The Fukushima Daiichi Accident

Technical Volume 4/5
Radiological Consequences

IAEA
International Atomic Energy Agency

THE FUKUSHIMA DAIICHI ACCIDENT

TECHNICAL VOLUME 4
RADIOLOGICAL CONSEQUENCES

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TECHNICAL VOLUME 4

RADIOLOGICAL CONSEQUENCES

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The IAEA thanks the large number of experts who were involved in this report. It is the result of the dedicated efforts of many people. All participants listed at the end of this technical volume made valuable contributions, but a particularly heavy load was borne by the Co-Chairs and coordinators of the working groups. The efforts of many expert reviewers, including members of the International Technical Advisory Group, are also gratefully acknowledged.

THE REPORT ON THE FUKUSHIMA DAIICHI ACCIDENT

At the IAEA General Conference in September 2012, the Director General announced that the IAEA would prepare a report on the Fukushima Daiichi accident. He later stated that this report would be "an authoritative, factual and balanced assessment, addressing the causes and consequences of the accident, as well as lessons learned".[1]

The report is the result of an extensive international collaborative effort involving five working groups with about 180 experts from 42 Member States (with and without nuclear power programmes) and several international bodies. This ensured a broad representation of experience and knowledge. An International Technical Advisory Group provided advice on technical and scientific issues. A Core Group, comprising IAEA senior level management, was established to give direction and to facilitate the coordination and review. Additional internal and external review mechanisms were also instituted. The organizational structure for the preparation of this publication is illustrated in Fig. 1.

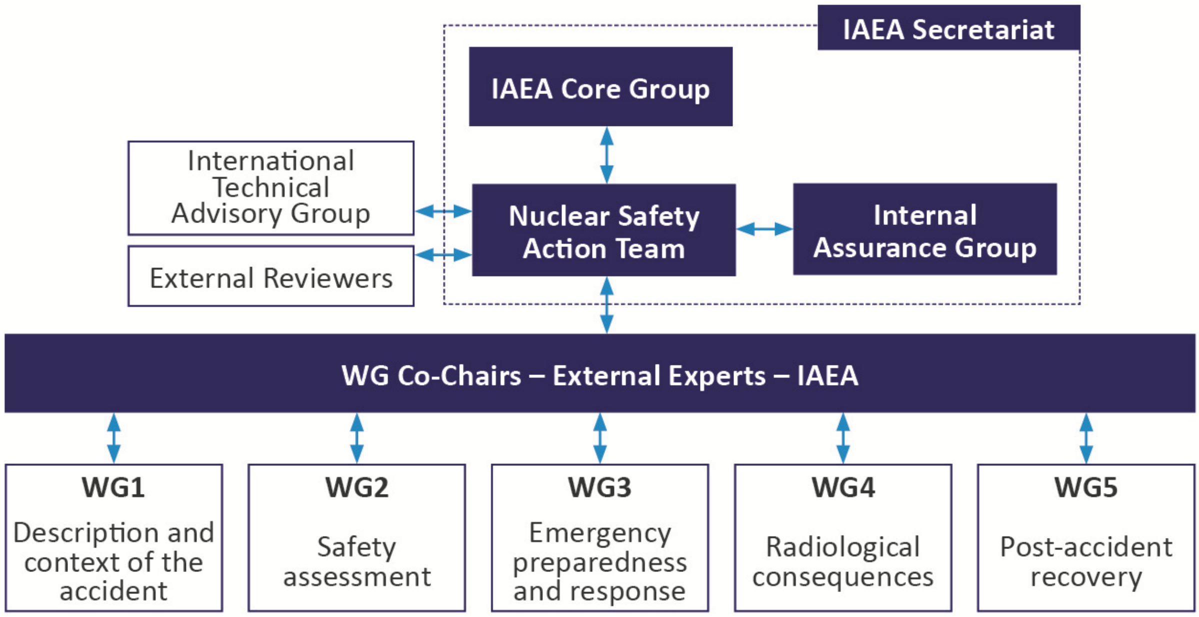

FIG. 1. IAEA organizational structure for the preparation of the report on The Fukushima Daiichi Accident.

The Report by the Director General consists of an Executive Summary and a Summary Report. It draws on five detailed technical volumes prepared by international experts and on the contributions of the many experts and international bodies involved.

The five technical volumes are for a technical audience that includes the relevant authorities in IAEA Member States, international organizations, nuclear regulatory bodies, nuclear power plant operating organizations, designers of nuclear facilities and other experts in matters relating to nuclear power.

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[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Introductory Statement to Board of Governors (2013), https://www.iaea.org/newscenter/statements/introductory-statement-board-governors-3.

The relationship between the content of the Report by the Director General and the content of the technical volumes is illustrated in Fig. 2.

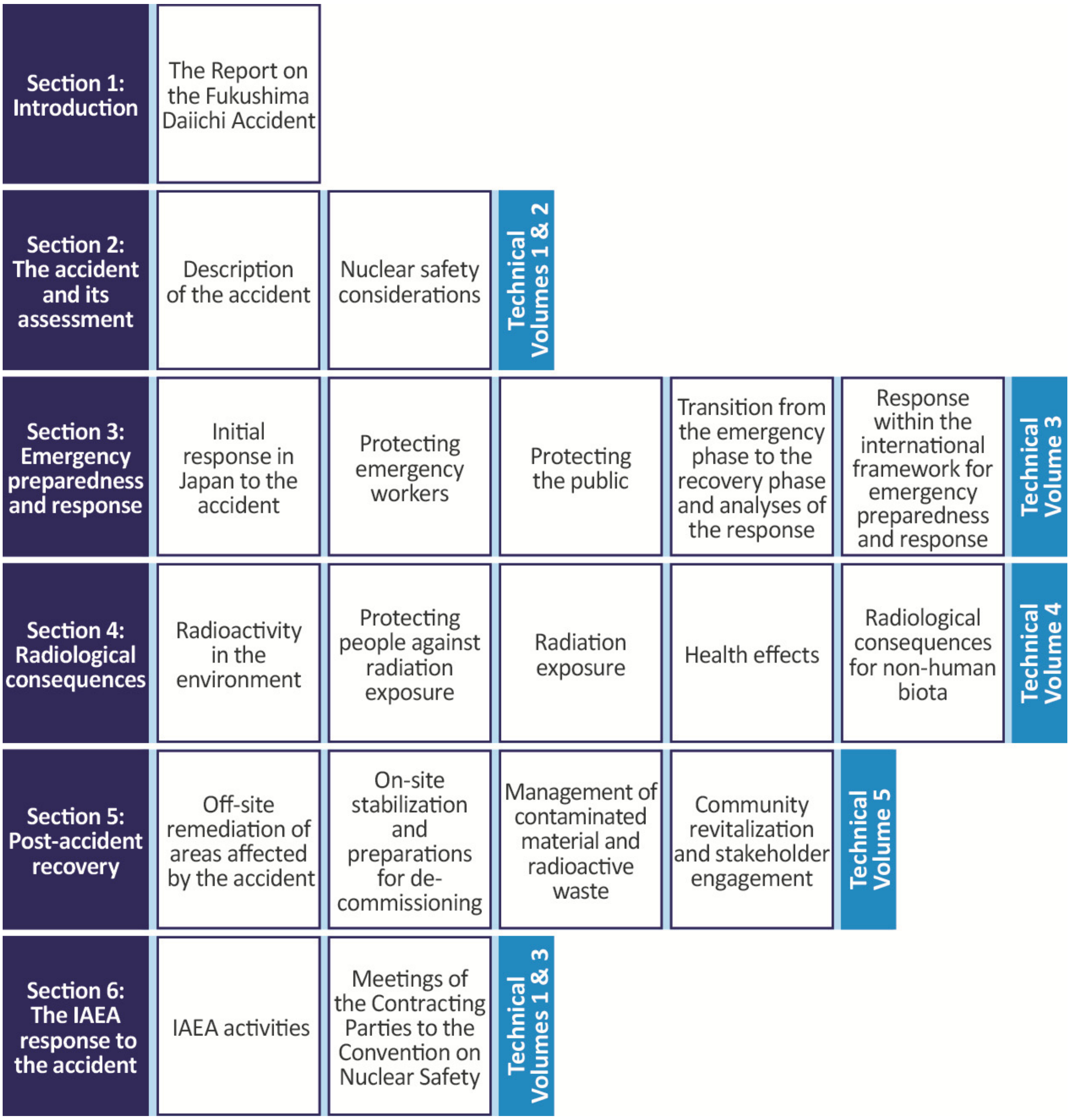

FIG. 2. Structure of the Summary Report and its relationship to the content of the technical volumes.

CONTENTS

RADIOLOGICAL CONSEQUENCES

4. INTRODUCTION

This technical volume describes the consequences associated with radioactivity and radiation from the accident at the Fukushima Daiichi nuclear power plant (NPP) for people and the environment. A number of international organizations have already issued reports on the potential health and environmental consequences of the accident, notably the World Health Organization (WHO) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). The intention of the assessments presented in this volume is to build on their work, using more recent data where available. Quantitative information arising from both personal and environmental monitoring has been provided by the Government of Japan.

Section 4.1 provides the best estimates of the magnitude and form of radioactive releases during the accident to the atmosphere and directly into the surrounding sea. It also explains the movement of the discharged radionuclides through air and water and the eventual deposition of the atmospheric activity on land in Japan and other countries worldwide, as well as on the open oceans. The goal is to provide a consolidated repository of information on releases to, and levels of radionuclides in, the environment. Some of this information is used in the analyses in subsequent sections of this volume.

Section 4.2 gives an overview of exposures to the main groups of emergency workers at the Fukushima Daiichi NPP, to groups of off-site workers and to members of the public. Where sufficient data are available, average effective dose and thyroid equivalent doses derived from personal measurements are compared with the results of previous assessments for specific locations, population groups and time periods.

Section 4.3 summarizes relevant aspects of the system of radiation protection in place at the time of the accident. It includes an overview of the legislation and guidance used to implement the radiation protection framework in Japan. This section also provides a description of the main aspects of radiation protection related to the accident at the Fukushima Daiichi NPP.

Section 4.4 presents a review of post-accident studies of the health of members of the public and workers, including the possible radiation induced health effects and psychological consequences to individuals resulting from the accident.

Section 4.5 covers the impact of the radioactive releases from the Fukushima Daiichi NPP on the environment (more specifically on non-human biota). The International Commission on Radiological Protection (ICRP) methodology has been applied to estimate dose and effects to a range of reference animals and plants from the marine, terrestrial and freshwater environments.

There are 2 appendices and 12 annexes that provide supplementary information. Appendix I contains maps of levels of radioactivity and radionuclides in the environment. Appendix II provides details of a statistical analysis of individual dose data. The annexes are included on the CD-ROM attached to this volume and provide the following information:

- Annex I: Characteristics and measurement of radioactivity and radiation levels.
- Annex II: Local and regional meteorological conditions in east Japan during 11–23 March 2011.
- Annex III: Levels of radioactivity in the terrestrial environment.
- Annex IV: Radioactivity in the marine environment arising from releases following the Fukushima Daiichi accident.
- Annex V: UNSCEAR assessment of the dose to the public.

— Annex VI: Information on measurement studies investigated in the production of this Technical Volume 4.
— Annex VII: Analysis of thyroid measurements of children conducted in Fukushima Prefecture, 26–30 March 2011.
— Annex VIII: Conventions, recommendations, safety standards, laws and regulations.
— Annex IX: Introduction to radiation effects on the thyroid.
— Annex X: Radiation and health effects and inferring radiation risks from the Fukushima Daiichi accident.
— Annex XI: Risk assessments for workers and the population following the Chernobyl accident.
— Annex XII: Calculations used in the assessment of doses to non-human biota.

4.1. RADIOACTIVITY IN THE ENVIRONMENT

The accidental releases from the Fukushima Daiichi NPP resulted in an increase in levels of artificial radioactivity in parts of the Japanese terrestrial environment and the marine environment to the east of Japan. Radioactive material released to the atmosphere was transported according to the meteorological conditions prevailing at the time and was deposited on land masses and the ocean. The majority of the atmospheric releases occurred during the period from 12 to 23 March 2011 [1]. Variations in the emission rates, in the physical and chemical properties of individual elements released from each of the three damaged reactors, and in the changing meteorological conditions during this period resulted in complex and heterogeneous dispersion of the radioactive material. The spatial variation of deposition densities on land was further complicated by the influence of precipitation, topography and land cover.

Direct releases of radionuclides to the ocean also occurred via a variety of mechanisms including runoff of contaminated water from the flooded plant, deliberate release of low level waste and drainage of contaminated groundwater. This material, as well as that deposited from atmospheric releases, was dispersed in the ocean under the influence of wind, tides and currents. Some of the radioactive material became attached to suspended sediments and was subsequently deposited onto riverbed sediments and plants.

Once dispersed and deposited, radioactive material migrated through the environment and led to elevated activity concentrations in soil and marine sediments and in plants and animals, including foods. It also resulted in additional radiation exposures of residents of the affected areas (see Section 4.2).

