Discharges of produced water TENORM to the Norwegian continental shelf - overview of available data

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Contents

List of definitions

Bq	One Bq (Becquerel) is defined as the activity of a quantity of radioactive material in which one nucleus decays per second.
KLIF	Klima og forurensningsdirektoratet
LOQ	Limit of Quantification
Radionuclides	Radioactive elements quantified by measuring decay, usually in Bq
SFT	Statens Forurensningstilsyn
TENORM	Technologically Enhanced Naturally Occurring Radioactive Materials
PW	Produced Water
WCM	Water Column Monitoring
^{226}Ra	The most stable isotope of radium (product of ^{238}U decay), which has a half-life of 1600 years and decays into radon gas.
^{228}Ra	A product of ^{232}Th breakdown, with a half-life of 5.75 years.
^{210}Pb	Isotope of lead, with a half-life of 22.20 years.
^{210}Po	Isotope of polonium , with a half-life of 138 days.
^{228}Th	Isotope of thorium with a half-life of 91 years.
α-spectrometry	Alpha s spectrometry, method for testing for (and measuring) alpha emitters.
γ - spectrometry	Gamma-ray spectrometry is the quantitative study of the energy spectra of gamma-ray sources.

1 Introduction

The production of oil and gas generates large quantities of produced water (PW). PW is the aqueous fraction extracted along with oil and gas from geological formations. After separation from the oil and gas and subsequent treatment, PW is either discharged to the sea or re-injected back into the reservoir.

PW contains elevated levels of radionuclides that originate from dissolved metals in the oil/water/gas reservoirs; mostly in the form of ^{226}Ra and ^{228}Ra. Annual discharges of PW from the Norwegian continental shelf may be as large as 150 million cubic meters (130,8 Mm^3 in 2006, OLF 2011).

Available environmental data for the radionuclides ^{226}Ra and ^{228} Ra on the Norwegian continental shelf has been reviewed. Documentation on the discharges of these radionuclides through the PW from all installations is good. However the availability of sediment activity data is considerably more limited and data from seawater and biota is scarce.

In an attempt to illustrate the possible impact of the radioisotopes from the PW to the marine environment, data from fields from where sediment, water or biota data are available were selected. From these fields we have described the long term trends in discharge to see if it is possible to trace any impact on sediment or other compartments.

2 Analytical methods

The activity concentrations of ^{226}Ra, ^{228}Ra and ^{210}Pb can be determined by gamma spectrometry. ^{226}Ra and ^{210}Pb are determined directly, while ^{228}Ra is determined through its progeny ^{228}Ac (half-life 6.13 h). Employing gamma spectrometry considerably simplifies their determination, as all three radionuclides can be detected simultaneously, after a suitable pre-concentration.

For low levels of ^{226}Ra (in environmental samples), gamma spectrometry will give results below the detection limit. For obtaining a lower detection limit, alpha spectrometry can be used. This involves dissolution of the sample (solid samples) in nitric acid, followed by chemical separation of radium from the sample by lead and barium sulphate precipitations. The chemical yield is determined through addition of ^{133}Ba to the sample.

^{210}Po is an alpha emitter and does not emit any gamma rays when decaying to stable ^{206}Pb. The determination of ^{210}Po will therefore require an additional radiochemical analysis. ^{210}Po must be pre-concentrated from the PW sample and the precipitate treated with mineral acids and oxidizing agents to remove organic matter, before polonium can be deposited on Ni, Ag or Cu planchets for subsequent determination by alpha spectrometry.

Low concentrations of ^{210}Pb can be determined by performing an analysis of its progeny ^{210}Po. ^{210}Po originally present in the sample is first removed and the sample is set aside for ingrowth of new ^{210}Po from ^{210}Pb. Performing a ^{210}Po determination then allows for the calculation of the amount of ^{210}Pb present in the sample. In this manner mBq levels of ^{210}Pb can be determined using alpha spectrometry. This is however a time consuming procedure and depending on the concentration of ^{210}Pb present in the sample, the ingrowth period will vary from a few weeks to several months.

3 Radioisotopes in produced water

Data for selected radionuclides in PW from all Norwegian installations are available from 2003. These data have been submitted to KLIF (SFT) in annual reports. The data is available at the OLF web site (http://www.olf.no/publikasjoner/miljorapporter). In the present report, a limited number of fields has been selected based on availability of data for measurements of radioactivity in the environment close to the respective field. The selected fields are given in Table 1.

Table 1. Fields selected to give an overview of TENORM discharge from the Norwegian sector in the North Sea. The fields are arranged according to total amount of ^{226}Ra and ^{228}Ra discharge. Approximate water depths for each field are indicated.

Field	Depth (m)	Discharge of the selected radioisotopes
Statfjord	150	Lowest discharge
Oseberg	100	
Ekofisk	75	
Veslefrikk	84	
Snorre	350	
Gyda	66	
Gullfaks	200	
Jotun	130	
Brage	140	
Troll	330	Highest discharge

In order to give a general picture of the discharges from the selected fields, the discharge situation in 2010 is shown in Figure 1 a and b. This indicates that the fields with highest activity of the selected radionuclides generally have the largest total discharges. Activity in the discharges from *Gyda* and *Jotun* is relatively high but these fields are not the largest contributors of radioactivity to the environment.

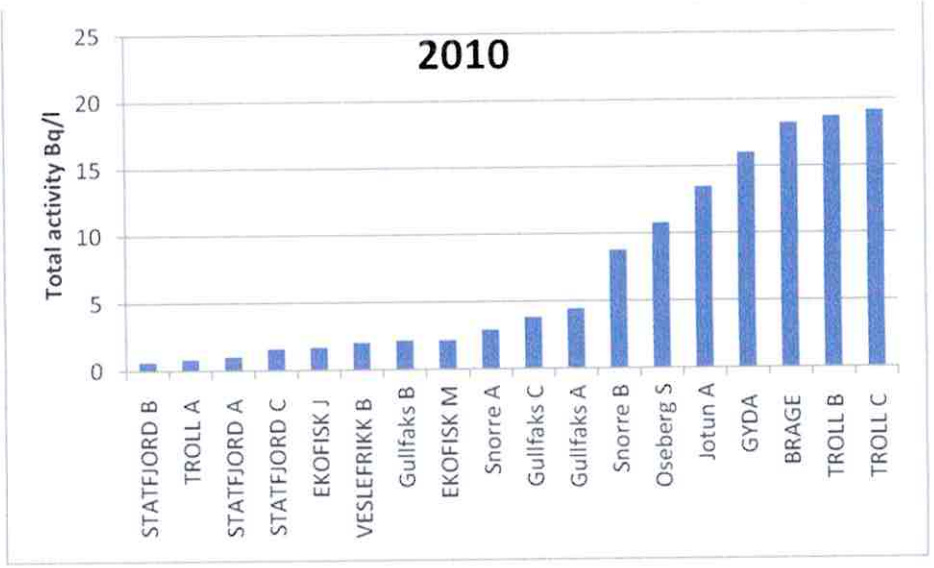

Figure 1 a: Discharge of ^{226}Ra and ^{228}Ra. The figure shows the activity in the PW with the fields sorted from low to high activity. (this does not reflect the total discharge from produced water in the North Sea).

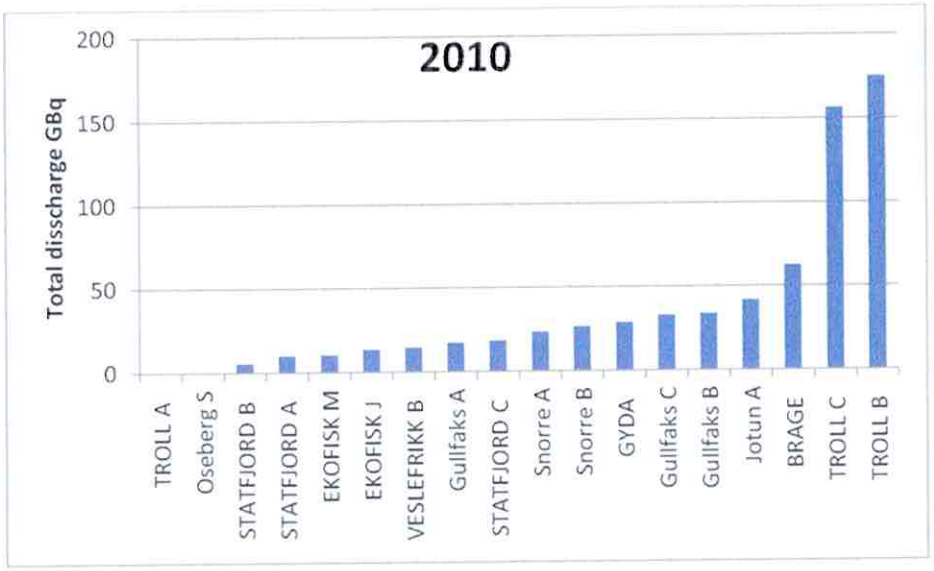

Figure 1b. Discharge of ^{226}Ra and ^{228}Ra. The figure shows the total discharge in the PW with the field sorted from low to high discharges. (this does not reflect the total discharge from produced water in the North Sea).

When linking the PW discharges of these radionuclides with observations in sediment, water and biota it is important to understand the timeframe and variations of the discharges. Trends in discharges of the selected radioisotopes date from 2003 and onwards from the selected fields are clear. The discharges for the last 8 years seem to be quite stable for these fields. For 2003 and 2004 only data for ^{226}Ra is available as it was considered to be the major contributor of radioactivity from PW. However from this collection of data it is clear that for most of the fields, the discharges of ^{228}Ra must also be considered as about 50 % of the discharges come from this nuclide. Data is also available for ^{210}Pb, however the contribution of this compound is limited. Some attempts have been made to measure ^{228}Th, however the ^{228}Th has a small contribution compared to ^{226}Ra and ^{228}Ra. The ^{228}Th and ^{210}Pb values may still valuable data that can help evaluating the impact on sediment and biota.

