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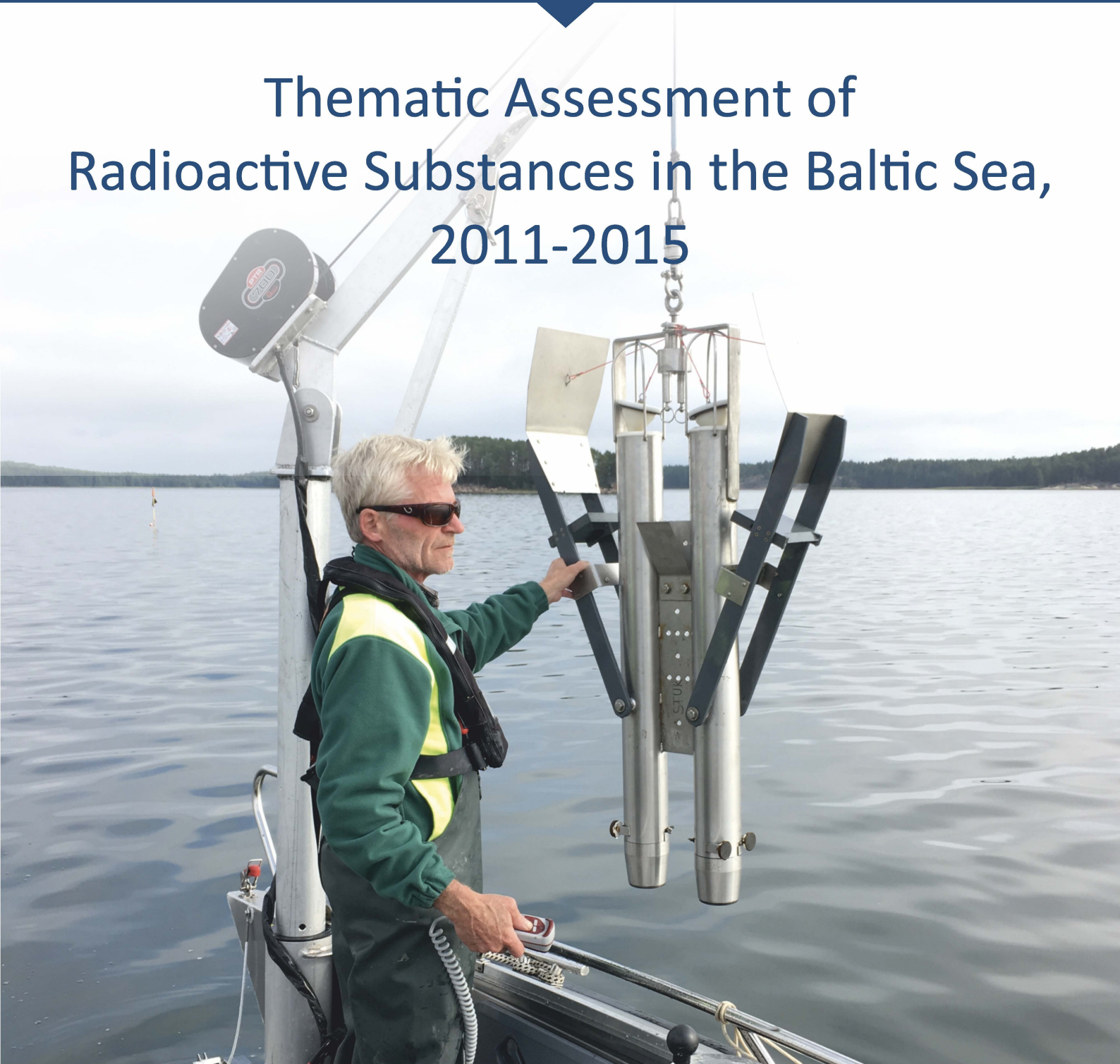
Baltic Marine Environment Protection Commission

Thematic Assessment of Radioactive Substances in the Baltic Sea, 2011-2015



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1.Introduction

Sven P. Nielsen

The Helsinki Convention and its governing body HELCOM were established to protect the marine environment of the Baltic Sea from all sources of pollution. Radioactive substances were considered among the hazardous substances and the contracting parties to the Convention formed an expert group on Monitoring of Radioactive Substances (MORS) in 1984. In the same year, the members of the group started collecting data with focus on the occurrence and impact of man-made radioactive substances. Results of this work have been summarized in previous thematic reports prepared by the MORS group and published in HELCOM's Baltic Sea Environment Proceedings. The reports covered the time periods 1984-1991 (HELCOM 1995), 1992-1998 (HELCOM 2003), 1999-2006 (HELCOM 2009) and 2007-2010 (HELCOM 2013).

All living organisms are exposed to radioactive substances and ionizing radiation. Natural sources of radiation are cosmic rays and naturally occurring radioactive substances from rocks and minerals of the earth. Human activities involving use of radiation and radioactive substances cause radiation exposure in addition to natural exposure. Some of those activities simply enhance the exposure from natural radiation sources, e.g. mining and use of ores containing naturally occurring radioactive substances. Other human activities involving use of nuclear energy have given rise to releases of radioactive substances to the environment that in some cases have comprised substantial amounts causing significant human exposures. During 1945-1962 military use of nuclear energy involving testing and use of nuclear weapons in the atmosphere caused global radioactive pollution. In 1986 and 2011 severe accidents at the nuclear power plants at Chernobyl in Russia and Fukushima in Japan caused comprehensive local radioactive pollution as well as regional radioactive pollution.

This report describes work carried out by HELCOM's Expert Group on the Monitoring of Radioactive Substances in the Baltic Sea during 2011-2015. Chapter 2 describes the sources of man-made radioactivity in the Baltic Sea. Chapter 3 describes the concentrations of man-made radionuclides in seawater, sediments and biota. Chapter 4 presents work on modelling and evaluations of the risks to man and environment caused by radioactivity in the Baltic Sea. Chapter 5 compares levels of man-made radioactivity in the Baltic Sea with other marine regions. Chapter 6 summarises the project's conclusions. Work on data quality is presented in an appendix.

2. Sources of radioactivity in the Baltic Sea

Vesa-Pekka Vartti, Maria Lüning

2.1. Introduction

This chapter covers the different anthropogenic sources of the current amount of radioactive substances found in the Baltic Sea. The sources are divided as follows:

- Nuclear Facilities in the Baltic Sea drainage area (NPPs, research reactors, waste handling, fuel handling, etc). The locations of the facilities are shown in **Figure 2.1.1**
- Non-nuclear facilities in the Baltic Sea drainage area (e.g. hospitals, non-nuclear industries, etc)
- Discharges from facilities located outside the Baltic Sea drainage area
- The Chernobyl accident
- The Fukushima accident
- Atmospheric nuclear weapons tests

The introduction of ^{137}Cs and ^{90}Sr to the Baltic Sea from the different sources are also presented in **Figure 2.1.2** and **2.1.3.**

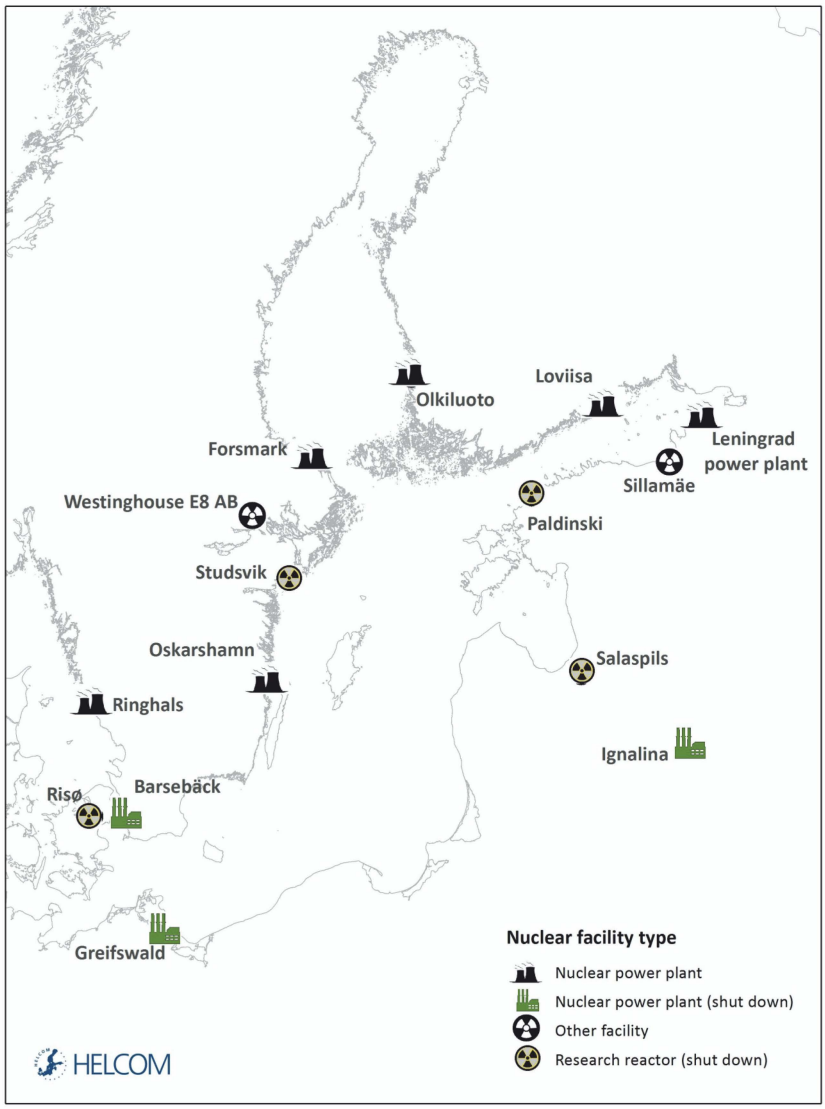


Figure 2.1.1 Location of the nuclear facilities in the Baltic Sea region.

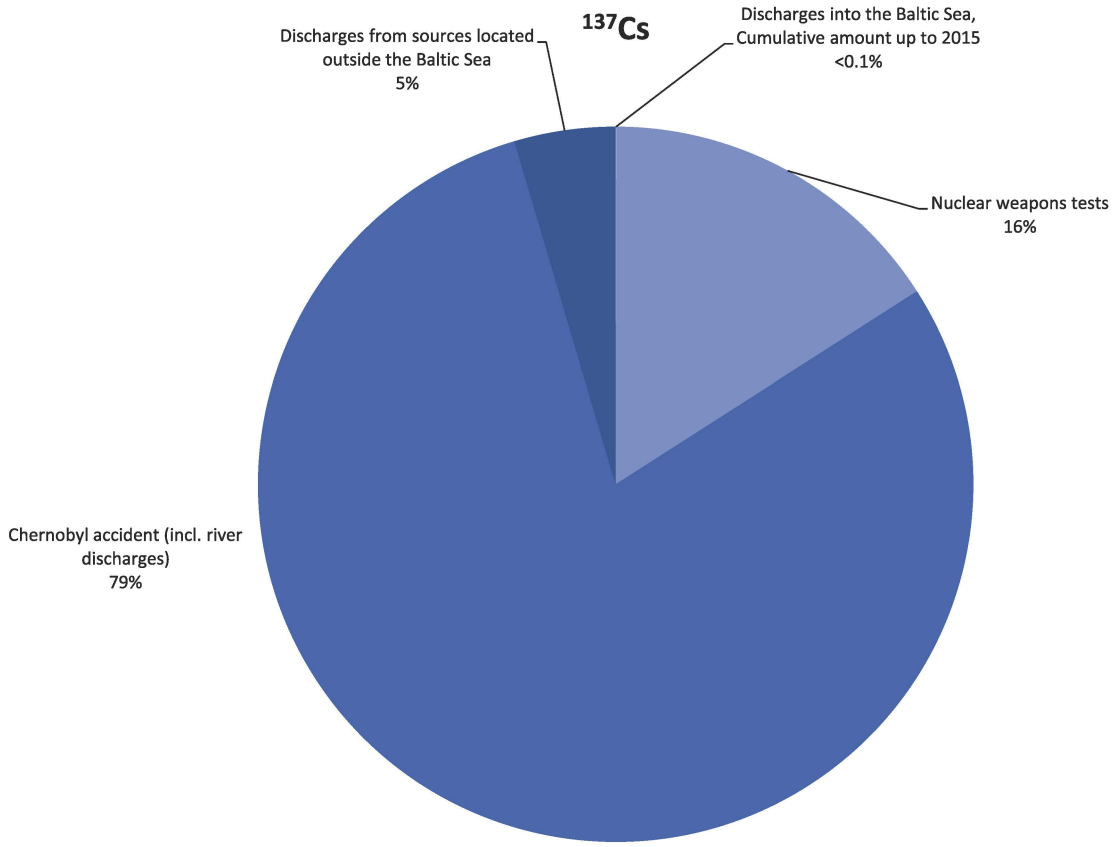


Figure 2.1.2
Total inputs of ^{137}Cs into the Baltic Sea from different sources up to 2015.

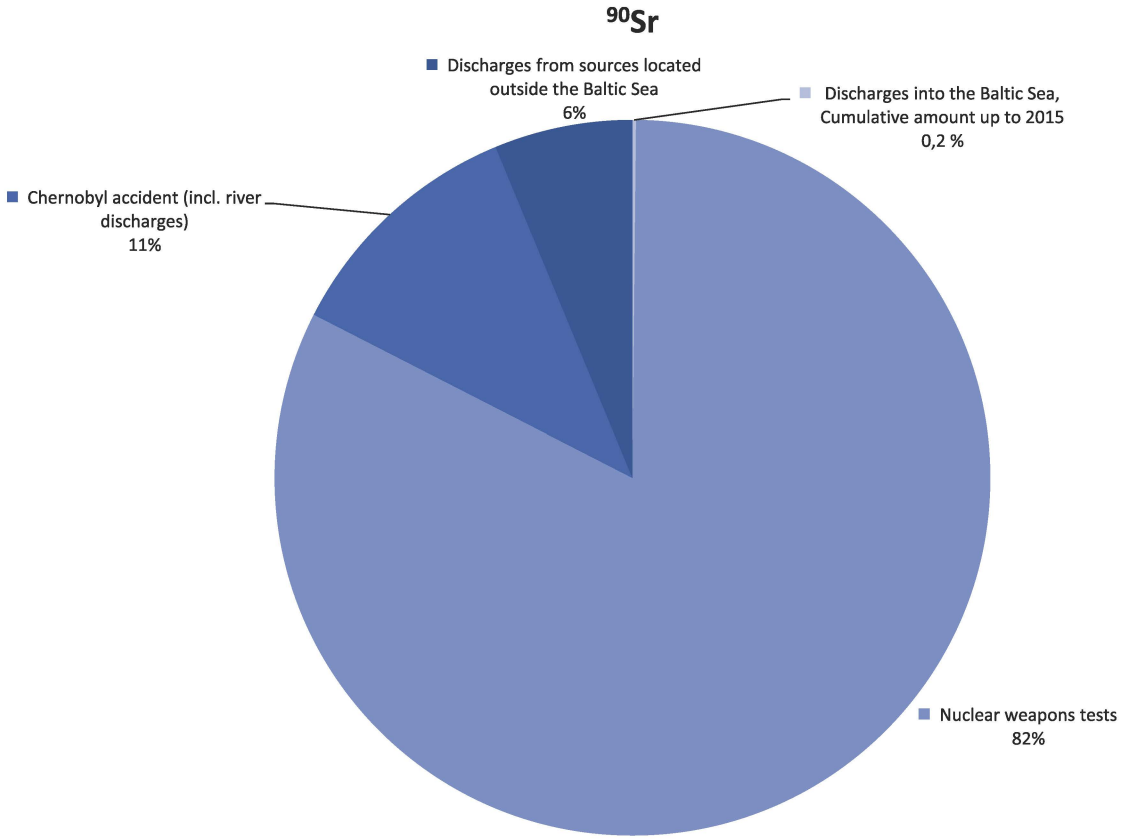


Figure 2.1.3
Total inputs of ^{90}Sr into the Baltic Sea from different sources up to 2015.

2.2. Discharges from facilities in the Baltic Sea drainage area

Nuclear Facilities (NPPs, research reactors, waste handling, fuel handling, etc).

This includes all nuclear facilities (power reactors, research reactors, waste handling facilities, fuel production, etc) that are located in the drainage area of the Baltic Sea and which discharge directly or indirectly into the Baltic Sea. The main characteristics of the facilities are summarised in **Table 2.2.1.**

The discharge pattern for most of the NPPs is similar and the most abundant nuclides present in the discharges are also shown in **Table 2.2.1.** The amounts of the most significant radionuclides discharged are shown in **Figures 2.2.1-2.2.3.**

In Sweden it has been decided to shut down two reactors in Ringhals and two in Oskarshamn. The timeframe is that OKG2 is already in decommissioning and OKG1 will stop operation in 1st July 2017. Ringhals will cease operation of Ringhals 2 in 2019 and Ringhals 1 in 2020.

Regarding new facilities the Swedish Radiation Protection Authority is now working with an Application made by SKB regarding the final repository for spent nuclear fuel. Included in this application is a facility for encapsulation of fuel and waste (Clink) and the time frame is that it will not start building before 2020. The final respository is proposed to be situated close to present repository of low and intermediate waste (SFR) at the Forsmark site and the encapsulation facility is proposed to be situated near the present intermediary repository (Clab) at the Oskarshamn site.

In Finland the third reactor in Olkiluoto site is excepted to start producing electricity in 2018. Fennovoima is planning to build its nuclear power plant Hanhikivi 1 (FH1). The plant is planned to be built in Pyhäjoki in Northern Finland. The company is excepting the construction license in 2018 and according to plans the plant is expected to produce electricity in 2024.

Table 2.2.1
Nuclear facilities in the drainage area of the Baltic Sea and the main discharge nuclides.

Facility	Country	Type of facility; number of units	Main radionuclides discharged	Remarks
Loviisa	Finland	Power plant; 2 PWR	^{3}H, ^{60}Co, ^{137}Cs, ^{110m}Ag, ^{124}Sb, ^{58}Co, ^{54}Mn	
Olkiluoto	Finland	Power plant; 2 BWR	^{3}H, ^{60}Co, ^{137}Cs, ^{51}Cr, ^{58}Co, ^{54}Mn, ^{134}Cs	
Greifswald	Germany	Power plant; 5 PWR	^{3}H, ^{137}Cs, ^{60}Co	Shut down in 1990
Ignalina	Lithuania	Power plant; 2 RBMK	^{3}H, ^{137}Cs, ^{60}Co	First reactor was shut down in 2004 and the second in 2009
Leningrad	Russia	Power plant; 4 RBMK	^{137}Cs, ^{60}Co	H-3 not reported
Barsebck	Sweden	Power plant; 2 BWR	^{3}H, ^{60}Co, ^{51}Cr, ^{58}Co, ^{137}Cs, ^{54}Mn	First reactor was shut down in 1999 and second in 2005
Forsmark	Sweden	Power plant; 3 BWR	^{3}H, ^{60}Co, ^{137}Cs, ^{65Z}n, ^{134}Cs, ^{58C}o, ^{110m}Ag, ^{51}Cr, ^{131}I	

Table 2.2.1 (continues)
Nuclear facilities in the drainage area of the Baltic Sea and the main discharge nuclides.

Facility	Country	Type of facility; number of units	Main radionuclides discharged	Remarks
Oskarshamn	Sweden	Power plant; 3 BWR	^{3}H, ^{60}Co, ^{51}Cr, ^{58}Co, ^{54}Mn, ^{137}Cs, ^{125}Sb, ^{65}Zn, ^{110m}Ag	
Ringhals	Sweden	Power plant; 3 PWR, 1 BWR	^{3}H, ^{60}Co, ^{58}Co, ^{51}Cr, ^{124}Sb, ^{137}Cs, ^{54}Mn, ^{110m}Ag ^{125}Sb	
Risø	Denmark	Research reactor	^{3}H	Shut down in 2000
Salaspils	Latvia	Research reactor	^{3}H, ^{137}Cs, ^{134}Cs	Shut down in 1998
Studsvik	Sweden	Research reactor, Waste handling facility	^{3}H, ^{90}Sr, ^{137}Cs, ^{60}Co, ^{134}Cs, ^{51}Cr, ^{144}Ce, ^{106}Ru, ^{192}Ir	Research reactor was shut down in 2005
Paldiski	Estonia	Training centre for nuclear submarines	^{3}H, ^{137}Cs, ^{90}Sr	Shut down in 1989
Sillame	Estonia	Chemical metallurgy plant, waste depository	^{238}U, ^{226}Ra	Waste depository has been covered in 2009
Westinghouse Electric Sweden AB	Sweden	Fuel fabrication plant	^{234}U, ^{238}U, ^{60}Co	

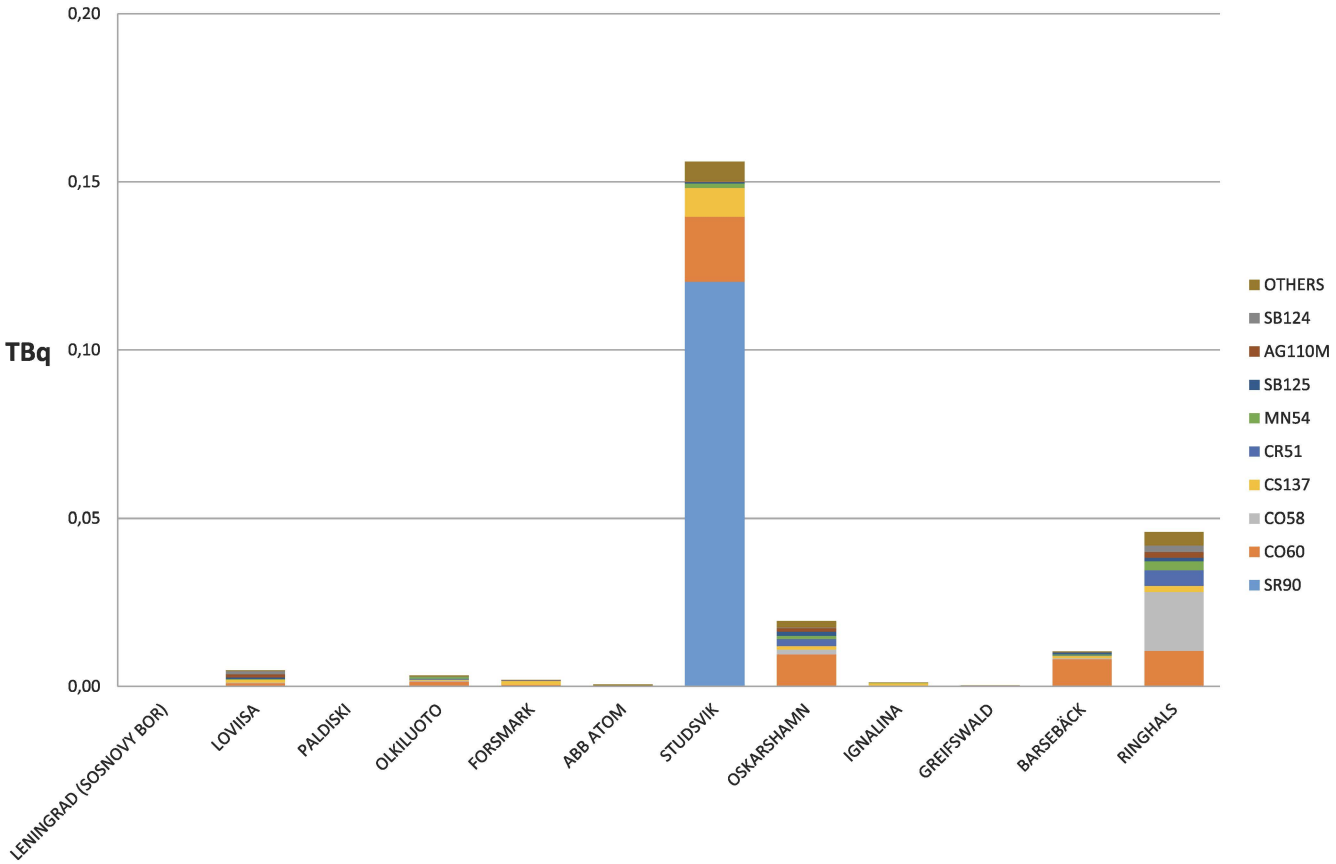


Figure 2.2.1
Total aquatic discharges from local nuclear facilities into the Baltic Sea in 2005-2015, excluding ^{3}H.

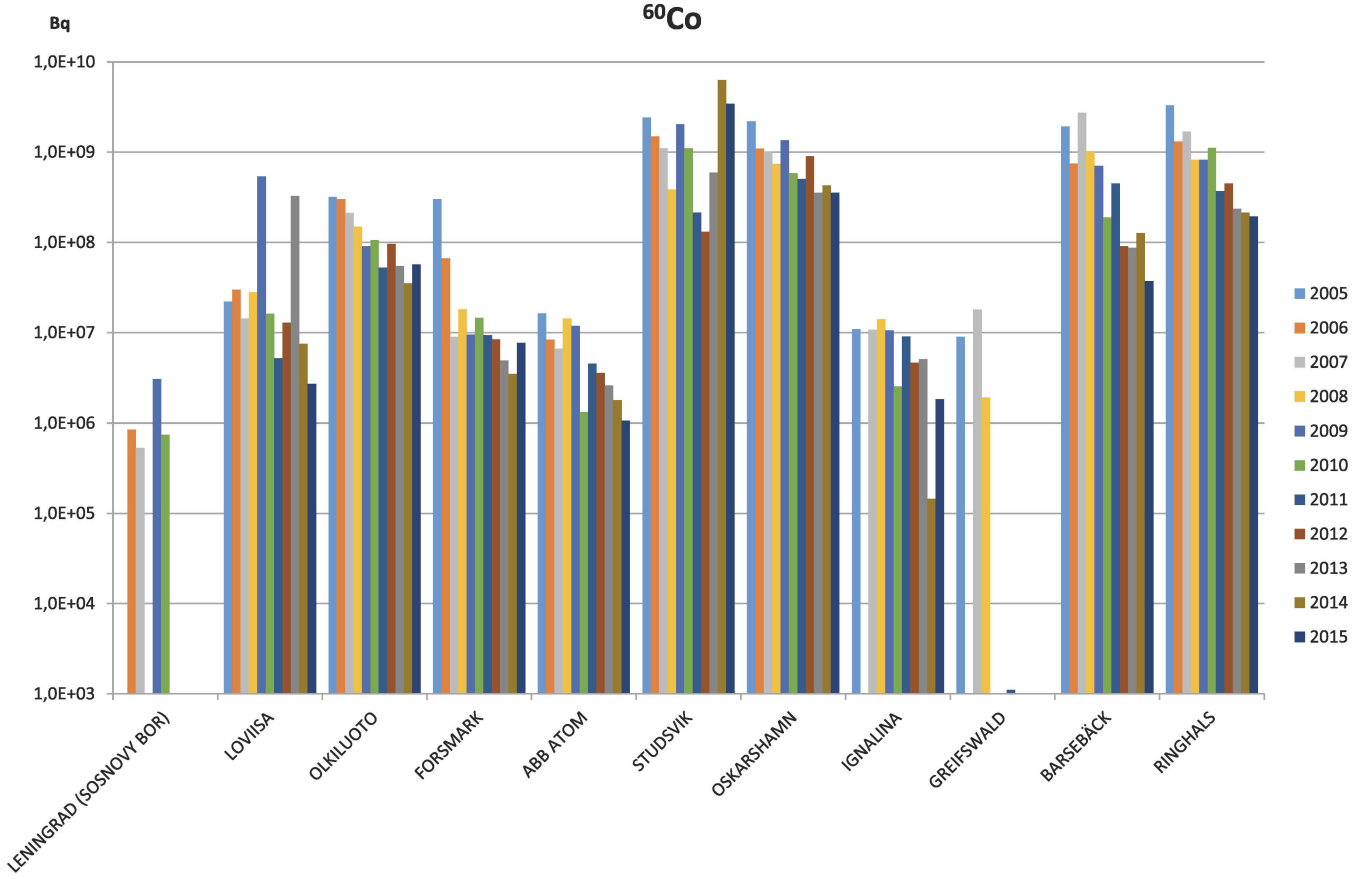


Figure 2.2.2
Annual ^{60}Co discharges from local nuclear facilities into the Baltic Sea in 2005-2015.

