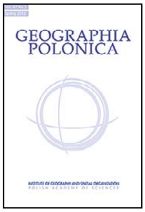

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LONG-TERM CHANGES IN WATER LEVEL OF THE NORTHWESTERN PART OF THE BLACK SEA

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Abstract

The characteristics of sea water level (SWL) in the northwestern part of the Black Sea and the main influencing factors were studied. Based on observation data, it was found that the mean SWL at hydrological stations along the coast is similar. Over the past four decades, an increase in SWL has been observed, with an average rate of about 3.3 mm per year. This rise is comparable to the average increase observed in the World Ocean. Since about 2000, the increase in level has practically disappeared. It was shown that this feature is caused by the changes of the Black Sea water balance. The increase of air temperature in the studied region is greater than worldwide. This increase is observed alongside with the increase in water temperature and a significant increase in evaporation from the sea surface. The inflowing river runoff, which has been less than usual in recent years, also has an effect on SWL. In addition to long-term changes, seasonal fluctuations also occur. During a year, the smallest increase is observed in May and June, the largest – in November and February. The intra-annual distribution of water runoff from the Danube and Dnipro rivers is the primary factor that influences the seasonal changes of SWL.

Keywords

water level • northwestern part of the Black Sea • river runoff • air temperature

Introduction

The global rise in SWL is an alarming problem that concerns a large part of humanity. It is believed that this issue is closely connected to the rise in global temperature (Church & White, 2006; Wuebbles et al., 2017; Krishnan et al., 2021).

In the 20th century, SWL was primarily caused by the mass loss of glaciers and ice caps, which are now known as glaciers, and by ocean thermal expansion (IPCC, 2019, 2023). However, since 1990, both the Antarctic Ice Sheet and Greenland Ice Sheet have increasingly contributed to the increase in SWL (Bamber et al., 2018; The IMBIE Team, 2018; Shepherd et al., 2021).

Generally, the SWL increase has been around 3.0-3.5 mm per year over the past few decades, with essential deviations in particular conditions (Tsimplis et al., 2000; Tsimplis et al., 2004; Cazenave, 2014; Krishnan et al., 2021; Avşar, 2022).

The studies of SWL were originally based on real measurements at gauging stations until recently, but now these data have been supplemented by remote sensing (Meli et al., 2023). According to many authors (Tsimplis et al., 2004; Church & White, 2006; Wuebbles et al., 2017), the increase in water levels has a tendency to accelerate.

A variety of scientific papers have been published on the Black Sea, covering its hydrography, water balance, salinity, climate, and more.

The Black Sea has a surface area of around 440,000 km^2, with a maximum depth of 2200 m and an average depth of 1240 m, respectively. It is connected with the Marmara Sea through the Bosphorus, which is the one of world's narrowest strait, with an average width of 1.6 km, mean depth of 35 m and a total length of 31 km. The smallest width of the Bosporus is about 710 m. In the north, the Black Sea is connected through the Kerch Strait with small the Sea of Azov (Bakan & Büyükgüngör, 2000; García et al., 2022).

In general, the Black Sea with the Sea of Azov can be considered as the most remote seas of the World Ocean. In addition to the Sea of Marmara, there is a very large Mediterranean Sea between the Black Sea and the Atlantic Ocean.

The important factor impacting the level of the Black Sea is its water balance. The volume of river runoff and precipitation significantly exceeds the amount of evaporation. As a result, there is a prevailing movement of water from the Black Sea to the Marmara Sea. The corresponding results can be found in the paper Efimov et al. (2012). For the period of 1958-2001, the computed amount of precipitation was 235 km^3/year (564 mm) and evaporation was 385 km^3/year (924 mm). At the same time, the river runoff was 350 km^3/year (840 mm). The inflow rate from the Sea of Azov is estimated at 20 km^3 per year. Thus, the balance of water in the Bosphorus is estimated as 220 km^3/year (528 mm).

These data are similar to those ones published in paper (García-García, 2022), where the net water mass transport from the Black Sea to the Mediterranean Sea was estimated in volume 248 ± 22 km^3/year.

