Oceanologia 64 (2022) 553—566

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.journals.elsevier.com/oceanologia

ORIGINAL RESEARCH ARTICLE

Coastal cliff erosion as a source of toxic, essential and nonessential metals in the marine environment

Magdalena Bełdowska[a], **Jacek Bełdowski**[b], **Urszula Kwasigroch**[a],
Marta Szubska[b], **Agnieszka Jędruch**[b,*]

[a] *Institute of Oceanography, University of Gdańsk, Gdynia, Poland*
[b] *Institute of Oceanology, Polish Academy of Sciences, Sopot, Poland*

Received 27 December 2021; accepted 15 April 2022
Available online 4 May 2022

KEYWORDS
Metals;
Coastal erosion;
Cliffs;
Sediments;
Baltic Sea

Abstract Due to the rising environmental awareness, emissions and releases of pollutants, including metals, have been considerably reduced in the last decades. Therefore, the remobilization of natural and anthropogenic contaminants is gaining importance in their biogeochemical cycle. In the marine coastal zone, this process occurs during the erosion of a shore, especially the most vulnerable cliffs. The research was conducted in the Gulf of Gdańsk (southern Baltic Sea) from 2016 to 2017. The sediment cores were collected from four cliffs; additionally, marine surface sediments were also taken. The concentrations of essential (Cr, Mn, Fr, Cu, Zn) and nonessential (Rb, Sr, Y, Zr, Ba) metals were analyzed using the XRF technique. The levels of the analyzed metals were relatively low, typical of nonpolluted areas. However, considering the mass of eroded sediments, the annual load of metals introduced into the sea in this way is significant. In the case of Cu, Zn, and Y the load can amount to a few kilograms, for Cr and Rb — over ten kilograms, for Mn, Sr, and Zr — several tens of kilograms, for toxic Ba — over 100 kg, and in the case of Fe — 4.8 tonnes. During strong winds and storms, when the upper part of a cliff is eroded, especially the load of Zn and Cr entering the sea may increase. The content of Cr, Zr, and Ba in the cliffs was higher compared to marine sediments from the deep accumulation bottom, which indicates that coastal erosion may be an important source of these metals.

---

[*] Corresponding author at: Institute of Oceanology, Polish Academy of Sciences, Powstańców Warszawy 55, 81-712 Sopot, Poland.
E-mail address: ajedruch@iopan.pl (A. Jędruch).

Peer review under the responsibility of the Institute of Oceanology of the Polish Academy of Sciences.

Production and hosting by Elsevier

https://doi.org/10.1016/j.oceano.2022.04.001

1. Introduction

The main sources of metals in the marine environment are atmospheric deposition and terrestrial runoff. The latter is of particular importance in the coastal zone, especially near the outlets of large rivers. These account for up to 80—90% of the metal load introduced into the Baltic Sea (HELCOM, 2021; Uścinowicz et al., 2011). Direct point sources make the smallest contribution to the total input of metals (about 2%, except Zn, for which they constitute almost 5%). However, as indicated by HELCOM (2021), the role of point sources can be underestimated. One of the potentially important sources, which has been overlooked so far, is the erosion of the shore (Bełdowska et al., 2016). Given the significant volume of sediments introduced into the sea by landslides and other mass movements (Regard et al., 2022), coastal erosion may play a role in the metal budget in the marine environment (Wells et al., 2003), which was demonstrated in the example of the Hg inflow into the Gulf of Gdańsk (Bełdowska et al., 2016; Kwasigroch et al., 2018).

The emission of metals, especially toxic ones, to the environment has been reduced in recent decades. In European and North American countries, high public awareness has led to a series of restrictions and programs aimed at reducing the levels of toxic substances in the environment, e.g., the Clean Water Act (US EPA), the Baltic Marine Environment Protection Commission, more usually known as the Helsinki Convention (Helsinki Commission), the Convention for the Protection of the Marine of the North-East Atlantic, also known as the OSPAR Convention (Oslo and Paris Commissions), the Convention on Long-range Transboundary Air Pollution, often abbreviated as the Air Convention (UNECE), the Stockholm Convention on Persistent Organic Pollutants (UNEP), or the Minamata Convention for Mercury (UNEP). Despite the decrease in emissions in Europe, both from the industry sector (mainly from the energy supply, manufacturing, and extractive industries) and individual households (EEA, 2021), the concentration of many metals in the environment is not decreasing proportionally to the introduced restrictions (HELCOM, 2021; Jędruch et al., 2021). One reason for this situation is the reemission and remobilization of pollutants that have been deposited for decades in soils, land, and sea sediments. These so-called 'legacies' have the potential to continue to impact the environment long after they were first introduced (Clarke et al., 2015; Zaborska et al., 2019). The release and mobility of metals from terrestrial and marine deposits may be intensified under climate change-induced alterations of meteorological or hydrological conditions: increased precipitation, thaws, downpours, floods, storms, higher temperatures, and changes in acidic conditions (Bełdowska et al., 2016; Biswas et al., 2018; Saniewska et al., 2014a; Xu et al., 2015). As people are unable to control these processes, it is essential to recognize their scale and significance.

An example of remobilization is the erosion of the shore, which is of particular importance in marine coastal areas. Given recent observations and predictions of climatic evolution in the Baltic Sea basin, the risk of erosion of the Polish coast will increase. The consequences include a higher frequency of extreme weather phenomena, but also a rise in sea level, milder winters, and a decrease in ice cover, which will also increase the exposure of the coast to hydrodynamic forces (Bełdowska, 2015; Meier et al., 2022; Różyński and Lin, 2021). The combination of these factors will promote the release of chemical elements accumulated over the years in coastal deposits into the marine environment. In the near past, the average rate of shore retreat in the study area was 0.5 m per year (Zawadzka-Kahlau, 2012). In recent years, an increase in erosion has been observed along most of the length of the Polish coast. Further intensification of this process is also inevitable in the next decades, and the most threatened areas include the vicinity of the Tricity agglomeration (Dubrawski and Zawadzka-Kahlau, 2006; Pruszak and Zawadzka, 2008).

It is continuously discussed which elements should be classified as toxic, beneficial, or essential for living organisms. Nowadays, around 20 of the known elements are defined as essential for humans. It applies to basic organic elements (H, C, N, O), seven macroelements (Na, Mg, P, S, Cl, K, Ca) and several trace elements (Cr, Mn, Fe, Co, Cu, Zn, Se, Mo) (Kabata-Pendias and Mukherjee, 2007; Zoroddu et al., 2019). As for Cr, despite its effect on metabolism, it is sometimes excluded from the list of essential elements (Di Bona et al., 2011; Vincent, 2017). In addition to their beneficial functions, essential elements can be toxic if the dose is high enough, pointing to the principle 'the dose makes the poison'. Excess of essential trace metals may lead to neurological and metabolic disorders, DNA damage, and promote carcinogenesis (Emsley, 2011) (Table 1). The level of metals listed as priority environmental pollutants (e.g., Hg, Pb, Cd, As, Cr, Cu, Zn) is monitored according to the guidelines of the EU Water Framework Directive and the regulations of the Environment Ministry in Poland (HELCOM, 2021; Zaborska et al., 2019). On the contrary, little is known about the level of trace metals that do not have a known biological role in humans, and their toxicity is moderate. Certain elements have attracted much attention in recent years due to their increased industrial and economic importance. These include elements extensively used in modern technology: advanced electronics, lighting, power generation, medicine, space, and aeronautic industries. These 'tech metals' are relatively rare in the environment; however, in recent years, their use has gradually increased and due to future demand, growth will continue to increase in the coming decades (Goodenough et al., 2017; Mikulski et al., 2016). Consequently, the inflow of these metals into the natural environment will increase simultaneously and the environmental consequences of it are difficult to predict given the low number of studies. Therefore, it is important to recognize and estimate the sources of these elements in the sea.

This study aims to determine the inflow of selected essential (Cr, Mn, Fe, Cu, Zn) and nonessential (Rb, Sr, Y, Zr, Ba) trace metals (Table 1) to the marine environment along with the eroded shore, based on the example of the Gulf of Gdańsk (southern Baltic Sea) (Figure 1). Cliffs are one of the clearest examples of coastal erosion. They are also a significant component of world coastal zones (Zelaya Wziątek et al., 2019). Despite that, cliffs have not received as much attention as other possible sources of elements in the marine ecosystem, and their role in the biogeochemical cycle of metals is still poorly recognized. However, as shown in previous works concerning Hg, erosion introduces a significant load of this metal into the marine en-

Table 1 Biological properties and use of the studied metals (Emsley, 2011; Kabata-Pendias and Mukherjee, 2007; Rumble, 2021).

	Beneficial role	Harmful role	Uses
Ba	No known biological role	Toxic: neurological disorders	Geotechnics, metallurgy, electronics, paint and glassmaking, medicine
Cr	Essential: role in insulin metabolism, DNA synthesis	Toxic in excess: damage to the DNA, increased cancer risk, gastrointestinal disorders	Metallurgy, aerospace, military, automotive, manufacture of many everyday items
Cu	Essential: important components of many enzymes, energy transfer in cells	Toxic in excess: brain, cardiac and gastrointestinal disorders	Electronics, civil engineering, industrial machinery, agriculture
Fe	Essential: blood production, oxygen and electron transport, DNA synthesis	Toxic in excess: cardiac and gastrointestinal disorders, increased cancer risk	Metallurgy, civil engineering, oil and petroleum industry, aerospace, automotive, medicine
Mn	Essential: a cofactor for many enzymes	Toxic in excess: anaemia, depression, neurological disorders, impotence	Metallurgy, electronics, paints, medicine
Rb	No known biological role	Toxic in higher concentrations: growth and reproduction disorders	Various electronic and chemical applications, medicine
Sr	No known biological role	Toxic in higher concentrations: calcium metabolism disorders leading to e.g. bone diseases	Various electronic applications, medicine
Y	No known biological role	Toxic: lung diseases, increased cancer risk	Various electronic and chemical applications, medicine applications
Zn	Essential: involved in numerous aspects of cellular metabolism	Toxic in excess: increased cancer risk, immune system suppression	Metallurgy, civil engineering, electronics, manufacture of many everyday items, medicine
Zr	No known biological role	Toxic in higher concentrations: lung diseases	Nuclear power stations, superconducting magnets, aerospace, many biomedical applications