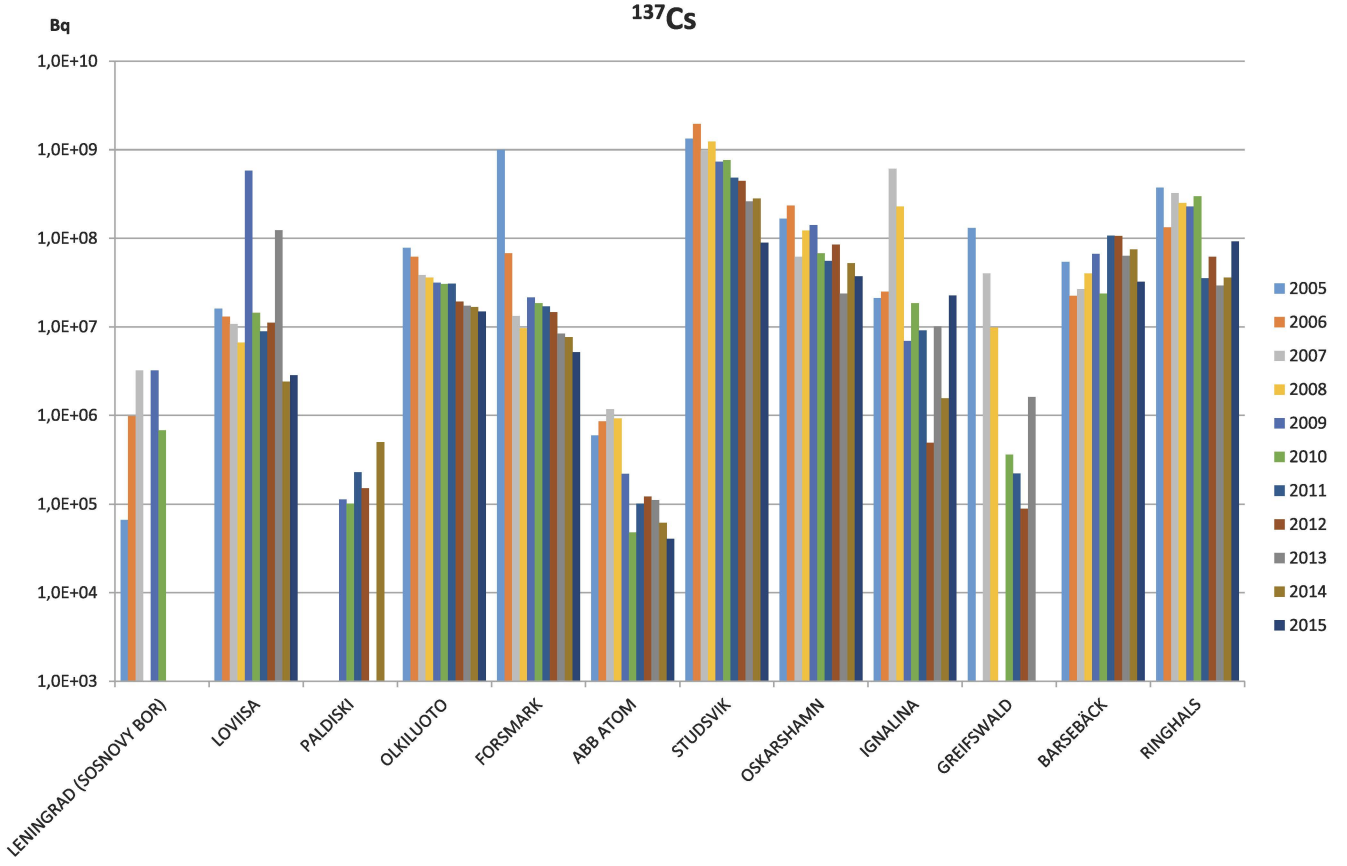


Figure 2.2.3
Annual ^{137}Cs discharges from local nuclear facilities into the Baltic Sea in 2005-2015.

Non-nuclear facilities (e.g. hospitals, non-nuclear industries, etc)

This area includes hospitals, research institutes, non-nuclear industries using radioactive substances and NORM-industries. Information about discharges from non-nuclear facilities in the Baltic Sea area is scarce and it is not possible to obtain reliable information about discharges from these sources.

Radionuclides are used for various purposes in the industry, medicine and research, and their use is increasing. However, according to reports of UNSCEAR, their contribution to overall man-made exposures is relatively insignificant. Most radionuclides used in hospitals are short-lived; therefore their discharges are small and their impact on the radioactivity in the Baltic Sea is negligible and very local (Ilus and Ilus, 2000).

2.3. Discharges from facilities located outside the Baltic Sea region

Nuclear reprocessing plants

A small proportion of the discharges from Sellafield, situated on the west coast of England and discharging into the Irish Sea, and La Hague, situated on the northwest coast of France and discharging into the English Channel, are transported by the inflow of saline water through the Danish Straits into the Baltic Sea. The transport time for the radionuclides is about 4-5 years after discharge into the Irish Sea (Sellafield) or about 2 years after discharge into the English Channel (La Hague) (Nies et al., 1995). Model calculations indicate that only about 4% of the discharges from Sellafield and about 8% of the discharges from La Hague reach the Skagerrak. Due to efficient mixing of water masses in the Kattegat and the Belt Sea the main part of the activity returns to the Skagerrak and only about 1% enters the Baltic Sea (Nielsen at al., 1995).

Chernobyl accident

The accident at the Chernobyl NPP occurred in April 1986 and has since then been the main source of radioactivity in the Baltic Sea **(Table 2.3.1)**.

The total input of ^{137}Cs from the Chernobyl accident into the Baltic Sea area was estimated to be 4,700 TBq (Nielsen et al., 1999), while decay corrected to 2015 the input is estimated to be 2,700 TBq. Forty-five TBq of ^{90}Sr (decay-corrected to 2015) were also injected into the Baltic Sea as a consequence of the Chernobyl accident (Nies et al., 1995). The deposition of the Chernobyl fallout was very unevenly distributed in the drainage area of the Baltic Sea; the most contaminated areas were situated in the land areas surrounding the Bothnian Sea and the eastern Gulf of Finland.

Table 2.3.1
Total injections of ^{137}Cs and ^{90}Sr into the Baltic Sea from different sources, decay corrected to 2015.

Source	^{137}Cs Tbq	Percent of total amount	^{90}Sr TBq	Percent of total amount
Chernobyl accident [1)4)] / incl. river discharges [5)]	2,700 / 200	79	45	11
Nuclear weapons tests [6)]	540	16	330	82
Discharges from sources located outside the Baltic Sea [2)3)]	155	5	25	6
Discharges into the Baltic Sea [1)], Cumulative amount up to 2010	1.2	0.04	0.7	0.2

1) based on measurements; 2) estimated; 3) according to the Nies et al., 1995; 4) according to Nielsen et al., 1999; 5) according to Ilus& Ilus, 2000; 6) according to Nielsen (pers. comm.)

River discharges

The amount of Chernobyl-derived ^{137}Cs carried into the Baltic Sea by river runoff has been evaluated in Finland for all Finnish rivers discharging into the Baltic Sea (Saxén and Ilus 2000), in Russia for 5 rivers discharging from the former Soviet Union and in Poland for the River Vistula. The total river input of ^{137}Cs was estimated at 300 TBq during 1986-1996 (Ilus and Ilus 2000). During 2005-2011 the total input of ^{137}Cs to Gulf of Gdańsk mainly from Vistula river was estimated at 0.4 TBq (Saniewski and Zalewska 2016). The total river input of ^{137}Cs into the Baltic Sea, decay corrected to 2015, is estimated at 200 TBq.

Fukushima accident

In 2011, man-made radionuclides were detected in the atmosphere over Europe as a consequence of the Fukushima accident in Japan. Although the extent of the fallout over the Baltic Sea was very low (0.1-100 Bq m^{-2} for ^{137}Cs), it is a source of radioactivity to the Baltic Sea (Kanisch and Aust, 2013).

Atmospheric nuclear weapons tests

The impact of global fallout caused by the nuclear weapons tests in the 1950s and 1960s as a source of radioactivity in the Baltic Sea has been thoroughly considered in the first Joint Evaluation Report of the HELCOM MORS Group (Nies et al., 1995). According to recent calculations (Nielsen, pers. comm.), the total injections of weapons-test ^{90}Sr and ^{137}Cs into the Baltic Sea were 330 and 540 TBq, respectively (decay-corrected to 2015). Inventories based on measured concentrations of these nuclides in water and sediments of the Baltic Sea resulted in quite similar values: 220 TBq for ^{90}Sr and 280 TBq for ^{137}Cs (calculated and decay corrected to 2015) (Salo et al., 1986).

Dumping of radioactive waste

Five officially confirmed dumpings of radioactive waste on three different dump sites have been reported in the Baltic Sea region. All these small-scale dumpings were performed in the late 1950s or early 1960s. A radiological assessment of these dumpings showed that doses to man from these activities were negligible (Nielsen et al., 1999; IAEA 2015a). No new information has been found concerning the dumping sites section.

2.4. Conclusions

The most significant source with respect to the total inventory of artificial radionuclides in the Baltic Sea is the fallout caused by the accident at the Chernobyl NPP in 1986. The most important radionuclides present in the deposition were ^{137}Cs and ^{134}Cs. Until 2015, the decay-corrected total input of ^{137}Cs from Chernobyl to the Baltic Sea has been estimated at 2700 TBq. The decay-corrected post-Chernobyl river discharges of ^{137}Cs were estimated in the Marina Balt Study at 200 TBq comprising about 7% of the total injection.

The second most important source is global fallout from atmospheric nuclear weapons tests that were carried out during the late 1950s and early 1960s. The predominant radionuclides in the global fallout were ^{137}Cs and ^{90}Sr in an activity ratio of about 1.6. Until 2015, the decay-corrected amounts of weapons-test ^{137}Cs and ^{90}Sr in the Baltic Sea have been evaluated at 540 and 330 TBq, respectively.

The predominant radionuclide in the discharges from the nuclear power plants and research reactors in the Baltic Sea region is ^{3}H. The total discharges of ^{3}H from these local sources have amounted to 3800 TBq and those of other beta-gamma nuclides to about 24 TBq until the end of 2015. The total discharges of alpha nuclides have been 0.005 TBq. These discharges have not been decay-corrected.

For ^{137}Cs, the main source of contamination was the fallout from Chernobyl (79%) and nuclear weapons tests (16%). For ^{90}Sr, the main source was the fallout from nuclear weapons tests (82%), while the proportion of fallout from Chernobyl was smaller (11%).

3. Radioactivity in the Baltic Sea (trends and regional distribution)

3.1. Radionuclides in seawater

Stefanie Schmied, Tamara Zalewska, Eia Jakobson

Introduction

This chapter describes the distribution of artificial and naturally occurring radionuclides in seawater of the Baltic Sea from 2011 to 2015. During this period, nine countries contributed the results of about 1050 seawater samples from nearly all sub-regions of the Baltic Sea to the HELCOM MORS database. The monitoring programme covered all sub-basins except for the Quark and Åland Sea (see **Figure 3.1.1a** and **3.1.1b**). As presented in earlier reports (Panteleev et al. 1995; Mulsow et al. 2003; Herrmann et al. 2007) and Chapter 2 of this report, the predominant radionuclide in the Baltic Sea is ^{137}Cs with a half-life $T_{1/2}$ = 30.05 years. It was released in great amounts by the Chernobyl accident in 1986 and deposited also over the Baltic Sea by the nuclear fallout. ^{134}Cs, the other main contaminant of the Chernobyl event, has vanished to concentrations below detection limit because of its relatively short physical half-life of 2.07 years.

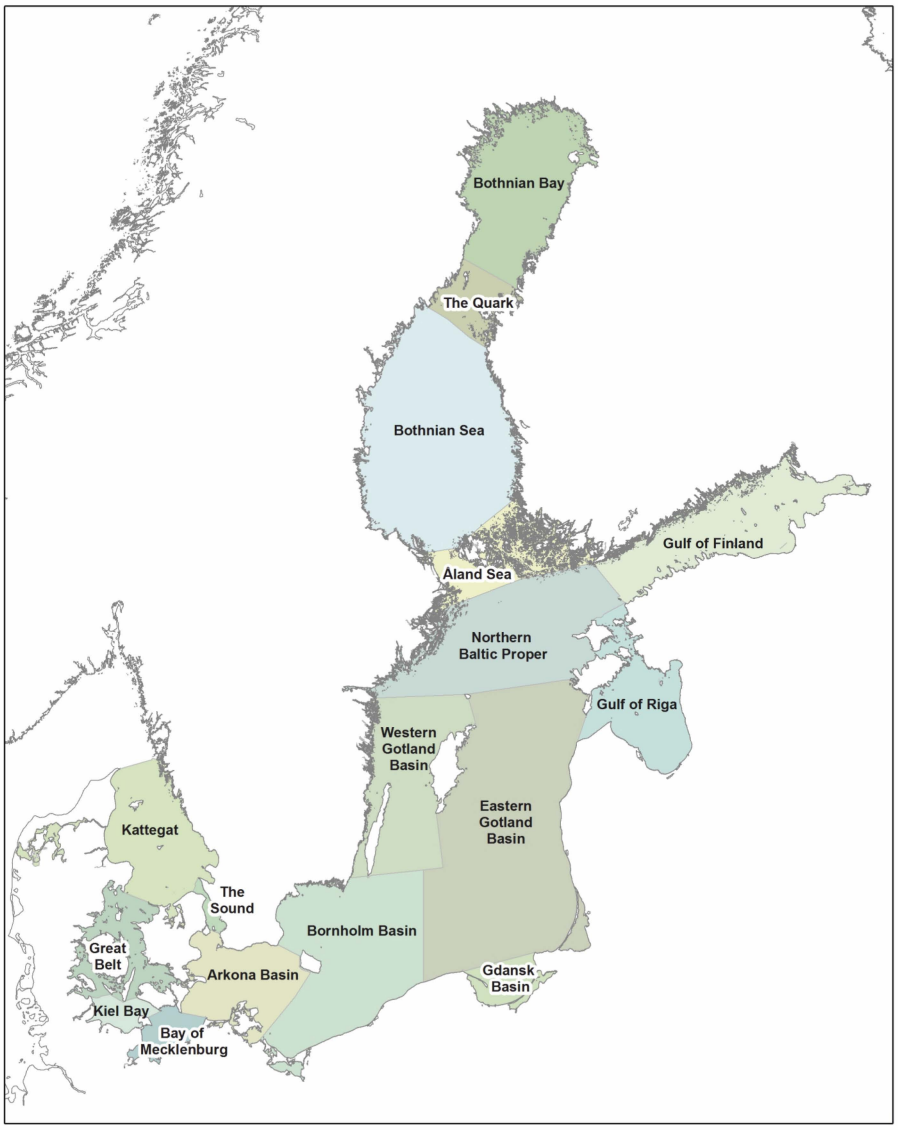
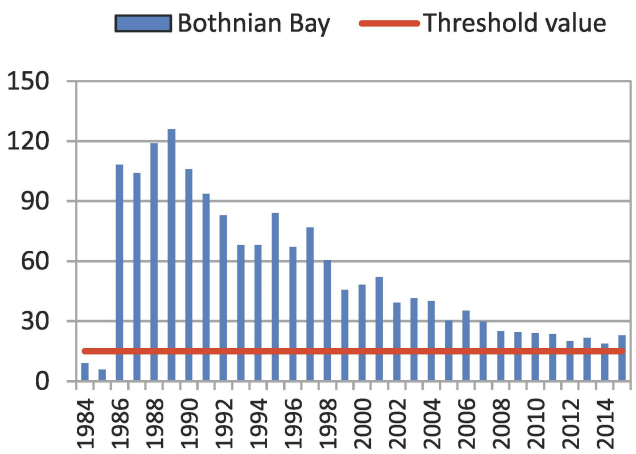


Figure 3.1.1a. Map of the Baltic Sea presenting the HELCOM sub-division into 17 sub-basins, according to the HELCOM Monitoring and Assessment Strategy (HELCOM 2014).


Bothnian Bay
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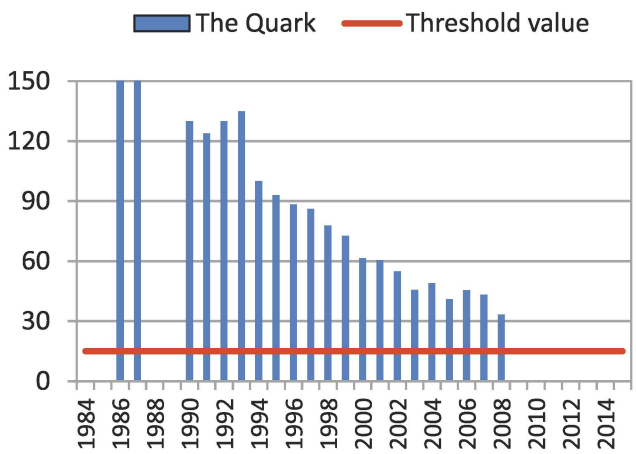
The Quark
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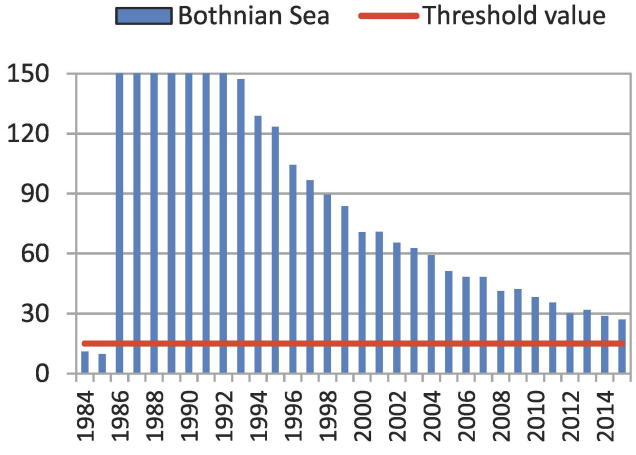
Bothnian Sea
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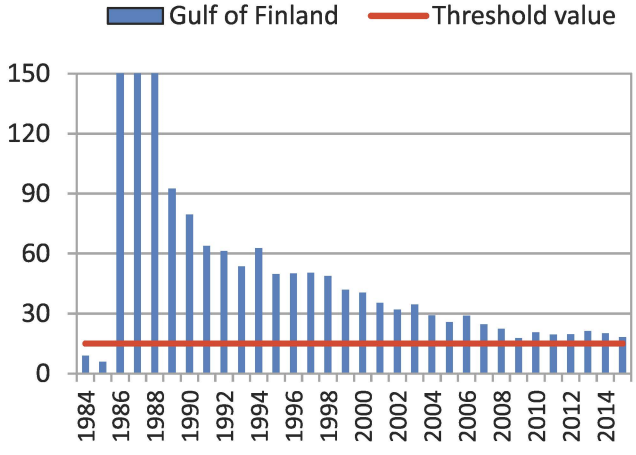
Gulf of Finland
Threshold value
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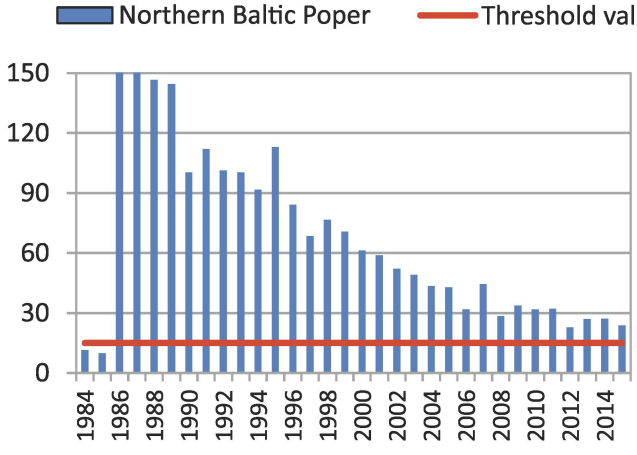
Northern Baltic Poper
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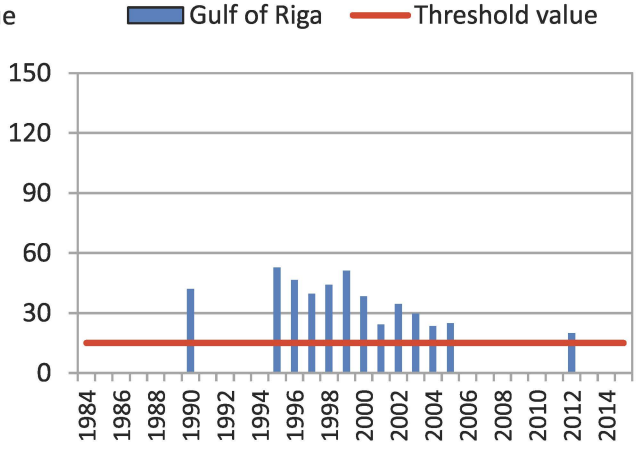
Gulf of Riga
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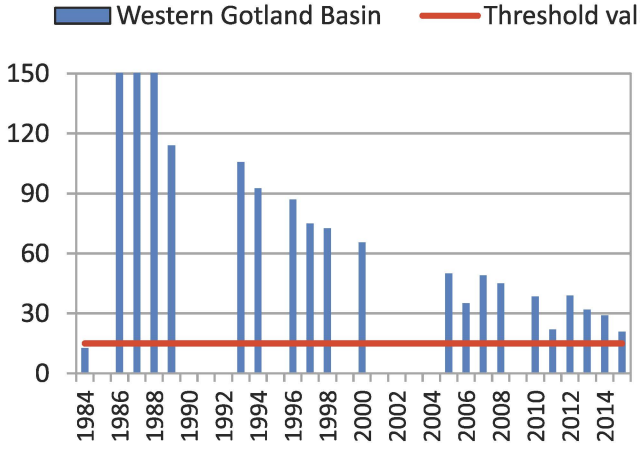
Western Gotland Basin
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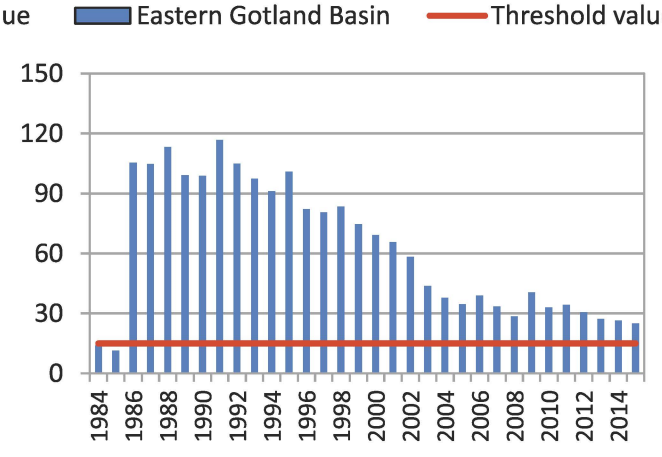
Eastern Gotland Basin
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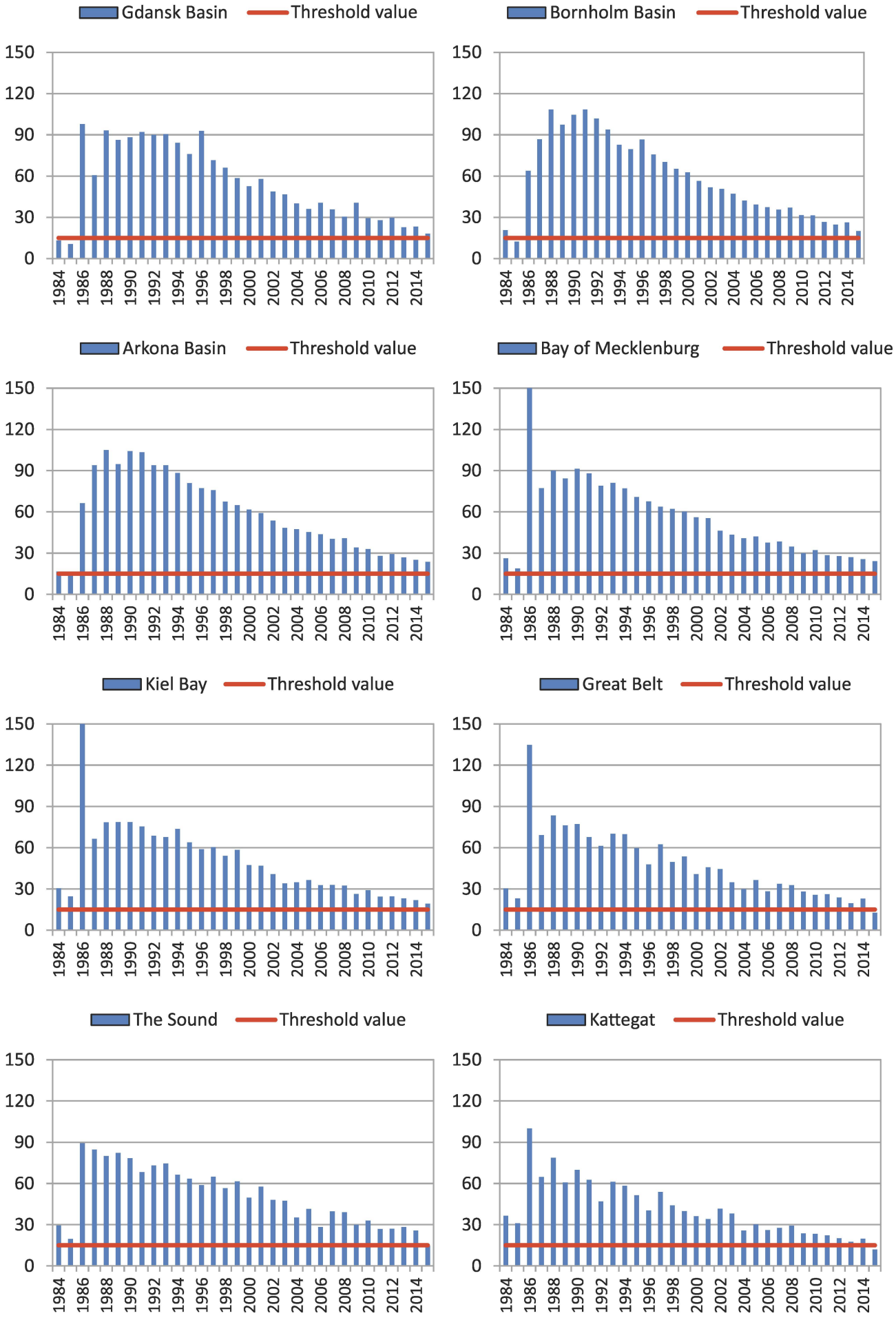


Figure 3.1.1b.
^{137}Cs concentrations (in Bq m^{-3}) in seawater (sampling depth less than 10 m) in 1984-2015, as annual mean values by sub-basin. Red line indicates the threshold value (15 Bq m^{-3}) calculated as average of pre-Chernobyl (1984-1985) concentrations.

Other artificial radionuclides of relevance in seawater of the Baltic Sea are ^{90}Sr, $^{(239+240)}$Pu and ^{99}Tc. Monitoring of ^{137}Cs and ^{90}Sr is mandatory according to the HELCOM Recommendation 26/3, while other radionuclides are reported on a voluntary basis. The sources of the mentioned radionuclides are described in Chapter 2. Also, naturally occurring radionuclides have been taken into account for the present reporting period. Therefore, ^{40}K, ^{226}Ra, ^{210}Po and ^{210}Pb are considered closer.

Generally, concentrations mentioned in this chapter are understood as activity concentrations. A detailed description of the methods is given in an earlier thematic assessment (HELCOM 2013). The collection of monitoring data was accompanied by a thorough internal quality assurance programme covering ^{137}Cs and ^{90}Sr in seawater in annual exercises. Further relevant information is given in the appendix of this report.

The Fukushima Daiichi nuclear accident took place in March 2011. A short passage gives information about the consequences to the seawater in the Baltic Sea.

Distribution and temporal evolution of ^{137}Cs

The fate of any pollutant introduced into the sea is determined by its chemical properties as well as by the hydrographic conditions of the sea itself. As a relatively small, semi-enclosed brackish sea - connected to the North Sea and thereby to the North Atlantic only by the narrow Danish Straits - the Baltic Sea suffers from contamination possibly more than any other part of the World. Therefore the Baltic is very vulnerable. The Chernobyl accident made this situation clear as its legacy is still abundant more than 30 years after the event.

The Chernobyl accident caused a very uneven ^{137}Cs deposition in the Baltic Sea region. The Bothnian Sea and the Gulf of Finland were the two most contaminated sub-basins. Since 1986, the spatial and vertical distribution of Chernobyl derived ^{137}Cs has changed as a consequence of river discharges, mixing of water masses, sea currents and sedimentation processes (Ilus et al. 2007). Shortly after the Chernobyl accident, ^{137}Cs concentrations decreased rapidly in the Gulf of Finland and in the Bothnian Sea, while at the same time they increased in the Baltic Proper (**Figures 3.1.2** and **3.1.3**). The concentrations of ^{137}Cs have continued to decrease in all sub-basins of the Baltic Sea during the period from 2011 to 2015. At the beginning of 2011, the highest ^{137}Cs concentrations were reported in the Åland Sea where the concentrations decreased from 39 to 31 Bq m-^{3} during the monitoring period. In the Eastern Gotland Basin, the concentrations decreased from about 38 to 27 Bq m^{-3}. The concentrations were lower at around 20 Bq m^{-3} in the Gulf of Finland in 2015.

The concentrations of ^{137}Cs in the Southern Baltic Proper started at 38 Bq m^{-3} in 2011 and decreased to around 29 Bq m-^{3} in 2015. For the Bornholm Sea, ^{137}Cs concentrations started at 37 Bq m^{-3} in 2011 and decreased to around 22 Bq m^{-3} in 2015. Mean concentrations in the Gotland West decreased from 22 Bq m^{-3} to 12 Bq m^{-3} during the monitoring period. The Kattegat, as the transition area to the North Sea, showed concentrations in surface water decreasing from 25 Bq m^{-3} to 14 Bq m^{-3} in 2015. For the first time, in 2015 the Flensburg Bay had an activity concentration below the target level of ^{137}Cs for the ecological quality objective of 15 Bq m^{-3}. The ^{137}Cs concentrations in surface water to 10 m vary between different sub-basins of the Baltic Sea by a factor of 2.6.

As described above, the vertical distribution of radionuclides in the water column is mainly influenced by physical and biological processes. Whereas in former years the ^{137}Cs concentrations in surface water were markedly higher compared to those in near-bottom waters of the Baltic Proper, this situation has changed during the reporting period. Although the concentrations in near bottom waters are still lower than in the surface in the areas with stronger halocline, the data show evidence that the Chernobyl contamination has finally reached waters deeper than 200 m by vertical transport processes. In other compartments of the Baltic, such as the Bothnian Sea, the Gulf of Finland and the Bothnian Bay, this vertical exchange was much more efficient because of a lack of stratification. Therefore, a homogeneous distribution with a clear tendency towards higher ^{137}Cs concentrations in near-bottom waters was observed much earlier. No evidence of remobilization of ^{137}Cs from bottom sediments has yet been detected. Besides vertical distribution, also horizontal circulation of near-bottom waters can redistribute the ^{137}Cs contamination by transferring contaminated near-bottom water from the Bothnian Sea e.g. to the Baltic Proper. The ^{137}Cs concentration in near-bottom waters is highest in the Bothnian Sea and decreases towards the Sound and the Kattegat, with concentrations ranging from 31 Bq m^{-3} to 15 Bq m^{-3} within the reporting period.