There are quite a few papers devoted to the climate change in the region of the Black Sea. Many authors (Hadi & Tombul, 2018; Vyshnevskyi et al., 2023a) indicate the increase in air temperature in this region. Thus, the air temperature in the city of Odesa during the period 1894-2021 increased by more than 2.5°C. The increase in case of approximation by a linear trend is less – about 1.8°C or 0.15°C per decade. It is worth noting that the last years in the studied region were the warmest during all observed period (Vyshnevskyi et al., 2023a). The highest increasing trend for air temperature was found in summer period (Hadi & Tombul, 2018).

It is important that increase of air temperature causes the increase of water temperature. According to the results (Vyshnevskyi et al., 2023a), the mean annual water temperature in the northwestern part of the Black Sea during period of 1915-2021 increased by approximately 2.0°C. The largest increase of water temperature is observed in summer period, which corresponds to the increase of air temperature.

In turn, the increase of water temperature led to the increase of evaporation from the sea water surface. As it was shown in the studies (Vyshnevskyi, 2022; Vyshnevskyi & Shevchuk, 2022), the dependence between air temperature and evaporation is nonlinear.

The largest increase of evaporation at meteorological stations, located near the sea, is observed in summer period. In recent time, the measured evaporation at meteorological stations located in the south of Ukraine reached 1000 mm/year (Vyshnevskyi, 2022; Vyshnevskyi & Shevchuk, 2022).

As it was mentioned before, the important component of the water balance of the Black Sea is precipitation. As a rule, this component is calculated using observation on the meteorological stations, located near the sea shore. According to study (Ilyin, at al., 2012), the precipitation on the Black Sea surface during 1923-2011 had the tendency to increase. More recent works (Yilmaz & Imteaz, 2014; Hadi & Tombul, 2018; Garcia-Garcia et al., 2022) contain statements regarding the absence of noticeable changes in precipitation. In any case, the difference between evaporation and precipitation is significant, and now it is increasing.

One of the factors, impacting the Black Sea, is the river runoff, in particular the runoff of the Danube River and Dnipro River. The corresponding study (Vyshnevskyi & Shevchuk, 2022) shows that mean long-term runoff of the Danube River at the top of the delta during 1921-2020 is 6510 m^3/s, or 205 km^3 during the year. Almost the same value is given in other works (Levashova et al., 2004; Gastescu, 2009; Stagl & Hattermann, 2015).

It is worth noting that the water runoff of the Danube River in the last decade was less than usual (Vyshnevskyi & Shevchuk, 2022). The same changes were registered as to the Turkish rivers. In general, during last decades the inflow of river water has the tendency to decrease (Garcia-Garcia et al., 2022). The decrease of river runoff is predicted in the future (Yilmaz & Imteaz, 2014).

Similar to the global changes, water level in the Black Sea has the tendency to rise. Such results can be found in papers of many scientists (Stanev & Peneva, 2002; Tsimplis et al., 2004; Goryachkin & Ivanov, 2006; Peychev et al., 2010; Andrianova, 2012; Ilyin et al., 2012; Yeremeyev et al., 2015; Gavrilyuk & Kornilov, 2016; Andrianova et al., 2017; Avşar et al., 2022; Garcia-Garcia et al., 2022).

According to the results of (Avşar et al., 2022), based on satellite altimetry data, water level in the entire Black Sea from January 1993 to May 2017 was increasing with the speed 2.5 ± 0.5 mm/year. It is important, that during last period 2010-2017 the mean SWL had the tendency to decrease (Avşar et al., 2022). This fact indicates that changes in the water level in the Black Sea are significantly different from global ones.

To some extent, the water level in the studied northwestern part of the Black Sea depends on wind regime and wind-driven sea level fluctuations. In some cases the fluctuations of SWL caused by wind impact can reach 1 m (Komorin & Tuchkovenko, 2002; Komorin et al., 2008; Gavrilyuk & Kornilov, 2016).

It can be added that rising sea levels can cause flooding of low-lying lands located near the sea. First of all, it concerns the southern part of Kherson region on the south of Ukraine.

The study by Bănăduc et al. (2023) showed the ecological impact of sea level changes on the ichthyofauna of the Danube Delta. Approximately one third of fish species are projected to face significant impacts.

The main objective of this research is to determine modern changes in sea water level in the northwestern part of the Black Sea and the major factors that contribute to these changes.

