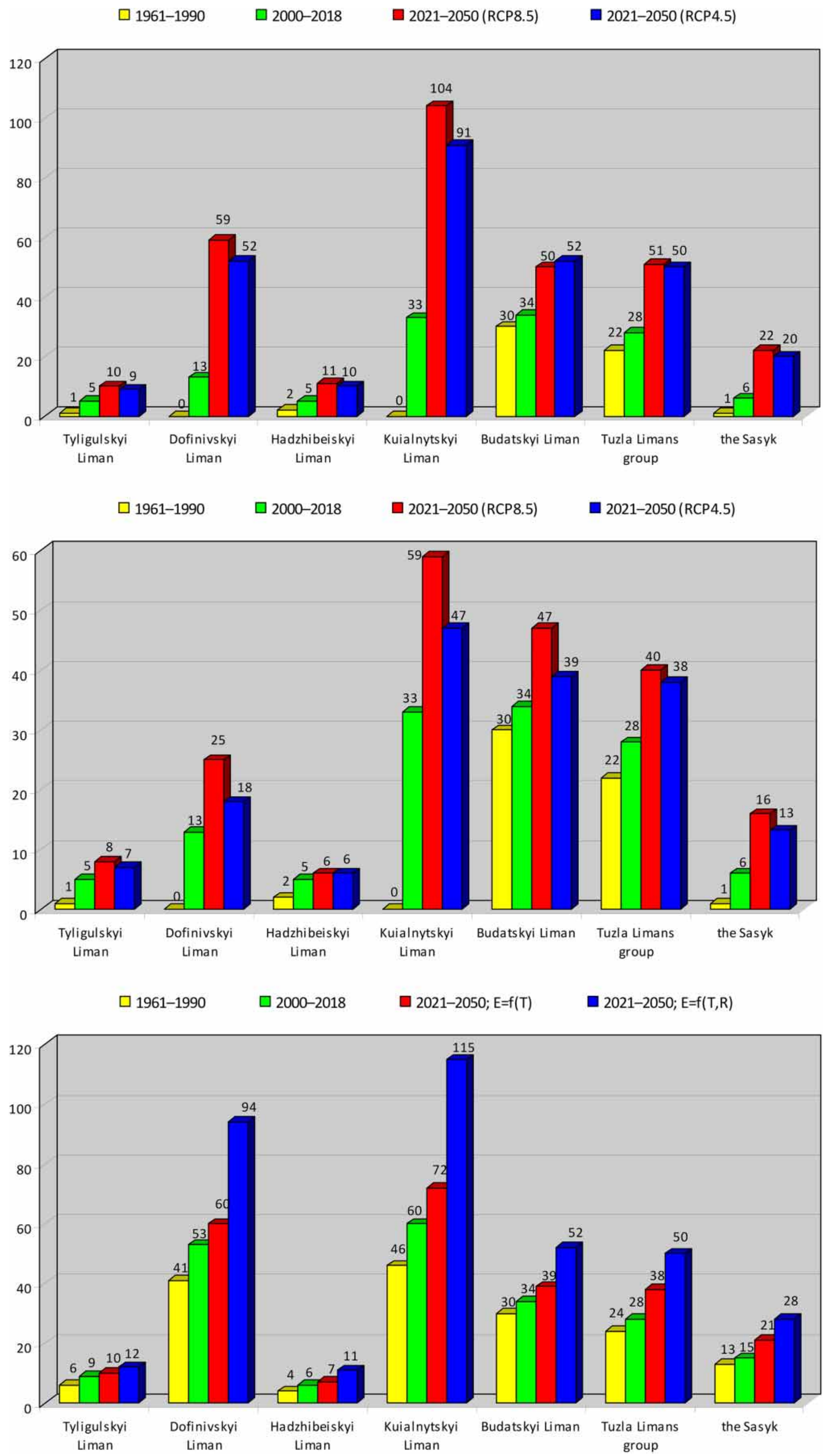


Figure 2 | Percentage shortage of the annual freshwater balance as related to the annual mean water volume in the quasi-closed lagoons on the North-Western Black Sea coast: top panel – I_{PRE} calculated considering both temperature and relative humidity (RCP4.5 and RCP8.5 scenarios); middle panel – I_{PRE} calculated with considering temperature only (RCP4.5 and RCP8.5 scenarios); bottom panel – I_{PE} calculated for RCP4.5 scenario ($E = f(T, R)$ – with considering both temperature and relative humidity; $E = f(T)$ – with considering temperature only).