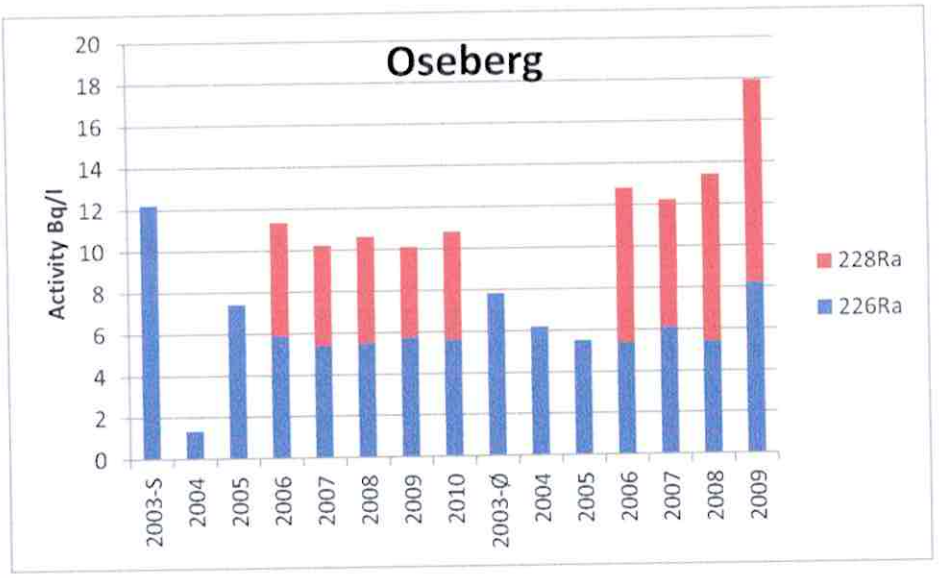

Figure 2a: Trends in the amount of activity in the PW of radionuclides at *Oseberg S* and *Oseberg Ø*. In 2003-2005 only ^{226}Ra was measured.

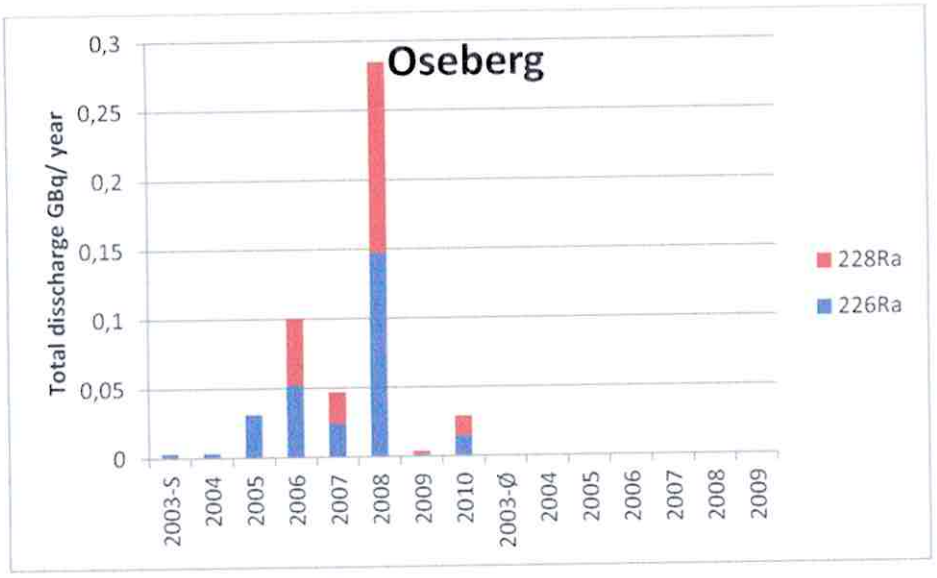

Figure 2b: Trends in the total discharges of radioactivity of selected radionuclides at *Oseberg S* and *Oseberg Ø*. In 2003-2005 only ^{226}Ra was measured.

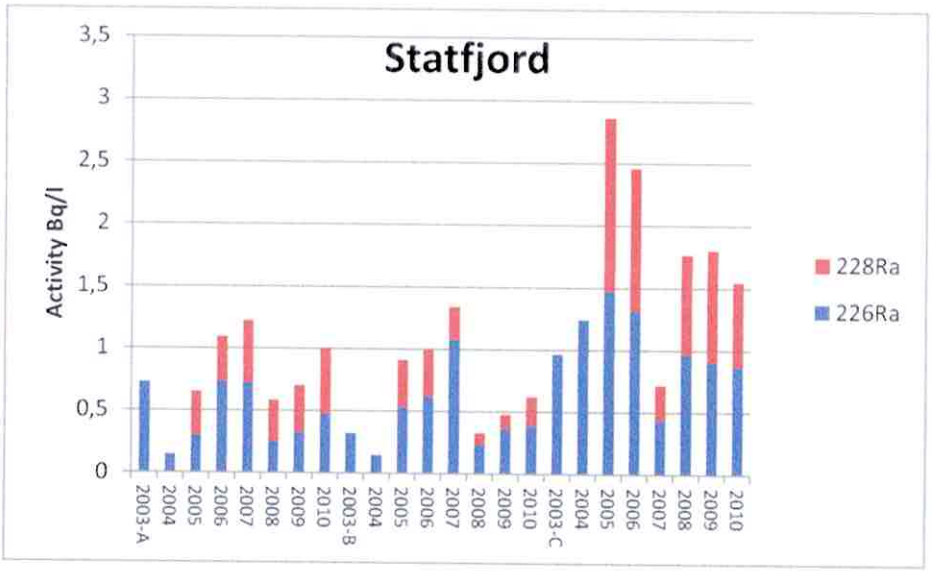

Figure 3a: Trends in the activity of the discharges of radionuclides at *Statfjord A, Statfjord B* and *Statfjord C.* In 2003-2004 only ^{226}Ra was measured.

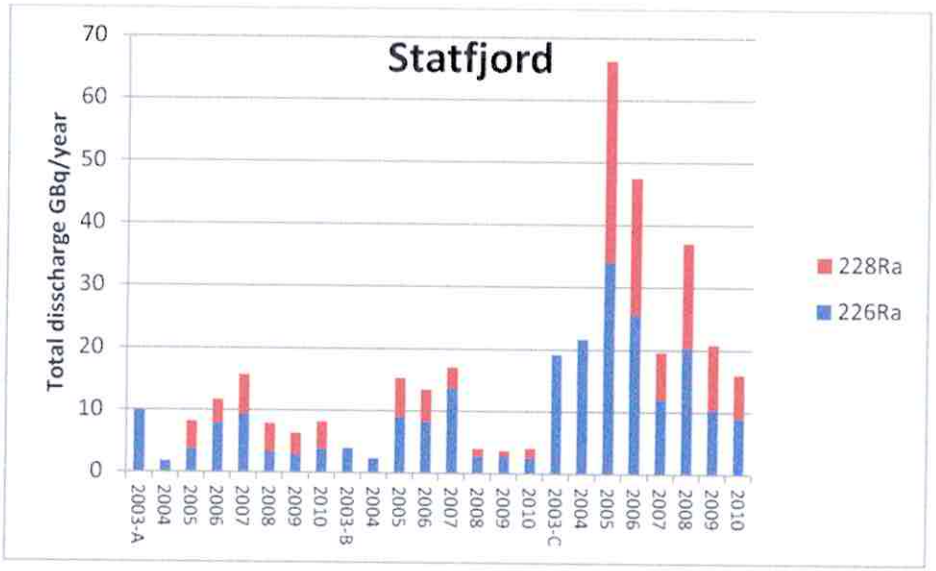

Figure 3b: Trends in the total discharges of total radioactivity of selected radionuclides at *Statfjord A, Statfjord B* and *Statfjord C.* In 2003-2004 only ^{226}Ra was measured.

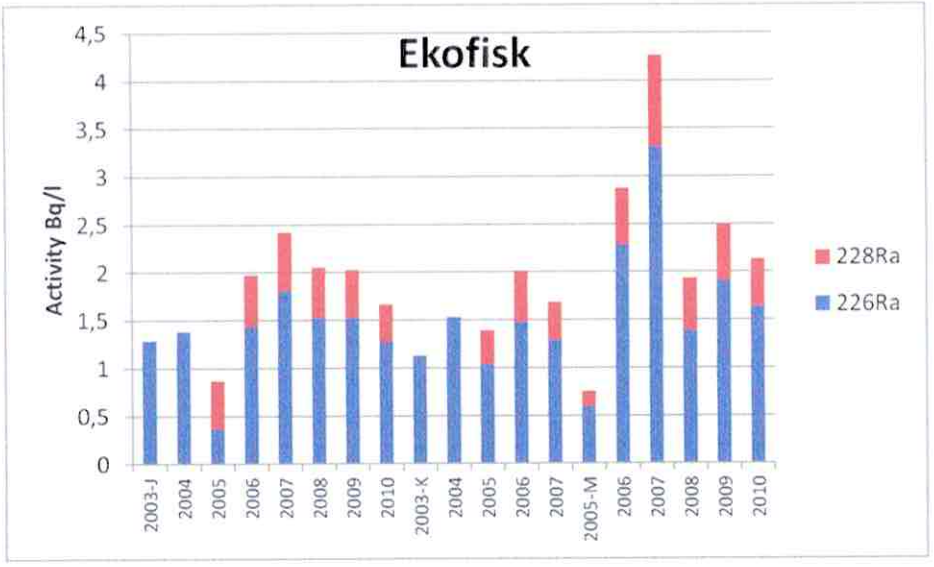

Figure 4a: Trends in the activity of the discharges of radionuclides at *Ekofisk J, Ekofisk K* and *Ekofisk M*. In 2003-2004 only ^{226}Ra was measured.

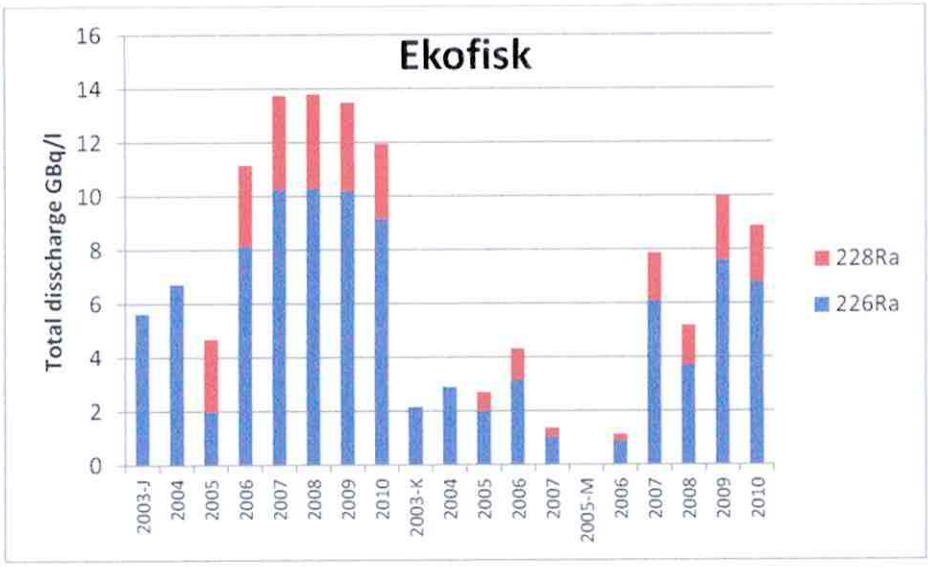

Figure 4b: Trends in the total discharges of total radioactivity of selected radionuclides at *Ekofisk J, Ekofisk K* and *Ekofisk M*. In 2003-2004 only ^{226}Ra was measured.