Study area

The region being studied is the northwestern and shallow part of the Black Sea. The water depth in this part of the sea is less than 100 m. Three significant rivers flow into the studied part of the sea: the Danube River in the south, the Dnipro River in the North-East and Dnister River between them. The city of Odesa, which is the largest city on the Black Sea coast, is located in the studied area (Fig. 1).

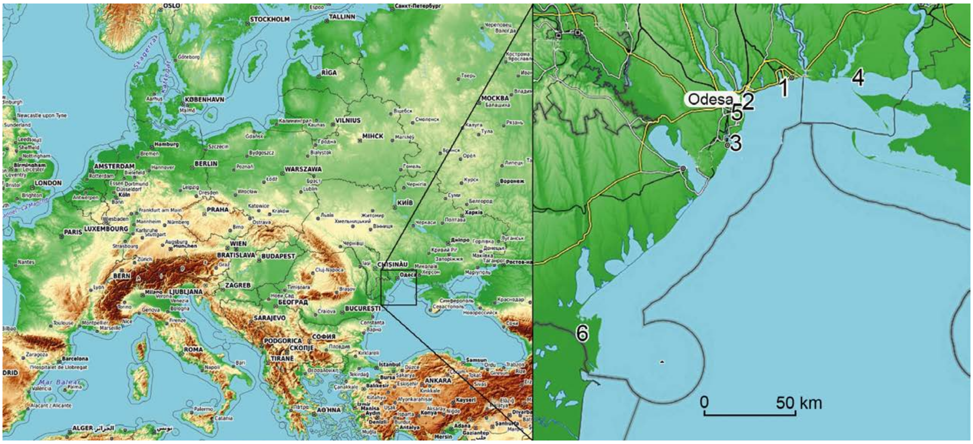

Figure 1. Location of the studied part of the Black Sea and the network of hydrometeorological observation: 1 – Pivdennyi, 2 – Odesa, 3 – Chornomorsk gauging stations, 4 – Ochakiv, 5 – Odesa and 6 – Vylkove meteorological stations (https://opentopomap.org)

Data and methods

The study of the sea water level was carried out on the base of mean monthly data of three hydrological stations Pivdennyi, Odesa and Chornomorsk located on the sea shore in the northwestern part of the Black Sea. All these stations are located in the water areas of the ports, where the wind waves are not high.

The SWL data at the Odesa and Chornomorsk stations were analyzed for the period 1963-2022, and at the Pivdennyi station for the period 1981-2022. The "0" of measurements of these stations is minus 5.00 m. The available data are practically without gaps. There are only three gaps in data at Odesa station in February and March 2007, and in February 2017.

SWL changes were assessed by using the Mann-Kendall trend test to determine their reliability.

In the study, the information from meteorological stations Ochakiv, Odesa, and Vylkove that are located near the seashore was used as well. Such parameters as air temperature, precipitation and repeatability of wind were studied. Additionally, the evaporation from the water surface at the Vylkove station was studied. Corresponding measurements are carried out using an evaporator with a water surface of 3000 cm^2.

The impact of river runoff on SWL was studied using data observation on the Danube River at Reni station and on the Dnipro River at Kakhovka HPP station. It is widely known that the last one was destroyed on June 6, 2023 during the military aggression of Russia against Ukraine (Vyshnevskyi et al., 2023b).

Results and discussions

The long-term changes

The mean long-term sea water level at Pivdennyi, Odesa and Chornomorsk stations is practically the same. The mean water level at the Pivdennyi station during 1981-2022 was 488 cm above the measurement zero or -0.12 m (0.12 m below the world sea level). In turn, the mean SWL at Odesa station in 1963-2022 was 487 cm or minus 0.13 m. Finally, at Chornomorsk station the mean water level in 1963-2022 was 487 cm or minus 0.13 m.

The obtaining data are slightly higher than those obtained in previous studies (Goryachkin & Ivanov, 2006; Cazenave et al., 2014). The changes in water level during the observed period are presented in Figure 2.