and RCP8.5 scenarios. Taking into account the small size of the territory, as well as the larger increase in temperature by the RCP8.5 scenario, one can only assume that the sea smooths out the temperature difference between the scenarios in the lagoons located on the Black Sea coast. However, the influence of the sea should decrease with distance from it, and larger evaporation will be observed due to the higher air temperature under the RCP8.5 scenario closer to the sources of the rivers flowing into the lagoons. Accordingly, the runoff of these rivers into the lagoons will be less under the RCP8.5 scenario. Figure 3 confirms this assumption – during the spring months, when the main part of the annual runoff is usually generated, the temperature nearer to a river's source according to the RCP8.5 scenario significantly exceeds that under the RCP4.5 scenario, while this is not observed near the Black Sea coast. Such a distribution of meteorological variables, precipitation, or temperature, is not unique and can be observed for other climatic conditions and regions (e.g., Ramadhan *et al.* 2021).

The bottom panel in Figure 2 shows the I_{PE} values for the RCP4.5 scenario. They indicate a contribution of precipitation and evaporation differences to the freshwater balance of the lagoons. As can be seen, even under a relatively moderate RCP4.5 scenario, two lagoons (Kuialnytskyi Liman and Dofinivskyi Liman) can almost completely disappear, and two more (Budatskyi Liman and Tuzla Liman group) will lose half of their water volume in the lack of river water inflow and with increasing evaporation.

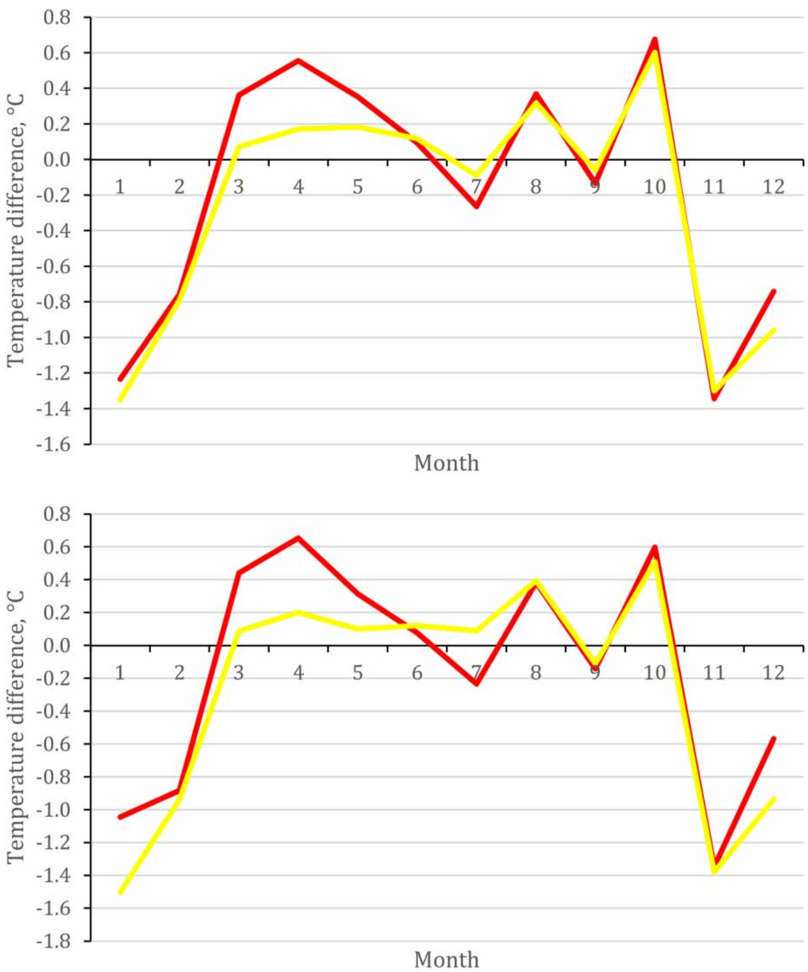


Figure 3 | Difference between air temperatures by RCP8.5 and RCP4.5 scenarios closer to the river sources (red) and near the Black Sea coast (yellow). The top panel is for Artsyz site (45.98N, 29.43E) and the Sasyk, and the bottom panel is for Ananiv site (47.72N, 29.98E) and Tyligulskyi Liman. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wcc.2023.109.

