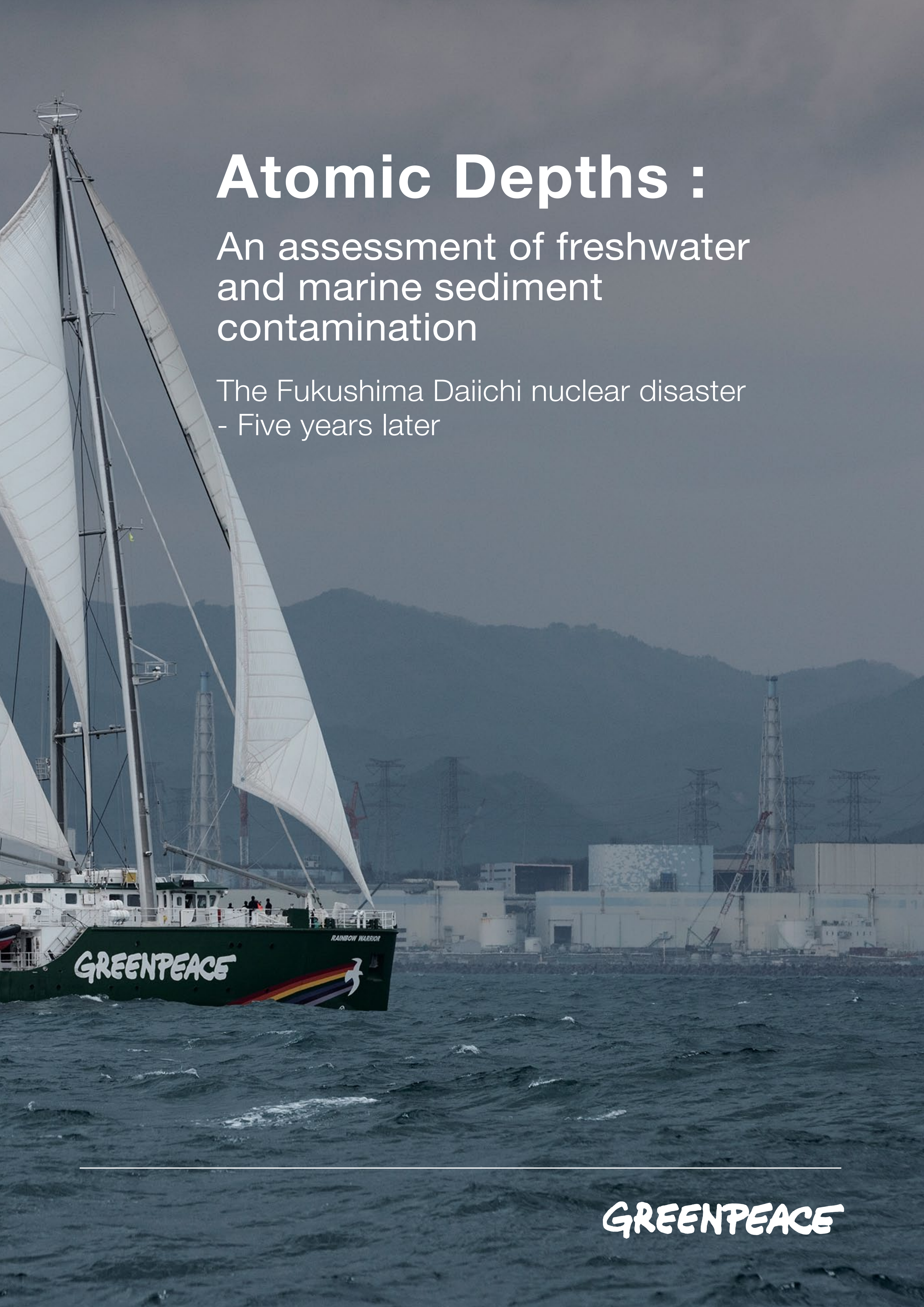
Atomic Depths :

An assessment of freshwater and marine sediment contamination

The Fukushima Daiichi nuclear disaster
- Five years later



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1 INTRODUCTION

The Fukushima Daiichi nuclear accident, which began on 11 March 2011, released large amounts of radioactivity into the Pacific Ocean. In fact, as calculated by the French Institute for Radiological Protection and Nuclear Safety (IRSN), ***"this is the largest one-off injection of artificial radionuclides into the marine environment ever observed."***[1]

This report is based on a review of the extensive scientific research that has been conducted since 2011 on radiocesium in seabed sediments in the Pacific Ocean along the Fukushima coast and in river systems and lakes. It also includes the results of Greenpeace radiation surveys conducted in the coastal waters, estuaries, and rivers of Fukushima prefecture in early 2016,[2] as well as in Lake Biwa, Shiga prefecture.

Fukushima Daiichi nuclear plant showing reactors 1-6 from Greenpeace chartered research vessel Asakaze, March 2016.

2 RADIOLOGICAL SOURCES TO THE PACIFIC OCEAN

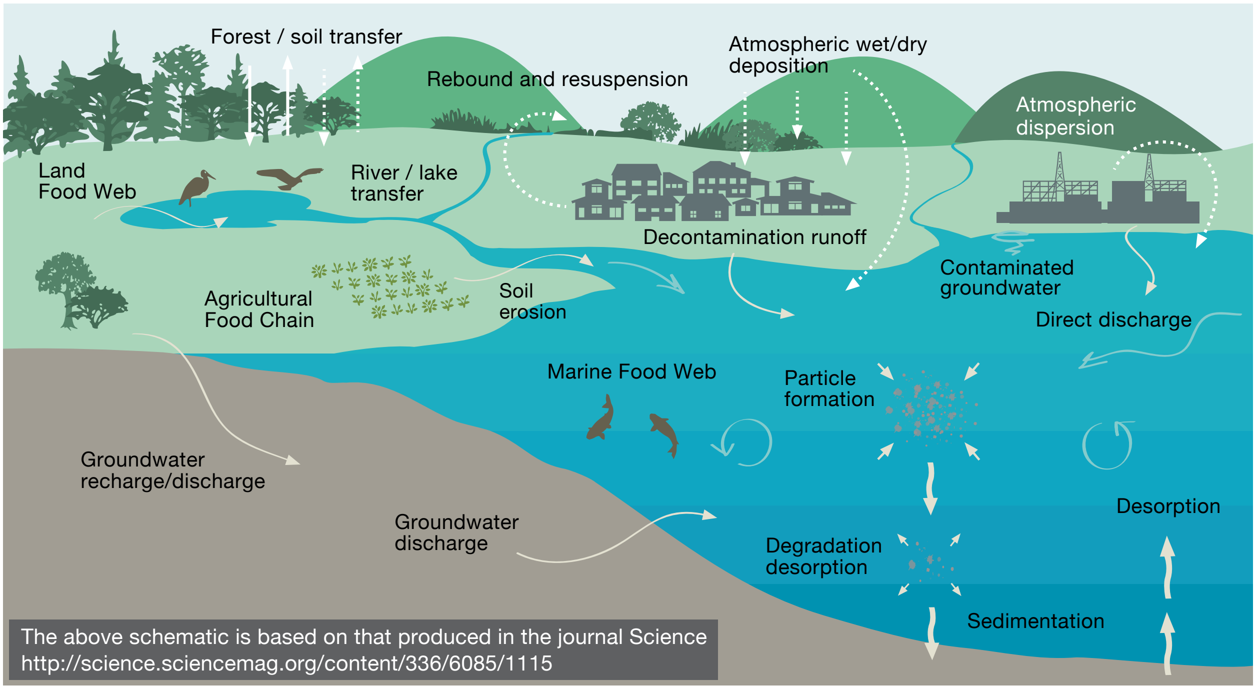
In order to understand the radioactive releases into the Pacific Ocean from the Fukushima Daiichi accident, and the impacts of these on marine ecosystems, it is necessary to have an overview of the known and the potential releases. Having a complete picture of what has been released into the ocean is particularly challenging, as the releases themselves do not come from one single source. To better understand, it is useful to look at the phases of the liquid radioactive discharges since the accident.