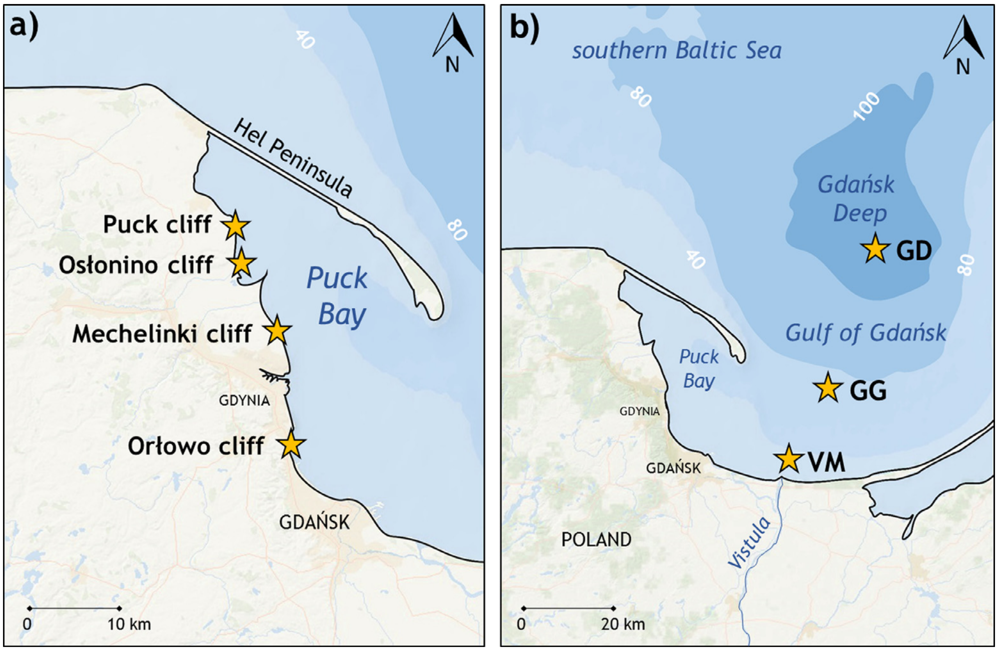


Figure 1 Location of sampling stations in the Gulf of Gdańsk (southern Baltic Sea) and the type of collected material: a) cliff sediments, b) marine sediments (VM — Vistula mouth, GG — Gulf of Gdańsk, GD — Gdańsk Deep).

vironment, acts as its nonpoint source, and should not be neglected (Bełdowska et al., 2016; Jędruch et al., 2017; Kwasigroch et al., 2018). As evidenced by Andriolo and Gonçalves (2022), coastal erosion can also be accounted as a diffuse source of marine littering pollution. Given that the eroded sediments are mostly fine-grained, they can easily be transported to distant regions and deposited in the deeper areas of the bottom. Therefore, our objective was also to estimate the distribution of metals in marine sediments under specific depositional conditions.

2. Material and methods

2.1. Study area

The Polish shore is a nontidal area with short-term sea level variations. Its coastal forms are mainly composed of loose sand, till, and peat, which results in low durability and vulnerability to degradation processes. Cliffs occupy about 20% (about 101 km in total) of the length of the Polish coast (without internal lagoons) (Łabuz, 2014; Uścinowicz et al., 2004). The genesis of the cliffs goes back to the Littorina transgression, during which they were formed in postglacial formations composed of Quaternary deposits, Pleistocene tills, clays and sands on moraine uplands, and Holocene muds and sands on lowlands. On the western coast of the Gulf of Gdańsk, Tertiary (Miocene) sandy and sandy-clayey deposits are also cropped out in the cliffs (Mojski, 2000; Uścinowicz et al., 2004). The rate of coastal cliff retreat depends on its geological structure, as well as factors controlling coastal hydrodynamics (e.g., wave climate, sea-level fluctuations, coastal orientation, and antecedent or nearshore morphology).

Waves are mainly responsible for the destruction of the cliffs of the Gulf of Gdańsk, triggering landslides and subsidence processes. Storm surges and extreme meteorological events are the most important factors in the development of cliff slopes (Zaleszkiewicz and Koszka-Maroń, 2005). These phenomena are episodic, and their frequency varies throughout the year. However, over the past decades, the number and intensity of storms in the study area has been increasing (Różyński and Lin, 2021; Stanisławczyk, 2012). The coastline is also shaped by weathering, erosion, and mass movements, the extent of which depends on the type of rock, the geometry of the cliff slope, and the vegetation. Flushing of slopes caused by rainwater and snowmelt also plays an important role in the studied area. Unlike extreme phenomena, these processes have a continuous character (Zaleszkiewicz and Koszka-Maroń, 2005). The magnitude and occurrence of coastal erosion are also affected by and anthropogenic activities, which generally accelerate the process (Janušaitė et al., 2021; Różyński and Lin, 2021).

The catchment of the Gulf of Gdańsk has an agricultural and forestry character. Agriculture constitutes about half, while 30—40% is forested. Artificial surfaces account for about 5—6% of the region's area, with their share gradually increasing, particularly transportation networks, commercial, industrial, and housing areas (Bielecka et al., 2020). Gdańsk (Figure 1), the largest city in the studied region, forms together with Sopot and Gdynia the Tricity agglomeration. In 2021, Tricity was inhabited by 750,000 people, while its metropolitan area had a population of between 1 and 1.5 million people, depending on the definition of its boundaries. Tricity is a large industrial center related mainly to the maritime economy. The chemical, machinery, metal, and electronics industries have also developed in agglomeration. Tricity is also an important transport hub (air, sea, rail and road). In the rest of the region, the economy is based mainly on agriculture, fishing, and the food and wood processing industries. Combined heat and power plants, a refinery and shipyards contribute the most to air pollution by metals (http://emgsp.pgi.gov.pl).

The research was conducted in the area of four cliffs located on the western coast of the Gulf of Gdańsk: Orłowo (650 m in length, 1544 m high), Mechelinki (250 m in length, 25—30 m high), Osłonino (400 m in length, 15 m high) and Puck (500 m in length, 10 m high) (Figure 1a). The most active part of the Gulf of Gdańsk shore is the Orłowo cliff. The other three cliffs are characterized by a much less retreat rate due to the protective nature of the Hel Peninsula (Łabuz, 2013; Zawadzka-Kahlau, 2012) (Figure 1a). The cliff sediments in Orłowo and Osłonino are mostly built of clay mixed with fluvioglacial sands and laminated silts and sandy silts, while in Mechelinki and Puck are dominated by boulder clays with sand and gravel layers (Kaulbarsz, 2005; Łęczyński and Kubowicz-Grajewska, 2013).

2.2. Sample collection

Samples of cliff sediments were collected during three sampling campaigns in June 2016 and March 2017. On each cliff (Figure 1a), three stations were set at intervals of about 50 m. During the study period, the location of the sampling sites remained the same and was determined each time using a high-sensitivity GPS receiver (eTrexH, GARMIN, USA). In the case of cliffs in Mechelinki, Osłonino, and Puck, six sediment cores (0—65 cm) were collected from each cliff using a soil core probe (AMS, USA): three vertical cores, taken from the top of the cliff, and three horizontal cores, taken from the cliff colluvium (Figure 2). The Orłowo cliff is located within a nature reserve (Kępa Redłowska), which made it impossible to collect sediment cores. In this case, the sediments from the colluvium and the top of the cliff were collected manually (approx. 20 cm of the sediment surface layer). In addition, during the r/v *Oceania* cruise in May 2016, with use of the van Veen grab sampler, three samples of surface sediments (approx. top 20 cm) were taken at each of three stations that differed in terms of environmental conditions and sediment characteristics: near the mouth of the Vistula River (VM, depth of 16 m, distance from the shore approx. 5 km, transportation bottom), in the central part of the Gulf of Gdańsk (GG, depth of 70 m, distance from the shore approx. 20 km, area of temporary sediment deposition), and from the Gdańsk Deep (depth of 105 m, distance from the shore approx. 50 km, accumulation bottom) (Burska and Szymczak, 2019; Damrat et al., 2013; Jędruch et al., 2015) (Figure 1b). The total number of sediment samples collected was 129, including 120 cliff sediment samples and 9 samples of marine sediments.

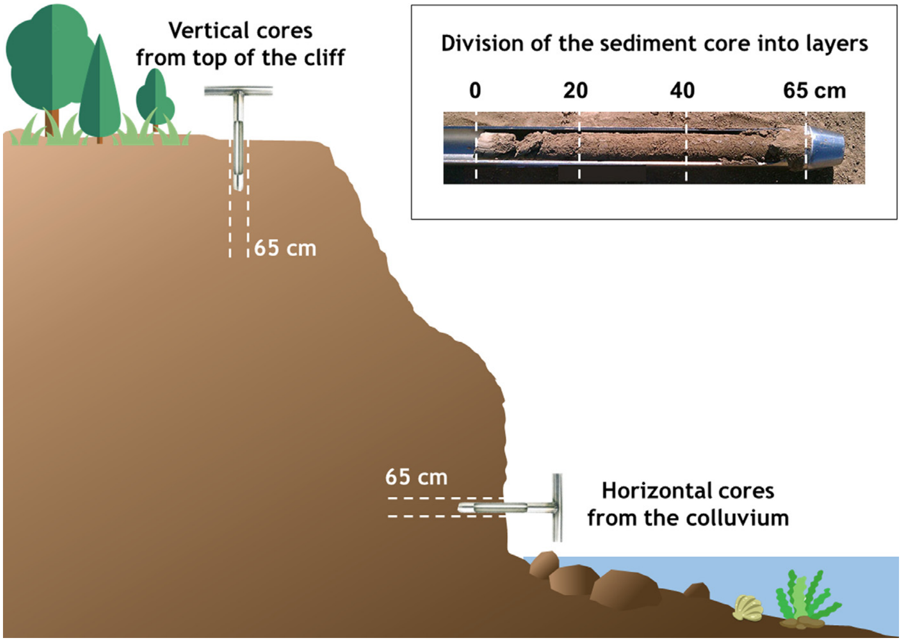


Figure 2 Scheme of the sediment cores collection (reproduced from a study by Kwasigroch et al. (2018) under the terms of the Creative Commons Attribution 4.0 International License http://creativecommons.org/licenses/by/4.0/).

2.3. Laboratory analysis

The sediment cores were divided into layers: 0—20 cm, 20—40 cm, and 40—65 cm (Figure 2). Samples for metal analysis were stored in polythene zip-lock bags at −20°C, freeze-dried (Alpha 1—4 LDplus, Martin Christ, Germany) and homogenized in a ball mill (8000D Mixer/Mill, SPEX Sample Prep, USA) with a tungsten vessel immediately before analysis.

