



## Distribution of mercury in different environmental compartments in the aquatic ecosystem of the coastal zone of the Southern Baltic Sea

Dominika Saniewska<sup>1</sup>, Magdalena Beldowska<sup>1,\*</sup>, Jacek Beldowski<sup>2</sup>, Michał Saniewski<sup>3</sup>,  
Justyna Kwaśniak<sup>1</sup>, Lucyna Falkowska<sup>1</sup>

1. Institute of Oceanography, University of Gdansk, Al. Pilsudskiego 46, 81-378 Gdynia, Poland. E-mail: [d.murawiec@gmail.com](mailto:d.murawiec@gmail.com)

2. Institute of Oceanology, Polish Academy of Sciences, ul. Powstancow Warszawy 55a, 81-712 Sopot, Poland

3. Institute of Meteorology and Water Management, Maritime Branch, ul. Waszyngtona 42, 81-342 Gdynia, Poland

### Abstract

The aim of this study was to characterize mercury (Hg) contamination in the coastal waters of the Southern Baltic Sea, and to investigate transformations of Hg in the initial links of the marine food chain. Concentrations of Hg in water, particulate matter, plankton and macrophytes at various stations in the coastal zone (a bay with restricted water exchange, near an industrial city, river mouths, and the open sea) were measured in 2006–2008. Hg concentrations observed in the Southern Baltic varied greatly, showing the highest average values in all environmental compartments near the river mouths. In shallow, sheltered parts of the gulf, where water exchange is restricted, Hg concentrations in the water and in macrophytes were elevated relative to those in the coastal zone of the deeper part of the bay and in the open Baltic. Distance to the river mouth, terrestrial runoff, and quantity and quality of organic matter were more important than seasonal variations in controlling Hg and Hg<sub>SPM</sub> concentrations in water samples. Mercury concentrations in the surface microlayer at the air/sea interface were over 10 times higher than those in the bulk surface water. Concentrations of Hg in macrophytes in the winter were significantly higher than those in the warm seasons (spring, summer, autumn). This was probably the combined effect of higher availability of Hg in porewaters and leaf growth inhibition.

**Key words:** mercury; Baltic Sea; coastal zone; water; particulate matter; plankton; macrophytes

**DOI:** 10.1016/S1001-0742(09)60230-8

### Introduction

The Baltic Sea is an inland sea surrounded by economically-developed and industrialized countries. For this reason, it is particularly vulnerable to anthropogenic pollution originating from urbanized and densely populated Eastern and Central Europe. Pollutants enter the Baltic Sea through terrestrial runoff from the drainage basin and atmospheric deposition; they accumulate and have a toxic impact on the ecosystem of the Baltic Sea. The depth of the Baltic Sea (average 52 m) and low rate of water exchange with the North Sea favor the accumulation of pollutants (HELCOM, 1986).

For many years, mercury (Hg) has been recognized as one of the most dangerous anthropogenic pollutants. In offshore marine water, Hg concentrations do not exceed 1 ng/L. A different situation is observed in the coastal zones, where the concentrations can be many times higher than those measured offshore (Mason et al., 1998; Horvat et al., 2003; Laurier et al., 2004). Rivers transport various chemical substances which enter the water with terrestrial runoff from the drainage basin. They are therefore very often considered to be responsible for the pollution of the coastal zones. Hg transported to the sea by rivers is mainly

accumulated in the coastal areas and estuaries and does not reach the offshore areas (Cossa and Martin, 1991).

Investigations of Hg concentration levels in the Baltic Sea have been performed for many years. However, they have been focused mainly on the determination of Hg concentrations in the surface waters and sediments of the offshore areas of the Baltic Sea. Neither seasonal nor diurnal variability of Hg levels in the coastal zone, which is potentially the most polluted area of the Baltic Sea, have been sufficiently characterized (Brzezińska, 1984; Falandysz, 1994; Wrembel, 1997; Pempkowiak et al., 1998; Szefer, 2002; Boszke et al., 2003; Beldowski and Pempkowiak, 2007; Kuss and Schneider, 2007; Bartnicki et al., 2008; Pohl and Hennings, 2008).

The goal of this study was to determine Hg concentrations in different coastal areas (a bay with restricted water exchange, an industrial city, river mouths and the open sea). To achieve this goal, the concentrations of Hg in several compartments of the marine environment (water, particulate matter, plankton, and macrophytes) at various stations located in the coastal zone of the Southern Baltic Sea were analyzed. These measurements were used to calculate the value of the bioconcentration factor (BCF) for the planktonic organisms and macrophytobenthos. The authors paid particular attention to the river mouths.

