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ORIGINAL RESEARCH ARTICLE

Budget of ^{90}Sr in the Gulf of Gdańsk (southern Baltic Sea)

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Summary In the period from 2005 to 2011 the major source of ^{90}Sr to the Gulf of Gdańsk was the Vistula river. Its contribution was 99.7% of the total load. The main processes responsible for the decrease in ^{90}Sr activity in the Gulf of Gdańsk were: radioactive decay (87%) and sediment deposition (13%). Average increase in the activity of ^{90}Sr in the Gulf of Gdańsk during the study period was 5.0% (114 GBq), which was almost 2 times higher than the loss of ^{90}Sr due to radioactive decay. In the years 1997–2015, the effective half-life of ^{137}Cs was 9.1 years and that of ^{90}Sr was 50.3 years. Assuming a further decrease in ^{137}Cs and maintaining ^{90}Sr concentrations at present level, it is expected that ^{90}Sr will become the major anthropogenic isotope having impact on the level of radioactivity in the Gulf of Gdańsk.

1. Introduction

The Baltic Sea is an inland sea which is practically closed since the only connection with the North Sea and the Atlantic Ocean through the Danish Straits (Skagerrak and Kattegat between southern Sweden and the Danish islands) is relatively narrow. As a consequence, the water exchange between the Baltic Sea and North Sea is limited and amounts to 0.05% per year (Wängberg et al., 2001). This makes the Baltic Sea very sensitive to contamination with different pollutants (HELCOM, 2010), including radionuclides (IAEA, 2005). The Baltic Sea is still considered as one of the water bodies that is most polluted with ^{90}Sr and ^{137}Cs in the world

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(HELCOM, 2009; IAEA, 2005). The major sources of radionuclides inputs into the Baltic Sea were: atmospheric testing of nuclear weapons carried out during the late 1950s and early 1960s, the Chernobyl accident in 1986, discharges from nuclear reprocessing plants located outside the Baltic Sea (Sellafield and La Hague) and discharges from nuclear facilities in the Baltic Sea drainage area (Baklanov and Sorensen, 2001; HELCOM, 2009; Nielsen et al., 1999; Nies et al., 1995). It has been estimated that the total load of ^{90}Sr and ^{137}Cs introduced into the Baltic Sea from all sources amounts to 621 TBq and 5752 TBq, respectively.

Among many pollutants introduced into the Baltic Sea, the ^{90}Sr isotope is considered to be particularly dangerous, due to its specific nature and relatively long half-life (28.8 years) (Kryshev, 2006). Its chemical similarity to calcium is the reason why strontium is quite easily taken up and accumulated in a body, especially in bone tissues. However, data on the activity levels of ^{90}Sr in various compartments of the marine environment and biota is largely limited. At the same time knowledge on the ^{90}Sr levels in particular elements of the marine environment and knowledge on factors controlling its temporal and spatial distribution, are crucial for determining the degree of environmental contamination, especially in incidental situations. Information on the concentration factors in organisms is of special importance as allows to determine the exposure of organisms to the radioactivity related to ^{90}Sr presence.

Long-term observations of the variability in concentrations of ^{90}Sr and ^{137}Cs showed that the decrease of ^{90}Sr levels is not as significant as in the case of ^{137}Cs. Moreover, the decrease is smaller than expected from the radioactive decay. Therefore, based on the analysis of data on radionuclide concentrations in various components of the marine environment (abiotic – seawater and sediment, and biotic – fish and macrophytobenthic plants), obtained in the period of 2005–2011, the study, which results would become the basis for future scenarios concerning ^{90}Sr levels in the Baltic Sea, was undertaken. The assessment of the present level of ^{90}Sr pollution in the Baltic Sea was carried out in relation to current sources – riverine and atmospheric inputs of this isotope, based on the results of ^{90}Sr concentrations in the Vistula and atmospheric deposition, obtained for the same period as mentioned above. Finally, the main factors controlling distribution of the ^{90}Sr in the marine ecosystem were indicated, also in relation to long-term changes observed after potential introduction of significant ^{90}Sr loads into the Baltic Sea.