The Western Baltic has special hydrographic conditions, different from the rest of the Baltic Sea due to the fact of being a transition area between the North Sea and the Baltic Sea. Most notably, it is shallow, with an average depth of around 20 m. The bottom waters are characterized by higher concentrations of oxygen and higher salinity, and are steadily supplied by currents from the North Sea. The surface waters have a net current out of the Baltic Sea because the great catchment area results in a surplus of fresh water into the Baltic Sea. This water exchange is dominated by wind forces that result in a current system of high intra-annual and inter-annual variability. As an indicator of the inflow of bottom waters, the mean ^{137}Cs concentration of seven selected stations inside the German economic zone is given in **Figure 3.1.3**.

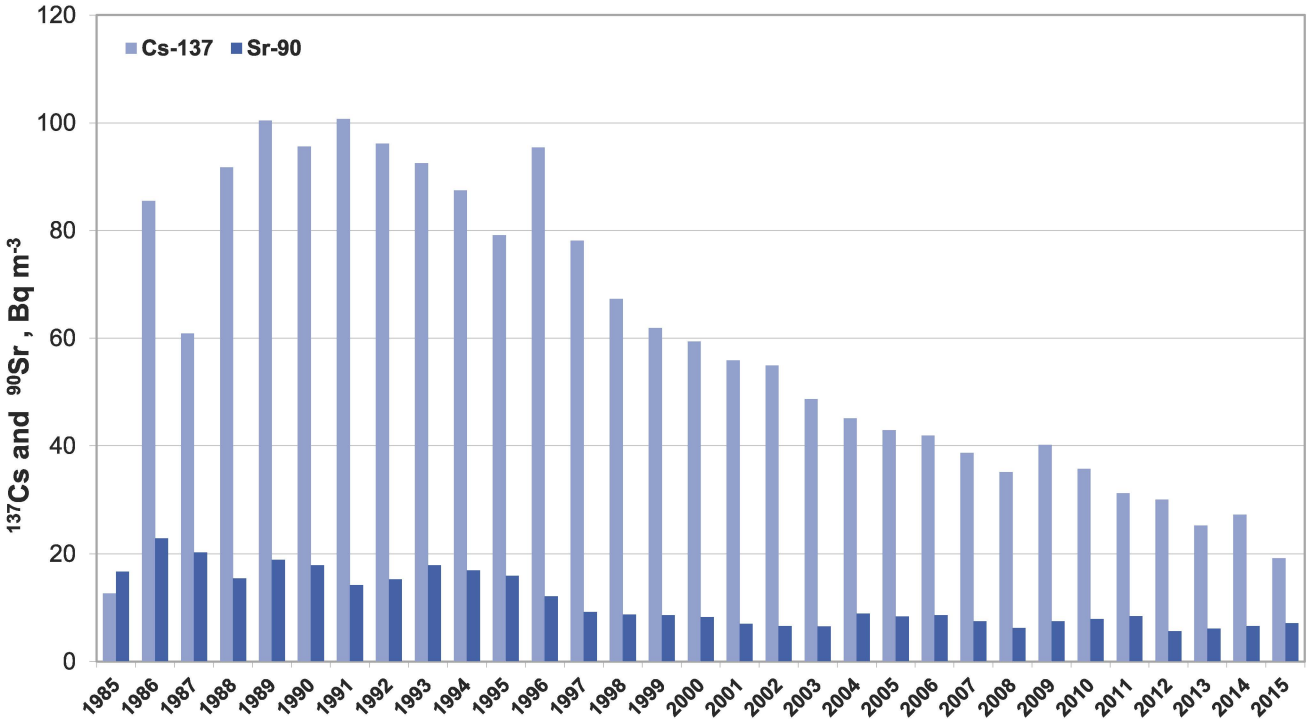


Figure 3.1.2.
Time series of ^{137}Cs and ^{90}Sr mean concentrations in the Polish area of the Baltic Sea (Bornholm Basin, Gdansk Basin and Eastern Gotland Basin)

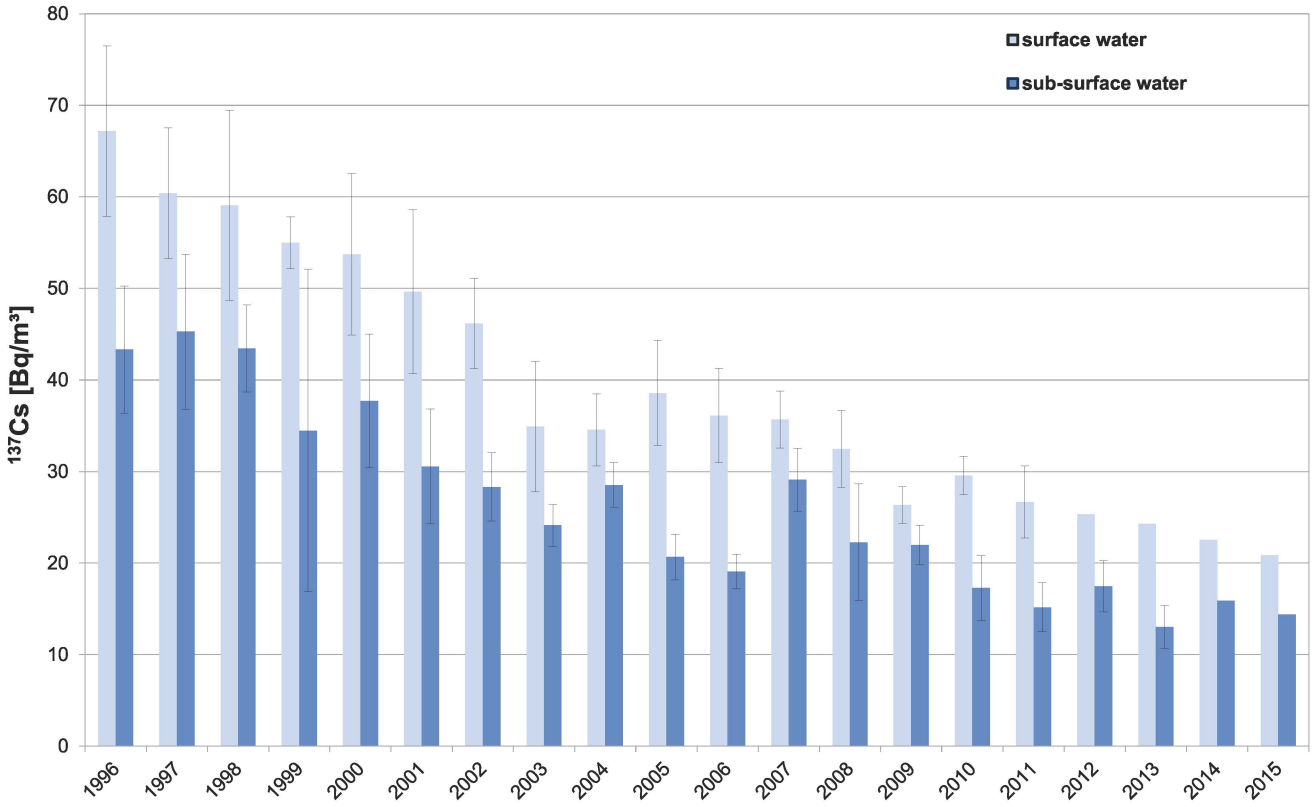


Figure 3.1.3.
Time series of ^{137}Cs mean concentrations from German monitoring stations (KOTN12, FBELT1, FBELT2, KIBU1, KIBU2, KALKGR, SCHLEI) characterizing the inflow of bottom water into the Western Baltic.

Besides the general decreasing trend of the ^{137}Cs concentrations, **Figure 3.1.3** gives information about the variability of surface and bottom water concentrations, which was much less in recent years compared to 1999. The year with the smallest difference between surface and bottom waters was 2009, obviously at a time when bottom waters from the Kattegat with low ^{137}Cs concentration did not reach the indicator stations within the described area.

The bottom waters from the North Sea also supply the Baltic Sea with contaminants such as ^{239}Pu, ^{99}Tc and ^{129}I from the La Hague and Sellafield spent nuclear fuel reprocessing sites, whereas the outflowing surface waters of the Baltic Sea represent a significant source of ^{137}Cs to the North Sea. The effects are detectable along the entire south coast of Norway at least until 60°N. Today, the Baltic Sea can be regarded as the strongest source of ^{137}Cs to the North Atlantic. While the quantification of this source is still unclear because of the high variability of the outflow, it is estimated at tens of terabecquerels per year.

Effective half-life of ^{137}Cs

The effective half-life is the period during which the quantity of a radionuclide in biological systems is reduced by half through interaction of physical, chemical and biological processes. It is specific to the radionuclide and the environment where the radionuclide is present. Currently, the effective half-life of ^{137}Cs in surface waters of the Baltic Sea varies from about nine years in the Bothnian Sea to about 11 years in the Baltic Proper and the Gulf of Finland. The longer retention time of ^{137}Cs in the Baltic Proper and the Gulf of Finland is due to the inflow of more contaminated waters from the northern part of the Baltic Sea and the higher river inflow. The average effective half-life of ^{137}Cs calculated for the Baltic Sea is equal to 10.2 years.

From 1986 to 1988 - the time period following the Chernobyl accident - the effective half-lives of ^{137}Cs were much shorter in most contaminated regions: 0.8 years in the Gulf of Finland and 2.5 years in the Bothnian Sea. The shorter effective half-life of ^{137}Cs in the Gulf of Finland compared to the Bothnian Sea during 1986 to 1988 was probably due to the different water exchange and sedimentation processes in these regions (Ilus et al. 1993). Over time, the effective half-lives increased in both regions. Today, the effective half-lives seem to have started to decrease since the amount of ^{137}Cs input through river inflow to the Baltic Sea has been decreasing (Saniewski and Zalewska 2016).

The target level for the ^{137}Cs concentration in Baltic seawater is defined as 15 Bq m^{-3} as averages of pre-Chernobyl concentrations. Based on calculated effective half-lives, this level will be reached by 2017-23 in all HELCOM sub-basins, which is earlier than previously estimated (by e.g. Herrmann et al. 2007). However, it has to be noticed that these are only rough estimations which are only valid if the effective half-lives remain constant and no substantial remobilization of ^{137}Cs from the sediment takes place.

Inventories of ^{137}Cs in seawater

The inventories were estimated by calculating the ^{137}Cs inventories for seawater in various regions of the Baltic Sea (Bothnian Bay, Bothnian Sea, Gulf of Finland, Gulf of Riga, Baltic Proper, Kattegat, and Belt Sea) and then by combining these estimates. Inventories for different basins were calculated using their volumes (HELCOM, 2013) and their average ^{137}Cs concentrations, which were calculated from the data observed. The inventories of ^{137}Cs in the Baltic seawater are given in **Table 3.1.1.** These estimates show that the inventory of ^{137}Cs in the Baltic water mass was 1090 TBq in 2003, and had decreased to 470 TBq in 2015 due to radioactive decay, bioaccumulation, sedimentation processes and outflow from the Baltic Sea area. The temporal evolution of the ^{137}Cs inventory in the Baltic seawater is presented in **Figure 3.1.4.** The estimates were calculated with the assumption that the estimated mean concentration of ^{137}Cs was the same for the entire Baltic Sea.

Year	^{137}Cs (TBq)
2003	1090
2004	1030
2005	950
2006	870
2007	890
2008	770
2009	770
2010	730
2011	660
2012	610
2013	560
2014	560
2015	470

Table 3.1.1. Estimated ^{137}Cs inventories in the Baltic seawater.

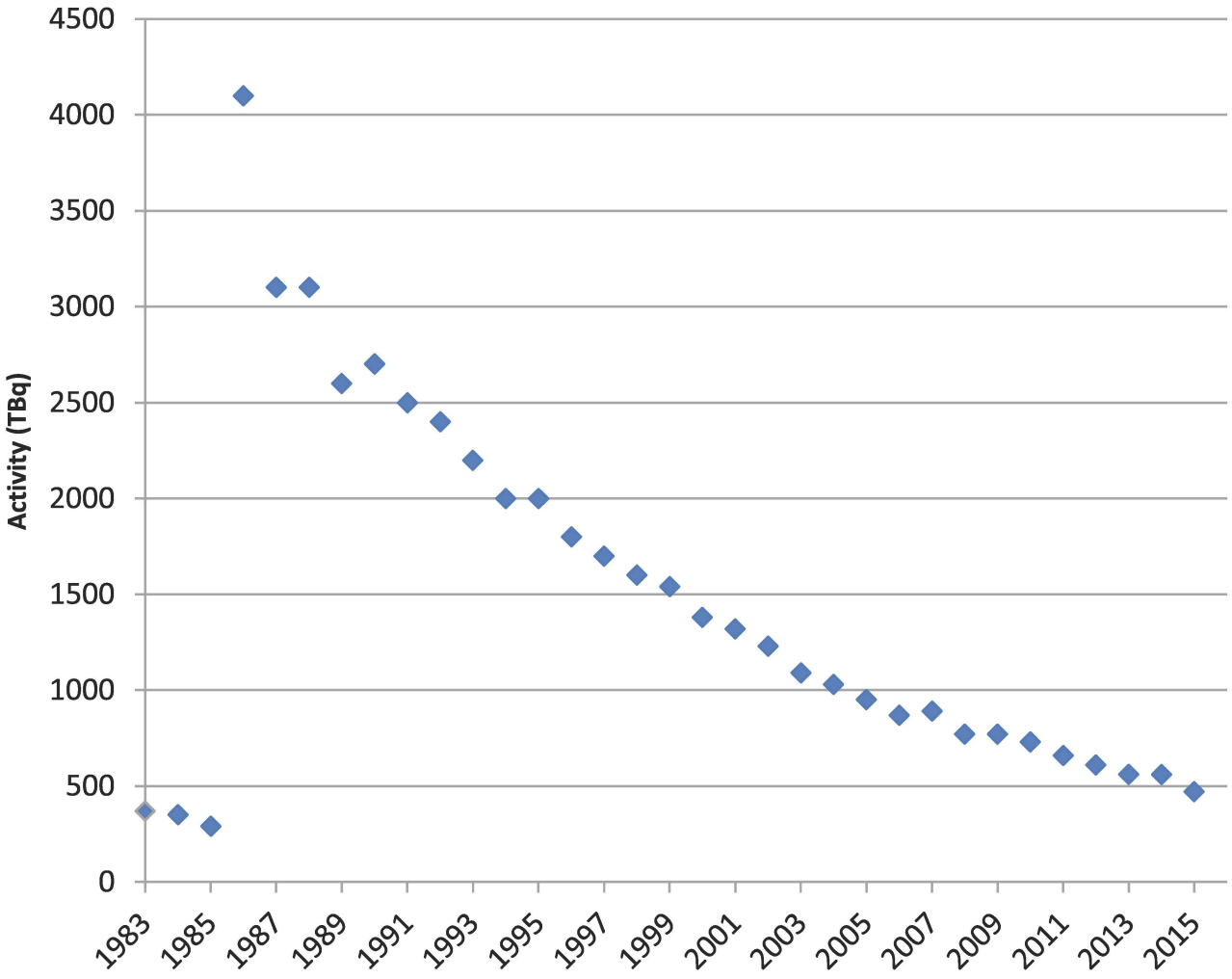


Figure 3.1.4.
Inventories of ^{137}Cs in the Baltic seawater during 1983-2015

Other radionuclides

^{90}Sr

^{90}Sr ($T_{1/2}$ = 28.8 years) concentrations in Baltic seawater varied from 4 Bq m^{-3} to 11 Bq m^{-3} in surface waters from 2011 to 2015. Similar levels were detected in the water column and the near bottom waters. The exception is the Kattegat, where the near bottom waters originate from the North Sea and have activity concentrations of ^{90}Sr of only about 2 Bq m^{-3}. ^{90}Sr inventory in the Baltic Sea was about 154 TBq in 2015. The ^{90}Sr concentration decreases slowly with time and its behaviour in seawater is different from ^{137}Cs. The effective half-life of ^{90}Sr in seawater is longer than that of ^{137}Cs; from 1987-2010 it was around 20 years and from 2010-2015 the effective half-life was about 73 years.

$^{(239+240)}Pu$

In 2011 the concentrations of $^{(239+240)}Pu$ in surface seawater were largely equalized. The highest values were found in the Gulf of Finland (5.0 mBq m^{-3}) and in the Bothnian Sea (6.4 mBq m^{-3}). Insignificantly lower activities were detected in the Bothnian Bay (3.4 mBq m^{-3}) and in the Eastern Gotland Basin (2.6 mBq m^{-3}).

^{99}Tc

There is no data reported for the assessed period, but in 2010 the lowest average concentration of ^{99}Tc was found in Arkona Basin (0.076 Bq m^{-3}), a slightly higher concentration (0.1 Bq m^{-3}) was in Bornholm Basin and the highest value (0.3 Bq m^{-3}) was specific to the Kattegat.

^{3}H

In the reporting period, the tritium activity concentration in surface waters varied from 1,000 Bq m^{-3} to 4,000 Bq m^{-3} (**Fig. 3.1.5**). The highest concentrations were found in Kattegat with the average value equal to 2136 Bq m^{-3}, while the lowest ones within the range 969 Bq m^{-3} – 991 Bq m^{-3} were specific to the Arkona Basin, the Bay of Mecklenburg and the Bornholm Basin.

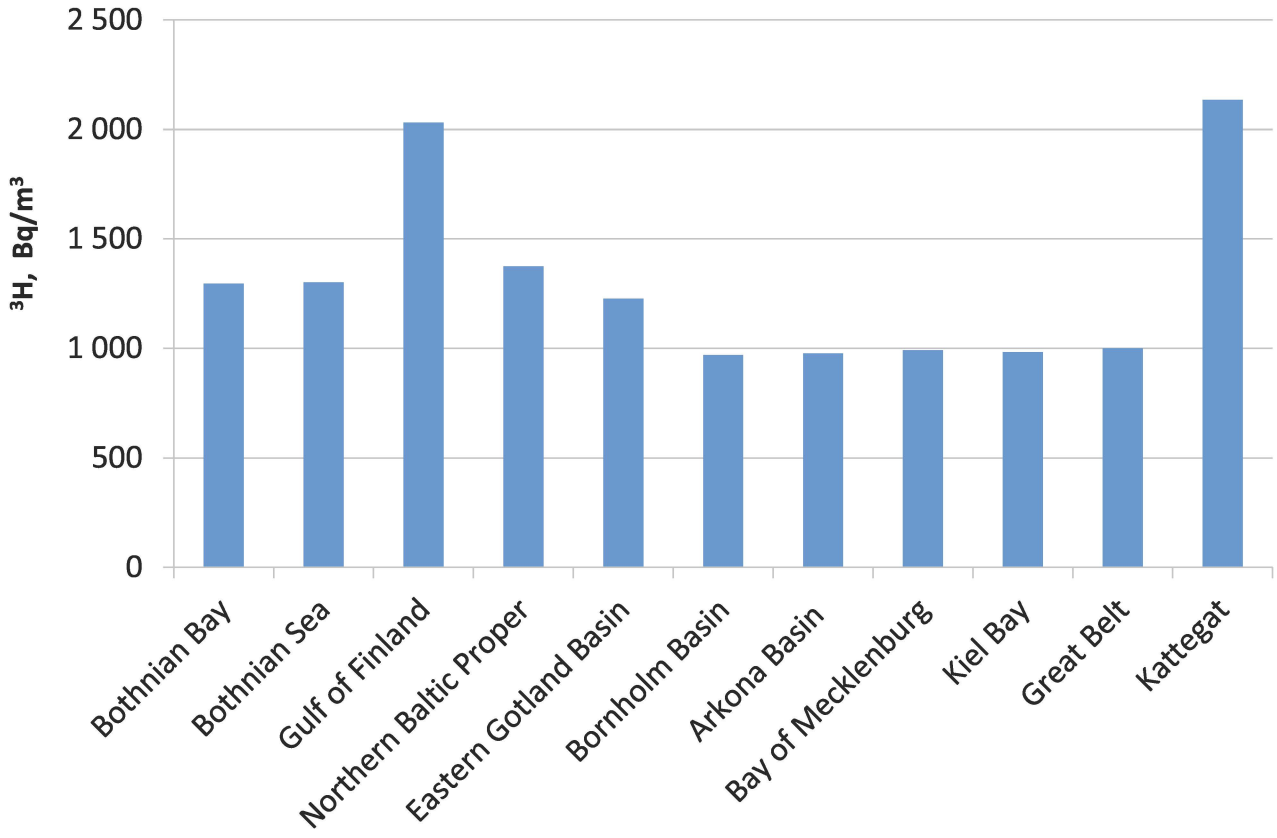


Figure 3.1.5.
Mean concentrations of ^{3}H (calculated for the period 2011-2015).

Naturally occurring radionuclides (^{40}K, ^{226}Ra, ^{210}Pb and ^{210}Po)

^{40}K is one of the non-series primordial, naturally occurring radionuclides with a half-life of 1.3 x 10^9 years. Its concentration in sea water is in correlation with the level of salinity, as evidenced by the varying ^{40}K concentrations detected in the Baltic Sea areas with different salinity and at different depths (**Fig. 3.1.6**). The lowest average concentration set for the period 2011-2015 was recorded in the surface and bottom waters of the Bothnian Bay, with concentrations of 935 Bq m^{-3} and 1,379 Bq m^{-3} and salinities ranging from 2 to 4 PSU, respectively. The highest average concentration of ^{40}K, occurred in near-bottom water of the Bornholm Basin equal to 5412 Bq m^{-3}, where a significant impact of inflowing waters from the North Sea is observed and the salinity reaches 16-17. Similar concentrations levels were found in the surface water in the Eastern Gotland Basin, the Gdańsk Basin and the Bornholm Basin, in the range of 2500 Bq m^{-3} to 2800 Bq m^{-3}.

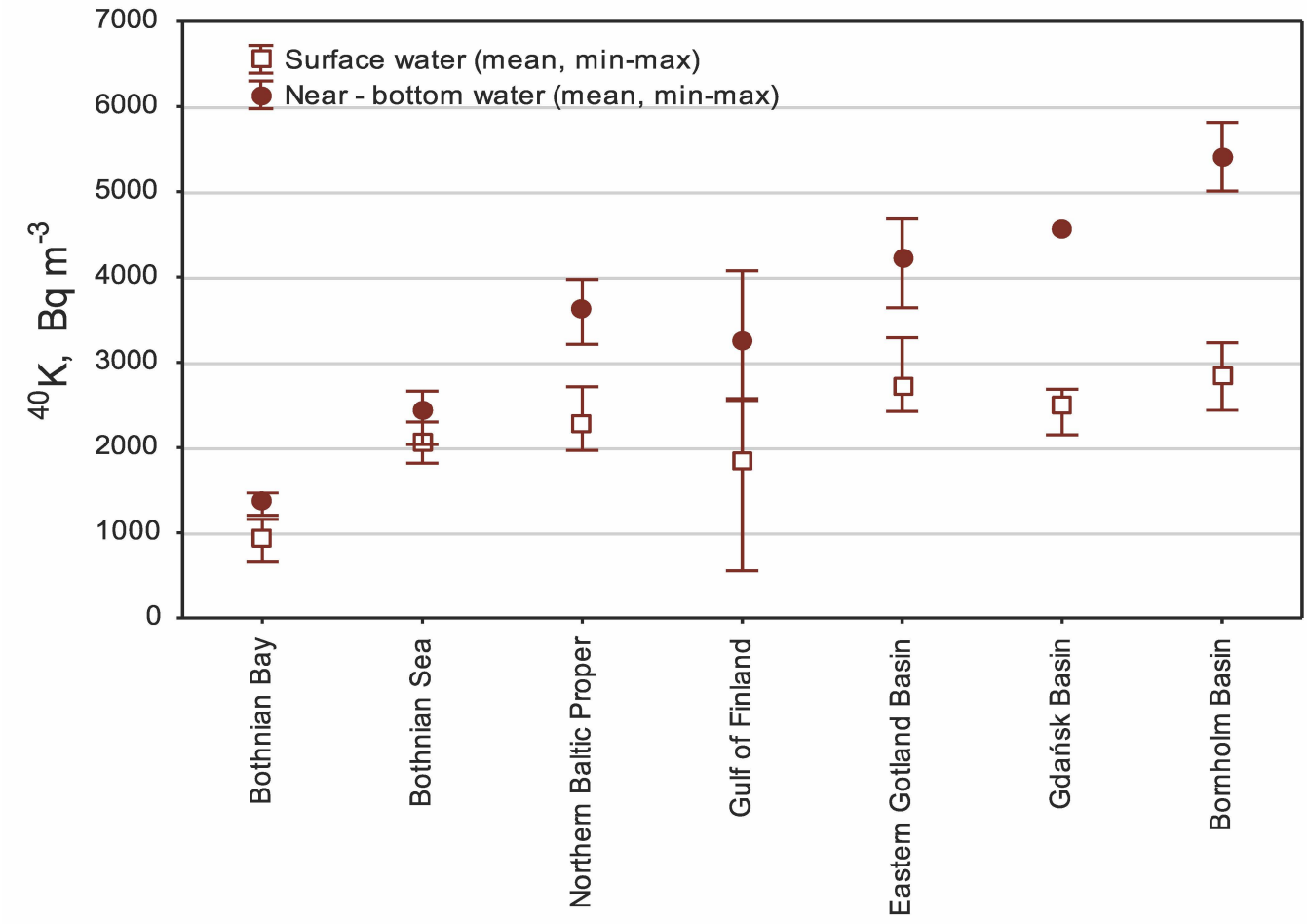


Figure 3.1.6.
Mean concentrations of ^{40}K in the surface and near-bottom water (calculated for the period 2011-2015).

^{226}Ra is naturally occurring uranium - radium series radionuclide with a half-life of 1602 years. In the period from 2011 to 2015, the ^{226}Ra concentrations in surface waters of the Gdańsk Basin, the Eastern Gotland Basin and the Bornholm Basin changed in a narrow range from 2.5 Bq m^{-3} to 3.6 Bq m^{-3} **(Fig. 3.1.7)**. Insignificantly higher concentrations of ^{226}Ra of 4.5 Bq m^{-3} were recorded in the near-bottom waters of the Gdańsk Basin and the Bornholm Basin.

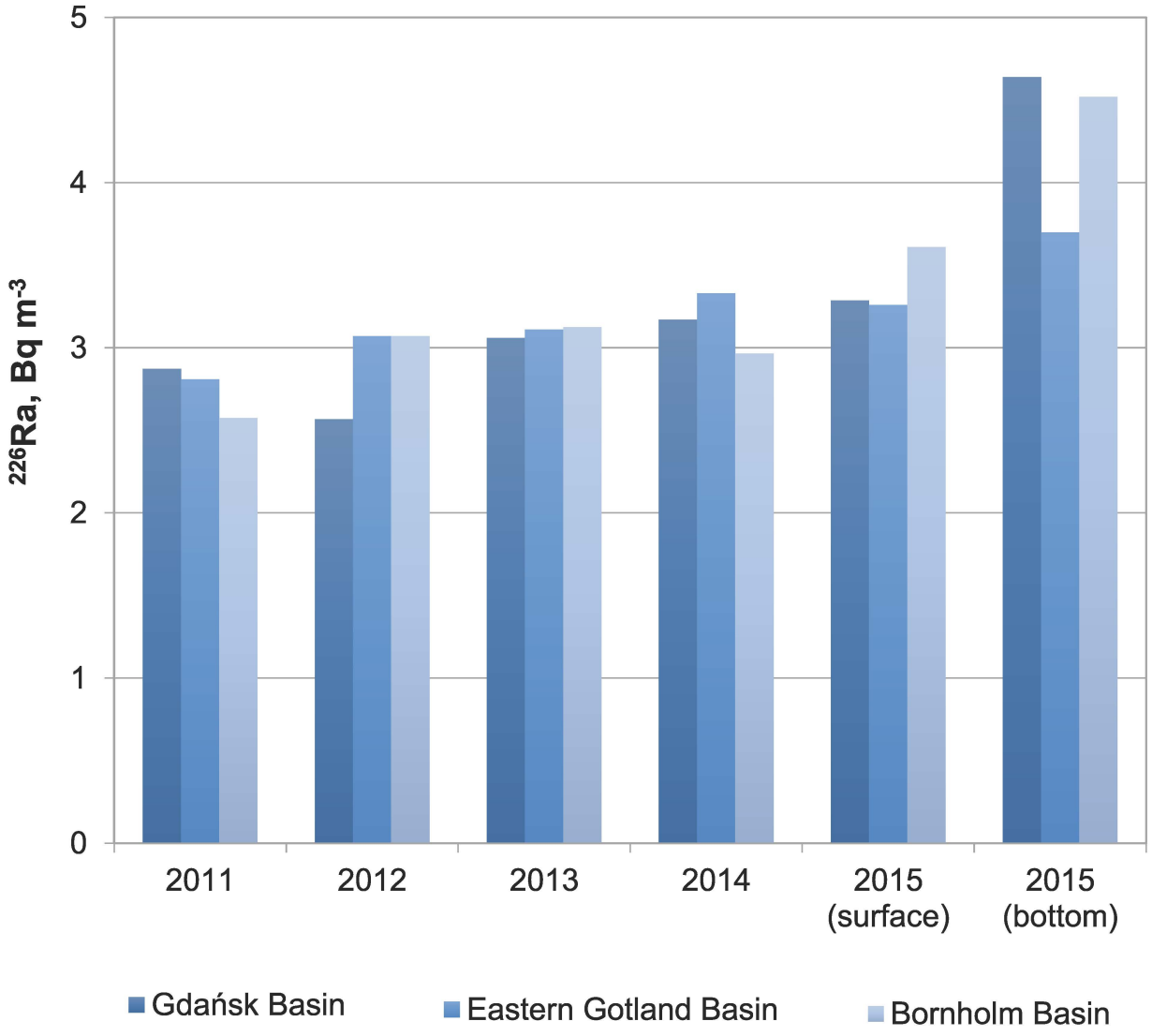


Figure 3.1.7.
Mean concentrations of ^{226}Ra (calculated for three sub-basins) in the surface and near-bottom water.

