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Vertical distribution of ^{137}Cs, ^{210}Pb, ^{226}Ra and $^{239,240}Pu$ in bottom sediments from the Southern Baltic Sea in the years 1998–2000

Maria M. Suplińska

Abstract This paper presents vertical distribution of ^{137}Cs, ^{226}Ra and $^{239,240}Pu$ in bottom sediments collected from the Southern Baltic Sea in the years 1998–2000. In the southern part of Baltic Sea the highest concentrations of ^{137}Cs and $^{239,240}Pu$ were observed at the Gulf of Gdansk. Deposition of ^{137}Cs ranged from 1990±402 Bq m^{-2} in the Bornholm Basin to 3260±820 Bq m^{-2} in the Gulf of Gdansk. Depositions of $^{239,240}Pu$ in the Bornholm Basin were 28.1–30.4 Bq m^{-2} and in Gulf of Gdansk 162–174 Bq m^{-2}. The concentration peaks of long-lived radionuclides, owing to the sedimentation processes, show the maximum fallout period in different sediment layers. The observed differences in distribution of radiocaesium and plutonium along the profile confirm two main sources of contamination – Chernobyl fallout for ^{137}Cs and global fallout in case of $^{239,240}Pu$. In chosen core samples from the Gdansk Basin vertical distribution of ^{210}Pb concentrations were determined. Evaluated sedimentation rates based on decrease of unsupported ^{210}Pb ranged in the Gdansk Basin from 1.9 to 2.3 mm year^{-1}. Calculations based on $^{239,240}Pu$ peaks show sedimentation rate, in the range from 1.6–2.2 mm year^{-1} for P110 region.

Key words Baltic Sea • contamination • radionuclides • sedimentation rate

Introduction

The total input of ^{137}Cs from the Chernobyl accident into the Baltic Sea area was estimated to be 4.7 PBq [6]. It was the main source of artificial radionuclides. Another source of radioactive contamination in this environment was the fallout after nuclear weapons tests. The Baltic Sea extends from 54°N to 66°N, which means that it belongs to the most intensive global fallout zone. The cumulative deposition of ^{137}Cs from this source was estimated to be 0.93 PBq [7]. The input of ^{137}Cs from discharges of Sellafield and La Hague transported by the inflow of saline water through the Danish Straits was estimated to be 0.38 PBq. The Baltic Sea nuclear installation input was estimated to be 0.65 TBq [7].

The activities of ^{137}Cs, as well as plutonium, in sediments reflect deposition directly to the Baltic Sea and through the drainage areas. However, these activities depend also on the sediment type and sedimentation rate at various locations. In the bottom sediments for 1991 inventories of 1.4 PBq for ^{137}Cs and 0.018 PBq of $^{239,240}Pu$ were estimated [4]. Compared to the early 1980s these inventories have increased by factors of 5.1 and 1.2, respectively [4].

The knowledge on vertical distributions of artificial radionuclides in bottom sediments gives opportunity to observe current contamination of the marine environment as well as its changes in time. Additionally, taking into account vertical distributions of ^{210}Pb and $^{239,240}Pu$, the sedimentation rate in different regions of the Baltic Sea may be evaluated.

M. M. Suplińska
Department of Radiation Hygiene,
Central Laboratory for Radiological Protection,
7 Konwaliowa Str., 03-194 Warsaw, Poland,
Tel.: +48 22 /811 00 11 ext. 227,
e-mail: suplinska@clor.waw.pl

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Experiments

Bottom sediment samples were collected from various regions of southern part of the Baltic Sea (Fig. 1), during the sampling cruises into the Baltic Sea with r/v "Baltica" organized once a year by the Institute of Meteorology and Water Management (July 1998, August 1999 and 2000). At each sampling station, five parallel core samples have been taken with a gravity corer (Niemisto type with inner diameter 55 mm). Core samples were sectioned into 1 or 2 cm sub-samples from 0 to 19 cm depth, and parallel sub-samples were combined for analyses. The determination of ^{137}Cs and ^{226}Ra were performed each year and determinations of ^{238}Pu and ^{239,240}Pu in two years period. ^{210}Pb was analyzed only in selected samples from the Gdansk Basin. The co-ordinates and depth of sampling stations are presented in Table 1.

The ^{137}Cs activity concentration was determined by gamma spectrometry with an HPGe detector, with energy resolution 1.8 keV for ^{60}Co (1332 keV) and a relative efficiency of 30%. The detector was connected to a multichannel analyser, Canberra, Series 90. Minimum detectable activity (MDA) for counting time 86,000 s was 0.06 Bq/sample (1.5 Bq kg^{-1}) [11]. Plutonium was separated by ion exchange, followed by electrodeposition onto stainless steel disks. ^{242}Pu was used as an internal tracer for counting alpha activity and chemical recovery. Activity of plutonium was measured by alpha spectrometry using a PIPS detector with an efficiency of 32% placed in a vacuum chamber. MDA for counting time of 164,000 s was 0.2 mBq/sample (0.007 Bq kg^{-1}) [10]. Concentration of ^{226}Ra was determined radiochemically using the emanation method (measurement of ^{222}Rn in Lucas-type scintillation chambers) preceded by separation of radium [1]. MDA with the counting time of 21,600 s was equal to 0.73 mBq/sample (0.73 Bq kg^{-1}). Concentration of ^{210}Pb was determined by beta activity measurement of ^{210}Bi deposited on a nickel disk. MDA with the counting time of 21,600 s was equal to 0.017 Bq/sample (3.4 Bq kg^{-1}) [1]. Minimum detectable activities were calculated at the probability of the type I and II errors equal to 0.05.

Table 1. Sampling stations for bottom sediment in HELCOM MORS programme.

