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Environmental change between 1980 and 2020 followed by societal change in the Gulf of Gdańsk, Southern Baltic, a review

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The Gulf of Gdańsk belongs to the best-known marine areas in the Baltic, with regular environmental observations since mid-20th century. It covers the widest array of marine habitats in Polish Maritime areas (from large river mouth to Gdańsk Deep), shallow vegetated lagoon and stony reefs and the highest resources of species diversity (about 400 Metazoa and over 300 Protista species). The area was also important as a fishing ground as well as a key site for the marine industry, shipping and tourism. The review of the changes in the Gulf of Gdańsk over last 40 years shows that it follows some of the global trends (increase in temperature, storminess, sea level rise, decrease in ice and oxygen), while the specific local phenomena like eutrophication and contamination are more difficult to assess (e.g., strong reduction in nutrient discharge did not change the levels of P and N in the system). After recovery from the environmental crisis in the 1980s, the toxic compounds in sediment and seawater are below the accepted thresholds. The reduction in some toxins resulting from better management (e.g., Mercury or chlorinated compounds) is blurred by the negative effects of climate warming (expansion of anoxic sediments) and contamination connected with its biogeochemical activity. Formerly degraded coastal habitats are recovering (especially seagrass), while the commercial fish catch collapsed, likely caused by the large-scale phenomena (climate warming), not directly connected with the local conditions of the Gulf. The societal use of the Gulf changed from industrial/fishery to largescale tourism and service, with fast growing pressure for coastline urbanization. The key phenomena (drivers of events) of the area include eutrophication, industrialization and biodiversity recovery.

KEYWORDS

baltic, climate change, societal change, biodiversity, Gulf of Gdańsk

Introduction

The Gulf of Gdańsk at the Southern Baltic belongs to the best-known marine areas in the region, as large harbour and metropolis of Gdańsk-Sopot-Gdynia, several high schools and universities, research institutes and fishery centre are situated at its coast

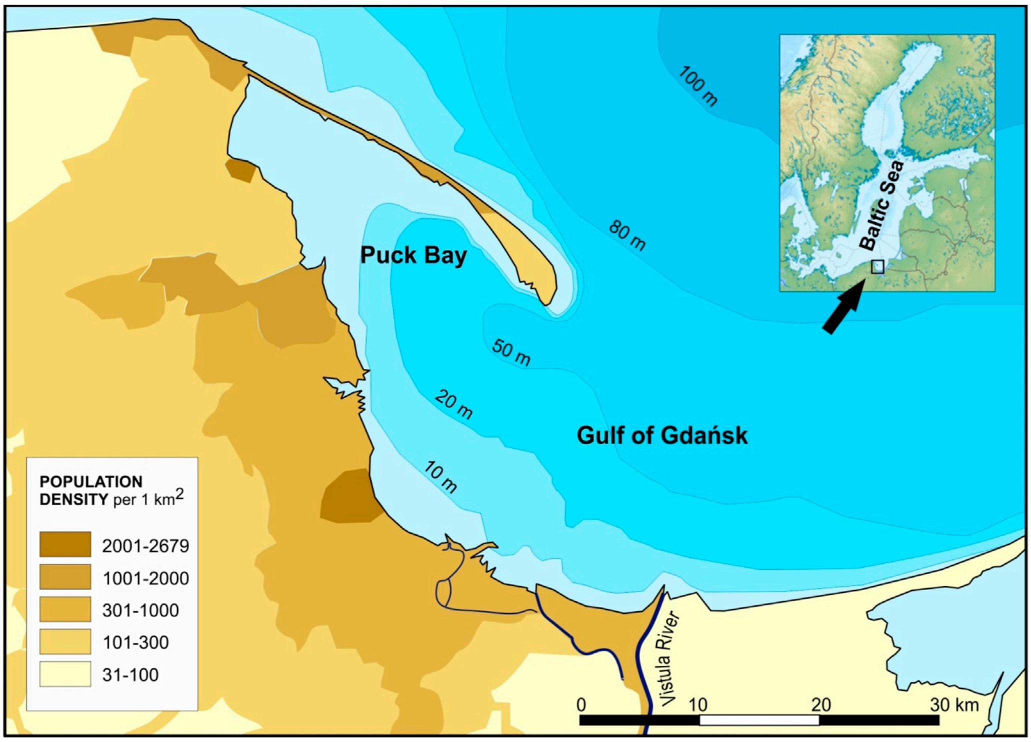

FIGURE 1
Gulf of Gdansk with density of population on the coast and main bathymetric features.

(Figure 1). We have the records of the changes in the Gulf since the beginning of the 20th century – Lakowitz 1907; Demel 1935; Pliński and Wiktor 1987). This very area has been suppressed between 1970 and 1990 with extreme environmental stress due to the industrial, agricultural and household contaminants. The original habitats and communities of the Gulf have been heavily disturbed, mainly by oxygen deficit connected with heavy eutrophication (Żmudziński and Osowiecki, 1991; Ciszewski et al., 1991; Szaniawska et al., 1999) or physically destroyed (like exploitation of drifting fucoids and red algae (Andrulewicz, 2021; Kotwicki et al., 2024). The untreated wastewater from the area resulted in closing the coastline for bathing and even water sports almost every summer, with record count of *Escherichia coli* index of a few thousand cells per ml (Sobol and Szumilas, 1992). Massive investments in the water treatment facilities started in 1994, after adopting the EU regulations, and the pollution issue has largely been controlled since (Pastuszak et al., 2018). At the same time, global warming started to be recorded in the area, as the whole Baltic Sea belongs to the fast-warming areas of the globe (IPCC, 2014; Meier et al., 2022; Dutheil et al., 2022). Those two independent processes – better care of the environment from the level of the state and the global warming, drive the changes of marine ecosystem in different ways, causing confusion in the public debate about the state of coastal environment.

The biogeochemical structure and variability of the water column in the Gulf of Gdańsk are driven mostly by the large-scale biogeochemical processes and hydrological circulation occurring in the entire Baltic Proper and the inflow of the Vistula River waters (the second largest river entering the Baltic Sea with an average water flow of 1055 $m^3 s^{-1}$, IMGW, 2024).

The Gulf of Gdańsk is monitored by the Polish Institute of Meteorology and Water Management (IMGW), with monitoring cruises conducted 4–12 times per year since 1989. The Institute of Oceanology Polish Academy of Sciences (IOPAN) also conducts systematic studies in the Southern Baltic, conducting four expeditions annually (Rak and Wieczorek, 2012). The SatBaltyk program (www.satbaltyk.iopan.gda.pl) provides SST and other sea surface properties, while the Argo-Poland program (www//Argo Poland//iopan.pl) supplies CTD and dissolved oxygen (DO) data from Argo floats operating in the Southern Baltic (Walczowski et al., 2020).

Thanks to the activity of HELCOM, the updated reports on the state of the Baltic are available, from the ecosystem health parameters (HELCOM, 2023) to the detailed study of benthic fauna and its habitats (e.g., Gogina et al., 2016). However, small yet important areas such as the Gulf of Gdańsk may have its own dynamics, and hence we want to present a review of the recent marine environmental changes in this very area with a special focus on the marine biodiversity and the corresponding societal response of local inhabitants within the recent decades.

Materials and methods

The majority of material presented comes from cited literature. The methods used to reanalyse the data on sea ice change are presented below.

To analyse the ice variability in the last 40 years in the Gulf of Gdańsk, the daily raster data of sea ice fraction with a spatial resolution of 0.02° × 0.02° and temporal extent from 1 January 1982, to 30 September 2023, were used. The data were obtained from the Copernicus Marine Service (https://doi.org/10.48670/moi-00156) for the Gulf of Gdańsk area. They include high-resolution sea ice concentration data from SMHI for the period between 1982 and 2011 and the Copernicus SI-TAC product from 2012. Ice thickness was not considered due to the lack of reliable data. See the appendix for details about the methods.

Results

Atmosphere – wind and storminess

In the Baltic Sea region, the winds, especially in winter when most extreme storms occur, are strongly correlated with the North Atlantic Oscillation (NAO) index of zonal circulation (Rutgersson et al., 2015). The results of studies suggesting the increasing storminess in the recent decades (cf. Różyński, 2010; Wolski and Wiśniewski, 2021) may be biased by starting the time series with the negative NAO and low storminess of the 1970s and ending it with the predominantly positive NAO and high storminess period in the 1990s or the recent series of nine winters with positive NAO (2014–2022).

The Gulf of Gdańsk geographical position makes it susceptible mostly to storm waves and surges with northerly winds, from NW to NE, while being mostly protected with more prevalent storm winds from SW and W directions (Różyński et al., 2006). This protection causes significant wave height being on average about twice smaller in the Gulf than in the open Baltic coast of Poland (Różyński, 2010), resulting in historic extreme storm surges lower than elsewhere on the Polish coast (Zeidler et al., 1995), even though the number of hours with surges greater than 70 cm are higher in the Gulf compared to other areas (Wolski and Wiśniewski, 2020; Wolski and Wiśniewski, 2021).

That said, the highest storm surge in the Gulf of Gdańsk in recent decades was recorded on 2 January 2019 (storm Zeetje with 161 cm surge recorded in the Gdańsk Port Północny). There are reasons to believe that the winter NAO index (and therefore also the Baltic storminess) may be related to the ongoing global warming (Blackport and Fyfe, 2022), implying anthropogenic influence of the recent storminess trends. That would match the existing consensus amongst studies regarding a projected increase in the mean significant wave height in the Baltic Sea in the 21st century (Morim et al., 2018), as well as the recent projections of increase in average and extreme wind speeds in Poland (Gąska, 2023). The risk of future storm surges in the Gulf of Gdańsk is exacerbated by the increasing sea level, the long-term trend of which in the Baltic Sea is close to the global one (Hünicke et al., 2015).