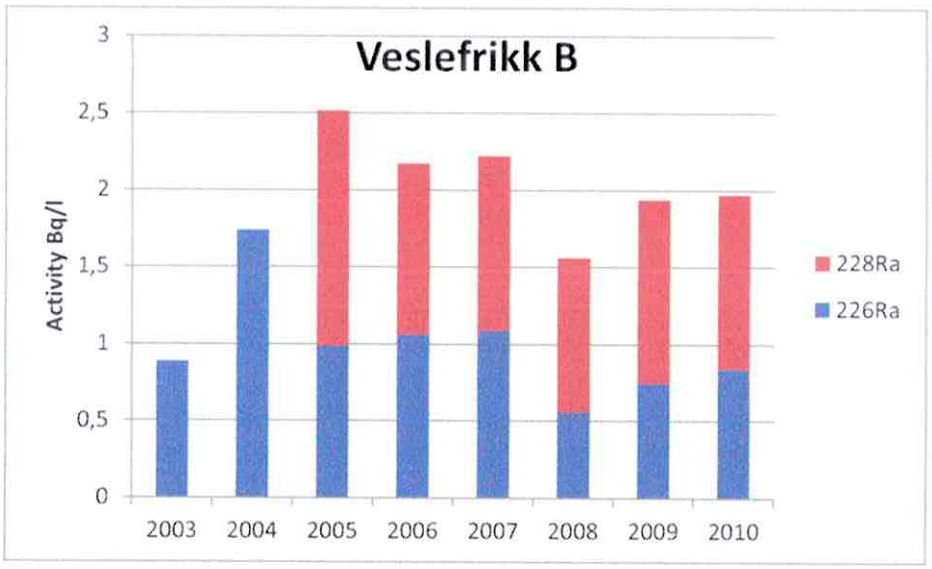

Figure 5a: Trends in the actability of the discharges of radionuclides at *Veslefrikk B*. In 2003-2004 only ^{226}Ra was measured.

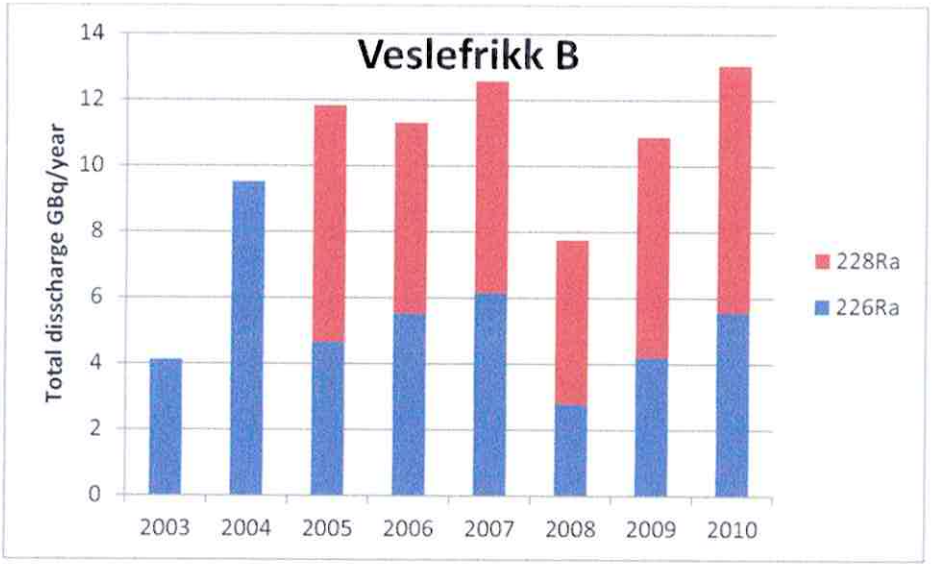

Figure 5b:Trends in the total discharges of total radioactivity of selected radionuclides at *Veslefrikk B*. In 2003-2004 only ^{226}Ra was measured.

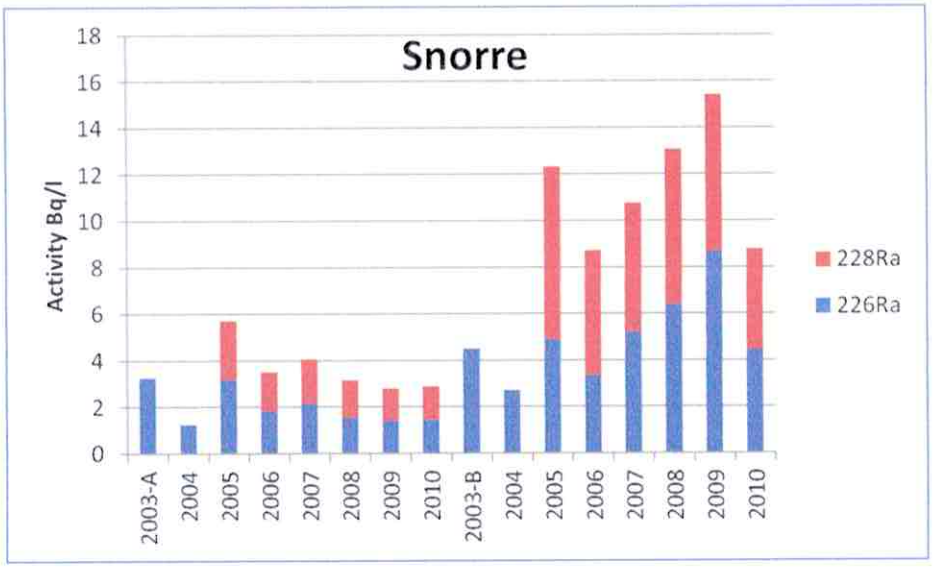

Figure 6a: Trends in the actability of the discharges of radionuclides at *Snorre A* and *Snorre B*. In 2003-2004 only ^{226}Ra was measured.

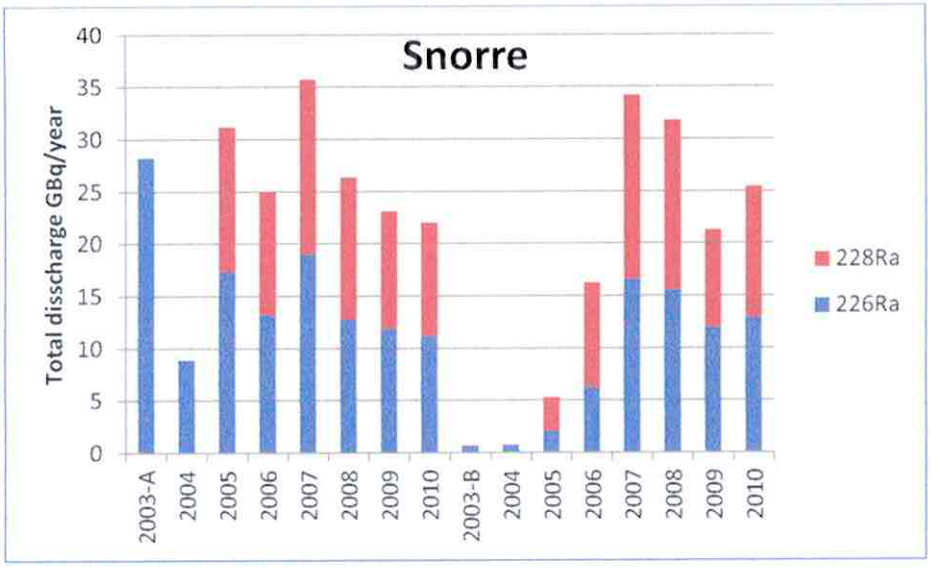

Figure 6b: Trends in the total discharges of total radioactivity of selected radionuclides at *Snorre A* and *Snorre B*. In 2003-2004 only ^{226}Ra was measured.

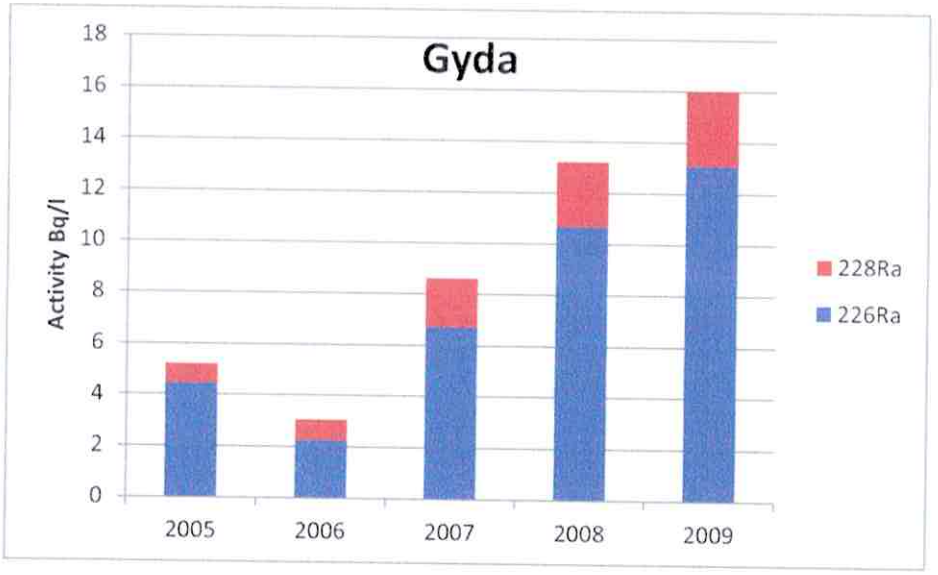

Figure 7a: Trends in the activity of the discharges of radionuclides at *Gyda*.

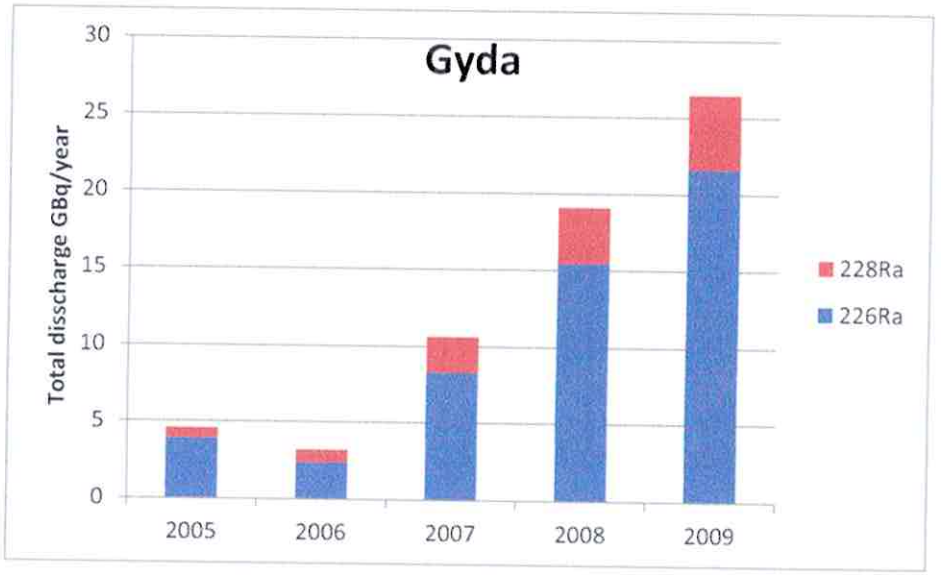

Figure 7b: Trends in the total discharges of total radioactivity of selected radionuclides at *Gyda*.