The analysis of selected metals (Cr, Mn, Fe, Cu, Zn, Rb, Sr, Y, Zr, and Ba) was performed using X-ray fluorescence spectroscopy (XRF). In this method, atoms of the analyzed material are externally excited by X-rays, making electrons move, which results in the release of energy emitted as photons. Each element emits characteristic energy, the intensity of which increases with the concentration of the element. The XRF technique is characterized by good selectivity and a low detectability limit of ppm-ppb; moreover, it is also fast, cost-effective, and environmentally friendly (Dijair et al., 2020). It also belongs to the nondestructive analytical methods that do not damage the sample under study (Szyczewski et al., 2009). About seven grams of each sample were used to determine the element concentrations, as in the studies by Gashi et al. (2009) and Allafta and Opp (2020). The samples were placed in open-ended XRF cups with a diameter of 40 mm and sealed with a 4.0 μm-thick X-ray film. To perform analysis, a portable XRF (pXRF) analyzer S1 Titan (Bruker, Germany), using the Geochem calibration package designed for trace element analysis in geochemical matrices adjusted for coastal and bottom sediments. XRF readings were performed in triplicate for 60 s in dual soil mode. The final results were obtained by averaging three scanning results. The accuracy of the method was verified using certified reference material JMS-1 — marine sediment (GCJ, Japan) (78 mg kg^{-1} of Cr, 22.6 g kg^{-1} of Mn, 109.6 g kg^{-1} of Fe, 447 mg kg^{-1} of Cu, 166 mg kg^{-1} of Zn, 65 mg kg^{-1} of Rb, 454 mg kg^{-1} of Sr, 254 mg kg^{-1} of Y, 220 mg kg^{-1} of Zr and 1.8 g kg^{-1} of Ba), which was analyzed five times, at the beginning of each measurement series. The recovery values of the method were, respectively: 96.0% for Cr, 102.3% for Mn, 100.4% for Fe, 95.7% for Cu, 95.5% for Zn, 94.2% for Rb, 98.1% for Sr, 96.9% for Y, 92.6% for Zr, and 97.1% for Ba. The precision of the analysis, given as a relative standard deviation, is equal to 1.3% for Cr, 1.9% for Mn, 0.8% for Fe, 0.5% for Cu, 1.2% for Zn, 1.5% for Rb, 0.9% for Sr, 1.6% for Y, 1.4% for Zr, and 0.8% for Ba.

The physical parameters of the collected sediments were also analyzed. The content of water (W) was determined by drying the sample at 60°C for 24 h, while the content of organic matter (OM) in sediments was determined using a loss of ignition (LOI) at 550°C for 6 h. The granulometric composition of sediments was investigated by sieve analysis using a mechanical shaker for 10 min, through the following mesh sizes: 2.0, 1.0, 0.5, 0.25, 0.125, and 0.063 mm. Sediments with a diameter below 0.063 mm were defined as a fine particle sediment fraction (FSF).

2.4. Cliff erosion analysis

A load of individual metals introduced to the Gulf of Gdańsk with coastal erosion was estimated based on its concentration in cliff sediments and the mass of deposits crumbling to the sea during the year. A sedimentary material was calculated by analyzing the temporal changes in the active layer of deposits of the investigated cliffs with the use of an airborne laser scanning (ALS) technique using a light detection and ranging (LiDAR) sensor. The LiDAR surveys were conducted in 2009 and 2013 by the ZUI Apeks geodetic company, providing a 4-year period to analyze changes in cliff profiles. Scanned sections included cliffs in Orłowo, Mechelinki, and Osłonino (Figure 1a) with a total length of about 1.3 km. Based on LiDAR data (density: 7.32 points m^{-2}), high-resolution elevation models of the investigated cliffs were created (vertical resolution: ±0.15 m, lateral resolution: ±0.20 m) using SURFER 12 software (Golden Software). A detailed description of spatial data processing was provided in the previous work by Bełdowska et al. (2016). Comparative analysis of models from two different periods enables to determine the volumetric changes in cliff profiles (Earlie et al., 2015; Zelaya Wziątek et al., 2019). The mass of the crumbling deposits was calculated with constant sediment density of 2.65 g cm^{-3} — typical values for clays, sandy clays and clay sands (Myślińska, 1992). Based on the results obtained for surveyed cliffs, an average annual sediment loss per km of the cliff shore was calculated (29,460 tonnes). A total load of deposits introduced to the Gulf of Gdańsk was calculated assuming that the combined length of the cliffs along its coast is 3.05 km (Dubrawski and Zawadzka-Kahlau, 2006). To estimate the present load of metals, concentrations in the surface layer (0—20 cm) of colluvium were used (Figure 2). To calculate the load introduced to the sea during extreme events, concentrations measured in sediments collected from the top (0—60 cm) of the cliff were used. Estimation of the future load was based on metal concentrations in deeper layers of colluvial sediments (0—40 cm).

2.5. Processing of results

Statistical analysis was carried out using STATISTICA 12 software (StatSoft). To assess the distribution of the data, the Shapiro-Wilk normality test was used (α=0.05). Except for Rb (p=0.09), data on the concentrations of most investigated elements were not normally distributed ($p<0.05$). Therefore, to determine the strength and direction of association between the analyzed variables the nonparametric Spearman rank-order correlation coefficient (ρ) was used (α=0.05). All calculations for sediment grain size statistical parameters were performed using the GRADISTAT 9.1 software package (Blot and Pye, 2001) running in Microsoft Excel 365. The grain size of the sediments was determined on the Wentworth (1922) classification. To describe the relationship between the size fractions, the Folk's (1974) scheme was used. The map of the study area with the distribution of sampling stations was created using ArcGIS 10.4.1 software (ESRI).

3. Results and discussion

3.1. Lithologic features of sediments

Samples of sediments collected from cliffs had grains of varying sizes (from silt-sized particles with diameters below 0.063 mm to gravel with grains over 2 mm) and were mostly poorly sorted, which is characteristic for glacial sediments, deposited by the slow plowing action of an ice sheet (Easterbrook, 1982). Based on texture, the cliff sediments were mostly classified as silty sands (Table 2), which is consistent with the results of previous studies (Bełdowska et al., 2016; Woźniak and Czubała, 2014). The contribution of FSF ranged from 3.9 to 27.8%, however, the vertical cores of sediments collected from the top of the cliff contained more than two times more FSF and OM (17.8% and 5.0% on average, respectively) compared to horizontal cores from the colluvium (7.9% and 1.9% on average, respectively), which was influenced by eluviation of these constitutes from the top soil. The physical sediment properties of the studied cliffs were similar, although in the Puck cliff the proportion of FSF and OM was the lowest, while the content of coarse sediments (sand and gravel) was the highest. Given the lithological and morphogenetic criteria, all investigated cliffs were classified as sandy-clay and fall-landslide types, respectively (Kostrzewski et al., 2020).

The distribution of surface sediments in the Gulf of Gdańsk followed the general scheme of grain sorting in the water bodies distribution of sediments in the Gulf of Gdańsk and was associated with water depth and energy of the environment (Łukawska-Matuszewska and Bolałek, 2008). The samples collected in the shallow water area of the Vistula mouth (VM) were poorly sorted and dominated by fine-grained sands (Table 2). It is typical of a dynamic estuarine environment, in which the movement of sea water is generated by a number of factors, including the inflow of Vistula waters, waves, as well as surface and near-bottom currents. An interplay of these factors prevents the sedimentation of fine particles near the mouth and determines their remobilization, transport, and redeposition (Damrat et al., 2013; Szymczak and Burska, 2019). Consequently, sediments from the VM station contained significantly less FSF and OM (20.6% and 5.8%, respectively) than sediments deposited in the deeper areas of the Gulf of Gdańsk. The sediment properties of the samples collected in the central part of the Gulf of Gdańsk (GG) and Gdańsk Deep (GD), known as the depositional bottom (Burska and Szymczak, 2019; Kwasigroch et al., 2021), were similar to each other: they both mainly consisted of sandy silts and contained 34.1—35.2% of FSF and 12.4—14.3% of OM.

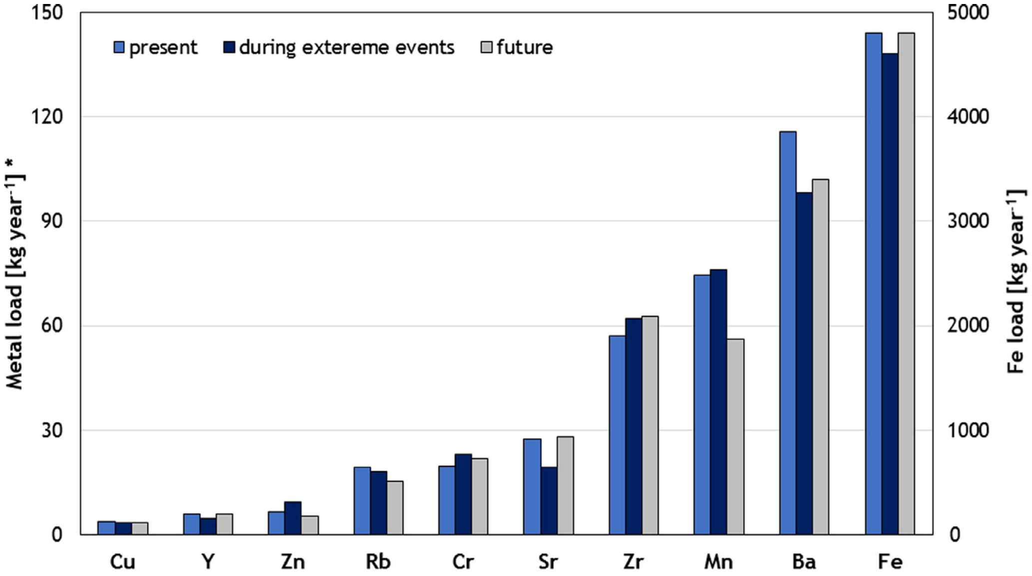
3.2. Concentration of metals in cliff sediments

The concentration of the investigated essential (Cr, Mn, Fe, Cu, Zn) and non-essential (Rb, Sr, Y, Zr, Ba) metals in the horizontal cores of sediments collected at the base of the cliff colluvium and the vertical cores taken from the top of the cliff in Orłowo, Mechelinki, Osłonino and Puck was characteristic of sediments from uncontaminated areas (Kabata-Pendias and Mukherjee, 2007). Taking into account the median, the concentrations of metals increased as follows: Cu (9.3 mg kg^{-1}) < Y (14.0 mg kg^{-1}) < Zn (20 mg kg^{-1}) < Rb (50.7 mg kg^{-1}) < Cr (60.3 mg kg^{-1}) < Sr (62.2 mg kg^{-1}) < Zr (164.0 mg kg^{-1}) < Mn (200.0 mg kg^{-1}) < Ba (273.7 mg kg^{-1}) < Fe (13 g kg^{-1}) (Figure 3). The lowest concentration variability was found for Cu, Zn, Cr, and Rb, and the highest range was found for Fe values (Table 3). The strongest positive correlations were found between Fe, Zn, and Rb (ρ=0.77 and higher, $p<0.05$), which indicate the similar geochemical behavior or common origin (Algül and Beyhan, 2020). The concentrations of Fe, Cu, Rb and Sr correlated with the content of fine sediment fraction (ρ=0.43, ρ=0.40, ρ=0.46, ρ=0.48, respectively, $p<0.05$) (Table 4). This is related to the fact that fine sediment particles have a higher ability to adsorb metals due to the increase of specific surface area, the presence of clay minerals, as well as Fe and Mn oxides (Jędruch et al., 2015; Pempkowiak, 1997;

Table 2 Physical characteristics of the cliff and marine sediments (values are medians and ranges).