\* Corresponding author. E-mail: [ryba@ocean.ug.gda.pl](mailto:ryba@ocean.ug.gda.pl)

jesc.ac.cn

## 1 Materials and methods

### 1.1 Study area

The research was performed in the Southern Baltic Sea (Fig. 1). The Baltic Sea, because it is surrounded by developing countries, for many years has been considered to be an area characterized by elevated Hg levels. In addition, the Gulf of Gdansk with the Vistula River (the largest Polish river) mouth has been recognized as one of the most polluted water reservoirs in the entire world (Brzezińska, 1984; Wrembel, 1997; Bartnicki et al., 2008).

The sampling stations (P1–P5, Fig. 1) were situated in the coastal zone of the Gulf of Gdansk. The station near Oslonino (P1) was located in a small bay with restricted water exchange. Shallow depth and the structure of the bay enhance the growth of aquatic organisms, leading, together with low water dynamics, to the accumulation of organic matter, which directly influences the physical and chemical conditions (light, dissolved oxygen) prevailing at this station. Additionally, because of restricted access and a location distant from large cities, this station is under little anthropogenic influence. Industrial Gdynia (P2) is a harbor city situated at the Gulf of Gdansk. It is part of a metropolitan area (together with Gdansk and Sopot) called Tricity (Trójmiasto). It has a total area of 135 km<sup>2</sup> with a population of almost 250,000. Numerous industrial plants (e.g., power plants, municipal waste incinerators, cement and paint plants, refinery and shipyards) located in this region introduce pollutants to the environment through atmospheric deposition and terrestrial runoff. Three stations (P3–P5) were situated near river mouths, and one station (P6) was located in the open Baltic Sea near coast Łeba (Fig. 1). This latter station was considered a background station because it is distant from mercury sources.

### 1.2 Sampling

Samples of subsurface water were collected bimonthly between June 2006 and December 2008, except for the station in Gdynia (P2), where the samples were collected twice a month. Additionally, the surface microlayer was sampled at this station (by means of the Garrett screen sampler). Water samples for the determination of Hg concentration were collected directly in borosilicate bottles with Teflon lined caps. The water was stored at 4°C until analysis. Water samples for determination of mercury content in the suspended particulate matter (SPM) were filtered through ignited glass fiber filters (Whatman GF/F) and were stored at –20°C until analysis.

Samples of plankton were collected with a 50 µm mesh net. Algae and aquatic vascular plants were collected manually between 2006 and 2008. The organisms were placed in new polyethylene bags and transported to the laboratory, where they were deep frozen (–20°C). Samples of algae, aquatic vascular plants, and plankton were dried at room temperature before analysis. Weights of the samples were measured prior to analysis.

### 1.3 Analysis

Water samples for mercury analysis were oxidized by the addition of BrCl and pre-reduced with hydroxylamine hydrochloride solution one hour prior to analysis by CV-AFS (TEKRAN 2600, Canada), according to US EPA method 1631 (US EPA, 2002). Quality control procedures for water samples included blanks and water spiked with mercury nitrate in the range of 0.5–25 ng/L, and produced adequate precision (1% RSD) and recovery (98%–99%). Samples of particulate matter and biological material were analyzed by CV-AAS (AMA 254, Altec Ltd., Czech Republic). The detection limit for solid materials was 0.005 ng/g, while for water it was as low as 0.05 ng/L.

Quality control for solid samples included analysis of samples in triplicates, and analysis of certified reference

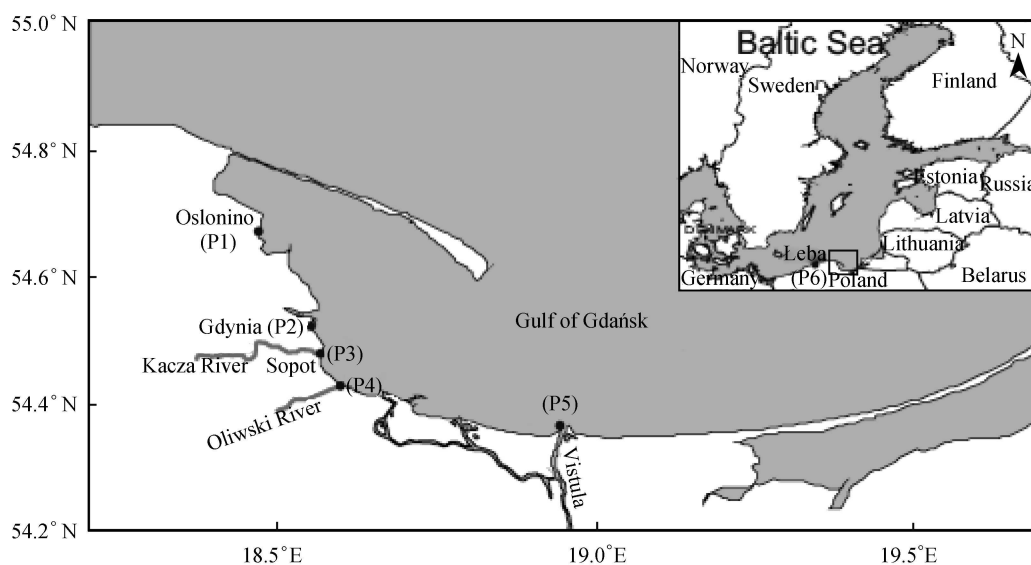


Fig. 1 Location of the sampling stations.

materials (CRMs). The CRMs included BCR-414 (Community Bureau of Reference) for plankton, QTM057 and QTM055BT (Quasimeme) for biota, and BCR-276 (indicative, Community Bureau of Reference) for macrophytes. Average errors did not exceed 5% for all materials except BCR-276, where relative error reached 8%.