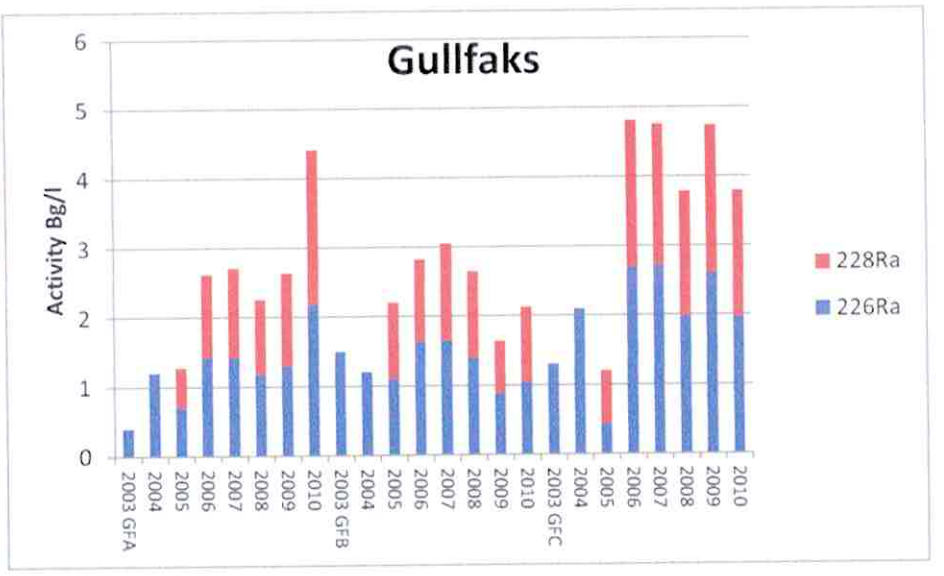

Figure 8a: Trends in the activity of the discharges of radionuclides at *Gullfaks A*, *Gullfaks B* and *Gullfaks C*. In 2003-2004 only ^{226}Ra was measured.

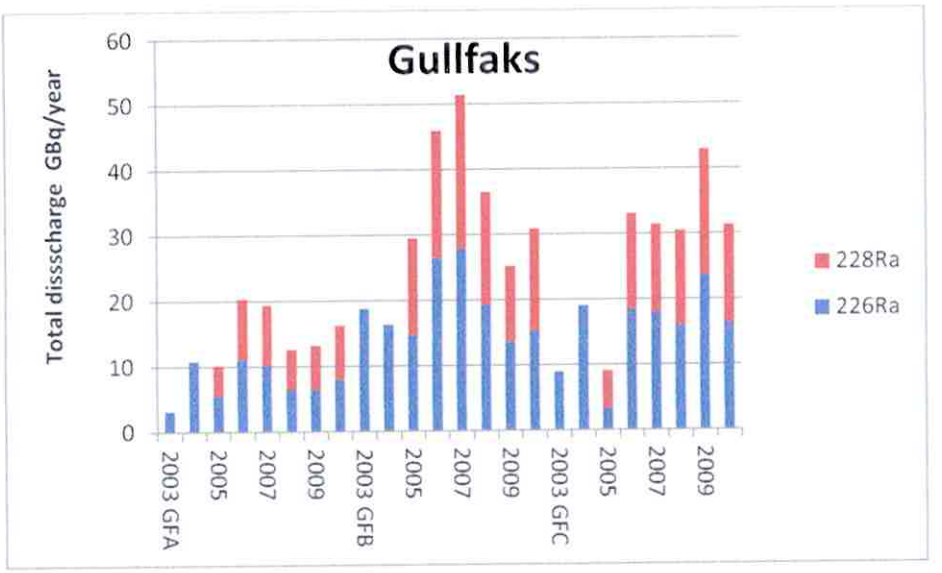

Figure 8b: Trends in the total discharges of total radioactivity of selected radionuclides at *Gullfaks A*, *Gullfaks B* and *Gullfaks C*. In 2003-2004 only ^{226}Ra was measured.

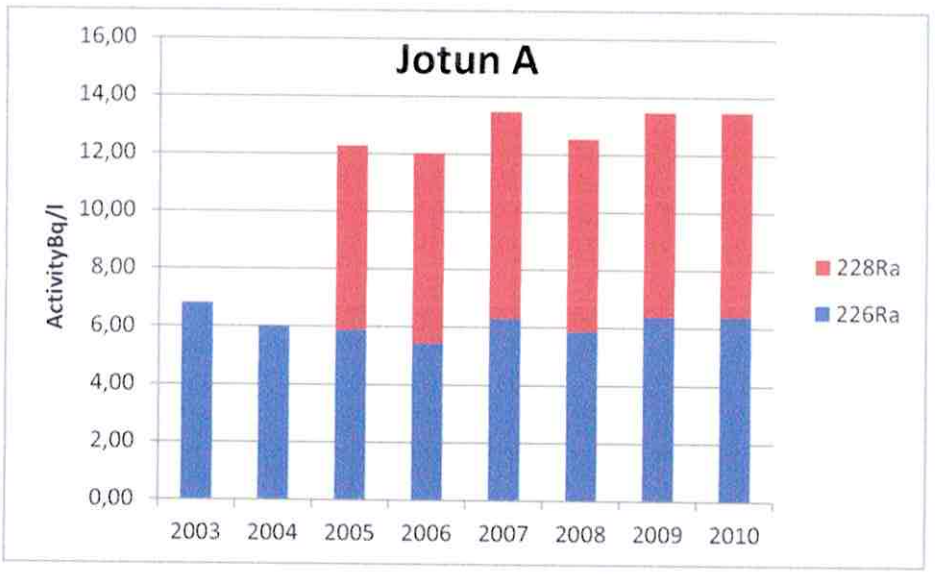

Figure 9a: Trends in the activity of the PW of radionuclides at *Jotun* A. In 2003-2004 only ^{226}Ra was measured.

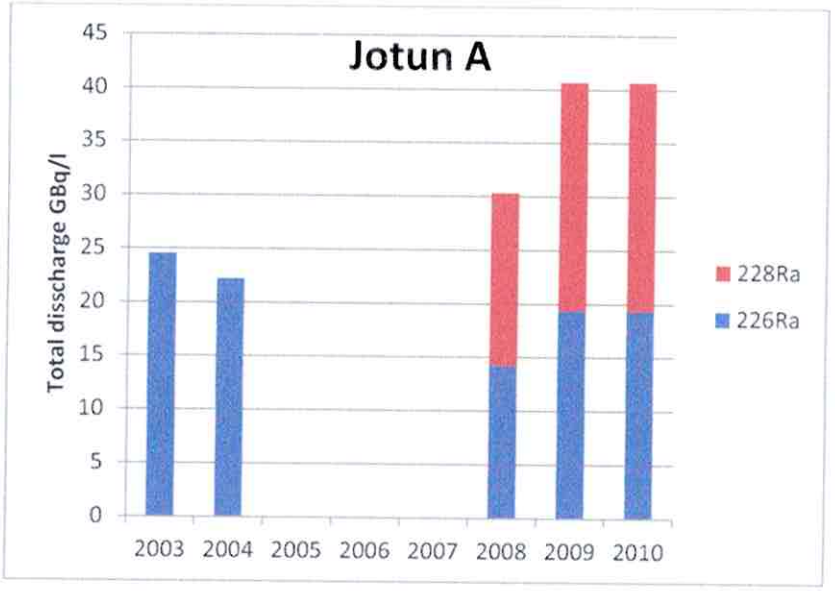

Figure 9b: Trends in the total discharges of total radioactivity of selected radionuclides at *Jotun* A. In 2003-2004 only ^{226}Ra was measured.

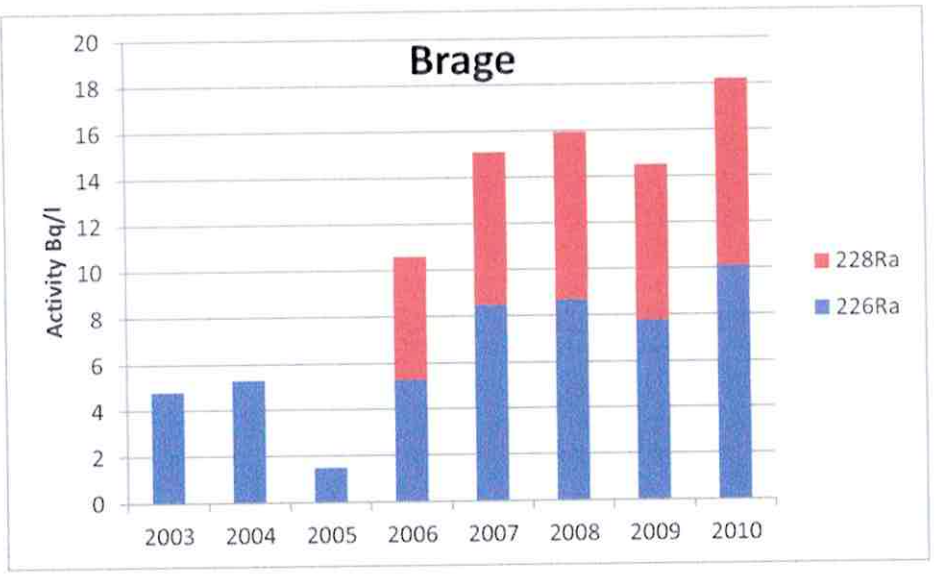

Figure 10a: Trends in the activity of the discharges of radionuclides at *Brage*. In 2003-2005 only ^{226}Ra was measured.