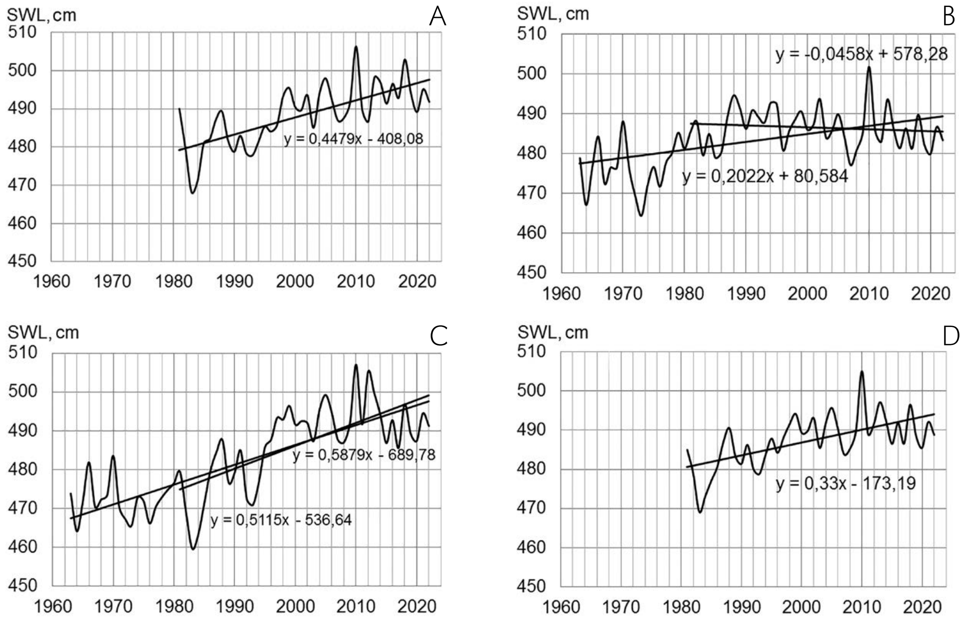

Figure 2. The changes of water level in the northwestern part of the Black Sea:
A – Pivdennyi, B – Odesa, C – Chornomorsk, D – averaged for 1981-2022

In general, the available data show SWL increase. The largest increase (0.51 cm per year) during all observation period is observed at Chornomorsk station, the lowest one (0.20 cm per year) at Odesa station. In case of use the data for period 1981-2022 we can see the trend to SWL decrease at Odesa station. This feature can be explained by the vertical movement of measurement place. Unfortunately, the data, which prove this suggestion, are absent. In fact, there are no data about the accuracy of measurements at all three stations. In this case, it is possible to use averaged data of all three stations. Operating with data at Odesa and Chornomorsk stations for period 1963-2022 the mean trend is 0.36 cm per year. Almost the same trend (0.33 cm per year) is observed in case of use the data from all three stations and period 1981-2022. In total, this result is similar to those ones obtained by other researchers (Cazenave et al., 2014; Wuebbles et al., 2017; Krishnan et al., 2021) in which the annual trend is 3.0-3.5 mm per year.

Statistical trend analyses of these changes was carried out using the Mann-Kendall test for the annual average data.

For Pivdennyi station, the Mann-Kendall trend test revealed a Kendall's tau coefficient of approximately 0.499 with a statistically significant p-value 0.00000325. This positive tau value means a statistically significant increasing trend in available data.

In the case of Odesa, the Mann-Kendall trend test indicated a Kendall's tau coefficient of approximately 0.313, with a p-value 0.000517. This result also means a statistically significant increasing trend in the mean data over the years.

Finally, the Mann-Kendall trend test for Chornomorsk station demonstrated a Kendall's tau coefficient of around 0.542 with a p-value 1.03×10^{-9}, indicating a statistically significant increasing trend in the mean data over the observed period.

These results confirm that the SWL rise observed at all studied stations is statistically significant according to the Mann-Kendall trend test.

The highest SWL during the last decades was observed in 2010, when the water runoff of the Danube River at Reni station was 9470 m^3/s (299 km^3/year) or one and a half larger, than usual.

It is important that during last two decades starting around 2000, the increase of water level in the Black Sea is practically absent. After 2010, the water level even decreases. To some extent, these changes correspond to the results of study in Copernicus program (ESOTC, 2022; Copernicus Marine Service, 2023) where the water level increase in the Black Sea between 1993 and 2022 was much less than in other European seas. According to these studies the water level increase in the Black Sea for the period 1993-2022 is estimated as 1.4 mm per year. Based on data of three studied stations, we obtained for this period almost the same result – 1.6 mm per year.