The radionuclides ^{210}Pb and ^{210}Po were measured in the Gulf of Finland in 2011. The values of ^{210}Pb and ^{210}Po were found to be 1.7 Bq m^{-3} and 1.3 Bq m^{-3}, respectively.

The Fukushima Daiichi nuclear accident

Up to now, no increased values owing to the Fukushima accident could be detected in any sub-basin of the Baltic Sea.

Conclusions

The concentrations of ^{137}Cs are the main indicator of the radioactive status of the waters of the Baltic Sea. The highest concentrations in the report period were found in the Archipelago and Åland Sea. The ^{137}Cs activity in the whole Baltic Sea is steadily decreasing and is estimated that the pre-Chernobyl target value of 15 Bq m^{-3} will be reached between 2017 and 2023. Estimates of effective half-lives for different parts of the Baltic Sea have been updated as between 9 and 11 years, with an average value of 10.2 years. An updated calculation of the inventory of ^{137}Cs activity in the seawater of the Baltic Sea resulted in 470 TBq in 2015.

Any increase of concentrations due to the Fukushima Daiichi nuclear accident have not been detected in seawater. Therefore, the current state of knowledge shows no radiological effects caused by the Fukushima accident.

With regard to ^{137}Cs, the Baltic Sea is still one of the most contaminated seas in the world, even 30 years after the Chernobyl accident. The small volume and small scale water exchange with the North Sea makes the Baltic Sea very vulnerable for contamination with hazardous substances.

3.2. Radionuclides of the Baltic Sea sediments

Stefanie Schmied, Meerit Kämäräinen, Mats Eriksson

Introduction

Sediments usually act like sinks for pollution and can in the future act as a source if the environmental conditions change. The sediment conditions and the rate new sediments are formed on top of the older sediments are essential parameters to monitor in order to predict long-term effects. The Baltic Sea has many different sedimentary conditions, with erosion and accumulation zones affecting the spatial distribution of radionuclides in the Baltic Sea. Clay sediments of the Baltic Sea contain valuable information of the radioactivity in the marine environment. Radionuclides, especially ^{137}Cs, have a tendency to bind to clay and mud particles while they settle down. Due to the slow exchange of water between the Baltic Sea and the North Sea, and quite rapid sedimentation rates, the radionuclides have prolonged residence times in the Baltic Sea (Ikäheimonen et al. 2009).

Monitoring radioactivity in the Baltic Sea has been going on for several decades. With regard to HELCOM, data on the radioactivity of the sea bottom sediments have been gathered since 1984 from about two hundred monitoring stations in order to compile a baseline for the existing and changing radioactivity in the Baltic Sea. These results have been reported earlier in HELCOM thematic assessments (HELCOM 1995, 2003 and 2009). The radioactivity data have also been used for several studies, e.g. as a tracer in inter-comparison of sediment sampling devices (HELCOM 2000) and in the estimation of sediment accumulation rates and the dating of the sediments (Jensen et al. 2003; Mattila et al. 2006).

This report is a short summary of the radioactivity in the Baltic Sea sediments during the years 2011 – 2015, concentrating on the development in the last four years of the reporting period.

Material and Methods

During 2011-2015, 85 monitoring stations were sampled for the determination of sediment radioactivity, based on HELCOM (2013), while the sampling techniques used by different countries have been described in HELCOM (2003). The sampling techniques used by different countries have been described earlier by HELCOM (2003). Sediment types and the bottom morphologies in different parts of the Baltic Sea have also been described in several studies (e.g. Winterhalter et al. 1981; Winterhalter 1992, HELCOM 2003; Virtasalo 2006; Hutri 2007).

The methods used in the radionuclide monitoring programs are described elsewhere (Salo et al. 1986, HELCOM 2003; Ilus et al. 2007). In general, the inventories in sediments were based on the mean total amounts of radionuclide activity concentrations in sediments (Bq m^{-2}) and the surface areas of different basins, taking into account the surface areas and the activities in soft and hard bottoms (Ikäheimonen et al. 2009).

Results and Discussion

The inventories of artificial radioactivity have decreased or remained at the same level in the bottom sediments during the years 2011 – 2015, but there is spatial variation in the results. Today, most of the artificial radioactivity in the Baltic Sea is from ^{137}Cs. The highest activity is found in the bottom sediments in the Bothnian Sea and in the eastern part of the Gulf of Finland (**Figure 3.2.1**). Artificial radioactivity from the Chernobyl and global fallout will partly be buried in sediments in the accumulation bottoms that usually exist in sea basins and depressions.

The concentrations of ^{137}Cs have been relatively unevenly distributed along different monitoring stations of the Baltic Sea (**Figure 3.2.1**). Due to different local or areal accumulation, transportation and erosion rates at some monitoring stations (especially in the Southern Baltic Proper, the Western Baltic and the Gulf of Finland), sediments show a more fluctuant trend of activity concentration of ^{137}Cs. The sedimentation rate is relatively high in the Baltic Sea and varies widely (between 0.2 mm year^{-1} and 29 mm year^{-1}) depending on the area and local environmental factors (HELCOM 2000), which is clearly seen by the vertical profiles shown in **Figure 3.2.2.** In addition to the geological conditions, the differences in sampling techniques increase the variability of the results.

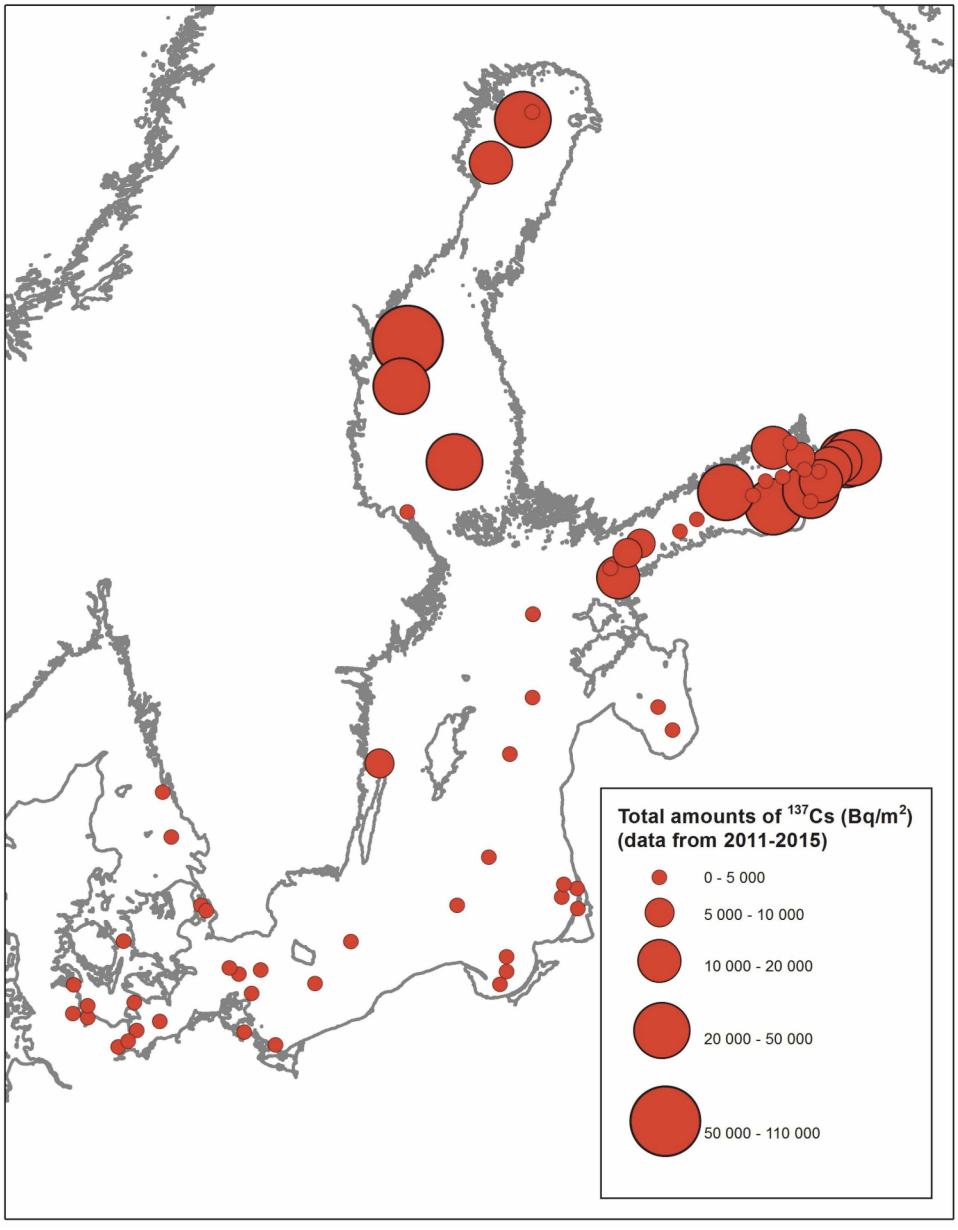
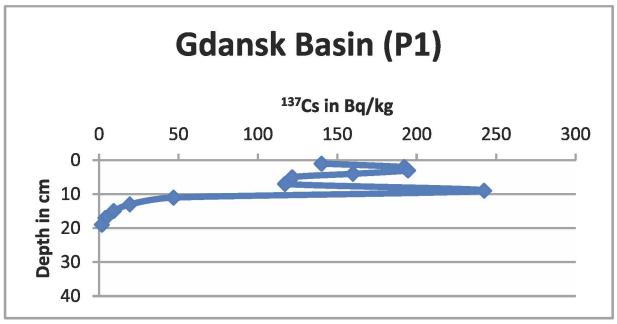
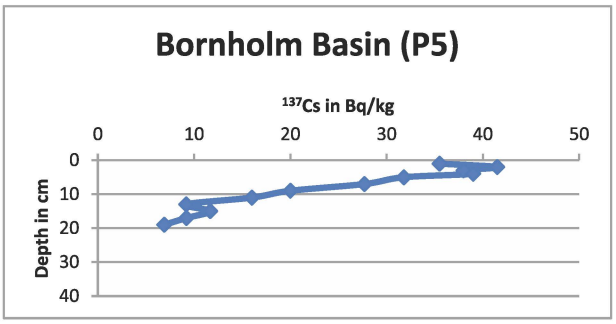
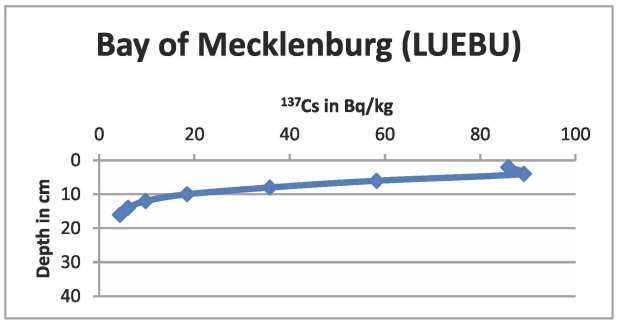
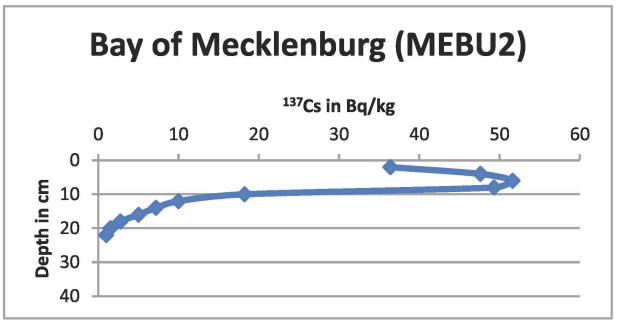


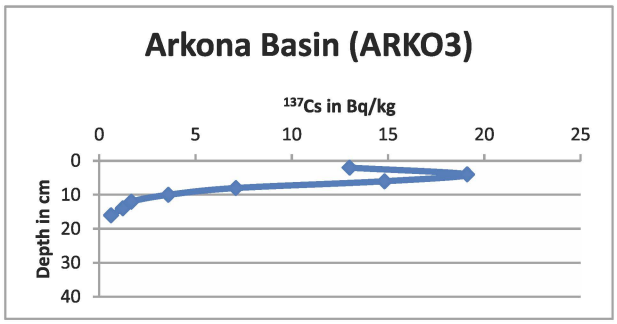
Figure 3.2.1. Mean total amounts of ^{137}Cs in Bq m^{-2} at different sampling stations in 2011 – 2015.

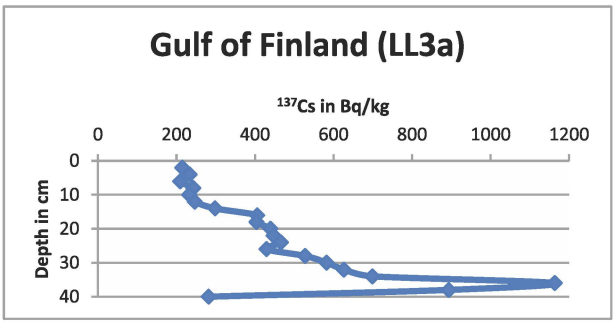


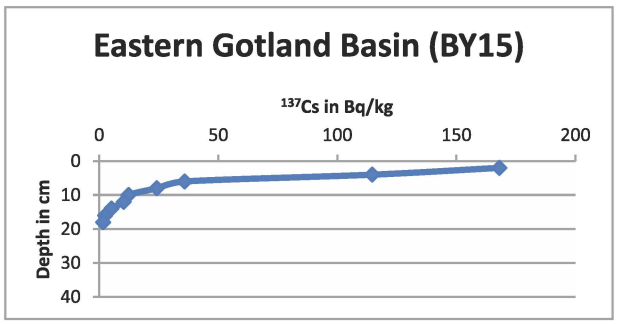


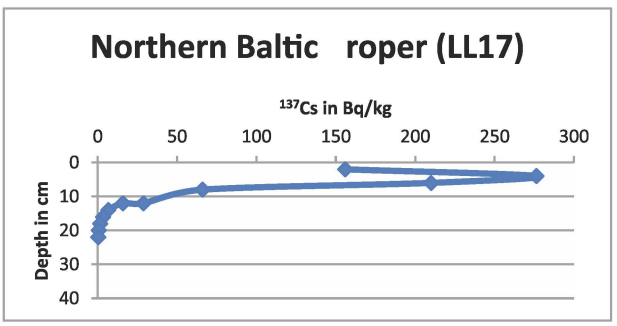


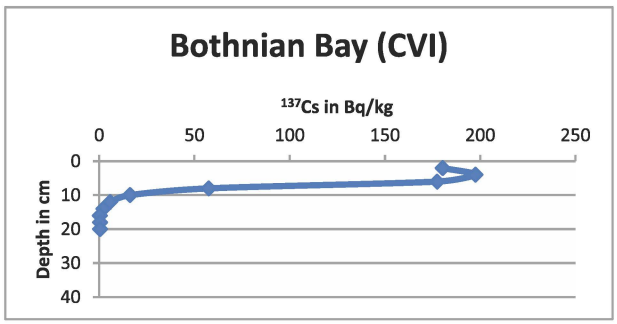












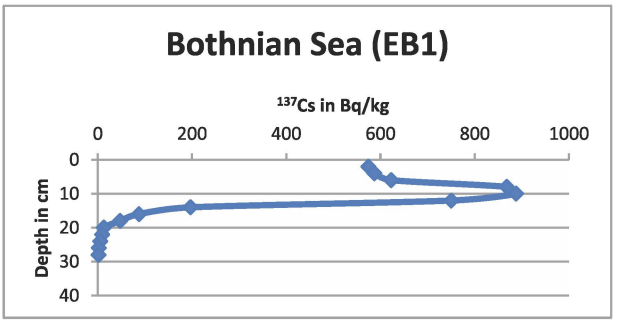


Figure 3.2.2.
Concentrations of ^{137}Cs (Bq kg^{-1} dry weight) as a function of depth at some HELCOM sub-basins in the Baltic Sea in 2015. The monitoring stations are given in brackets. The values below the detection limits are exempt.

Most of the amount of radioactivity in the sediments in the Baltic Sea originates from naturally occurring radionuclides with long half-lives such as ^{40}K, ^{226}Ra and ^{232}Th.

In the Baltic Sea sediments there are still considerable amounts of artificial radioactivity present, mainly originating from radionuclides with long half-lives. After the Chernobyl fallout, there were also elevated concentrations of many short-lived radionuclides such as ^{103}Ru (T½ 39.3 d), ^{106}Ru (T½ 372.6 h) and ^{110}mAg (T½ 249.8 d). However, because of their short half-lives, the activities of these radionuclides have decreased considerably and are today not detectable in the sediments.

In the recent inventory, it was estimated that the total amount of ^{137}Cs activity in the Baltic Sea sediments was about 2,200-2,500 TBq. This amount is about 8 - 9 times higher compared to the amounts of the pre-Chernobyl level at the beginning of the 1980s (HELCOM 2013). In recent years, ^{137}Cs has continued to deposit onto bottom sediments and, at the same time, the physical half-life (30.2 a) reduces the activities slowly. Most of the ^{137}Cs activity is found in the sea bottoms of the Bothnian Sea and in the eastern Gulf of Finland (**Figures 3.2.1 - 3.2.2**). The total concentrations of ^{137}Cs activities on so-called hard bottoms varied from 0.3% to nearly 14% of those on soft bottoms, when the average ratio was only about 4% (Ilus et al. 2007, more recent data by Outola et al., 2013).

The reported values during 2011-2015 of ^{239,240}Pu (^{239}Pu T½ 2.4x104 a, ^{240}Pu T½ 6,563 a) activities have ranged between 0.013 and 8.384 Bq kg^{-1} dry weight, and values of ^{238}Pu (T½ 87.7 a) activities between 0.005 and 0.513 Bq kg^{-1} dry weight. Most of the plutonium originates from the global fallout. However, there were small amounts of ^{238}Pu and ^{241}Pu in the fallout of the Chernobyl accident that could be seen in the activity ratios of ^{238}Pu/^{239,240}Pu and ^{241}Pu/^{239,240}Pu and in the excess amounts of ^{241}Pu (Ikäheimonen 2003). ^{241}Pu will increase the concentration of ^{241}Am in the sediments via radioactive decay. In the surveillance of the marine sediments of the Finnish nuclear power plants, the measured values of ^{239,240}Pu activities ranged between 0.42 and 3.3 Bq kg^{-1} dry weight. Due to the limited data, the sediment inventory of these radionuclides is difficult to estimate.

The activities of the artificial radionuclide ^{90}Sr (T½ 28.5 a) mostly originates from the global fallout. Because of the small share in the Chernobyl fallout and costly analytical methods, the interest on ^{90}Sr has been reduced and thus only relatively little data is available. In the years 2011 – 2015, the reported ^{90}Sr concentrations ranged from 0.16 Bq kg^{-1} dry weight to 17.9 Bq kg^{-1} dry weight. In the surveillance of the marine sediments of Finnish nuclear power plants, the measured values of ^{90}Sr ranged between 0.48 and 8.5 Bq kg^{-1} dry weight. Due to the limited data, the inventory of ^{90}Sr in sediment is difficult to estimate.

Soft and hard sediments

Roughly, sediments can be divided into soft and hard sediments. Soft sediments are fine-grained and consist mostly of clay or mud. In contrast, hard sediments are coarse and sandy. Soft sediments tend to accumulate radionuclides more than hard sediments. The reason for this is the different composition of these sediment types. Hard sediments consist mostly of sand which is composed of mineral particles. The most common constituent of sand is silica (SiO_2, silicon dioxide). Silica is chemically inert and therefore does not react eagerly with other substances under normal conditions. Furthermore, the reactive surface of fine-grained sediments is larger than that of coarse-grained ones.

The sea bottom of the Baltic Sea consists of both sediment types, soft and hard. To show the difference between the activity concentrations of ^{137}Cs of sediment cores of both sediment types in the same sub-basin, we chose two stations in the Arkona Basin (ODER and K4) and two stations in the Bothnian Sea (C14 and EB1). K4 and EB1 are soft sediment stations, while ODER and C14 are hard sediment stations. For ODER and K4 the concentration activities of the first 12 cm were added, whereas for C14 and EB1 the concentration activities of the first 20 cm were added. The data of 2013 was used for both station pairs to be compared. The results for ODER and K4 are 57 Bq kg^{-1} dry weight and 298 Bq kg^{-1} dry weight, respectively. So the concentration activity of the soft sediment station K4 is about five times higher than the one of the hard sediment station ODER. The results for C14 and EB1 are 1013 Bq kg^{-1} dry weight and 4337 Bq kg^{-1} dry weight, respectively. In this case the soft sediment station EB1 has an about four times higher concentration activity than the hard sediment station C14.

Comparison of the Inventory of ^{137}Cs in Sediment and Seawater

The total amount of ^{137}Cs activity in the Baltic Sea sediments was about 2,200-2,500 TBq. An updated calculation of the inventory of ^{137}Cs in the seawater of the Baltic Sea resulted in 470 TBq in 2015 (**Table 3.1.1**). So, the ^{137}Cs activity is about four times higher in the sediments of the Baltic Sea compared to seawater. In general, sediments accumulate substances from the water column and are therefore a fundamental depression for these substances. As a consequence of storms, bioturbation and trawl net fishery accumulated substances may be resuspended into the water column. Because of less water turbulence, substances in the Baltic Sea will sediment more rapidly than e.g. in the more turbulent waters of the North Sea.

Future Work and Recommendations

As sediments usually act as sinks for pollutants, monitoring of radioactivity in the sediments of the Baltic Sea is an essential part of environmental monitoring and will provide a realistic baseline, e.g. for possible radiation emergency situation modelling purposes. The continuous monitoring work and time trends of the radioactive substances are the bases for understanding the state of the Baltic Sea environment and its radioactivity. However, there is still limited knowledge of radioactivity in the sediments of the Baltic Sea, e.g. the concentrations and inventories of ^{90}Sr, ^{241}Am as well as naturally occurring radionuclides. Furthermore, modelling tools are needed to help understanding the environmental effects that a nuclear accident can cause in the Baltic Sea area. In the future, we should attempt to fill these gaps to form a more comprehensive picture of the radioactivity in the sediments of the Baltic Sea.

3.3. Radionuclides in biota

Marc-Oliver Aust, Maria Suplińska, Tamara Zalewska

Introduction

Radionuclides reaching waters of the Baltic Sea from different sources (e. g. atmospheric fallout, river discharges, controlled liquid and gaseous discharges from nuclear facilities) become distributed within different compartments of the marine environment.

As a consequence, they easily bioaccumulate in marine organisms and are transferred to higher trophic levels via the food web. The monitoring of commercially important fish species for radioactive isotopes is therefore a valuable tool to assess the potential hazard for human health issues.

Despite the fact that the main source of anthropogenic radionuclides in fish is their diet, levels of radionuclides in marine biota clearly correlate with the corresponding levels in seawater and sediments. As a consequence, ^{137}Cs concentrations in fish tissues (representing by far the dominant fraction of anthropogenic radionuclides in the Baltic Sea ecosystem) accurately reflect the decreasing trend of its activity in seawater (Zalewska and Suplińska 2013). Irrespective of the overall trend, populations of cod are still the most contaminated in the Baltic Sea compared to populations in the North Atlantic and its marginal seas (Karl et al. 2016).

In addition to fish, macroalgae (*Fucus vesiculosus, Rhodophyta*) are recommended as bio-indicators of radioactive contamination of the marine environment. In microalgae, ^{137}Cs is bioaccumulated with considerable efficiency from the surrounding environment.

A regular monitoring of radionuclides in Baltic Sea biota started in 1984. Therefore, long-term data are available for the evaluation of trends in specific activity. This section focuses on the economically and ecologically most important Baltic fish species: herring (*Clupea harengus*), cod (*Gadus morhua*), European Plaice (*Pleuronectes platessa*) and European Flounder (*Platichthys flesus*). Furthermore, data for the bladderwrack (*Fucus vesiculosus*), a well-established biological indicator algae for radionuclides, are presented. Although not covered in this report, it should be noted that pike is the species that is the most contaminated by ^{137}Cs in the Baltic Sea.

Material and methods

The sampling and analysis of the biota samples for radionuclides determination is carried out according to the MORS guidelines in their present form based on HELCOM Recommendation 26/3. The number of samples obtained in the period of 2011-2015 and the total number of samples per species are listed in a table, and sampling points illustrated on a map, in Appendix 10.2.

The main artificial radionuclides which were measured in biota in the assessment period were: ^{137}Cs, ^{90}Sr, ^{239,240}Pu and ^{241}Am in fish, and ^{137}Cs and ^{99}Tc in *Fucus vesiculosus*.

Results and discussion

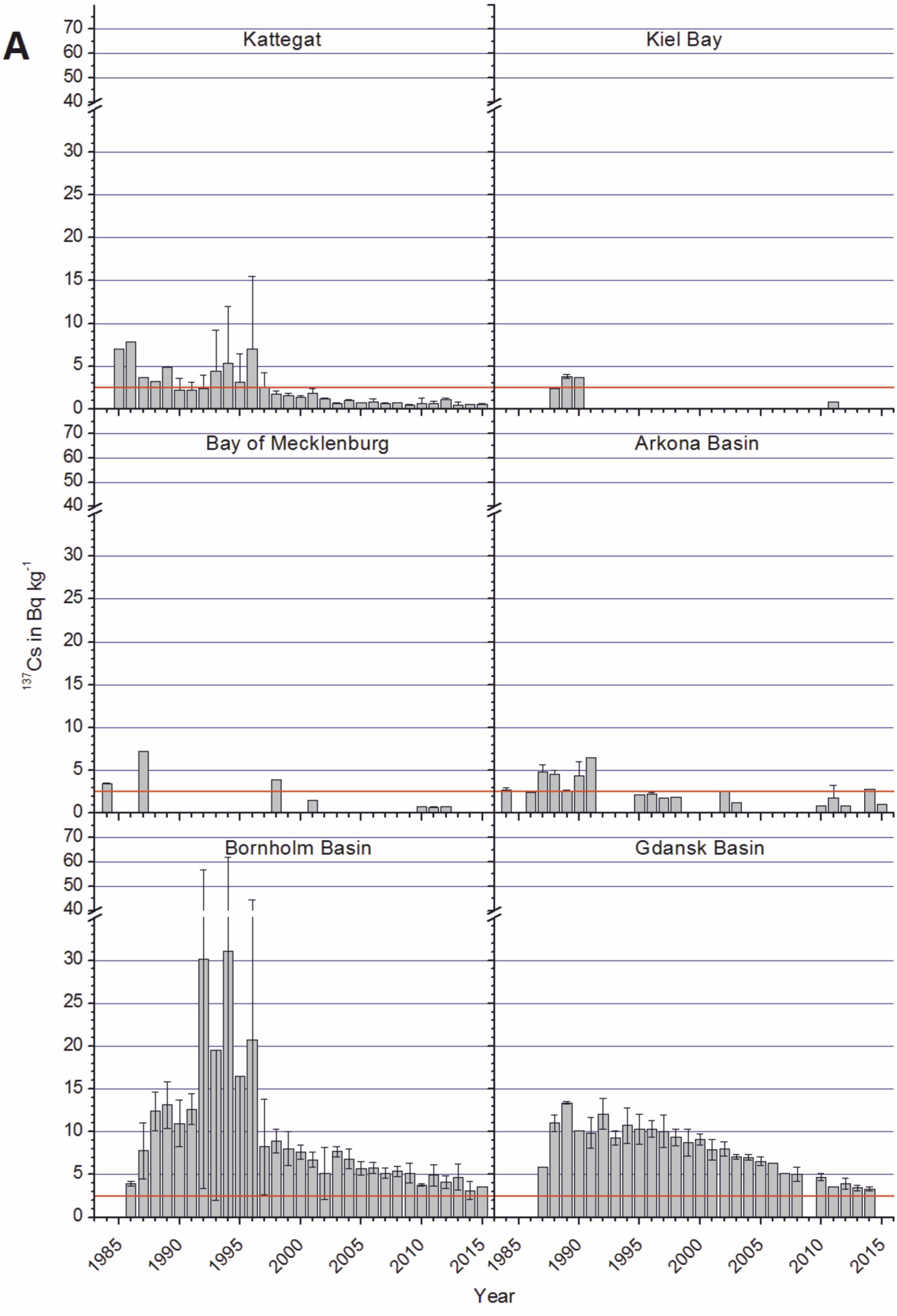
Time trends of ^{137}Cs activity concentrations

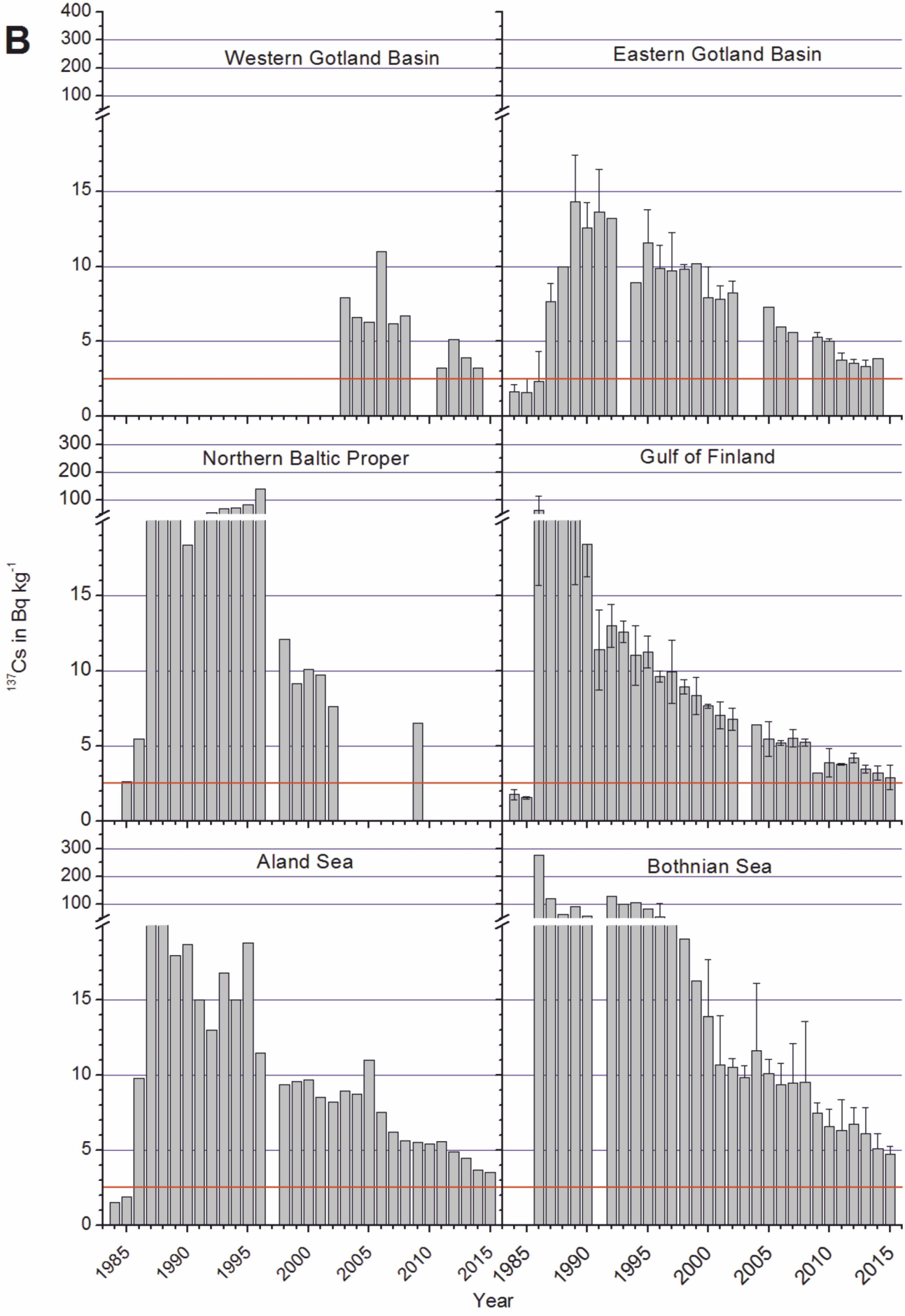
Time trends of ^{137}Cs specific activity in three fish species: herring *(Clupea harengus)*, cod *(Gadus morhua)* and flatfish (plaice and flounder) are presented for the period from 1984 to 2015.