The first part of this section deals with the characteristics of the environment around the Fukushima Daiichi NPP. This is followed by a description of the nature of the releases to the atmosphere, including estimates of the amounts of each radionuclide released. The factors influencing the dispersal and deposition of radioactive material released during the Fukushima Daiichi accident in the atmosphere and in the terrestrial environments are also outlined. The section then describes the results of the extensive environmental surveillance and assessment programmes undertaken in Japan following the accident. The second part of the section considers releases of radionuclides to the aquatic environment, the factors influencing the dispersion of radionuclides in this environment and the results of the environmental monitoring that has been conducted. The third part considers the levels of radionuclides in relevant foods. The final part describes the global transport and detection of very low levels of radiocaesium, radioiodine and other fission products in air samples and other environmental media. This compilation of all aspects of radioactivity in the environment resulting from the accident at the Fukushima Daiichi NPP provides a comprehensive resource for future analysis.

4.1.1. The natural environment around the Fukushima Daiichi NPP

The Fukushima Daiichi NPP (37°25′N, 141°02′E) is located on the north-eastern Pacific Ocean coast of Honshu (Japan's largest island), about 200 km north-east of Tokyo. In this area, the continental shelf is narrow, extending 40 km offshore, and broadens further north up to 70 km in the area of Sendai Bay. Offshore of the Fukushima Daiichi NPP, the ocean depth increases steadily, reaching some 200 m at 50 km from the coast. Beyond the shelf break, the slope plummets as deep as 9000 m into the Japan Trench. An abyssal plain lies further east, at depths of about 5000 m. As explained in more detail in Section 4.1.3.2, the Fukushima Daiichi NPP is located at the confluence of two wind-driven western boundary currents of the North Pacific: the Kuroshio Current, which transports warm, saline waters northwards along the south coast of Japan and then eastward; and the Oyashio Current, which transports cold, less saline, water southward. Another characteristic of the region is the Tsugaru Warm Current, flowing from the Sea of Japan through the Tsugaru Strait north of Honshu and then southward along the slope of the east coast.

The northernmost part of Japan (Hokkaido and neighbouring islands) is situated in the boreal zone. In addition, the eastern coast of Honshu has fauna similar to that of Hokkaido, because the area is influenced by the cold Oyashio Current. The ecosystem is characterized by rich primary production. The major primary producers are not only phytoplankton but also macro algae, especially brown algae. Such algae harbour rich fish and invertebrate fauna in the area [2].

Fukushima Prefecture is located in the southernmost part of the Tohoku region, which is situated on Honshu Island and borders on the Kanto region in the south. The centre of the Kanto region is the Kanto Plain, which is the largest plain in Japan and which adjoins the sea to the east and the south.

The Tohoku region, which occupies about 30% of Honshu Island, contains a mountainous expanse running from north to south. Some of the mountains are relatively high at more than 1500 m; they effectively divide the region into two distinct areas with different watersheds and climates, on the Sea of Japan side and the Pacific Ocean side. The Abukuma Mountains are located in Fukushima Prefecture on the east side of the Ou Mountain range, an area of approximately 170 km from south to north and 40 km from east to west. The Abukuma Mountains are gentle hills with an average altitude of about 600 m, with their highest point rising to 1192 m. They are characterized by small valleys with steep streams scattered among agricultural fields and forests. The Abukuma Mountains are surrounded by a 10 km wide narrow plain bounded to the east by the Pacific coast (Hamadori area), the Abukuma River plain to the west (Nakadori area) and the north, and the Kuji River valley to the south. The Ou Mountains also divide Fukushima Prefecture into two areas, the Nakadori area and the Aizu area. In the Abukuma River plain, many tributary rivers meet with the Abukuma River, which runs into the Pacific Ocean. The Uda, Mano, Niida and other rivers also run into the Pacific Ocean. A large part of the Aizu area is mountainous, with the exception of the Aizu Basin. The Tadami River and many tributaries meet the Agano River, which runs to the Sea of Japan. Lake Inawashiro (with an area of 104.8 km^2) and many small lakes are located in the mountain area on the east side of the basin.

The climate of the Tohoku region can be divided into different zones. The western area is characterized by warm days in the summer that are due to the föhn wind[1], while in winter, there are relatively short periods of sunshine and the area tends to have heavy snowfall. In the eastern area, the climate has both inland and Pacific coastal characteristics. Although temperatures occasionally rise owing to the föhn wind, summers tend to be cloudy with low temperatures, while the winter weather is usually mild, with occasional snowfall due to cold air masses moving in from the north.

[1] A generic term for warm, strong and often very dry downslope winds that descend in the lee of a mountain barrier.

About 80% of the area of Fukushima Prefecture is mountainous, with about 70% covered by forests; as of 2002, artificial forests accounted for 35% of the forested area. A large part of the non-mountainous area of the Tohoku region contains a mixture of paddy fields, farmlands, secondary deciduous forest and evergreen coniferous trees (primarily cedar), with a high biodiversity. The flora and fauna in the Tohoku region are as diverse as those of Japan as a whole. Since Fukushima Prefecture is located at the boundary between areas of deciduous broadleaf forests and evergreen broadleaf forests, an especially high diversity of plants can be found. Typical plants in the deciduous broadleaf forest are Fagaceae, and those in evergreen broadleaf forest include a species of Castanopsis, Japanese evergreen oak (*Quercus acuta*) and *Quercus salicina*. Regarding the fauna, surveys have shown that the following mammals, birds and reptiles inhabit the Tohoku region [3]:

— Mammals: Japanese monkey (*Macaca fuscata*), Asiatic black bear (*Selenarctos thibetanus*), Japanese raccoon, Japanese deer, Japanese serow (*Capricornis crispus*);
— Birds: Yellow Bittern (*Ixobrychus sinensis*), *Butastur indicus, Accipiter gentilis, Alcedo atthis*, belted kingfisher, Japanese green woodpecker, barn swallow, water wagtail, *Cinclus pallasii*;
— Reptiles: Forest green tree-frog, Tohoku salamander, blacked salamander, Japanese clawed salamander, black-spotted pond frog (*Rana nigromaculata*) [4].

The map in Fig. 4.1–1 shows the geographical features of Fukushima Prefecture.

FIG. 4.1–1. Geographical features of Fukushima Prefecture.

4.1.2. Releases of radionuclides to the atmosphere and radioactivity in the terrestrial environment

Technical Volume 1 includes a detailed description of the accident and the sequence of events that took place after the earthquake and tsunami on 11 March 2011. A detailed description of the deterioration of the conditions of the reactor cores and of the different barriers designed to prevent the release of fission products is provided in Technical Volume 1, Section 1.4. The aims of this section are to provide summaries of:

- The source term[2], including estimates of the total activities of the most important radionuclides released to the atmosphere and into the ocean as a result of the Fukushima Daiichi accident, as well as temporal variations in these releases.
- The dispersion and, for relevant radionuclides, subsequent deposition of radionuclides onto the terrestrial environment, taking into account both changing meteorological conditions and emission rates and other influences, including topography and land cover.
- The temporal and spatial variations in levels of radionuclides in the environment in order to provide the context for the discussions of exposures of members of the public and of workers in Section 4.2 and of non-human biota in Section 4.5.

4.1.2.1. Atmospheric releases

A detailed description of the various events which took place in Units 1, 2 and 3 of the Fukushima Daiichi NPP over the period from 11 March until the end of March 2011 and which led to releases of radioactivity to the environment is provided in Technical Volume 1. Key events included a hydrogen explosion in the reactor building of Unit 1 on 12 March, a hydrogen explosion in the reactor building of Unit 3 on 14 March and the failure of the Unit 2 primary containment vessel, leading to significant releases to the atmosphere on 15 March. Further releases occurred as a consequence of the venting of the different units [5].

As described in Technical Volume 1, Section 1.4, the accident source term has been estimated by many research groups, generally by using one of two complementary and well established approaches. Firstly, releases were estimated based on simulations of the accident progression and phenomena that contribute to the atmospheric release of radionuclides using severe accident simulation computer codes, such as MELCOR [6], ASTEC [7] or MAAP [8]. Secondly, reverse or inverse modelling of the transport and dispersion in the environment was used, which involves the use of measurements of radionuclides in the environment to estimate the source term. Both approaches were hampered by the complexity of the situation during the accident at the Fukushima Daiichi NPP and by the scarcity of key data (for the first approach, particularly information on key plant parameters over the period in question was lacking, and, for the second approach, measurements in the environment, especially in the early phase). In addition, the time periods over which source term estimates were integrated differed. The dispersion of released material over the sea was also a factor. As a result, significant uncertainties remain in estimates of the total releases of each radionuclide and, to an even greater extent, of release rates.

Despite these uncertainties, the different estimates of the releases of ^{131}I and ^{137}Cs are reasonably consistent. Technical Volume 1, Section 1.4 presents the total releases of key radionuclides estimated

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[2] The source term is of fundamental importance for assessing the consequences of releases of radionuclides following a nuclear accident. The source term describes the composition of the releases (the total amount of each radionuclide released) and the release rates (the temporal variation of the release of each radionuclide). It also includes information on the chemical form of each radionuclide released (for example, gaseous or particulate phase), particle size, release height, temperature and enthalpy (the total energy of a thermodynamic system indicating the energy of the released material which affects the effective height of the release).

by many different organizations around the world and explains the uncertainties involved. The atmospheric releases of ^{131}I and ^{137}Cs have been estimated to lie in the ranges 90–700 PBq and 7–50 PBq, respectively. If the very first estimates, made in March–April 2011 and based on the very limited information available at that time are excluded, then the range becomes narrower: 100–400 PBq for ^{131}I and 7–20 PBq for ^{137}Cs. The preliminary estimates of the source term for ^{133}Xe were more uncertain, being between 500 and 15 000 PBq. However, in more recent calculations [9], this uncertainty has also decreased (6000–12 000 PBq). The estimated atmospheric releases of ^{131}I, ^{137}Cs and ^{133}Xe are summarized in Table 4.1–1.

TABLE 4.1–1. ESTIMATED ATMOSPHERIC RELEASES OF KEY RADIONUCLIDES (PBq)

Nuclide	All estimates	Early estimates excluded[a]
I-131	90–700	100–400
Cs-137	7–50	7–20
Xe-133	500–15 000	6000–12 000

[a] Estimated releases excluding those made in March–April 2011.

Section 1.4 of Technical Volume 1 also describes a statistical analysis of the numerical estimates of the total releases of these key radionuclides. Bayesian techniques were used to obtain mean values of the total release and the confidence limits.

Section 1.4 in Technical Volume 1 also considers the estimates of releases of other radionuclides and compares them with those from the accident at Chernobyl. A summary of the published range of estimated releases of each of the key radionuclide is provided in Tables 4.1–1 and 4.1–2. The ranges of estimates are greater for radionuclides other than iodine and caesium, reflecting the lack of direct measurements of these isotopes around the site in the period immediately after the accident. However, it is clear that the releases of all radionuclides are significantly less than those from the accident at Chernobyl.

It is clear that a wide range of radionuclides are known to have been released to the atmosphere during the accident at the Fukushima Daiichi NPP [10–15]. Most have been detected by radiological measurements of environmental media.

The fission noble gases ^{85}Kr and ^{133}Xe were released during the early phase of the accident. Nearly the entire inventories of these gases were released as a result of ventings, explosions and other events in Units 1, 2 and 3.

The maximum temperature in the reactors at the time of the releases has been estimated as 2100–2300°C [16]. It can therefore be assumed that all releases of volatile elements with boiling points significantly less than this temperature [17] were in the form of vapour, which, with the exception of iodine, soon condensed onto particulate matter under ambient conditions.

Very low levels of semi- and low volatile elements were released. In particular, low-volatile gamma emitting fission products, including isotopes of ruthenium, ^{140}Ba/^{140}La and cerium, have not been detected at significant levels in the area around the Fukushima Daiichi NPP. During the accident, the release was mainly due to core overheating and fuel melting, without the presence of air; less volatile elements were therefore not released. Similarly, only very low levels of isotopes of strontium and the actinides, including plutonium, were released owing to the nature of the accident. This contrasts with the releases from the Chernobyl NPP, where there was an explosion at an operating reactor releasing fragments containing these less volatile elements. As described in Technical Volume 1, neutrons were detected near the main gate of the Fukushima Daiichi NPP (which is around 1 km away from Units 1–3), between 05:30 and 10:50 on 13 March. It is estimated that the neutrons came from the spontaneous nuclear fission of radionuclides that could have been released as a result of damage to the reactor core. Such a phenomenon was predictable and the presence of these radionuclides at relatively low levels, which are not of radiological concern, has been reported [18]. Zheng et al. [18] note that discharges of isotopes of plutonium based on their measurements of levels in soil are similar to other estimates of the discharges as given in Table 4.1–2.