The analysis results allowed us to calculate the bio-concentration factor (BCF), which is a measure of the propensity of mercury to accumulate in organisms, using the following equation.

$$BCF_{\text{alga}} = C_{\text{alga}}/C_{\text{water}}$$

where,  $C_{\text{alga}}$  (ng/kg dry weight (dw)) is the concentration of Hg in macrophytobenthos, and  $C_{\text{water}}$  (ng/L) is the concentration of Hg in water.

Due to a limited number of samples, the distribution of results was non-normal. Therefore, non-parametric (Kolmogorov-Smirnov) tests were employed to assess significance of differences.

## 2 Results and discussion

Total Hg concentrations in the coastal zone of the Southern Baltic Sea extended over a relatively wide range. The open Baltic Sea coast (Łeba-P6) was characterized by low Hg concentrations (from 0.1 to 3.9 ng/L with median 1.7 ng/L) (Fig. 2a). These values were similar to those observed offshore in the Baltic proper (Pempkowiak et al., 1998; Wurl et al., 2001; Murawiec et al., 2007; Beldowski et al., 2009). Concentrations of Hg in the water were almost two times higher in shallow, sheltered parts of the Gulf of Gdansk in Osłonino (from 1.6 to 7.5 ng/L, median 3.1 ng/L) and in the vicinity of the river mouths (from 0.2 to 7.0 ng/L, median 3.3 ng/L) than in the other areas. Those values differed significantly (Kolmogorov-Smirnov test  $p < 0.05$ ). River waters are usually rich in chemical substances leaching from the drainage area (Baeyens and Leermakers, 1998; Biliński et al., 2000). The Hg concentration level noted in Osłonino was influenced by restricted water exchange, which fostered organic

matter accumulation and decomposition in a shallow bay (Bonzongo and Donkor, 2003). The industrialized coastal zone of Gdynia was characterized by the highest variability of Hg concentrations (0.3–9.4 ng/L). The average Hg concentration during the study period was relatively low (1.9 ng/L), but 25% of the results were relatively high (between 3.0 and 9.4 ng/L). Increased Hg concentrations were caused by terrestrial runoff and atmospheric deposition (Beldowska et al., 2007; Murawiec et al., 2007).

Particulate Hg concentrations in the Gulf of Gdansk in the industrialized Gdynia area and in the vicinity of river mouths extended over a relatively wide range (Fig. 2b). Among all studied areas, the highest values of particulate Hg ( $Hg_{\text{SPM}}$ ) concentration were observed in river mouths, where the average concentration was above 300 ng Hg/g SPM. In other areas, the average concentrations of Hg in the particulate matter did not exceed 200 ng/g dw, which is consistent with previous studies (Murawiec et al., 2007). Differences of  $Hg_{\text{SPM}}$  concentrations between river mouths and other areas were statistically significant (Kolmogorov-Smirnov test,  $p < 0.05$ ), probably as a result of different organic matters transported by rivers and the presence of inland Hg point sources. In the coastal zone near Gdynia, the concentration of Hg in the particulate matter extended over the widest range. This was probably caused by differences in the quality and quantity of organic matter coming from surface runoff from the industrial city, as well as adjacent mouths of large rivers, transporting both ionic and particulate Hg (Laurier et al., 2003). A similar situation was observed in the coastal zone of the Mediterranean Sea, where the values of particulate Hg concentrations were about three times higher than those measured offshore (Ferrara et al., 2001).

Concentrations of Hg in water and particulate matter measured between 2006 and 2008 in the coastal zone near Gdynia were characterised by non-significant seasonal variability (Fig. 3). Variability of these Hg concentrations was probably caused by changes in solar radiation levels, in the quantity and quality of nonliving organic matter, and in phyto- and zooplankton biomass and species composition, which may affect phytoplankton-initiated Hg