Sedimenttype	Station	layer	N	Texturalgroup	FSF (%)	OM (%)	W (%)
Cliff	Orłowo	H	6	Silty sand	10.1 (9.8—10.3)	2.9 (2.8—3.1)	6.6 (6.2—7.1)
		V	6	Silty sand	24.9 (22.3—27.8)	8.4 (8.1—9.0)	8.5 (8.1—8.8)
	Mechelinki	H	18	Sand	7.9 (6.8—10.2)	2.4 (1.4—3.0)	6.4 (5.8—7.5)
		V	18	Silty sand	17.5 (12.2—22.9)	5.7 (4.6—6.5)	7.6 (5.8—9.6)
	Osłonino	H	18	Silty sand	10.1 (8.8—11.8)	1.6 (1.3—2.3)	6.7 (4.9—8.6)
		V	18	Silty sand	19.0 (14.2—24.2)	5.0 (3.2—8.1)	6.4 (4.9—7.9)
	Puck	H	18	Fine sand	4.5 (3.9—5.1)	1.4 (1.0—2.2)	6.4 (6.1—7.0)
		V	18	Silty sand	14.4 (6.9—22.8)	3.2 (1.5—5.5)	8.0 (4.3—14.5)
Marine	VM	T	3	Fine sand	20.6 (19.9—21.0)	5.8 (5.7—6.0)	48.4 (47.4—49.8)
	GG	T	3	Sandy silt	35.2 (34.8—35.7)	14.3 (14.2—14.4)	66.1 (65.2—66.7)
	GD	T	3	Sandy silt	34.1 (33.8—34.3)	12.4 (12.1—12.6)	71.1 (70.5—71.6)

VM — Vistula mouth, GG — Gulf of Gdańsk, GD — Gdańsk Deep
H — horizontal core, V — vertical core, T — top
N — number of samples, FSF — fine sediment fraction, OM — organic matter, W — water content



* excluding Fe

Figure 3 Load of metals entering the Gulf of Gdańsk along with the coastal erosion: at present with eroded colluvium, during extreme events with eroded top of the cliff, and in the future with deeper layers of sediments.

Yao et al., 2015). The formation of metal complexes with Fe and Me oxides was manifested in the dependence of Cu, Zn, Rb, and Zr concentrations on the content of Fe (ρ=0.57, ρ=0.87, ρ=0.81, ρ=0.66, respectively, $p<0.05$) and Mn (ρ=0.47; ρ=0.57, ρ=0.48, ρ=0.44, respectively, $p<0.05$) (Table 4). However, the lack of correlation between Fe and Mn (ρ=0.01, $p>0.05$) in cliff sediments may indicate an anthropogenic origin of one of these elements (Skorbiłowicz et al., 2020). The anthropogenic impact may also be evidenced by the absence of relationships between metal concentrations and both FSF and OM contributions (Algül and Beyhan, 2020; Jędruch et al., 2015), found for Zn (ρ=0.24 and ρ=-0,20 respectively, $p>0.05$) and Y (ρ=0.14 and ρ=-0,11 respectively, $p>0.05$).

The anthropogenic origin of metals in cliff sediments of the Gulf of Gdańsk is primarily related to the proximity to a large urban center. Average metal concentrations in the Tricity agglomeration area were higher compared to values in soils of undeveloped areas located by the Gulf of Gdańsk, especially in the case of Cu, Zn and Cr (Bielicka et al., 2009; Falandysz et al., 2011; http://emgsp.pgi.gov.pl). Therefore, this indicates the deposition of metals close to point emission sources. In contrast to areas far from potential pollution sources, higher metal concentrations were also found in plants (sea buckthorn *Hippohaë rhamnoides*) and fungi (king bolete *Boletus edulis*, fly agaric *Amanita muscaria*), considered indicator species, collected in the Tricity area (Falandysz et al., 2011, 2018; Prądzyński et al., 2010), as well as the algae *Enteromorpha* spp. collected in the urbanized coastal zone (Haroon et al., 1995). Elevated concentrations of metals, especially Cr, were also found in the sediments of streams and reservoirs in the Tricity area (Wojciechowska et al., 2019). However, apart from a few exceptions, the measured values were well below the ac-

Table 3 Statistical characteristic of metal concentrations [mg kg^{-1}] in cliff sediments (SD — standard deviation, SE — standard error).

	Mean	Median	Minimum	Maximum	SD	SE
Cr	60.1	60.3	27.7	86.3	13.9	2.0
Mn	216.7	200.0	102.3	386.7	82.4	12.0
Fe	13 819.3	12 924.5	4 839.7	32 935.0	6 018.6	877.9
Cu	10.5	9.3	6.0	21.3	3.3	0.5
Zn	22.1	20.0	8.0	46.0	10.1	1.5
Rb	50.8	50.7	29.5	85.0	14.5	2.1
Sr	69.2	62.2	40.0	130.2	22.7	3.4
Y	16.4	14.0	8.0	82.0	13.5	2.0
Zr	159.3	164.0	24.3	262.0	58.9	8.6
Ba	260.2	273.7	102.0	559.0	108.9	15.9
FSF	13.2	12.5	2.9	26.5	6.3	0.9
OM	3.3	2.6	0.7	8.2	2.2	0.3

FSF — fine sediment fraction, OM — organic matter.

Table 4 Spearman's rank-order correlation matrix of metal concentrations and physical characteristics of cliff sediments (values marked with a star symbol are statistically significant, $p<0.05$).

	Cr	Mn	Fe	Cu	Zn	Rb	Sr	Y	Zr	Ba	FSF	OM
Cr		0.44*	-0.39*	-0.11	-0.06	-0.28*	-0.16	0.41*	-0.42*	1.00	-0.23*	-0.08
Mn	0.44*		0.01	0.47*	0.58*	0.48*	0.08	0.65*	0.44*	0.44*	-0.12	-0.34*
Fe	-0.39*	0.01		0.58*	0.87*	0.81*	0.47*	-0.00	0.65*	-0.39*	0.43*	0.32*
Cu	-0.11	0.47*	0.58*		0.60*	0.54*	0.48*	0.18	0.30*	-0.11	0.40*	-0.14
Zn	-0.06	0.58*	0.87*	0.60*		0.77*	0.13	0.46*	0.46*	-0.06	0.27	0.20
Rb	-0.28*	0.48*	0.81*	0.54*	0.77*		0.45*	0.36*	0.77*	-0.28*	0.47*	0.29*
Sr	-0.16	0.08	0.47*	0.48*	0.13	0.45*		0.23*	0.35*	-0.16	0.49*	0.33*
Y	0.41*	0.65*	-0.00	0.18	0.46*	0.36*	0.23*		0.59*	0.41*	0.14	-0.11
Zr	-0.42*	0.44*	0.65*	0.30*	0.46*	0.77*	0.35*	0.59*		-0.42*	0.31*	0.03
Ba	0.08	0.23	0.08	0.17	0.09	0.19	-0.04	0.14	0.02		0.07	-0.23
FSF	-0.23*	-0.12	0.43*	0.40*	0.27	0.47*	0.49*	0.14	0.31*	0.07		0.62*
OM	-0.08	-0.34*	0.32*	-0.14	0.20	0.29*	0.33*	-0.11	0.03	-0.23	0.62*	

FSF — fine sediment fraction, OM — organic matter.

ceptable metal concentrations. As shown in the study by Falandysz et al. (2011), the concentrations of metals, including Mn, Fe, Cu, Zn, Sr, and Ba, in soils in the study area were similar to or lower than in soils in the Polish territory, especially those located in its heavily industrialized southern part of the country. Relatively low level of metals in the soils of the investigated area may be related with the outflow of metals to the Gulf Gdańsk. Given that watercourses are mostly regulated and their catchments are strongly modified by humans, the retention of chemicals in soils is low (Saniewska et al., 2014b; Wojciechowska et al., 2019). Therefore, the gradual growth of artificial surfaces and urbanized lands in the last decades, especially in the Tricity agglomeration, may contribute to the increased runoff of metals to the Gulf of Gdańsk (Bielecka et al., 2020). This indicates that the decrease in metal concentrations in the topsoil of the Tricity observed since the 1990s (Jędruch et al., 2021) may be attributed not only to the reduction of anthropogenic emission but also to the more intensive outflow of metals to the marine environment.

Cliffs of the Gulf of Gdańsk contained significantly less Cr, Fe, Cu, Zn, and Zr compared to cliffs of the Kerala coast (southwestern India) (Renjith et al., 2021). The level of elements in deposits of Kerala cliffs was from three (for Zn) to almost 30 times (for Fe) higher than in cliffs investigated in this study. The concentrations of Rb, Sr and Ba in both regions were similar, whereas in the case of Mn and Y higher values were measured in deposits from the Gulf of Gdańsk coast. However, given the differences in geology, it is difficult to compare the results of these regions with each other. Beaches of Kerala are world-famous for their heavy mineral concentration, especially Fe minerals, e.g., jarosite and ilmenite. In addition to the geology of the hinterland, the Kerala cliffs are also influenced by subtropical to tropical climates. A consequence is the varied structure of the cliffs, which consist of arkosic sand, kaolinitic sandy clay carbonaceous clay, and peat with plant remains (Singh et al., 2016).