TABLE 4.1–2. AN ILLUSTRATIVE RANGE OF ESTIMATES OF ATMOSPHERIC RELEASES OF A WIDER RANGE OF RADIONUCLIDES (PBq) AND COMPARISON WITH THOSE FROM THE CHERNOBYL ACCIDENT

Radionuclide	Fukushima Daiichi[a]	Chernobyl[b]
Fission noble gases		
Kr-85	6.4–32.6	33
Xe-133	6 000–12 000	6 500
Volatile fission products		
Te-129m	3.3–12.2	240
Te-132	0.76–162	$\sim 1.15 \times 10^{3}$
I-131	100–400	$\sim 1.76 \times 10^{3}$
I-133	0.68–300	2500
Cs-134	8.3–50	~47
Cs-136	—	36
Cs-137	7–20	~85
Semi- and low volatile fission products		
Sr-89	4.3×10^{-2}–13	~115
Sr-90	3.3×10^{-3}–0.14	~10
Ru-103	7.5×10^{-6}–7.1×10^{-5}	>168
Ru-106	2.1×10^{-6}	>73
Ba-140	1.1–20	240
Refractory elements		
Zr-95	0.017	84
Mo-99	8.80×10^{-8}	>72
Ce-141	0.018	84
Ce-144	0.011	~50
Np-239	0.076	400
Pu-238	2.4×10^{-6}–1.9×10^{-5}	0.015
Pu-239	4.1×10^{-7}–3.2×10^{-6}	0.013
Pu-240	5.1×10^{-7}–3.2×10^{-6}	0.018
Pu-241	3.3×10^{-7}–1.2×10^{-3}	~2.6
Cm-242	9.8×10^{-6}–10^{-4}	~0.4

[a] Range of estimates from JNES, 2012 [19], NISA, 2011 [20, 21], IRSN-2, 2012 [22–24], IBRAE, 2012 [25–27], with the exception of Xe-133, I-131 and Cs-137, where the estimated range is based on the greater number of estimates described in Technical Volume 1, Section 1.4 (excluding early estimates, made in March–April 2011).
[b] From Ref. [28].

Relatively small amounts of ^{129}I were released. This long lived radionuclide is not radiologically significant under such conditions, but has been used to reconstruct maps of the distribution of the much shorter lived ^{131}I in the environment.

Four years after the accident, atmospheric releases from the Fukushima Daiichi NPP continue, but at very low levels which are not of radiological concern. Since the summer of 2011, the levels measured on the Fukushima Daiichi NPP have been low (concentrations of ^{134}Cs and ^{137}Cs in air of the order of 1 Bq/m^3 or less for both ^{134}Cs and ^{137}Cs); since April 2012, they have been below detection limits [29].

4.1.2.2. Dispersion of radionuclides in the atmosphere and deposition onto the terrestrial environment

Radionuclides released to the atmosphere following the accident at the Fukushima Daiichi NPP were subjected to a variety of physical and chemical processes that determined their eventual fate. Both the meteorological conditions and the release rates of different radionuclides varied considerably during the period of atmospheric releases from the Fukushima Daiichi NPP [1].

The releases that contributed most to the observed deposition pattern in Japan occurred in the following three time periods [1, 5], which are also illustrated in part in Fig. 4.1–2:

(1) Early on 12 March 2011, the wind direction carried released material towards the Pacific Ocean. From the afternoon of 12 March until midnight, the releases following the venting and hydrogen explosion in Unit 1 were transported over north-east Fukushima Prefecture and the coastal area of Miyagi Prefecture, resulting in dry deposition.
(2) From the evening of 14 March to the morning of 16 March, releases (mainly from Unit 2) were transported by changing weather conditions over wider areas of Honshu. Initial southerly transport resulted in dry deposition along the south-eastern coastal area of Fukushima Prefecture and north-eastern parts of Ibaraki Prefecture. This material was subsequently dispersed more widely, leading to lower levels of dry deposition in the more distant areas towards the south-west. Light precipitation began during the afternoon of 15 March and resulted in wet deposition in northern areas of the Gunma, Tochigi and Fukushima prefectures. A major release on the morning of 15 March from Unit 2 moved initially toward the south-west and then, following a change in wind direction, the north-west, resulting in wet deposition over north-east Fukushima, south-east Yamagata and south-west Miyagi prefectures.
(3) From 20 to 22 March, release rates were lower. Dispersion was dominated by air movement towards the north-west in the afternoon of 20 March and southward transport from the late night of 21 March to the early morning of 22 March. Subsequently, further releases encountered wet deposition in a number of areas, such as parts of the prefectures of Iwate, Miyagi, Ibaraki, Chiba and other prefectures in the Kanto plain on 23 March.

This pattern of dispersion and deposition was largely supported by the results of early atmospheric dispersion modelling by researchers in Japan (e.g. [1, 30–34] although uncertainties remain [5, 35]).

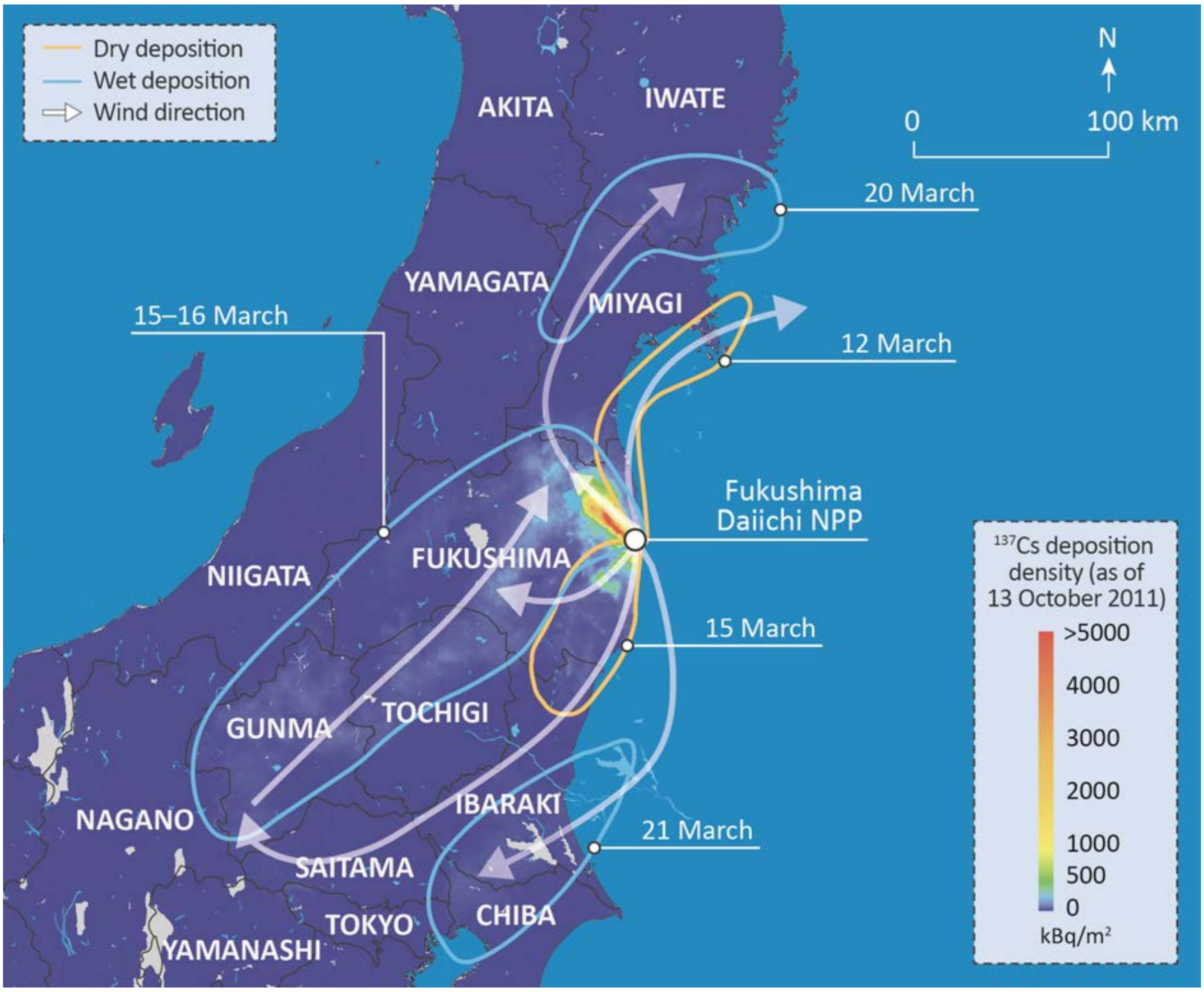


FIG. 4.1–2. Timing and locations of the main deposition events [36, 37].

A summary of the key events and factors influencing dispersion and deposition of radionuclides is summarized in Table 4.1–3.

TABLE 4.1–3. SUMMARY OF KEY EVENTS AT THE FUKUSHIMA DAIICHI NPP: RELEASE RATES, METEOROLOGICAL CONDITIONS, DRY AND WET DEPOSITION AND RELEVANT MONITORING RESULTS

No.[a]	Overview	Time period	Significant releases	Plume advection and dispersion	Precipitation and wet deposition	Monitoring results
	—	9–12 March (early morning)	—	—	Light rain	—
	—	12 March (early morning–afternoon)	—	Plume transported over the Pacific Ocean	—	—
1	Initial and substantive releases from venting and H_2 explosions in Units 1 and 3 with resultant dry deposition.	12 March (afternoon–midnight)	Venting of Unit 1 started approx. 14:00. H_2 explosion Unit 1 at 15:36.	High concentration plume first transported NNW over NE Fukushima Prefecture and then NNE over coastal area of Miyagi Prefecture.	—	Elevated ambient dose equivalents recorded at some local monitoring posts to the north of the site, at Minamisoma at 20:00 and at Onagawa at 00:00 on 13 March.
		13 March–14 March (night)	Venting of Unit 3 primary containment vessel started at approx. 08:45 (13 March). H_2 explosion Unit 3 at 11:01 (14 March).	Plume transported generally E/NE over the Pacific Ocean.	—	—

TABLE 4.1–3. SUMMARY OF KEY EVENTS AT THE FUKUSHIMA DAIICHI NPP: RELEASE RATES, METEOROLOGICAL CONDITIONS, DRY AND WET DEPOSITION AND RELEVANT MONITORING RESULTS (cont.)

No.[a]	Overview	Time period	Significant releases	Plume advection and dispersion	Precipitation and wet deposition	Monitoring results
2	Large releases mainly from Unit 2 due to melting of core and breach of reactor containment. Major contributor to deposition of radioactive material on (eastern) Japanese landmass. Changing weather conditions.	14 March (late night)–15 March (morning)	H_2 explosion in Unit 4 at approx. 06:00 (15 March) due to backflow of gases vented from Unit 3. Following failure of Unit 2 reactor pressure containment function on evening of 14 March, release of a large amount of radioactive material from approximately 07:38 (15 March). Peak ambient dose equivalent rates measured at approximately 09:00 at the site boundary.	Plume transported SSW along the SE coastal area of Fukushima Prefecture and NE Ibaraki Prefecture. Subsequently, a more dispersed plume was transported over the Kanto region, resulting in lower levels of dry deposition in Tokyo, and Saitama and Miyagi prefectures.	—	Increase in dose rates measured at Iwaki (Fukushima), Kitaibaraki and Tokai (Ibaraki) on morning of 15 March.
		15 March (afternoon–night)	—	High concentration plume transported NW. Plume transported generally S resulting in dry deposition over SE Fukushima and E Ibaraki prefectures.	Light precipitation due to a low pressure system passing eastwards over Honshu resulted in high levels of wet deposition which was higher than dry deposition over NE Fukushima, SE Yamagata and SW of Miyagi prefectures.	Increase in dose rates measured at some local monitoring posts and portable monitors at Fukushima and Iitate in the west and north-west direction from Fukushima Daiichi NPP.
						Two increases in dose rates measured at Kitaibaraki (Ibaraki) during 16 March.
		16 March (morning)–19 March	—	Plume transported generally E to SE (fluctuating) mainly over the Pacific Ocean.	—	—
		20 March (early morning)	—	Plume transported east over the Pacific Ocean.	—	—

TABLE 4.1–3. SUMMARY OF KEY EVENTS AT THE FUKUSHIMA DAIICHI NPP: RELEASE RATES, METEOROLOGICAL CONDITIONS, DRY AND WET DEPOSITION AND RELEVANT MONITORING RESULTS (cont.)