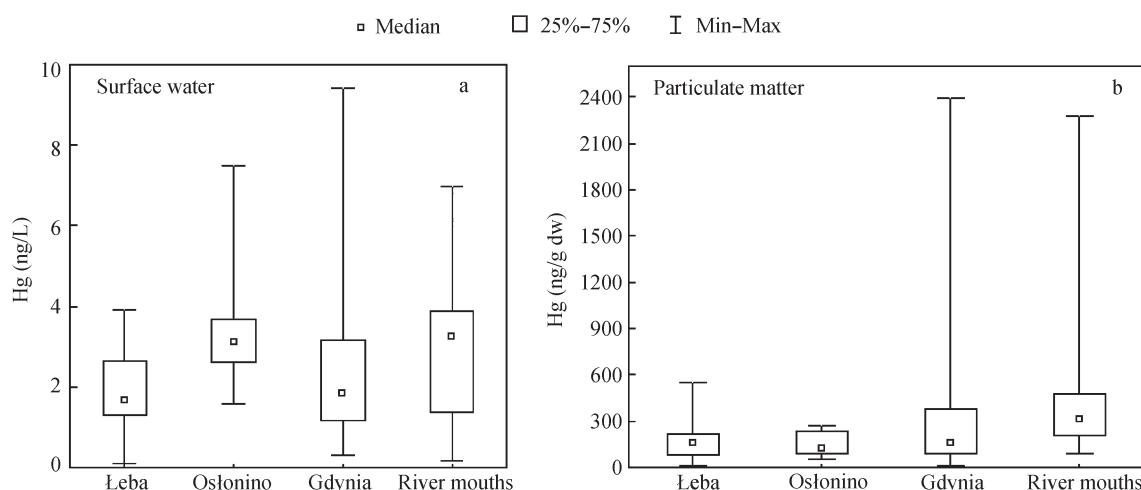


Fig. 2 Statistical characteristics of Hg concentrations in surface water (a) and particulate matter (b) at coastal stations of the Southern Baltic Sea.

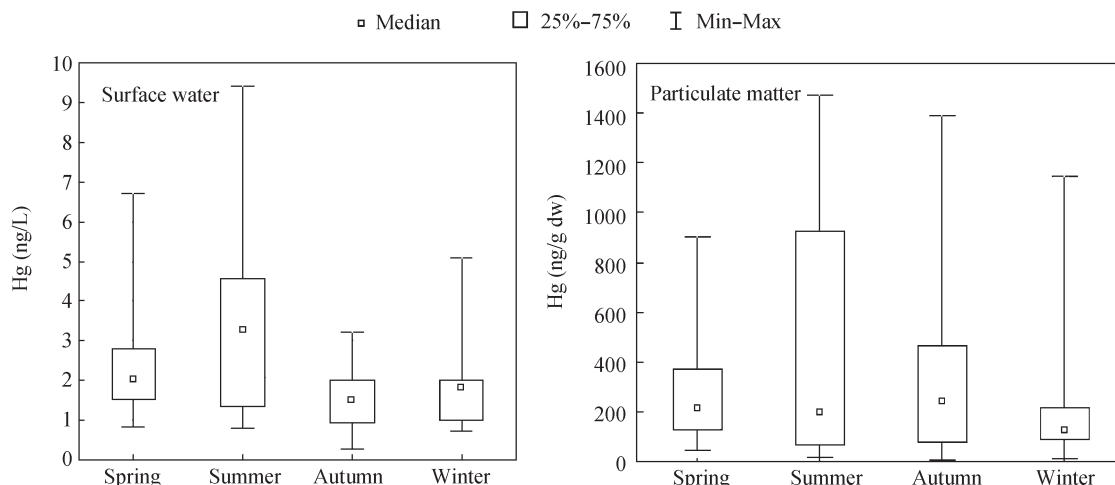


Fig. 3 Seasonal changes in Hg concentrations in the surface water and the particulate matter in Gdynia.

transformations (Costa and Liss, 1999, 2000; Schmitt et al., 2001; Bonzongo and Donkor, 2003; Beldowska and Falkowska, 2007). In addition, periodic increase of Hg concentrations in the water could be connected with seasonal terrestrial runoff resulting from snowmelt (Balogh et al., 2000).

During the study period, significant differences between the concentrations of Hg and Hg<sub>SPM</sub> in the surface microlayer and in the subsurface water were observed (Kolmogorov-Smirnov test,  $p < 0.05$ ). Medians of Hg in the water and Hg in SPM in the surface microlayer (SML) (respectively 18.0 ng/L, 760.8 ng/g dw) and their ranges (from 4.80 to 45.0 ng/L; from 54.9 to 7711.7 ng/g dw) were many times higher than those measured in the subsurface water (SW) (means: respectively 1.4 ng/L, 178.6 ng/g dw; and ranges from 0.3 to 9.4 ng/L, from 6.1 to 1186.1 ng/g dw). Characteristic physical-chemical conditions prevailing in the surface microlayer favor the accumulation of organic matter. It is also a specific barrier restricting Hg emission into the atmosphere as well as its transport backwards (Falkowska, 1999).