The concentrations of metals in cliffs of the Gulf of Gdańsk were similar to values measured in sediments collected from bluffs along the Chincoteague Bay coast (Maryland, USA) (Wells et al., 2003). Maryland coastal bays generally have low levels of metals (US EPA, 2002); therefore, given the same sandy-clay type of deposits at both locations, it can be concluded that metal burdens in sediments are comparable. However, the contribution of FSF in sediments eroded from the Chincoteague Bay coast (54.7% on average) (Wells et al., 2003) was a few times higher than in cliffs investigated in this study (Table 2). On the other hand, the bluff sediments contained significantly less OM (approx. 0.1% on average) compared to the cliff sediments of the Gulf of Gdańsk. As confirmed by higher ρ values (Table 4), the FSF content was the strongest factor determining the concentration of elements than OM in the case of both studies. Taking into account the differences in textural composition, the FSF-normalized metal concentrations in the Polish cliffs were, therefore, higher than in Chincoteague Bay.

In the case of the Baltic Sea, metal levels, other than Hg (Bełdowska et al., 2016; Kwasigroch et al., 2018), in cliff sediments have not been investigated so far. However, there are some studies on metal concentrations in deposits of southern Baltic beaches (Antonowicz et al., 2017; Karlonienė et al., 2021; Kupczyk et al., 2021). The concentrations measured in beach sands were lower than in cliff sediments: a few times for Zn, a few to about a dozen times for Cu and Mn, and several dozen times for Cr and Fe. The lower level of metals in beach deposits reflects the overall lower content of silt fractions in comparison to clays from cliffs. These differences may also indicate that Cr and Fe are adsorbed mainly on fine-grained particles, which are usually washed away from sandy sediments. Silty sediments of the southern Baltic Sea are mostly composed of micas and clay minerals (e.g., illite, glauconite, montmorillonite) which serve as a sink for Fe and Cr. On the other hand, metals such as Zn, Cu, and Mn co-occur with coarser quartz particles and are associated with heavy minerals (e.g., ilmenite, garnet, amphibole) or terrigenous carbonates (Karlonienė et al., 2021; Mikulski et al., 2016; Uścinowicz, 2011; Uścinowicz and Sokołowski, 2011; Wajda, 1970).

3.3. Load of metals released to the sea

Coastal erosion has been identified as an important source of sediments to the marine environment (Janušaitė et al., 2021; Łabuz, 2014; Uścinowicz et al., 2011; Wells et al., 2003). Along with sediments, chemicals sorbed onto particles are also released into the water, turning cliffs into a possible nonpoint source, which affects the quality of the coastal zone (Jędruch et al., 2017; Karlonienė et al., 2021; Wells et al., 2003). The impact of eroded coast on the input of chemical elements, including metals, to the sea, is rarely considered by researchers or monitoring institutions. Therefore, attempts to quantify that contribution and compare it to other sources are seldom (Jarsjö et al., 2017; Karlonienė et al., 2021). However, as shown in previous studies by Bełdowska et al. (2016), coastal erosion is the third most significant source of Hg introduced to the Gulf of Gdańsk, after rivers and wet atmospheric deposition. It should be noted that nearly all the riverine input of Hg to the Gulf of Gdańsk is introduced by the Vistula, the second largest river that disembogues into the Baltic Sea (Figure 1b). In comparison to the smaller, local rivers (e.g., Reda, Kacza, and Gizdepka), the importance of coastal erosion is more meaningful. It was shown that coastal erosion introduces to the sea over 13 times more Hg than these rivers combined (Bełdowska et al., 2014, 2016). If the contribution of the Vistula River is not included in the Hg budget in the Gulf of Gdańsk, the significance of coastal erosion increased to more than 30% of the Hg load reaching the basin. It means that the abrasion process may be a particularly significant source of Hg in areas far from the mouths of large rivers or in bays without major river outlets.

The erosion of the foot slope of the cliff is the main factor responsible for the formation of landslides and other mass movements (Kostrzewski et al., 2020; Uścinowicz et al., 2004). On the Polish coast, erosion is mainly caused by meteorologically forced storm surges. Storms are mostly recorded in the fall-winter months, from November to February. Storm surges are not a regular annual event. Their number differs from year to year, from a few to a dozen or so (Łabuz, 2014; Stanisławczyk, 2012). During storm surges of a relatively small scale, mainly the surface layer of a cliff face, located at the foot of the colluvium, is destroyed. A load of sediments released into the Gulf of Gdańsk with eroded cliffs was estimated at 89,854 tonnes annually (Bełdowska et al., 2016). Taking into account median concentrations of the investigated metals in sediments collected from the surface layer of the colluvium (first 20 cm of horizontal core), coastal erosion is responsible for introducing to the Gulf of Gdańsk following loads: several kilograms of Cu, Y and Zn, over ten kilograms of Rb and Cr, up to a few tens of kilograms of Sr, Zr, and Mn, over 100 kg of Ba, and as much as 4.8 tonnes of Fe (Figure 4).

Shore destruction is more significant when two or more storm surges occur in succession during a single season. However, the most dangerous are the most severe extreme storms. Along the coast of the southern Baltic, the number of such events is more than a dozen per decade (Łabuz, 2014). In the future, the frequency and strength of storms are expected to increase (Różycki and Lin, 2021). During the most severe storms, when the cliff wall is largely destroyed, also the upper part of the cliff may crumble. Given that the top of the cliff is often overgrown with trees and shrubs, the soil and underlying layers of sediments have different chemical compositions and sorption properties. Along with large landslides disturbing the upper parts of the cliff wall, the input of metals introduced into the sea changes. Compared to the load released into the Gulf of Gdańsk with eroded colluvium, the input of metals during extreme events may increase. As evidenced by the analysis of vertical cores of sediments taken from the top of the investigated cliffs, the load can increase by 41% for Zn, 18% for Cr, 9% for Zr, and 2% for Mn. On the other hand, for some of the elements, the load can be reduced by: 29% for Sr, 20% for Y, 15% for Ba, 8% for Cu, 6% for Rb, and 4% for Fe (Figure 4). These differences may be related to the natural occurrence of metals in cliff deposits, mainly associated with their mineralogical composition and the content of the fine fraction or organic matter. However, surface soil and underlying sediments may be affected by human activity. This substantial enrichment of clifftop sediments in Zn is probably an effect of atmospheric deposition of metal and its infiltration with rainfall, especially as Zn in precipitation in the coastal zone of the Gulf of Gdańsk is of anthropogenic origin (Szefer, 1990).

Currently, erosion affects the surface layer of the cliff face and the colluvium (0—20 cm). Estimation of changes in a metal load along with cliff erosion in the future was car-

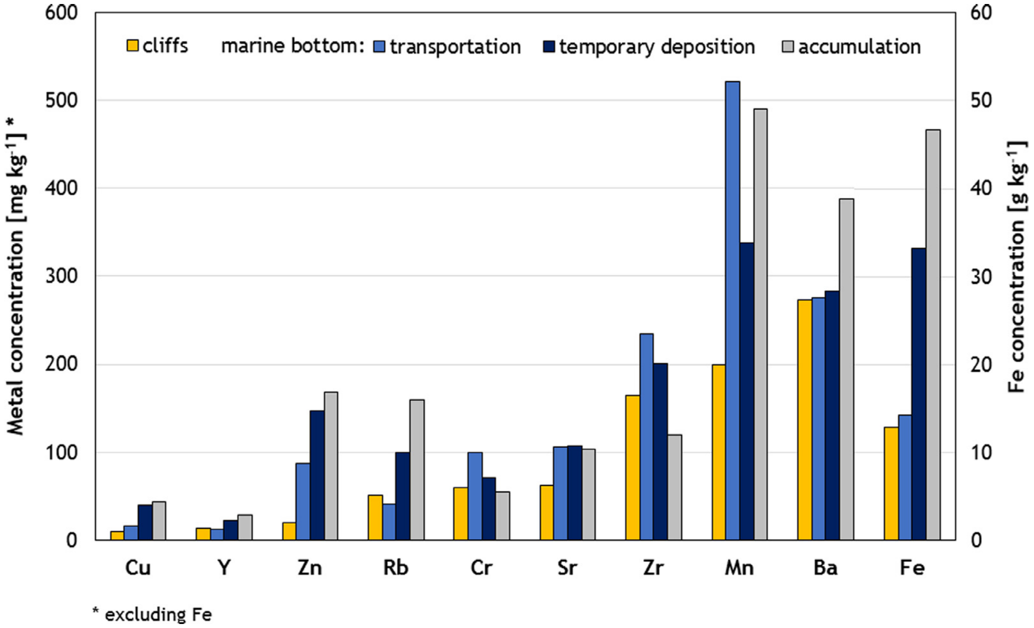


Figure 4 Concentrations of metals in sediments of a cliff and different types of marine bottom: transportation bottom (VM — Vistula mouth), area of temporary deposition of sediments (GG — Gulf of Gdańsk), and accumulation bottom (GD — Gdańsk Deep).

ried out based on the concentrations of metals in deeper layers of sediments (20—40 cm and 40—65 cm sections of the horizontal cores) deposited at the foot of cliffs. The obtained results indicated that a load of some metals introduced into the sea with coastal erosion in the future is expected to increase slightly: 11% for Cr, 10% for Zr, and 3% for Sr (Figure 4). On the other hand, the inflow of some metals will be lower: 25% for Mn, 21% for Rb, 20% for Zn, 12% for Ba, 8% for Cu, and 2% for Y, while the load of Fe will remain the same.

3.4. Distribution of metals in marine sediments

Landslides that are dominant mass movements on cliffs with a complex structure, such as those along the Gulf of Gdańsk shore, are most hazardous because they sometimes affect a zone of hundreds of meters away from the cliff edge (Uścinowicz et al., 2004). Consequently, both the metals accumulated in cliff deposits and remobilized from resuspended marine sediments recovered are released into the water. The influence of coastal erosion on metal concentration in the marine environment was previously evidenced in the example of Hg and the Orłowo cliff (Bełdowska et al., 2016; Jędruch et al., 2017). After the introduction of a considerable load of eroded sedimentary material into the coastal zone, the concentration of Hg in suspended particulate matter increased almost three times, while, in phytoplankton, a ten-fold increase was observed. This confirms the potential impact of coastal erosion on metal inflow into the marine trophic chain. It should also be noted that these changes occurred as a consequence of a single, one-day event that was engineering work conducted for safety reasons.