Water transparency

From the start of Secchi disc depth (Z_{SD}) observations in the Gulf of Gdańsk in the late 1950s the declining trend was observed, and for the period between 1980–90 the mean values of 4.5 m were reported (Sagan, 1991; Trzosińska, 1992). Since 2003, the regular observations of Z_{SD} were carried out in the Gulf on evenly distributed grid of several stations in spring (months M, A, M) and autumn (months S, O, N). As a result, a weak trend of the increase in water transparency Z_{SD}, of 0.012 m/yr., is observed, (Figure 2).

In 2015, the average value of Z_{SD} exceeded 5 m. In terms of the depth of euphotic zone, Z_{eu}, the decadal change ranges from ~16 m to ~18 m. The increase in mean transparency may be attributed to the reported decrease in pollution load from the terrestrial sources, and it corresponds with the observed trend of decreasing the chlorophyll content in the Gulf of Gdańsk in the last 20 years (Stoń-Egiert and Ostrowska, 2022). Also, analysis of long-term trends of Z_{SD} in the open Baltic areas show its increase in the southernmost sub-basins, opposite to the decrease in the central and northern part of the Baltic (Fleming-Lehtinen and Laamanen, 2012).

Salinity and temperature

Estimates of the average SST increase in the Baltic vary, but within the same order of magnitude. Stramska and Białogrodzka (2016) estimated the SST increase of 0.05°C/year for the period between 19822013, and Liblik and Lips (2019) determined an average SST increase of 0.05°C/year between 19822016. Generally, over the last 30 years, the average SST increase ranges from 0.04°C to 0.06°C/year (Meier et al., 2022). The SST increase is seasonal, with the highest warming occurring in the summer months (May to September) and lower trends in winter (Stramska, Białogrodzka, 2016; Kniebusch et al., 2019; Liblik and Lips, 2019). The SST increase is not uniform across the entire Baltic Sea (Stramska and Białogrodzka, 2016), with the Bay of Bothnia and Gulf of Finland experiencing the strongest growth. The temperature trend in the Baltic Sea is not constant and is correlated with atmospheric temperature. In 2018, Europe experienced the warmest summer in the instrumental measurement period, including the warmest summer in the Southern Baltic in the last 30 years (Naumann et al., 2019).

The Cold Intermediate Layer (CIL), also referred to as the "dicothermal layer" forms during spring when the upper layer warms from the surface, contrasting with the cold winter waters below, and persists throughout the summer, usually disappearing during autumn convection (Lepparanta and Myrberg, 2009). In the Gdańsk Deep, CIL reaches a depth of 40–70 m and can last at this depth until the next cold season.

Over decades, surface salinity in the Baltic Sea has been decreasing (Stockmayer and Lehmann, 2023). The salinity increases with depth, reaching its highest values near the bottom (up to 14 PSU). The salinity variability is influenced by inflows from the North Sea, especially major Baltic inflows (MBI) (Figure 3).

The sea surface temperature (SST) time series from between 2009–2020 provided by SatBaltyk (Figure 4), alongside strong seasonal variability, indicates that during this period, the average annual SST increase was significantly higher than previously reported for the entire Baltic Sea, amounting to 0.12°C/year. The notion of a greater SST increase in summer is not confirmed. On the contrary, the trend was highest in winter (January-March) at 0.25°C/year, while in summer (July-September), it was close to

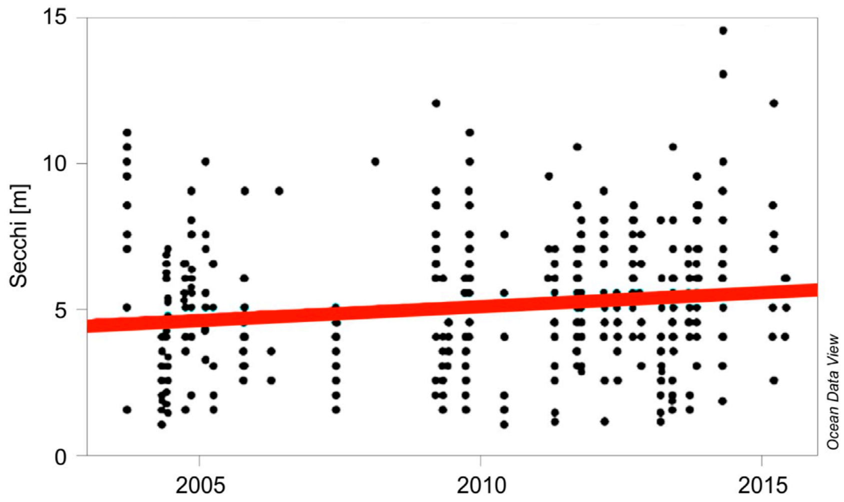

FIGURE 2
Increase of water transparency in the Gulf of Gdansk in last decades. Secchi depth observed in the Gulf of Gdansk, years 2003–2015 n = 463, thick line shows trend of 0.012 m/year. Original unpublished data from IOPAN archive.

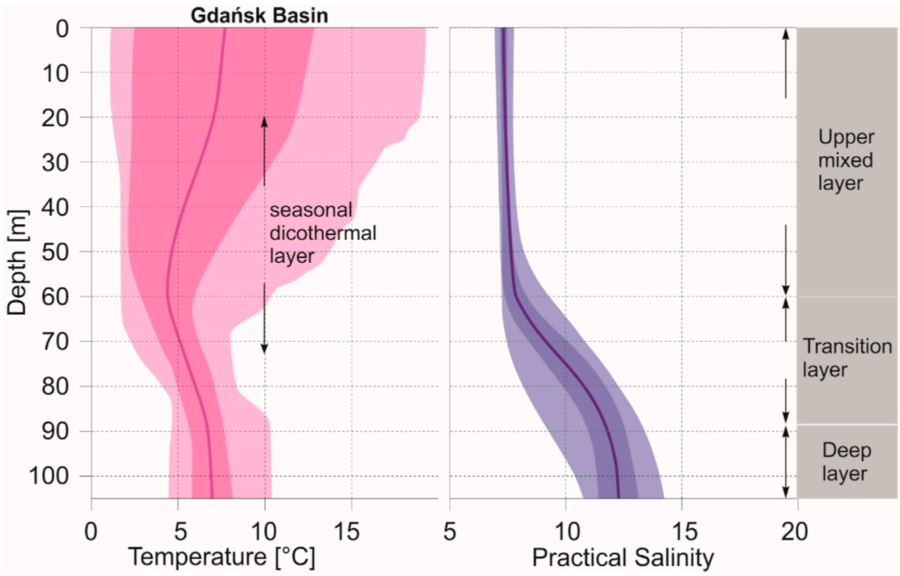

FIGURE 3
Vertical profiles of temperature and salinity in the Bay, original unpublished data from IOPAN archive.

0°C/year. The highest summer temperatures were recorded in 2010, 2014, with a record-setting 2018.

There is considerably less information on the interannual changes in the water column structure, thermocline depth, and halocline depth. Rak and Wieczorek (2012) analysed the water structure, temperature variability, and salinity changes for selected areas of the Southern Baltic from between 1994–2010. From *in situ* data collected during 68 voyages of r/v Oceania, the temperature trend for the surface layer (0–10 m) for the period between 1994–2010 was 0.11°C/year for the Gulf of Gdańsk. The salinity changes in the layer up to 50 m were approximately 0.038 PSU/year, and at a depth of 90 m, they reached up to 0.07 PSU/year.

Sea ice

During the winter between 2005–2006, ranging from strong to mild severity, ice in the inner part of the Gulf persisted for 70–80 days, while in the outer part, it lasted for 10–20 days (Urbanski and Kryla, 2006). In the remaining part of the Gulf of Gdańsk, ice phenomena occurred for about a month only during severe winters, and in milder winters, it failed to occur at all (Schmelzer et al., 2008).

The variability of ice phenomena over a 40-year period in the Gulf of Gdańsk is shown in Figure 5. Multi-year periods of extensive or moderate ice cover, lasting from two to 5 years, are interrupted by

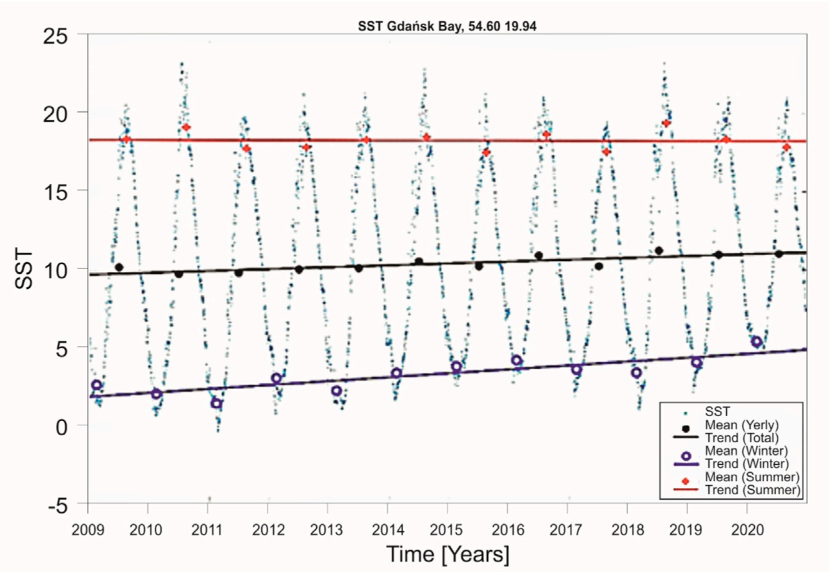

FIGURE 4
Sea surface temperature in the Gulf of Gdansk in the last decades (unpublished original data from IOPAN archive).