No.[a]	Overview	Time period	Significant releases	Plume advection and dispersion	Precipitation and wet deposition	Monitoring results
3	Releases dispersed over Japanese landmass encountering rainfall on occasions. Release rates lower from 23 March.	20 March (morning–afternoon)	—	Plume transported south over the Kanto region.	—	—
		20 March (afternoon)	—	Plume transported NW over W Miyagi, E Yamagata and S Iwate prefectures.	Precipitation in the evening causes wet deposition over the same areas.	—
		20 March (late night)–21 March	—	Plume transported S into Ibaraki Prefecture via the ocean and then dispersed over the Kanto region (Tokyo, and Ibaraki, Chiba and Kanagawa prefectures).	Precipitation during the morning of 21 March causes wet deposition over the same areas.	Increase in dose rates measured at Tokai, Setagaya (Tokyo), Chiba, Wako, Tsukuba (mainly in the Kanto plain) from the morning of 21 March.
		22 March	—	Plume transported in fluctuating E/SE directions over the Pacific Ocean. Plume due to releases from 21 March remain (stagnant) over the Kanto region.	Precipitation in the evening results in wet deposition over E Fukushima Prefecture and over the Kanto region.	
		23 March–24 March (morning)	—	Lower concentration plume transported generally S and SE, resulting in dry deposition along coastal parts of Ibaraki and Chiba prefectures and subsequently into the SE part of the Kanto region.	Precipitation from evening until late night results in wet deposition over the same areas.	—
		24 March (morning)–25 March (morning)	—	Plume transported over the Pacific Ocean.	—	—
		25 March (morning)–26 March (morning)	—	Plume transported NW over Fukushima Prefecture and southern parts of Yamagata and Miyagi prefectures.	Precipitation results in wet deposition over the same areas.	—

TABLE 4.1–3. SUMMARY OF KEY EVENTS AT THE FUKUSHIMA DAIICHI NPP: RELEASE RATES, METEOROLOGICAL CONDITIONS, DRY AND WET DEPOSITION AND RELEVANT MONITORING RESULTS (cont.)

No.[a]	Overview	Time period	Significant releases	Plume advection and dispersion	Precipitation and wet deposition	Monitoring results
		26 March (morning)	—	Plume transported SE over the Pacific Ocean.	—	—
		26 March (morning)–29 March	—	Plume transported eastwards over the Pacific Ocean.	—	—
		30 March (morning–afternoon)	—	Plume transported SW into the Kanto region resulting in dry deposition.	Precipitation in the afternoon results in wet deposition over Tochigi and Ibaraki prefectures.	—
		30 March (afternoon–night)	—	Plume transported NW.	—	—
		31 March	—	Plume transported mainly over the Pacific Ocean.	—	—

[a] These numbers relate to the summary of the main sequence of events presented above.

The combined influence of these factors has been analysed by several research groups [1], the World Meteorological Organization (WMO) [38], UNSCEAR [5], and the model review report by the Science Council of Japan [35]. A task group of WMO undertook an analysis of the meteorological conditions influencing the dispersion and deposition of the releases, the key features of which are presented in Annex II. This group also compared the results with different atmospheric transport dispersion and deposition models and with environmental monitoring data.

An illustration of the results of a global dispersion model is presented in Fig. 4.1–3 [39]. The figure shows activity concentrations in air; the original colours of the reference are retained so that small changes in the degree of colour correspond to a one order of magnitude change in the activity concentration. This shows that the activity concentrations in air decrease significantly with distance from the Fukushima Daiichi NPP.

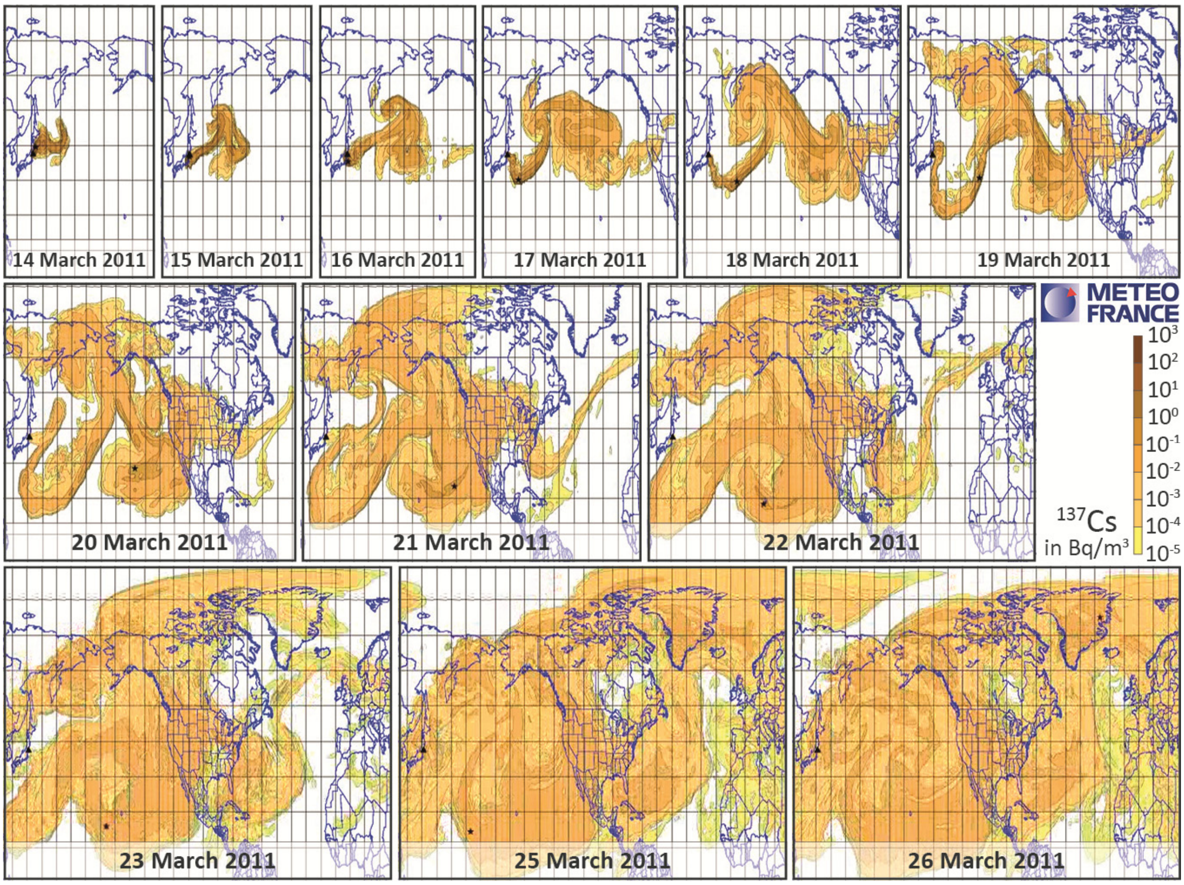


FIG. 4.1–3. Results from one of the global models of the atmospheric dispersion of ^{137}Cs, presented in its original colour scale (see Ref.[39] for details) (Illustration courtesy of Meteo-France).

In general, the pattern of dispersion and deposition can also be confirmed by the results of environmental monitoring at locations at, or close to, the Fukushima Daiichi NPP and throughout the affected area.

Measurements of ambient dose equivalent rates

The pattern of releases can be correlated with ambient dose rate measurements exemplified by those measured at the front gate of the Fukushima Daiichi NPP (Fig. 4.1–4). For example, the contribution of the early release of fission noble gases to the elevated ambient dose equivalent rates that were measured at the Fukushima Daiichi NPP is evident from Fig. 4.1–4.

Unit	Symbol in Fig.	Time of occurrence	Event
1	1a	12.03.2011 14:00	Venting No.1
	1b	12.03.2011 15:36	Explosion
2	2a	14.03.2011 21:00	Venting No.1 or PCV leakage
	2b/4a	15.03.2011 06:15	Loud sound in torus room
	2c	15.03.2011 11:25	Pressure drop in dry well
3	3a	13.03.2011 09:20	Venting No.1
	3b	13.03.2011 12:30	Venting No.2
	3c	13.03.2011 20:30	Venting No.3
	3d	14.03.2011 05:20	Venting No.4
	3e	14.03.2011 11:01	Explosion
	3f	14.03.2011 16:00	Venting No. 5
	3g	15.03.2011 16:05	Venting No.6
	3h	16.03.2011 02:00	Venting No.7

The variation of dose rates associated with later events are presented in Technical Volume 1, Section 1.4 (Fig. 1.4–3)

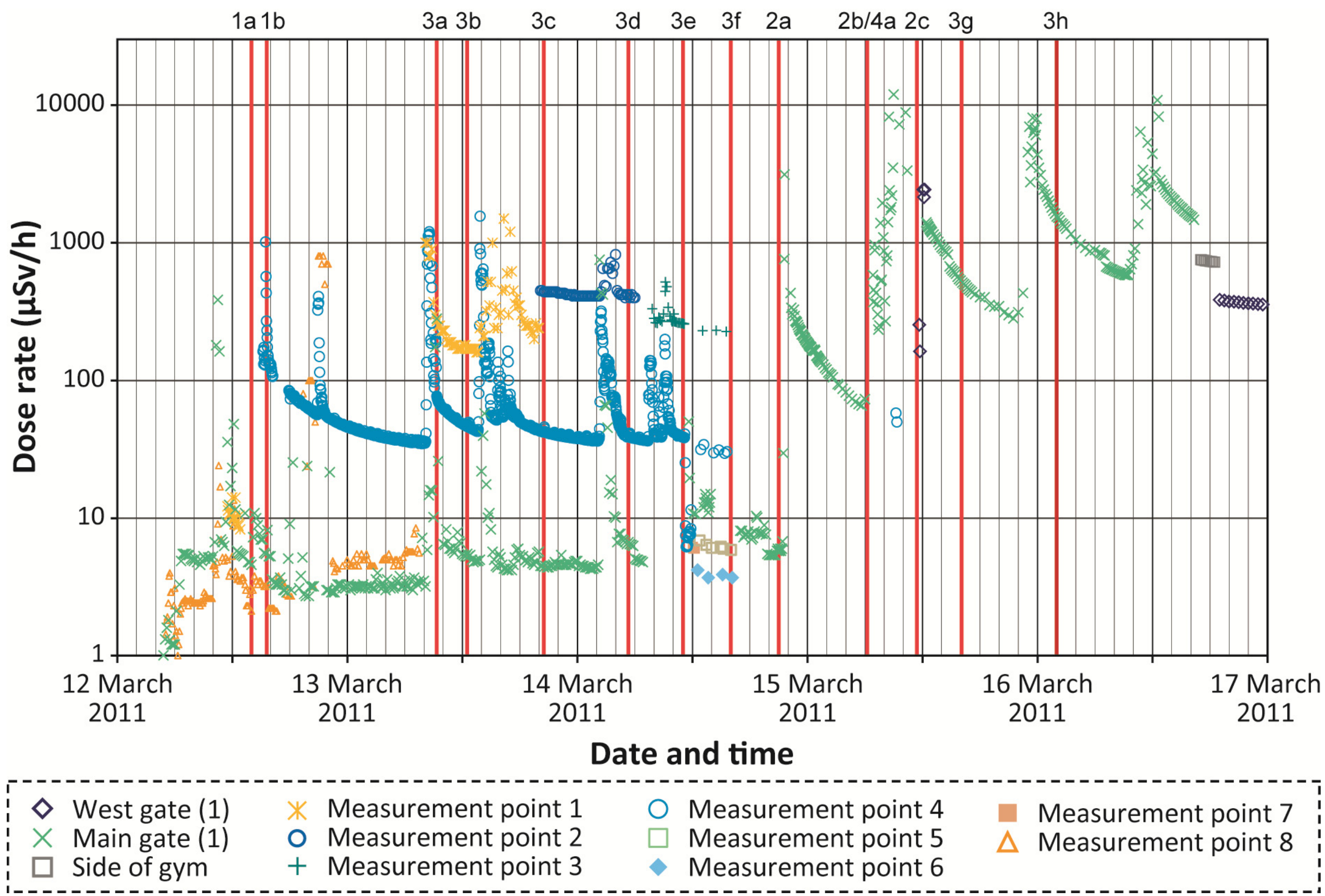


FIG. 4.1–4. Graph of dose rates measured at the Fukushima Daiichi NPP between 11 and 17 March 2011 (the vertical red lines indicate the major events registered during the accident) [40].

The movement of the plume can be demonstrated from the fluctuation in ambient dose equivalent rates measured at the fixed monitoring points and by portable monitors deployed by Fukushima Prefecture and observations at the Japan Atomic Energy Agency (JAEA) site at Tokaimura Village. The monitoring points are shown on the map in Fig. 4.1–5 [41].