The specific activity of ^{137}Cs still keeps decreasing, which is demonstrated by **Figure 3.3.1** showing for herring *(Clupea harengus)*. In the western parts of the Baltic Sea, i.e. Kattegat, Kiel Bay, Bay of Mecklenburg and Arkona Sea, the values already show levels being slightly below the target value of the Baltic Sea Action Plan (HELCOM 2007) of 2.5 Bq kg^{-1} wet weight (see **Figure 3.3.1**). In the remaining Baltic Sea basins, the target value is still exceeded, in the Bothnian Bay and in the Gotland area, by a factor of up to 2.

The decrease in specific ^{137}Cs activity described for herring *(Clupea harengus)* is also valid for cod *(Gadus morhua)*. At the end of the assessment period the mean specific activities were below 5 Bq kg^{-1} (see **Figure 3.3.2**). As no data are available from the pre-Chernobyl time for this species, it was impossible to define a target value for the Baltic Sea Action Plan (HELCOM 2007).

For the flat fish group consisting of flounder *(Platichthys flesus)* and plaice *(Pleuronectes platessa)*, **Figure 3.3.3** shows the ^{137}Cs time series in the western and southern Baltic Sea areas. At the end of the assessment period (2015), the values were far below the target value listed in HELCOM (2007) of 5 Bq kg^{-1} wet weight.


A
Kattegat
Kiel Bay
Bay of Mecklenburg
Arkona Basin
Bornholm Basin
Gdansk Basin
137Cs in Bq kg-1
Year


B
Western Gotland Basin
Eastern Gotland Basin
Northern Baltic Proper
Gulf of Finland
Aland Sea
Bothnian Sea
^{137}Cs in Bq kg^{-1}
Year
400
300
200
100
15
10
5
0
1985
1990
1995
2000
2005
2010
2015

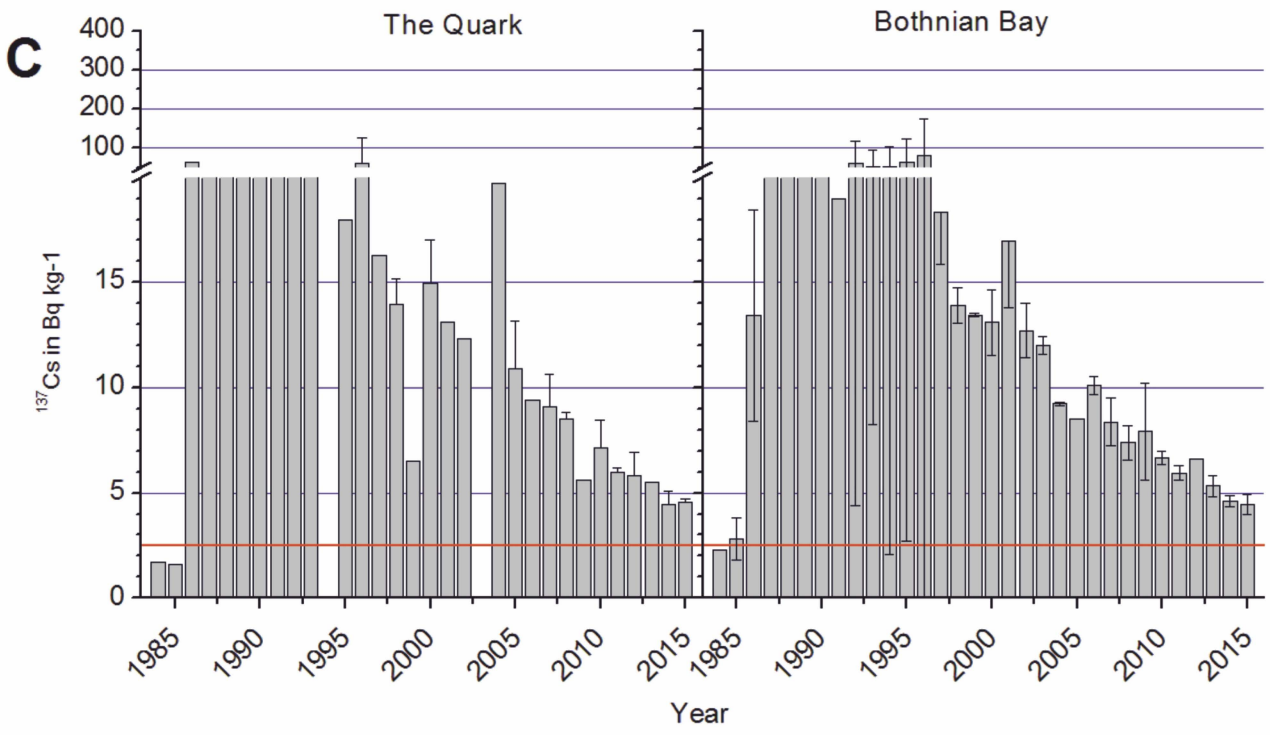
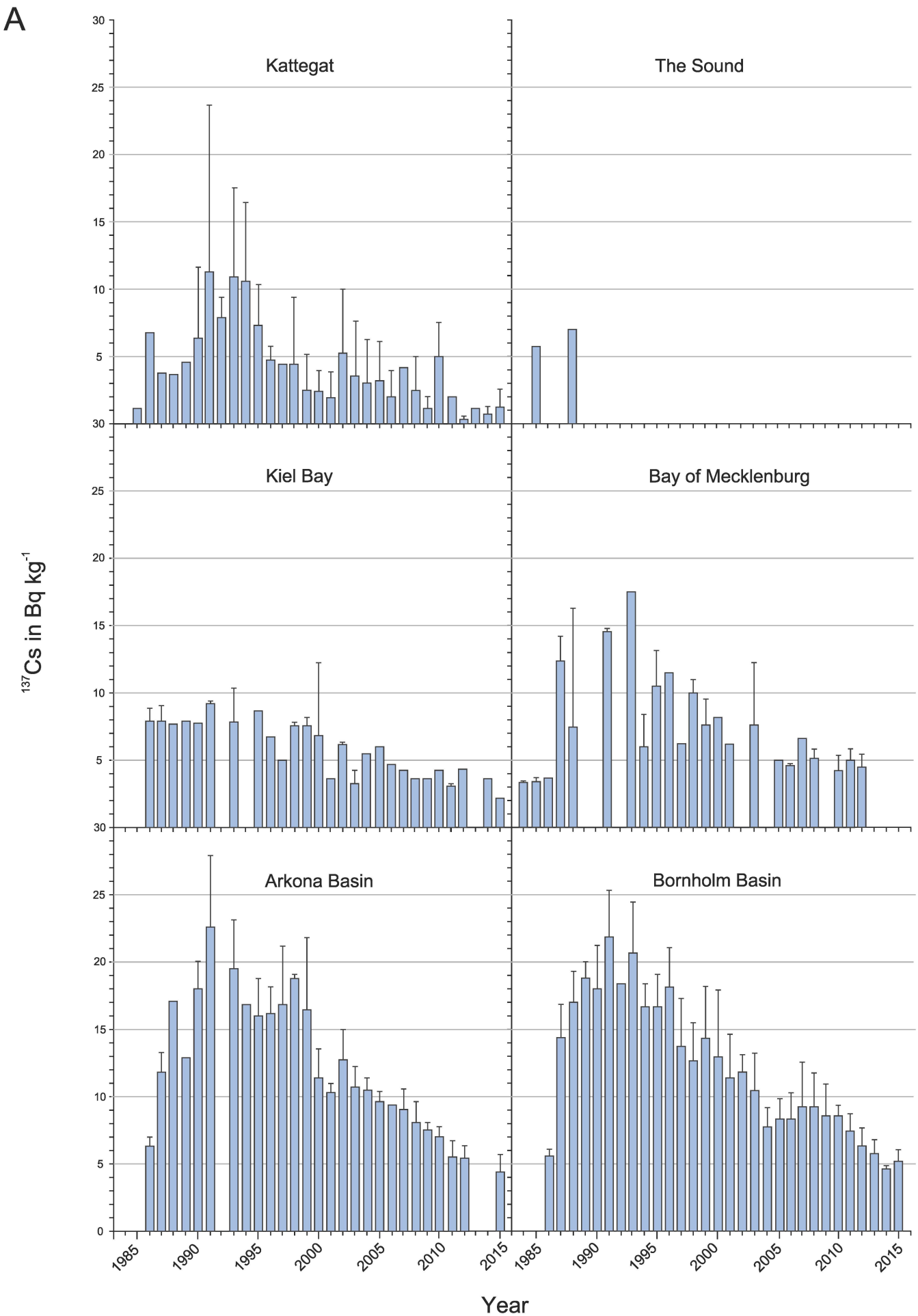


Figure 3.3.1.
Annual average specific ^{137}Cs activity (Bq kg^{-1} wet weight) in herring (flesh without bones and whole fish without head and entrails) in 1984-2015 in the more westerly (A) and more easterly (B and C) basins of the Baltic Sea (see **Figure 3.1.1a** for definition). The threshold value of 2.5 Bq kg^{-1} wet weight (red line) has been calculated as average of the pre-Chernobyl (1984-1985) specific activity.


A
Kattegat
The Sound
Kiel Bay
Bay of Mecklenburg
Arkona Basin
Bornholm Basin
^{137}Cs in Bq kg^{-1}
Year
0
5
10
15
20
25
30
1985
1990
1995
2000
2005
2010
2015

B

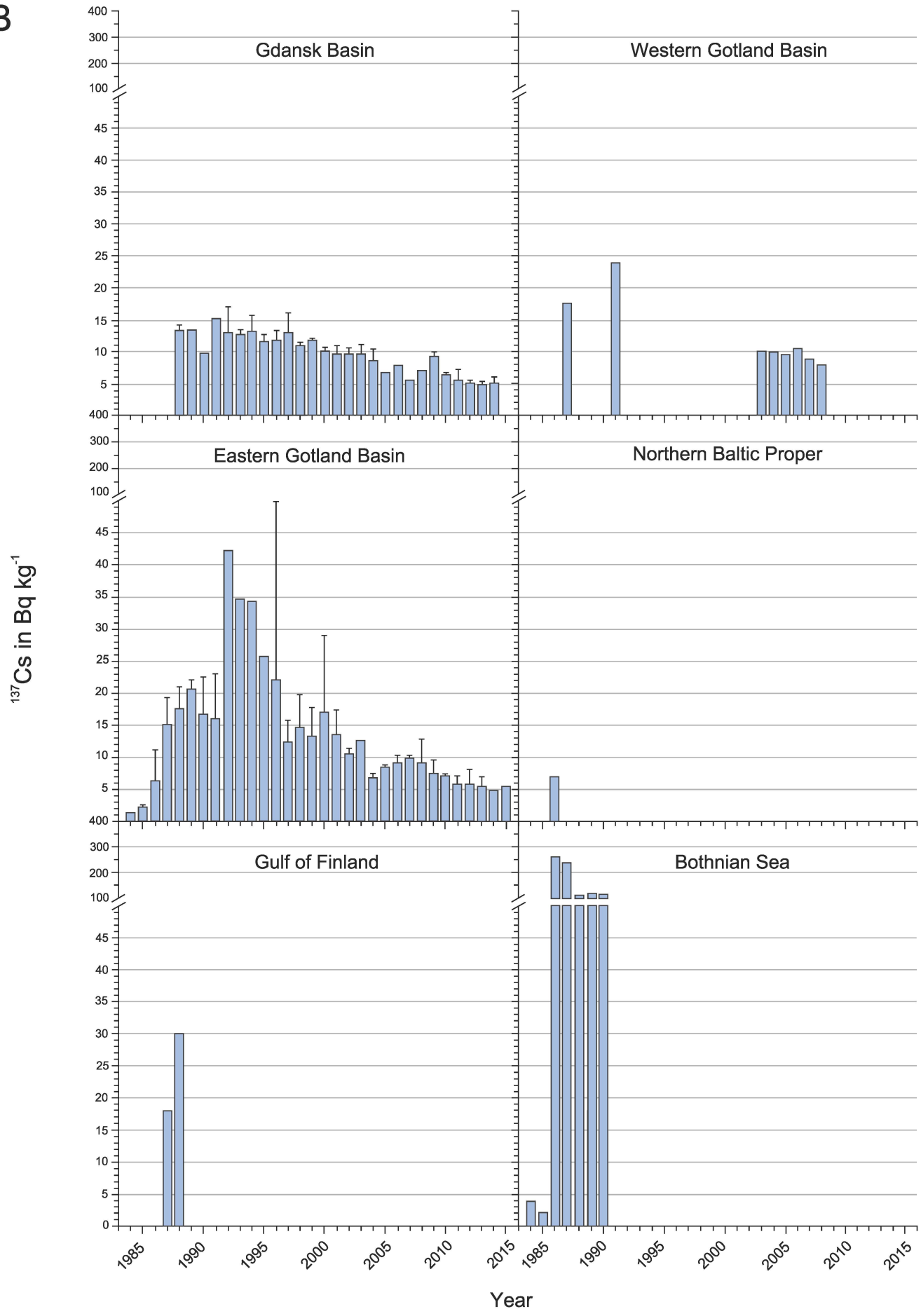


Figure 3.3.2.
Annual average specific ^{137}Cs concentrations (Bq kg^{-1} wet weight) in cod (flesh without bones/ fillets/muscle) in the more westerly (A) and more easterly (B) basins of the Baltic Sea (see **Figure 3. 1.1a** for definition) in the period 1984-2015.

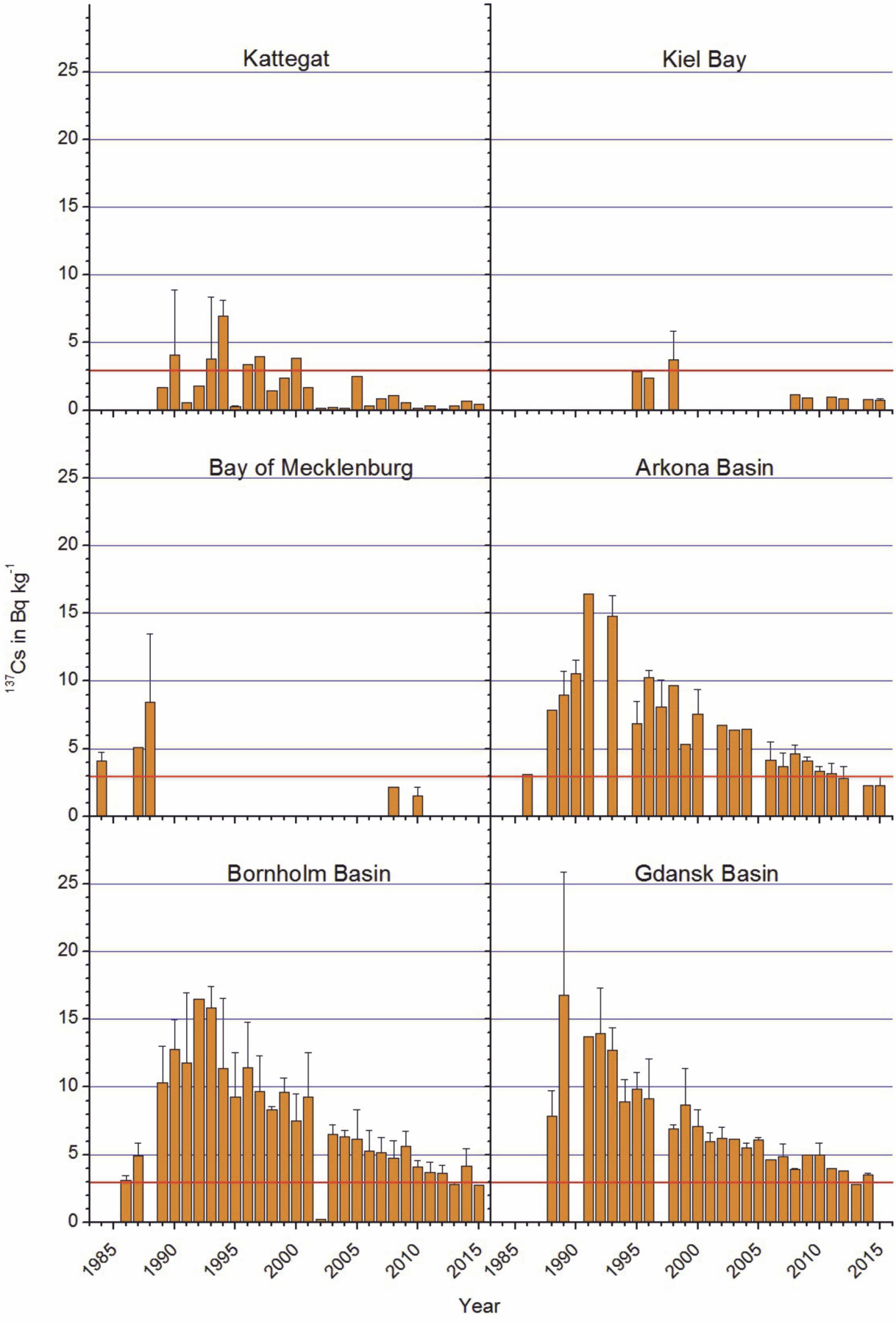


Figure 3.3.3.
Annual average ^{137}Cs concentrations (Bq kg^{-1} wet weight) in plaice and flounder (flesh without bones/fillets/ muscle) in 1984-2015. The target value (red line) has been calculated as average of the pre-Chernobyl (1984-1985) activity concentrations.

The decrease seen in **Figures 3.3.1** to **3.3.2** can be described numerically by calculation of the effective half-life of ^{137}Cs using least squares fitting. The results of such calculations are shown in **Figure 3.3.4** for herring, plaice and cod.

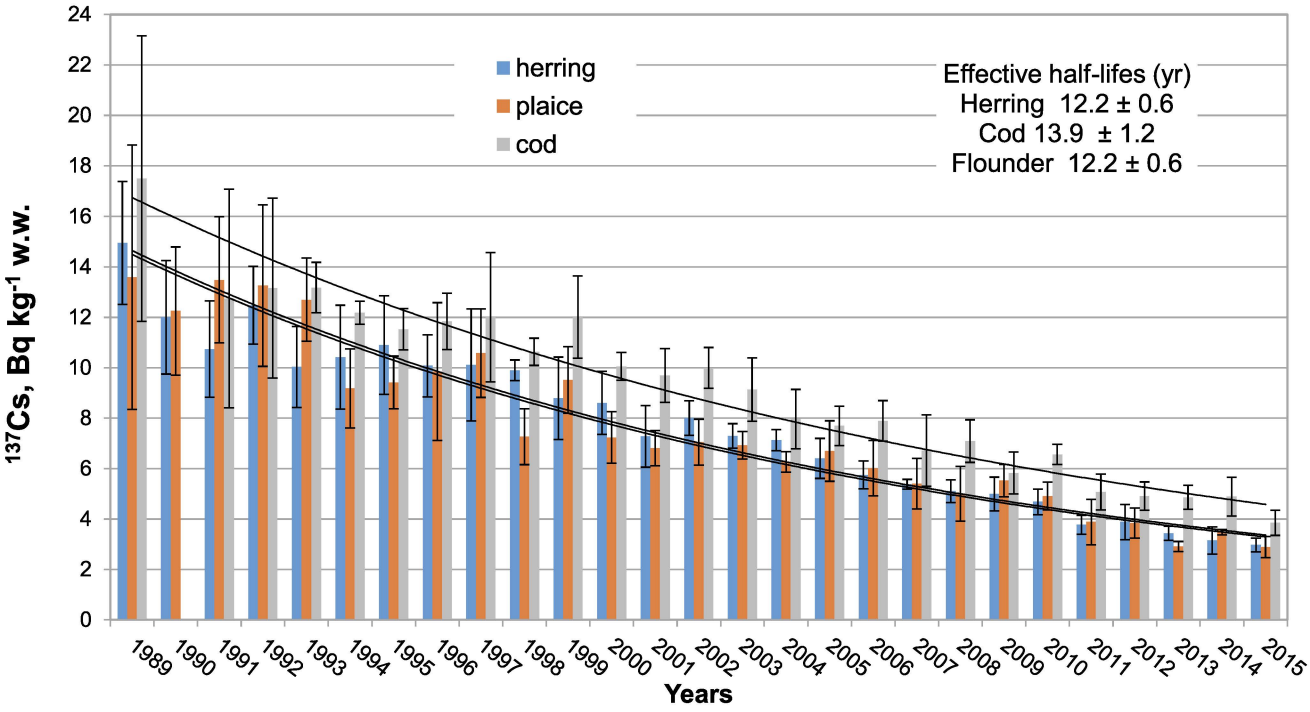


Figure 3.3.4.
Annual average specific ^{137}Cs activity in herring, cod and plaice muscle (fillets) collected in the southern Baltic Sea in the period 1989 – 2015 (the whiskers represent one standard deviation). Effective half-lives were calculated using least-squares fitting exponential decay curves (shown).

Other radionuclides

For the radionuclide ^{90}Sr, the origin of which is mainly the nuclear weapon's fallout and related runoff from rivers, values of the specific activity in fish flesh are more than two orders of magnitude lower than those of ^{137}Cs. The ^{90}Sr activities in flesh of flat fish species (flounder, plaice) exhibit slightly larger values than in round fish species (herring, cod, whiting and mackerel), because the analysed samples of the former may contain more of small parts of bones which accumulate much more ^{90}Sr than fish muscle. The ^{90}Sr values of herring analysed as "edible parts" (fish without head and entrails, i.e. containing larger fractions of bones) are significantly larger than those of herring flesh. Samples of flesh of flat fish also suffer from increased bone fractions leading to slightly larger ^{90}Sr activities.

The radionuclides ^{239,240}Pu and ^{241}Am exhibit maximum activity values which are even one to two orders of magnitude lower than those of ^{90}Sr; so, they do not have any significance with respect to the dose accumulated by fish consumption.

The radionuclide which is the most important with respect to dose by fish consumption is the alpha-emitting ^{210}Po belonging to the naturally-occurring radionuclides. The activity values of 122 samples of fish flesh which were collected in the Kattegat and the Bornholm Sea since 1990 have been summarised in the Appendix. Maximum values, between 1.49 Bq kg^{-1} wet weight and 8.50 Bq kg^{-1} wet weight, were slightly different between the three species considered in these measurements. The average of the three median values is about 0.65 Bq kg^{-1} wet weight. These values listed in **Table 3.3.1** are comparable to a former evaluation of ^{210}Po in fish from Danish waters including the North Sea (Dahlgaard, 1996), in which average values of 0.35 Bq kg^{-1} wet weight, 0.65 Bq kg^{-1} wet weight and 0.96 Bq kg^{-1} wet weight were observed for cod, herring and plaice fillets, respectively. Other natural radionuclides like ^{40}K and ^{226}Ra show small deviations in their specific activity between years, but are more characteristic for fish species (see **Figures 3.3.5** and **3.3.6**).

Table 3.3.1.
Activity values of the naturally occurring alpha emitting radionuclide ^{210}Po in Baltic Sea fish (flesh), in Bq kg^{-1} wet weight (1990-2015)

Species	Number of samples	^{210}Po			
		min.	max.	mean	median
Herring	39	0.19	8.50	1.30	0.78
Cod	41	0.04	1.49	0.38	0.29
Flounder	42	0.26	3.37	1.06	0.90

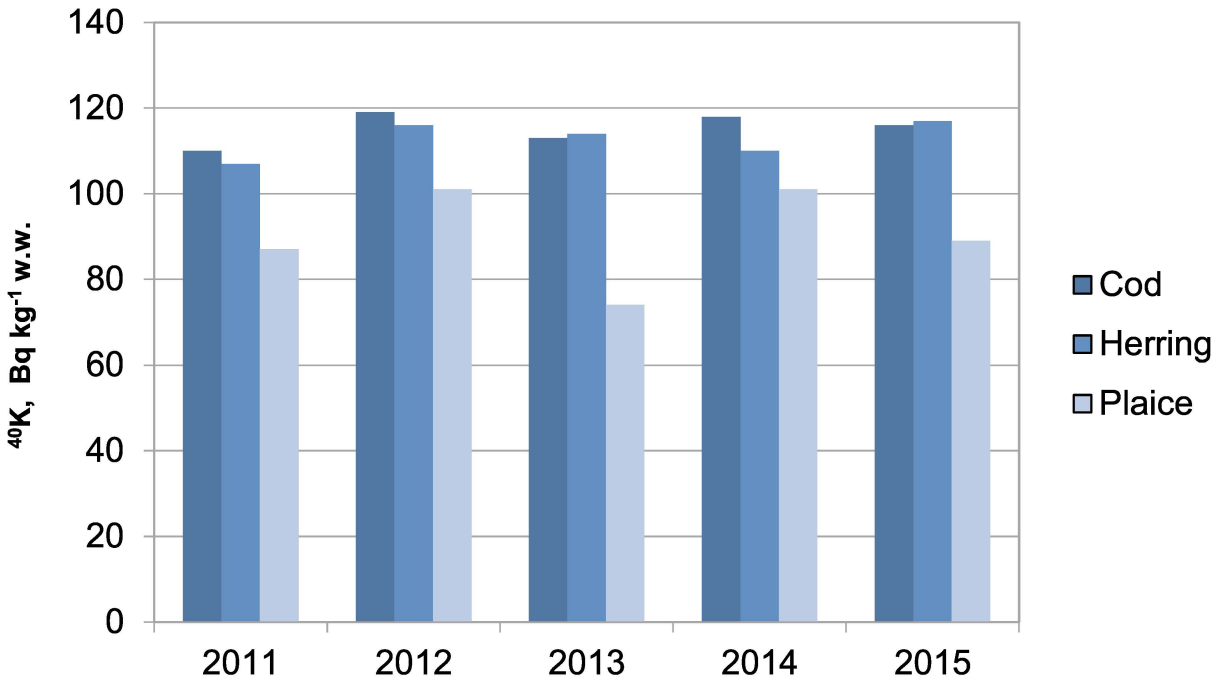


Figure 3.3.5.
Specific ^{40}K activity in fish muscle collected in the southern Baltic Sea in 2011-2015

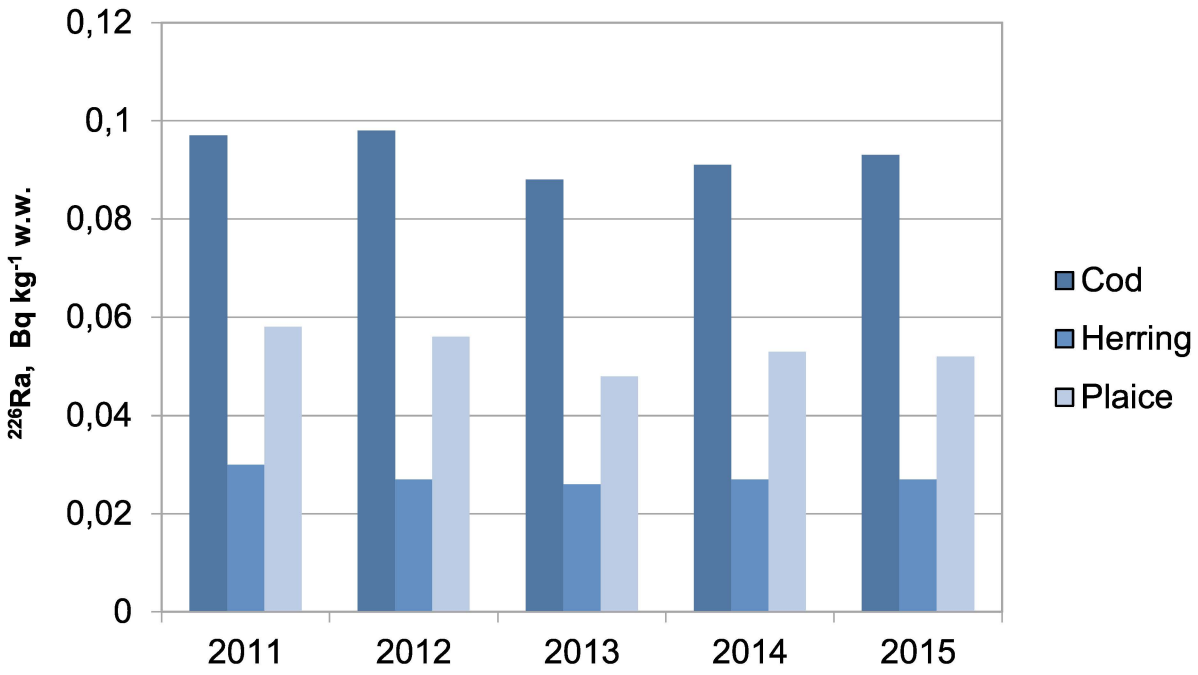


Figure 3.3.6.
Specific ^{226}Ra activity concentrations in fish muscle collected in the southern Baltic Sea in 2011-2015

^{137}Cs in macrophytobentic organisms

Bladderwrack, *Fucus vesiculosus*, is accumulating various radionuclides (IAEA 2004) to such an extent that these are good measurable, especially some gamma-emitting radionuclides. At the present *F. vesiculosus* can be sampled only in some of the Baltic Sea areas. ^{137}Cs in *F. vesiculosus* has been monitored since 1984 in many of the HELCOM sub-basins. The ^{137}Cs values in *Fucus vesiculosus* continued to decrease slightly after 2011. By the end of this period (2015), specific activity of *F. vesiculosus* approached values of 2 Bq kg^{-1} dry weight in the west (Kattegat) and about 20 Bq kg^{-1} dry weight in the eastern and northern basins (Baltic Sea east and west, Bothnian Bay, Gulfs of Riga and Finland).