These features can be explained by less than usual river runoff in the last years. In particular, in 2009-2022 the mean water runoff of the Danube River was 6230 m^3/s, or 196 km^3 per year. In particular, it was very small in recent years: in 2020 and 2022. The water runoff of the Dnipro River in recent years was less than usual as well (Fig. 3).

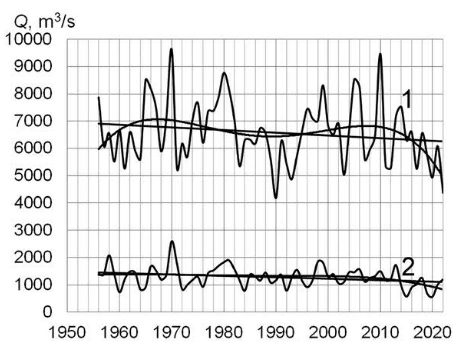

Figure 3. Long-term changes of water runoff of the Danube River at Reni station (1) and Dnipro River at Kakhovka HPP (2)

Taking into account the area of the Black Sea, it can be seen that the difference in 1 km^3 of water is equal to 2.3 mm of SWL. This shows the important role of the river runoff in SWL changes.

The decrease of river runoff is also found in the study (Garcia-Garcia et al., 2022). This decrease is partly due to climate change, partly due to increased water withdrawals for irrigation.

The second important factor, impacting the water level in the Black Sea is the climate change, primarily the significant increase of air temperature primarily in the last three decades (Fig. 4).

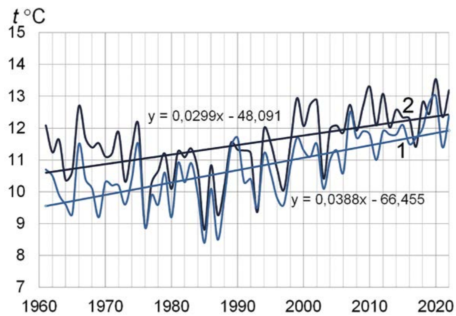

Figure 4. Long-term changes of mean annual air temperature (1) and mean water temperature (2) at meteorological and hydrological stations in Odesa

As can be seen in Figure 4 during the last decades there has been an obvious increase in air temperature. During this period, the air temperature increased by about 2°C or even more. This is much larger than globally (IPCC, 2023). At the same time, the increase in air temperature is greater than the increase in water temperature, which is logical. The highest air and water temperature was observed in recent years. Recent years have been the warmest for the entire observation period.

In turm, the increase in air and water temperature caused the significant increase in evaporation from the sea water surface. This is confirmed by available observation data at Vylkove meteorological station, where the measurements of evaporation from the water surface is actually provided. Available data show that evaporation has increased significantly in recent decades (Fig. 5).

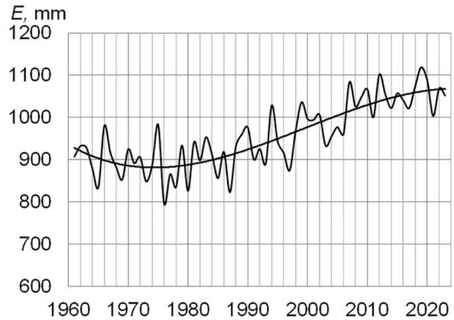

Figure 5. Long-term changes of evaporation from water surface at Vylkove meteorological stations

It should be added that according to a study (Vyshnevskyi, 2022) the evaporation measured with the aforementioned evaporator is slightly higher than the actual one. In any case, these data indicate that evaporation from the water area in the south of Ukraine and in the Black Sea as a whole reached 1000 mm/year. Similar results were published in papers (Garcia-Garcia et al., 2022; Tuchkovenko et al., 2023).

As it was mentioned in the Introduction, the precipitation in the studied region is about twice less than evaporation. According to available data at three meteorological stations it has not practically changed in recent decades (Fig. 6).