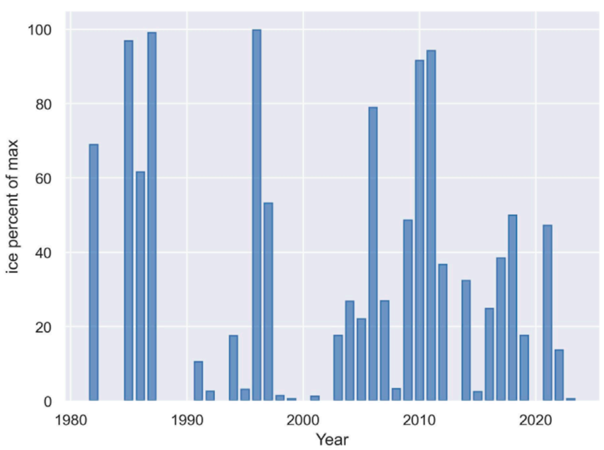

FIGURE 5
The percent of maximum accumulated sea ice in the Gulf of Gdansk for years 1982–2023, data from IMGW data repository (IMGW, 2024).

periods with low or no ice. Up to 2003, there were two such periods lasting approximately 4-5 years. However, after 2003, winters with low ice cover in the Gulf of Gdańsk occurred individually, with the majority of winters characterized by moderate ice cover. Average values were calculated from the time series presented as 30-year climatological normals for the periods between 1982–2011 and 1992–2021 to determine whether they differ from each other. Due to the non-normal distribution of the analysed data, the non-parametric Mann-Whitney U test was employed. The calculated U statistics was 432.5, with a p-value of 0.8, indicating that there is no significant difference in means.

A more detailed analysis was conducted separately for the two previously discussed areas of the Gulf. The histograms (Figure 6) illustrate the variability in the number of ice days, with the cover above 10% of the maximum cover in a given area, for two consecutive two-decade intervals: between 1982–2001 and 2002–2021.

Without analysing the statistical significance of the conclusions, several characteristic features of these distributions can be noted. In the Puck Bay, the duration of ice cover exceeded 50 days in 5 years between 1982–2001 and in 3 years between 2002–2021. A higher number of milder winters between 1982–2001 resulted in more frequent occurrences of no ice in the Puck Bay during that time. In the coastal waters of the Gulf of Gdańsk, ice occurred only three times throughout the entire 40-year period analysed.

Coastal change and erosion

Coastal change over the years is connected mainly with the technical measures against the erosion of soft sediment shores (Subotowicz, 1982; Pruszak and Zawadzka, 2008). The increase in technical infrastructure prevailed in the outer part of the Polish Baltic Sea coast, while in the inner part mainly beach nourishment was used almost every year (Łabuz, 2015). There was no considerable expansion of hard infrastructure on the shores of the Gulf except for the prolonged concrete walls at the Vistula River mouth, and the new (2020) artificial opening between the Gulf and Vistula Lagoon. The massive loss of reed in the inner part of the Gulf between 1980–90, was caused by the uncontrolled expansion of recreational infrastructure (camping owners) and was recently stopped by law, and active protection – reed planting was successfully applied (Zostera, 2024).

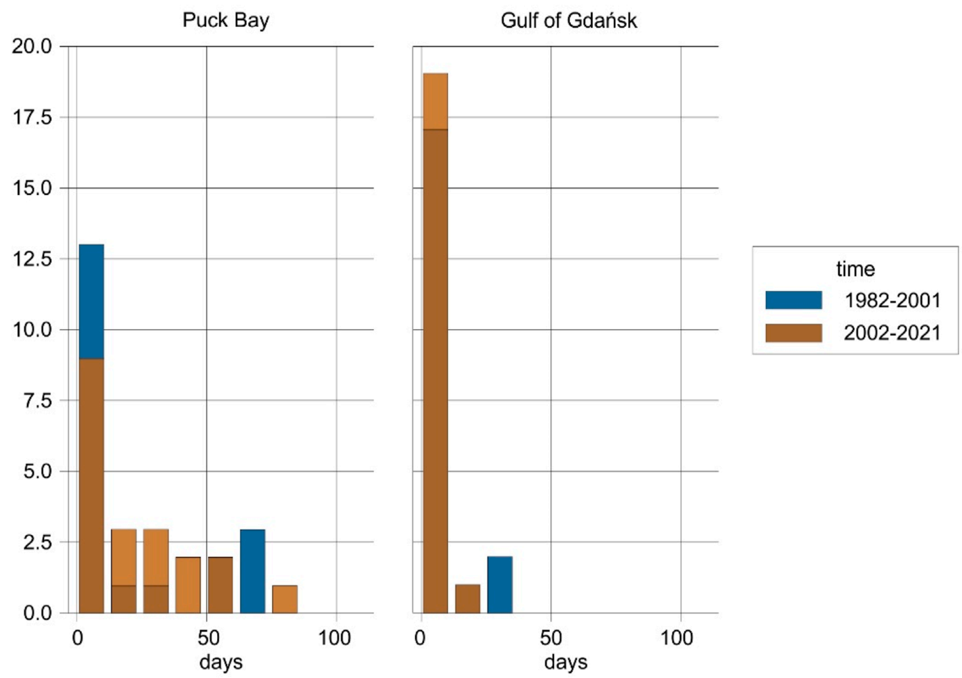

FIGURE 6
The number of ice days during the periods 1982–2001 and 2002–2021.

Biogeochemical change in water column

Depending on the wind speed and direction as well as the freshwater discharge, the river water plume may extend from 9 to 27 km horizontally from the river mouth and from 0.5 to 12 m vertically in the water column. Due to the predominance of westerly winds, the Vistula River waters are mostly directed eastward and then spread to the northeast being introduced into the anticyclonic circulation of the surface waters in the Baltic Proper (Matciak and Nowacki, 1995). The Vistula River, draining large and highly agriculturally transformed catchment, is a great source of nutrients to the Gulf of Gdańsk. This triggers primary production in the region, which between 1993 and 2018 was on average 6%–17% higher and started about 1 month earlier than in the open waters of the southern Baltic Sea (Zdun et al., 2021). As a consequence, during the productive season, the surface waters of the Gulf of Gdańsk are often oversaturated with O_2 and undersaturated with CO_2 (Stokowski et al., 2021) thus performing important environmental functions, namely, being a source of O_2 to the atmosphere and a sink for atmospheric CO_2. By contrast, during winter Stokowski et al. (2021) found the surface waters in the Vistula River plume to be close to saturation or slightly undersaturated with O_2 and oversaturated, sometimes significantly, with CO_2 as a result of high CO_2 levels in the Vistula waters accumulated in the course of terrestrial organic matter remineralization.

The measures taken in recent decades, mostly within the HELCOM framework, resulted in a substantial reduction in riverine nutrient loads to the Baltic Sea (Kuliński et al., 2022). For the Vistula River, the flow normalised loads of total phosphorus decreased from 7,700 tons P/year in 1993 to ca. 5,000 tons P/year between 2013 and 2014. An even larger drop was found for phosphates, for which loads decreased by at least 50%, from 4,000 to 4,900 tons P/year in the 1990s to ca. 2,000 tons P/year between 2013 and 2014. A substantial reduction has been also observed for total nitrogen, for which the flow normalized loads declined from 125,000 tons N/year in 1988 to ca. 74,000 tons N/year between 2013–2014 (Pastuszak et al., 2018). This small response in productivity of the Gulf of Gdańsk to the reduction in nutrient loads is not a region-specific phenomenon but is a consequence of the biogeochemical changes occurring in the entire Baltic Proper. In short, eutrophication of the Baltic waters, triggered in the second half of the 21st century by the high nutrient input (with its maximum in the 1980s), caused the expansion of hypoxic and anoxic bottom waters in the Baltic. Such conditions favoured nitrogen removal from the system through denitrification and hampered phosphorus burial in sediments (higher P recycling in the system and additional P release from sediments that turned to anoxic). This led to the shift in N:P ratio and, consequently, a higher P availability for the after-spring-bloom period, which was beneficial for N_2-fixing cyanobacteria additionally stimulated by the rising temperatures. In that way, the Baltic Proper, including the Gulf of Gdańsk, has been pushed into "a vicious circle" – a mechanism of self-sustaining eutrophication (Vahtera et al., 2007; Kuliński et al., 2022).

Oxygen conditions above the oxycline are good, with an average DO value of 12 mg/L, characterized by significant seasonal variability, with two maxima in March/April and November (Rak et al., 2020). The oxycline begins at a depth of 60 m, with a permanent oxygen deficit (below 4 mg/L) reached at a depth of

85 m. In the bottom layer, the average DO drops below 2 mg/L. Similarly to salinity and temperature, oxygen conditions below the oxycline are shaped by MBI inflows from the North Sea. In contrast to upstream basins (Bornholm Basin), the increase in DO due to inflows is short-lived (Rak et al., 2020). Argo float profiling, conducted at a high frequency (1-2 days), reveals that even small baroclinic inflows reach the Gdańsk Basin and may influence both oxygen and halocline conditions in this area (Walczowski et al., 2020).

The oxygen deficits in the bottom waters exist mostly in the central and northern parts of the Gulf Gdańsk, the so-called Gdańsk Deep region, where the water column is permanently stratified, and sediments are rich in organic matter. The stratification of the water column with a halocline occurring at a depth of approx. 50–70 m hampers the vertical mixing and is the root cause of the hypoxia and anoxia occurring in the deep waters (Rak et al., 2020). Although the occurrence of oxygen deficits was known for the Gdańsk Deep already from the 1960s; their extent and frequency have increased ever since, just as it was observed for the entire Baltic Sea (Hansson and Viktorsson, 2023). On the other hand, the shallow parts of the Gulf of Gdańsk are generally free from hypoxia and anoxia as the water column is well-mixed to the bottom. This also refers to the inner part of the Gulf of Gdańsk that is well-oxygenated, although partially separated from the open sea circulation by the Hel Peninsula (Pryputniewicz-Flis et al., 2022). Still, several short-lasting (<4 days) episodic hypoxic events have been identified off the southwestern coast of the Gulf of Gdańsk at a depth of 7-8 m (Brzana et al., 2020). These events have been recorded in the vicinity of the manmade concrete foundations (part of the torpedo testing complex from World War II) that likely influence the natural water circulation and organic matter sedimentation in the region. Still, along with the climate warming and thus an increasing potential for the seasonal occurrence of sharp thermal stratification, the coastal episodic hypoxia may start to occur more often in the Gulf of Gdańsk in the future, as it has already been observed for the Stockholm Archipelago and the Finnish Archipelago Sea (Conley et al., 2011).