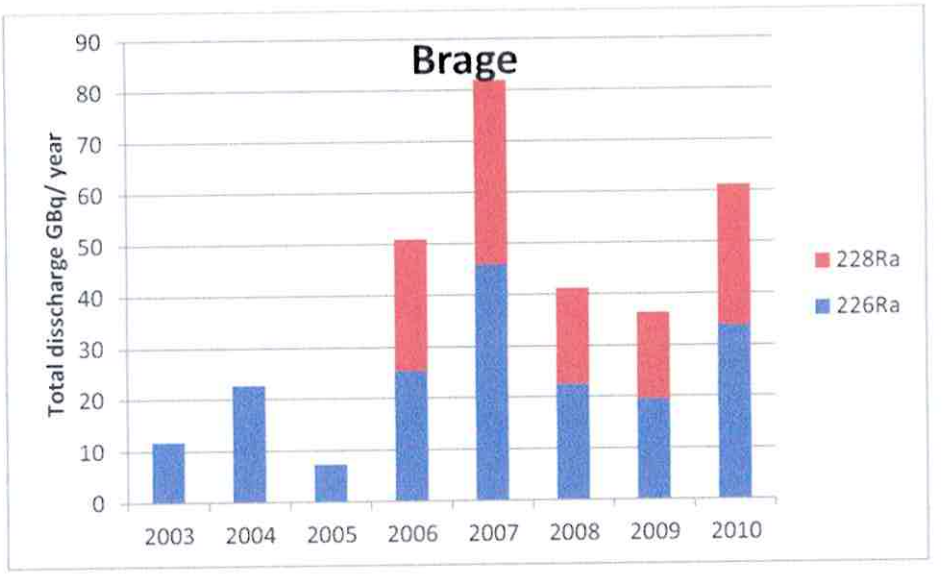

Figure 10b: Trends in the total discharges of total radioactivity of selected radionuclides at *Brage*. In 2003-2005 only ^{226}Ra was measured.

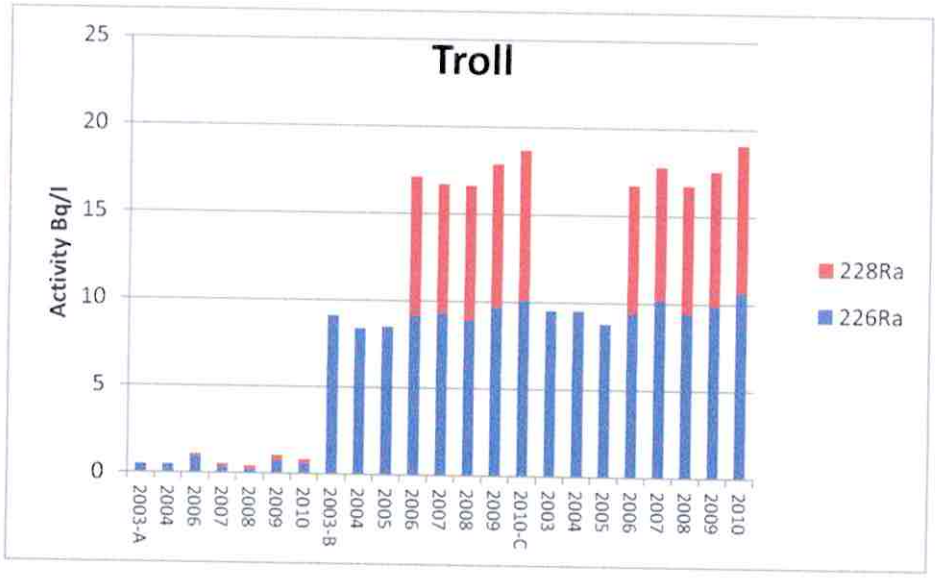

Figure 11a: Trends in the activity of the discharges of radionuclides at *Troll A*, *Troll B* and *Troll C*. In 2003-2005 only ^{226}Ra was measured.

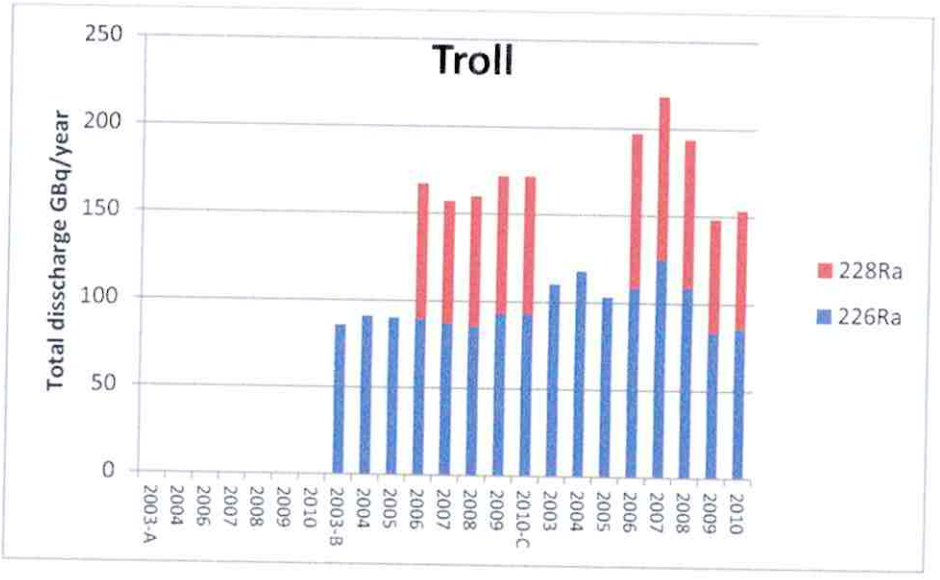

Figure 11b: Trends in the total discharges of total radioactivity of selected radionuclides at *Troll A*, *Troll B* and *Troll C*. In 2003-2005 only ^{226}Ra was measured.

Table 2: Average activity and radionuclide ratio for the period 2003-2010.

	^{226}Ra	^{228}Ra	$^{228}Ra/^{226}Ra$
	activity Bq/l		Ratio
Oseberg Ø	6.35	7.48	1.206
Statfjord B	0.46	0.24	0.417
Troll A	0.57	0.18	0.344
Statfjord A	0.46	0.40	0.928
Statfjord C	1.02	0.86	0.815
Ekofisk J	1.33	0.51	0.502
Veslefrikk	0.99	1.18	1.389
Gullfaks B	1.30	1.12	0.865
Ekofisk M	1.86	0.55	0.297
Snorre A	2.02	1.74	0.945
Gullfaks C	1.98	1.77	0.828
Gullfaks A	1.23	1.28	0.939
Snorre B	5.03	5.99	1.085
Oseberg S	6.14	4.96	0.882
Jotun A	6.15	6.89	1.123
Gyda	7.45	1.75	0.246
Brage	6.50	6.78	0.854
Troll B	9.15	7.96	0.671
Troll C	9.69	7.67	0.770

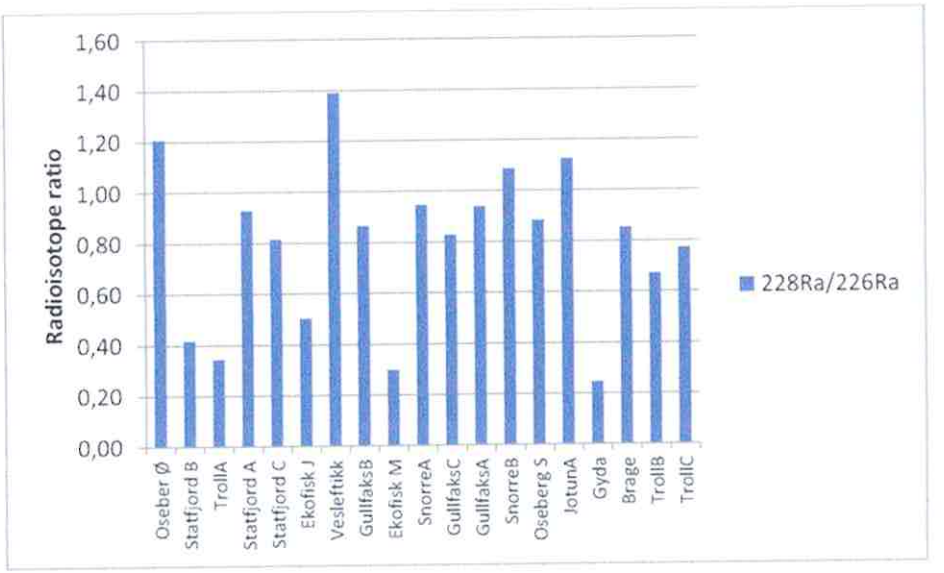

Figure 12: Ratio of radionuclides in the produced water.

4 Radionuclides in sediment

During the last 5 years, analyses of TENORM have been included in the some of the sediment monitoring programs (Table 3). The number of stations and surveys where these radioisotopes has been included is very limited.

Table 3: Fields where radionuclide analyses have been included in the sediment surveys. Year, responsible company and data status in indicated.

Field	Available sediment data	Company	Status
Statfjord	2007	UNIFOB	Few data
Gullfaks	2007	UNIFOB	Few data
Snorre	2007	UNIFOB	Few data
Oseberg	2007	DNV	Few data
Veslefrikk	2007	DNV	Few data
Ekofisk	2008	Akvaplan NIVA	Few data
Jotun Varg	2008	UNI-Reserach	Few data
Brage	2010	DNV	Good dataset
Troll	2007	DNV	Few data
Troll	2010	DNV	Good dataset

The available data varies in quality regarding detection limits and number of replicates. Assessment of the data in an environmental perspective is further restricted by the fact that the uncertainty is given as counting statistics and not as actual variation based on replicate samples.

Table 4 summarises all the available results relevant for accessing the possible impact of the selected nuclides. Where the data allows it, the average is calculated. With this relatively small dataset it is not possible to calculate normal uncertainty.

Table 4: Summary of available sediment activity data from the "sediment monitoring program". In cases where a range is given, all data is below detection limit and the range represents the different detection limits given. 1-6 cm indicates the depth of the sediment analysed.