5. DISCUSSION

The climate change impact on the meteorological and hydrological parameters of coastal marine areas and adjacent lagoons has a pronounced regional aspect (Hesse *et al.* 2015; Sellami *et al.* 2016; Jakimavičius *et al.* 2018). Therefore, knowledge and understanding of these features are extremely interesting both for specialized researchers and for representatives of government bodies responsible for the rational use and conservation of natural resources in coastal areas.

Above, we assessed regional climate changes in the North-Western Black Sea region. Summarizing the results, we can state that the following changes in meteorological parameters, which determine the components of the annual freshwater balance in quasi-closed lagoons, have occurred since the beginning of the 21st century and are expected in the near future:

- the annual mean precipitation is insignificantly changing – the maximum (decrease up to 11% by the RCP4.5 scenario) will observe along the western coast of the north-western part of the Black Sea;
- the air temperature is gradually increasing – the annual mean temperature in 2000–2018 is 10–14% (1.1–1.5 °C) higher and expected in 2021–2050 will be 23–36% (2.3–3.6 °C) higher compared to 1961–1990;
- the annual mean air relative humidity in 2021–2050 will be 10–16% higher compared to 1961–1990;
- the annual mean evaporation from the water surface of the lagoons in 2021–2050 compared to 1961–1990 will increase by 11–20% only due to increasing temperature and by 29–56% if substantial changes in annual mean relative humidity are also considered.

These changes in meteorological parameters are leading to:

- decreasing inflow of freshwater into the lagoons from rivers and other watercourses by 52% under the RCP4.5 scenario and by 68% under the RCP8.5 scenario in 2021–2050 as compared to the reference period if considering the unaltered water management activities in catchments of the lagoons;
- increasing evaporation depending on the water area of the lagoons due to increasing air temperature and decreasing air relative humidity;
- increasing shortage of the annual freshwater balance due to (i) a significant evaporation from the water surface of the lagoons, (ii) a decreasing inflow of water from their catchment basins, and (iii) an insignificant, within a few percent on average, decrease in precipitation.

The ratio of the annual freshwater balance shortage to the annual water volume of the lagoon shows a portion of the water volume would be extracted from the lagoon because of the prevailing sink over the source components in the water balance (see Equation (1)). Using this indicator one can be approximately assessed a time before the lagoon would completely dry if the water shortage could not be at least partially compensated by providing water exchange with the sea or additional water inflow from other sources, as, e.g., for Hadzhibeiskyi Liman and Budatskyi Liman. For example, Kuialnytskyi Liman would dry out in 1 year, Budatskyi Liman, Dofinivskyi Liman, and Tuzla Limans group – in 2 years, the Sasyk – in about 5 years if both air temperature and relative humidity would change under the RCP4.5 and RCP8.5 scenarios in 2021–2050 (see Figure 2). If the relative humidity of air would decrease less drastically, the 'drying out' time will increase.

Even if the lagoons will not dry out within the above timeframes due to additional water inflow from sources or other factors not to be mentioned here, the suggested indicator shows how quickly each lagoon can lose its initial volume as related to the other lagoons under the same climatic conditions. As a result, the decrease in the water volume of the lagoon leads to worsening hydro-ecological conditions due to increased eutrophication, increasing salinity, and high concentration of pollutants in the water (e.g., Vargas *et al.* 2017; Kaushal *et al.* 2023). Therefore, the magnitude of the indicator can be considered an indicator of the vulnerability to climate change in the lagoons.

Of course, the above estimates of the 'drying out' time for the lagoons are only a first approximation since we did not take into account the expected decrease in the total volume of water in the lagoon resulting in decreasing water area of the lagoons and, accordingly, lesser volume of evaporated water. Also, we did not consider the impact of salinity on the evaporation rate as the water salinity in the lagoons is mainly defined by anthropogenic control of the water exchange between the lagoon and the sea, not only by climatic forcing. High values of water salinity reduce the evaporation rate. For example, the evaporation for Kuialnytskyi Liman can be 25–50% smaller considering its water salinity of 150–300‰. These issues can be addressed in future studies.