Sediment alterations – biogeochemical, industrial, and natural sedimentation

The Gulf of Gdańsk is impacted by numerous anthropogenic stressors related to the industrial, traffic, municipal, and agriculture activities (Zaborska et al., 2019; HELCOM, 2023); thus, the anthropogenic influence on the chemical composition of its sediments seems to be evident. The sedimentary material in the Gulf of Gdańsk originate from moraine cliff erosion, riverine transport and human activity. The rate of sediment accumulation and distribution of sediments on the seabed is dependent on a number of factors such as the sources of sediments, intensity of biological processes, depth of seabed with its geological composition, and local hydrodynamic regimes (Szmytkiewicz and Zalewska, 2014). The most dynamic areas are the shallow coastal zones with a dominance of sandy sediments. The organic matter in sediments of the study area shows stabilization in the transect from shallow areas to depositional ones, as a result of biochemical stability of the terrestrial fraction (Winogradow and Pempkowiak, 2018). Fine grained silt-clays, rich in OM are deposited in the central and northern (deepest) part of the Gulf of Gdańsk and occur also in front of the Vistula outlet (Uścinowicz, 2011). The data presented by Winogradow and Pempkowiak in 2018 show that the organic carbon burial rate in the Gdańsk Deep represents 49% of the carbon deposited into the sediments of the entire Gulf.

Hazardous substance spatial distribution in the Gulf is highly variable and is substance-, location- and/or environmental conditions/sediment properties dependent. The most polluted sediments are identified in the Vistula estuary, receiving large inputs of riverine transported pollutants, and in the Puck Bay semi-closed area with numerous pollution sources and little water exchange and in Gdańsk Deep - a depositional area (Staniszewska et al., 2016; Filipkowska et al., 2018; Zaborska et al., 2019). The elevated level of contamination in coastal areas is also observed in the vicinity of shipwrecks and munition dumpsites (Rogowska et al., 2015). The general picture is that hazardous substance levels are near background values or slightly elevated (thus posing no or low risk to wildlife), except for the above-mentioned specific areas, where high values have been periodically observed (Zaborska et al., 2019; Rogowska et al., 2015; Staniszewska et al., 2016). The social, political and economic system initiated in the 1990s in Poland combined with international restrictions or even prohibitions on using the so-called legacy pollutants resulted in the decrease in contaminant emissions followed by the downward trends in atmospheric deposition and partially, in waterborne input (HELCOM, 2023). Despite this, based on the results obtained for undisturbed sediment cores from the depositional area- Gdańsk Deep, common pattern in the temporal trends of individual contaminant concentration is hard to observe. Moreover, the reliable assessment of certain pollutant changes over time is difficult due to the uncertainty and scarcity of the results (HELCOM, 2023). According to the latest findings the decrease in Hg concentrations after the 1990s (close to 40%) seems to be apparent (Jędruch et al., 2023). The concentrations of other metals (Pb, Cd, and Zn) are not always decreasing (e.g., Zalewska et al., 2015), fluctuating since the 1990s without showing any clear trend, which might be related directly to the considerable amounts of heavy metals discharged to the Gulf by the Vistula River, but also to the secondary sources like surface run-off and/or sediment resuspension. Despite the ban on persistent chlorinated hydrocarbons (e.g., organochlorine pesticides, PCBs) these compounds can still be detected in the entire Gulf; however, a general decline of chlorinated substances is obvious (Zaborska et al., 2019; Pazikowska-Sapota et al., 2020). A declining trend in the deposition of some other organic contaminants (nonyl phenols and tributyltin) in the Gulf of Gdańsk sediments has also been observed by Kot-Wasik et al. (2004), Filipkowska et al. (2018). However, harbours, shipping routes and anoxic sediments may still be significantly contaminated with organotin compounds. On the other hand, Staniszewska et al. (2016) reported sharp increase in phenolic compounds in the youngest deposits (from about the last 10–15 years) in the Gdańsk Deep, which could be associated with the increase in the areal extent and volume of hypoxia and anoxia. There was no such distinct temporal variation in the polycyclic aromatic hydrocarbons (PAHs) concentrations over the last 100 years. Similar patterns were also reported for other areas of the Baltic Sea (Lubecki et al., 2019). This phenomenon may be explained by the predominant number of PAHs originating from pyrogenic sources such as domestic burning of coal and/or wood for heating purposes.

As described above, brief overview of the available literature data shows that although restrictions or prohibitions on using all legacy pollutants resulted in the decrease in contaminant emission, their concentrations are not always decreasing. For example, reemission and remobilization of contaminants accumulated over the years on land and at sea bottom is expected (Szefer and Szefer, 1991; Zaborska et al., 2019; Jędruch et al., 2023). Such phenomena were already observed for mercury (Saniewska et al., 2018). The enhanced remobilization of pollutants may result in accelerated accumulation in the trophic chain. The climate-driven changes may also influence the eutrophication and/or organic matter preservation in a greater extent than the direct anthropogenic impact, which was suggested by Szymczak-Żyła and Kowalewska (2009) based on pigment analyses (used as proxies of eutrophication) in sediment cores taken from the Gdańsk Basin.

Pelagic life diversity, primary production

The number of microplankton (below 200 mkm size) species found in the water column of the Gulf of Gdańsk (Baltic Proper) area exceeds 739 (Hallfors, 2004) taxa. This number refers to the southern Baltic Sea as defined by HELCOM. For the Gulf of Gdańsk alone, this number is lowered to 245 taxa (GIOŚ database), among those only two alien or invasive taxa are reported (Olenina et al., 2010). Twenty years of the observations of chlorophyll concentration in the waters of the Gulf of Gdańsk showed a slight downward trend (−0.206 mkg Chl a/dm3/year (Stoń-Egiert and Ostrowska, 2022). The number of taxa is variable and depends on a season and year. However, the high reduction in nutrient loads (Pastuszak et al., 2018) has not resulted in a substantial change in primary production so far. The level of primary production in southern Baltic slightly lowered since the 1990s (Renk et al., 2000) ranging between 32 and 2297 (mean 1210 mgC/m^{-2} /day) while slightly higher values 3820 mgC/m^{-2}/day were also reported (Witek et al., 1997; Janecki et al., 2023). According to the review by (Zdun et al., 2021), unlike in the open Baltic Sea, where a decline in primary production is observed, the Gulf of Gdańsk production remains unchanged, with a slight upward trend in spring and a downward trend in summer and autumn.

Benthic life – habitats, and species

The seabed habitats remained stable over the last 40 years, as the Gulf of Gdańsk is dominated by just three main types of habitats – vegetated sand in shallow and sheltered part, sand, muddy sand and mud in open and deeper parts of the area (Figure 1). The small area habitats (e.g., small stony reefs or reeds belts at the coast) were not marked in the map and are presented in Table 1. Over the last decades, some habitats expanded (seagrass beds, reeds belt, perennial algae on the stones) and some shrank e.g., toxic muddy bottom below halocline (Warzocha, 1995; Warzocha et al., 2001; 2018; Sokołowski et al., 2015; Sokołowski et al., 2021; Błeńska and Osowiecki, 2015; Brzana and Janas, 2016; Gic-Grusza et al., 2009). Consequently, the important bioturbator *Scoloplos armiger* and some other oxygen demanding and cold-water species (*Astarte* bivalves) are practically absent in the area (Osowiecki et al., 2008; Warzocha et al., 2018). In general, a set of macrobenthic and nectobenthic species increased – with twelve species that settled in the area during the last 40 years (Table 2) and no species lost except one - the bladderwrack – *Fucus vesiculosus*; however, the drifting form of this algae apparently reappeared (Kotwicki et al., 2024; Bałazy et al., 2024) along with the reappearance of rare perennial rhodophycean – *Coccotylus brodiei* (Zgrundo and Złoch, 2022). Interesting is the increase in the abundance of big crustaceans (two species of shrimps and American crab – *Palaemon elegans, Palaemonetes varians, Rhitropanopaeus harrisi*), that were very rare in the 1980s. Small isopods associated with mixed and hard bottom are less frequent than in the 1980s. The lack of records of some species that are difficult to identify for non-taxonomists might be the cause of the absence of species reported as rare in the 1980s (*Gammarus locusta, G. inaequicauda*) Jęczmień and Szaniawska (2000). Generally, the local biota belongs to the very resilient to the environmental alterations (Włodarska- Kowalczuk et al., 2010).

Fishes and fishery

The fish assemblage of the Gulf of Gdańsk ecosystem is spatially variable. The greatest diversity of species occurs in the shallow water part of the Puck Bay and the Vistula River estuary (Draganik, 1996; Draganik et al., 2005). The most significant negative impact on the fish assemblage refers to anadromous species (Atlantic salmon *Salmo salar,* sea trout *Salmo trutta*, European whitefish *Coregonus lavaretus)* - hydrotechnical construction on rivers, for freshwater spawning species (northern pike *Esox lucius*, roach *Rutilus rutilus*) - drainage of coastal areas (Bartel et al., 2016). For species associated with submerged meadow habitat (broadnosed pipefish *Syngnathus typhle,* straightnose pipefish *Nerophis ophidion*) – the loss of habitat area (Margoński, 1994; Andrulewicz and Witek, 2002; Bartel et al., 2007; Psuty, 2022; Psuty et al., 2023). These conditions together with the environmental pollution facilitated the expansion of eurytopic species not affected by the fishing pressure - three-spined stickleback *Gasterosteus aculeatus* and ninespine stickleback *Pungitius pungitius*. As early as in the late 1980s, they began to dominate the coastal pelagic zone (Sapota and Skóra, 1996; Sapota, 2001). In the 1990s, the roundhead goby *Neogobius melanostomus* colonised the entire coastal zone over the course of about 20 years (Sapota and Skóra, 2005). The species is now a permanent component of the ecosystem of the coastal zone of the Gulf of Gdańsk and serves as important food for piscivorous birds and predatory fish but is not present in numbers sufficient for profitable fishery exploitation. At about the same time, the previously sizeable population of the eelpout *Zoarces viviparus* declined (Psuty-Lipska, 2000).