Field / location	Year	^{226}Ra	^{228}Ra	^{210}Pb	^{228}Th	^{228}Ra / ^{226}Ra	^{210}Pb / ^{226}Ra
		Bq/kg				Ratio	
Statfjord A	2007	39.0	24.0	100.3	16.7	0.62	2.57
Statfjord B	2007	34.0	23.5	91.3	16.0	0.69	2.69
Statfjord C	2007	61.7	45.5	93.3	34.3	0.74	1.51
Reg ref 6R	2007	26.3	27.0	127.3	5.5	1.03	4.84
Gullfaks B	2007	23.25	6-49	138	10.2	DL	5.94
Snorre TLP	2007	173.3	103.7	216.7	90.7	0.60	1.25
Snorre B	2007	18.7	27.0	182.3	11.3	1.45	9.77
Reg ref 16R	2007	32	19-27	300	21	DL	9.38
VF-12R (5000m)	2007	6.9	≤ 1.7	87	6.9	DL	12.61
Troll B	2007	25.1	24.7	417	32.1	0.98	16.61
OSEF-09 (474m)	2007	5.5	≤ 1.7	61	5.7	DL	11.09
VF-09 (509m)	2007	7.4	10.7	153	10.6	1.45	20.68
OSEG-17A (5000m)	2007	5.6	≤ 1.5	35	4.7	DL	6.25
Troll A-A	2007	21.5	29.9	409	39.7	1.39	19.02
REG3-06	2007	23.7	31.7	390	40.5	1.34	16.46
EKO-Avr	2008	6.0	6.9	25.7	2.1	1.16	4.30
Reg1-03	2008	6.3	7.4	19.6	1.9	1.17	3.11
Varg	2009	D.L.	D.L.	31-39	4-7	DL	DL
Jotun	2009	11-15	16-30	50-91	15-18	DL	DL
Reg 3 ref 9	2009	D.L.	D.L.	D.L.	6-13	DL	DL
Reg 3 ref 7	2009	D.L.	D.L.	53-438	5-45	DL	DL
Brage average	2010	18	22	12	61	1.21	3.33
Brage average 0-1 cm	2010	21.0	24.3	10.7	62.8	1.16	2.99
Brage average 1-3cm	2010	21.3	22.6	11.5	65.1	1.06	3.06
Brage average 3-6cm	2010	13.7	21.3	12.8	55.9	1.56	4.08
Troll avr	2010	50.3	47.5	37.3	317.9	0.95	6.33
Troll Avr 0-1cm	2010	45.9	43.4	39.8	401.3	0.95	8.75
Troll Avr 1-2 cm	2010	50.5	54.6	40.3	341.3	1.08	6.76
Troll Avr 3-6 cm	2010	54.4	42.8	32.0	211.3	0.79	3.89
REG3-06, 0-1 cm	2010	≤16	≤28	31	400	DL	DL
REG3-18, 0-1 cm	2010	16	≤16	≤6	73	DL	DL

In the RAIV project, several samples of sediment and seawater were collected and analysed. The results from the sediment analyses of the samples collected during the project period show that the concentrations vary in the range of 1-60 Bq/kg dry weight. The results seem to group into two activity ranges, 1-10 Bq/kg and 10-60 Bq/kg respectively. No distinct profiles of radium in the samples are seen. (Table 5,Figure 13).

Table 5. Analytical results for sediment samples collected in 2004 (RAIV project). The uncertainty is given as 2 standard deviations (appr. 95 % confidence interval)

Sample	Depth	Measured activity [Bq/kg dry weight]
	[cm]	^{226}Ra
RIII – 07 / 22.05.2004	0-1	11.1 ± 2.6
	1-2	≤ 0,8
	2-3	1.9 ± 1.1
	3-4	10.6 ± 1.7
	4-5	13 ± 4
HUL 16R / 22.05.2004	0-1	7.1 ± 2.7
	1-2	8.6 ± 1.9
	2-3	9 ± 4
	3-4	11 ± 6
	4-5	10.8 ± 2.1
	5-6	11.3 ± 2.8
VFR 12R / 23.05.2004	0-1	8.4 ± 1.8
	1-2	3.8 ± 1.3
	2-3	5.0 ± 2.0
	3-4	1.4 ± 1.1
	4-5	15 ± 6
RIII – 2 / 25.05.2004	0-1	2.5 ± 1.6
	1-2	8 ± 6
	2-3	4.9 ± 1.8
	3-4	≤ 1.8
	4-5	2.4 ± 0.8
	5-6	≤ 1.4
OSC 01 – R / 25.05.2004	0-1	6.2 ± 2.1
	1-2	7.9 ± 1.4
	2-3	6.2 ± 0.7
	3-4	1.7 ± 0.7
	4-4.5	10 ± 4
OSS 14 – R / 28.05.2004	0-1	8.2 ± 2.3
	1-2	2.9 ± 0.9
	2-3	≤ 1.0
	3-4	≤ 4
	4-5	8.1 ± 0.6
OSG 17 – R / 28.05.2004	0-1	7.1 ± 1.6
	1-2	9 ± 4
	2-3	11.3 ± 2.0
	3-4	7.8 ± 1.5
	4-5	14.2 ± 1.6
	5-6	14.1 ± 1.8
ALVHEIM REF / 30.05.2004	0-1	8.7 ± 1.3
	1-2	6.0 ± 2.8
	2-3	4 ± 2
	3-4	7 ± 3
	4-5	3.5 ± 0.8
TOG 11R / 01.06.2004	0-1	25.8 ± 2.6
	1-2	12.7 ± 1.5
	2-3	18 ± 7

Sample	Depth	Measured activity [Bq/kg dry weight]
	[cm]	^{226}Ra
	3-4	21 ± 6
	4-5	14 ± 4
RIII – 08B / 02.06.2004	0-1	49 ± 4
	1-2	37 ± 3
	2-3	30 ± 5
	3-4	49 ± 4
	4-5	36 ± 8
TRC 99R / 04.06.2004	0-1	40 ± 6
	1-2	28 ± 6
	2-3	47 ± 4
	3-4	40 ± 11
	4-5	32.1 ± 2.6
	5-6	39.2 ± 2.9
FRAM A2 – 7R / 04.06.2004	0-1	53 ± 9
	1-2	56 ± 7
	2-3	44 ± 9
	3-4	47 ± 5
	4-5	39 ± 5

Analyses of ^{226}Ra in archive samples from AkvaplanNiva show concentrations in approximately the same range, up to about 40 Bq/kg (Table 6). There are no evident time trends in the samples from the same location during the period from 1998 to 2004.

Results for the analyses of radium in the seawater samples are shown in Table 7 and Figure 14. The concentrations are a little higher than the average for seawater (ΙΑΕΑ, 1990), but the results include radium adsorbed to particles in the water which may explain the discrepancy.

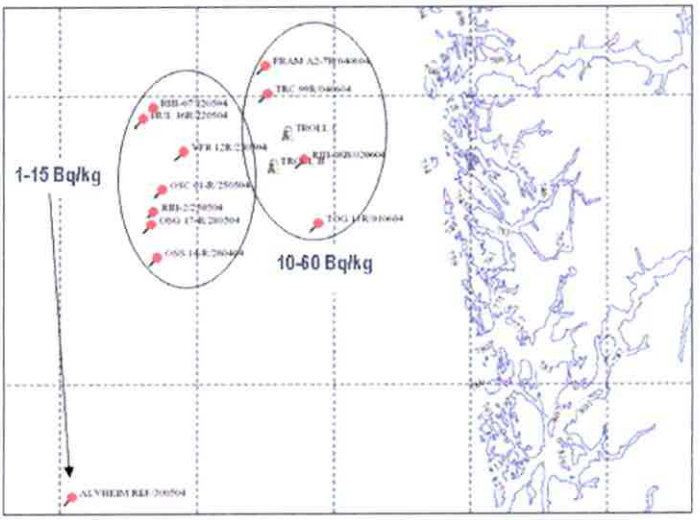

Figure 13. Sediment locations and ^{226}Ra concentration ranges for samples collected in 2004 (RAIV project).

Table 6. Analytical results for archived sediment samples from AkvaplanNiva (RAIV project). The uncertainty is given as 2 standard deviations (appr. 95 % confidence interval)

Sample	Date	Measured activity [Bq/kg dry weight]
		^{226}Ra
Reg st. 2-7	05.05.1998	4.4 ± 0.3
Reg st. 6-6	09.05.1998	22 ± 10
Reg st. 7-6	17.05.1998	3.2 ± 1.4
Reg III 02-8	20.05.2001	10.3 ± 1.1
Reg III 06-6	28.05.2001	27 ± 5
Reg III 07-6	22.05.2001	3.4 ± 1.9
HC: R3-02-13	25.05.2004	4.5 ± 0.8
HC: RIII-06-7	01.06.2004	26 ± 6
HC: Reg 3 07-7	22.05.2004	4.3 ± 1.1
TRB 07-8	26.05.2001	23 ± 8
TRB 21-6	26.05.2001	20 ± 7
TRB 26-8	26.05.2001	33 ± 5
TRB 32-7	26.05.2001	27 ± 11
TRB 33-8	25.05.2001	27 ± 13
TRB 35-7	25.05.2001	25.1 ± 2.7
HC: TRB 04-1-8	03.06.2004	27 ± 7
HC: TRB 04-2-7	02.06.2004	21.5 ± 2.4
HC: TRB 04-05-6	02.06.2004	18 ± 7
HC: TRB 04-06-8	02.06.2004	17 ± 6
HC: TRB 04-08-6 (1-3)	02.06.2004	42 ± 4

Table 7. Analytical results for seawater samples collected in 2006 (RAIV project). The uncertainty is given as 2 standard deviations (appr. 95 % confidence interval)

Sample	Depth	Measured activity [mBq/litre]
	[m]	^{226}Ra
VAR14R / 21.05.2006	Surface	2.07 ± 0.22
SIG17R / 21.05.2006	Surface	2.68 ± 0.35
RII-06 / 20.05.2006	Surface	3.54 ± 0.34
RII-06 / 20.05.2006	Middle	3.61 ± 0.40
RII-06 / 20.05.2006	Bottom	2.54 ± 0.22
RII-04 / 28.05.2006	Surface	3.57 ± 0.55
RII-08 / 25.05.2006 *	Surface	-
RII-09 / 27.05.2006 *	Surface	-
RII-09 / 27.05.2006 *	Middle	-
RII-09 / 27.05.2006	Bottom	2.46 ± 0.31

**Analysis failed*

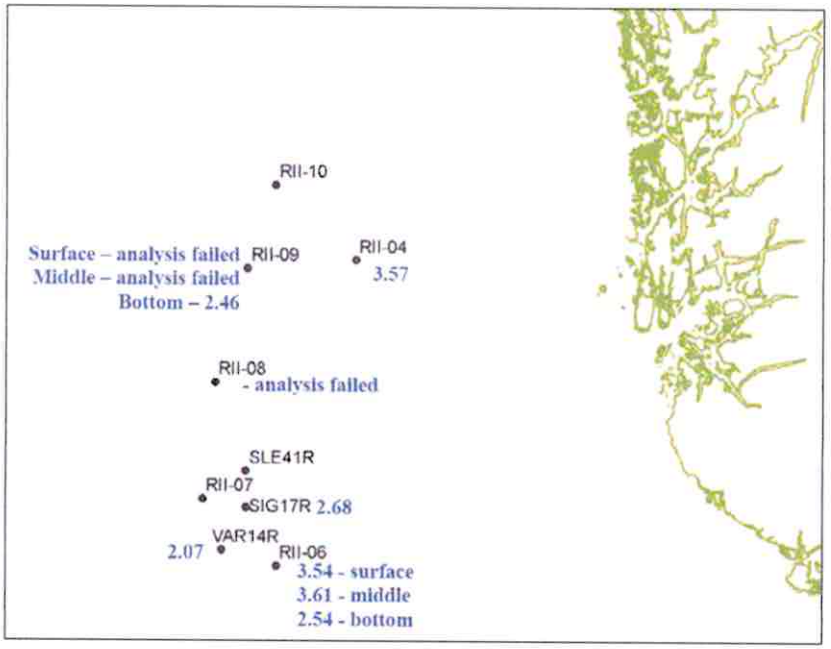

Figure 14. Seawater locations and ^{226}Ra concentrations (mBq/litre) for samples collected in 2006.