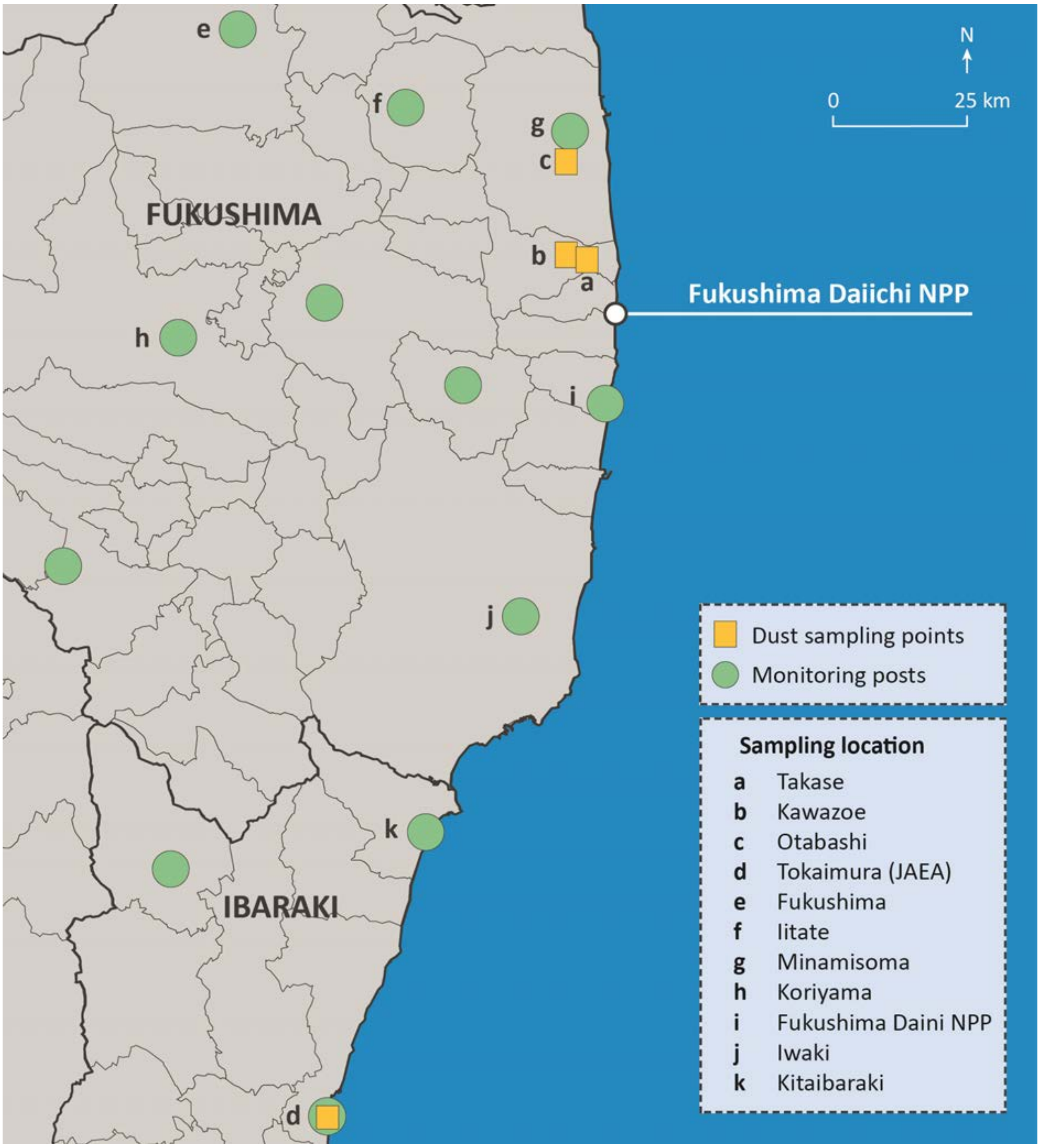


FIG. 4.1–5. Map of environmental monitoring points in Fukushima Prefecture [41].

The environmental monitoring data in the early stage of the accident were incomplete; consequently, it is not possible to analyse all aspects of the movement of the plume. However, the observations mentioned above support the results of the atmospheric dispersion simulation shown in Fig. 4.1–3. The various deposition events related to the main release periods which resulted in deposition onto the terrestrial environment (12, 14–16 and 20–22 March) can thus be observed in measurements of ambient dose equivalent rates from fixed locations in Fukushima Prefecture and surrounding areas [42]. These measurements also provided information that was important for decisions concerning public safety at the time of the accident. Figure 4.1–6 shows aerially measured ambient dose equivalent rates as a function of time resulting from deposits following releases that spread to the north-west of the Fukushima Daiichi NPP. The largest long lived deposits of ^{137}Cs were found in this area of Japan, where the total deposition of ^{137}Cs has been estimated to have been around 2–3 PBq [43].

Dry deposition occurred in the afternoon of 12 March and during the night of 14–15 March, relatively close to the Fukushima Daiichi NPP. Subsequent wet deposition occurred at a greater distance from the Fukushima Daiichi NPP due to the wide precipitation area over East Japan. The highest dose rates shown in Fig. 4.1–6 illustrate the importance of wet deposition, which created higher levels of deposition over a wider area than did dry deposition. Precipitation is a key factor in determining the contamination of water, land and agricultural products.

Measurements of airborne radionuclides

Time series results of measurements of airborne radionuclides at four monitoring locations — the Fukushima Daiichi NPP, Tokaimura, Takasaki City, Tsukuba City (locations shown in Fig. 4.1–5) — are shown in Figs 4.1–7 (a)–(d). All off-site monitoring of activity concentrations of airborne radionuclides was performed at locations generally to the south-west of the plant. Three off-site locations were selected for Figs 4.1–7 (b)–(d). Activity concentrations of ^{134}Cs and ^{137}Cs were measured at all locations. Total ^{131}I was measured at all locations except for Takasaki City, where only particulate ^{131}I was sampled. Xenon-133 was also measured at Takasaki City, where a station of the International Monitoring System of the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) is located. Data for approximately the first 50 days after the accident are shown [45–49].

Figure 4.1–7 (a) [45] shows the results of measurements performed at the Fukushima Daiichi NPP. It needs to be pointed out that significant releases had been occurring for approximately a week before on-site monitoring of activity concentrations of airborne radionuclides began. It should also be noted that on-site monitoring will detect most releases, even those eventually transported over the ocean, whereas the detection of releases at off-site locations will depend on the prevailing wind direction. Maximum activity concentrations of ^{131}I in air of almost 10 000 Bq/m^3 were measured in the period of 19–23 March 2011 and remained above 100 Bq/m^3 until mid-April. Activity concentrations of gaseous phase ^{131}I were consistently higher than particulate phase ^{131}I. Activity concentrations of ^{134}Cs and ^{137}Cs in air at the Fukushima Daiichi NPP were between 10 and 100 Bq/m^3 during March and early April for each radionuclide; elevated levels of well over 100 Bq/m^3 were measured later in April. These levels are particularly relevant when considering the exposure of workers on the site during the accident.

Figures 4.1–7 (b)–(d) [46–49] show the results of measurements performed at off-site monitoring locations. A number of peaks can be observed in these figures, detected with a fair degree of consistency at approximately the same dates at each location. The first was observed around 14–16 March. Measured levels of airborne ^{131}I were generally high relative to those of radiocaesium. The Japan Chemical Analysis Center [50] reported, on the basis of measurements using an in situ (outdoor) high purity germanium (HPGe) gamma spectrometer in Chiba, that the sharp rise observed during this period resulted from airborne ^{133}Xe, ^{131}I and ^{132}I. Two subsequent, more sustained, peaks were observed around 20–21 March and 29–30 March. Levels of ^{131}I, ^{134}Cs and ^{137}Cs were roughly equal in these later peaks. The timing of these peaks corresponds qualitatively to the main release periods that resulted in deposition onto the terrestrial environment; some influence of these releases can be observed in the results from all three locations. These results therefore support the pattern of releases and dispersion described earlier.

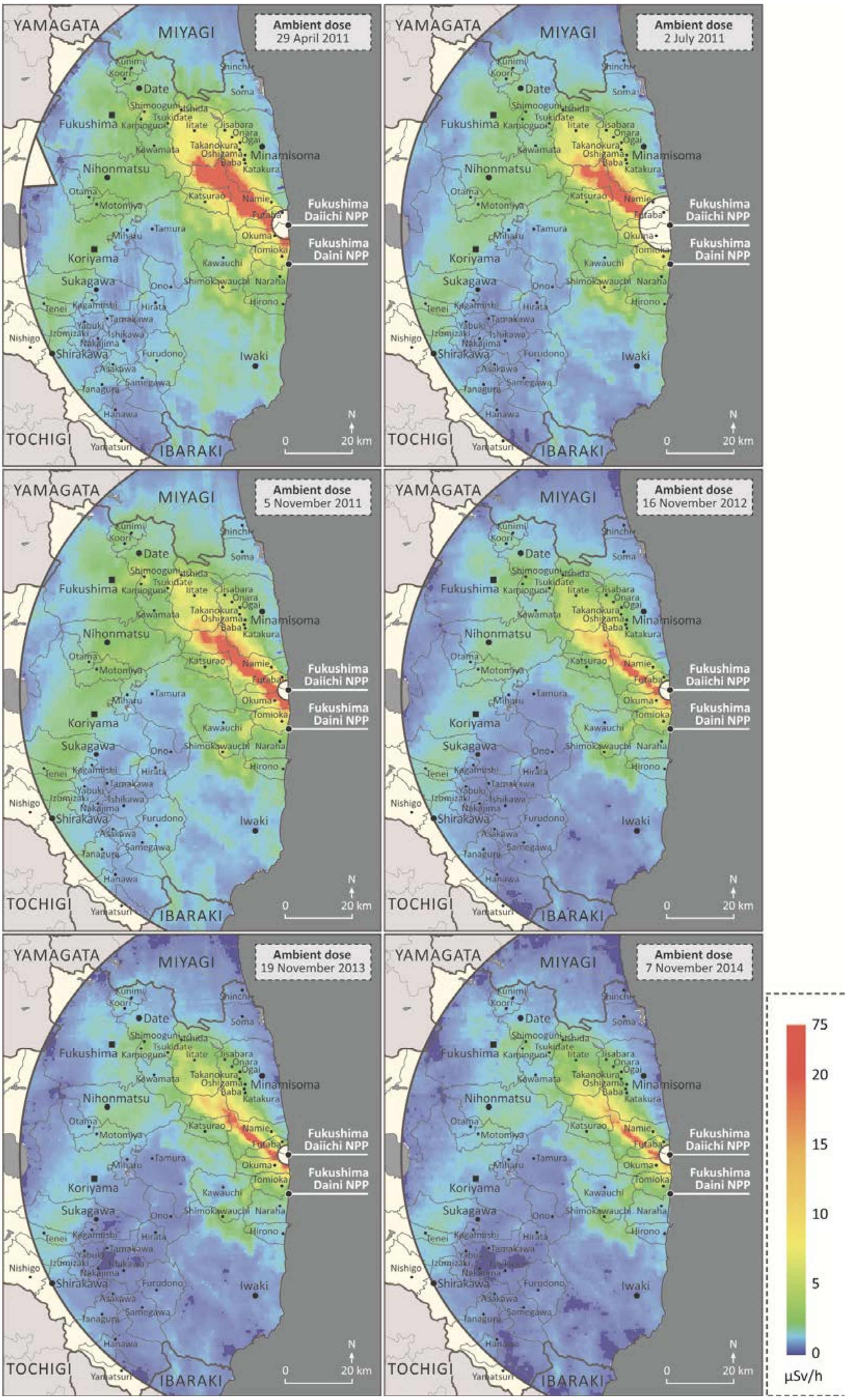


FIG. 4.1–6. Measured aerial ambient dose equivalent rate (in µSv/h) resulting from deposits from the releases that spread in areas to the north-west of the NPP [44].

Smaller peaks were observed in late April and in May, confirming that lower level releases from the Fukushima Daiichi NPP continued after the main release period of 12–23 March.

A maximum activity concentration of ^{131}I in air of 1600 Bq/m^3 was measured in Tokai City, the closest monitoring point to the Fukushima Daiichi NPP, on the morning of 15 March. Maximum activity concentrations of ^{134}Cs and ^{137}Cs of 180 and 190 Bq/m^3, respectively, were measured during the same sampling period. These values are of the same order of magnitude as those measured by Tokyo Electric Power Company (TEPCO) at the Fukushima Daiichi NPP (Fig. 4.1–7(a)) [45]. The maximum concentration of ^{133}Xe measured at Takasaki City was 400 Bq/m^3 on 16 and 17 March 2011.