In the last two decades, two distinct processes were observed in the fish assemblage of the Gulf of Gdańsk: the recovery of fish populations associated with submerged meadows and a further decline in commercial fish stocks. Broadnosed pipefish and straightnose pipefish have become numerous, despite the persistent dominance of stickleback. This was connected not only with the restoration of submerged meadows, but also with the fish reproduction strategy, which protects the fry during their most vulnerable period of life, thus reducing the predation pressure of stickleback fish. The habitat degradation is the main barrier to the

TABLE 1 Habitat types in the Gulf of Gdansk, with the score of three types of values associated.

Gulf of Gdansk – habitat type – EUNICE level 4	Key genus	Area km2	Socioeconomic value	Cultural value	Ecological value
			1,2,3 – low, medium, high	1,2,3 – low, medium, high	1,2,3 – low, medium, high
Benthic habitats					
Baltic supralitoral sandy beach	*Talitrus*	2	3	3	2
(MA531) Baltic hydrolittoral sandy substrata characterized by emergent vegetation	*Phragmites*	0.16	2	1	3
(MA532) Baltic hydrolittoral sand characterised by submerged rooted plants	*Chara*	0.2	1	1	3
(MB131) Perennial algae on Baltic infralittoral rock and boulders	*Furcellaria*	1.97	1	2	3
(MB532 & MB 332) Baltic infralittoral sand characterised by submerged rooted plants	*Zostera*	1134	3	3	3
(MB632) Baltic infralittoral mud sediment characterised by submerged rooted plants	*Zanichella*	0.1	2	1	3
(MC13G) Baltic circalittoral hard anthropogenically created substrates	*Balanus*	0.1	3	2	1
(MC63) Baltic circalittoral mud	*Macoma*	1854	3	1	2
Hypoxix & unoxic infralittoral muds	*Nematoda*	3874	1	1	1
river mouths coarse sediment	*Corophium*	2	3	3	3
Pelagic habitats					
shallow surface coastal waters above pycnokline	*Acartia*		3	3	3
shallow near bottom waters below pycnokline	*Eukhronia*		2	1	2

recovery of pike and perch populations spawning in the Puck Bay as it was observed in other Baltic areas (Nilsson, 2006).

Climate change and excessive fishing pressure have contributed to the decline of the most important species to the Gulf of Gdańsk fishery - Eastern Baltic cod *Gadus morhua* (Voss et al., 2019). Its fishing has been suspended in the Baltic since 2019 and, for the time being, there are no signs of the population recovery. No other fish predator has taken its place. Turbot *Scophthalmus maximus*, which would have had a chance to occupy this niche in the coastal zone, is an increasingly rare species. Fishermen no longer target this species, but undersized turbot are a by-catch in flounder fisheries (Draganik et al., 2005). The pike population of the Puck Bay has not yet recovered, despite intensive stocking in the last decade (Psuty et al., 2023). However, access to freshwater spawning grounds has not been provided. Despite many years of efforts under the Polish Marine Stocking programme, salmonid populations have declined (Dębowski, 2018). In the coastal zone of the Gulf of Gdańsk, sea trout are caught in particular, but traditional fishing methods have become unprofitable due to the pressure from the increasing grey seal population. The Atlantic mackerel *Scomber scombrus* enter the Gulf of Gdańsk sporadically and garfish *Belone belone* migrate to the Puck Bay only for a short spring spawning season (Sea Fishery Institute unpublished data).

Out of the remaining commercial species, the drastic decrease in the European eel (*Anguilla anguilla)* availability is caused by the stocking only. The prospect of a fishing ban on this once most valuable species for fishermen is imminent (Moriarty and Dekker, 1997; Hanel et al., 2019). The availability of herring

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TABLE 2 Selected benthic species from the Gulf of Gdansk, with the score of three types of values associated.

Species group	Latin name	Status 1980-ties	Status 2020- ties	Functional trait, remarks	Socioeconomic value	Cultural value	Ecological value
					1,2,3 – low, medium, high	1,2,3 – low, medium, high	1,2,3 – low, medium, high
macro algae	*Fucus vesiculosus*	rare	Extinct	Key habitat builder	3	3	3
	Phyllophora brodiaei	Rare, declining	Rare, returning	Habitat builder	3	3	3
	Furcellaria lumbrilicaris	Rare, declining	Returning, common	Habitat builder	3	3	3
	Chara spp	Rare, declining	Rare, returning	Habitat builder	2	1	3
	Ectocarpacae (Pilayella & Ectocarpus)	Dominant, very common	Declining, common	algal mats formation, biomass accmulation	1	1	1
	Ceramium sp	common	common	algal mats formation, biomass accmulation	1	1	2
	Cladophora sp	Dominant, very common	common	algal mats formation, biomass accmulation	1	1	2
	Enteromorpha sp	Dominant, very common	common	algal mats formation, biomass accmulation	1	1	2
	Ulva lactuta	common	common	algal mats formation, biomass accmulation	2	1	2
plants	*Zostera marina*	Rare, declining	Returning, common	Key habitat builder, sediment stabilisation and oxygenation	3	3	3
	Phragmites sp	Declining	returning	habitat builder, sediment stabilisation	3	3	3
	Ruppia sp	Declining	returning	habitat builder, sediment stabilisation	2	2	2
	Zanichella sp	Declining	returning	habitat builder, sediment stabilisation	2	2	2

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TABLE 2 (*Continued*) Selected benthic species from the Gulf of Gdansk, with the score of three types of values associated.

Species group	Latin name	Status 1980-ties	Status 2020- ties	Functional trait, remarks	Socioeconomic value	Cultural value	Ecological value
Polychaeta	*Scoloplos armiger*	rare	Extinct from the area	Key habitat builder, sediment stabilisation and oxygenation	3	1	3
	Hediste diversicolor	common	common	micropredator	3	2	3
	Marenzellaria viridis	Absent till 1989	common	filtrator	2	1	2
	Marenzelleria neglecta	Absent till 1989	common	filtrator	2	1	2
	Pygospio sp	common	common	filtrator	1	1	2
Mollusca	*Rangia cuneata*	absent	Locally common and abundant	Filtration feeder, carbon and biomass accumulation	2	1	2
	Cerastoderm glaucum	common	common	Filtration feeder, carbon and biomass accumulation	2	3	2
	Dreissena polymorpha	rare	rare	Filtration feeder, carbon and biomass accumulation	3	2	1
	Lymnaea stagnalis (L.)	relatively common	relatively common	herbivore on microphytobenthos	1	1	2
	Macoma balthica (L.)	dominant, very common	dominant, very common	Filtration feeder, carbon and biomass accumulation	2	2	3
	Mya arenaria L	common	common	Filtration feeder, carbon and biomass accumulation	3	2	3
	Mytilus trosulus edulis	dominant, very common	very common	Filtration feeder, carbon and biomass accumulation	3	2	3
	Radix auricularia	rare	rare	herbivore on microphytobenthos	1	1	2
	Viviparus contectus	relatively common	relatively common	herbivore on microphytobenthos	1	1	2
	Viviparus viviparus	relatively common	relatively common	herbivore on microphytobenthos	1	1	2
	Hydrobia sp	dominant, very common	very common	herbivore on microphytobenthos	1	1	2
	Theodoxus fluviatilis	relatively common	rare	herbivore on microphytobenthos			

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TABLE 2 (*Continued*) Selected benthic species from the Gulf of Gdansk, with the score of three types of values associated.

Species group	Latin name	Status 1980-ties	Status 2020-ties	Functional trait, remarks	Socioeconomic value	Cultural value	Ecological value
Crustacea	*Balanus improvisus*	common	common	Filtration feeder, carbon and biomass accumulation	2	2	3
	Bathyporeia pilosa	common	common	Micropredator, prey component of fish diet	3	1	3
	Crangon crangon	common	common	Micropredator, prey component of fish diet	3	3	3
	Cyathura carinata	relatively common	rare	Micropredator, prey component of fish diet	1	1	2
	Eriocheir sinensis	rare	rare	Carrion feeder, micropredator	3	3	3
	Gammarus oceanicus	rare	rare	Micropredator, prey component of fish diet	2	1	2
	Dikerogammarus haemobaphes	absent	rare	Micropredator, prey component of fish diet	1	1	1
	Pontogammarus robustoides	absent	rare	Micropredator, prey component of fish diet	1	1	1
	Obesogammarus crassus	absent	rare	Micropredator, prey component of fish diet	1	1	1
	Gammarus salinus	common	common	Micropredator, prey component of fish diet	2	1	2
	Gammarus tigrinus	absent	common	Micropredator, prey component of fish diet	2	1	2
	Gammarus zaddachi	common	common	Micropredator, prey component of fish diet	2	1	2
	Hemimysis anomala	Absent	rare	Micropredator, prey component of fish diet	2	1	2
	Idothea balthica	common	common	herbivore	2	1	3
	Idothea chelipes	common	rare	herbivore	2	1	3
	Mesidotea entomon	common	rare	Micropredator, key prey component of large fish diet	3	2	3
	Neomysis integer	common	common	Micropredator, prey component of fish diet	3	1	3
	Palaemon adspersus	rare	common	Micropredator, prey component of fish diet	3	2	2

(Continued on the following page)

TABLE 2 (*Continued*) Selected benthic species from the Gulf of Gdansk, with the score of three types of values associated.