Concentration factors

The concentration factor (CF), calculated as a ratio of the radionuclide activity concentrations in biota to those in seawater, can be regarded as a measure of bioaccumulation efficiency. It can be used as the simplest approximation to a food chain sub-model. It is generally used in emergency cases to predict the behaviour of radionuclides in the environment. The derived CFs are specific for each HELCOM sub-basin and may only safely be used in the case of a quasi-stationary state of the seawater activity concentration level.

This is due to the freshwater input to Baltic seawater, which is characteristic for each sub-basin and prohibits the use of the generic marine biota CFs as recommended by IAEA (1985 and 2004). Therefore, species and radionuclide dependent CF values have been estimated in earlier work of the MORS EG group (HELCOM 1995) and adapted to the present situation. More recently (HELCOM 2009), the influence on some values by non-stationary conditions, during the first few years after the Chernobyl accident, could be down-weighted by adding CF values from the more recent years.

A repeated evaluation of CF values up to 2015 did not reveal significant deviations from the previous assessments when variation inside the individual regions is taken into account.

For marine fish species, the CF values for ^{137}Cs increase from less than or around 100 in the western Baltic Sea areas, to about 160 in the south/eastern areas, to about 200-240 in the northern areas.

Conclusions

Within the current assessment period the Chernobyl-derived ^{137}Cs continued to be the most dominant man-made radionuclide in Baltic Sea fish regarding activity concentrations. By the end of this period (2015), mean values in various Baltic Sea basins were:

a) between 0.3 Bq kg^{-1} wet weight and about 8 Bq kg^{-1} wet weight were found in the group of marine round fish (cod, herring, whiting);
b) between 0.2 Bq kg^{-1} wet weight and 5 Bq kg^{-1} wet weight in marine flat fish (plaice, flounder, dab), i.e. slightly lower mean values for the (marine) round fish.

Baltic Sea basin specific concentration factors of ^{137}Cs, which had been evaluated within the previous assessment for fish and bladderwrack, *Fucus vesiculosus*, have been confirmed by extending this evaluation to 2015 to within the associated standard uncertainties. They were based on seawater and biota data of the MORS-PRO Group from the years 1988/1990 until 2015.

3.4. ^{137}Cs in fish and surface seawater – radioactivity core indicator for environmental status assessment

Tamara Zalewska

At present, environmental protection and the specific measures to improve its condition and to preserve it in the least altered form are of increasing public interest. As a result the HELCOM Baltic Sea Action Plan (the first regional programme in the world concerning protection of marine environment) and the Marine Strategy Framework Directive (Directive 2008/56/EC) were set in order to evaluate, and if needed re-establish healthy marine ecosystem that is free of negative inputs. In order to assess the status of the Baltic Sea marine environment on a regular basis, a critical set of 'core indicators' and their target values have been established. With respect to hazardous substances, radioactivity is one of the key elements influencing the final status of the environment with respect to hazardous substances, and therefore ^{137}Cs in fish and surface seawater was established as a core indicator for radioactive substances.

Data on the current concentration of ^{137}Cs in selected matrices (fish and seawater) related to the threshold values allow an assessment of the state of marine areas in terms of contamination by radioactive substances.

The threshold values defining the boundary between the good status and inadequate environmental conditions are based on reference conditions. Good status is achieved when the activity concentration of the radionuclides is below 2.5 Bq kg^{-1} for herring, 2.9 Bq kg^{-1} for flounder and plaice and 15 Bq m^{-3} for seawater which corresponds to pre-Chernobyl levels, in other words the levels that were measured before 1984. The confidence of the target values is considered to be high, as there are numerous observations from pre-Chernobyl time though the length of this time series is short (1984-1985).

Based on data from 2011-2015, good status for ^{137}Cs in herring is not achieved in most of the HELCOM sub-basins, except for the Arkona Basin, Bay of Mecklenburg, Kiel Bay and Kattegat (**Fig. 3.4.1**). For flatfish, good status is not achieved in the Eastern Gotland Basin, Gdańsk Basin and Bornholm Basin, while ^{137}Cs concentrations below the threshold values were found in the Arkona Basin, Kiel Bay and Kattegat. For surface seawaters, good status is not achieved in any of the HELCOM sub-basins.

The Baltic Sea radioactivity assessment based on ^{137}Cs in fish and seawater core indicator covering period 2011-2015 will be a part of the HELCOM holistic assessment on the ecosystem health of the Baltic Sea covering the period 2011-2016.

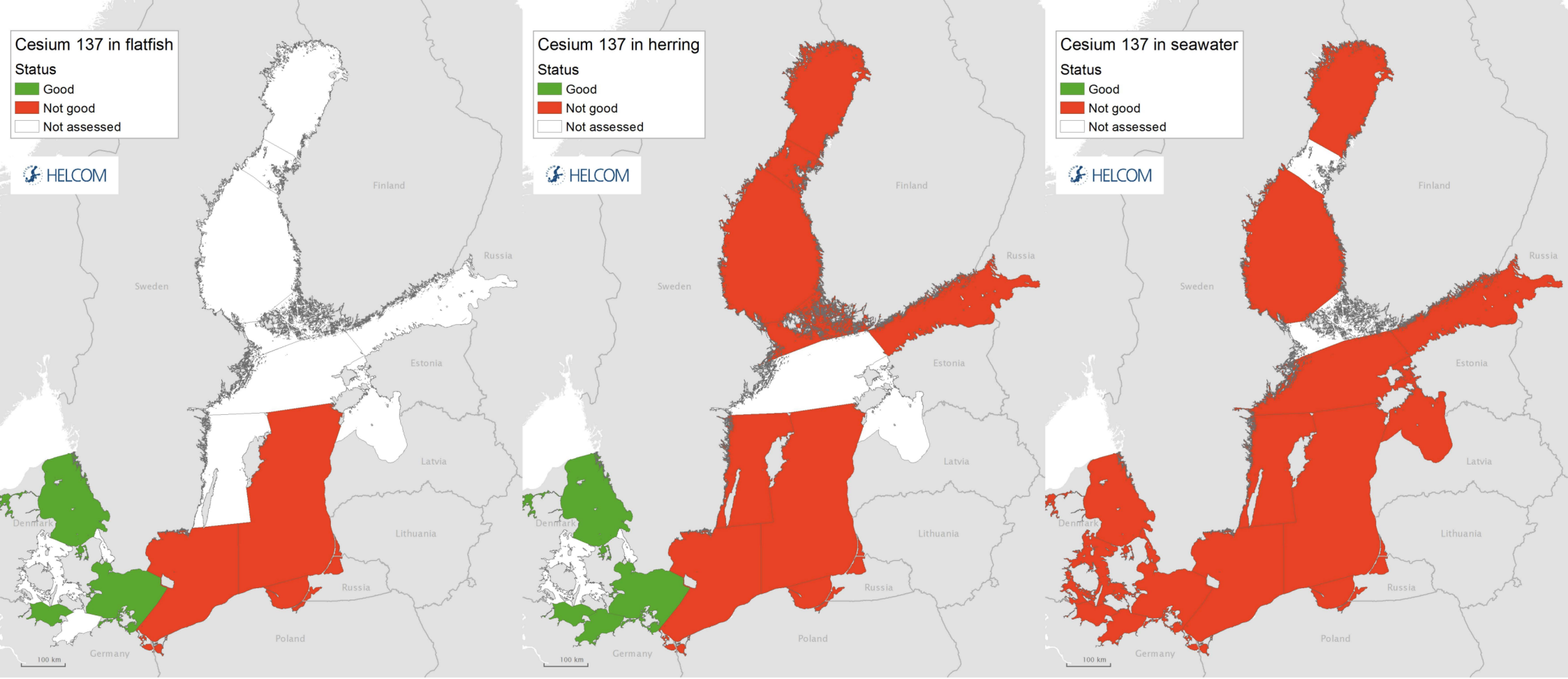


Fig. 3.4.1.
Radioactivity status assessment regarding ^{137}Cs concentrations in herring, flatfish and surface seawater; good status=green, not good status=red.

4. Modelling and Dose Calculations

Model simulations of radionuclides in the Baltic Sea and assessments of radiation doses to humans covering the years 1950-2006 are described in previous HELCOM reports (1995, 2003, 2009 and 2013). The assessments include the impact of radioactive fallout from the Chernobyl accident in 1986. No significant input of man-made radioactivity to the Baltic Sea has occurred since then, and concentrations of radionuclides, especially of ^{137}Cs, in water and biota have continued to decrease (see Chapter 3). Fallout from the Fukushima accident in Japan in 2011 was low in Europe and no contribution was observed in marine samples from the Baltic Sea (Kanisch and Aust 2013). Therefore, the impact from Fukushima fallout in the Baltic Sea area has been negligible and it has not been important to repeat model calculations.

4.1. Modelling

Sven P. Nielsen

Model calculations of radionuclides in the Baltic Sea have been made in connection with activities organised by the Nordic Nuclear Safety Research (NKS). The COSEMA study covers consequences of severe radioactive releases to Nordic marine environment (Iosjpe et al. 2013; Iosjpe et al. 2014) and the EFMARE study covers effects of dynamic behaviour of Nordic marine environment to radio-ecological assessments (Halldorsson et al. 2015; Iosjpe et al. 2016).

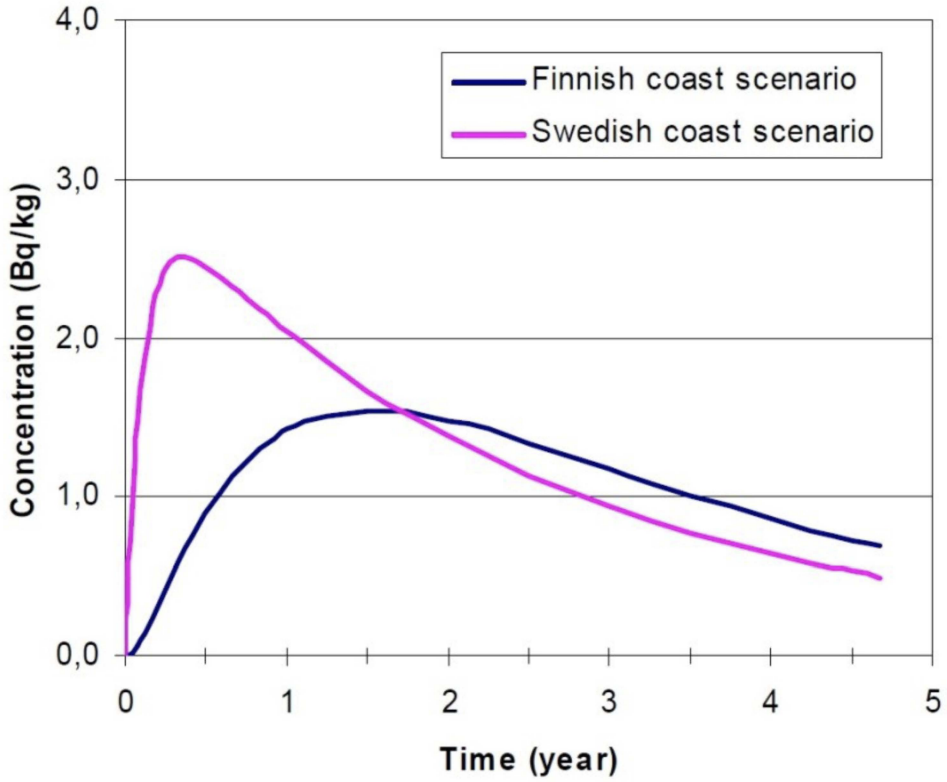


Figure 4.1.1.
COSEMA comparison of estimated ^{137}Cs concentrations in the Baltic Sea water between the 'Finnish coast' and the 'Swedish coast' release scenarios (Iosjpe et al. 2014).

COSEMA assumed reference releases of radionuclides to the Baltic Sea due to hypothetical severe accidents in nuclear power plants. Two scenarios were considered: Release from the Finnish coast and release from the Swedish coast; calculations were carried out with the DETRA-code. Individual doses to humans could be from tens to hundreds of millisieverts in local sea areas. In the Baltic Sea area the maximum individual dose rate was 0.02 mSv year^{-1} from the release event. The collective dose estimate was 880 manSv. A comparison of predicted concentrations of ^{137}Cs in seawater from the two release scenarios is shown in **Fig. 4.1.1**, and **Fig. 4.1.2** shows estimated dose rates in the Baltic Sea area from consumption of fish and external radiation.

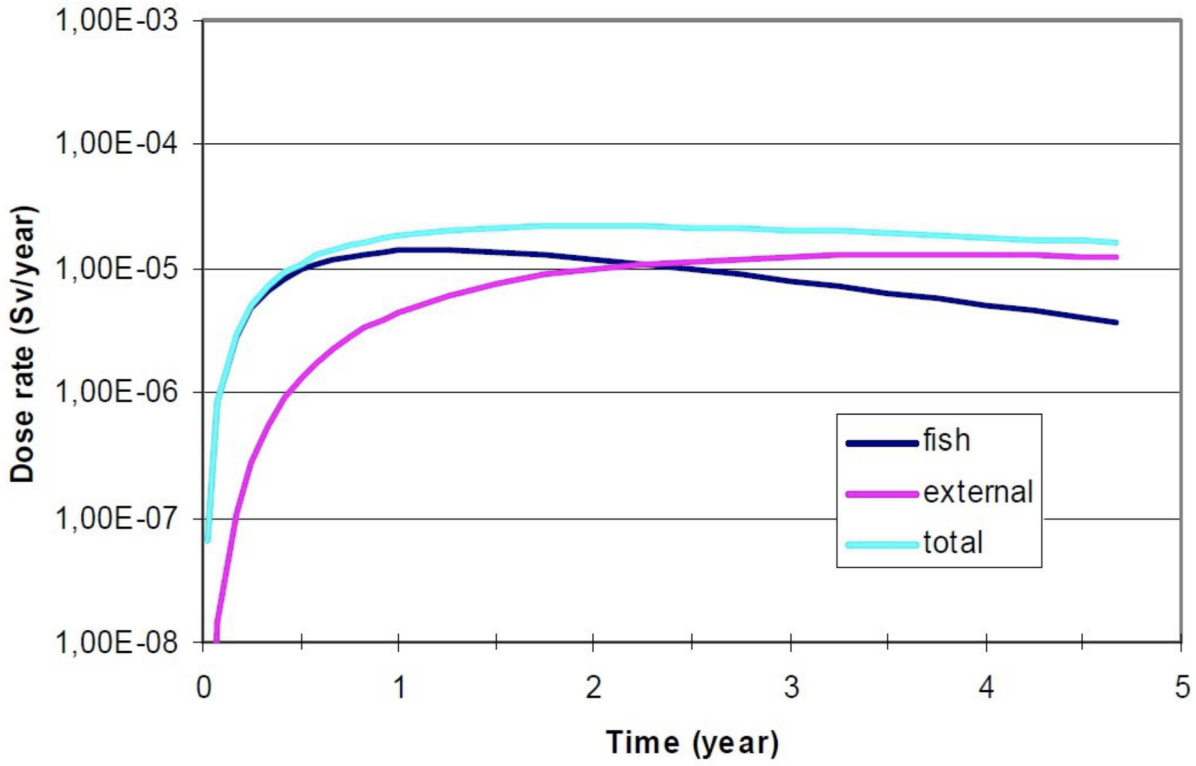


Figure 4.1.2.
COSEMA estimated individual dose rates from consumption of fish and from external exposure from shoreline sediments as well as total dose rate after a hypothetical severe nuclear power plant accident in the Baltic Sea area (Iosjpe et al. 2014).

The Goals of EFFMARE covered an analyses of consequences of radioactive releases into the marine environment, with special attention to the effects of the dynamic behaviour of the Nordic seas and development and implementation of bioaccumulation processes into models. The models used were the DETRA-code and the NRPA box model. Implementation of kinetic bioaccumulation processes demonstrated significant difference between kinetic modelling and use of constant concentration factors. A comparison between seawater concentrations of ^{137}Cs in the Gulf of Finland predicted with the NRPA box model and environmental data shows that the model predictions are reasonably accurate (**Fig. 4.1.3**). Concentrations calculated with the DETRA-code of ^{137}Cs in fish from the Gulf of Finland after a hypothetical release of 10 PBq to the sea are shown in **Fig. 4.1.4.** The fish categories considered are prey and predatory fish (small perch of size 15-20 g, medium perch of size 25-100 g and pike).

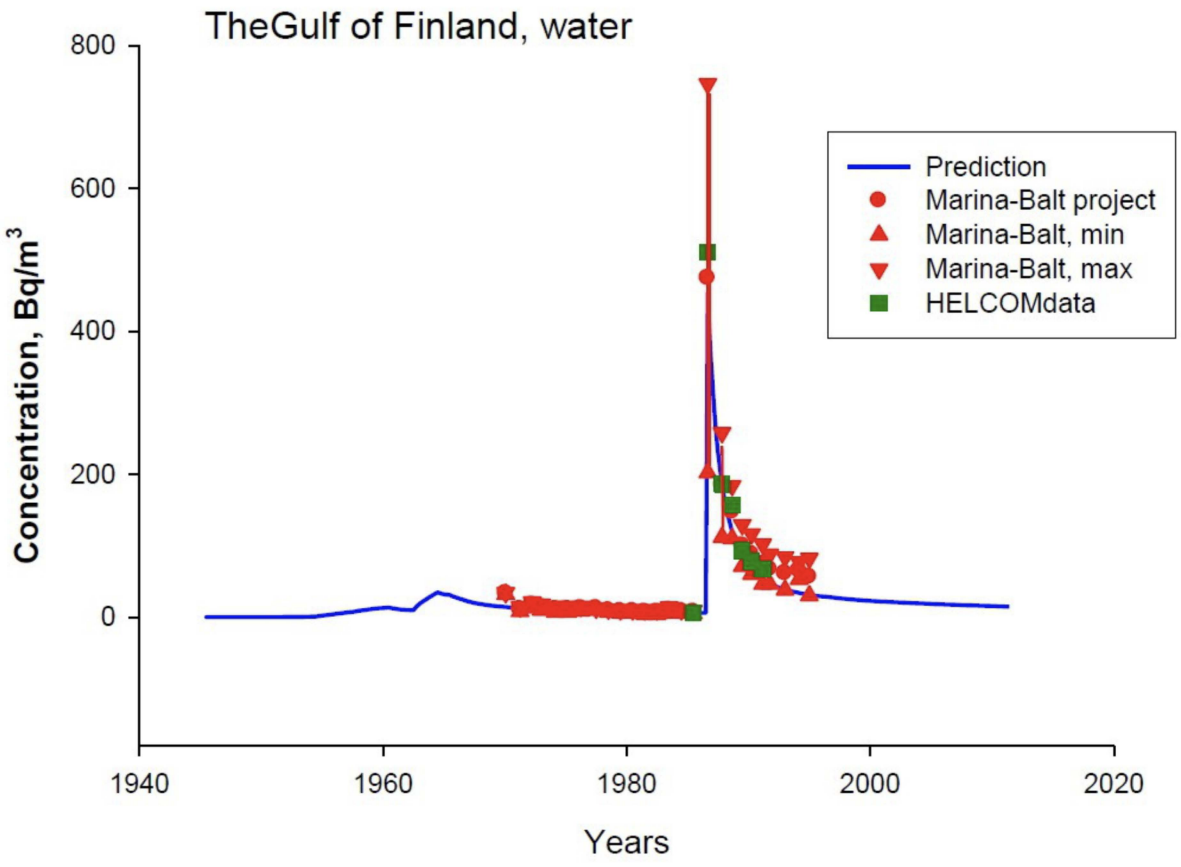


Figure 4.1.3.
Comparison between seawater concentrations of Cs-137 in the Gulf of Finland predicted with the NRPA box model and environmental data (Iosjpe et al, 2016).

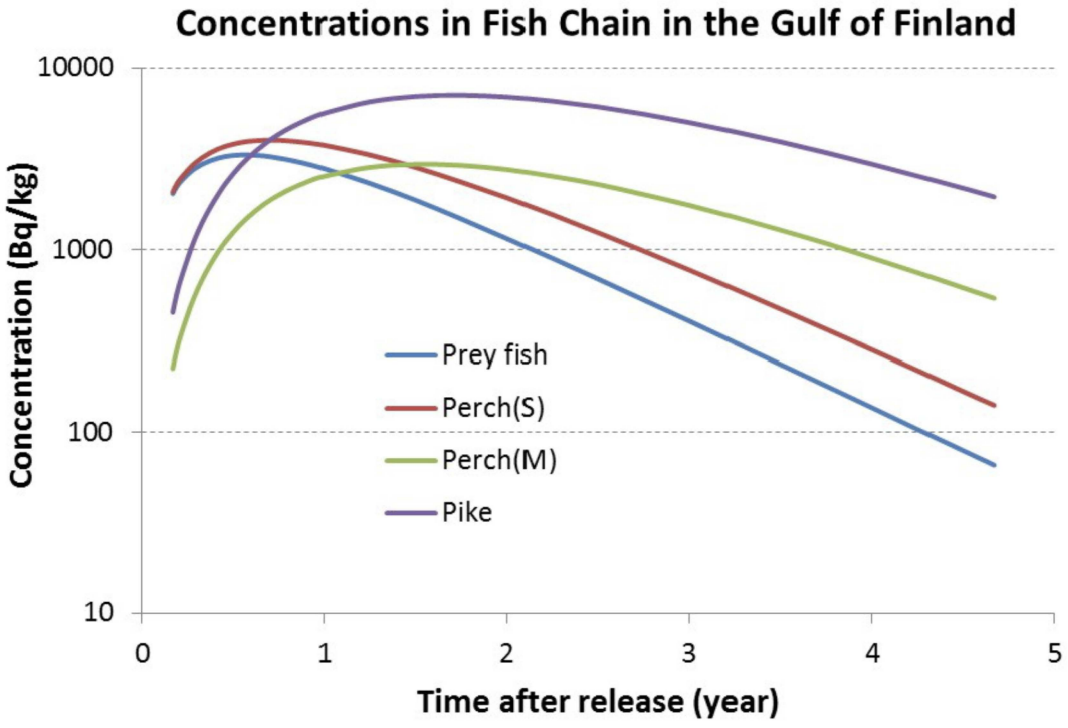


Figure 4.1.4.
Concentrations of ^{137}Cs in fish after a hypothetical release of 10 PBq to the Gulf of Finland calculated with the DETRA-code (Iosjpe et al, 2016).

4.2. Dose calculations

Sven P. Nielsen

Estimates of radiation doses until the year 2000 to human individuals and populations from radioactivity in the Baltic Sea were made by the MORS Group in HELCOM (2003). The estimates were based on model calculations and included a range of exposure pathways including ingestion of fish, crustaceans and molluscs, inhalation and external exposure. Doses to individuals were based on human habits assumed to be characteristic for a critical group expected to receive the largest radiation dose. The dominating exposure was found to be due to ^{137}Cs and ingestion of fish.

The concentrations of the dominating man-made radionuclides in the Baltic Sea, ^{90}Sr and ^{137}Cs, have been declining since 2000. Only minor amounts of the man-made radionuclides ^{99}Tc and ^{129}I discharged from the European reprocessing facilities at Sellafield and La Hague show increasing trends in Baltic seawater, but these are insignificant in terms of radiation dose to man.

For the reporting period covered by the present report we estimate an upper bound for individual doses from man-made radionuclides in the Baltic Sea. During 2011-2015 the concentrations of ^{137}Cs in fish from the Baltic Sea have been below 8 Bq kg^{-1}. For an individual having a high-rate consumption of 90 kg fish per year this concentration corresponds to an annual radiation dose of about 10 µSv. This dose is well below the limit of the annual radiation dose to a member of the public of 1000 µSv (IAEA, 2014). The corresponding annual dose from naturally occurring radionuclides in fish is about 100 µSv of which the dominating contribution is from ^{210}Po.

4.3. Assessment of doses to biota

Beata Vilimaite-Silobritiene

Introduction

In recent years, much effort has been directed internationally to the development of the scientific basis for the protection of biota against ionising radiation and the related risk assessment. International bodies essential in the development of the radiological criteria or standards for the protection of non-human species have carried out a lot of work in this field (ICRP 2003, 2007, 2008, 2009; Pröhl et al. 2011; UNSCEAR 2011). In the draft version of EU Basic Safety Standards (Draft European Basic Safety Standards Directive, 2010) requirements and recommendations for safety and protection of non-human species or the total environment were introduced. However, in the most recently issued document these requirements were omitted, only the requirements on ensuring that an appropriate environmental monitoring programme in place was left in the document (Council Directive 2013/59/Euratom). In the Directive, Environmental monitoring is defined as the measurement of external dose rates due to radioactive substances present in the environment or of concentrations of radionuclides in different environmental media.

Recommendations on protection of non-human species are presented in the International Atomic Energy Agency (IAEA) safety standard No. GSR Part 3 (2014), in which the definition "protection of the environment" includes the protection and conservation of non-human species, both animal and plant, and their biodiversity. IAEA continues its work in the field of environmental impact assessments with such projects as MODARIA and MODARIA II.

The potential harmful effects of radiation to biota include increased mortality and reduced reproductive success of a population. These effects are addressed in environmental risk assessment methods, whereas factors such as variation in radiosensitivity between individuals, interactions between species and adaptation of populations to radiation exposure are omitted due to inadequate scientific knowledge. Furthermore, possible effects of other contaminants on doses are still excluded in current risk assessment methods.

A variety of tools have been developed to enable the assessment of doses and risk caused by ionizing radiation to biota. We have used the ERICA Assessment Tool (Brown et al. 2008) in this study. Intercomparisons of different tools have revealed a wide variability of the results, mainly generated by using default transfer coefficients provided by the tools instead of using site-specific data on activity concentrations (e.g. Beresford et al. 2008; Vives I Batlle et al. 2007, 2011; Yankovich et al. 2010). Therefore, we have used measured activity concentrations in biota and in different environmental media to obtain more accurate estimations of dose rates to biota.

Material and methods

The description of data on average activity concentrations of ^{137}Cs, ^{40}K, ^{90}Sr, ^{210}Po, ^{210}Pb, $^{(239+240)}Pu$ in surface water, sediment and biota currently in the Gulf of Finland and in the Bothnian Sea have been given in Outola et al. (2011). The species considered were seaweed *(Fucus vesiculosus)*, fish (*Esox lucius*) and bottom living crustacean *(Saduria entomon)*. Activities of radionuclides in different environmental media that are used for calculation of exposure insignificantly decreased during the period 2011-2015 compared with the earlier period 2006-2010, so a new evaluation was not carried out for the Gulf of Finland and the Bothnian Sea. The graphs of the evaluation are presented in **Fig. 4.3.1.**

However, a new evaluation of exposure was carried out for the Southern Baltic Proper. The average activity concentrations of ^{137}Cs, ^{40}K, ^{90}Sr in surface water, sediment and biota from the HELCOM-MORS database were used. The species considered for this part of the sea included seaweed *(Furcellaria lumbricalis)* and three types of fish *(Platichthys flesus, Gadus morhua, Clupea harengus)*.

The use of the ERICA Assessment Tool to calculate dose rates to biota has been described in Outola et al. (2011). The same method was used for evaluation of dose rates for biota in the Southern Baltic Proper. Additionally, for evaluation of possible differences due to the size of the organism – fish, new organisms with real sizes (taken from HELCOM MORS database) were created and dose evaluation was done for them. The difference between benthic fish from the Erica database and *Platischthys flesus* from the Southern Baltic Proper was found (1.31 kg versus 0.4 kg) while the size of pelagic fish is very close to *Gadus morhua*, but strongly differs from *Clupea harengus* (0.565 kg, 0.603 kg and 0.04 kg, respectively).