Stations code	Sampling area	Depth (m)	Co-ordinates
P110	Gulf of Gdansk	64–71	54°30'N;19°06.8'E
P116		86–90	54°39.1'N;19°17.6'E
P1	Gdansk Deep	106–107	54°50'N;19°20'E
P140	open sea area	88–89	55°33'N;18°24'E
P5	Bornholm Basin	88–91	54°15'N;15°59'E
P39		63–68	54°44.5'N;15°08'E

The reliability of applied methods was checked by participation in inter-comparison exercises organized by the IAEA and Risø National Laboratory (Table 2).

Results

The concentrations of ^{137}Cs in sediments differ depending on sampling site and sampling depth. The highest concentrations were found in the Gulf of Gdansk (Table 3). In the upper 0–3 cm layer of sediments, ^{137}Cs concentrations in the years 1998–2000 ranged from 220 to 393 Bq kg^{-1} d.w. (P110 and P116) and their values decrease along the profiles (Fig. 2). In the sediments from the Bornholm Basin (P39 and P5), the ^{137}Cs concentrations were evidently lower and ranged from 77 to 129 Bq kg^{-1} d.w. (Table 3). Similar values (87–117 Bq kg^{-1} d.w.) were observed in the Pomeranian Bay by Bojanowski *et al.* [2]. In the years 1998–2000, the average deposition of ^{137}Cs for the Gulf of Gdansk was equal to 3260±820 Bq m^{-2}. Much lower deposition of ^{137}Cs, 1990±402 Bq m^{-2}, was found for

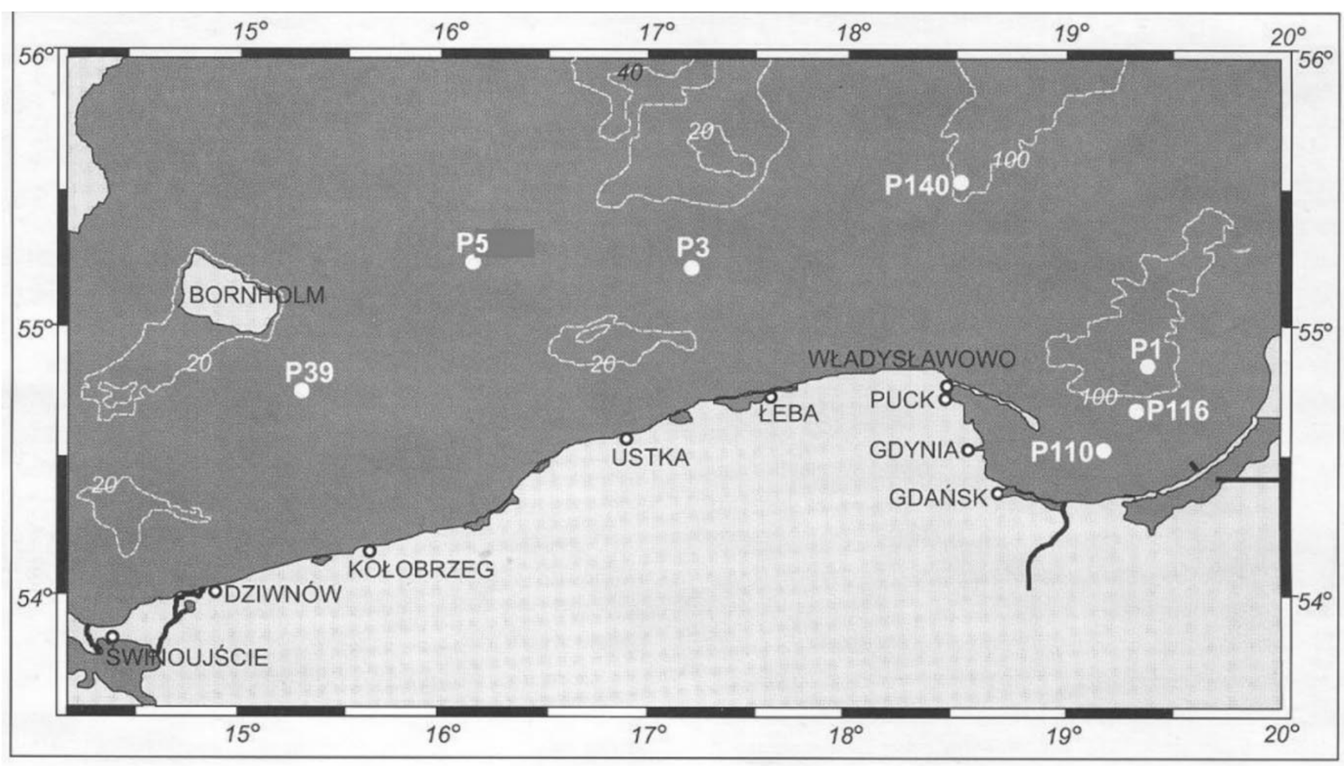

Fig. 1. Sampling sites of sediment for measurements of radioactive substances, 1998–2000.

Table 2. ^{137}Cs, ^{210}Pb, ^{226}Ra and $^{239,240}Pu$ measurements in inter-comparison samples.

Nuclide	CLRP	Median AQCS values (range accepted)	CLRP	Median AQCS values (range accepted)
	IAEA 378		**IAEA 379**	
^{137}Cs	5.4±0.5	5.7 (3.2–6.5)	37.9±3.0	39.5 (37.9–45)
$^{210}Pb^{*)}$	207±11.8	188 (153–191)	212±10.4	229 (204–240)
^{226}Ra	132±15	118 (103.2–132)	40.6±5.6	29 (22.1–48)
$^{239,240}Pu$	0.120±0.024	0.135 (0.11–0.15)	3.6±0.5	3.8 (3.2–4.1)
	IAEA 300		**IAEA 381**	
^{134}Cs	73.3±10.9	69 (57–94)	–	–
^{137}Cs	1097±142	1053 (940–1101)	0.496±0.02	0.482 (0.48–0.50)
^{238}Pu	–	–	3.1±0.4	3.17 (3.1–3.5)
$^{239,240}Pu$	3.2±0.4	3.43 (3.09–3.9)	13.2±1.5	13.2 (13.0–14.0)

*) determinations of ^{210}Pb in the IAEA samples as secondary standard material.

the Bornholm Basin. The differences in deposition of ^{137}Cs between consecutive years, observed in particular sampling sites, indicate that even at small area the radionuclide concentration may vary to a large degree.