Species group	Latin name	Status 1980-ties	Status 2020-ties	Functional trait, remarks	Socioeconomic value	Cultural value	Ecological value
	Palaemon elegans	absent	common	Micropredator, prey component of fish diet	3	2	2
	Praunus flexuosus	rare	rare	Micropredator, prey component of fish diet	3	1	2
	Rhitropanopeus harrisi	rare	common	Carrion feeder, micropredator	2	3	3
Pisces	*Anguilla anguilla*	relatively common	rare	medium benthic predator, carrion feeder	3	3	1
	Belone belone	rare	relatively common	medium pelagic predator	3	3	2
	Clupea harrengus	common	common	pelagic micropredator	3	3	3
	Cyclopterus lumpus	rare	rare	medium benthic predator	1	2	2
	Esox lucius	rare	rare	medium pelagic predator	3	3	2
	Gadus morhua	common	rare	medium pelagic and benthic predator	3	3	3
	Gasterosteus aculeatus	dominant	common	micropredator, prey component of cormorants	1	1	1
	Myxocephalus scorpius	common	rare	benthic micropredator	1	1	2
	Neogobius melanostomus	absent	common	benthic micropredator	2	1	2
	Nerophis ophidion	rare	common	benthic micropredator	1	1	3
	Platichthys flesus	common	rare	medium benthic predator	3	3	2
	Pomatoschistus microps	rare	rare	benthic micropredator	1	1	3
	Pomatoschistus minutus	rare	rare	benthic micropredator	1	1	3
	Psetta maxima	rare	rare	medium benthic predator	1	3	2
	Pungitus pungitus	common	rare	pelagic micropredator	1	1	2
	Sprattus sprattus	common	common	pelagic micropredator	3	3	3
	Syngnathus typhle	rare	relatively common	benthic micropredator	1	2	3
	Zoarces viviparus	rare	rare	medium benthic predator	3	2	3

TABLE 3 Charismatic species in the Gulf of Gdansk with the score of three types of values associated.

Targeted group	Latin name	Status 1980-ties	Status 2020- ties	Functional trait, remarks	Socioeconomic value	Cultural value	Ecological value
					1,2,3 – low, medium, high	1,2,3 – low, medium, high	1,2,3 – low, medium, high
sea mammals	*Phocaena phocaena*	rare	rare	top predator, visitor	1	3	2
	Halichoerus grypus	absent	relatively common	top predator, visitor	2	3	2
	Phoca vitulina	absent	rare	top predator, visitor	1	3	2
	Phoca hispida	absent	rare	top predator, visitor	1	3	2
seabirds	*Anas platyrhynhos*	common	common	benthic feeder, wintering	2	2	2
(nesting, feeding and wintering at sea)	*Branta canadensis*	rare	rare	benthic feeder, wintering	1	3	1
	Bucephala clangula	common	common	benthic feeder, wintering	1	3	2
	Calidris alpina	common	common	coastal micropredator	1	2	2
	Charadriu hiaticula	common	common	coastal micropredator	1	2	2
	Chroicocephalus ridibundus	common	common	surface carrion feeder and predator	1	2	2
	Clangula hyemalis	common	common	benthic feeder, wintering	1	3	2
	Cygnus cygnus	rare	rare	benthic feeder, wintering	1	3	2
	Cygnus olor	common	common	benthic feeder, wintering	1	3	1
	Fulica atra	common	common	benthic feeder, wintering	1	2	2
	Larus argentatus	common	common	surface carrion feeder and predator	1	2	1
	Melanitta fusca	common	rare	benthic feeder, wintering	1	2	2
	Melanitta nigra	common	rare	benthic feeder, wintering	1	2	2
	Mergus albellus	rare	rare	benthic feeder, wintering	1	2	2
	Mergus merganser	relatively common	relatively common	benthic feeder, wintering	1	3	2

(Continued on the following page)

TABLE 3 *(Continued)* Charismatic species in the Gulf of Gdansk with the score of three types of values associated.

Targeted group	Latin name	Status 1980-ties	Status 2020- ties	Functional trait, remarks	Socioeconomic value	Cultural value	Ecological value
	Phalacrocorax carbo	relatively common	common	top predator	1	3	2
	Sommateria mollissima	common	rare	benthic feeder, wintering	1	2	2
	Sterna hirundo	rare	rare	surface carrion feeder and predator	1	2	2

Clupea harengus and perch *Perca fluviatilis* for fishing is strongly dependent on the fecundity of single generations, which means that these stocks are also showing signs of overfishing. Only flounder *Platichthys flesus* stocks remain relatively stable, although according to fishermen the size of their population is lower than 20 years ago (Rakowski et al., 2020).

Charismatic species

Seabirds (both nesting and wintering) and sea mammals (all seasonal migrants) in the area are almost all under strict protection, and a set of species known from the1980s increased with no species loss (Table 3). The extensive Baltic monitoring for the common porpoise (*Phocaena phocaenat*) does not indicate a change in the abundance of this rare species in the Central Baltic (SAMBAH, 2024). Grey seal (migrants) and black cormorant (nesting) are more abundant in 2020s compared to the previous time. The abundance of wintering seabirds (diving ducks) decreased in southern Baltic, which might result from milder winters and shorter migration moves (Gedas, 2001; Skov et al., 2011); however, substantial mortality in fishing nets was also reported (Stempniewicz, 1994; Marchowski, 2021). The monitoring of wintering birds in Southern Baltic (including the Gulf of Gdańsk) shows a decrease in two species (*Clangula hyemalis* and *Larus argentatus*) and increase in three (*Melanitta nigra, Uria aalge, Gavia stellata*) – between 2012 and 2018 (Chylarecki et al., 2018).

Public health

From June to the end of August, the Gulf coastal waters are key touristic areas, and hence are being monitored by the state sanitary authorities, for the safety of bathing waters. At the beginning of 1980s, there were regular summer beach closure decisions due to the high level of bacterial contamination (coli index) – Sobol and Szumilas (1989), Sobol and Szumilas (1992), Sobol and Szumilas (1998). In the 1990s, 50% of the 37 monitored coastal bathing sites was closed to the public (IMMT, 1995). After the introduction of water cleaning facilities, the coli index is very rarely high, with no closure decisions after 2000 (Szumilas et al., 2004). On the other hand, the beach closure due to potentially toxic bluegreen algae blooms happens every summer (Sanepid, 2024). Although currently it is not considered a significant threat to the public health in the Gulf of Gdańsk, there are already indications that climate change will increase the abundance of pathogenic *Vibrio* bacteria in the Gulf shallow waters. This may cause infections in humans either through direct contact with marine water (i.e., through swimming or bathing) or the consumption of raw food (Bartelt et al., 1982; Amato et al., 2018; Riedinger et al., 2024). In the long run, these might become a potential issue not only for the local healthcare system but also for the tourism sector; although at present it is overridden by other environmental and economic issues, the possible implications of pathogenic bacteria growing communities are already acknowledged by the representatives of the local tourism sector (Wolska et al., 2022; Rakowski et al., 2023).

TABLE 4 Four summary characteristics of the Gulf of Gdansk.

Values	0- None	1-Low	2-Medium	3-High	4-Very high
Socio cultural values					
spiritual value, religious, emotional	none	few narratives	known places	Nationaly famous places with sea history	most visited churches, marine narratives
traditional value, historical, etnographic	none	professional knowledge	known places	famous places with sea history	most celebrated sites for etnography
esthetic value, popular views, arts	not recorded	small group recognition	known places	famous places	most photographed and painted sites
socialising, popular site	not recorded	small group recognition	known places	famous sites	most visited sites
educational, scientific, inspirational value	not recorded	small group recognition	known places	often visited and reported sites	key training sites for students & researchers
health, fitness, recreation	not recorded	small group recognition	known places	often visited and reported sites	most popular coastal recreation & sport centers
Socio-economical values					
commercial fishery landings	not recorded	mariginal	profitable	important fishing areas for pelagic	key fishing areas for demersal and pelagic fish
recreational fishery	not recorded	mariginal	profitable	important fishing areas for pelagic	key fishing areas for demersal and pelagic fish
stationary tourism (hotels)	not recorded	low, small scale	medium	high density of places offered	large scale hotels, highest density
small scale tourism (camping etc.),beach bars, coastal service	not recorded	small scale	medium	high density of places offered	highest density
science, education, experimental and testing areas	not recorded	places of low importance	places of medium importance	places commonly used for science & tests	places of key projects and tests
harbor shipyard & associated installations	not recorded	small scale, not lasting infrastructure	small, stable harbors	important harbors	top country harbors and installations
shipping and yachting routes	occasional	sport boats and small scale crafts	secondary shipping route for large and small vessels	important shipping route	key shipping route of large vessels
space for cables and pipelines	not recorded	temporary installations	secondary areas for seabed infrastructure	important cables and pipelines	key pipelines and installations oin the seabed
extraction or deposition of sediments	not recorded	rare extraction	occasional activity	often extracted	regular extraction-waterways
gas and oil concessions	not recorded	potential disputed	potential claimed	registred	exploited
culture & entertainment facilities	not recorded	rare events organised	small scale events	regular large enents	key profit based infrastructure
sea sports areas	not recorded	rare events organised	small scale events	regular large enents	key profit based infrastructure
Human impact/Disturbance					
local population and tourism encroachment	no or single visitors over most of the area	low population density, few tourists per square	medium population density, frequent tourists most of the area	high population density, localised mass tourism	large city, mass tourism over large area

(Continued on the following page)

TABLE 4 (*Continued*) Four summary characteristics of the Gulf of Gdansk.