The investigation of Hg concentration levels in plankton was carried out at two neighboring stations: near Ośłonino (P1) and near industrial Gdynia (P2). Average Hg concentrations at both stations were similar (129 and 121 ng/g dw, respectively), and some differences in the Hg concentrations in plankton were not significant (Kolmogorov-Smirnov test). Half the results (25%–75%) measured in Gdynia extended over a much wider range than in Ośłonino (92.4–219.1 ng/g dw and 83.3–139.7 ng/g dw, respectively). Therefore, it can be assumed that the strongest changes in the Hg concentration in plankton in the coastal zone are probably the consequence of different taxonomical compositions of the phytoplankton, a phenomenon frequently observed in the area (Majewski, 1990). Moreover, differences in the values of the bioconcentration factor (BCF) in Gdynia and Ośłonino ( $6.5 \times 10^5$  and  $3.5 \times 10^5$ , respectively) were observed, which might be the result of the presence of larger amounts of bio-available Hg near Gdynia.

Mercury concentrations in plankton measured both in

Gdynia and in Ośłonino were lower than those measured by Boszke et al. (2003) (48–480 ng/g dw) in Puck Bay between 1995 and 1998. These differences are mainly caused by differences in the species composition in collected samples, however they could also be caused by the improvement of water quality in the studied area during last ten years.

Numerous studies indicate an important role of benthic macrophytes in marine food chains (McIntosh et al., 1978; Larsen and Schierup, 1981; Schierup and Larsen, 1981; Kraus et al., 1986; Wilson, 2002). The significant differences (Kolmogorov-Smirnov test,  $p < 0.05$ ) of Hg concentrations in benthic macrophytes were observed between the river mouths and the remaining stations. The median value for river mouth samples (29.7 ng/g dw) was over 4 times higher than in Łeba (median 6.2 ng/g dw), Gdynia (median 7.4 ng/g dw), and Ośłonino (median 9.5 ng/g dw) (Fig. 4a). Moreover, differences in the values of the BCF at all sampling sites were noted. The highest BCF values were measured near the river mouths ( $9.1 \times 10^4$ ). Almost 3-fold lower values were measured at every other stations (Łeba  $2.8 \times 10^4$ ; Ośłonino  $3.1 \times 10^4$ ; Gdynia  $3.3 \times 10^4$ ). Such high values of the Hg concentration in phyto-benthos and the BCF near the river mouths could be caused by the presence of bio-available forms of Hg in the water and sediments in this region (Beldowski and Pempkowiak, 2007). Mercury concentrations in macrophytes depend on the Hg concentrations in water and sediments. Higher Hg concentrations in leaves and roots were measured in contaminated areas as compared to remote areas (Ward, 1987; Coquery and Welbourn, 1994; Capiomont et al., 2000). Laboratory experiments indicate that Hg can be accumulated both through roots from the sediment and through leaves from the water (Coquery and Welbourn, 1994). This is why elevated Hg concentrations in macrophytes occur in areas of the Southern Baltic Sea where higher concentrations of Hg in water and sediments were observed (Beldowski and Pempkowiak, 2007), i.e., in river mouths and in the shallow, sheltered parts of the Gulf of Gdansk where water exchange is restricted (Ośłonino) (Figs. 2 and 4a).

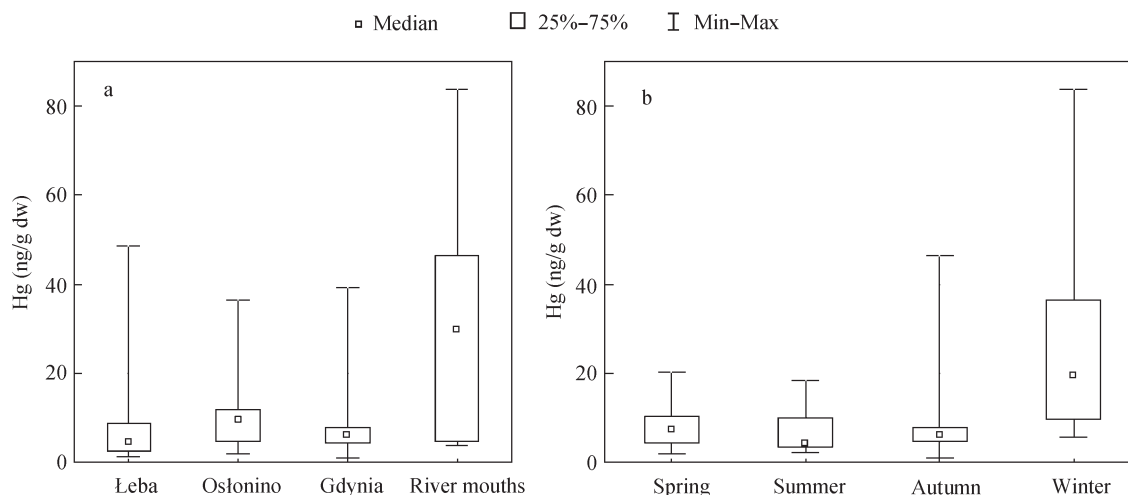


Fig. 4 Hg concentrations in macrophytes at coastal stations of the Southern Baltic Sea (a) and their seasonal changes (b).