Similarly as for radiocaesium the highest concentrations of plutonium in bottom sediments were found in the Gulf of Gdansk, however the maxima of ^{238}Pu and $^{239,240}Pu$ were observed always in deeper layers. In core samples taken from station P110 the maximum of $^{239,240}Pu$ concentration, 7.2±1.2 Bq kg^{-1} d.w., was observed in 7–9 cm layer in 1998 and 6.1±0.66 Bq kg^{-1} d.w. in 5–7 cm layer in 2000 (Table 4a). In core samples from P116 station maxima of concentrations 5.27±0.62 and 5.46±0.59 Bq kg^{-1} d.w. were found in 4–5 cm layers in both years (1998 and 1999). The concentrations of plutonium in the Bornholm Basin are uniform along the profiles even to the depth of 11 cm (Table 4b) and concentrations of $^{239,240}Pu$ ranged from 0.785 to 1.01 Bq kg^{-1} d.w. in 1998. The deposition of $^{239,240}Pu$ were found to be 28.1–30.4 Bq m^{-2} in the Bornholm Basin (P5), 95 Bq m^{-2} in the Gdansk Deep (P1) and 162–174 Bq m^{-2} in the Gulf of Gdansk (P110)(Table 4a). Similar values were found in previous years [10–12]. Comparable values (48 Bq m^{-2} for the Bornholm Basin and 98 Bq m^{-2} for the Gdansk Deep) were determined also by Skwarzec and Bojanowski [9].

The distributions of ^{226}Ra concentration were similar along the profiles (Fig. 3), however, differences between particular sub-regions were observed. Lower concentration of ^{226}Ra, 28±1.4 Bq kg^{-1} d.w., were found in the Gulf of Gdansk (P110, P116) and higher, 40±1.7 Bq kg^{-1} d.w. and 46±2.3 in the Gdansk Deep (P1) and the Bornholm Deep (P5), respectively.

Determinations of ^{210}Pb were performed in four core samples from the Gdansk Basin. ^{210}Pb concentration ranged from 338 to 434 Bq kg^{-1} d.w. in the first 0–1 cm layer in the Gdansk Basin area and decreased exponentially along the profiles to the 40–85 Bq kg^{-1} d.w. in the layer 17–19 cm depending on the sampling site (Table 5). The deposition of unsupported ^{210}Pb, for sediment layer 0–19 cm, observed in P110 sampling site was 9960±310 Bq m^{-2} in 1998 and 7400±249 Bq m^{-2} in 2000. In sampling site P1 this deposition was equal to 7020±191 Bq m^{-2} and in P116 to 5480±173 Bq m^{-2}. The concentrations in the analyzed lowest layers were still 14.2–46.2 Bq kg^{-1} d.w. depending of sampling site.

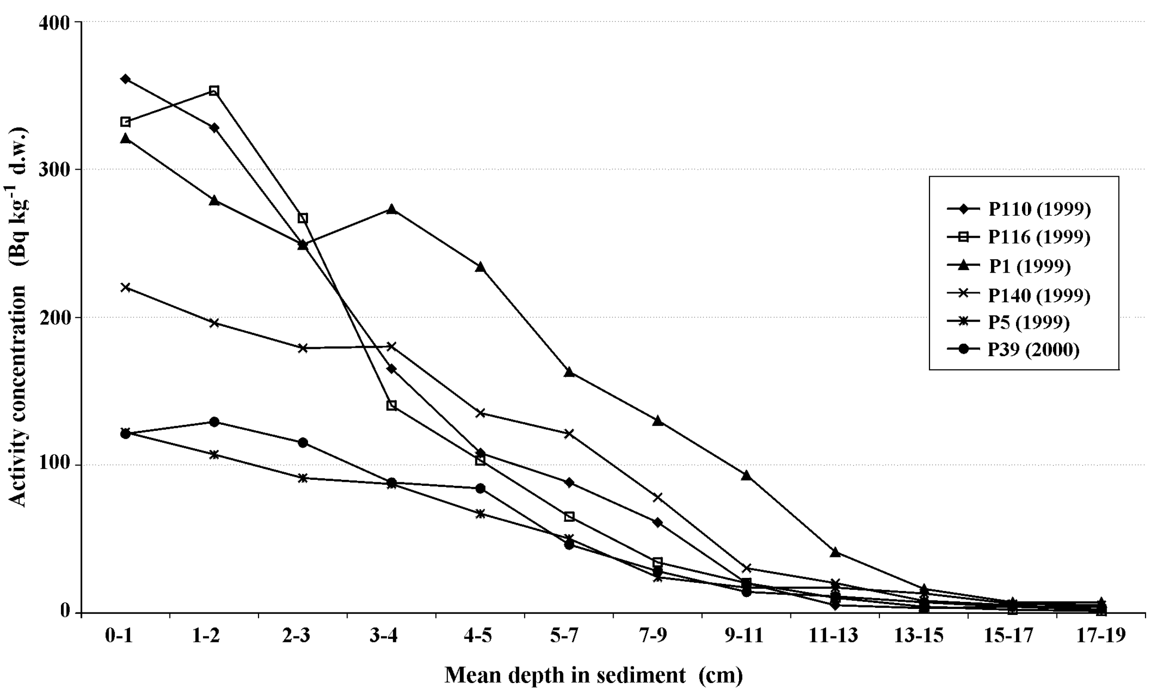

Fig. 2. Vertical distribution of ^{137}Cs in bottom sediments from the Southern Baltic Sea.