- **Phase 1** – 12th March 2011 - end of March - peak gaseous and particulate atmospheric releases resulting from the initial hydrogen explosions and venting of Fukushima Daiichi reactor units 1-3 and subsequent plume releases; [3]
- **Phase 2** – March 2011 – May – direct liquid releases from the Fukushima Daiichi plant via the northern and southern discharge channels with reports suggesting this from 26th March;
- **Phase 3** – from May 2011 to the present – liquid releases from the nuclear plant via contaminated groundwater migration and leaks from basement facilities;
- **Phase 4** – March 2011 ongoing – land run off via river systems, groundwater, and estuaries from coastal and inland Fukushima, with peaks during snow melt, typhoon season and heavy rains.

Releases Phase 1 and 2 – March to May 2011:

Releases from the Fukushima accident are based on estimations, measurement data and modeling.[4] However there remain significant uncertainties, with multiple and varied estimation. TEPCO data in 2013 estimated that 3.5 PBq of Cesiums-134 (Cs-134) and 3.6 PBq of Cesium-137 (Cs-137) were released into the marine environment between 26th March and 30th September 2011.[5] The TEPCO figures contrast with those of the Institute for Radiological

Diagram 1: Land to ocean transfer of radionuclides



The above schematic is based on that produced in the journal Science http://science.sciencemag.org/content/336/6085/1115

Protection and Nuclear Safety (IRSN), which in 2012 estimated that the Cs-137 releases from 21st March to mid-July 2011 were 27 PBq (27 x 1015 Bq).[6]

As Buesseler et al. observe, ***"the total activity of Cs released is still uncertain, ranging from 4-90 PBq, with most of the combined releases in the 15 to 30 PBq range for each Cs isotope."*** [7]

Release Phase 3 – May 2011 to the present:

The initial days and weeks of the accident led to the highest levels of release, but in the intervening 63 months radioactivity has continued to enter the Pacific Ocean.

Fukushima Daiichi plant – In terms of total direct radiological release to the Pacific Ocean since the peak period in spring 2011, no one precisely knows due to the lack of monitoring in the early phases, the complexity of the hydrology on the site, and the conditions resulting from the accident. However, it is accurate to state that the releases from the Fukushima Daiichi plant in the period from 2011 through to 2016 are a fraction of the early phase releases.

On the available data from TEPCO, a total of 33 TBq was discharged from the site to the Pacific from May 2011 through to the end of 2014[8], equal to 0.1% - 0.9% of the liquid releases to the marine environment during the early phases of the accident. No total data has been published by TEPCO for the period through 2016.

However, the reported unplanned release of 33 TBq of Cs-137 between May 2011 to December 2014 resulting from the disaster is an enormous radioactive discharge when compared to the routine releases from the European Union's largest nuclear plant, Graveline in northern France. For example, the six nuclear PWR reactors at this site discharged 0.000066 TBq of Cs-137 for the year of 2008.[9] The Fukushima Daiichi releases in the 3.5 year window from May 2011 to December 2014 are equivalent to 500,000 years of discharges from Graveline.[10]

Release Phase 4 – March 2011 to the present:

Land based releases (via river systems)

As detailed in the March 2016 Greenpeace report, Radiation Reloaded,[11] as a result of the atmospheric releases and deposition in March-April 2011, the mountainous forest and freshwater ecosystems of Fukushima-impacted areas throughout the prefecture and in neighboring regions have become vast reservoirs of radioactivity. A portion of the radiocesium deposited on forested land migrated to water systems (i.e. through rapid wash off) in the initial phase post-accident. The remainder is stored in the forest catchment and freshwater systems for long-term recirculation and slow low-level downstream migration.[12] Rivers move cesium downstream, deposit contaminated sediments where water velocities slow enough for particulate-bound cesium to drop out of the water column, and can resuspend particulate cesium, particularly during heavy precipitation events and snowmelt. Even with low discharge rates,[13] the redistribution of cesium via watersheds can be significant due to the sheer magnitude of the vast contaminated forests and land.

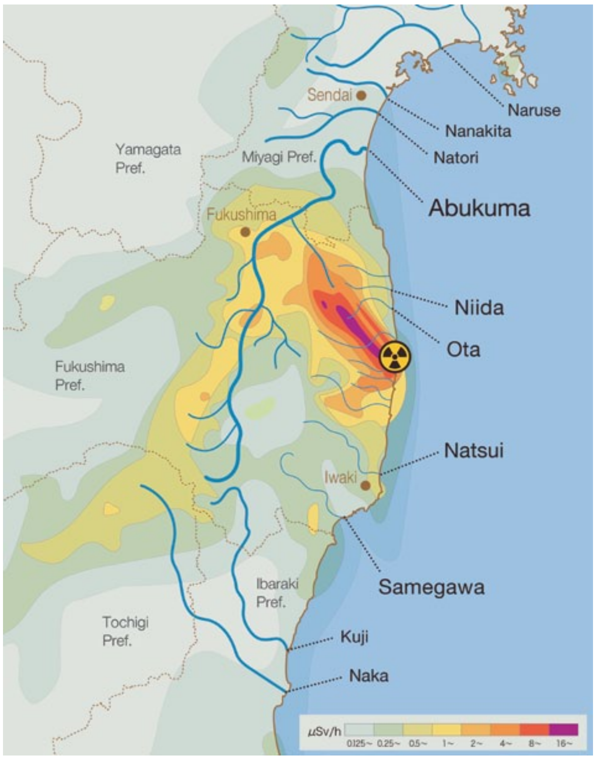
Fukushima prefecture and neighboring prefectures have a number of major and minor river systems that flow from contaminated upland forests to coastal plains, and ultimately empty into the Pacific Ocean. These river systems, in particular the Abukuma, Naruse, Nanakita, Natori, Kuji and Naka, as well other smaller river systems including the Mano, Nitta, Ota, and Ukedo, have catchments of thousands of square kilometers.

Evrard et al. report that ,*"the Abukuma catchment received the most radiocesium fallout during March-April 2011, followed by the Ukedo and Niida catchments. Radiocesium inventories for the 14 coastal catchments ranged between 734.9 TBq in*

the Abukuma to 16.2 TBq in the Ide catchment. The Abukuma catchment received approximately 30% of the fallout received by these 14 catchments, followed by 26% for the Ukedo and 12% for the Niida." [14]
In terms of the release of this inventory to the ocean, a study[15] that looked at the Abukuma River's 5,172km^2 catchment between June 2011 and May 2012 estimated that 1.13% of the initial radiocesium inventory (890 TBq) within the catchment had been exported to the Pacific Ocean.[16]

The groundbreaking work of J. Kanda has revealed the potential scale of land based contamination being translocated via water systems to the marine environment.[17] Kanda estimated the release of Cs-137 via the river systems of Fukushima through comparing published data of radionuclide concentrations in the artificial harbor and surrounding ocean. It was estimated that the total radionuclide released into the Pacific Ocean from 1 June to 30 September 2012 was 17.1 TBq.[18] This is only a fraction of the radiocesium inventory of the upland forests of Fukushima prefecture.