Macrophyte Hg concentrations observed in Łeba, Gdynia and Osłonino as well as in the vicinity of river mouths were lower than those observed in macrophytobenthos by Boszke et al. (2003) in the shallow part of Gulf of Gdansk (1995–1998) (15–512 ng/g dw) and Falandysz (1994) in the Gulf of Gdansk (1988–1989) (22–130 ng/g dw). This supports the hypothesis of a decrease in the concentration of bio-available Hg in studied areas.

Hg concentrations in benthic macrophytes were characterized by seasonal variability. This is shown here by the example of Gdynia, where enough material was collected each season (Fig. 4b). Seasonal variability of metal concentrations in macrophytes has been observed before by other researchers: for Zn (Pulich et al., 1976); for Cd, Cu, Pb and Zn (Lyngby and Brix, 1982); for Cd, Cu, and Pb (Ward, 1987); and for Pb and Cu (Malea et al., 1994).

The highest Hg concentrations in benthic macrophytes were measured in winter (19.4 ng/g dw), when the process of Hg accumulation prevailed (BCF:  $9.5 \times 10^4$ ). Wintertime concentrations were significantly different than those of the other seasons (Kolmogorov-Smirnov test,  $p < 0.05$ ). A similar increase in macrophyte Hg concentrations in winter was recorded by Capiomont et al. (2000) and Ward (1987). This is caused by both leaf growth inhibition and enhanced Hg accumulation through roots. According to Capiomont et al. (2000), higher Hg content in macrophytes in winter might be the result of the oxidation of mercury sulfide (HgS) present in sediments, which was formed during summer in areas rich in organic matter and low in oxygen (Covelli et al., 1999). According to Beldowski and Pempkowiak (2007), HgS might represent more than 75% of the total Hg in surficial sediments of the Gulf of Gdansk. The high content of organic matter in surface sediments may cause oxygen deficiencies accompanied by HgS production. This would lead to Hg reduction to insoluble HgS, which can be oxidized to soluble  $\text{HgSO}_4$  in colder months and accumulated by macrophytes.

In spring, increases in solar radiation and temperature stimulate the process of plant growth, resulting in lower Hg concentrations in the organisms (BCF  $2.8 \times 10^4$ ). The lowest Hg concentrations in macrophytobenthos were

observed during summer, when their growth is most intense (BCF  $1.6 \times 10^4$ ). In autumn, a slight increase in the average Hg concentration in macrophytobenthos was observed (BCF  $3.7 \times 10^4$ ) due to growth inhibition and enhanced metal accumulation from porewaters (Covelli et al., 1999). The decrease of metal concentrations in leaves in warm seasons (spring–autumn) might be caused on one hand by the intensive growth of the organisms, and on the other, by “downward” transport of Hg in the plant. Such translocation of Hg from the leaves to the roots of *Eriocaulon septangulare* was observed in a laboratory study by Coquery and Welbourn (1994).

### 3 Conclusions

The highest average Hg concentrations in every environmental compartment considered were observed in samples collected near the river mouths. High average concentrations of Hg in the water and macrophytes were also observed in the shallow, sheltered parts of the Gulf of Gdansk (Osłonino), where the water exchange was restricted. The highest variability of Hg concentration in water and macrophytes was recorded in the coastal zone of the industrial city of Gdynia. This was caused by terrestrial runoff and currents transporting river water from the mouth areas.

Significant differences between Hg concentrations in the coastal zone of the Gulf and the open sea (for water) and between river mouths and the coastal zone (for suspended matter) indicate that the parameters controlling Hg concentration levels in the Southern Baltic Sea are the quantity and quality of nonliving organic matter, phyto- and zooplankton biomass, and species composition. In winter, when both freezing and thawing temperatures occurred, an additional source of Hg to the industrial coastal zone could have been melting snow. These factors appeared to control mercury concentrations in water and suspended matter to a larger extent than seasonal variations.

Hg concentrations in macrophytes were significantly higher in winter than in the warm seasons (spring, summer, autumn). This was probably the combined effect of higher

availability of Hg in porewaters (resulting from the oxidation of HgS in the topmost sediments) and leaf growth inhibition. During the warm seasons, Hg concentrations decreased due to leaf growth and probable downward transport of Hg inside the plant. Those processes are highly temperature-dependent, so a changing climate with cooler summers and warmer winters might lead to an inhibition or even reversal of those trends.

Concentrations of dissolved and particulate Hg in the surface microlayer at the air/sea interface were over 10 times greater than those observed in bulk surface water. This was caused by characteristic physical-chemical conditions prevailing in the surface microlayer. The Hg concentrations in macrophytobenthos and plankton in the coastal zone of the Southern Baltic Sea observed in this study were lower than those observed during previous investigations (1988–1998).