Table 3. Caesium-137 in layers of bottom sediment from the Gdansk Basin (P110, P116, P1) and from the Bornholm Basin (P5, P39), content of this radionuclide in particular layers and its total deposition.

Station	Layer (cm)	^{137}Cs 1998 Activity (Bq kg^{-1} d.w.)	1998 Content[a] (Bq m^{-2})	1999 Activity (Bq kg^{-1} d.w.)	1999 Content (Bq m^{-2})	2000 Activity (Bq kg^{-1} d.w.)	2000 Content (Bq m^{-2})
P110	0 – 1	312±8.70[b]	409±36.0[c]	361±13.0	713±68.4	272±8.72	311±28.6
	1 – 2	299±11.4	648±63.5	328±13.8	795±81.1	232±8.60	632±61.8
	2 – 3	233±9.36	611±62.4	249±9.71	653±64.7	163±7.00	556±57.2
	3 – 4	162±7.42	449±47.6	165±8.56	465±52.0	93.4±3.46	362±35.1
	4 – 5	102±6.10	311±37.3	108±5.39	315±34.6	78.2±4.70	280±33.6
	5 – 7	77.6±4.96	429±40.3	88.8±2.91	554±34.9	63.9±3.71	456±40.1
	7 – 9	69.6±2.92	454±32.7	61.1±2.93	469±36.2	35.0±2.10	308±27.8
	9 – 11	41.5±2.62	325±30.0	19.9±1.61	198±22.0	12.1±1.15	181±22.8
	11 – 13	12.6±1.47	112±16.5	5.12±0.830	52.0±10.0	5.19±1.04	53.6±12.4
	13 – 15	3.08±0.729	31.7±8.47	2.59±0.565	25.8±6.41	<MDA	–
	15 – 17	2.04±0.300	22.4±3.96	3.56±0.797	35.6±8.98	<MDA	–
	17 – 19	2.17±0.353	21.2±4.10	2.33±0.596	21.8±6.22	<MDA	–
	0 – 19		38±130[d]		4290±150		3140±115
P116	0 – 1	374±13.1	269±25.6	332±9.62	506±45.0	329±11.2	146±13.7
	1 – 2	257±10.2	302±33.5	353±9.17	445±38.3	393±11.0	398±35.0
	2 – 3	220±11.0	306±33.7	267±8.28	444±40.4	326±11.1	330±31.0
	3 – 4	153±9.80	277±34.4	140±4.77	236±22.2	230±9.45	337±34.0
	4 – 5	125±7.99	262±32.5	103±7.43	204±26.9	159±8.57	266±30.4
	5 – 7	85.9±4.64	356±29.9	64.7±4.60	263±26.5	134±3.61	591±33.7
	7 – 9	41.0±2.42	206±18.4	34.5±1.90	178±15.1	116±3.59	451±27.5
	9 – 11	18.0±1.79	114±14.7	19.8±0.814	88.4±6.28	84.6±2.45	366±21.6
	11 – 13	5.07±0.674	30.6±4.98	10.2±1.12	54.1±7.58	61.8±2.78	314±23.6
	13 – 15	3.14±0.517	21.9±4.27	4.11±0.621	24.5±4.44	40.0±2.16	200±16.8
	15 – 17	<MDA	–	2.04±0.468	12.3±3.39	26.6±1.12	154±11.1
	17 – 19	2.15±0.624	17.0±5.45	<MDA	–	14.7±1.01	109±10.8
	0 – 19		2170±81.7		2460±86.1		3660±88.8
P1	0 – 1	349±12.2	279±26.5	321±8.68	379±32.9	368±12.2	241±22.4
	1 – 2	299±13.2	387±40.3	279±11.2	440±44.0	246±10.8	357±37.1
	2 – 3	275±12.9	409±43.8	249±76.96	427±37.6	185±6.12	332±30.9
	3 – 4	304±12.8	471±48.1	273±11.2	506±51.1	118±5.48	258±27.4
	4 – 5	244±11.2	453±48.0	234±10.6	484±50.8	56.6±3.81	133±17.0
	5 – 7	128±6.28	467±36.9	163±3.76	627±33.3	34.8±2.22	177±16.6
	7 – 9	76±3.38	323±23.9	130±7.42	539±46.9	11.2±1.15	59.4±7.89
	9 – 11	46.8±2.62	227±19.5	93.4±3.18	408±26.1	3.94±0.81	23.5±5.53
	11 – 13	32.5±2.37	172±17.7	40.6±2.40	183±16.3	2.30±0.66	13.6±3.89
	13 – 15	11.0±1.41	62.7±10.0	15.7±1.58	78.6±10.3	2.78±0.66	17.2±4.10
	15 – 17	5.15±0.70	28.0±4.67	6.86±0.92	34.9±5.72	<MDA	–
	17 – 19	3.61±0.52	19.6±3.39	7.13±1.05	38.0±6.73	<MDA	–
	0 – 19		3300±108		4144±66		1627±30
P5	0 – 1	118±5.86[b]	166±18.2[c]	122±5.23	196±20.2	90.2±6.13	103±13.1
	1 – 2	85.6±6.93	171±24.1	107±5.43	177±19.7	92.2±6.63	145±17.5
	2 – 3	76.4±6.04	171±23.6	91.4±4.57	173±19.1	74.3±4.61	165±20.2
	3 – 4	79.0±6.88	192±28.3	86.8±5.64	195±24.4	82.8±5.05	184±22.3
	4 – 5	53.7±3.11	130±15.4	67.0±3.28	156±17.0	72.6±4.79	182±23.0
	5 – 7	64.6±4.52	352±35.3	50.2±2.21	245±18.1	68.9±3.17	297±22.6
	7 – 9	57.8±2.83	300±23.7	23.8±2.02	126±14.5	45.5±2.91	222±20.9
	9 – 11	58.3±2.86	293±23.1	16.6±1.49	97.4±11.7	30.9±2.04	161±15.5
	11 – 13	54.0±2.97	271±23.2	17.1±1.54	88.0±10.6	11.9±0.869	72.2±7.44
	13 – 15	34.1±2.15	184±17.1	13.0±1.30	69.9±9.09	8.06±0.604	48.9±5.13
	15 – 17	16.6±1.11	104±10.1	6.09±0.938	32.9±6.05	2.51±0.388	14.0±2.58
	17 – 19	16.0±0.98	101±9.20	5.32±1.04	29.8±6.74	<MDA	–
	0 – 19		2440±76.6[d]		1590±54.7		1600±56.4
P39	0 – 1	114±5.69	163±17.9			120±6.51	177±20.2
	1 – 2	126±9.96	229±31.9			129±6.69	296±33.1
	2 – 3	123±8.73	263±34.5			115±6.42	290±33.6
	3 – 4	114±8.70	277±37.7			87.6±4.82	275±31.6
	4 – 5	111±9.06	312±44.3			84.0±3.91	276±29.4
	5 – 7	76.8±6.14	388±42.7			46.4±2.60	266±22.8
	7 – 9	55.5±2.61	277±21.3			27.6±1.71	155±14.3
	9 – 11	49.0±3.59	190±23.2			13.7±1.32	75.4±9.50
	11 – 13	26.8±2.19	142±16.0			10.9±1.19	61.5±8.54
	13 – 15	13.8±1.63	72.4±10.7			6.90±0.690	41.1±5.35
	15 – 17	4.42±1.10	24.3±6.79			4.23±0.583	24.9±4.19
	17 – 19	2.84±0.440	14.9±2.76			3.57±0.603	24.1±4.80
	0 – 19		2350±95.7				1960±73.8