Map 1: River systems along Fukushima and neighbouring prefecture coastline discharging radioactivity into Pacific Ocean



This map is based on the radiation contour map of the Fukushima Daiichi accident, by Prof. Yukio Hayakawa. (also Map 3 on the page 12)

Contaminated Estuaries

As detailed in Greenpeace's 'Radiation Reloaded,[19] one consequence of downstream migration of radionuclides is the contamination of estuaries along the Fukushima coast. Due to the high nutrient inputs from rivers, and the fact that estuaries are often sheltered from strong coastal currents, shellfish, and marine animals use estuaries for food and as breeding grounds. Although some of the suspended cesium-bearing particulates are deposited along riverbanks,[20] a large portion of the mineral-bound radiocesium is discharged into marine estuaries.[21] As demonstrated by C. Chartin, et al. (2013), the river catchments will be a long-term, ongoing source of radiocesium to estuaries and coastal areas. A small percentage of the particulate-bound cesium experiences desorption with rising salinity, when rivers empty to the ocean. Although the percentage of the total inventory is very small, the total amount of newly liberated, dissolved radiocesium can be quite high due to the large total loads of radioactivity water systems can carry. This can then ***"easily accumulate in marine biota"***.[22]

In February 2016, Greenpeace observed major construction works in river estuaries along the Fukushima coastline.[23] The work includes the construction of concrete levees and the canalization of the river mouths. In addition to the negative ecological impact such projects will have on the wildlife that would otherwise depend on these destroyed estuaries, it potentially will effect the deposition of radiocesium at river mouths and offshore.

Greenpeace sediment sampling in Abukuma river, Miyagi prefecture, February 2016. The Abukuma has a 5,172km^2 catchment[15] which is largely in Fukushima prefecture, before entering the Pacific ocean in Miyagi prefecture.

3 RADIOCESIUM MARINE DISPERSAL AND COASTAL SEABED SEDIMENTS

Greenpeace Remotely Operated Vehicle (ROV) returning to survey vessel Asakaze off the coast of Fukushima prefecture, February 2016.

The decline in radiocesium concentrations in Pacific seawater (not including the port area of the Fukushima Daiichi plant) is explained by the rapidity of horizontal and vertical mixing rates in ocean water, which act much faster than the very slow migration in soil horizons after the initial phase post-deposition. Near coastal radiocesium, and specifically that found remaining in seabed sediments, it has been estimated to represent 1-3% of the total marine discharge (from the period March-May 2011).[24] It is this benthic radiocesium repository that is considered a key factor contributing to the higher levels of radiocesium found in benthic invertebrates and demersal fish.[25]

The distribution and fate of radiocesium in Fukushima's coastal sediments is governed by a number of factors, including: the rates at which it enters the marine environment, settles through the water column, the mixing of deposited contaminated sediment and burial beneath new sediment layers, as well sediment resuspension and transport offshore.

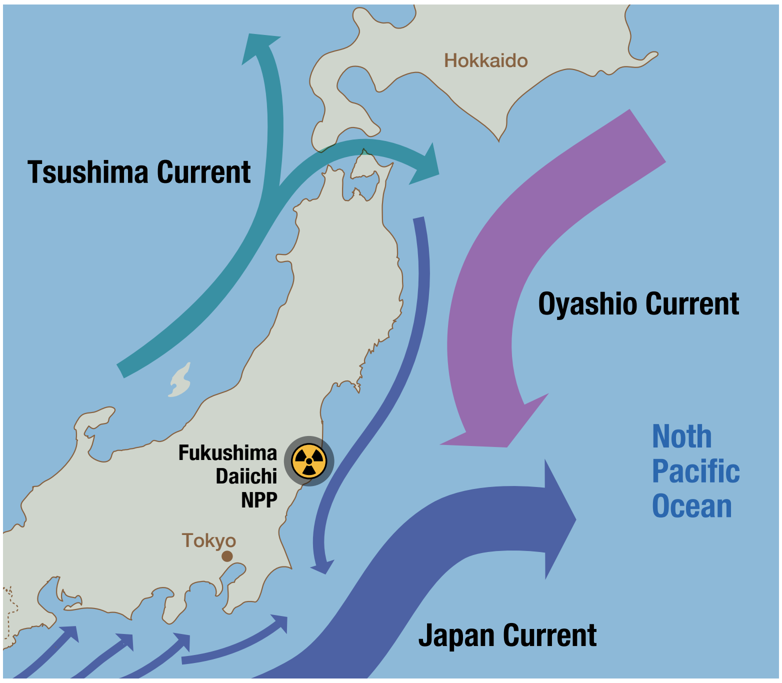
In core samples taken in 2013, Otosaka et al., identified that Cs-134 had penetrated to 1-2 cm depth and was not detected below 3 cm.[26] Estimates from Buesseler and Black suggest bioturbation will lower radiocesium surface sediment activity over the long period of 0.5-30 years. They conclude that the current radiocesium concentrations on surface seafloor sediments will remain contaminated for decades, ***"and so will the demersal fish that live on the seafloor."*** [27]

Localised anomalies:

As would be expected radiocesium concentrations are not uniformly distributed in seafloor sediments. In a towed gamma spectrometry survey conducted between November and February 2013, considerable variability of Cs-137 concentrations was identified in an area within a 20km radius of the Fukushima Daiichi site.[28] The survey detected relatively high levels within a 4 km coastal strip, averaging 292 Bq/kg. The highest levels detected were found 1-2 km south of the plant, which averaged 438 Bq/kg. The Cs-137 levels decreased further out from shore averaging 69 Bq/kg between 4-12 km from the coastline. These anomalies were found at the base of vertical features on the seafloor, sheltered from underwater currents, confirming that the local terrain is a strong determinant of the radiocesium concentrations in sediment.[29] The anomalies ranged in size from a few meters to several hundreds of metres in length. In addition, the highest anomalies identified were areas of a few meters of Cs-137 >40,152Bq/kg +/- 398 Bq/kg.

The researchers concluded that the anomalies are ***"likely to remain relatively unchanged over the timescales of a few years,"*** [30] and that, ***"The lack of information raises concerns regarding our ability to predict the effects of the accident on the marine ecosystem and limits our ability to form effective recovery strategies."***

Map 2: Ocean currents affecting dispersal of Fukushima Daiichi radioactive releases



Due to the influence of the Oyashio current offshore of Fukushima prefecture that bring cold waters from the north, and the Kuroshio current bringing warm waters from the south, this coastline of north eastern Honshu has rapid transport of water into the open Pacific Ocean*. As such the area is a highly dynamic mixing zone which has presented major challenges to the scientific community when assessing the dispersal of radioactivity released as consequence of the Fukushima Daiichi accident.

* "Fukushima radionuclides in the NW Paci c, and assessment of doses forJapanese and world population from ingestion of seafood" Pavel P. Povinec (Department of Nuclear Physics and Biophysics, Comenius University, Bratislava, Slovakia,) & Katsumi Hirose (Department of Materials and Life Sciences, Sophia University, Tokyo, Japan), Scientific Reports, See; http://www.ncbi.nlm.nih.gov/pubmed/25761420, accessed 16 June 2016.