Local sedimentation conditions

There are significant differences among the selected fields from the perspective of sedimentation. The *Ekofisk* area is relatively shallow (70m) and with a sandy bottom. Wave action may reach the bottom, affecting the sediment surface and preventing a build up of contaminants as documented from sediment surveys the last 20 years. At the *Troll* and *Brage* area the situation is different. These areas are considerably deeper and with organic rich sediment, indicating settling of particles on the bottom. The physical nature of the deep water areas in combination with large discharges of PW associated isotopes makes these locations suitable for fate studies.

4.1 Radium in seawater

In the report "ND/E-19/03" an attempt was made to calculate the different contributions to ^{226}Ra, the predominant radionuclide in PW, in the North Sea. The estimates were made on the assumption of a ^{226}Ra activity concentration in the sea water of 5 mBq/litre. More recent results show that this should be reduced down to 2-3 mBq/litre. The imbalance between sources and sink can probably be explained by lower levels of ^{226}Ra in surrounding oceans, leading to a net loss of radium from the North Sea (Table 9).

Table 8. Data from ^{226}Ra and ^{228}Ra from seawater samples from the *Gullfaks A* field and some data from region 2 (background levels).

Field	**Year**	**^{226}Ra**	**^{228}Ra**	**^{228}Ra / ^{226}Ra**
		Activity mBq/l		Ratio
Gullfaks A	2008	6.73	4.63	0.66
Ref -11R	2007	6	3.9	0.65
Reg 2	2006	3,1		

Table 9. ^{226}Ra in the North Sea estimates (ND/E-19/03). Because of the lack of enough data, the values must be used with caution.

	^{226}Ra
Concentration	~ 5 mBq/litre
Total amount	$3x10^{14}$ Bq
Sources:	
Ingrowth from uranium	$9x10^{11}$ Bq/year
Leakage from sediments	$6x10^{11}$ Bq/year
Contribution from rivers	$6x10^{11}$ Bq/year
Sink:	
Radioactive decay	$1x10^{11}$ Bq/year

5 Radioisotopes in biota

Only a few measurements of ^{226}Ra, ^{228}Ra, ^{210}Pb in biota are available. Levels in bottom living organisms from the *Troll* area are reported to range between 4-8 Bq/kg fresh weight (RAIV WP1 Summary). Sediment data from the same project show ^{226}Ra levels in sediment between 20-33 Bq/kg. The same project presented fish data from various

regions measured with alpha-spectrometry to be in the range of 8-14 mBq/kg fresh weight. During the water column monitoring 2009 at *Ekofisk* (region 1) ^{226}Ra was measured in different tissues from fish and mussels in the exposed locality closest to the PW discharges and from a regional reference station. The mussel tissue had activity for ^{226}Ra in the range of 30-50 mBq/kg wet weight and the cod muscle had activity in the range of 7-17 mBq/kg wet weight. There were no statistical difference in activity levels between biota from the exposed locality and the reference locality.

Bioaccumulation factors for ^{226}Ra in the range of 100-10000 have been reported. With such a high accumulation factor it should be possible to find some of the discharged ^{226}Ra in PW exposed biota if the compound is bio-available in such an exposure scenario. However this has not been indicated by measured activity concentrations.

^{226}Ra, ^{228}Ra and ^{210}Pb content in fish and mussel samples analysed with gamma spectrometry has also been reported (see Table 10 and 11). Samples were collected at different positions 500-8000 m from *Troll B*. There was no clear difference between activity concentrations in samples collected close to the rig compared to samples collected further away, suggesting that the measured levels are equivalent to background levels of natural radioactivity.

Table 10. Activity concentrations in mussels sampled in the vicinity of *Troll B*, per 2003-10-14.

	Measured activity (Bq/kg fresh weight)			
Sample	**^{226}Ra**	**^{228}Ra**	**^{210}Pb**	**^{210}Po**
Reference mussel "zero tissue"	≤ 0.1	≤ 0.2	2.7 ± 0,9	29 ± 10
Mussel tissue 500m	0.7 ± 0.4	≤ 0.4	8.8 ± 1.2	35 ± 6
Mussel tissue 1000m	1.8 ± 0.7	≤ 0.3	11.5 ± 2.8	22 ± 6
Mussel tissue 2000m	0.8 ± 0.7	≤ 1.1	11.1 ± 2.6	30 ± 8
Mussel shell 500m	7.1 ± 3.0	≤ 2.6	≤ 6	6.5 – 29 *
Mussel shell 1000m	6.9 ± 1.6	≤ 2.1	≤ 7	6.6 – 29 *
Mussel shell 2000m	5.3 ± 2.8	≤ 2.6	≤ 7	7.3 – 21 *

* Where ^{210}Po was detected but not ^{210}Pb, it is not possible to determine how much ^{210}Po comes from growing in from non-detectable ^{210}Pb. In these cases an activity range is given for ^{210}Po. The max value corresponds to there only being ^{210}Po and no ^{210}Pb in the sample. The min value corresponds to the opposite; all ^{210}Po comes from growing in from ^{210}Pb and no ^{210}Po has been taken up directly from the water.

Table 11. Activity concentrations in fish sampled in the vicinity of *Troll B*, per 2003-10-14.

	Measured activity (Bq/kg fresh weight)			
Sample	**^{226}Ra**	**^{228}Ra**	**^{210}Pb**	**^{210}Po**
Reference fish "zero meat"	≤ 0.2	1.3 ± 0.6	≤ 0.9	0.038 – 0.027 *
Fish meat 500m	≤ 0.2	≤ 0.4	≤ 0.8	0.15 – 1.1 *
Fish meat 1000m	≤ 0.1	≤ 0.2	≤ 0.4	0.067 – 0.48 *
Fish meat 8000m	≤ 0,1	≤ 0,2	≤ 0,3	0,074 - 0,53 *
Reference fish "zero bone"	2.6 ± 1.1	≤ 1.2	≤ 2.8	0.31 – 2.2 *
Fish bone 500m	3.6 ± 2.4	≤ 2.7	≤ 7	0.34 – 2.2 *
Fish bone 1000m	4.6 ± 1.8	≤ 2.5	≤ 6	0.39 – 2.8 *
Fish bone 8000m	4.8 ± 1.8	≤ 1.2	≤ 2.2	0.26 – 1.9 *

* See explanation below table 10.

Table 12 shows an overview of concentrations found in literature for the mentioned radionuclides in fish and mussels. These values represent natural variation of radioactivity in fish and mussels (background). A comparison with measured levels in RAIV WP1, OLF samples from 2003 as well as the mentioned *Ekofisk* data confirms that the measured activity concentrations are to a large extent within natural variation found in background radioactivity. The only exception is ^{210}Pb in mussel showing an activity concentration somewhat higher than reported background. Background data for the North Sea to confirm this is not available.

Table 12. Literature values for activity concentrations of ^{226}Ra, ^{228}Ra, ^{210}Pb and ^{210}Po in mussels and fish. All values are given in Bq/kg fresh weight.

Matrix	**^{226}Ra**	**^{228}Ra**	**^{210}Pb**	**^{210}Po**
Mussel tissue	0.08-1.39 [1]	0.8-2.2 [1]	0.6 – 2.6 [2, 3]	19 -132 [2*, 3]
Mussel shell	0.111-5.18 [1]	12 [1]	ND	ND
Fish meat	0.007-2.15 [1, 2]	0.27- 0.65 [1]	0.0024 – 0.8 [2]	0.064 – 4.5 [2*]
Fish bone	0.24- 5.15 [1]	2.1 – 33.3 [1]	ND	ND

[1] IAEA (1990). "The environmental behaviour of radium"

[2] EC (2002). "MARINA II- Update of the MARINA project on the radiological exposure of the European Community from radioactivity in North European marine waters."

[3] Carvalho, F.P. (1995). "^{210}Po and ^{210}Pb intake by the Portuguese Population: The contribution of seafood in the dietary intake of ^{210}Po and ^{210}Pb"

* Note that enhanced activity concentrations that indicate a contamination of the area due to industrial activity are not included in this overview.

ND: No data found

6 Doses to biota and humans

The effective doses to humans and biota depend on the source strength, the type and energy of the radiation, if the source is located outside or inside the organism, and the radiological sensitivity of the organ or organism being irradiated. The chemical properties of the radionuclide also play an important role for the biological uptake in the organism. Total absorbed dose rate, in the unit gray (Gy) per hour, is used to measure exposure for ionizing radiation.

A conceptual mode of responses of organisms, populations and ecosystems to ionising radiation in the environment has been proposed by Polikarpov (1998). The model considers 5 zones of exposure (Figure 15). A "dose limit" of 5mGy/y would ensure that exposure is within zone 1 or 2.

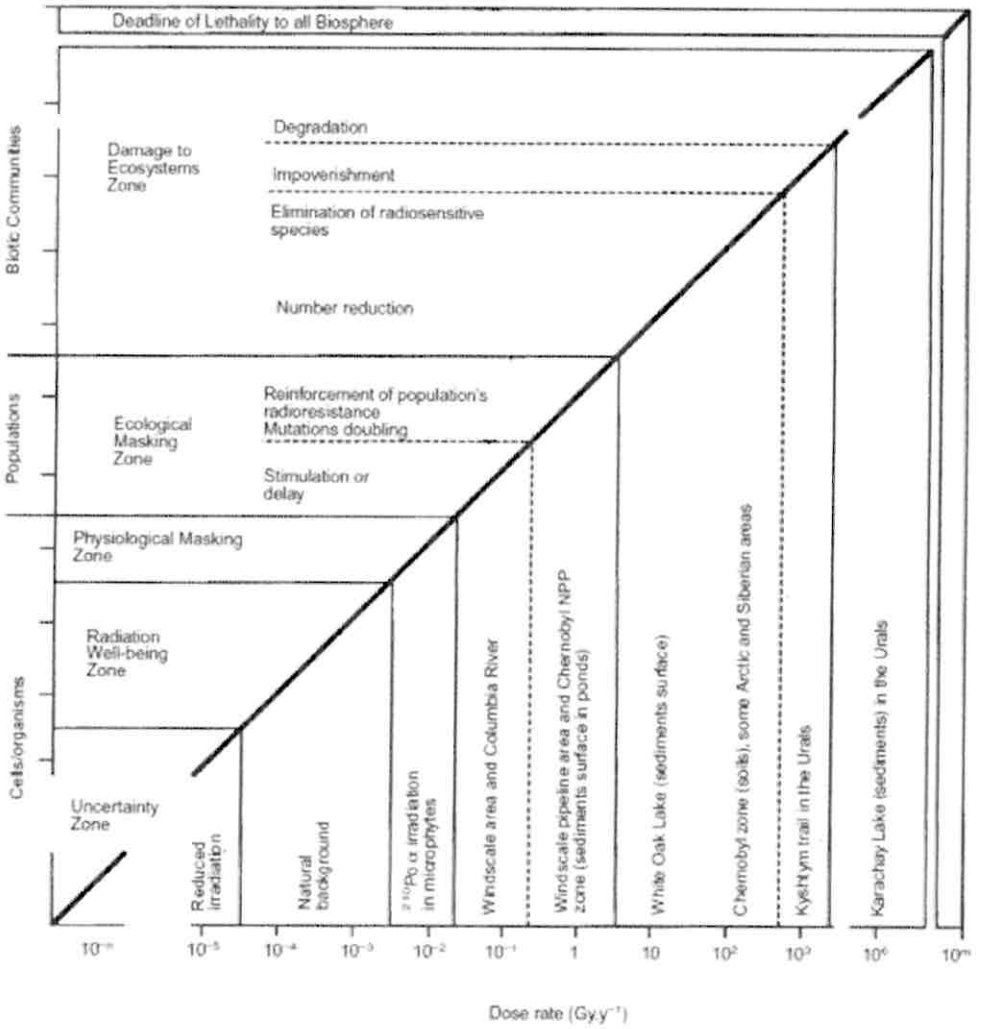

Figure 15 Conceptual model for doses to biota. A "dose limit" of 5 mGy/y would ensure that exposure is within zone 1 or 2.