[a] content of ^{137}Cs was calculated as activity of radionuclide in sample divided by sampling surface.
[b] activity concentration ± uncertainty due to counting of sample at the 95% confidence level.
[c] content ± uncertainty due to counting of sample and sampling at the 95% confidence level.
[d] total deposition ± combined uncertainty due to counting of sample and sampling of all layers at the 95% confidence level.

Table 4a. Plutonium-239,240 in layers of bottom sediments from the Gdansk Basin, content of this radionuclide in particular layers and its total deposition.

Layer (cm)	$^{239,240}Pu$							
	P110/1998		P110/2000		P116/1998		P116/1999	
	Activity (Bq kg⁻¹ d.w.)	Content[a)] (Bq m⁻²)	Activity (Bq kg⁻¹ d.w.)	Content (Bq m⁻²)	Activity (Bq kg⁻¹ d.w.)	Content[a)] (Bq m⁻²)	Activity (Bq kg⁻¹ d.w.)	Content (Bq m⁻²)
0 – 1	1.29±0.22	1.72±0.39	2.85±0.36	3.25±0.60	3.73±0.47	2.70±0.50	3.44±0.49	5.23±1.06
1 – 2	1.56±0.25	3.39±0.74	2.51±0.35	6.87±1.37	4.35±0.47	5.14±0.87	3.13±0.66	3.94±1.07
2 – 3	2.32±0.30	6.40±1.22	3.21±0.36	11.0±1.87	4.89±0.57	6.87±1.21	3.71±0.33	6.16±0.91
3 – 4	2.96±0.30	8.29±1.34	3.41±0.39	13.3±2.32	5.23±0.60	9.53±1.66	4.01±0.33	6.81±0.97
4 – 5	3.83±0.70	11.8±2.87	3.75±0.40	13.5±2.24	5.27±0.62	11.1±1.98	5.46±0.59	10.8±1.81
5 – 7	5.90±0.73	32.8±5.02	6.07±0.66	43.5±5.97	4.42±0.46	18.4±2.46	3.33±0.33	13.5±1.74
7 – 9	7.18±1.15	47.1±9.00	5.23±0.54	46.4±6.17	3.13±0.35	15.8±2.24	2.06±0.22	10.6±1.44
9 – 11	5.32±0.50	41.6±5.16	1.52±0.20	23.0±3.69	1.36±0.17	8.65±1.32	1.90±0.21	8.53±1.21
11 – 13	2.06±0.35	18.5±3.74	0.07±0.03	0.75±0.40	0.18±0.04	1.08±0.29	0.75±0.13	4.01±0.79
13 – 15	0.23±0.06	2.43±0.68	MDA	–	0.05±0.02	0.38±0.16	0.05±0.03	0.32±0.21
0 – 15		174±12.6		162±10.2		79.7±4.70		69.7±3.81

a) content of $^{239,240}Pu$ was calculated as activity of radionuclide in sample divided by sampling surface.
b) activity concentration ± uncertainty due to counting of sample at the 95% confidence level.
c) content ± uncertainty due to counting of sample and sampling at the 95% confidence level.
d) total deposition ± combined uncertainty due to counting of sample and sampling of all layers at the 95% confidence level.

Table 4b. Plutonium-239,240 in layers of bottom sediments from the Gdansk Deep and Bornholm Deep, content of this radionuclide in particular layers and its total deposition.