2. Material and methods

2.1. Study area

The Gulf of Gdańsk is located in the southeastern part of the Baltic Sea. Its northern boundary is the straight line connecting Cape Rozewie (54°50′N, 18°20′E) with Cape Taran (54°58′N, 19°59′E). The area of the Gulf of Gdańsk is 4940 km^2 (Łukawska-Matuszewska and Bolałek, 2008), while the volume of water is estimated at 291.2 km^3 (Majewski, 1990). The Gulf of Gdańsk has an average depth of about 50 m, and a maximum of 118 m.

2.2. Methods of budget calculations

In order to balance the loads of ^{90}Sr in the Gulf of Gdańsk, it was assumed that the main sources of this isotope are: atmospheric deposition and Vistula river waters, while the factors having impact on the decrease of ^{90}Sr concentration in seawater are: radioactive decay, bioaccumulation and sedimentation processes (Fig. 1). The bioaccumulation took into account in the calculations was related only to marine plants and fish. The loads of ^{90}Sr were calculated based on literature data (mainly from own research) concerning concentrations of this isotope in particular components of the marine environment, measured in the period of 2005–2011, adopted for the estimation of the ^{90}Sr budget in the Gulf of Gdańsk.

Data on ^{90}Sr loads introduced into the Gulf of Gdańsk with atmospheric deposition and riverine runoff was obtained from the study by Saniewski and Zalewska (2016).

The concentrations of ^{90}Sr in seawater were measured in samples collected between 2005 and 2011 at five stations located in the Gulf of Gdańsk. The samples were obtained from the sea surface, from the bottom, and additionally along vertical profiles (every 20 m) at two stations (Fig. 1, Table 1). The analysis of ^{90}Sr distribution in seawater of the Gulf of Gdańsk, for the abovementioned study period, was presented in the work by Saniewski (2013).

Mean activity of ^{90}Sr in sediments was calculated based on literature data (Zalewska and Suplińska, 2013) and unpublished own data. The bottom areas with intensive sedimentation processes, associated with the transportation type of bottom (LOI – loss on ignition, values of 4–10%) and the accumulation bottom (with LOI values >10%) (Håkanson et al., 2003) account for respectively 1426 km^2 and 1840 km^2 of the Gulf of Gdańsk (Carman and Cederwall, 2001). Therefore, it was assumed that the ^{90}Sr deposition into sediments is most intensive in the area of 3266 km^2 (Fig. 1).

Since ^{90}Sr is bioaccumulated and biomagnified in the trophic chain, the concentrations of ^{90}Sr in macrophytobentic plants and selected fish species specific to the Gulf of Gdańsk were taken into account in the budget calculations. To estimate the load of ^{90}Sr removed with the caught fish, the average activity values of ^{90}Sr in fish species (Zalewska et al., 2016) and the mass of fish caught in 2005–2011 in the study area (Szostak et al., 2006, 2007, 2008, 2009, 2010, 2011, 2012) were used.

The estimation of ^{90}Sr accumulated in marine plants was carried out using data on ^{90}Sr concentrations in selected species of macrophytobenthic plants (Zalewska, 2015). The amount of biomass having the potential for bioaccumulation was assessed on the basis of data collected during macrophytobenthos monitoring campaigns carried out in two locations: Orłowo Cliff and Kuźnica Hollow (Brzeska and Saniewski, 2012). The sampling for monitoring purposes took place in June, i.e. in the period of intensive primary production and rapid growth of both macroalgae and vascular plants. Samples were taken by a diver, along transects, from a depth of 1 m to a maximum depth of plant occurrence. The plant material was collected from the area determined by a randomly placed frame (0.5 m × 0.5 m). The frame was placed three times at each depth. The collected material was analyzed macroscopically and microscopically to sepa-

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