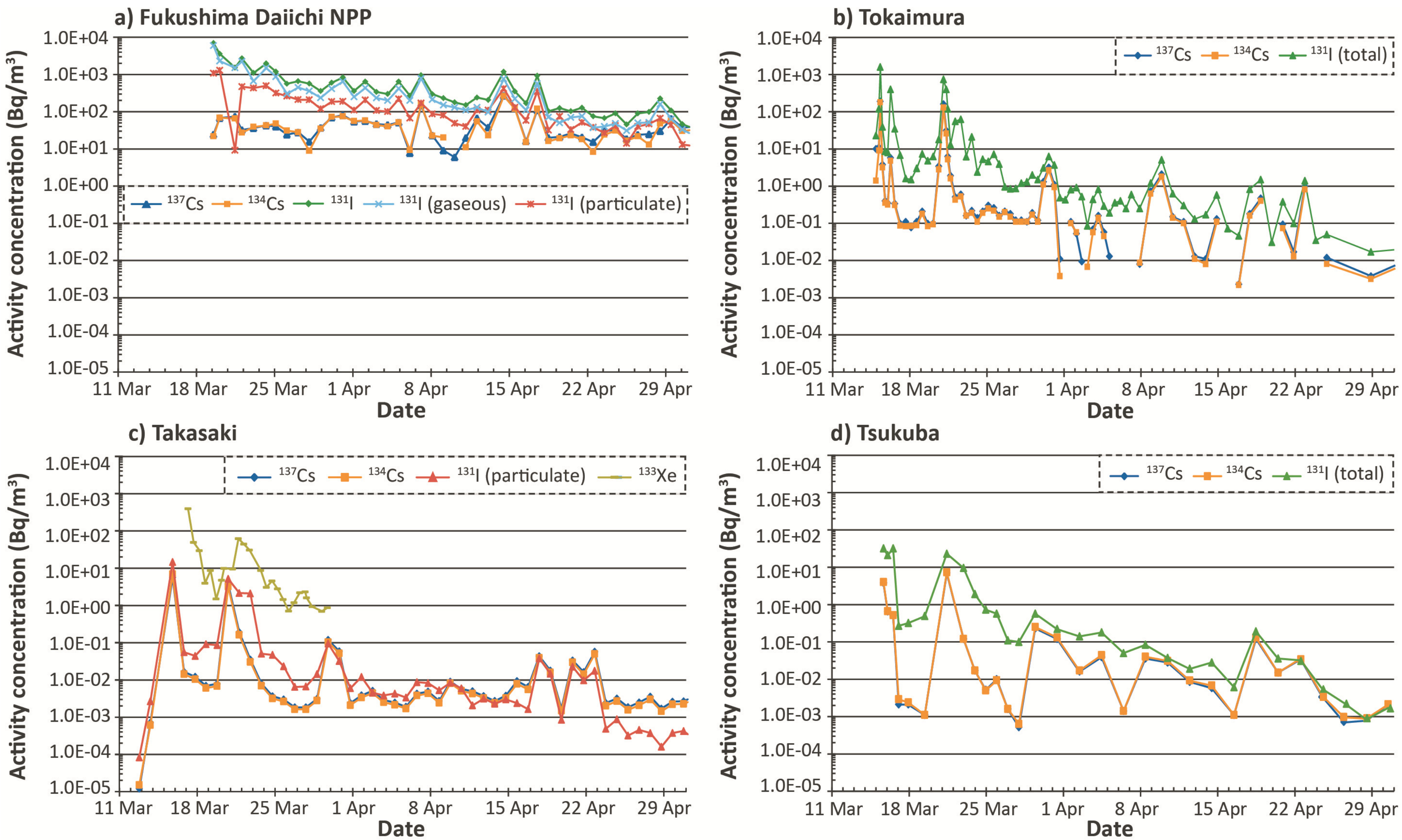


FIG. 4.1–7. Results of measurements of airborne radionuclides at four monitoring locations: at the Fukushima Daiichi NPP, Tokaimura, Takasaki, Tsukuba [45–49].

As can be seen from Fig. 4.1–8, the observed ratio of ^{134}Cs to ^{137}Cs was approximately 1 at all locations.

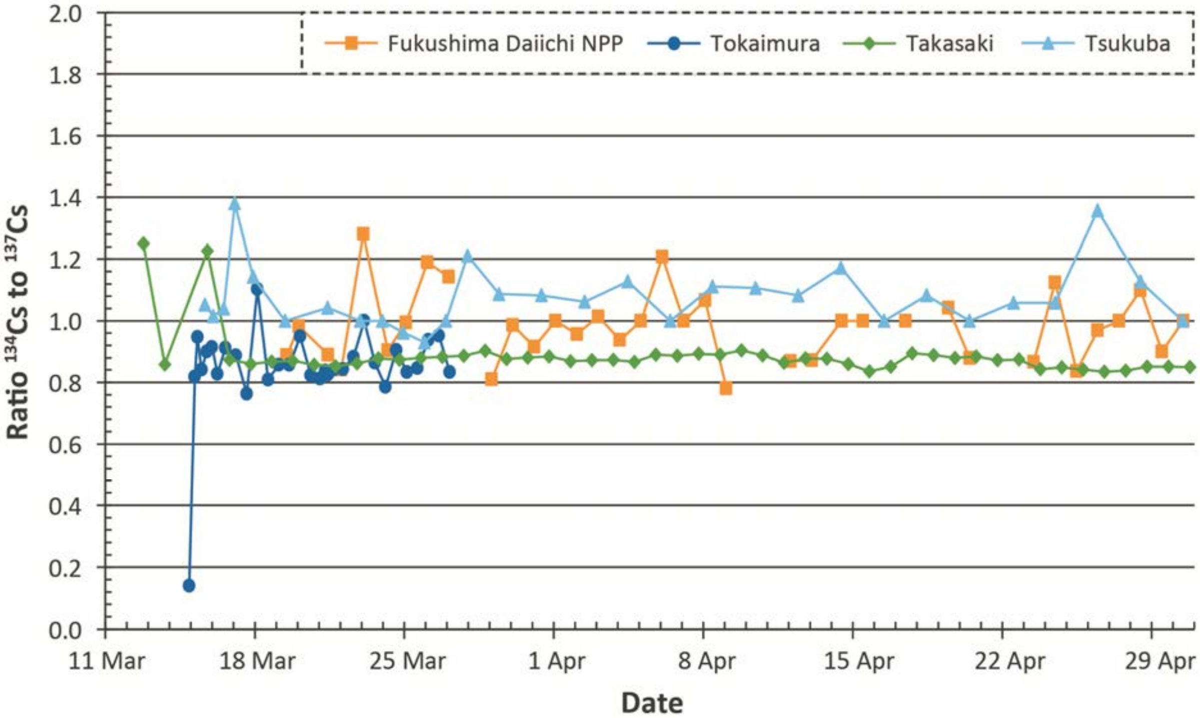


FIG. 4.1–8. Ratios of activity concentrations of airborne ^{134}Cs to ^{137}Cs [45–47].

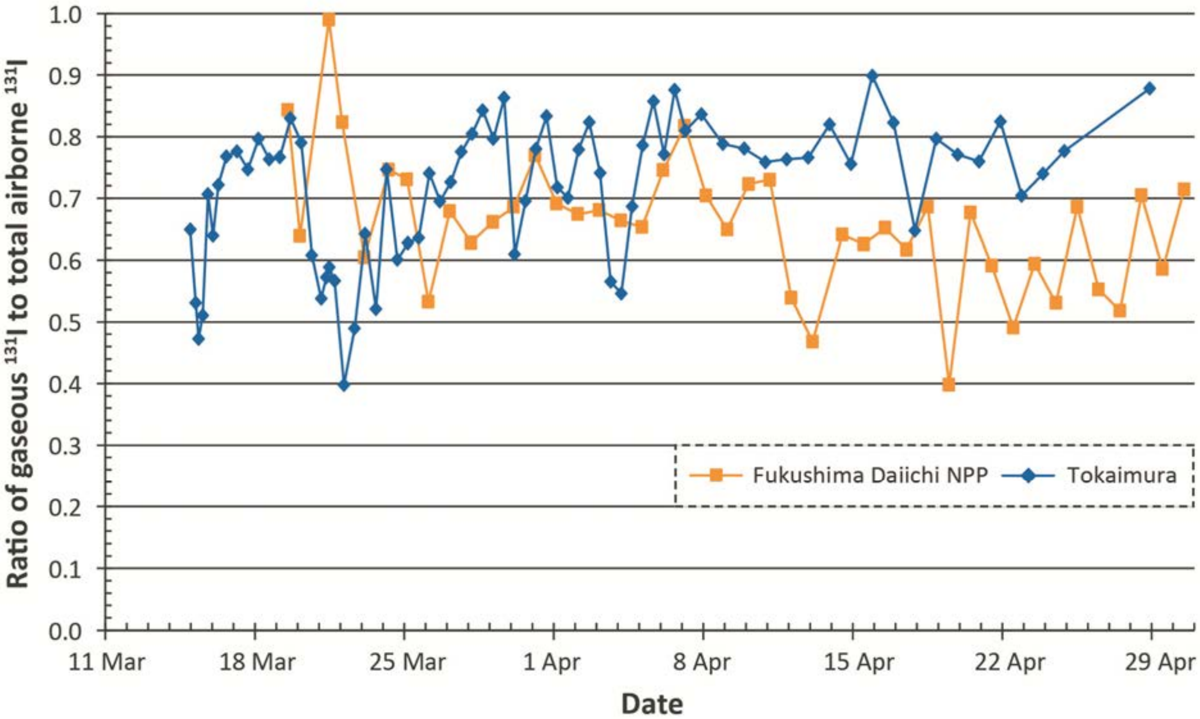


FIG. 4.1–9. Ratios of activity concentrations of gaseous ^{131}I to total airborne ^{131}I measured at the Fukushima Daiichi NPP site and at Tokai [45, 46].

The ratio of gaseous ^{131}I to total airborne ^{131}I is shown for two locations in Fig. 4.1–9. This ratio varied significantly with time and location, due in part to such factors as the different dry and wet deposition of the different forms of iodine, but it averaged around 0.8. Particulate iodine included all chemical species, particularly iodide (I^-) and iodate (IO^{3-}) [51]. The chemical form of iodine in rainwater was mainly in the anion exchangeable form. However, this also varied with time and location, with indications having been found that a portion of ^{131}I was bound to organic matter [52].

Daily deposition rates of ^{137}Cs and ^{131}I were measured in all prefectures in Japan from 18 March 2011, following the Fukushima Daiichi accident. The results for Fukushima Prefecture are shown in Fig. 4.1–10 for ^{137}Cs and ^{131}I. The results for surrounding prefectures are presented in Annex III. This monitoring was hampered in the early period by the damage caused by the earthquake and tsunami, particularly in Fukushima Prefecture. Elevated deposition rates in the period 20–23 March were measured in all prefectures, presumably as a result of the third period of significant releases, which resulted in terrestrial deposition of radionuclides from the Fukushima Daiichi NPP between 20 and 22 March.

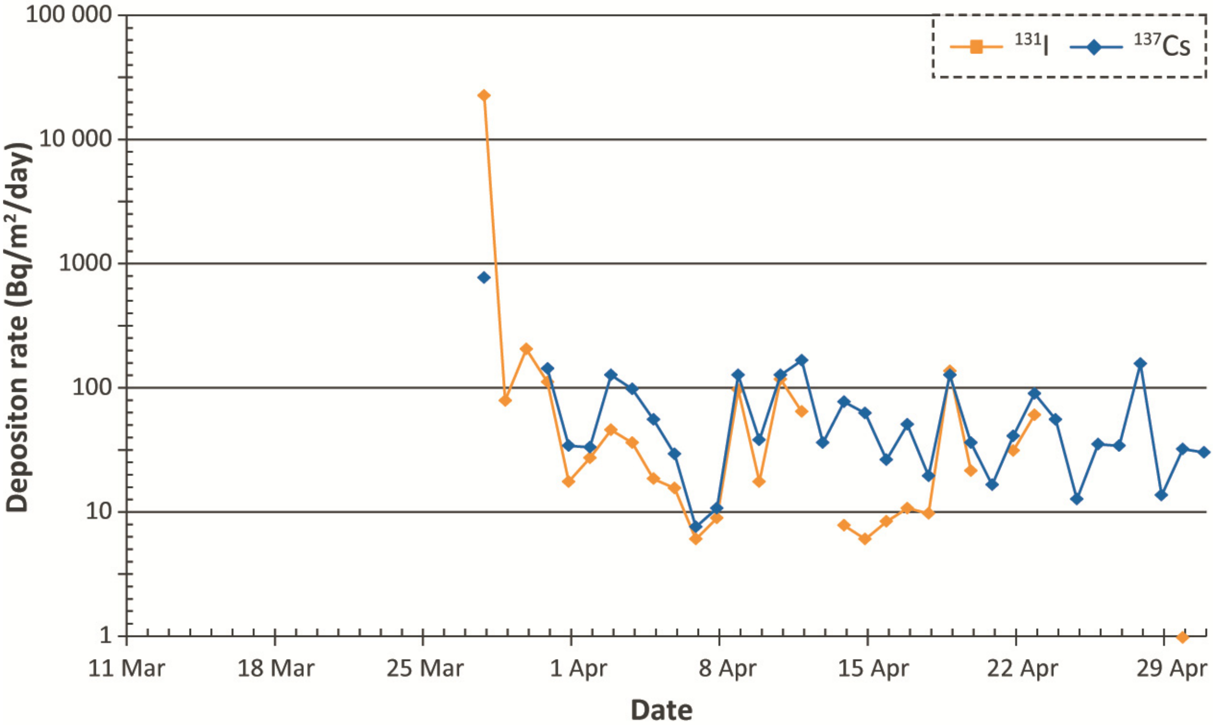


FIG. 4.1–10. Measurements of daily deposition of ^{131}I and ^{137}Cs in Fukushima Prefecture in 2011.