Although the concentrations of metals in the cliff deposits were mostly relatively low (Table 3, Figure 4) the influence of coastal erosion on their input to the sea cannot be ignored. The importance of this source is not related to the high concentration of metals in cliff sediments, but to the large mass of sediments introduced into the marine environment annually. Fine-grained sediments eroded from the cliff are quickly washed out of the coastal zone and transported to deeper parts of the bottom. The area considered to be the site of final sediment deposition in the Gulf of Gdańsk is the Gdańsk Deep (Burska and Szymczak, 2019). Nevertheless, fine-grained sediments also temporarily accumulate in shallower places, e.g., Puck Bay or the Vistula River prodelta (Damrat et al., 2013; Sokołowski et al., 2021) (Figure 1). Given the complex pattern of surface and bottom currents, the fate of sediments delivered to the Gulf of Gdańsk is difficult to determine (Zachowicz et al., 2002). Identification of the origin of deposited particles is difficult due to the variety of sources of terrigenous matter, e.g., eroded cliffs, rivers, soils, snowmelt water (Jędruch et al., 2017; Sokołowski, 2009).

Cu, Y, and Zn in the cliff sediments were similar to those measured in the sands of the southern Baltic Sea, in which their concentrations were, respectively: below 20 mg kg^{-1}, between 6 and 69 mg kg^{-1}, and between 5 and 50 mg kg^{-1} (Mikulski et al., 2016; Uścinowicz et al., 2011). The same applies to Mn and Fe, belonging to the main constituents of the Baltic Sea sediments. In the cliff sediments, the levels of these elements were low, close to the typical values for sand sediments, in which they represented 10 to 9,500 mg kg^{-1}, and not more than 19 g kg^{-1}, respectively (Uścinowicz and Sokołowski, 2011). In the case of Rb, Cr and Sr, their concentrations in cliff deposits were higher relative to sand, but comparable to fine-grained silty clay sediments of the southern Baltic Sea, in which they were around 60 mg kg^{-1} for Rb and from 40 to 70 mg kg^{-1} for both Cr and Sr (Kumblad and Bradshaw, 2008; Uścinowicz et al., 2011). The level of Zr in southern Baltic sediments is not well recognized, as previous studies have focused on possible Zr concentrates, including Fe-Mn nodules. However, the level of Zr in cliff sediments was high enough to be comparable to values measured in metal-rich nodules in a range of 110 to 185 mg kg^{-1} (Szamałek et al., 2018). The amount of Ba in the cliff sediments was also elevated, higher than in the silt-clay deposits, which contained 100 to 200 mg kg^{-1}. Concentrations of Ba similar to the values measured in cliffs occurred only locally in the soft bottom of the southern Baltic, in the Eastern Gotland and the Gulf Basin (Uścinowicz et al., 2011). The results obtained indicate that the investigated cliffs are not a significant source of Cu, Y, Zn, Mn, and Fe in the sediments of the southern Baltic Sea. Instead, they may, to some extent, be a source of Rb, Cr, and Sr, whereas, in the case of Zr and Ba, the influence of cliffs seems undeniable. For Ba, the level measured in cliff deposits was also a few times higher than found in river sediments in Poland (below 52 mg kg^{-1}), as well as alluvial deposits in Germany, Denmark, Lithuania and Latvia (up to 128 mg kg^{-1}) (Bojakowska, 2011). The high content of Ba in the cliff deposits is probably due to the presence of feldspar and plagioclases, as well as terrigenous Ba sulfate (Szamałek et al., 2018).

In coastal areas, especially in estuaries, rivers are generally the most important source of metals in marine sediments (Bełdowska et al., 2021; HELCOM, 2021). Rivers transport metals washed out from the catchment area and those originating from treated and untreated sewage. Therefore, the concentrations of metals in the bottom sediments increase in the areas where riverine material is transported and deposited. It is confirmed by the higher concentrations of Zn, Cr, Sr, Zr, and Mn in sediments collected from the station located near the mouth of the Vistula River (VM), compared to the concentration of these metals in the cliffs (Figure 4). Due to the dynamics of the sedimentary environment, only a small part of the material carried by the Vistula is deposited near its mouth. It is estimated that more than two thirds of the sediment mass can be remobilized and then redeposited in deeper parts of the Gdańsk Basin (Damrat et al., 2013). The distance from the mouth of the river significantly influences sediment accumulation rates and the fate of sediments in the Gulf of Gdańsk. As it increases, the terrigenous material is dispersed in seawater, and the metal load reaching the sediments is diluted.

The decrease in concentrations, resulting from the mixing of river material with marine sediments with lower concentration, was recorded for Cr and Zr (Figure 4). Because Cr contents show exponential dependence on the grain size of the sediments and are usually highest in fine-grained sediments (Uścinowicz et al., 2011), elevated Cr concentrations found in sands of the Vistula mouth are most likely an indicator of anthropopressure. This is confirmed by the fact that Cr concentrations measured in sediments collected near the river outlet were approximately 10 times higher than the average Cr content in sands of the southern Baltic Sea (about 10 mg kg^{-1}) (Uścinowicz et al., 2011). They were also a few times higher compared to the Cr level in the sediments of most rivers that flow into the southern Baltic Sea (below 13 mg kg^{-1}) (Bojakowska, 2011). In the case of Zr, its content in coastal sediments was probably related to limited mobility in the marine environment resulting from its high gravity and specific grain shape, as well as chemical resistance (Kabata-Pendias and Mukherjee, 2007; Wajda, 1970). In the second half of the twentieth century, the possibility of obtaining Zr from beaches and marine sands in the southern Baltic region was even taken into consideration (Pilch et al., 1990). However, the amounts of Zr in the sediments of the Gulf of Gdańsk were sub-economic. An increase in concentration with distance from the Vistula mouth was recorded for Cu, Y, Zn, Rb, Sr, Ba, and Fe, which may indicate additional sources of metals. In the case of Cu, Zn, Sr, and Fe, due to their low concentration in cliff sediments, the role of coastal erosion is rather small. For Y, Rb, and Ba concentrations in cliff sediments were similar or higher compared to Vistula mouth sediments, therefore it can be concluded that the role of cliffs in a load of this metal introduced to the Gulf of Gdańsk may be important.

4. Conclusions

In the coming years, as a result of the combination of declining ice phenomena and increased hydrodynamic forces, the abrasion of the southern Baltic coast will accelerate. Consequently, the retreat rate of the most erosion-prone cliffs will most likely increase. Moreover, many parts of the coast that were inactive or persisted in an equilibrium state will be eroded. Although a considerable part of the cliff section of the Polish coast is under protection (or is planned to be in the near future), the management strategy for the Gulf of Gdańsk is unlikely to change. The most important form of maintaining the coast and preventing the loss of beaches in the studied area is nourishment. The cliff in Orłowo is additionally protected by three submerged breakwaters, two stone groins, and a concrete seawall. However, conducted research has shown that the influence of underwater thresholds on shoreline transformation is minor (Łęczyński and Kubowicz-Grajewska, 2013). The probability of introducing more effective methods to protect the Orłowo cliff from erosion is low. Due to its unique natural character, interference with the cliff landscape raises objections from both scientists and the public. The projected changes are expected to result in a substantial increase in the mass of terrestrial deposits entering the marine environment. Numerous studies and models indicate that as a result of the reduction in anthropogenic emissions and releases, reemission from land will be the major source of metals in the coastal seas. As shown in this study, coastal erosion is an important source of elements in the marine environment and should be considered along with rivers, atmospheric deposition or point sources. The erosion of soft cliffs composed of fine-grained sediments affects not only the coastal zone, but also the features of the distal bottom, as confirmed by the results of isotopic analyzes of suspended matter described in earlier work by the authors (Jędruch et al., 2017). As shown in the example of metals, the cliff sediments contained more Y, Rb and Ba than sediments collected near the mouth of Vistula, the main source of pollutants to the Gulf of Gdańsk, as well as one of their most important sources in the Baltic Sea. The concentrations of Cr, Zr and Ba in cliff sediments were also higher than in the fine-grained sediments from the accumulation bottom of the southern Baltic Sea. Cliff sediments can be carriers not only of metals, but also of contaminants that have accumulated in them over decades. Therefore, we recommend that cliff sediments be included in studies of marine pollution and sampled for purposes of environmental monitoring purposes.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This work was supported by the National Science Centre grant No. 2014/13/B/ST10/02807.

Acknowledgements

The authors express their gratitude to Jakub Bełdowski and Dorota Pałubicka for help with sample collection. We also thank the Editor and two anonymous Reviewers for their suggestions to improve and clarify the manuscript.

References

Algül, F., Beyhan, M., 2020. Concentrations and sources of heavy metals in shallow sediments in Lake Bafa, Turkey. Sci. Rep. 10, 11782. https://doi.org/10.1038/s41598-020-68833-2

Allafta, H., Opp, C., 2020. Spatio-temporal variability and pollution sources identification of the surface sediments of Shatt Al-Arab River, Southern Iraq. Sci. Rep. 10, 6979. https://doi.org/10.1038/s41598-020-63893-w

Andriolo, U., Gonçalves, G., 2022. Is coastal erosion a source of marine litter pollution? Evidence of coastal dunes being a reservoir of plastics. Mar. Pollut. Bull. 174, 113307. https://doi.org/10.1016/j.marpolbul.2021.113307

Antonowicz, J.P., Grobela, M., Opalińska, M., Motała, R., 2017. Heavy metals in beach deposits, bottom sediments of a Baltic fishing port and surface water. Balt. Coast. Zone 21, 211–224.

Bełdowska, M., 2015. The influence of weather anomalies on mercury cycling in the marine coastal zone of the Southern Baltic — future perspective. Water Air Soil Pollut. 226, 2248. https://doi.org/10.1007/s11270-014-2248-7

Bełdowska, M., Saniewska, D., Falkowska, L., 2014. Factors influencing variability of mercury input to the southern Baltic Sea. Mar. Pollut. Bull. 86, 283–290. https://doi.org/10.1016/j.marpolbul.2014.07.004

Bełdowska, M., Jędruch, A., Łęczyński, L., Saniewska, D., Kwasigroch, U., 2016. Coastal erosion as a source of mercury into the marine environment along the Polish Baltic shore. Environ. Sci. Pollut. Res. 23, 16372–16382. https://doi.org/10.1007/s11356-016-6753-7

Bełdowska, M., Jędruch, A., Sieńska, D., Chwiałkowski, W., Magnuszewski, A., Kornijów, R., 2021. The impact of sediment, fresh and marine water on the concentration of chemical elements in water of the ice-covered Lagoon. Environ. Sci. Pollut. Res. 28, 61189–61200. https://doi.org/10.1007/s11356-021-14936-w

Bielecka, E., Jenerowicz, A., Pokonieczny, K., Borkowska, S., 2020. Land Cover Changes and Flows in the Polish Baltic Coastal Zone: A Qualitative and Quantitative Approach. Remote Sens. 12, 2088 http://dx.doi.org/10.3390/rs12132088

Bielicka, A., Ryłko, E., Bojanowska, I., 2009. Zawartość pierwiastków metalicznych w glebach i warzywach z ogrodów działkowych Gdańska i okolic. Ochr. Środ. Zas. Nat. 40, 209–216 (in Polish).