4 GREENPEACE MARINE, RIVER and LAKE SURVEY : February - March 2016

Greenpeace radiation specialist Jacob Namminga on board research vessel off the coast of Fukushima Daiichi, removing marine sediment sample collected by Remotely Operated Vehicle (ROV), March 2016.

Between 21st February and 11th March 2016, Greenpeace conducted a radiation survey and sampling program along the coast, in the selected river systems of Fukushima prefecture, and the estuary of Abukuma in Miyagi prefecture. The survey work was conducted from a Japanese research vessel, supported by the Greenpeace's flagship, Rainbow Warrior. Radiation specialists from Greenpeace and ACRO, a French independent radiation laboratory, using an underwater remotely operated vehicle (ROV) with gamma spectrometer and sample grabber, measured radiation levels on seabed sediment within 10km of the coast. Land survey teams also took samples along the Abukuma, Ota, Natsui, Samegawa and Niida rivers, both near the coast and upstream. Sediment samples were collected and sent for analysis to the Chikurin radiation laboratory in Japan.

The survey team also conducted baseline sediment survey work in Lake Biwa with the ROV, gamma spectrometer and sample grabber, in Shiga prefecture western Japan. This ancient lake is under threat from potential restarts of Kansai Electric's (KEPCO) nuclear reactors in Fukui prefecture.

Results:

Rivers

The survey work confirmed the presence of high levels of radiocesium contamination along the Abukuma, Niida, and Ota rivers banks. Samples taken in the Abukuma River estuary, whose catchment lies largely within Fukushima prefecture, though it enters into the sea in Miyagi prefecture, showed Cs-137 levels ranging from 260-5,500 Bq/kg.

The concentrations in samples from the

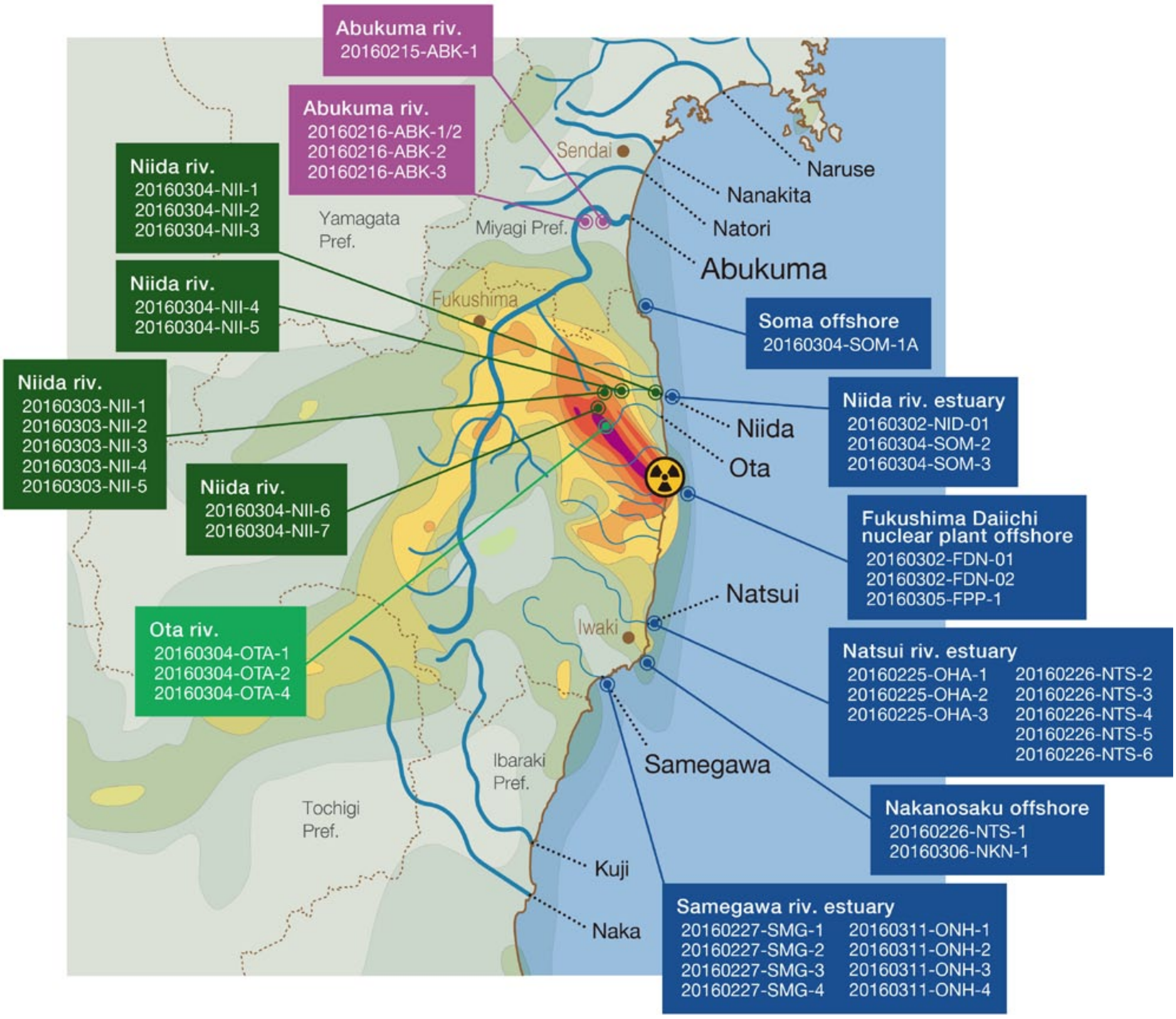
banks of the Niida and Ota river Cs-137 ranged from 920-25,000 Bq/kg. The samples were taken along the banks of the river, near dams, and upstream in the mountains, close to headwaters.

Activity of dried sediment/soil samples collected along river banks

No.	Location	Sample ID	Cs-137 (Bq/kg)	Cs-134 (Bq/kg)	Total Cs (Bq/kg)
1	Abukuma river bank	20160215-ABK-1	2,600±370	520±75	3,120
2		20160216-ABK-1/2	5,500±760	1,000±150	6,500
3		20160216-ABK-2	3,700±510	700±100	4,400
4		20160216-ABK-3	260±40	49±8.8	309
5	Niida river bank	20160303-NII-1	15,000±2,200	3,000±420	18,000
6		20160303-NII-2	3,500±490	680±98	4,180
7		20160303-NII-3	7,500±1000	1,500±210	9,000
8		20160303-NII-4	1,500±220	280±41	1,780
9		20160303-NII-5	1,600±220	310±44	1,910
10		20160304-NII-1	1,700±230	320±46	2,020
11		20160304-NII-2	920±130	180±26	1,100
12		20160304-NII-3	3,000±420	580±82	3,580
13		20160304-NII-4	3,300±470	620±90	3,920
14		20160304-NII-5	1,400±210	270±40	1,670
15		20160304-NII-6	25,000±3,500	4,800±690	29,800
16		20160304-NII-7	13,000±1,800	2,500±340	15,500
17	Ota river bank	20160304-OTA-1	20,000±2,900	3,800±540	23,800
18		20160304-OTA-2	2,800±380	540±76	3,340
19		20160304-OTA-4	18,000±2,600	3,400±490	21,400

Greenpeace ROV at a depth of 30 metres taking sediment sample on seabed off coast of Fukushima prefecture, 26 February 2016.