Monthly deposition rates have been measured at the prefectural level in Tokyo since 1954 and in neighbouring Tsukuba City since 1980 [53]. Figure 4.1–11 shows a series of monthly deposition rates of ^{137}Cs and ^{90}Sr, covering the period from 1955. The figure illustrates the effects of above ground nuclear weapons testing and the increased levels of deposition following the accident at the Chernobyl NPP. Also shown are the highest levels of deposition measured following the releases from the Fukushima Daiichi NPP in 2011. Levels of ^{137}Cs were around 2.3×10^4 Bq/m^2 per month in March 2011, compared with a peak from weapons fallout of 5.5×10^2 Bq/m^2 per month in June 1963. In contrast, the highest deposition rate of ^{90}Sr measured in March 2011 was 4.4 Bq/m^2 per month, which is significantly less than the highest deposition from weapons fallout of 170 Bq/m^2 per month in June 1963. This provides confirmation that low levels of ^{90}Sr were released from the Fukushima Daiichi NPP, as explained earlier.

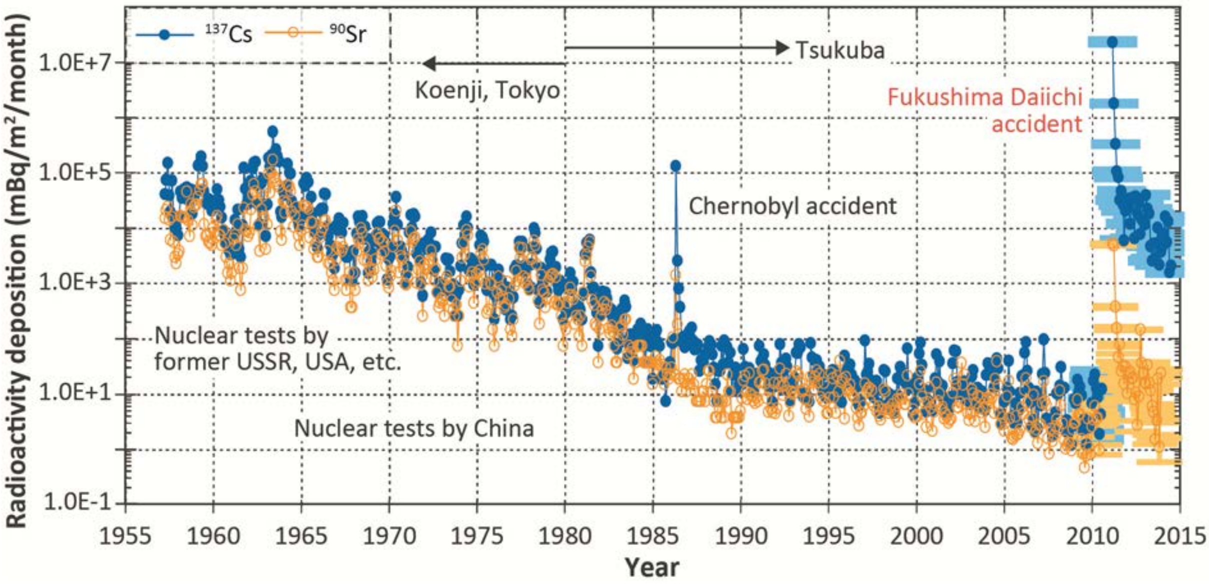


FIG. 4.1–11. Monthly deposition rates of ^{137}Cs and ^{90}Sr measured in Japan since 1955 (in Suginami ward, Tokyo, before 1980, and in Tsukuba City after 1980) [54].

It can also be observed that monthly deposition rates of ^{137}Cs measured in Tsukuba City are still elevated and comparable to those from fallout from atomic weapons tests measured in the mid-1960s [53]. Hirose [55] has analysed the temporal variation in deposition rates measured in several locations in Fukushima Prefecture and the Kanto plain for more than one year from the beginning of the releases and has concluded that there is evidence of resuspension supporting continued deposition of ^{137}Cs. The measured levels are not considered to be radiologically significant.

Information is available on the size distribution of the caesium particulates in the atmosphere. Kaneyasu et al. [56] measured size distributions of ^{134}Cs and ^{137}Cs in aerosols collected in Tsukuba City up to 47 days after the accident (see Fig. 4.1–5 — map of sampling locations). The median aerodynamic diameters of ^{134}Cs and ^{137}Cs in the first sampling period (28 April–12 May 2011) were found to be 0.54 µm and 0.53 µm, respectively, and their value in the second sampling period (12–26 May) was 0.63 µm in both cases. The authors concluded that caesium was associated with sulphate. Given this particle size, gravitational settling was not a significant dry deposition mechanism.

4.1.2.3. Distribution of radionuclides in the terrestrial environment

The radionuclides of most significance for assessing radiation exposures of people are ^{134}Cs, ^{137}Cs, ^{131}I and, to a lesser extent, ^{129m}Te. Caesium-134 and ^{137}Cs will persist in the environment for longer periods, determined by their physical half-lives (of around 2 and 30 years, respectively) and the behaviour of caesium in the environment. With a half-life of approximately eight days, ^{131}I was present in this environment for a few months following the accident, until the summer of 2011. Tellurium-129m persisted until about the end of 2011. Short lived radionuclides, particularly ^{136}Cs, ^{132}Te, ^{132}I and ^{133}I, lasted only days to weeks in the environment but may have contributed to early inhalation and external exposures as described in Section 4.2 below. Isotopes of strontium and plutonium were released in low quantities and were detectable in soil and other environmental samples and, with the exception of ^{89}Sr, will persist for many years.

A number of maps of the deposition densities of radionuclides released after the accident at the Fukushima Daiichi NPP has been produced. The most accurate are those based on soil sampling followed by laboratory analysis. Measurements in surface soil of ^{134}Cs, ^{137}Cs, ^{131}I, ^{129m}Te, ^{110m}Ag, ^{89}Sr,

^{90}Sr, ^{238}Pu and $^{239,240}Pu$ have been performed according to consistent sampling and analytical procedures (see Appendix I for details) and used to develop maps of the distribution of each radionuclide in Fukushima Prefecture and surrounding areas (see Appendix I). The area within a radius of 80 km of the Fukushima Daiichi NPP was divided into 2 km × 2 km grid squares. Five samples were taken from each grid square during a period between June and July 2011 and measured individually. The average result for each radionuclide was reported with a reference date of 14 June 2011. This information, together with in situ measurements of ambient dose equivalent rates, was used in the UNSCEAR assessment of radiation doses to the public living in different locations [5].

Maps of the deposition densities of ^{134}Cs, ^{137}Cs and ^{131}I have also been derived from aerial survey data. Repeated aerial surveys have resulted in the availability of 'snapshot' views of the deposition densities of ^{134}Cs and ^{137}Cs at intervals of a few months, thus enabling changes over time to be inferred (^{131}I had decayed to levels below the detection limit before the second and subsequent surveys). More information is presented in Appendix I.

A map of the deposition density of ^{137}Cs derived from laboratory analyses of soil samples is shown in Fig. 4.1–12. The map shows that the highest levels were measured in the evacuated areas: the Restricted Area within a radius of 20 km of the Fukushima Daiichi NPP and the Deliberate Evacuation Area[3] to the north-west of the plant. A maximum value of 15.5 MBq/m^2 was measured in a grid square from the municipality of Okuma located just north of the Fukushima Daiichi NPP. An average ambient dose equivalent rate of 54.8 μSv/h was measured in this grid at the same time as soil sampling was performed. Deposition densities of ^{137}Cs greater than 3 MBq/m^2 were measured in several other locations close to the plant — in Namie Town, Futaba Town and Tomioka Town, as well as in further locations in Okuma Town.

A similar map was developed for ^{134}Cs (see Appendix I). A $^{134}Cs/^{137}Cs$ isotopic ratio of 0.92 ± 0.07 was calculated from all measurements. After correcting the reported values for physical decay to the start of the main release phase on 12 March 2011, the ratio was found to be 1.00 ± 0.07. Therefore, it can be concluded that the two main isotopes of caesium were deposited in equal quantities. This decay corrected isotopic ratio is consistent with that derived from the results of monitoring of airborne radionuclides (see above).

[3] See Technical Volume 3 for more details on the various evacuation areas.

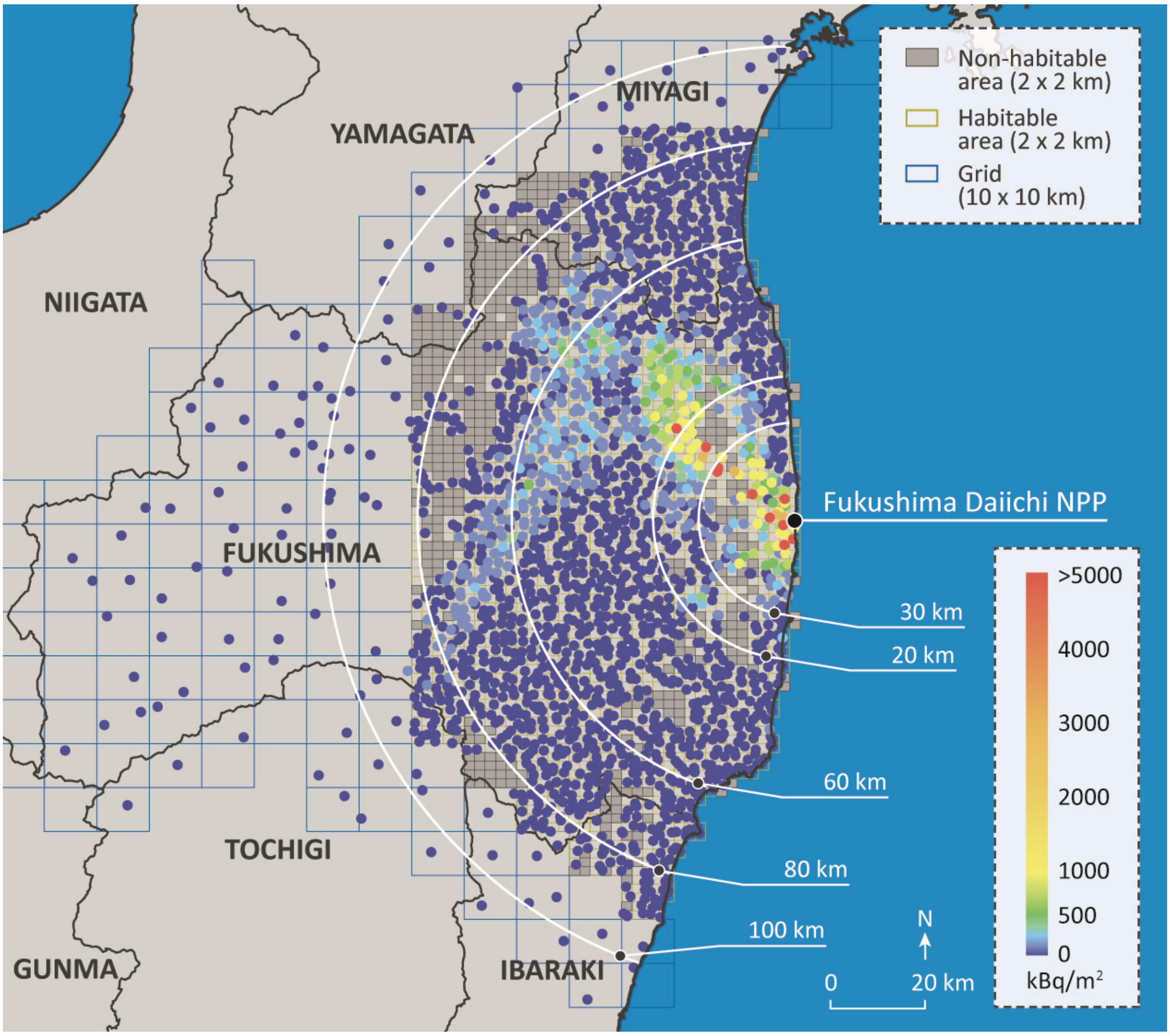


FIG. 4.1–12. Deposition density of ^{137}Cs from soil sampling and laboratory based analysis (decay corrected to 14 June 2011).

Maps of ^{134}Cs and ^{137}Cs derived from aerial survey results [7, 57–68] are shown for regular time intervals in Figs 4.1–13 and 4.1–14, respectively. It can be observed that the results are qualitatively consistent with those derived from laboratory analyses of soil samples. Some decrease in the levels of ^{134}Cs relative to those of ^{137}Cs can be observed for later surveys owing to radioactive decay of the shorter lived radionuclide.

The consistency of the soil sample measurements with the results of the first aerial[4] survey has been analysed quantitatively [69]. A high degree of correlation was found, thus providing confidence in the reliability of these key measurements of the pattern of radionuclides in the terrestrial environment.

[4] Referred to as ‘airborne surveys’ in MEXT literature.