### Acknowledgments

This work was supported by the Regional Fund for Environment Protection and Water Management in Gdansk (No. WFOS/D/210/130/2008).

### References

- Baeyens W, Leermakers M, 1998. Elemental mercury concentrations and formation rates in the Scheldt estuary and the North Sea. *Marine Chemistry*, 60: 257–266.
- Balogh S J, Meyer M L, Hansen N C, Moncrief J F, Gupta S C, 2000. Transport of mercury from a cultivated field during snowmelt. *Journal of Environmental Quality*, 29: 871–874.
- Bartnicki J, Gusev A, Aas W, Fagerli H, Valiyaveetil S, 2008. Atmospheric supply of nitrogen, lead, cadmium, mercury and dioxines/furanes to the Baltic Sea in 2006. EMEP Centers Joint Report for HELCOM EMEP/MSW, Technical Report 3/2008.
- Beldowska M, Falkowska L, 2007. Exchange of mercury between air and seawater in day/night cycle, during summer and winter. *Oceanological and Hydrobiological Studies*, 36: 51–68.
- Beldowska M, Falkowska L, Siudek P, Gajecka A, Lewandowska A, Rybka A et al., 2007. Atmospheric mercury over the coastal zone of the Gulf of Gdansk. *Oceanological and Hydrobiological Studies*, 36: 9–18.
- Beldowski J, Miotk M, Pempkowiak J, 2009. Mercury fluxes through the sediment water interface and bioavailability of mercury in southern Baltic Sea sediments. *Oceanologia*, 51: 263–285.
- Beldowski J, Pempkowiak J, 2007. Mercury concentration and speciation changes along source/sink transport pathway (Southern Baltic). *Estuarine, Coastal and Shelf Science*, 72: 370–378.
- Bilinski H, Kwokal Z, Plavsic M, Wrisher M, Branica M, 2000. Mercury distribution in the water column of the stratified Kirk River estuary (Croatia): Importance of natural organic matter and of strong winds. *Water Research*, 34: 2001–2010.
- Bonzongo J C J, Donkor A K, 2003. Increasing UV-B radiation at the earth's surface and potential effects on aqueous mercury cycling and toxicity. *Chemosphere*, 52: 1263–1273.
- Boszke L, Siepak J, Falandysz J, 2003. Total mercury contamination of selected organisms in Puck Bay, Baltic Sea, Poland. *Polish Journal of Environmental Studies*, 12: 275–285.
- Brzezińska A, 1984. The occurrence of mercury in the Southern Baltic Sea. *Oceanologia*, 18: 109–116.
- Capiomont A, Piazzoli L, Pergent G, 2000. Seasonal variations of total mercury levels in foliar tissues of *Posidonia oceanica*. *Journal Marine Biology Association U.K.*, 80: 1119–1123.
- Coquery M, Welbourn P M, 1994. Mercury uptake from contaminated water and sediment by the rooted and submerged aquatic macrophyte *Eriocaulon septangulare*. *Archives of Environmental Contamination and Toxicology*, 26: 335–341.
- Cossa D, Martin J M, 1991. Mercury in the Rhone delta and adjacent marine areas. *Marine Chemistry*, 36: 291–302.
- Costa M, Liss P S, 1999. Photoreduction of mercury in sea water and its possible implications for Hg<sup>0</sup> air-sea fluxes. *Marine Chemistry*, 68: 87–95.
- Costa M, Liss P, 2000. Photoreduction and evaluation of mercury from seawater. *The Science of the Total Environment*, 261: 125–135.
- Covelli S, Faganeli J, Horvat M, Brambati A, 1999. Porewater distribution and benthic flux measurements of mercury and methylmercury in the Gulf of Trieste (Northern Adriatic Sea). *Estuarine, Coastal and Shelf Science*, 48: 415–428.
- Falandysz J, 1994. Mercury concentrations in benthic animals and plants inhabiting the Gulf of Gdansk, Baltic Sea. *The Science of the Total Environment*, 141: 45–49.
- Falkowska L, 1999. Sea surface microlayer: A field evaluation of teflon plate, glass plate and screen sampling techniques. Part 2: Dissolved and suspended matter. *Oceanologia*, 41: 223–240.
- Ferrara R, Mazzolai B, Lanzillotta E, Nucaro E, Pirrone N, 2001. Temporal trends in gaseous mercury evasion from the Mediterranean seawaters. *The Science of the Total Environment*, 259: 183–190.
- HELCOM, 1986. Water balance of the Baltic Sea. *Environment Proceedings*, 16: 1–174.
- Horvat M, Kotnik J, Logar M, Fajon V, Zvonaric T, Pirrone N, 2003. Speciation of mercury in surface and deep-sea waters in the Mediterranean Sea. *Atmospheric Environment*, 37: 93–108.
- Kraus M L, Weis P, Crow J H, 1986. The excretion of heavy metals by the salt marsh cord grass, *Spartina alterniflora*, and *Spartina's* role in mercury cycling. *Marine Environmental Research*, 20: 307–316.
- Kuss J, Schneider B, 2007. Variability of the gaseous elemental mercury sea-air flux of the Baltic Sea. *Environmental Science and Technology*, 41: 8018–8023.
- Larsen V J, Schierup H H, 1981. Macrophyte cycling of zinc, copper, lead, and cadmium in the littoral zone of a polluted and a nonpolluted lake. II. Seasonal changes in heavy metal content of above-ground biomass and decomposing leaves of *Phragmites australis* (Cav.). *Aquatic Botany*, 11: 211–230.
- Laurier F J G, Mason R P, Gill G A, Whalin L, 2004. Mercury distributions in the North Pacific Ocean – 20 years of observations. *Marine Chemistry*, 90: 3–19.
- Laurier F J G, Cossa D, Gonzalez J L, Breviere E, Sarazin G, 2003. Mercury transformations and exchanges in a high turbidity estuary: The role of organic matter and amorphous oxyhydroxides. *Geochimica et Cosmochimica Acta*, 67: 3329–3345.
- Lyngby J E, Brix H, 1982. Seasonal and environmental variation in cadmium, copper, lead and zinc concentrations in eelgrass (*Zostera marina* L.) in the Limfjord, Denmark.