Map 3: Greenpeace radiation sediment sampling points from February-March 2016 survey



Marine sediments

The Greenpeace marine survey confirmed some of the findings of the scientific research conducted during the past 5 years. The results of survey and sampling in proximity to the Samegawa river estuary identified elevated levels of radiocesium. The Samegawa estuary to the south of Onahama, Iwaki district, and approximately 60km south of the Fukushima Daiichi plant, Cs-137 samples ranged from 52-120 Bq/kg, and Cs-134 of 8.9-21 Bq/kg. At the same time, samples from the Niida and Natsui river estuary ranged from 11 to 27 Bq/kg Cs-137. The range of cesium concentrations compare with sediments samples measured in the Sea of Japan, which were in the range of 0.25 Bq/kg.[31]

The Greenpeace marine survey was not able to confirm the results of the 2012/2013 survey (Thornton, Ohnishi et al.), which had identified radiocesium anomalies within a 20km radius of the Fukushima Daiichi plant. Factors include the highly localized nature of the anomalies and the efficiency of water which shields radiation, where even >40,000Bq/kg would not be detected at one meter. The sediment levels measured by Greenpeace ranged from 34-120 Bq/kg Cs-137. The Greenpeace results are inconclusive as to whether the anomalies continue to exist, or whether the radiocesium sediment has migrated and or dispersed.

Activity of dried marine sediment samples collected along Fukushima coast

No.	Location	Sample ID	Depth ROV (m)	Cs-137 (Bq/kg)	Cs-134 (Bq/kg)	Total Cs (Bq/kg)
1	Soma offshore	20160304-SOM-1	7.4	110±19	24±4.9	134
2	Niida river estuary	20160302-NID-01	9.6	16±4.2	<2.3	16
3		20160304-SOM-2	21.9	11±3.2	<2.7	11
4		20160304-SOM-3	22.2	10±3.1	<3.4	10
5	Fukushima Daiichi Nuclear plant offshore	20160302-FDN-01	18.7	110±18	18±4	128
6		20160302-FDN-02	16.7	120±19	24±4.8	144
7		20160305-FPP-1	24	34±7.3	5.3±2.1	39.3
8	Natsui river estuary	20160225-OHA-1	16	44±8.6	9.3±2.5	53.3
9		20160225-OHA-2	14	36±7.7	9.4±2.7	45.4
10		20160225-OHA-3	29	17±4.7	<6.4	17
11		20160226-NTS-2	26.1	25±6.1	5.2±2.1	30.2
12		20160226-NTS-3	26.2	27±6.2	<5.3	27
13		20160226-NTS-4	30.8	27±6.2	6.5±2.2	33.5
14		20160226-NTS-5	30.6	21±5.2	<5.4	21
15		20160226-NTS-6	30.6	22±5.9	<5.6	22
16	Nakanosaku offshore	20160226-NTS-1	26.2	23±6	<5.5	23
17		20160306-NKN-1	28.7	37±7.5	7.2±2.3	44.2
18	Samegawa river estuary	20160227-SMG-1	22.4	82±14	13±3.3	95
19		20160227-SMG-2	22.1	120±20	24±4.8	144
20		20160227-SMG-3	29.6	6.5±2.2	<2.7	6.5
21		20160227-SMG-4	29.6	16±4.2	<3	16
22		20160311-ONH-1	21.7	110±19	21±4.5	131
23		20160311-ONH-2	28.7	52±10	8.9±2.7	60.9
24		20160311-ONH-3	24.3	82±15	13±3.3	95
25		20160311-ONH-4	21.5	120±21	20±4.5	140

Note: When the sample is below the detection limit, the total is counted as 0 Bq/kg as a matter of practical convenience.

Lake Biwa, Shiga prefecture

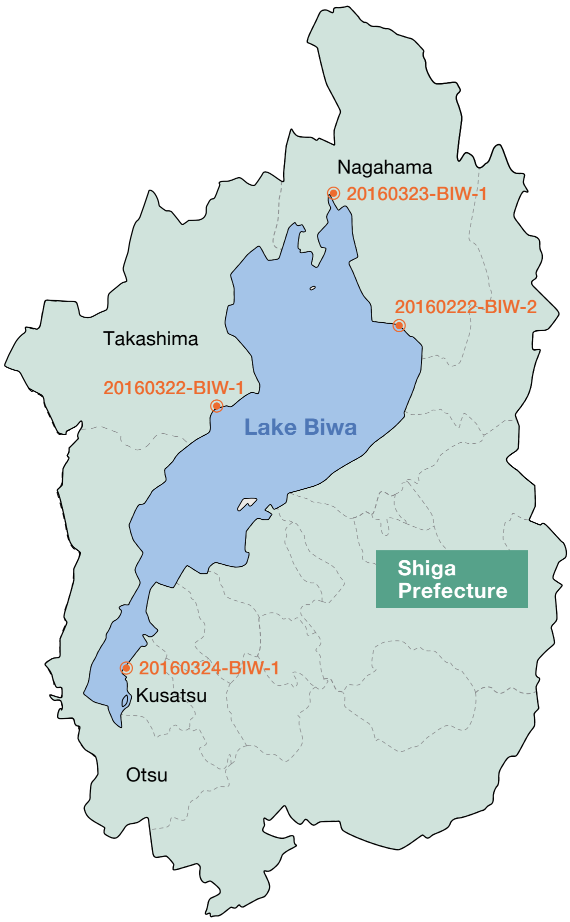
Greenpeace conducted a baseline sediment sampling survey in Lake Biwa. This ancient lake lies 44km and 64km from the Mihama and Takahama nuclear power plants in Fukui prefecture, which are owned by Kansai Electric. The lake and its predecessors in the region have existed for approximately 3.5 million years, and it is thus classified as one of the world's truly ancient lakes. It is home to 595 animals, 491 plants, including 62 endemic species and subspecies.

In fact, one of the principal reasons that led to a citizen legal challenge the restart of the Takahama reactors in the Otsu District Court, resulting in a successful injunction barring the restart of reactors 3&4, was the environmental threat from the restart of reactors in Fukui to Lake Biwa. This lake also supplies drinking water to 14 million people in the Kansai region.[32]

Activity of dried sediment samples collected in Lake Biwa

No.	Location	Sample ID	Depth ROV (m)	Cs-137 (Bq/kg)	Cs134 (Bq/kg)	Total Cs (Bq/kg)
1	Takashima city nearshore	20160322-BIW-1	3.8	<6.4	<4.5	ND
2	Nagahama city nearshore	20160322-BIW-2	7.7	13±4.6	<6.0	13
3		20160323-BIW-1	4.2	7.1±3.7	<7.2	7.1
4	Kusatsu city nearshore	20160324-BIW-1	3.1	<6.8	<5.1	ND

Note: When the sample is below the detection limit, the total is counted as 0 Bq/kg as a matter of practical convenience.



Map 4: Greenpeace radiation sampling points in Lake Biwa, March 2016

Results

The sediment sample analysis showed levels of radiocesium at 7-13 Bq/kg. This concentration was lower than that measured in 1997, prior to the Fukushima Daiichi accident.[33] This starkly contrasts with the widespread radiocesium contamination of lakes, reservoirs and dams throughout Fukushima prefecture, highlighting the importance and urgency of protecting Lake Biwa from radiological contamination.