Layer (cm)	$^{239,240}Pu$					
	P1/1999		P5/1998		P5/1999	
	Activity (Bq kg⁻¹ d.w.)	Content[a)] (Bq m⁻²)	Activity (Bq kg⁻¹ d.w.)	Content (Bq m⁻²)	Activity (Bq kg⁻¹ d.w.)	Content (Bq m⁻²)
0 – 1	2.89±0.35[b)]	4.11±0.74[c)]	0.785±0.17	1.12±0.30	1.15±0.17	2.25±0.46
1 – 2	2.76±0.37	5.25±1.02	0.905±0.14	1.82±0.40	1.32±0.19	2.66±0.55
2 – 3	3.79±0.43	7.85±1.36	0.919±0.49	2.05±0.49	1.16±0.13	2.65±0.46
3 – 4	3.57±0.42	7.99±1.43	1.01±0.20	2.48±0.64	1.15±0.16	3.13±0.65
4 – 5	3.76±0.42	9.38±1.61	0.96±0.24	2.35±0.73	1.17±0.13	3.28±0.65
5 – 7	3.23±0.44	15.0±2.48	0.86±0.09	4.72±0.66	0.82±0.07	4.82±0.89
7 – 9	2.94±0.35	14.7±2.18	0.79±0.13	4.13±0.79	0.72±0.10	4.62±0.60
9 – 11	2.93±0.34	13.6±1.97	0.81±0.12	4.06±0.72	0.60±0.05	4.27±0.85
11 – 13	1.76±0.22	9.57±1.48	0.63±0.11	3.17±0.65	0.30±0.04	1.85±0.38
13 – 15	1.23±0.22	7.43±1.56	0.40±0.08	2.19±0.51	0.14±0.02	0.89±0.26
0 – 15		94.90±5.24[d)]		28.10±1.92		30.40±1.91

a) content of $^{239,240}Pu$ was calculated as activity of radionuclide in sample divided by sampling surface.
b) activity concentration ± uncertainty due to counting of sample at the 95% confidence level.
c) content ± uncertainty due to counting of sample and sampling at the 95% confidence level.
d) total deposition ± combined uncertainty due to counting of sample and sampling of all layers at the 95% confidence level.

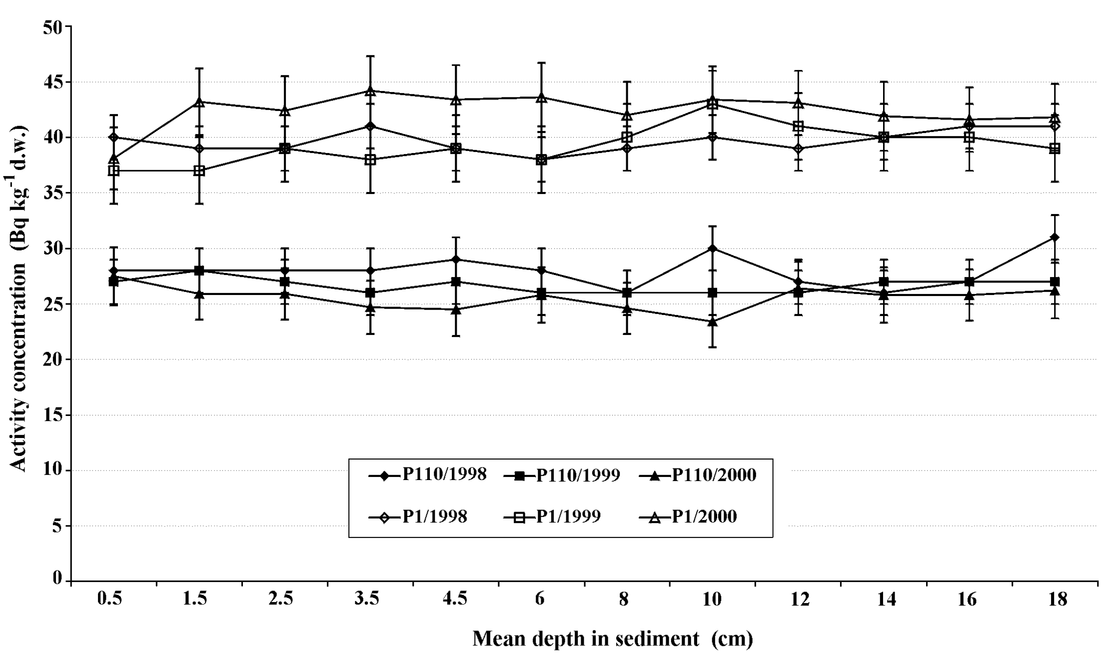

Fig. 3. Vertical distribution of ^{226}Ra in bottom sediments from the Gdansk Basin.

Table 5. Lead-210 (total and unsupported) in layers of bottom sediments from the Gdansk Basin, content of unsupported ^{210}Pb in particular layers and its total deposition.