Values	0- None	1-Low	2-Medium	3-High	4-Very high
fishery (fixed nets, pelagic trawling)	no commercial, sport or artisanal fishery	sport fishery only	artisanal, small boat fishery, single fixed nets on the area	commercial- trawl fishery, intensive artisanal fishery, numerous fixed nets	intensive commercial fishery, fixed nets cover most of the area
other disturbance – shipping, noise	silent area, away from antropgenic activity	infrequent noise of low level, small boats only	frequent noise, medium ship traffic	frequent noise, harbour, important shipping area	constant noise, main shipping line, large harbor, underwater installations
Ecological Valuation (seabed)					
species richness related to undistrurbed habitat	low, impoverished species set	lack of key species	key speciesa are present	majority of species are present	full species set known from this habitat
presence of habitat builders/engineers	none	bioturbators only	some encrusting – bushy species	habitat builders present	numerous habitat builders
presence of rare and protected species	none	ocasionaly observed	present	often observed	regular occurrence, key area
naturalness level	very low resemblance to natural system	serious change in the habitat	medium disturbance, visible deviation from undistrubed site	small scale disturbance in the past	no human disturbance recorded
ability for recovery	very fast recovery	usually seasonal recovery	usually annual recovery	multiyear but possible	long, difficult and problematic
presence of large, long living species	none	ocassional presence	large species observed	large species present	numerous long living and large species
area important as breeding – nesting area	none	occasional observation	some species breed and feed here	area used for spawning and nursery	key area for spawning and nursery of migrant species
important area for gregariousness – biomass concentration	lowest recorded values in the area	low values	medium values	high biomass and density	highest recorded densities and biomass of the area

Valuation of each square on the map–Figure 7 based on authors expert judgement. All values are relative to the studied area only (i.e., presents the score from low to high within the Gulf of Gdansk).

Tourism and economic development

The waters of the Gulf of Gdańsk and the adjacent land have always been popular among tourists and visitors, and they continue to be so (Kozak, 2006; Nędza and Matlingiewicz, 2022). Its most sheltered part (the Puck Bay) is not only popular for "3s" mass tourism but is also one of the largest sites for water sports in the South Baltic (Węsławski et al., 2010). With the increasing wealth of society (Borkowski, 2019) accompanied by a constant increase in active tourism (Szwichtenberg, 2019), there is an increasing pressure for further development of the tourism-related services and coastal infrastructure. Indeed, during the summer season, some coastal municipalities receive several times more visitors than the number of their permanent residents (Borkowski, 2019). These large numbers overwhelm the local tourism infrastructure (Węsławski et al., 2011) and have negative consequences on the real estate market. The prices of housing in the coastal areas, and especially around the Tri-City, are among the highest in Poland, and continue to grow (as cited in: rankomat.pl). Many apartments are bought as high-return investment for short-term rentals, which results in conflicts with local residents (Jasińska, 2019).

On the other hand, many small coastal towns and villages are, effectively, economically dependent on tourism (Krzymiński, 2014). This tourism benefits from the coastal landscapes and marine seascapes (DS, 2012; Sagan and Masik, 2018; DS, 2021). However, the SWOT analysis performed for the Pomeranian province of Poland indicates that the state of natural environment and the increased pressures towards the marine and coastal ecosystems can limit the regional ability to develop and impact negatively the health and wellbeing of the regional residents (DS, 2012; DS, 2021).

This pressure from the tourism sector has two consequences. First, it results in a rapid development of new forms of tourism, including wellness and spa, yachting, diving, biking and nature and cultural tourism (Wendt and Wiskulski, 2017; Szwichtenberg, 2019; Piwowarczyk and Zaucha, 2021). Their availability extends the tourism season beyond the short summer but nonetheless

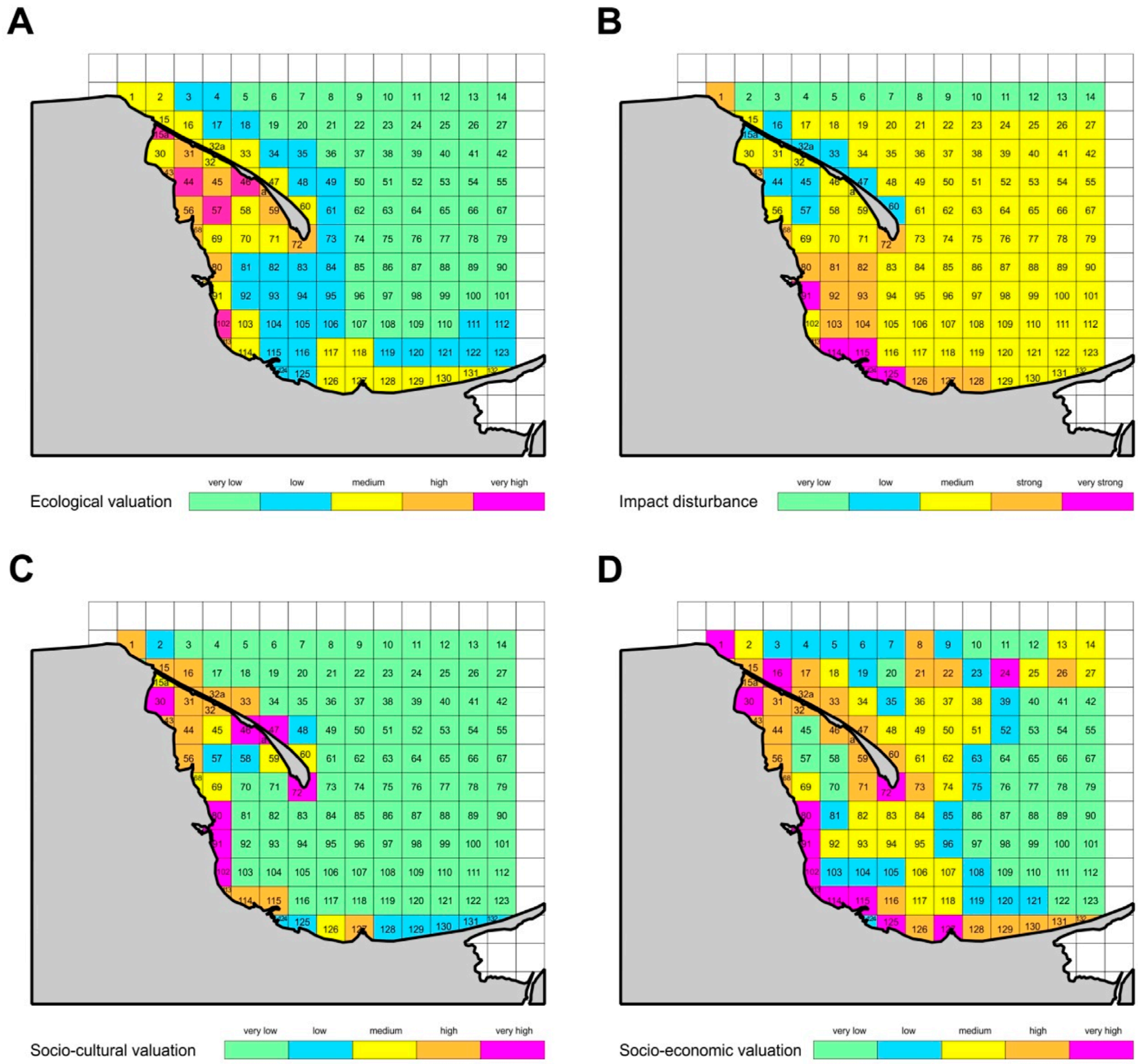

FIGURE 7
Four characteristics of the Gulf of Gdansk as of decade 2014–2024, **(A)** Ecological valuation of seabed from Weslawski et al., 2009 with update, **(B)** human impact/disturbance, **(C)** socio-cultural valuation, **(D)** socioeconomic valuation – criteria taken from Table 4, values after authors expert judgement.

does not prevent the local businesses from maximizing profits in summer at the expense of nature and society (Wendt and Wiskulski, 2017; Piwowarczyk and Zaucha, 2021). Second, the development of tourism infrastructure permanently alters the coastal landscapes and seascapes (e.g., Andrulewicz, 2021). Examples include improving beach access through nourishments, construction of breakwaters, new roads, parking lots, hotels and other facilities such as beach bars and restaurants (Węsławski et al., 2010; Węsławski et al., 2011; Szwichtenberg, 2019; Andrulewicz, 2021). These investments not only alter natural habitats but also threaten the cultural landscape. For instance, old fishery harbours are replaced with concrete constructions of sometimes undefined use, leading to the coastal municipalities losing their specific character (Andrulewicz, 2021). Such pressures are not always properly addressed by the local municipalities (Borkowski, 2019; Andrulewicz, 2021). Oftentimes, the local municipalities lack the tools to fight unauthorized activities of local entrepreneurs, for instance, the extension of camping sites in the Puck Bay or coastline modifications, including beach widening (Wendt and Wiskulski, 2017), and the maritime administration is not always efficient (Wendt and Wiskulski, 2017; Pikner et al., 2022). Sometimes, the municipalities themselves apply for national or European funding for misguided investments (Borkowski, 2019).

Other threats from tourism include excessive noise, boats and vessels not matching the environmental standards, changes in hydrological conditions and mechanical destruction of habitats, including reeds and underwater meadows (Wendt and Wiskulski, 2017; Borkowski, 2019). Indeed, the demands of the tourism sector are the focal point of the human vs ecosystems conflict in the Gulf of Gdańsk, and the carrying capacity of

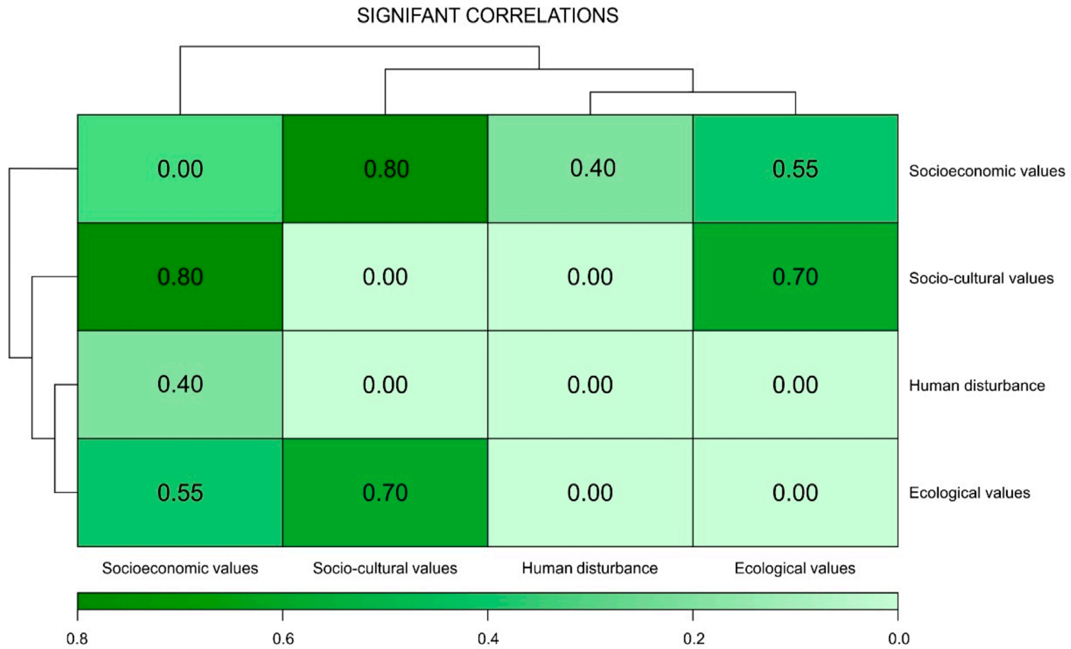

FIGURE 8
Pearson Correlation among characteristics – values presented on Figure 7, values considered listed in Table 4.

the coastal areas has already been exceeded in many places (Kistowski, 2005).