As discussed above, studies of dams, lakes, and reservoirs in Fukushima-impacted watersheds have been shown to be both sinks for radiocesium and potential sources of significant downstream cesium deposition.[34] Lake Hayama for example, which lies 39 km NNW from the Fukushima Daiichi nuclear power plant, has been found to be highly contaminated. In 2012, sediment samples revealed radiocesium concentrations of 24,189 Bq/kg +/- 5636 (wet weight).[35] The result of which was uptake of radiocesium in lake fish. As O. Evrard et al. (2013) concluded, ***"the storage of contaminated sediment in reservoirs and in coastal sections of the river channels now represents the most crucial issue."*** [36]

Greenpeace Remotely Operated Vehicle (ROV) collecting sediment samples in Lake Biwa, Shiga prefecture, March 2016.
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Lake Biwa.
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5 CURRENT AND FUTURE THREATS

Nuclear waste storage area at Lake Hayama, Iitate village district, Fukushima prefecture, October 2015. Lake Hayama was heavily contaminated as a result of the March 2011 Fukushima Daiichi accident, in addition to radiocesium in the lake bed sediments, the forested mountains surrounding the lake are contaminated. Japanese government efforts to decontaminate along the roads, around houses and in fields in Fukushima has led to the generation of millions of cubic metres of nuclear waste stored in over 114,000 locations as of September 2015 (The Mainichi, 10th December 2015).

The radiological impacts of the Fukushima nuclear disaster on the marine environment, with consequences for both human and nonhuman health, are not only in the first years. There are both ongoing and future threats, principally the continued releases from the Fukushima Daiichi plant itself and translocation of land-based contamination throughout Fukushima prefecture, including upland forests, rivers, lakes and coastal estuaries.

Fukushima Daiichi

The estimates for the Cs-137 and Cs-134 radiological inventory in the reactor cores of Fukushima Daiichi 1-3 at the time of the accident was 700 PBq for each isotope respectively.[37] In terms of what was released to the marine environment through direct discharge during the weeks of March through September 2011, the actual percentage is dependent upon which estimated PBq release is selected. Aoyama et al., estimate that 3.5 PBq of Cs-137, equal to 0.50% of the of Cs-137 inventory in the three reactor cores at Fukushima Daiichi, was released into the Pacific Ocean.[38] Taking the higher estimated range as cited by Buesseler et al of 15-30 PBq Cs-137 released directly into the Pacific Ocean, would mean 1.6-3.26% of the total Cs-137 inventory.

An estimated 140 PBq of Cs-137, equal to 20% of the 700 PBq inventory, was released in contaminated water into the reactor buildings.[39] As of 16 June 2016, TEPCO estimates that there are

59,000 cubic meters of this water in the 1-4 reactor buildings.[40] It is this highly contaminated water that has been one of the major hazards and challenges over the past 5 years. The generation of highly contaminated water continues on a daily basis as TEPCO are required to continue to circulate cooling water into the 1-3 reactors. As of 16 June 2016, TEPCO was pumping 321 cubic meters each day into the reactors,[41] and a total of 652,710 cubic meters of highly contaminated treated water is retained in storage tanks, together with another 179,525 cubic meters of strontium-contaminated treated water.[42]

TEPCO has processed 1.5 million tons of water for removal of radiocesium, also as of 16 June 2016, with processing technologies deployed to remove up to 90% of a range of isotopes, including strontium. Further processing of the strontium water is on-going. However, the processing has not removed radioactive tritium, which have levels ranging from 0.6 Bq/l - 4.2 million Bq/l. In total as of February 2016, TEPCO estimated that there would be approximately 900 TBq of tritium within the storage tanks at the Fukushima Daiichi site.[43] A total of over 3.5 PBq of tritium is estimated to have been in reactors 1-3 core fuel as of March 2011.

Options for managing the vast quantities of tritiated water on the Fukushima Daiichi site were put to tender in 2013. The result was the selection of six technologies, the developers of which were tasked with demonstrating separation technology by 2016 [44] – a challenging technical task given that tritium is a radioactive isotope of hydrogen. TEPCO recently suggested the alternative of evaporation.[45] However in 2016, the Ministry of Economy, Trade and Industry (METI) announced, that both for practical and cost reasons, the recommended option would not be separation, evaporation or long term storage but direct discharge to the Pacific Ocean.[46] No formal decision has been made as it requires the approval of communities within Fukushima, in particular the fisheries associations most directly impacted by the 2011 accident.

There are major uncertainties regarding the long-term effects posed by radioactive tritium.[47] Thus, the planned release cannot be considered without risk to the marine environment and human health, particularly at the local level. This is the reason why the direct ocean discharge of this radioactive, tritiated water is opposed by Fukushima citizens groups and fishermen associations.[48]

Land-based contamination via river systems

As described in 'Radiation Reloaded' and discussed above, the widespread contamination of the upland forests, river and lake systems of Fukushima prefecture and throughout the impacted region, present a long term radiological threat to both the terrestrial and marine environment. There is an urgency for scientific research to continue, not least due to the direct exposure pathways both to the human and non-human environment. As documented in the significant body of scientific research, as well as Greenpeace survey work, the terrestrial concentrations of radiocesium in the forests, land and river systems of Fukushima prefecture are significantly higher than the concentrations generally found in marine sediment.

Greenpeace Japan radiation specialist Mai Suzuki preparing sediment sample on board research vessel Asakaze, off the coast of Fukushima Daiichi nuclear plant, March 2016.

6 CONCLUSION

Due to the radionuclides released by the Fukushima nuclear accident, and their incorporation into the materials cycle of ecosystems, the impacts of the disaster will last for decades to centuries. The widespread contamination of the marine environment has been extensively investigated over the past 5 years, but much remains to be understood. In particular, there is a significant lack of research pertaining to species and ecosystem impacts, as most research has focused on concentrations in specific marine animals or in sediments. These do not, however, provide sufficient insight into the impacts of these concentrations on species fitness nor a comprehensive understanding of how these radionuclides behave in complex marine ecosystems.

The results of survey work show that in comparison to radiocesium contamination on land in Fukushima prefecture, the concentrations in marine sediment are significantly lower. One major factor for this is that Fukushima Daiichi lies on the coastline of the world's largest ocean, subject to powerful currents. Radiocesium in such conditions, including that deposited in sediments, is subject to much faster mixing and dispersal when compared to deposition within terrestrial ecosystems. That said, there is clear evidence of concentrations of radiocesium in coastal sediments whose impacts on marine ecosystems and organisms, including benthic species, has yet to be fully explored and is far from understood.

The large scale inventory of radiocesium in the upland forests and lakes of Fukushima prefecture, are, and will remain, an ongoing and long-term source of radiocesium inputs into the Pacific Ocean. This persistent, slow-moving, vast stock of radioactivity in terrestrial and freshwater systems presents a major hazard to both communities and non-human biota for the foreseeable future. There is an urgency to recognizing and understanding these threats, in light of the imminent lifting of evacuation orders in 2017 in areas known to be heavily contaminated, and which cannot be decontaminated.

Alongside this, the emergency conditions and radiological inventory at the Fukushima Daiichi site remains a clear and enormous potential source of even greater contamination to the coastal and wider marine environment than that released in the initial days and weeks of the nuclear accident. It is essential that the dedicated research and investigations of independent scientists continues so that the victims of the Fukushima accident and the people of Japan may better understand the impacts of this man-made, ongoing nuclear disaster.

At the same time, the Japanese government has a duty to apply the precautionary principle and act first and foremost in the interests of protecting public health and the environment. This means reversing policy choices that will compound the impacts of the nuclear disaster, including the deliberate release of radioactive water to the ocean and the lifting of evacuation orders for areas with high levels of radiation.