Layer (cm)	^{210}Pb (total) Activity (Bq kg^{-1} d.w.)	^{210}Pb (unsupported) Activity (Bq kg^{-1} d.w.)	^{210}Pb (unsupported) Content[a)] (Bq m^{-2})	^{210}Pb (total) Activity (Bq kg^{-1} d.w.)	^{210}Pb (unsupported) Activity (Bq kg^{-1} d.w.)	^{210}Pb (unsupported) Content (Bq m^{-2})
	P110/1998			**P110/2000**		
0 – 1	434±15.5[b)]	406±15.7[c)]	537±53.0[d)]	338±12.1	310±12.5	357±44.7
1 – 2	413±15.6	385±15.8	839±84.7	289±8.28	264±8.59	721±66.7
2 – 3	316±13.8	295±14.0	812±87.3	227±7.33	202±7.68	692±67.8
3 – 4	390±14.4	362±14.6	987±100	206±7.09	182±7.48	709±71.9
4 – 5	323±13.6	294±13.8	906±96.9	198±6.96	173±7.36	623±63.8
5 – 7	267±12.7	240±12.9	1330±112	211±7.16	185±7.59	1330±94.2
7 – 9	260±12.6	234±12.8	1530±130	141±6.08	117±6.51	1030±88.7
9 – 11	162±6.76	133±7.22	1040±87.5	92.3±5.07	69.0±5.56	1050±116
11 – 13	108±5.90	81.3±6.36	728±78.8	56.7±4.28	30.4±4.91	316±60.5
13 – 15	90.1±5.43	64.1±6.00	665±82.1	50.6±4.15	24.8±4.85	249±56.1
15 – 17	65.8±4.93	38.8±5.55	428±74.1	44.5±74.1	18.7±4.65	188±52.4
17 – 19	46.2±4.57	15.7±5.23	154±56.2	40.3±3.94	14.2±4.67	139±50.0
0 – 19			9960±310[e)]			740±249
	P116/1999			**P1/1999**		
0 – 1	397±13.3	369±13.5	567±54.7	349±9.38	312±9.85	443±40.6
1 – 2	467±15.2	440±15.4	559±53.1	314±8.69	277±9.17	528±49.2
2 – 3	403±14.4	375±14.6	628±62.0	270±8.12	230±8.70	477±46.6
3 – 4	300±12.0	270±12.0	458±48.3	284±8.30	246±8.81	551±52.8
4 – 5	287±12.4	257±12.4	511±55.8	255±7.95	215±8.55	537±53.5
5 – 7	215±10.6	185±10.6	756±67.1	248±7.89	211±8.44	975±68.4
7 – 9	131±5.66	101±5.66	522±47.8	218±7.46	177±8.09	888±67.1
9 – 11	118±5.57	88.8±5.57	398±39.4	203±7.32	160±8.03	843±67.6
11 – 13	94.1±5.32	65.4±5.23	349±41.1	160±5.61	119±6.42	646±54.3
13 – 15	81.6±5.01	52.9±5.01	317±43.0	113±5.80	73.9±6.55	448±53.2
15 – 17	70.8±4.67	41.9±4.67	253±39.5	102±5.71	62.4±6.50	383±51.4
17 – 19	56.4±4.64	26.8±4.64	162±36.8	85.3±5.39	46.2±6.20	297±48.8
0 – 19			5480±173			7020±191

a) content of ^{210}Pb was calculated as activity of radionuclide in sample divided by sampling surface.
b) activity concentration ± uncertainty due to counting of sample at the 95% confidence level.
c) activity concentration ± combined uncertainty due to counting of sample at the 95% confidence level.
d) content ± uncertainty due to counting of sample and sampling at the 95% confidence level.
e) total deposition ± combined uncertainty due to counting of sample and sampling of all layers at the 95% confidence level.

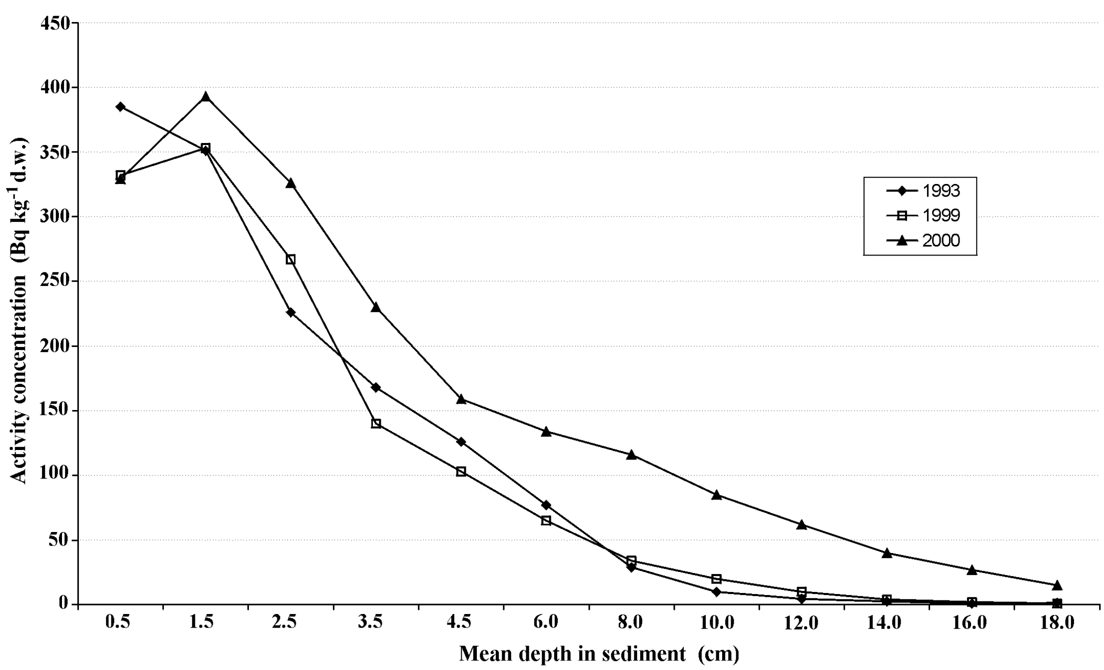

Fig. 4. Vertical distribution of ^{137}Cs in bottom sediments from the Gulf of Gdansk (P116).

Discussion

Decrease of ^{137}Cs concentration in bottom sediment proceeds very slowly. The ^{137}Cs concentrations are similar to these observed in 1990 (258–395 Bq kg^{-1} d.w. in 0–3 cm layer). The patterns of ^{137}Cs vertical distribution in P116 core samples (Gulf of Gdansk) (Fig. 4) show that the maximum observed in the layer 0–1 cm in 1993 was moved to the 1–2 cm layer in 1999 and 2000 years. Concentrations of ^{137}Cs in bottom sediments from the Gdansk Basin decrease exponentially with depth and in the deeper layers of the cores the influence of global fallout contamination was still observed.