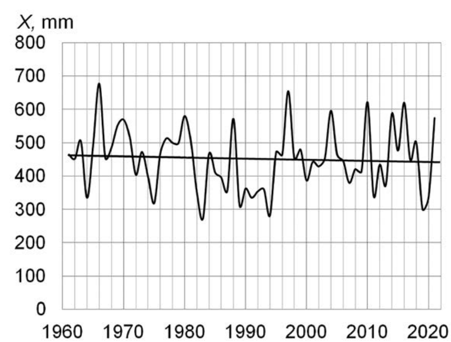

Figure 6. Long-term averaged annual precipitation at Ochakiv, Odesa and Vylkove meteorological stations

It can be added that reliable data as to precipitation at three mentioned meteorological stations were obtained for the period finished in 2021. As a result large-scale Russian aggression against Ukraine, which began in 2022, the data at Ochakiv and Odesa stations that year turned out incomplete. At the same time, the available data for 2022 show, that precipitation in that year was very small or even the smallest. Thus, at Vylkove meteorological station it was 283 mm, or one and a half less, than usual.

Similar results regarding the stability of precipitation over the last decades were obtained in the study (Yilmaz & Imteaz, 2014; Hadi & Tombul, 2018; Garcia-Garcia et al., 2022), but in recent years, precipitation has been less than usual.

These data show that water balance of the Black Sea has changed. During the last decade, evaporation from the sea's surface has increased, while river runoff has decreased. These changes have moderated the rise in global SWL rice in recent years.

Seasonal changes of SWL

The highest water level in the studied part of the Black Sea during the year is observed in May and June, the lowest one in October. This is characteristic of all three hydrological stations (Fig. 7).

The differences in mean water level between the highest and lowest monthly values at each station are similar. It is 15.4 cm at Pivdennyi station, 14.3 cm at Odesa station, and 14.5 cm at Chornomorsk station. As can be seen, the data at Odesa and Chornomorsk stations are similar. The small difference with Pivdennyi station can be explained by two factors: the location in the corner of Odesa Bay and the impact of water runoff of the Dnipro River. The same results were obtained in the study (Gavrilyuk & Kornilov, 2016).

In general, the observed intra-annual features of SWL correspond to the intra-annual fluctuation of water runoff of the Danube and the Dnipro rivers with delay about one month. The highest water level in the Black Sea is observed after the spring flood, the

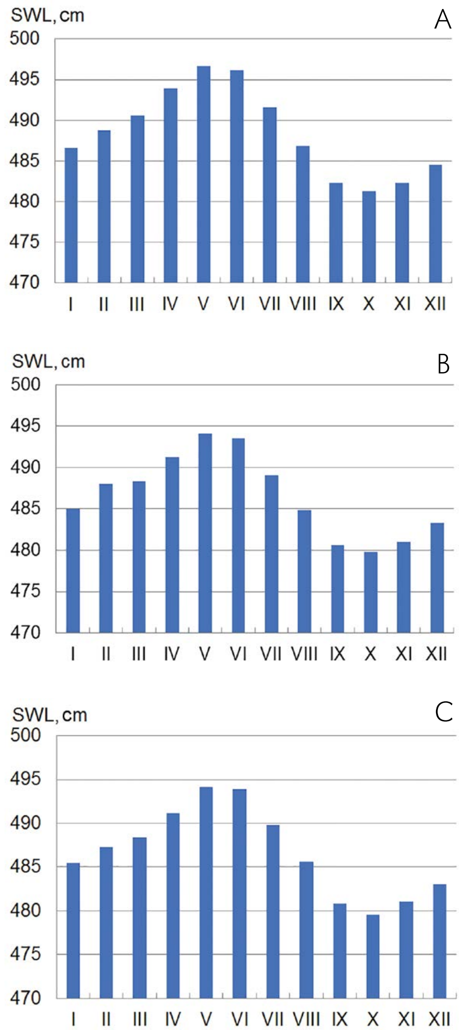

Figure 7. The repeatability of wind of different directions in November at Odesa: (A) and Ochakiv (B) meteorological station: 1 – 1961-1990, 2 – 1991-2020

lowest one at the end of warm period after the low water (Fig. 8).

To some extent, the SWL depends on correspondence between precipitation and evaporation. In winter season, the precipitation on the sea surface exceeds the evaporation and vice versa in warm period.