Due to the decreasing water resources of rivers and other watercourses, an effective way to stabilize the hydro-ecological regime of quasi-closed lagoons in the North-Western Black Sea region under the increasing shortage of freshwater balance due to climate change is to ensure a permanent year-round two-directional water exchange with the sea through artificial connecting channels, which could prevent the accumulation of salt, nutrients, organics, and toxic pollutants in the lagoons in the future. As for some lagoons in that region, this problem has been solved by Kushnir & Tuchkovenko (2018, 2020), Tuchkovenko *et al.* (2019), and Tuchkovenko & Kushnir (2022) using numerical mathematical modeling. If necessary, the effects of waves on the hydraulic facilities being constructed should be considered (Rodríguez-Martín *et al.* 2022).

Hydrodynamic models are widely used and provide acceptable results (e.g., Umgiesser *et al.* 2016; García-Oliva *et al.* 2018, 2019). On the other hand, if the input information for such models is lacking or of inappropriate quality – this may be the case in the North-Western Black Sea region – other techniques can be used (e.g., Kavehkar *et al.* 2011; Aslan *et al.* 2022).

In any case, modeling results are defined by input data into a model. The current study uses both observational data and the outcomes of the EURO-CORDEX Project as input to the balance model described by Equation (1). The number of specific results for 2021–2050 may be largely due to the uncertainty of the future climate and a lot of its simulations (see, e.g., C3S Climate Data Store https://doi.org/10.24381/cds.bc91edc3). Here, we used the approach of selecting one simulation from the model ensemble; the outcomes from this simulation are as close as possible to the ensemble mean values. In other words, the modeling results for 2021–2050 are averaged and do not consider possible extreme climatic events in the near future, which can either improve or worsen, most likely, the hydro-ecological conditions in the lagoons.

6. CONCLUSION

The current study presents the first estimates of climate-induced changes in annual freshwater balance of all quasi-closed lagoons on the North-Western Black Sea coast using a single methodological approach. This allows us to reveal general features of the climate change impact on the system of lagoons as a whole and to assess separately the vulnerability of each lagoon to climate change by analyzing comparatively the quantitative indicators suggested here.

The general features, which are essential to understand the features of climate change impact on the hydrological regime of the lagoons, include:

- a remarkable decrease of freshwater inflow into the lagoons from rivers and other watercourses, resulting in a decreasing significance of this inflow for the water balance of lagoons if the current approach to water management would not be changed;
- a significant increase in evaporation from the water surface of lagoons, e.g., by 30% for Kuialnytskyi Liman, and a shortage of freshwater balance with increasing aridity if considering both the expected decrease in air humidity and increase in air temperature.

Let us note that the differences between the RCP4.5 and RCP8.5 scenarios for 2021–2050 are most prominent in the estimates of freshwater inflow into the lagoons from rivers and other watercourses compared to other balance components.

We confirmed that changes in climatic conditions that have already occurred and are expected in the near future should cause an increasing shortage of the annual freshwater balance of all quasi-closed lagoons in the North-Western Black Sea region. For some lagoons, e.g., Kuialnytskyi Liman, Dofinivskyi Liman, and Tuzla Limans group, these changes can result in excessive shallowing, salinization and even the complete disappearance due to the lack of or insufficient water exchange with the sea. This requires the development of new strategies for water and environmental management of quasi-closed lagoons. In terms of vulnerability to climate change due to the significant annual shortage of the freshwater balance and the absence of other sources of water inflow, e.g., from the Black Sea, the lagoons are ranked as follows: Kuialnytskyi Liman, Dofinivskyi Liman, Budatskyi Liman (if water inflow from Dnistrovskyi Liman is lacking), Tuzla Limans group, the Sasyk, Tyligulskyi Liman, Hadzhibeiskyi Liman (if anthropogenic runoff is lacking).

Our results should be taken into account when water and environmental management plans are created and implemented for each lagoon considered in this study. For example, the necessary capacity of the channels connecting the lagoon with the sea should be calculated to compensate for the freshwater shortage, and the economic feasibility and effectiveness of various scenarios for rational land and water use in the catchment areas of the lagoons should be assessed to ensure the maximum possible inflow of the freshwater from rivers and other watercourses into the lagoons. Our estimates are intended to motivate the state authorities of Ukraine to consider the features of the climate change impact on the components of water balance for the lagoons when developing river basin management plans and integrated coastal zone management plans. First of all, management plans should be developed for the lagoons, which are most vulnerable to climate change.

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DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories: https://doi.org/10.5281/zenodo.7078864.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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