Biswas, B., Qi, F., Biswas, J.K., Wijayawardena, A., Khan, M.A.I., Naidu, R., 2018. The Fate of Chemical Pollutants with Soil Properties and Processes in the Climate Change Paradigm — A Review. Soil Syst. 2, 51. https://doi.org/10.3390/soilsystems2030051

Blott, S.J., Pye, K., 2001. GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments. Earth Surf. Process. Landf. 26, 1237–1248. https://doi.org/10.1002/esp.261

Bojakowska, I., 2011. Geochemical Characteristics of River Sediments in the Baltic Sea Catchment Area. In: Uścinowicz, S. (Ed.), Geochemistry of Baltic Sea surface sediments. Polish Geological Institute, Warsaw, 36–46.

Burska, D., Szymczak, E., 2019. The conditions of sedimentation of Gdańsk Bay sediments (Baltic Sea, Poland) in the light of lithological features and carbon content. IOP Conf. Ser.: Earth Environ. Sci. 362, 012098. https://doi.org/10.1088/1755-1315/362/1/012098

Clarke, L.W., Janerette, G.D., Bain, D.J., 2015. Urban legacies and soil management affect the concentration and speciation of trace metals in Los Angeles community garden soils. Environ. Pollut. 197, 1–12. https://doi.org/10.1016/j.envpol.2014.11.015

Damrat, M., Zaborska, A., Zajączkowski, M., 2013. Sedimentation from suspension and sediment accumulation rate in the River Vistula prodelta, Gulf of Gdańsk (Baltic Sea). Oceanologia 55 (4), 937–950. https://doi.org/10.5697/oc.55-4.937

Di Bona, K.R., Love, S., Rhodes, N.R., McAdory, D., Sinha, S.H., Kern, N., Kent, J., Strickland, J., Wilson, A., Beaird, J., Ramage, J., Rasco, J.F., Vincent, J.B., 2011. Chromium is not an essential trace element for mammals: effects of a "low-chromium" diet. J. Biol. Inorg. Chem. 16, 381–390. https://doi.org/10.1007/s00775-010-0734-y

Dijair, T.S.B., Silva, F.M., Teixeira, A.F.S., Silva, S.E.G., Guilherme, L.R.G., Curi, N., 2020. Correcting field determination of elemental contents in soils via portable X-ray fluorescence spectrometry. Cienc. Agrotecnologia 44, e002420. https://doi.org/10.1590/1413-7054202044002420

Dubrawski, R., Zawadzka-Kahlau, E., 2006. Przyszłość ochrony polskich brzegów morskich. Maritime Institute in Gdańsk, Gdańsk, 302 pp. (in Polish).

Earlie, C.S., Masselink, G., Russell, P.A., Shail, R.K., 2015. Application of airborne LiDAR to investigate rates of recession in rocky coast environments. J. Coast. Conserv. 19, 831–845. https://doi.org/10.1007/s11852-014-0340-1

Easterbrook, D.J., 1982. Characteristic Features of Glacial Sediments. In: Scholle, P.A., Spearing, D. (Eds.), Sandstone Depositional Environments. American Association of Petroleum Geologists, Tulsa, 1–10. https://doi.org/10.1306/M31424C2

EEA, 2021. European Union emission inventory report 1990-2019, under the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP), EEA Report, 5/2021. European Environment Agency, 161 pp.

Emsley, J., 2011. Nature's Building Blocks: An A-Z Guide to the Elements. Oxford Univ. Press, New York, 710 pp.

Falandysz, J., Frankowska, A., Jarzyńska, G., Dryżałowska, A., Kojta, A.K., Zhang, D., 2011. Survey on composition and bioconcentration potential of 12 metallic elements in King Bolete (Boletus edulis) mushroom that emerged at 11 spatially distant sites. J. Environ. Sci. Health B 46, 231–246. https://doi.org/10.1080/03601234.2011.540528

Falandysz, J., Mędyk, M., Treu, R., 2018. Bio-concentration potential and associations of heavy metals in *Amanita muscaria* (L.) Lam. from northern regions of Poland. Environ.

Sci. Pollut. Res. 1730, 25190—25206. https://doi.org/10.1007/s11356-018-2603-0

Folk, R.L., 1974. The petrology of sedimentary rocks. Hemphill Publ. Co., Austin, 182 pp.

Gashi, F., Frančišković-Bilinski, S., Bilinski, H., 2009. Analysis of sediments of the four main rivers (Drini i Bardhë, Morava e Binçës, Lepenc and Sitnica) in Kosovo. Fresenius Environ. Bull. 18, 1462—1471.

Goodenough, K.M, Wall, F., Merriman, D., 2017. The rare earth elements: demand, global resources, and challenges for resourcing future generations. Nat. Resour. Res. 27, 201—216. https://doi.org/10.1007/s11053-017-9336-5

Haroon, A.M., Szaniawska, A., Surosz, W., 1995. Changes in heavy metal accumulation in *Enteromorpha* spp. from the Gulf of Gdańsk. Oceanologia 37 (1), 99—110.

HELCOM, 2021. Inputs of hazardous substances to the Baltic Sea. Balt. Sea Environ. Proc. 179, 48 pp.

Janušaitė, R., Jarmalavičius, D., Pupienis, D., Žilinskas, G., Jukna, L., 2021. Nearshore sandbar switching episodes and their relationship with coastal erosion at the Curonian Spit, Baltic Sea. Oceanologia, (in press). https://doi.org/10.1016/j.oceano.2021.11.004

Jarsjö, J., Chalov, S.R., Pietroń, J., Alekseenko, A.V., Thorslund, J., 2017. Patterns of soil contamination, erosion and river loading of metals in a gold mining region of northern Mongolia. Reg. Environ. Change 17, 1991—2005. https://doi.org/10.1007/s10113-017-1169-6

Jędruch, A., Bełdowski, J., Bełdowska, M., 2015. Long-term changes and distribution of mercury concentrations in surface sediments of the Gdansk Basin (Southern Baltic Sea). J. Soil Sed. 15, 2487—2497. https://doi.org/10.1007/s11368-015-1148-9

Jędruch, A., Kwasigroch, U., Bełdowska, M., Kuliński, K., 2017. Mercury in suspended matter of the Gulf of Gdańsk: Origin, distribution and transport at the land—sea interface. Mar. Pollut. Bull. 118, 354—367. https://doi.org/10.1016/j.marpolbul.2017.03.019

Jędruch, A., Falkowska, L., Saniewska, D., Durkalec, M., Nawrocka, A., Kalisińska, E., Kowalski, A., Pacyna, J.M., 2021. Status and trends of mercury pollution of the atmosphere and terrestrial ecosystems in Poland. Ambio 50, 1698—1717. https://doi.org/10.1007/s13280-021-01505-1

Kabata-Pendias, A., Mukherjee, A., 2007. Trace elements from soil to human. Springer, Berlin Heidelberg, 550 pp. https://doi.org/10.1007/978-3-540-32714-1

Karlonienė, D., Pupienis, D., Jarmalavičius, D., Dubikaltinienė, A., Žilinskas, G., 2021. The impact of coastal geodynamic processes on the distribution of trace metal content in sandy beach sediments, south-eastern Baltic Sea coast (Lithuania). Appl. Sci. 11, 1106. https://doi.org/10.3390/app11031106

Kaulbarsz, D., 2005. Geology and glaciotectonics of the Orłowo Cliff in Gdynia, northern Poland. Prz. Geol. 53, 572—581.

Kostrzewski, A., Winowski, M., Zwoliński, Z., 2020. Morphodynamic types of postglacial cliffs of the Southern Baltic. EGU General Assembly, 20486. https://doi.org/10.5194/egusphere-egu2020-20486

Kumblad, L., Bradshaw, C., 2008. Element composition of biota, water and sediment in the Forsmark area, Baltic Sea, Technical Report TR-08-09. Swedish Nuclear Fuel and Waste Management, 109 pp.

Kupczyk, A., Kołecka, K., Gajewska, M., Siedlewicz, G., Szubska, M., Grzegorczyk, K., Walecka, D., Kotwicki, L., Bełdowski, J., Bełdowska, M., Graca, B., Staniszewska, M., Chubarenko, B., Schubert, H., Woelfel, J. (Eds.), 2021. Nutrient and pollutant flux to coastal zone originating from decaying algae and plants on beaches. Case studies for innovative solutions of beach wrack use, 63—73.

Kwasigroch, U., Bełdowska, M., Jędruch, A., Saniewska, D., 2018. Coastal erosion — a „new" land-based source of labile mercury to the marine environment. Environ. Sci. Pollut. Res. 25, 28682—28694. https://doi.org/10.1007/s11356-018-2856-7

Kwasigroch, U., Bełdowska, M., Jędruch, A., Łukawska-Matuszewska, K., 2021. Distribution and bioavailability of mercury in the surface sediments of the Baltic Sea. Environ. Sci. Pollut. Res. 28, 35690—35708. https://doi.org/10.1007/s11356-021-13023-4

Łabuz, T., 2013. Sposoby ochrony brzegów morskich i ich wpływ na środowisko przyrodnicze polskiego wybrzeża Bałtyku: Raport. WWF Poland, Warszawa, 187 pp. (in Polish).

Łabuz, T., 2014. Erosion and its rate on an accumulative Polish dune coast: the effects of the January 2012 storm surge. Oceanologia 56 (2), 307—326. https://doi.org/10.5697/oc.56-2.307

Łęczyński, L., Kubowicz-Grajewska, A., 2013. Studium przypadku: Klif Orłowski. In: Łabuz, T. (Ed.), Sposoby ochrony brzegów morskich i ich wpływ na środowisko przyrodnicze polskiego wybrzeża Bałtyku: Raport. WWF Poland, Warszawa, 152—161 (in Polish).