The radiological conditions that Greenpeace has documented in the river and lake systems of Fukushima stands in dramatic and terrible contrast to the conditions found in Lake Biwa, in Shiga prefecture. Given the proximity of Biwa lake to the multiple reactors in Fukui prefecture, a severe nuclear disaster would potentially have even greater environmental impact than that experienced in Fukushima. This must be avoided at all costs.

ENDNOTE

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Activity of dried marine sediment samples collected along Fukushima coast (1/2)

GREENPEACE

No.	Sample ID	collected date	Location	From Fukushima Daiichi (km)	From Coastline (km)	Water Depth (m)	Cs-137 (Bq/kg)	Cs-134 (Bq/kg)	Total Cs (Bq/kg)	GPS N	GPS E
1	20160304-SOM-1	2016-03-04	Soma offshore	46	0.1	7.4	110 ± 19	24 ± 4.9	134	37.8309010	140.96443123
2	20160302-NID-01	2016-03-02	Niida river Estuary	24.5	0.6	9.6	16 ± 4.2	<2.3	16	37.6405321	141.03151064
3	20160304-SOM-2	2016-03-04		22.5	2.8	21.9	11 ± 3.2	<2.7	11	37.6229021	141.05520993
4	20160304-SOM-3	2016-03-04		23	2.9	22.2	10 ± 3.1	<3.4	10	37.6278683	141.05561025
5	20160302-FDN-01	2016-03-02	Fukushima Daiichi Nuclear plant offshore	3	1.6	18.7	110 ± 18	18 ± 4	128	37.3997703	141.0528200
6	20160302-FDN-02	2016-03-02		2	1.6	16.7	120 ± 19	24 ± 4.8	144	37.4093794	141.05209229
7	20160305-FPP-1	2016-03-05		4.3	3	24	34 ± 7.3	5.3 ± 2.1	39.3	37.3954257	141.07004605
8	20160225-OHA-1	2016-02-25	Natsui river Estuary	40.8	1.6	16	44 ± 8.6	9.3 ± 2.5	53.3	37.0562913	140.99280174
9	20160225-OHA-2	2016-02-25		40.8	1.6	14	36 ± 7.7	9.4 ± 2.7	45.4	37.0562913	140.99280174
10	20160225-OHA-3	2016-02-25		41.5	3	29	17 ± 4.7	<6.4	17	37.0480251	141.00756859
11	20160226-NTS-2	2016-02-26		40.8	2.7	26.1	25 ± 6.1	5.2 ± 2.1	30.2	37.0551375	141.00557856
12	20160226-NTS-3	2016-02-26		40.8	2.7	26.2	27 ± 6.2	<5.3	27	37.0551375	141.00557856
13	20160226-NTS-4	2016-02-26		40.9	3.6	30.8	27 ± 6.2	6.5 ± 2.2	33.5	37.0541541	141.01509342
14	20160226-NTS-5	2016-02-26		41.4	3.6	30.6	21 ± 5.2	<5.4	21	37.0494397	141.01495753
15	20160226-NTS-6	2016-02-26		40.9	3.6	30.6	22 ± 5.9	<5.6	22	37.0544156	141.01495851
16	20160226-NTS-1	2016-02-26	Nakanosaku Offshore	56.6	7.4	26.2	23 ± 6	<5.5	23	36.9128920	141.00492379
17	20160306-NKN-1	2016-03-06		54.5	3.6	28.7	37 ± 7.5	7.2 ± 2.3	44.2	36.9341782	140.9702648

From Fukushima Daiichi (km): Approximate linear distance from Fukushima Daiichi Plant.
From coastline (km): Approximate distance from the nearest coastline.
Water Depth (m): Measured with Remotely Operated Vehicle (ROV)'s position.
Total Cs (Bq/kg) : When the sample is below the detection limit, the total is counted as 0 Bq/kg as a matter of practical convenience.
The analysis were performed by gamma spectrometry with high-purity germanium detector at Chikurin (RMCC,Radioactivity Monitoring Center for Citizen), Tokyo.

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Activity of dried marine sediment samples collected along Fukushima coast (2/2)

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No.	Sample ID	collected date	Location	From Fukushima Daiichi (km)	From Coastline (km)	Water Depth (m)	Cs-137 (Bq/kg)	Cs-134 (Bq/kg)	Total Cs (Bq/kg)	GPS N	GPS E
18	20160227-SMG-1	2016-02-27	Samegawa River estuary	61.4	1.9	22.4	82 ± 14	13 ± 3.3	95	36.8945650	140.82825808
19	20160227-SMG-2	2016-02-27		61.4	1.9	22.1	120 ± 20	24 ± 4.8	144	36.8946643	140.8283252
20	20160227-SMG-3	2016-02-27		62.9	4	29.6	6.5 ± 2.2	<2.7	6.5	36.8768778	140.84079777
21	20160227-SMG-4	2016-02-27		63	3.7	29.6	16 ± 4.2	<3	16	36.8770630	140.83773408
22	20160311-ONH-1	2016-03-11		62.1	1.9	21.7	110 ± 19	21 ± 4.5	131	36.8892308	140.82371361
23	20160311-ONH-2	2016-03-11		64.2	3.8	28.7	52 ± 10	8.9 ± 2.7	60.9	36.8668867	140.83213466
24	20160311-ONH-3	2016-03-11		63.3	2.3	24.3	82 ± 15	13 ± 3.3	95	36.8781281	140.81990153
25	20160311-ONH-4	2016-03-11		64.2	1.6	21.5	120 ± 21	20 ± 4.5	140	36.8723860	140.80851525

From Fukushima Daiichi (km): Approximate linear distance from Fukushima Daiichi Plant.
From coastline (km): Approximate distance from the nearest coastline.
Water Depth (m): Measured with Remotely Operated Vehicle (ROV)'s position.
Total Cs (Bq/kg) : When the sample is below the detection limit, the total is counted as 0 Bq/kg as a matter of practical convenience.
The analysis were performed by gamma spectrometry with high-purity germanium detector at Chikurin (RMCC,Radioactivity Monitoring Center for Citizen), Tokyo.

According to Nuclear Regulatory Agency "Environment Radiation Database", Activity of Sediment sample collected at the seabed of Fukushima offshore in 2010 was
Cs-137 0.23～0.26Bq/kg Cs-134 Not Detectable
http://search.kankyo-hoshano.go.jp/servlet/search.top , accessed 2016-07-11

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Activity of dried sediment/soil samples collected along river banks (1/2)