6.1 Doses to biota

Table 13 shows calculated external doses to fish. In the calculations only ^{226}Ra (and daughters) is taken into account. External doses are calculated for fish living in water with background levels of ^{226}Ra, but also for fish living in water with activity concentrations of ^{226}Ra corresponding to the levels in PW from Troll. As can be seen, even the "undiluted" highest ^{226}Ra concentration doses to fish are within the "radiation well-being zone". No calculations have been done using RAIV WP1 results since these levels are considered to be natural background levels.

Table 13. External dose to fish from ^{226}Ra.

^{226}Ra in sea water	**External dose rate [µGy/h]**	**External dose [µGy/year]**
Background level – 2 mBq/l	$4.7 \cdot 10^{-6}$	0.04
Troll prod.water – 1:100 dilution	$9.3 \cdot 10^{-5}$	0.8
Troll prod.water – 10 Bq/l	$9.3 \cdot 10^{-3}$	81.5

Similar simple calculations have been done for internal doses. Here, background concentrations of ^{226}Ra, as well as an activity concentration of 2 Bq/kg (highest observation in literature, IAEA) have been used. The latter gives a conservative dose estimate considering that all measured values for ^{226}Ra are lower than 2 Bq/kg. Calculated doses must be considered very low. See table 14.

Table 14. Internal doses to fish from ^{226}Ra

^{226}Ra in cod	**Internal dose rate [µGy/h]**	**Internal dose [µGy/year]**
Background level – < 0,1 Bq/kg in tissue	$1.8 \cdot 10^{-3}$	16
Example – 2 Bq/kg	$3.6 \cdot 10^{-2}$	315

6.2 Doses to humans

The most important route of exposure for humans will be intake of fish from areas affected by discharges of radioactivity. Below, a literature review on doses to humans from TENORM in discharges from oil and gas industry is presented.

6.2.1 Doses from natural radioactivity

In the MARINA II report the effective dose rate to humans from natural radioactivity in the marine environment was estimated to be 45 μSv/year. When corrected for the use of different dose coefficients, this is the same order of magnitude as estimated by UNSCEAR 1993 (66 μSv/year).

A summary of publications giving estimates of doses to the population from natural radioactivity in the marine environment is given in Smith and Simmons (2009). The individual dose rates from radioactivity in the marine environment will be between 0.015 and 0.10 mSv/year, while the total dose rate from all natural sources including radon has been estimated (based on UK data) to be 2.23 mSv/year (Watson *et al.* 2005). About half of this is from radon exposure indoors.

6.2.2 Doses from release of produced water

The MARINA II study has calculated dose rates to the European population from discharges from anthropogenic sources for the years 1980-2000. Calculations of future dose rates have also been made assuming cessation of all discharges after year 2000, and alternatively assuming future discharges at the same level as in 2000. ^{210}Po gives the highest contribution to the estimated collective dose rates at all times. Both direct discharges of polonium and ingrowth from discharged ^{226}Ra and ^{210}Pb have been taken into account. However, the most important source of ^{210}Po in the North Sea Central compartment is discharge from the phosphate industry with a relatively small contribution from the decay of ^{226}Ra and ^{210}Pb discharged from the oil and gas industry (Povinec and Sanchez-Cabeza 2006). No concentration of ^{210}Po at the time of discharge has been given in the report.

For the year 2000 the estimated dose rate from radioactivity in discharged PW was 78 manSv/year. The calculations are however based on inadequate data sets concerning both total volume of discharged PW and concentrations of radionuclides in the water. It has been shown (ND/E-17/03) that the amount of ^{226}Ra discharged with PW from the Norwegian shelf is approximately 10% of the calculated discharge in the MARINA II study (Povinec and Sanchez-Cabeza, 2006). Using real discharge data will therefore reduce the MARINA II estimate significantly. Also, the MARINA II uses different concentration factors (CFs) for ^{210}Po in fish when calculating doses due to natural sources (1.5×10^3, calculated from an activity concentration of 1.5 Bq/kg fresh weight and an assumed sea water concentration of 1 mBq/liter) than for anthropogenic sources (2×10^4). The recommended CF from the IAEA is 2×10^3 (IAEA 2004).

7 Discussion and conclusions

The total discharge of radioactivity is dominated by contribution from a few fields and available data indicate low inter-annual variation in the discharges.

Of the radioisotopes measured in the PW it is clear that only ^{226}Ra and ^{228}Ra are of major concern for potential radiation effects to the marine environment. However it is valuable to also measure ^{210}Pb and ^{228}Th as they represent the dominating background level in the sediment.

The set of data available for the sediment activity situation around these platforms is very limited. The dataset from the *Troll* region 2010 (DNV 2011) is a good start when trying to assess whether the activity from the PW ends up in the sediment in the vicinity of the platforms. This study also provided results from vertically sectioned samples down to 6 cm. The deeper sediments deposited before the start of oil and gas production can be important for comparison. However, age of the sediment has to be confirmed by other parameters or a proper ^{210}Pb dating, or using the ^{137}Cs signal from the fallout from the nuclear weapon tests in the 1950s and 1960s. The present sediment data indicate significant differences in detection limits e.g. due to differences in sample quality and amount of available material.

The dataset indicate more or less the same level of ^{226}Ra and ^{228}Ra for all samples from *Brage* and *Troll* with a little higher activity at *Troll*. The ^{228}Ra/^{226}Ra ratio is similar to what is found in the PW. The general pattern of all measured radionuclides in the sediment differs largely from the typical pattern in the PW, indicating a limited contribution from PW discharges.

There are only a few suitable data available from biota on ^{226}Ra and no data on ^{228}Ra. Accumulation of ^{226}Ra in biota is indicated from high exposure situations like caging studies (WCM), however accumulation is not confirmed in wild fish collected in the vicinity of *Troll B* platform.

^{210}Pb in produced water

The method employed today for PW simultaneously gives determination of all the relevant radionuclides (^{226}Ra, ^{228}Ra and ^{210}Pb) after pre-concentration (precipitation) and gamma spectrometry. The method has a detection limit varying between 0.5 and 1 Bq/litre for 2 litre samples. Up until today, ^{210}Pb has not been detected in any PW samples from the Norwegian continental shelf. Some analyses of ^{210}Po in PW have been performed and the results show levels in the mBq/litre area. It is not unlikely that the levels of ^{210}Pb are in the same order of magnitude.

When reporting results to the Norwegian Radiation Protection Authority (NRPA), the detection limit for ^{210}Pb is multiplied by 0.5 and the obtained number is used as a probable level of ^{210}Pb in the PW. This number is again multiplied with the total volume of PW discharged the relevant year and NRPA reports this to OSPAR. The real concentration of ^{210}Pb in PW is probably much lower than 1 Bq/litre, maybe as low as a

few mBq/litre. As a consequence, the Norwegian discharge of ^{210}Pb is highly overestimated. The OSPAR goal for discharges of naturally occurring radioactive material is a reduction to background levels. It is unfortunate that Norway overestimates the discharge of ^{210}Pb.

To obtain better results for ^{210}Pb in PW, it is necessary to analyse ^{210}Pb radio-chemically via the daughter ^{210}Po. This method is both more time consuming and more expensive than the method used today.

Water exchange and dilution of PW discharges

In the areas on the Norwegian continental shelf where PW is being discharged, the typical net surface current speed is 20-100 cm/s causing a rapid dilution and transport away from the outfall. In areas like *Gullfaks* the discharge will typically be transported towards North, and a counter current transporting the Atlantic water south-eastwards may transport diluted and precipitated PW components to the North Sea and Skagerrak. Based on dispersal modeling, Rye *et al.* (2009) indicated that the added radiation levels on the sea floor caused by deposition of PW related ^{226}Ra will be of limited significance, compared to other natural sources and fluxes of ^{226}Ra. With the analytical precision in use and due to natural variability in radiation levels, it is unlikely that increased levels of activity in seawater or sediment can be detected. The current model "NorKyst -800" developed by HI, NIVA and The Norwegian Meteorological Institute (Havforskningsnytt 8-2011) may be suitable for further assessing the fate issue.

8 Suggestions for improvement of knowledge

Even though the possibility of negative biological effects is generally considered to be low, there is a need for documentation. Below, suggestions for relevant improvements of future monitoring of PW related radioactivity discharges are given.

- There is a potential for improvement of the scientific quality and suitability of the data from future investigations by better planning and coordination of the investigations. The most obvious need is to ensure a sufficiently low "limit of quantification" for the analytical approaches. Since the activity levels in the environment are typically very low, a high resolution is needed to detect possible differences. Standardised detection limits should be sufficient to reach background levels. Method recommendation: gamma-spectrometry for sediment and alpha - spectrometry for water and biota.

- Replicates samples should be analysed so that real uncertainties could be calculated, "counting statistics" from the spectrometer should only be complimentary data.

- More sediment and biota data is needed. Water data is needed primarily to define background in an area.

- Only reference stations with bottom substrate comparable to the sediment at the "oil field stations" should be selected.

- By including measurements of more elements (e.g. stable metals) the knowledge about transport processes and mechanisms could be improved.

- Use of sediment traps could be used as an alternative to bottom sediment sampling. The use of this approach is more costly than the direct use of bottom sediments but could provide better results.

- Determination of ^{210}Pb in PW by chemical separation, ingrowth of ^{210}Po and alpha spectrometry for correct estimates of discharges and impact of this radionuclide.

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