Łukawska-Matuszewska, K., Bolałek, J., 2008. Spatial distribution of phosphorus forms in sediments in the Gulf of Gdańsk (southern Baltic Sea). Cont. Shelf Res. 28, 977—990. https://doi.org/10.1016/j.csr.2008.01.009

Meier, M., Dieterich, C., Gröger, M., Dutheil, C., Börgel, F., Safonova, K., Christensen, O.B., Kjellström, E., 2022. Oceanographic regional climate projections for the Baltic Sea until 2100. Earth Syst. Dynam. 13, 159—199. https://doi.org/10.5194/esd-13-159-2022

Mikulski, S.Z., Kramarska, R., Zieliński, G., 2016. Rare earth elements pilot studies of the Baltic marine sands enriched in heavy minerals. Miner. Resour. Manage. 32, 5—28. https://doi.org/10.1515/gospo-2016-0036

Mojski, J.E., 2000. The evolution of the southern Baltic coastal zone. Oceanologia 42 (3), 285—303.

Myślińska, E., 1992. Laboratoryjne badania gruntów. PWN, Warszawa 244 pp. (in Polish).

Pempkowiak, J., 1997. Zarys Geochemii Morskiej. University of Gdańsk Press, Gdańsk, 170 pp. (in Polish).

Pilch, W., Stachurski, J., Sztaba, K., 1990. Badania i możliwości wykorzystania minerałów ciężkich z bałtyckich piasków plażowych. Physicochem. Probl. Miner. Process. 23, 71—79 (in Polish).

Prądzyński, W., Zborowska, M., Waliszewska, B., Szulc, A., 2010. Chemical composition and content of selected heavy metals in the wood of common sea buckthorn (*Hippohaë rhamnoides* l.) growing in the coastal regions of the Baltic Sea. Acta Sci. Pol. Silv. Colendar. Rat. Ind. Lignar. 9, 45—51.

Pruszak, Z., Zawadzka, E., 2008. Potential Implications of Sea-Level Rise for Poland. J. Coast Res. 24, 410—422. http://www.jstor.org/stable/30137846

Regard, V., Prémaillon, M., Dawez, T.J.B., Carretier, S., Jeandel, C., Godderis, Y., Bonnet, S., Schott, J., Pedoja, K., Martinod, J., Viers, J., Fabre, S., 2022. Rock coast erosion: An overlooked source of sediments to the ocean. Europe as an example, Earth Planet. Sci. Lett. 578, 117356. https://doi.org/10.1016/j.epsl.2021.117356

Renjith, R.A., Rejith, R.G., Sundararajan, M., 2021. Evaluation of coastal sediments: an appraisal of geochemistry using ED-XRF and GIS techniques. In: Rani, M., Seenipandi, K., Rehman, S., Kumar, P., Sajjad, H. (Eds.), Remote Sensing of Ocean and Coastal Environments. Elsevier, Amsterdam, 99—116. https://doi.org/10.1016/B978-0-12-819604-5.00007-X

Różyński, G., Lin, J.G., 2021. Can climate change and geological past produce enhanced erosion? A case study of the Hel Peninsula, Baltic Sea, Poland. Appl. Ocean Res. 115, 102852. https://doi.org/10.1016/j.apor.2021.102852

Rumble, J.R., 2021. CRC Handbook of Chemistry and Physics. CRC Press, Boca Raton, 1624 pp.

Saniewska, D., Bełdowska, M., Bełdowski, J., Jędruch, A., Saniewski, M., Falkowska, L., 2014a. Mercury loads into the sea associated with extreme flood. Environ. Pollut. 191, 93—100. https://doi.org/10.1016/j.envpol.2014.04.003

Saniewska, D., Bełdowska, M., Bełdowski, J., Saniewski, M., Szubska, M., Romanowski, A., Falkowska, L., 2014b. The impact of land use and season on the riverine transport of mercury into the marine coastal zone. Environ. Monit. Assess. 186, 7793—7604. https://doi.org/10.1007/s10661-014-3950-z

Singh, M., Rajesh, V.J., Sajinkumar, K.S., Sajeev, K., Kumar, S.N., 2016. Spectral and chemical characterization of jarosite in a palaeolacustrine depositional environment in Warkalli formation in Kerala, South India and its implications. Spectrochim. Acta Mol. Biomol. Spectrosc. 168, 86—97. https://doi.org/10.1016/j.saa.2016.05.035

Skorbiłowicz, M., Skorbiłowicz, E., Łapiński, W., 2020. Assessment of Metallic Content, Pollution, and Sources of Road Dust in the City of Białystok (Poland). Aerosol Air Qual. Res. 20, 2507—2518. https://doi.org/10.4209/aaqr.2019.10.0518

Sokołowski, A., 2009. Tracing the Flow of Organic Matter Based upon Dual Stable Isotope Technique, and Trophic Transfer to Trace Metals in Benthic Food Web of the Gulf of Gdansk (Southern Baltic Sea). Univ. Gdańsk Press, Sopot, 213 pp.

Sokołowski, A., Jankowska, E., Bałazy, P., Jędruch, A., 2021. Distribution and extent of benthic habitats in Puck Bay (Gulf of Gdańsk, southern Baltic Sea). Oceanologia 63 (3), 301—320. https://doi.org/10.1016/j.oceano.2021.03.001

Stanisławczyk, I., 2012. Storm-surges Indicator for the Polish Baltic Coast. Int. J. Mar. Navig. Saf. Sea Transp. 6, 123—129.

Szamałek, K., Uścinowicz, K., Zglinicki, K., 2018. Rare earth elements in Fe-Mn nodules from the southern Baltic sea — a preliminary study. Biul. Państw. Inst. Geol. 472, 199—212. https://doi.org/10.5604/01.3001.0012.7118

Szefer, P., 1990. Mass-balance of metals and identification of their sources in both river and fallout fluxes near Gdańsk Bay, Baltic Sea. Sci. Total Environ. 95, 131—139. https://doi.org/10.1016/0048-9697(90)90058-3

Szyczewski, P., Siepak, J., Niedzielski, P., Sobczyński, T., 2009. Research on Heavy Metals in Poland. Polish J. Environ. Stud. 18, 755—768.

Szymczak, E., Burska, D., 2019. Distribution of Suspended Sediment in the Gulf of Gdansk off the Vistula River mouth (Baltic Sea, Poland). IOP Conf. Ser.: Earth Environ. Sci. 221, 012053. https://doi.org/10.1088/1755-1315/221/1/012053

US EPA, 2002. Mid-Atlantic Integrated Assessment (MAIA) Estuaries 1997-98, Summary Report. US Environmental Protection Agency, 115 pp.

Uścinowicz, S.Uścinowicz, S. (Ed.), 2011. Surface Sediments and Sedimentation Processes. Geochemistry of Baltic Sea surface sediments, 76—80.

Uścinowicz, S., Sokołowski, K.Uścinowicz, S. (Ed.), 2011. Main constituents of the Baltic Sea sediments. Geochemistry of Baltic Sea surface sediments, 164—171.

Uścinowicz, S., Szefer, P., Sokołowski, K.Uścinowicz, S. (Ed.), 2011. Trace elements in the Baltic Sea sediments. Geochemistry of Baltic Sea surface sediments, 214—274.

Uścinowicz, S., Zachowicz, J., Graniczny, M., Dobracki, R., 2004. Geological structure of the southern Baltic coast and related hazards. Pol. Geol. Inst. Spec. Pap. 15, 61—68.

Vincent, J.B., 2017. New evidence against chromium as an essential trace element. J. Nutr. 147, 2212—2219. https://doi.org/10.3945/jn.117.255901

Wajda, W, 1970. Heavy minerals of the bottom sands (Polish Baltic Coast). Ann. Soc. Geol. Pol. XL, 131—149.

Wells, D.V., Hennessee, E.L., Hill, J.M., 2003. Shoreline Erosion as a Source of Sediments and Nutrients Middle Coastal Bays, Maryland. Maryland Geological Survey, Coastal and Estuarine Geology File Report No. 03-07, 163 pp.

Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediments. J. Geol. 30, 377—392. https://doi.org/10.1086/622910

Wojciechowska, E., Nawrot, N., Walkusz-Miotk, J., Matej-Łukowicz, K., Pazdro, K., 2019. Heavy Metals in Sediments of Urban Streams: Contamination and Health Risk Assessment of Influencing Factors. Sustainability 11, 563. http://dx.doi.org/10.3390/su11030563

Woźniak, P.P., Czubała, P., 2014. Nowe spojrzenie na gliny lodowcowe w Gdyni Orłowie. In: Sokołowski, R. (Ed.), Ewolucja środowisk sedymentacyjnych regionu Pobrzeża Kaszubskiego. Univ. Gdańsk Press, Gdańsk, 115—122 (in Polish).

Xu, W., Li, X., Wai, O.W.H., Huang, W., Yan, W., 2015. Remobilization of trace metals from contaminated marine sediment in a simulated dynamic environment. Environ. Sci. Pollut. Res. 22, 19905—19911. https://doi.org/10.1007/s11356-015-5228-6

Yao, Q., Wang, X., Jian, H., Chen, H., Yu, Z., 2015. Characterization of the particle size fraction associated with heavy metals in suspended sediments of the Yellow River. Int. J. Environ. Res. Public Health 12, 6725—6744. https://doi.org/10.3390/ijerph120606725

Zaborska, A., Siedlewicz, G., Szymczycha, B., Dzierzbicka-Głowacka, L., 2019. Legacy and emerging pollutants in the Gulf of Gdańsk (southern Baltic Sea) — loads and distribution revisited. Mar. Pollut. Bull. 139, 238—255. https://doi.org/10.1016/j.marpolbul.2018.11.060

Zachowicz, J., Laban, C., Uścinowicz, S., Ebbing, J., Emelyanov, E.M., 2002. Recent sedimentation in the Gulf of Gdansk and its geochemical expression. In: Emelyanov, E.M. (Ed.), Geology of the Gdansk Basin, Baltic Sea. Russian Academy of Sciences, Yantarny Skaz, 380—387.

Zaleszkiewicz, L., Koszka-Maroń, D., 2005. Activation processes of degradation of cliff coast of Puck Lagoon. Prz. Geol. 53, 55—62.

Zawadzka-Kahlau, E., 2012. Morfodynamika brzegów wydmowych południowego Bałtyku. Univ. Gdańsk Press, Gdańsk, 352 pp. (in Polish).

Zelaya Wziątek, D., Terefenko, P., Kurulczyk, A., 2019. Multi-Temporal Cliff Erosion Analysis Using Airborne Laser Scanning Surveys. Remote Sens. 11, 2666. https://doi.org/10.3390/rs11222666

Zoroddu, M.A., Aaseth, J., Crisponi, G., Medici, S., Peana, M., Nurchi, V.M., 2019. The essential metals for humans: A brief overview. J. Inorg. Biochem. 195, 120—129. https://doi.org/10.1016/j.jinorgbio.2019.03.013