No.	Sample ID	Collected Date	Name of river	Location / Sample type and note	From Estuary (km)	From Fukushima Daiichi (km)	dose rate (μSv/h) 1m	0.5m	10cm	Cs-137 (Bq/kg)	Cs-134 (Bq/kg)	Total Cs (Bq/kg)	GPS N / E
1	20160215-ABK-1	2016-02-15	Abukuma river	Miyagi pref. Watari River bank. Soil. Reed. Grass.	5.5	75	0.38	0.44	0.45	2,600 ± 370	520 ± 75	3,120	38.08632 140.89532
2	20160216-ABK-1/2	2016-02-16	Abukuma river	Miyagi pref. Watari River bank. Muddy Soil.	10.5	75	0.23	0.32	0.48	5,500 ± 760	1,000 ± 150	6,500	38.07738 140.85698
3	20160216-ABK-2	2016-02-16	Abukuma river	Miyagi pref. Watari River bank. Soil. Reed. Grass.	10.5	75	0.41	0.43	0.44	3,700 ± 510	700 ± 100	4,400	38.07786 140.85831
4	20160216-ABK-3	2016-02-16	Abukuma river	Miyagi pref. Watari Far side of river bank from river. Soil.	10.5	75	0.08	0.08	0.08	260 ± 40	49 ± 8.8	309	38.07585 140.85692
5	20160303-NII-1	2016-03-03	Niida river	Fukushima pref. Minamisoma, Haramachiku Ogai River bank. Near Nakagawara bridge. Sediment.	12.5	30	0.8	1.1	0.99	15,000 ± 2,200	3,000 ± 420	18,000	37.65999 140.90554
6	20160303-NII-2	2016-03-03	Niida river	Fukushima pref. Minamisoma, Haramachiku Ogai River bank. Near Nakagawara bridge. Sediment.	12.5	30	1.34	1.23	0.98	3,500 ± 490	680 ± 98	4,180	37.65999 140.90554
7	20160303-NII-3	2016-03-03	Niida river	Fukushima pref. Minamisoma, Haramachiku Ogai River bank. Below rain drainage pipe. Sediment.	12.5	30	4.12	2.33	1.72	7,500 ± 1,000	1,500 ± 210	9,000	37.65993 140.90568
8	20160303-NII-4	2016-03-03	Niida river	Fukushima pref. Minamisoma, Haramachiku Ogai Sandbar by bridge. Sediment.	12.5	30	0.44	0.38	0.35	1,500 ± 220	280 ± 41	1,780	37.65981 140.90549
9	20160303-NII-5	2016-03-03	Niida river	Fukushima pref. Minamisoma, Haramachiku Ogai Sand. Close to water.	12.5	30	0.35	0.36	0.36	1,600 ± 220	310 ± 44	1,910	37.65983 140.90558
10	20160304-NII-1	2016-03-04	Niida river	Fukushima pref. Minamisoma, Sukauchi Between water and bank. Sediment.	2	25	0.78	0.68	0.57	1,700 ± 230	320 ± 46	2,020	37.64338 141.00333
11	20160304-NII-2	2016-03-04	Niida river	Fukushima pref. Minamisoma, Sukauchi Sediment	2	25	0.63	0.33	0.33	920 ± 130	180 ± 26	1,100	37.64365 141.00313
12	20160304-NII-3	2016-03-04	Niida river	Fukushima pref. Minamisoma, Sukauchi Sediment	2	25	0.51	0.51	0.51	3,000 ± 420	580 ± 82	3,580	37.64361 141.00313
13	20160304-NII-4	2016-03-04	Niida river	Fukushima pref. Minamisoma, Nakagawara River bank. Sediment.	10	27	0.74	0.64	0.64	3,300 ± 470	620 ± 90	3,920	37.66825 140.93105
14	20160304-NII-5	2016-03-04	Niida river	Fukushima pref. Minamisoma, Nakagawara River bank. Sediment.	10	27	0.18	0.18	0.16	1,400 ± 210	270 ± 40	1,670	37.66743 140.93076

From estuary (km): Approximate distance from the river estuary.

From Fukushima Daiichi (km): Approximate linear distance from Fukushima Daiichi Plant.

The analysis were performed by gamma spectrometry with high-purity germanium detector at Chikurin (RMCC,Radioactivity Monitoring Center for Citizen), Tokyo.

Dose rate is measured with Thermo Scientific RadEye PRD-ER.

Activity of dried sediment/soil samples collected along river banks (2/2)

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No.	Sample ID	Collected Date	Name of river	Location Sample type and note	From Estuary (km)	From Fukushima Daiichi (km)	dose rate (μSv/h) 1m	0.5m	10cm	Cs-137 (Bq/kg)	Cs-134 (Bq/kg)	Total Cs (Bq/kg)	GPS N E
15	20160304-NII-6	2016-03-04	Niida river	Fukushima pref. Minamisoma, Haramachiku Takanokura Takanokura Dam. 2 m above water surface. Soil.	15	27	1.8	-	-	25,000 ± 3,500	4,800 ± 690	29,800	37.62719 140.87721
16	20160304-NII-7	2016-03-04	Niida river	Fukushima pref. Minamisoma, Haramachiku Takanokura Takanokura Dam. 1 m above water surface. Soil.	15	27	2.2	-	-	13,000 ± 1,800	2,500 ± 340	15,500	37.62719 140.87721
17	20160304-OTA-1	2016-03-04	Ota river	Fukushima pref. Minamisoma, Haramachiku Baba Near Yokokawa dam. 1 m from water. next to the small river feeding the dam. next to Akanesawa bridge. Soil.	14	23	1.15	0.88	0.72	20,000 ± 2,900	3,800 ± 540	23,800	37.59625 140.89121
18	20160304-OTA-2	2016-03-04	Ota river	Fukushima pref. Minamisoma, Haramachiku Baba Near Yokokawa dam. 1 m from water. next to the small river feeding the dam. next to Akanesawa bridge. Soil.	14	23	0.62	0.54	0.63	2,800 ± 380	540 ± 76	3,340	37.59625 140.89121
19	20160304-OTA-4	2016-03-04	Ota river	Fukushima pref. Minamisoma, Haramachiku Baba Near Yokokawa Dam. 4 m from water. Next to Akanesawa bridge. Soil. Small organic.	14	23	1.27	1.14	1.15	18,000 ± 2,600	3,400 ± 490	21,400	37.59625 140.89121

From estuary (km): Approximate distance from the river estuary.

From Fukushima Daiichi (km): Approximate linear distance from Fukushima Daiichi Plant.

The analysis were performed by gamma spectrometry with high-purity germanium detector at Chikurin (RMCC,Radioactivity Monitoring Center for Citizen), Tokyo.

Dose rate is measured with Thermo Scientific RadEye PRD-ER.

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Activity of dried sediment samples collected in Lake Biwa

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No.	Sample ID	Collected Date	Location	From Shore (m)	Water Depth (m)	Cs-137 (Bq/kg)	Cs-134 (Bq/kg)	Total Cs (Bq/kg)	GPS N	GPS E
1	20160322-BIW-1	2016-03-22	Takashima city	50	3.8	<6.4	<4.5	ND	35.302300	136.028460
2	20160322-BIW-2	2016-03-22	Nagahama city	30	7.7	13 ± 4.6	<6.0	13	35.371642	136.265970
3	20160323-BIW-1	2016-03-23	Nagahama city	30	4.2	7.1 ± 3.7	<7.2	7.1	35.503760	136.169187
4	20160324-BIW-1	2016-03-24	Kusatsu city	30	3.1	<6.8	<5.1	ND	35.032328	135.911876

From shore (m): Approximate distance from the nearest shore.
Water Depth (m): Measured with Remotely Operated Vehicle (ROV)'s position.
Total Cs (Bq/kg) : When the sample is below the detection limit, the total is counted as 0 Bq/kg as a matter of practical convenience.
The analysis were performed by gamma spectrometry with high-purity germanium detector at Chikurin (RMCC,Radioactivity Monitoring Center for Citizen), Tokyo.

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Greenpeace divers holding banners with the messages “Never Again Fukushima” at Fukushima Daichi nuclear plant, March 2016.

Greenpeace is an independent campaigning organisation. Founded in 1971, it acts to change attitudes and behavior, to protect and conserve the environment, and promote peace and sustainability.

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Greenpeace flagship, Rainbow Warrior sails past Fukushima Daiichi nuclear plant in support of radiation survey work in coastal waters off Fukushima prefecture. March 2016.