During the last decades, the increase of SWL in different months has not been consistent. The smallest increase is observed in

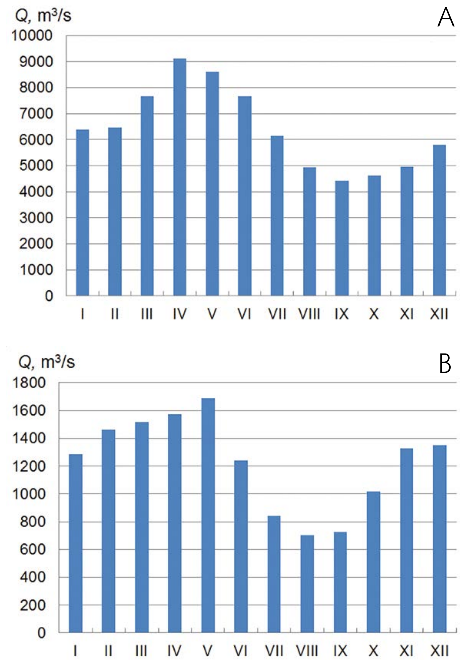

Figure 8. The intra-year changes of the water discharge: A – the Danube River at Reni station during 1981-2022, B – the Dnipro River at Kakhovka HPP during 1981-2021

May and June, the largest one – in November and February. These features can be explained by the changes in the water regime of the Danube River. As it was shown in the article (Vyshnevskyi & Shevchuk, 2022), the significant decrease of water runoff during the spring flood in April and May is observed in the last decades. Simultaneously, the water discharge in February and primarily in March has the tendency to increase. This affects SWL in the northwestern part of the Black Sea (Fig. 9).

The explanation of the SWL rise in November is more complicated. In our opinion, this increase is caused by the change in the wind regime. The repeatability of the eastern, southeastern, and southern winds in November in the past three decades has become larger than before. Simultaneously, the repeatability of wind which causes the decrease of water level in the studied region became less (Fig. 10).

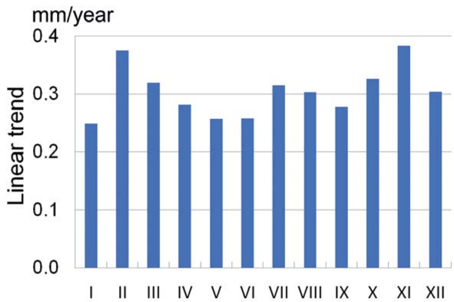

Figure 9. The linear trend of the sea water level increase by months averaged at Pivdennyi, Odesa and Chornomorsk stations during 1981-2022

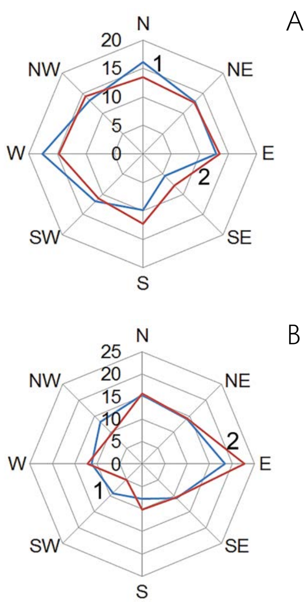

Figure 10. The repeatability of wind of different directions in November at Odesa (A) and Ochakiv (B) meteorological stations: 1 – 1961-1990, 2 – 1991-2020

It is important that wind velocity in November in the studied part of the Black Sea is the largest during the year. The additional effect on the sea level rise in October and November can have the observed increase of precipitation in September and October. At the same time, we have not relevant data for the entire Black Sea water area.

Conclusions

The water level at the hydrological stations located in the northwestern part of the Black Sea is similar, but the sea level rise at these stations has some peculiarities. The water level in the studied area of the sea increased by about 3.3 mm per year between 1981 and 2022. Since about 2000, the increase in level has practically disappeared. These features are caused primarily by an increase in air and water temperature, which is accompanied by an increase in evaporation. Another factor affecting SWL is river runoff. The river runoff in recent years has been lower than usual. The highest water level in recent decades was observed in 2010, which was caused by a large runoff of the Danube River.

During the year, the highest water level in the northwestern part of the Black Sea is observed in May and June, and the lowest in October. The main factor affecting the seasonal changes of SWL is the intra-annual distribution of river runoff.

During the year, the smallest trend of sea water level increase is observed in May and June, when the water runoff of the Danube River tends to decrease. In turn, the largest trend of SWL increase is observed in November, which can be explained by the changes in the wind regime. Nowadays, the repeatability of the eastern, southeastern, and southern winds in November is greater than at the beginning of observation.

Editors' note:
Unless otherwise stated, the sources of tables and figures are the author's, on the basis of their own research.

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