Currently, there are no internationally agreed, legally binding criteria or standards for dose rates to biota that must be met in accordance with regulation. Several dose rate values have been suggested to be used as a screening value, which means that if this value is exceeded further investigation is needed to better understand and quantify the risk. In this assessment, the screening value 10 μGy h^{-1} was used. The derivation of this value is based on examination of the available data on dose-effect relationships for various organisms obtained in laboratory or field experiments, and has been presented in Andersson et al. (2009) and Garnier-Laplace et al. (2008). The total (internal and external summed) dose rates estimated are compared directly to the selected screening dose rate to enable the assessment of risk to biota.

Results and discussion

In the Gulf of Finland and in the Bothnian Sea the total dose rate from all previously studied artificial radionuclides combined (^{137}Cs, ^{90}Sr, $^{(239+240)}Pu$) was 0.002 – 0.1 μGy h^{-1} and was dominated by ^{137}Cs (**Fig 4.3.1**). The lowest dose rates were to fish and the highest to sediment-associated organisms (Outola et al. 2011).

The doses to biota were mainly dominated by the natural radionuclide ^{210}Po. The contribution of ^{137}Cs to the dose was generally less than one tenth of the proportion of ^{210}Po. The dose rates from ^{40}K were in the same order as those from ^{137}Cs, except for pelagic fish where the dose rates from ^{40}K were ten times higher than those from ^{137}Cs. The contribution from the other evaluated radionuclides (^{90}Sr, $^{(239+240)}Pu$ and ^{210}Pb) to the total dose were of minor importance (Outola et al. 2011).

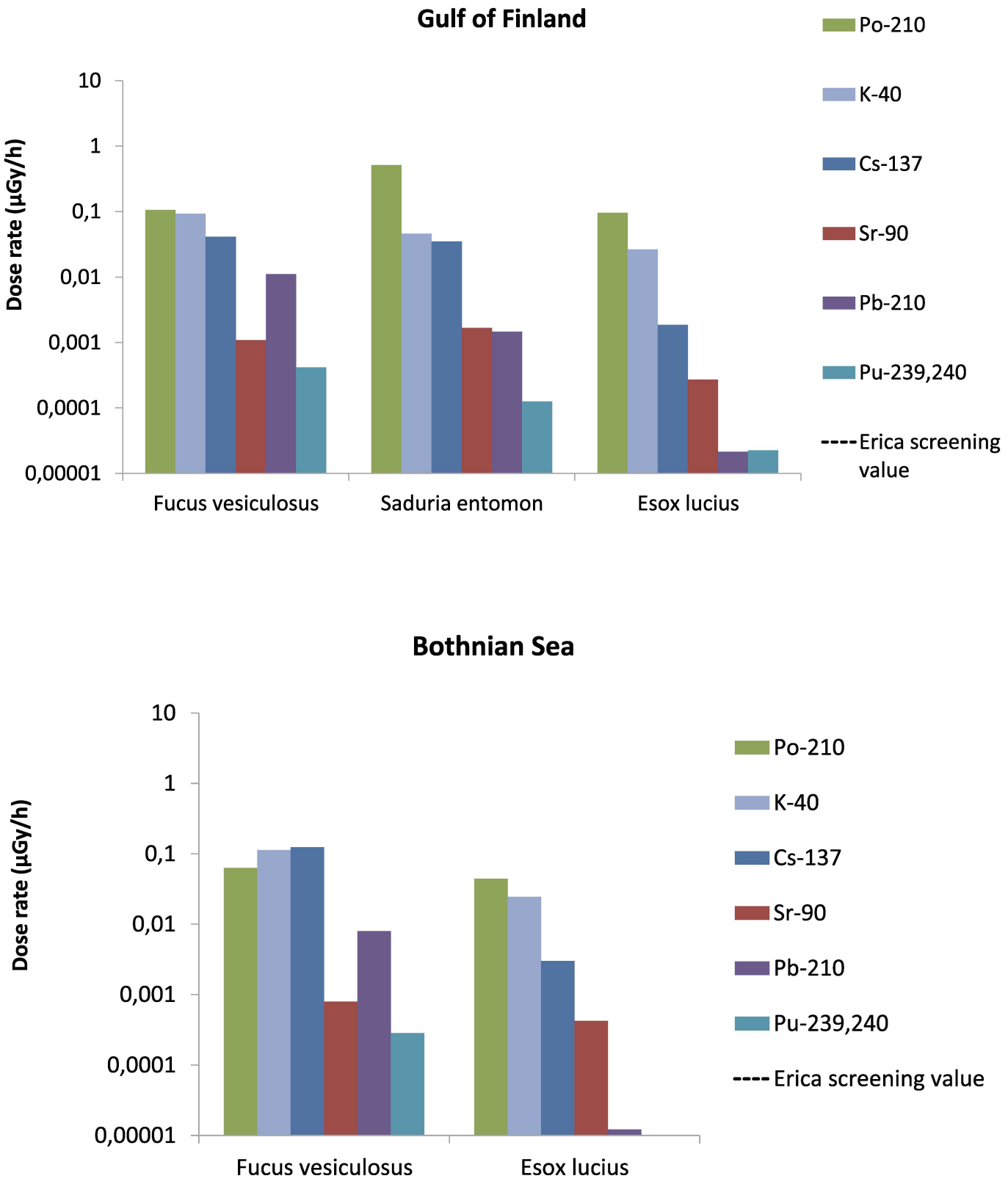


Fig 4.3.1.
Dose rates (µGy h^{-1}) from various radionuclides to biota in the Baltic Sea during 2006-2010 (Baltic Sea Environment Proceedings No. 135)

Similar results were obtained for the Southern Baltic Proper (**Fig. 4.3.2**). Here the lowest dose rates were to pelagic fish and the highest to seaweed. The reason for that difference is that there are higher activities of radionuclides in bottom sediments. It is also assumed that these species spend all their time in contact with the bottom sediments.

For all the analysed species the dose rates from ^{40}K were 3.5-60 times higher than those from ^{137}Cs. The contribution from ^{90}Sr to the total dose was negligible. Results received for the benthic fish originally created in Erica were similar to those calculated for *Platichtys flesus*. No large differences were observed for the pelagic fish, *Gadus morhua* and *Clupea harengus*).

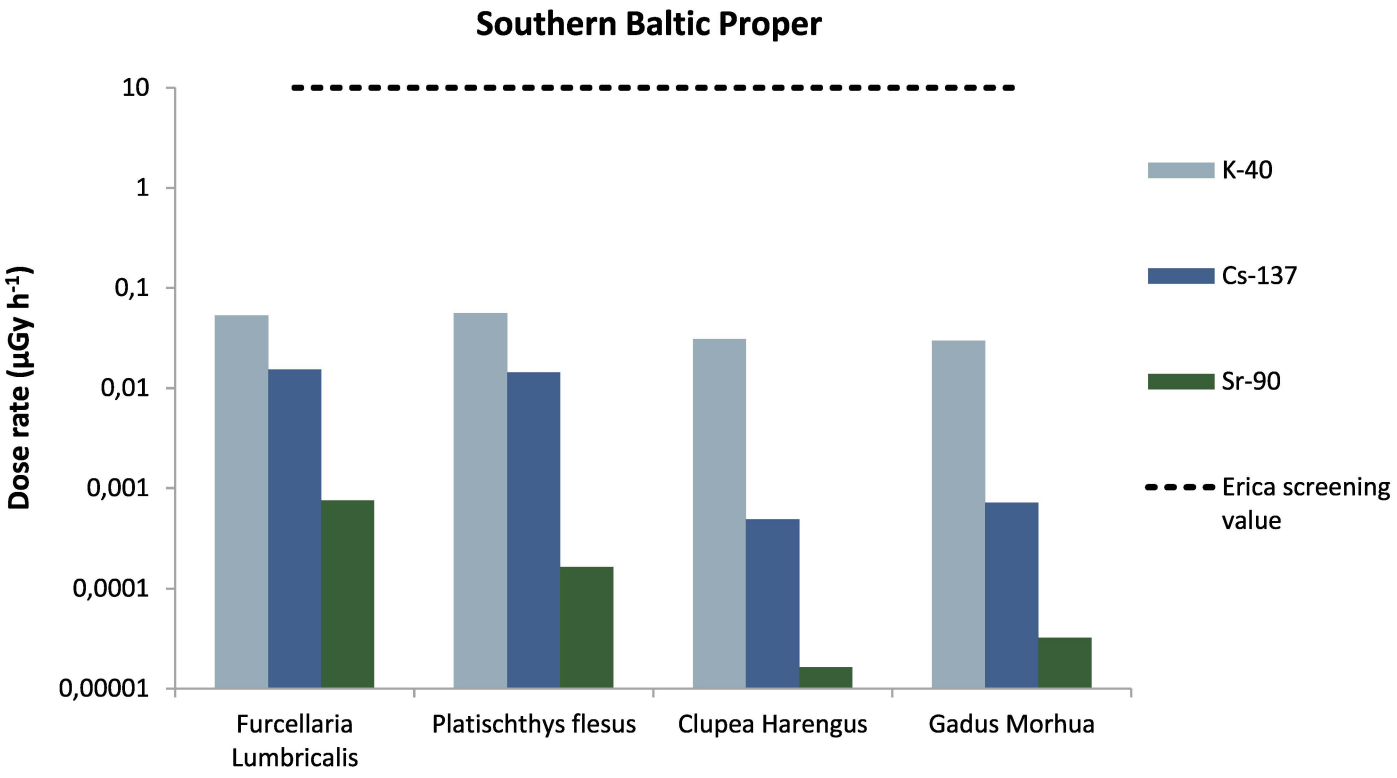


Fig 4.3.2.
Dose rates (µGy h^{-1}) from various radionuclides to biota in the Baltic Sea Southern Baltic Proper during 2011-2015

Conclusions

The dose rates from the evaluated radionuclides were clearly below the screening level of 10 µGy h^{-1}. The main contribution to the dose rate originate from naturally occurring radionuclides, only except in the Bothnian Sea where the main contributor the dose rate to *Fucus vesiculosus* is ^{137}Cs. This can easily be explained by high activities of ^{137}Cs that are present in this part of the Baltic Sea. The average activity of ^{137}Cs in the Bothnian Sea is several times higher than in the Southern Baltic Proper.

Therefore, the biological effects of ionising radiation on biota can be considered to be negligible in the current radiation situation. According to the present risk assessment methodology, the level of protection of biota against ionising radiation is adequate in the Baltic Sea.

5. Radioactivity in the Baltic Sea compared to other marine regions (including impacts of Fukushima)

Iolanda Osvath

The period covered by this thematic assessment was marked by the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident, which followed the major Tohoku earthquake and tsunami that devastated the north-eastern coast of Honshu, Japan on 11 March 2011. The FDNPP accident resulted in a massive radioactive release to the coastal environment, which was then further dispersed and diluted throughout the Northern Pacific. Release to the atmosphere and subsequent deposition on the ocean surface was the primary pathway of contamination of the marine environment, with notably ^{137}Cs, ^{134}Cs and ^{131}I (IAEA 2015b). Additional lesser amounts of radionuclides entered the coastal ocean through direct liquid releases, including unintentional releases of contaminated water, controlled discharges and groundwater, and through river input and runoff from land. These have been following a decreasing trend since the accident due essentially to the measures set in place by TEPCO (*http://www.tepco.co.jp/en/nu/fukushima-np/roadmap/conference-e.html*). It was estimated that the total ^{137}Cs activity entering the North Pacific was around 15 - 18 PBq (Aoyama, Mizuo et al. 2016), which is about 1.5-2 times more than the ^{137}Cs input from the Chernobyl accident to the Baltic, Black and Mediterranean Seas together (HELCOM 2009), diluted however in a much larger volume. Besides the radionuclides mentioned above, ^{3}H, ^{90}Sr, 110mAg and ^{129}I were reported to be measured in the marine environment. In addition, traces of short-lived radionuclides, such as ^{132}I, ^{132}Te, ^{136}Cs were detected in seawater nearshore FNDPP in the first few weeks after the accident (IAEA 2015b; *http://radioactivity.nsr.go.jp/en/*).

Japan has set in place an intensive monitoring programme for marine environmental radioactivity, including seawater, sediment and biota, continuously operated since 2011. The monitoring programme focuses on gross measurements and ^{3}H, ^{134}Cs, ^{137}Cs, ^{90}Sr and Pu isotopes at locations up to 20 km offshore and ^{134}Cs, ^{137}Cs up to about 300 km offshore FDNPP. The ^{137}Cs in seawater in the immediate proximity to FDNPP discharge points reached very high levels in the days and weeks following the accident (**Figure 5.1**), decreasing however steeply over the first month after the accident and with distance from the shore, such that levels measured in surface seawater 30 km offshore were around 1000 times less than those at the FNDPP release points (*http://radioactivity.nsr.go.jp/en/*). The decreasing time trend showed occasional punctual minor increases because of hydro-meteorological events, such as storms and precipitation, which have led to increased resuspension of sediments in the coastal area, increased runoff from land or submarine groundwater discharge.

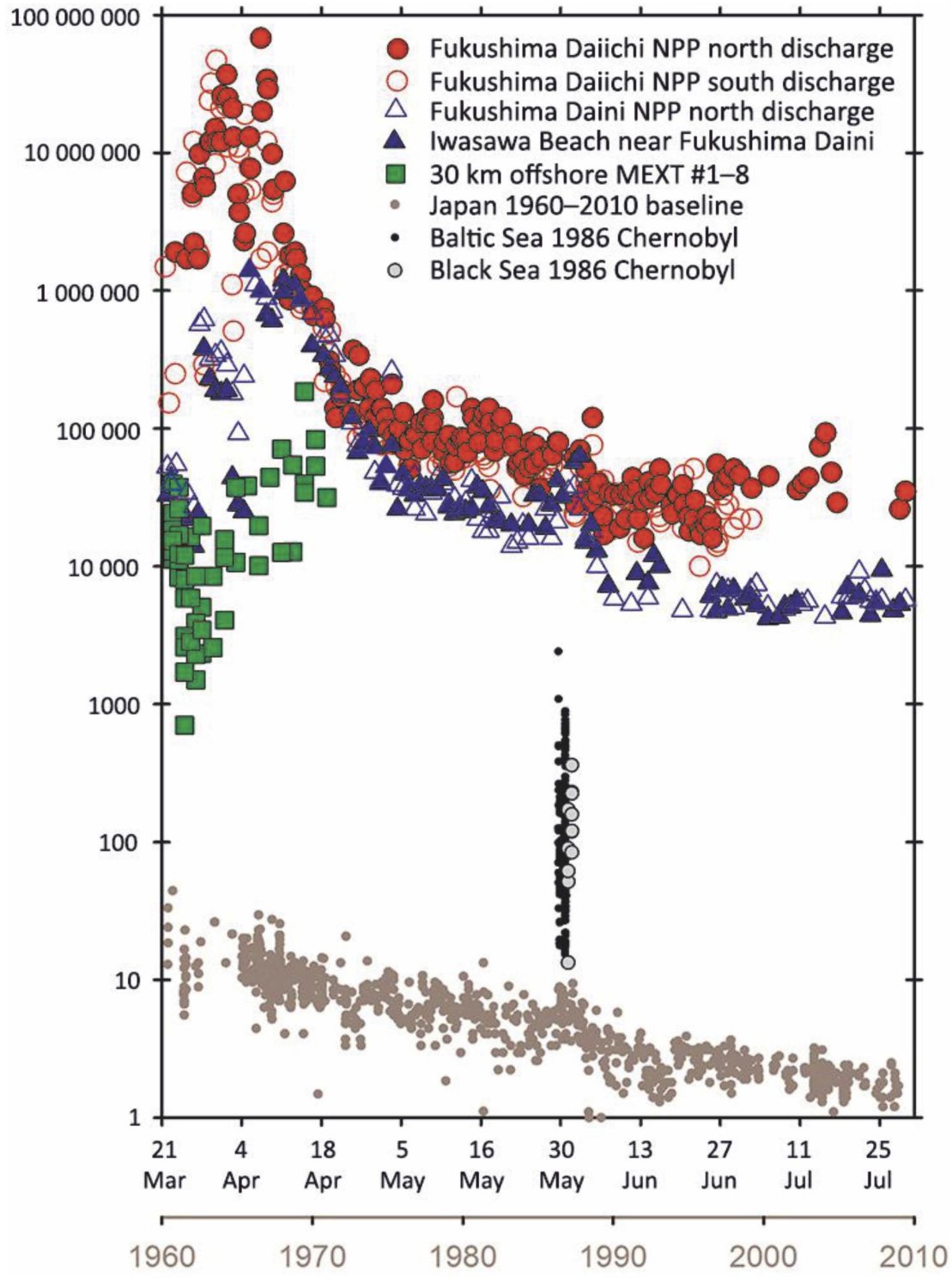


Figure 5.1.
Surface seawater concentrations of ^{137}Cs (Bq m^{-3}) between 21 March and 31 July 2011 for locations near Fukushima Daiichi NPP and Fukushima Daiini NPP discharges, Iwasawa beach near Fukushima Daiini NPP and 30 km offshore. For comparison, the lower part of the graph shows the variation between 1960-2010 of ^{137}Cs concentrations offshore the eastern coast of Japan and levels in the Black and Baltic Seas in 1986 after the Chernobyl accident (from Buesseler et al. 2011).

Based on numerous sampling campaigns in the months and years following the accident (Aoyama, Hamajima et al. 2016, Buesseler et al, 2017), the progression of the Fukushima signal could be traced across the Pacific. Due to the low-level counting capabilities used, the Fukushima footprint, indicated by the presence of ^{134}Cs and its ratio to ^{137}Cs, could be detected in migratory fish caught off California in August 2011 (Madigan et al. 2012) and the arrival of the Fukushima-origin radiocaesium in North American continental waters could be timed between June 2012 and June 2013 (Smith et al. 2015). The level of ^{137}Cs measured in Pacific bluefin tuna caught off the coast of California in August 2011, 6.0±1.5 Bq m^{-3}, were very similar to those measured in cod caught in the Bornholm basin in the period 2011-2015 (this report). The presence of ^{134}Cs in those samples showed that the respective fish had spent time in waters close to the coast of Japan, however the total radiocaesium ^{134}Cs + ^{137}Cs level of 10.6 ± 2.9 Bq kg^{-1} wet weight was far below any regulatory limits for radiocaesium in food (e.g. 1,250 Bq kg^{-1} wet weight for the European Union, 100 Bq kg^{-1} wet weight for Japan). The same fish contained around 370 Bq kg^{-1} wet weight natural ^{40}K, as compared to 70-120 Bq kg^{-1} wet weight in Baltic Sea fish (cod, herring and plaice) analysed in 2011-2015 (this report), the difference reflecting species, seawater salinity and environmental conditions specificities. Much higher levels of radiocaesium were measured in fish caught inside the Fukushima harbour (on-site FNDPP) and in demersal fish close to the Fukushima coast (Wada et al, 2016; Buesseler et al. 2017), and strict controls and fishing bans were set in place by the Japanese authorities (*http://www.mofa.go.-jp/files/000031595.pdf*).

Although atmospheric radioactivity monitoring programmes in Europe could detect releases from FDNPP, reporting very small increases in levels of ^{137}Cs, ^{134}Cs and ^{131}I (Masson et al. 2011, de Vismes Ott 2013) no increase could be detected in the marine environment neither in the Baltic Sea (this report) nor in the other European Seas. While inventories up to 100,000 Bq m^{-2} were reported for ^{137}Cs in bottom sediments in the proximity of FDNPP, profiles and inventories in the Baltic Sea bottom sediments (this report) showed no trace of any Fukushima impact. Traces of ^{134}Cs and slightly elevated levels of ^{137}Cs were reported in sediment in Amchitka, some 3,000 km north-east from FDNPP (USDOE 2013). The extensive marine monitoring around the coasts of Korea initiated a few days after the FDNPP accident in 2011 (Kim, C.-K. et al. 2012) did not evidence ^{134}Cs neither in seawater nor in fish or shellfish. ^{131}I, which was measured in atmospheric samples throughout Korea, was reported only for seaweed samples collected at the south-eastern coast, about 1,000 km south-west from Fukushima, end April-May 2011. The comparison between this area and the Baltic Sea, situated some 8,000 km away from FDNPP, shows that levels of ^{137}Cs in marine samples collected off the coast of Korea after the FDNPP accident are typically lower than those in the Baltic Sea, where a contribution from Fukushima was not measurable. In Korea ^{137}Cs was not detectable in seaweed (below 0.1 Bq kg^{-1} wet weight), in fish it was below 0.3 Bq kg^{-1} wet weight (1-2 orders of magnitude lower than in the Baltic Sea in 2011-2015, this report), and in surface seawater it was below 3 Bq m^{-3} as compared to over 15 Bq m^{-3} in the majority of the areas in the Baltic Sea during the same period. ^{210}Po in fish (flesh) of similar type are similar, up to a few Bq kg^{-1} wet weight (Kim et al. 2016).

Although ^{110m}Ag levels were not detectable in Pacific offshore water, they could be measured in different types of biota, such as plankton (Buesseler et al. 2011) and squids (Zhi Zeng et al. 2014; Yu et al. 2015), confirming the importance of appropriate bioindicators when monitoring for specific radionuclides.

Johansen et al. (2014) have estimated the total committed effective dose to a hypothetical human consuming 50 kg fish caught at 3 km from FDNPP in 2013 (despite the fishing and access restrictions in place) to be approximately 0.95 mSv year^{-1}. Only 14% (0.13 mSv year^{-1}) of this dose was attributable to FDNPP-origin radionuclides, which is about 10% of the 1 mSv year-1 limit for the exposure of the public and is 10 times higher than the annual dose from fish ingestion estimated for the Baltic (this report).

Johansen et al. (2014) estimate that the maximally exposed fish in FDNPP port have received over several years dose rates above 1 mGy d^{-1}. Notably high levels of radiocaesium could be measured in demersal benthic feeding species. A maximum level of 740 kBq kg^{-1} wet weight was measured in 2013 in greenling caught in the FDNPP port. The dose rate received by the same species 3 km away from FDNPP is three orders of magnitude (around 1,000 times) lower. Even further away, beyond 100 km offshore and across the Pacific, dose rates received by fish are 10,000 to over 1,000,000 times lower, being similar to those estimated in this report.

6. Conclusions

Tarja Ikäheimonen

The most significant source of man-made radioactivity in the Baltic Sea is fallout from the accident at the Chernobyl nuclear power plant in 1986. The most important radionuclides in the fallout were ^{137}Cs and ^{134}Cs. Because of the short half-life of ^{134}Cs (2.07 y), it has already disappeared. The decay-corrected (until 2015) total input of ^{137}Cs from Chernobyl to the Baltic Sea has been estimated at 2,700 TBq, and the post-Chernobyl river discharges of ^{137}Cs to the Baltic Sea were estimated at 200 TBq comprising about 7% of the total fallout.

The second most important source is global fallout from atmospheric nuclear weapons tests carried out during the late 1950s and early 1960s. During the late 1990s the decay-corrected amounts of weapons-test ^{137}Cs and ^{90}Sr in the Baltic Sea have been evaluated at 540 and 330 TBq, respectively.

Inputs originating from nuclear reprocessing plants in Western Europe are only of minor importance, due to significant reductions in discharges in recent years.

The predominant radionuclide in discharges from the nuclear power plants and research reactors in the Baltic Sea region is ^{3}H. Total discharges of ^{3}H from these local sources have amounted to 3, 800 TBq, and those of other beta-gamma emitting radionuclides amounted to about 24 TBq until the end of 2015. The total discharges of alpha emitting radionuclides have been 0.005 TBq. These discharges have not been decay-corrected.

For ^{137}Cs in the Baltic Sea, the main source is fallout from Chernobyl (79%), followed by nuclear weapons test fallout (16%). For ^{90}Sr, the main source of contamination is fallout from nuclear weapons tests (82%), while the proportion from Chernobyl fallout was smaller (11%). Cumulative amounts of discharges from the nuclear reactors in the Baltic Sea region in total injections were 0.04% and 0.2% for ^{137}Cs and ^{90}Sr, respectively.

Four reactors have been decided to shut down by 2020 in Sweden. One reactor is expected to start produce electricity in 2018 and one is planned to be built in Finland.

Today, ^{137}Cs is furthermore the main indicator of man-made radioactivity in Baltic seawater. The highest concentrations observed in seawater during the period 2011 - 2015 were found in the Archipelago and Åland Sea being 31 Bq m^{-3} in 2015. The general trend is steadily decreasing. It is estimated that the target value of 15 Bq m^{-3}, corresponding to pre-Chernobyl levels, will be reached between 2017 and 2023. First estimates of effective half-lives for different parts of the Baltic Sea have been calculated being between 9 and 11 years. The inventory of ^{137}Cs in the Baltic seawater in 2015 is estimated at 470 Tbq.

In regard of ^{137}Cs the Baltic Sea is still one of the most contaminated areas of the World Ocean, even 30 years after the Chernobyl accident. Current state of knowledge shows no radiological effects on the Baltic Sea caused by the Fukushima accident.

The results of the Sediment Baseline Study carried out by the MORS-PRO during the reporting period showed that the concentrations of naturally occurring radionuclides in Baltic Sea sediments remain at background levels. The concentrations of man-made radionuclides in sediments are higher than the target specified in HELCOM's ecological objective of "radioactivity at pre-Chernobyl level". This is particularly true for the Bothnian Sea and the Gulf of Finland, which received the largest amounts of Chernobyl fallout in the Baltic Sea. The total inventory of ^{137}Cs in the Baltic Sea sediments was estimated at 2,200 -2,500 TBq between 2011 - 2015. This amount is about 8 -9 times higher compared to the pre-Chernobyl level.

Monitoring of radioactivity in the Baltic Sea is an essential part of environmental monitoring and will provide a realistic baseline e.g. for possible radiation emergency situations modelling purposes. The continuous monitoring work and time trends of the radioactive substances are the base for understanding the state of the Baltic Sea environment and its radioactivity. However, there are still gaps in our knowledge of radioactivity in the sediments of the Baltic Sea e.g. amounts of Sr-90, Am-241 and natural radioactivity such as lead -210. In addition, an environmental distribution model for any kind of nuclear accident in the Baltic Sea area is needed. In the future, we should attempt to fill these gaps to form a more comprehensive picture of the radioactivity in the sediments of the Baltic Sea.

Concentrations of man-made radioactivity in fish show generally decreasing trends, in agreement with trends in concentrations in seawater. Chernobyl-derived ^{137}Cs continued to be the most dominant man-made radionuclide in Baltic Sea fish. By the end of the reporting period, mean values of 0.3 – 8 Bq kg^{-1} wet weight were found in marine round fish (cod, herring, whiting) in various Baltic Sea basins. In marine flat fish (plaice, flounder, dab) slightly lower mean values, 0.2 – 5 Bq kg^{-1}, were found than in marine round fish. The concentrations in pike varied from 5 to 24 Bq kg^{-1} wet weight on the Finnish coast.

Radiation doses to humans from man-made radionuclides in the Baltic Sea are due mainly to ingestion of ^{137}Cs in fish. Doses from ^{3}H are lower by several orders of magnitude. During 2011 - 2015 doses to members of the public from marine pathways have not exceeded an annual value of 0.01 mSv, which is well below the limit of 1 mSv for the general public set in the Basic Safety Standards of the European Council (EC, 1996) and the IAEA (IAEA, 1996). The corresponding annual dose from naturally occurring radionuclides in fish is about 0.1 mSv of which the dominating contribution is from polonium-210.

Concentrations of radioactive substances in the Baltic Sea are not expected to cause harmful effects to wildlife in the foreseeable future. However, in line with international developments, the future work of HELCOM will continue to include assessments of the radiological risks to the environment from radioactive substances in the Baltic Sea. The knowledge about the baseline is one of the key factors for the risk assessment.

As a whole, good status for ^{137}Cs in herring, is not achieved in the most of the HELCOM sub-basins. For flat fish, good status is achieved in four basins and not achieved in three basins. For surface seawater, GES is not achieved yet in any of the HELCOM sub-basins. This means that if a one-out-all-out-approach is used for the entire Baltic Sea for the three parameters, then good status is not achieved.

7. Recommendations

The objective of the HELCOM Expert Group on Monitoring of Radioactive Substances in the Baltic Sea (HELCOM MORS EG) is to implement the Helsinki Convention on matters related to monitoring and assessment of radioactive substances in the Baltic Sea. The work is based on relevant HELCOM Recommendations and will support the State and Conservation Working Group (HELCOM STATE & CONSERVATION).

HELCOM MORS EG's main responsibilities are:

1. to coordinate basic monitoring programmes on radioactive substances in the Baltic Sea carried out by the Contracting Parties in accordance with relevant HELCOM Recommendations and the valid Guidelines;
2. to annually compile data on discharges of radioactivity from civil nuclear facilities to the Baltic Sea reported by the Contracting Parties;
3. to annually compile data on discharges and environmental levels of radioactivity in the Baltic Sea submitted to the HELCOM databases, in accordance with relevant HELCOM Recommendations;
4. to annually validate all data in the HELCOM MORS databases of environmental and discharge data and to make them available on relevant electronic media to MORS EG;
5. to update as requested HELCOM Baltic Sea Environment Fact Sheets and the Core indicator report on radioactive substances in the Baltic Sea;
6. to keep the Guidelines updated on the monitoring of radioactive substances in the Baltic Sea;
7. to coordinate and organize intercomparison exercises on seawater, and encourage participation in other proficiency tests and intercomparison exercises to assure high quality of the monitoring data;
8. to produce periodic assessments on radioactivity in the Baltic Sea. These assessments will include levels, inventories and trends for radioactivity in the Baltic Sea and the radiological impact on humans and the environment;
9. to keep under observation the development of trends of export of radionuclides from the Baltic Sea to the North Sea and vice versa, especially the inflow of radioactivity (e.g. ^{99}Tc, ^{129}I) from Sellafield and La Hague to the Baltic Sea and the outflow of Chernobyl radioactivity from the Baltic Sea to the Skagerrak;
10. to produce thematic reports as requested, e.g. on naturally occurring radionuclides in the Baltic Sea, releases of man-made radionuclides from non-nuclear activities (e.g. hospitals), simple procedures for assessing doses to humans from radioactivity in the Baltic Sea.