- Aquatic Botany*, 14: 59–74.
- McIntosh A W, Shephard B K, Mayes R A, Atchison G J, Nelson D W, 1978. Some aspects of sediment distribution and macrophyte cycling of heavy metals in a contaminated lake. *Journal of Environmental Quality*, 7: 301–305.
- Malea P, Haritonidis S, Kevrekidis T, 1994. Seasonal and local variations of metal concentrations in the seagrass *Posidonia oceanica* (L) Delile in the Antikyra Gulf, Greece. *Science of the Total Environment*, 153: 225–235.
- Majewski A, 1990. Zatoka Gdanska. Wydawnictwo Geologiczne, Warszawa. 500.
- Mason R P, Rolfhus K R, Fitzgerald W F, 1998. Mercury in the North Atlantic. *Marine Chemistry*, 61: 37–53.
- Murawiec D, Gajecka A, Beldowska M, Falkowska L, 2007. Investigation on mercury concentration levels in coastal and offshore waters of the Gulf of Gdansk. *Oceanological and Hydrobiological Studies*, 36: 83–97.
- Pempkowiak J, Cossa D, Sikora A, Sanjuan J, 1998. Mercury in water and sediments of the southern Baltic Sea. *The Science of the Total Environment*, 213: 185–192.
- Pohl C, Hennings U, 2008. Trace metals in Baltic seawater. In: State and Evolution of the Baltic Sea 1952–2005 (Feistel R, Nausch G, Wasmund N, eds.). John Wiley & Sons, Hoboken, NJ, USA, 367–393.
- Pulich W, Barends S, Parker P, 1976. Trace metals cycles in seagrass communities. In: Estuarine Process, Vol. 1, Uses, Stresses and Adaptation to the Estuary (Wiley M ed.). Academic Press, New York. 494–506.
- Schierup H H, Larsen V J, 1981. Macrophyte cycling of zinc, copper, lead and cadmium in the littoral zone of a polluted and a nonpolluted lake. I. Availability, uptake and translocation of heavy metals in *Phragmites australis* (cav.). *Aquatic Botany*, 11: 197–210.
- Schmitt A, Frimmel S, Posten D, 2001. The adsorption kinetics of metal ions onto different microalgae and siliceous earth. *Water Research*, 35: 779–785.
- Szefer J, 2002. Metals, Metalloids, and Radionuclides in the Baltic Sea Ecosystem. Elsevier, Amsterdam. 1–752.
- US EPA (US Environmental Protection Agency), 2002. Method 1631, Revision E: Mercury in water by oxidation, purge and trap, and cold vapor atomic fluorescence spectrometry. US Environmental Protection Agency, Office of Water 4303, EPA-821-R-02-019. 46.
- Ward T J, 1987. Temporal variation of metals in the seagrass *Posidonia australis* and its potential as a sentinel accumulator near a lead smelter. *Marine Biology*, 95: 315–321.
- Wilson S, 2002. Nutritional value of detritus and algae in blenny territories on the Great Barrier Reef. *Journal of Experimental Marine Biology and Ecology*, 271: 155–169.
- Wrembel H Z, 1997. Mercury in the Baltic Sea. Akademia Pedagogiczna w Słupsku. 6–177.
- Wurl O, Elsholz O, Ebighaus R, 2001. On-line determination of total mercury in the Baltic Sea. *Analitica Chimica Acta*, 438: 245–249.