The main source of plutonium in the Southern Baltic Sea was global fallout. The highest concentrations of plutonium were observed always in deeper layers of the sediment cores. The ratios of ^{238}Pu to $^{239,240}Pu$ in the majority of samples examined since 1991 ranged 0.03–0.05 [10, 11], being similar to the ratios found for the cumulative deposit from global fallout after the nuclear weapons tests [3]. The maximum of plutonium in core sample P110/2000 (Table 5) was found in 5–7 cm layer, however, in the year 1998 and the previous ones (1991–1997) this maximum was most frequently observed in the 7–9 cm layer. The sedimentation rate in this region, calculated from plutonium distribution and max. global fallout dated to 1963, ranged from 1.6 to 2.2 mm $year^{-1}$. The concentrations of $^{239,240}Pu$ in the core samples P116 and P1 in the layer 0–7 cm ranged from 3.13 to 5.46 Bq kg^{-1} d.w. and 2.74 to 3.79 Bq kg^{-1} d.w., respectively. Because the maxima of plutonium were not well marked, the sedimentation rate based on plutonium distribution was not calculated.

Dating by ^{210}Pb is another method, particularly in the environment with uniform sediment accumulation rates. In the aquatic environment ^{210}Pb originated mainly from atmospheric input and also *in situ* from decay of ^{226}Ra [5]. Geochronology of sediments is based on the decay of the unsupported ^{210}Pb. The ^{210}Pb analysis in sediments has been carried out in the layers, which represent several years of deposition. Under the assumption of steady deposition of ^{210}Pb from atmosphere and an exponential decrease of unsupported ^{210}Pb, the sedimentation rate was evaluated to be 1.8–1.9 mm $year^{-1}$ in P110 area. The unsupported ^{210}Pb concentrations were calculated as a difference between ^{210}Pb and ^{226}Ra concentrations determined along the profiles. Estimated sedimentation rate in the P116 area was equal to 2.2 mm $year^{-1}$ and in the Gdansk Deep (P1) – 2.3 mm $year^{-1}$. These values are in good agreement with sedimentation rates, equal to 1.86–2.25 mm $year^{-1}$, calculated by Pempkowiak *et al.* [8].

In general, the patterns of vertical distributions of unsupported ^{210}Pb were similar to ^{137}Cs distributions (Table 3 and 5) and (Fig. 5). It is suggested that a continued sedimentation of ^{137}Cs and/or ^{210}Pb – containing matter can be responsible for such a distribution of these radionuclides in the bottom sediments. From the data of [13, 14] it can be seen that the Baltic Sea water still contains large amount of ^{137}Cs from the Chernobyl accident. In the patterns of vertical distribution of $^{239,240}Pu$ a maximum concentration was observed at a deeper layer of 5–7 cm (Fig. 5). The loss of soft surface sediments and slicing errors during sampling may significantly affect the result of sedimentation rate if the calculation is based on $^{239,240}Pu$ peaks. This could be the reason of wide range of sedimentation rate (1.6–2.2 mm $year^{-1}$) calculated from $^{239,240}Pu$ peaks in sediments from station P110.

Conclusions

- The highest concentrations of ^{137}Cs, originated from the fallout after the Chernobyl accident, were observed in upper 0–3 cm layer of sediment. The patterns of ^{137}Cs vertical distributions suggested that ^{137}Cs containing sedimentation matter are still in new-formed layers of the bottom sediments.
- The maxima of $^{239,240}Pu$ concentrations observed in deeper layers of sediments indicate that the global fallout was the main source of plutonium contamination.
- The sedimentation rates in the Gdansk Basin based on vertical distribution of ^{210}Pb and $^{239,240}Pu$, ranged from 1.6 to 2.3 mm $year^{-1}$.

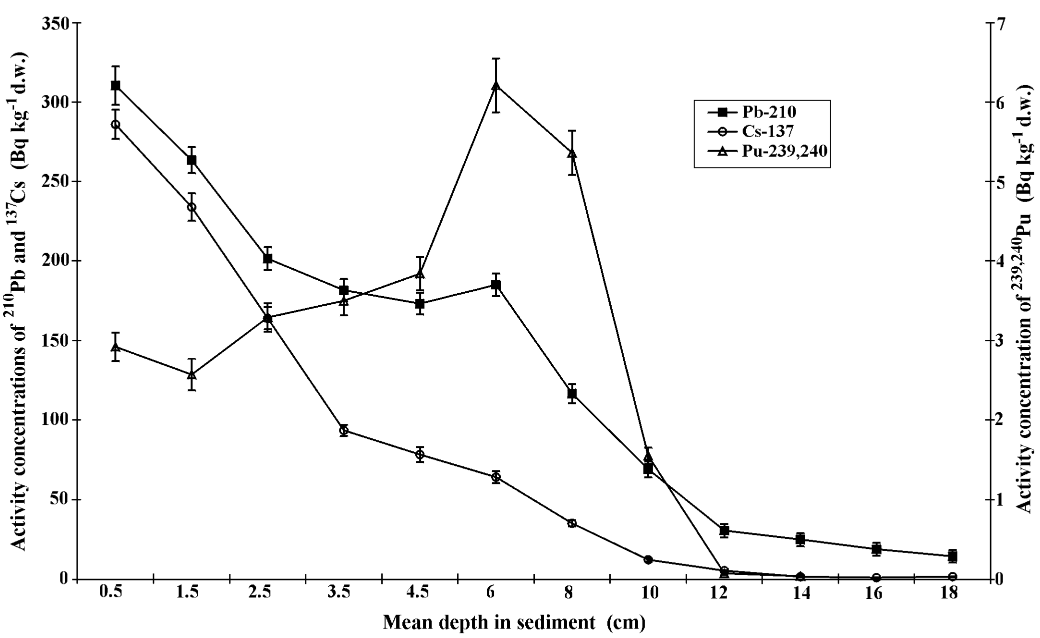

Fig. 5. Vertical distribution of ^{137}Cs, ^{210}Pb and $^{239,240}Pu$ concentrations in bottom sediments from the Gulf of Gdansk (P110) in 2000.

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