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10. Appendixes

10.1 Data Quality

Tarja Ikäheimonen

The laboratories from eight countries bordering the Baltic Sea have contributed to the monitoring programme during the years 2011 -2015. Analytical procedures and quality systems of different laboratories have been presented in the earlier assessment by Ikäheimonen and Outola (2009).

The intercomparison exercise of the Baltic Sea water has been continued during the reporting period organized by STUK, Finland. During the reporting period a new intercomparison sea water sample were sampled and delivered by Germany on 23rd June 2015. (**Photo 10.1.1**).

Laboratories, and also International Atomic Energy Agency (IAEA) laboratory, were asked to analyse ^{137}Cs and ^{90}Sr (if reporting ^{90}Sr-results of the monitoring) once a year. For 2011- 2014, from the old sea water intercomparison sample, the results were presented in **Figures 10.1.1** and **10.1.2** For the year 2015, from the new sea water sample, the results were presented in **Figures 10.1.3** and **10.1.4.**

The results indicate quite good agreements with each other. However, small instability can be seen mainly due to differences in measurement techniques. Also, harmonization of uncertainty calculations would improve the results. However, according these results, the monitoring data can be considered comparable.

Several laboratories have also participated in the other intercomparisons organized by the IAEA or other bodies.

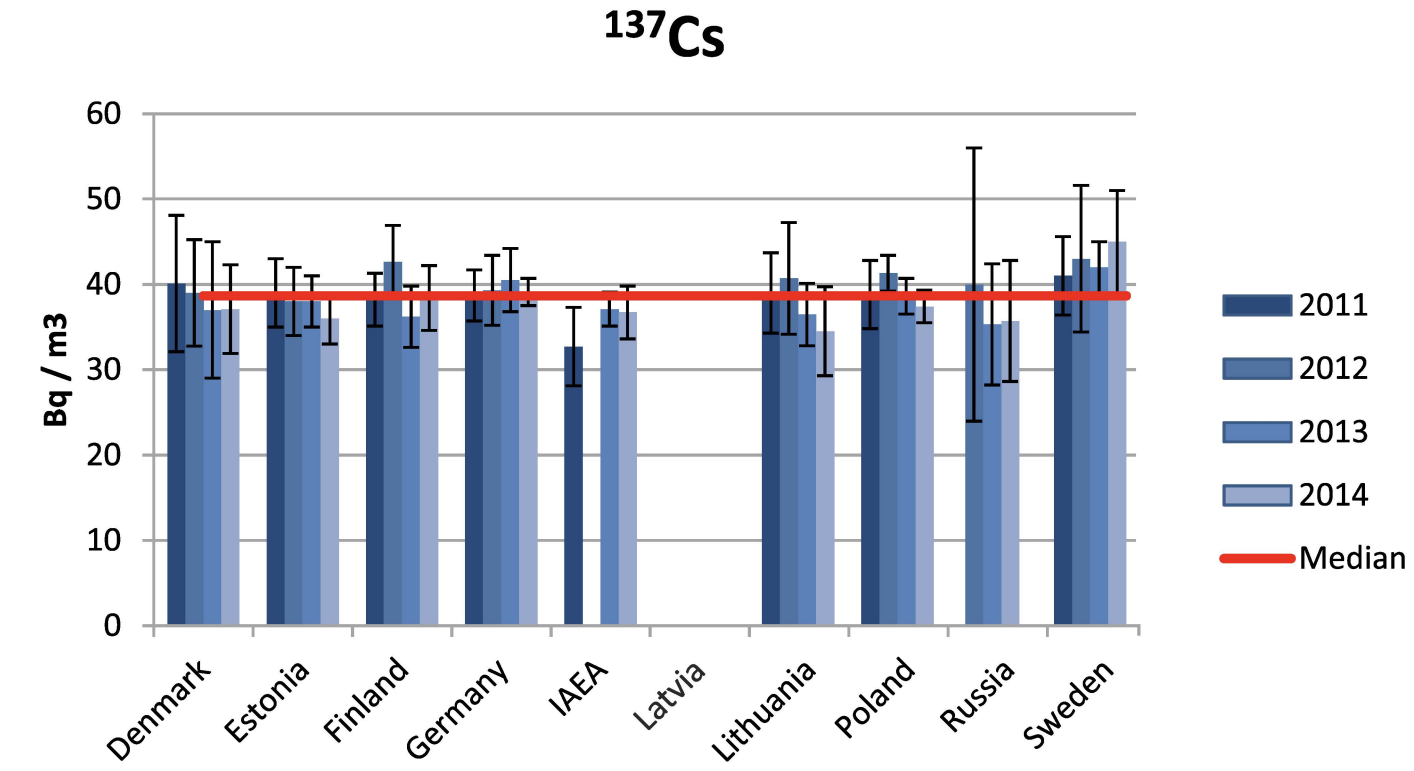

Figure 10.1.1
Intercomparison results of ^{137}Cs of different laboratories in 2011 – 2014 (old intercomparison sea water sample). Results are given with 95% confidence limits.

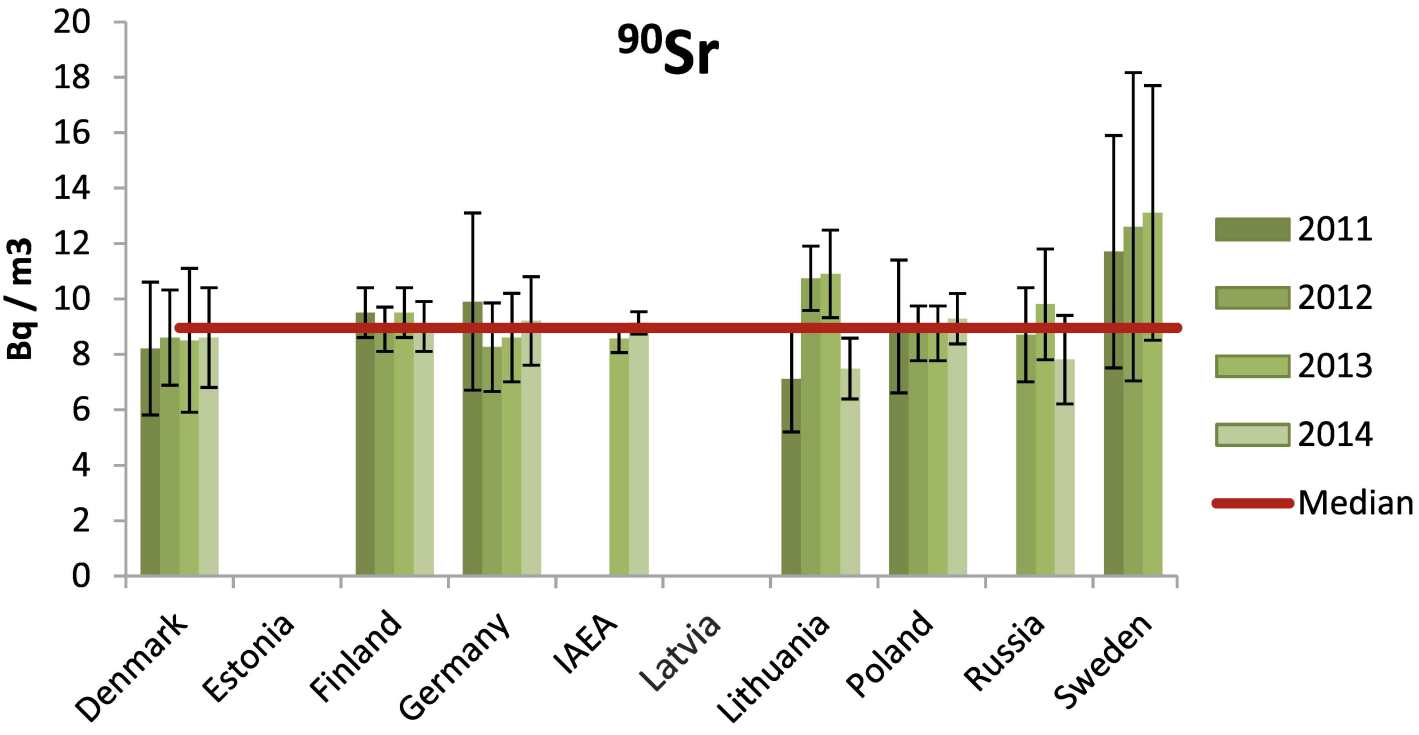

Figure 10.1.2
Intercomparison results of ^{90}Sr of different laboratories in 2011 -2014 (old sea water sample). Results are given with 95% confidence limits.

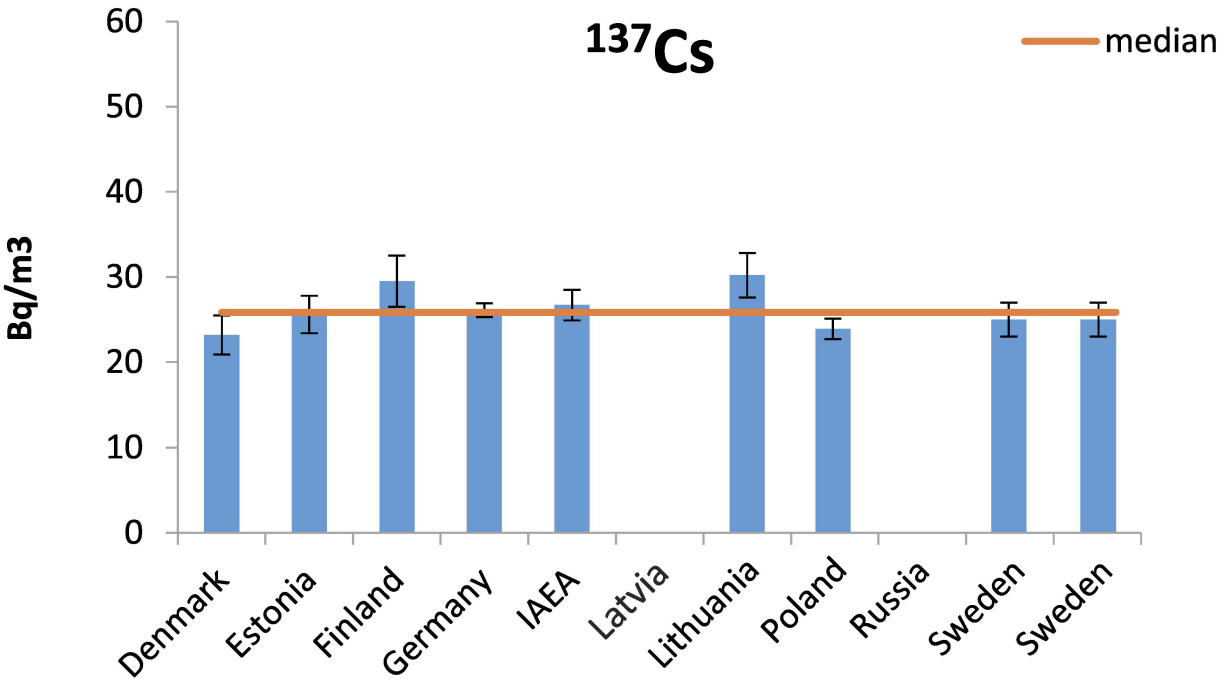

Figure 10.1.3
Intercomparison results of ^{137}Cs of different laboratories in 2015 (new intercomparison sea water sample). Results are given with 95% confidence limits.

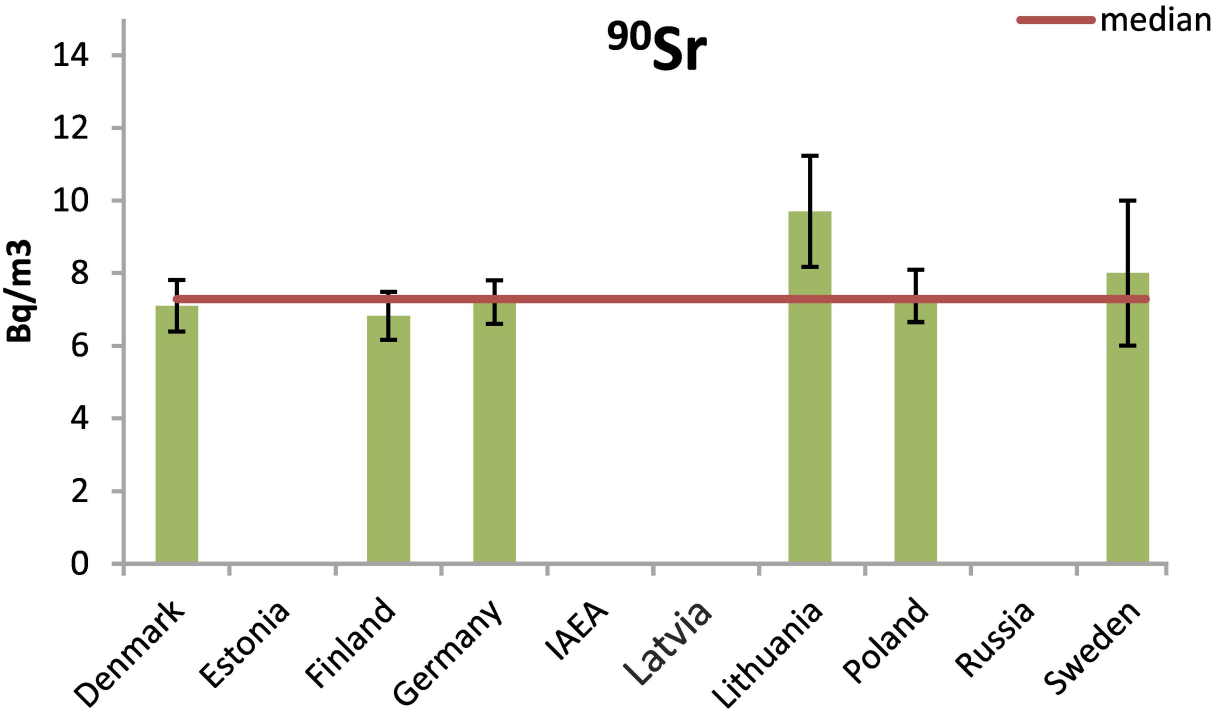

Figure 10.1.4
Intercomparison results of ^{90}Sr of different laboratories in 2011-2014 (new sea water sample). Results are given with 95% confidence limits.

Photo 10.1.1
Intercomparison sea water sampling on German research vessel SWRVDENEB in German station OBANK (54°29,97'N and 14°40,03'E). For every contracting party, except Latvia, 600 litres of seawater have been sampled.

10.2 Sampling details

Maps with stations of seawater, biota and sediment sampling as well as tables with total number of samples taken in the described period are presented in **figures 10.2.1-10.2.3** and **tables 10.2.1-10.2.3.**

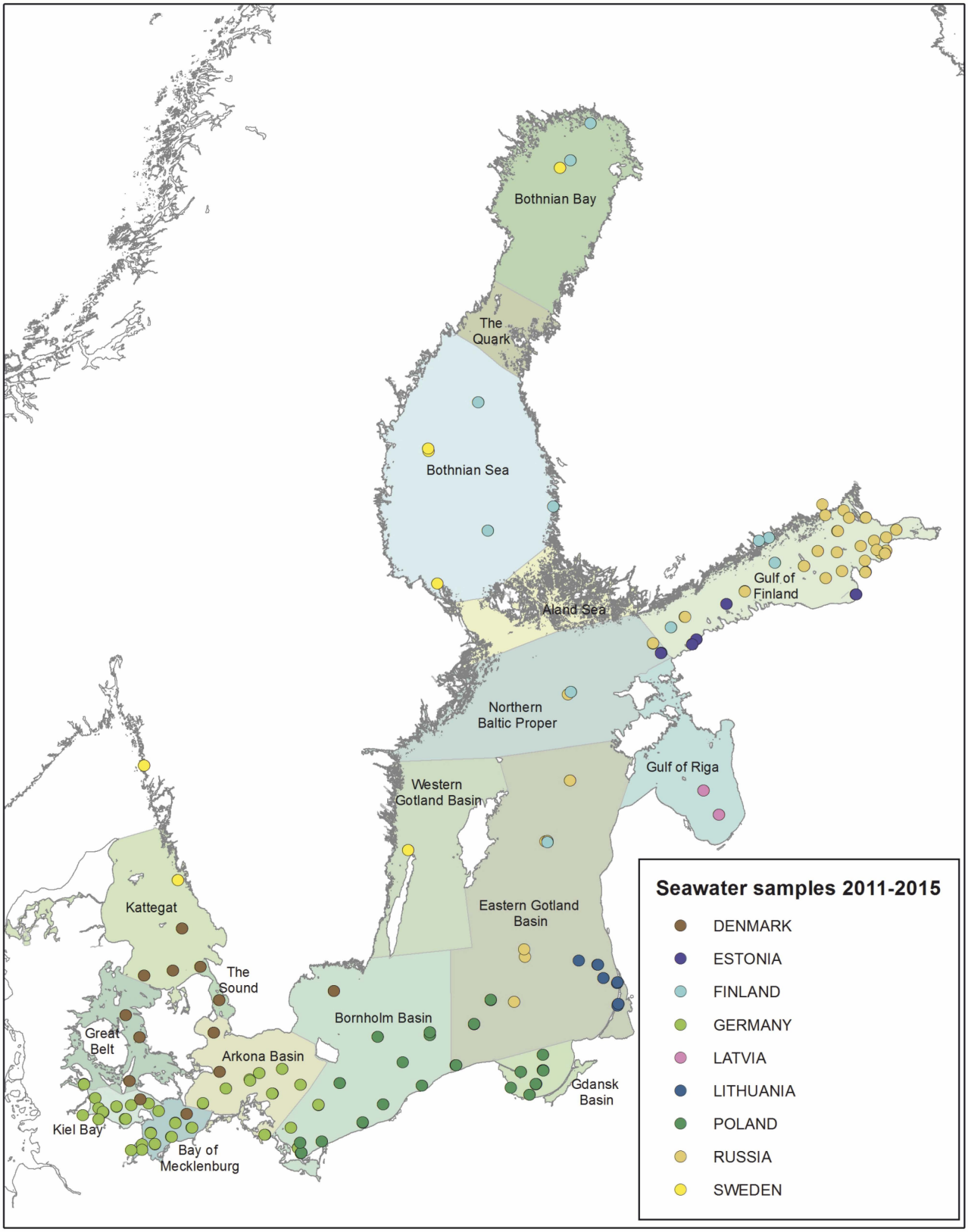

Figure 10.2.1.
Seawater sampling stations during 2011-2015.

Table 10.2.1.
No. of seawater samples per sub-basin during 2011-2015

Sub-basin	2011	2012	2013	2014	2015	SUM
Arkona Basin	23	22	23	21	16	**115**
Bay of Mecklenburg	20	20	20	16	14	**90**
Bornholm Basin	31	31	31	32	29	**154**
Bothnian Bay	4	4	4	4	3	**19**
Bothnian Sea	7	7	7	7	7	**35**
Eastern Gotland Basin	28	31	26	17	15	**117**
Gdansk Basin	17	17	17	19	17	**87**
Great Belt	14	14	14	6	12	**60**
Gulf of Finland	42	31	10	10	10	**103**
Gulf of Riga	4	4	-	-	-	**8**
Kattegat	15	16	15	10	16	**72**
Kiel Bay	22	21	22	22	28	**115**
Lake Ladoga	5	7	-	-	-	**12**
Northern Baltic Proper	5	5	3	3	3	**19**
Skagerrak	2	2	2	2	2	**10**
The Quark	-	-	-	-	-	**0**
The Sound	4	4	4	2	3	**17**
Western Gotland Basin	1	1	1	11	11	**25**
SUM	**224**	**237**	**199**	**182**	**196**	**1.058**

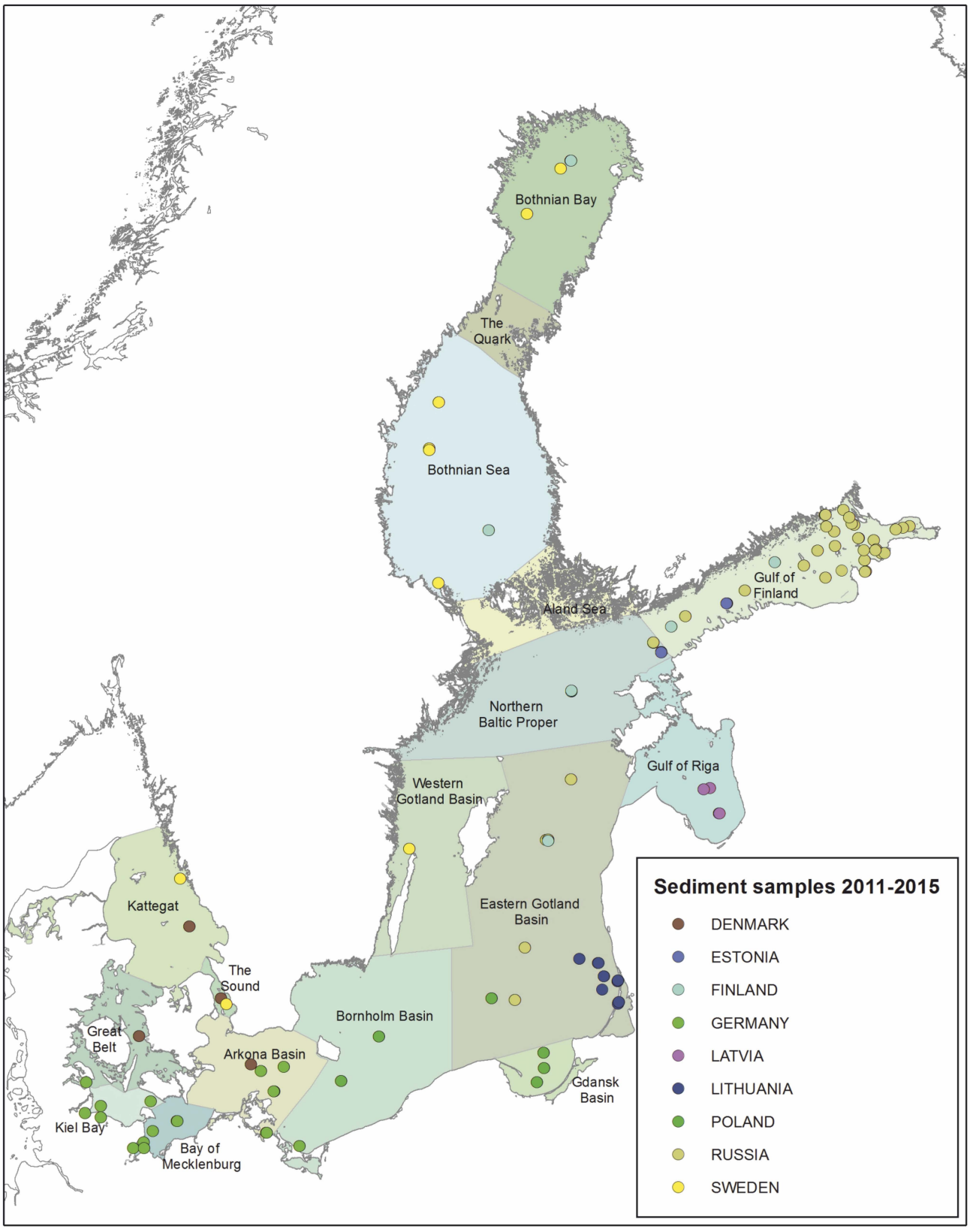

Figure 10.2.2.
Sediment sampling stations during 2011-2015.

Table 10.2.2.
No. of sediment samples per sub-basin during 2011-2015

Sub-basin	2011	2012	2013	2014	2015	SUM
Arkona Basin	47	41	41	43	43	**215**
Northern Baltic Proper	24	37	25	25	25	**136**
Gdansk Basin	36	36	36	36	36	**180**
Great Belt	15	10	16	10	10	**61**
Bornholm Basin	30	30	30	30	30	**150**
Bothnian Bay	29	29	29	28	29	**144**
Bothnian Sea	30	30	30	30	29	**149**
Eastern Gotland Basin	60	71	37	39	37	**244**
Western Gotland Basin	1	1	7	5	1	**15**
Gulf of Finland	165	220	45	49	45	**524**
Kattegat	17	1	8	1	1	**28**
The Sound	8	1	11	1	1	**22**
Gulf of Riga	24	24	-	-	-	**48**
Kiel Bay	41	39	40	39	40	**199**
Bay of Mecklenburg	37	29	37	27	27	**157**
Lake Ladoga	9	48	-	-	-	**57**
Grand Total	**573**	**647**	**392**	**363**	**354**	**2.329**

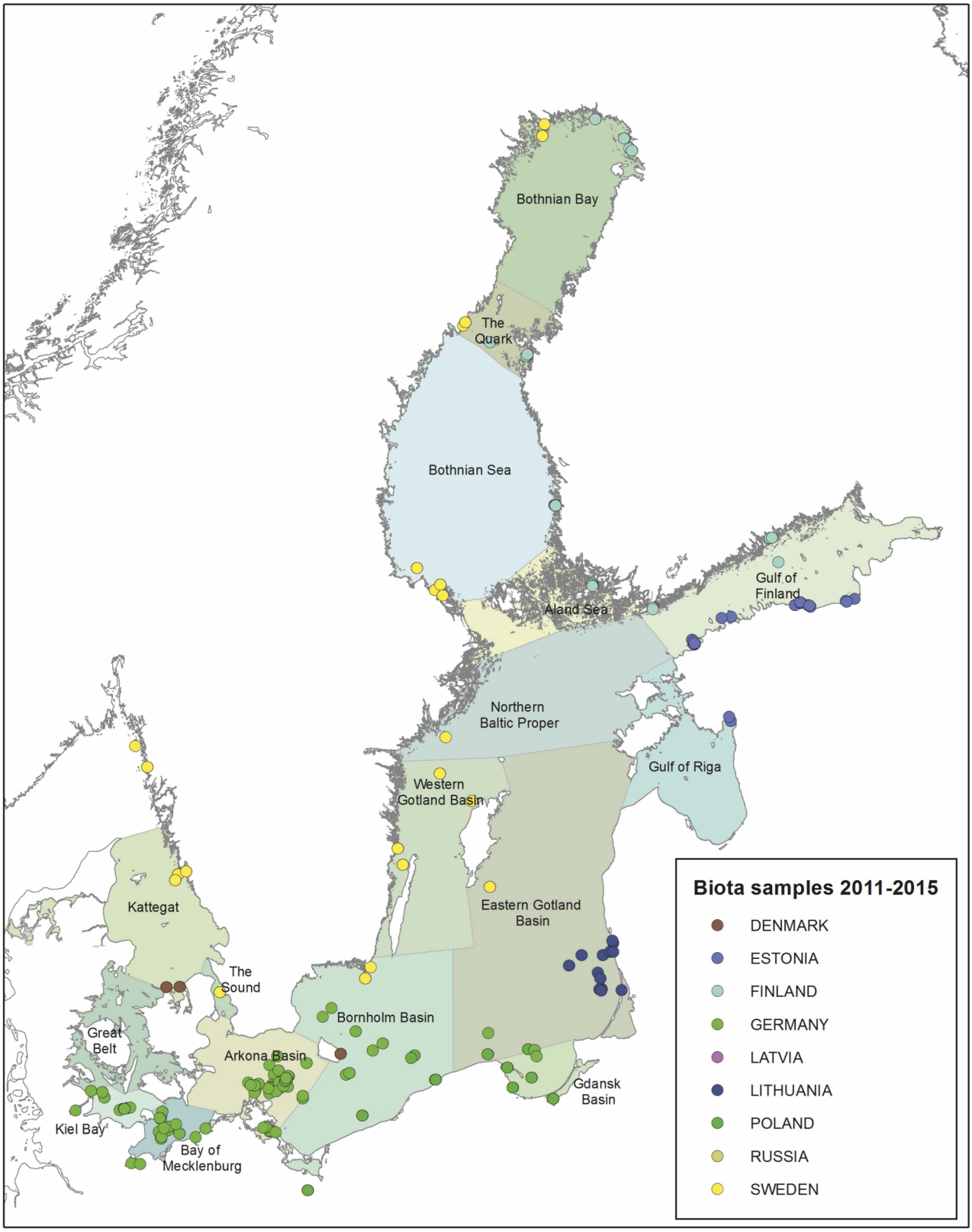

Figure 10.2.3.
Biota sampling stations during 2011-2015.

Table 10.2.3.
No. of biota samples per sub-basin during 2011-2015

Sub-basin	2011	2012	2013	2014	2015	SUM
Aland Sea	2	2	2	2	2	**10**
Arkona Basin	31	26	-	4	14	**75**
Gdansk Basin	5	7	8	52	46	**118**
Bornholm Basin	21	14	8	36	35	**114**
Bothnian Bay	3	2	3	3	3	**14**
Bothnian Sea	8	8	8	8	10	**42**
Eastern Gotland Basin	19	11	15	10	14	**69**
Western Gotland Basin	4	5	4	4	3	**20**
Gulf of Finland	9	12	13	10	10	**54**
Kattegat	11	11	11	11	10	**54**
The Sound	1	1	1	1	1	**5**
Gulf of Riga	-	-	2	-	-	**2**
Kiel Bay	9	6	-	2	8	**25**
Bay of Mecklenburg	11	17	-	-	-	**28**
The Quark	3	3	3	3	3	**15**
Skagerrak	1	1	1	1	1	**5**
SUM	**138**	**126**	**79**	**147**	**160**	**650**

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