The current managerial solutions are inadequate partially because of the ambiguity of laws and unclear responsibilities of governmental actors (Wendt and Wiskulski, 2017; Szwichtenberg, 2019; Pikner et al., 2022). Local residents, especially those who depend economically on tourism, recognize the need for a shift from mass tourism to more active, culture- or nature-oriented tourism, especially in the most crowded areas of the Gulf of Gdańsk. They postulate providing more tools and more support for local entrepreneurs and introducing limitations for the "big and rich" investors coming from outside the region (Piwowarczyk and Zaucha, 2021).

While the tourism industry plays the most important role in smaller towns, in bigger towns and large cities there are additional pressures coming from the maritime industry. The Pomeranian province strives to become an international transportation hub, aiming to promote the development of shipping, logistics and shipbuilding, also in the context of future off-shore investments (DS, 2021). Two ports of national importance and a number of smaller ports are located on the shores of the Gulf of Gdańsk (Krzymiński, 2014), and maritime and related logistic sectors constitute about 7% and 6%, respectively, of the regional economy (Sagan and Masik, 2014; 2018). Off-shore wind farms promise to provide additional source of revenue and jobs, but this sector is not developing so smoothly and still faces important legal barriers (DS, 2021). Even though none have yet been constructed, the farms already raise concerns, especially among the residents of coastal towns that will be most directly impacted (Laskowicz, 2021).

Since the 1990s, there were attempts to create universal index that will illustrate the health or the quality of marine ecosystem. There were numerous papers on this subject, some dealing specifically with the Baltic Sea (e.g., Tett et al., 2013; Blenckner et al., 2020; HELCOM, 2016; HELCOM, 2023; HELCOM, 2023a). There is an inherited problem for the assessment system that was designed for open ocean and its transfer to the specific brackish, coastal sea. The same is true when the scale is changed from the whole Baltic to the specific area – the Gulf of Gdańsk. That is why, we have summarized our knowledge on the present Gulf of Gdańsk area in the scale of 5 × 5 km squares, addressing each square with four types of phenomena – socio cultural value, socioeconomic value, human disturbance level and ecological value (Table 4). Each of these phenomena was scaled from 0- none to 4 very high value and consisted of several descriptors – see Table 4. In the case of human disturbance (impact), we have used only those effects that are directly dependent on human management. That is why we are not considering global warming that results in stronger water column stratification and resulting oxygen depletion below halocline as well as the freshening of the surface of Baltic waters (Meier et al., 2022). The results shown in a map in Figure 7B, present the current level of anthropogenic impact in the scale of the observed area. The main difference between the cumulative impact presented by HELCOM (2023) and our map (Figure 7B) involves considering tourism and shipping as the stressors. The most changed/impacted are the areas in the vicinity of harbours and large cities as well as main shipping routes and areas of fishery pressure (Figure 7B). The biological–ecological values (EVA – ecological values assessment, inherit biological value not related to the human use) were modified and updated from paper and are presented in Figure 7A. Here, important observation might be drawn – the low disturbance is not necessarily linked to the high ecological value and *vice versa* – areas of high ecological value are not always free from human impact (see the sectors near Gdynia harbour – 80, 91, 102–115) in Figure 7. Two additional characteristics of the area include socio economic values (those directly transferred to market economy) – Figure 7C and sociocultural values (representing public perception of the area) –Figure 7D. The criteria for such evaluation are listed in Table 4. Clearly, the economically important areas are those next to harbours, fishing grounds and most visited tourist resorts; to some extent those areas correspond to the places most valued by visitors. The Pearson correlation calculated in R programme shows the relatively strong correlation between socio-economic and socio-cultural values (mainly because of tourism and recreation that links the two areas) and weak correlation between ecological value and socio-cultural value. Interestingly the human disturbance does not correlate with any of the other factors analysed (Figure 8).

Conclusion

Due to very incomplete data, it is impossible to provide a complete image of other, the so-called emerging pollutants (e.g., pharmaceutical residues, plastic components), both in terms of time trends and even spatial distribution in the Gulf of Gdańsk. The projected climate-driven changes is another important factor which should be taken into account. The increase in strength and frequency of extreme weather phenomena, changes in water dynamics, decrease in oxygen conditions in the near-bottom zone, intensified coastal erosion) (Meier et al., 2022; Reckermann et al., 2020) are expected to have a major impact on hazardous substance cycles, including transfer along the trophic chain in the Baltic Sea.

Following Cormier et al. (2019) concept of “bow–tie” analysis, the chain of causes and consequences and key drivers of environmental change in the Gulf of Gdańsk include:

1) Eutrophication - land induced excessive transport of nutrients and phosphorus

Known from the 1970s as the main driver of the Baltic Sea ecosystem deterioration, eutrophication is being driven by surface runoff from agriculture and single outflows of Vistula and local minor rivers. The loads of nutrients were monitored, and after 1994, diminished from top 14 kilotons of phosphorus to the current 7 kilotons. Eutrophication drives the filamentous algae growth in coastal waters (estimated at a peak as 30 kilotons per year and now down to less than 10 kilotons) and pelagic primary production (from peak of 240 g C/m2/year to the current 150 g C/m2/year-co). The ungrazed algae are transported to seabed and cause oxygen deficit - this process continues with anoxic areas expansion to the depth of 50 m locally. Harmful algal blooms (bluegreen algae) are mainly based on phosphorus transport as the nitrogen can be obtained from the atmosphere, the blue green blooms are more common, due to the extreme heat waves in summer and windless weather. Unlike previous years, the blooms start in the central Baltic, not in the coastal waters. The further reduction in phosphorus transport from land is very difficult to obtain in Poland, as the Vistula watershed is very large and covers rich agricultural land. Per capita, the Polish farmer uses less nutrients that the Scandinavian one - who is cultivating much smaller arable area with much higher nutrient load (Pastuszak et al., 2018).

2) Industrialisation and infrastructure expansion - that started to increase after 1994 in the area, mainly as the tourist coastal infrastructure, and to a minor degree the pipelines, cables and other industrial installations in the Gulf. The ports of Gdynia and Gdańsk are constantly expanding with planned area change for the offshore installations (30% expansion of the existing area). Wind turbines and gas platforms are planned, but on the edge of the BBT area. In terms of biodiversity, the coastal infrastructure seems to be most destructive as it impacts the species-rich shallow water habitats, often leading to their complete destruction. On the other hand, some of the installations are beneficial for seabirds and sea mammals as resting areas with no disturbance from tourists.
3) Seagrass and coastal reeds vegetation change - prior to 1970, the shallow areas of the BBT were covered in 80% with seagrass and in coastal belt with rich reeds margin. Due to the environmental crisis in the 1980s, the seagrass shrank to less than 10% of the area and tourist expansion caused the reduction in reed belts by 30%. Now, seagrass is spontaneously expanding again - to 50% of its original occurrence as the protection of reeds belt caused its regeneration. Following these changes in the “vegetated shallow seabed” habitat, there are the changes in biodiversity - more species of crustaceans and other invertebrates are common in vegetated areas. So far, this is not having any effect on the fishery (except for the increased population of protected non-commercial fish). There were no observations of the adverse effects of new species (non natives) arrival, contrary to the common reports (Leppäkoski, 2002).

In summary, the Gulf of Gdańsk is, on the one hand, better managed and shows general improvement of ecosystem health because of the state nature protection policy, and natural recovery of species and habitats, while on the other, global warming brings some negative effects (alterations of oxygenation, stratification, cold water species retreat) that can cover the positive changes of the area. Similar dual development is observed in the societal and economic use of the area. On the one hand, the decrease in fishery and increase in soft sector of tourism and recreation, on the other, the increase in heavy industrial development of harbours and shipping and offshore business. All these observations lead to the somewhat unseen phenomenon of cohabitation between natural values, societal and economic interests.

Author contributions

JW: Conceptualization, Funding acquisition, Visualization, Writing – original draft, Writing – review and editing. JU: Formal Analysis, Investigation, Visualization, Writing – original draft, Writing – review and editing. JoP: Investigation, Writing – original draft, Writing – review and editing. LK: Conceptualization, Investigation, Writing – original draft, Writing – review and editing. JaP: Conceptualization, Investigation, Writing – original draft, Writing – review and editing. KK: Conceptualization, Investigation, Writing – original draft, Writing – review and editing. KP:

Conceptualization, Investigation, Writing – original draft, Writing – review and editing. JW: Conceptualization, Investigation, Writing – original draft, Writing – review and editing. SS: Conceptualization, Investigation, Writing – original draft, Writing – review and editing. IP: Investigation, Writing – original draft, Writing – review and editing. WW: Conceptualization, Investigation, Writing – original draft, Writing – review and editing. AK: Investigation, Visualization, Writing – original draft, Writing – review and editing

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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