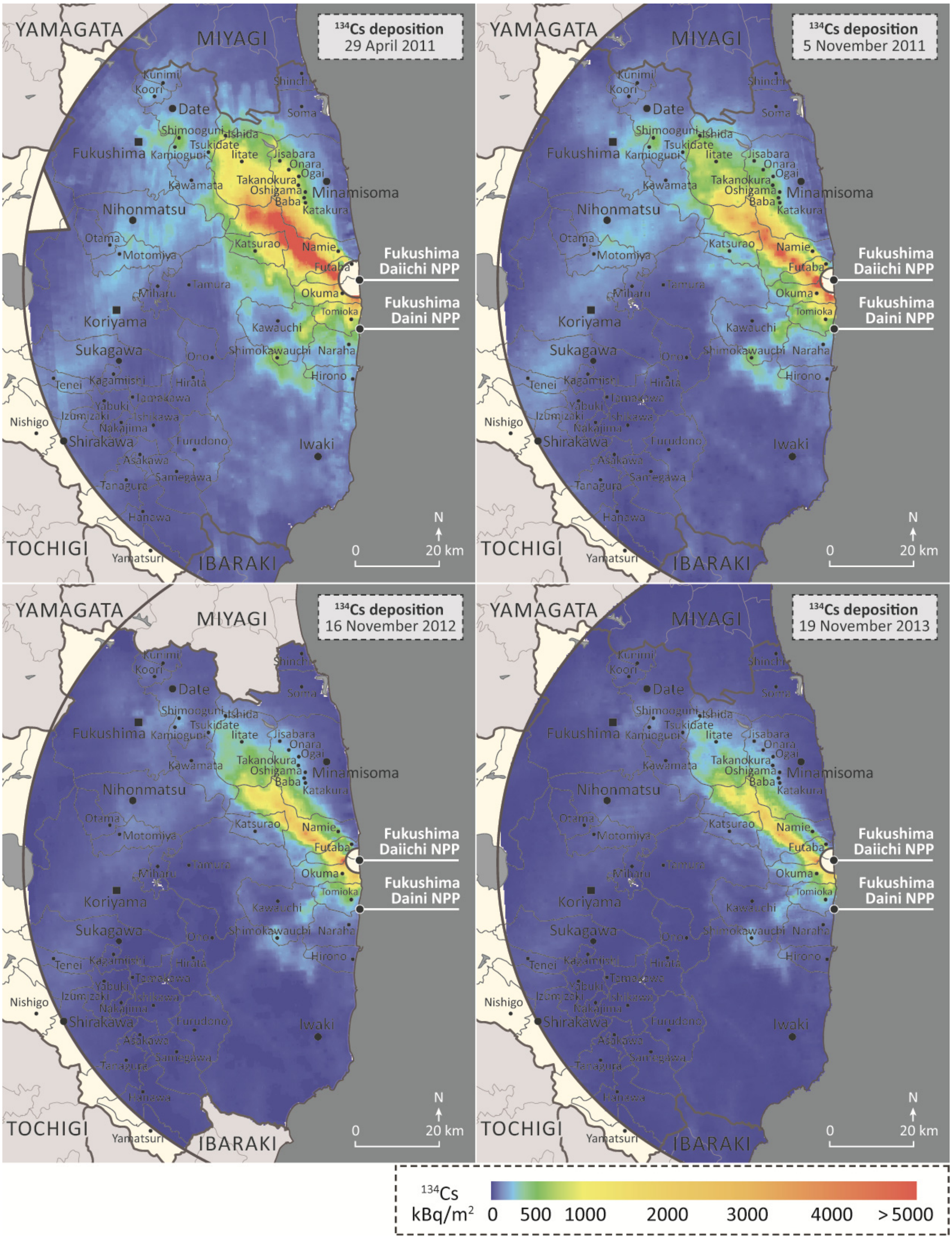


FIG. 4.1–13. Deposition density of ^{134}Cs as measured by aerial surveys.

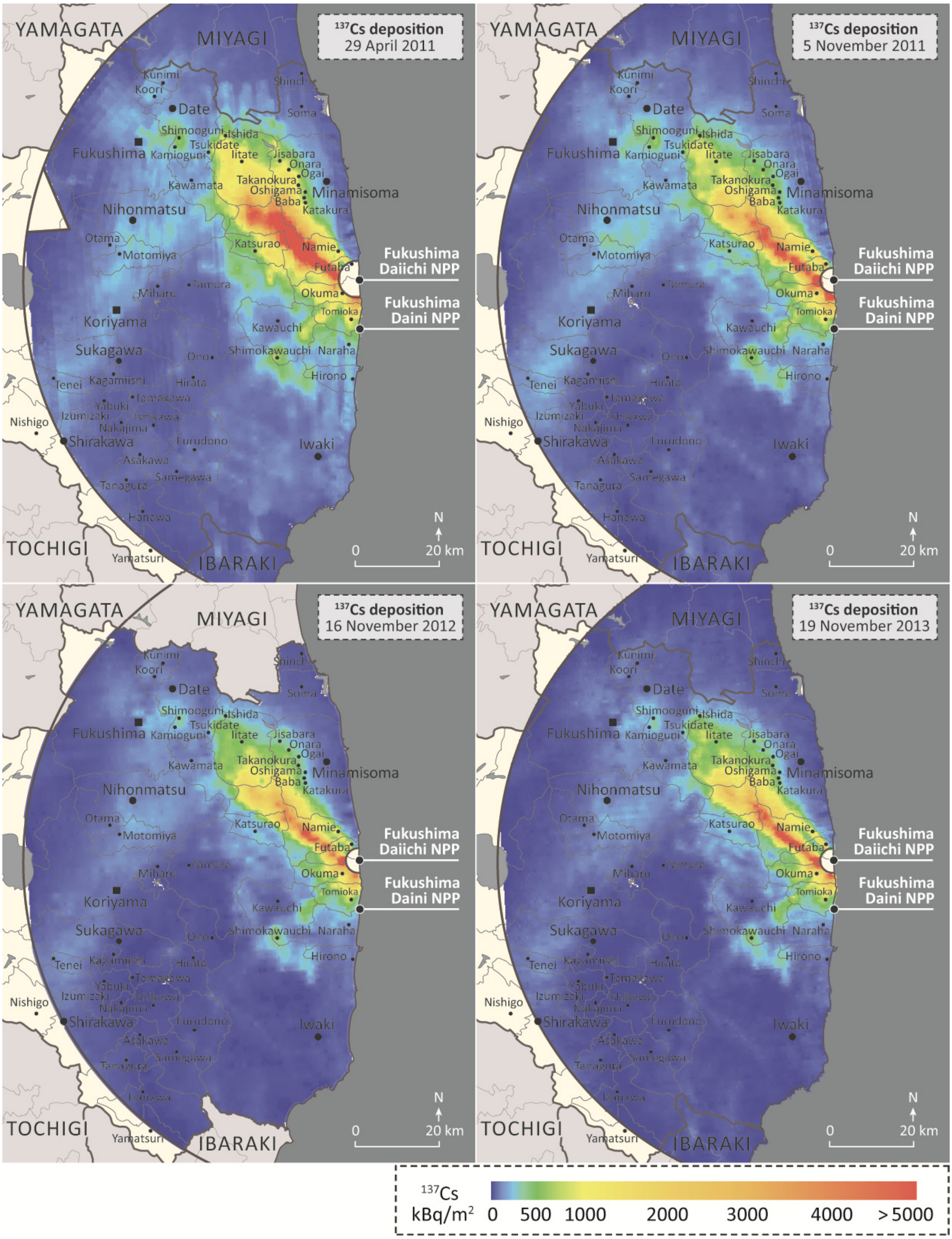
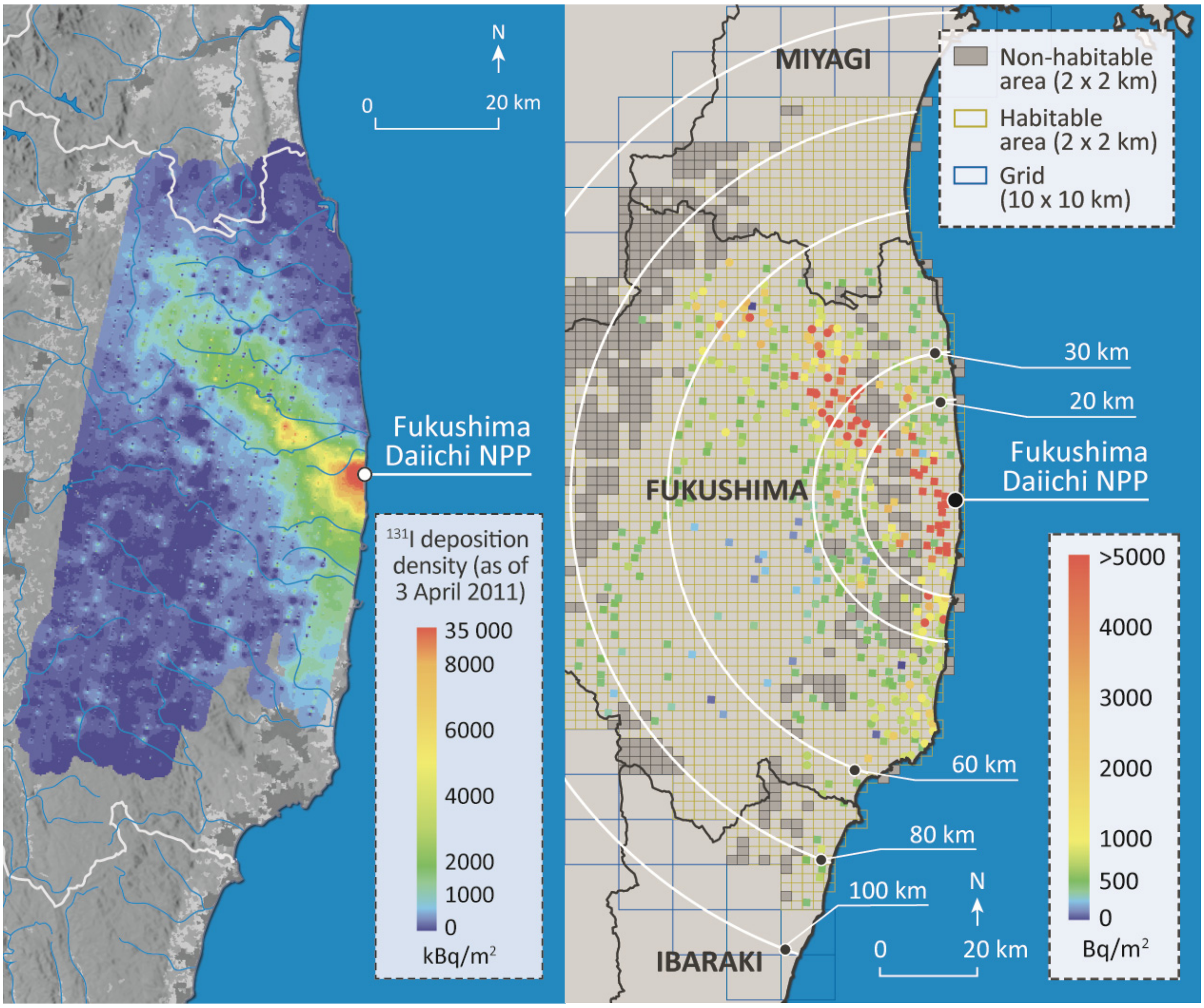


FIG. 4.1–14. Deposition density of ^{137}Cs as measured by aerial surveys.

Maps of the deposition density of ^{131}I derived from laboratory analyses of soil samples and from aerial survey results are shown in Fig. 4.1–15. The former dataset includes estimates of ^{131}I which were derived from accelerator mass spectrometry measurements of ^{129}I in the same soil samples using a calculated ^{129}I to ^{131}I conversion factor; the initial ratio between levels of the two isotopes ^{129}I/^{131}I was

~16 for rain water [70] and ~22.3 for soil samples, comparable with the estimated ratio from the operation history of the reactor (18–21) [71]. This additional analysis was required, as activity concentrations of ^{131}I in soil samples, collected some three to four months after the beginning of accidental releases from the Fukushima Daiichi NPP, had mostly decayed to levels that were undetectable by gamma spectrometry. The levels of ^{131}I were derived from aerial survey results by fitting iodine photo peaks to measured gamma spectra. This is a more accurate method than that used for the maps of ^{134}Cs and ^{137}Cs resulting from aerial surveys, which were derived by applying constant conversion coefficients.

A maximum value of 0.055 MBq/m^2 was recorded from a grid square in the municipality of Tomioka. This corresponds to some 187 MBq/m^2 when decay corrected to 12 March 2011. Deposition densities of ^{131}I of more than 5000 Bq/m^2 (17 MBq/m^2 when decay corrected to 12 March) were measured in several other locations close to the plant — in Okuma Town, Futaba Town, Tomioka Town, Namie Town, Iwaki City, Minamisoma City, Naraha Town and Iitate Village, as well as in further locations in Tomioka Town.



(a) (b)

FIG. 4.1–15. Deposition density of ^{131}I. (a) Map derived from aerial survey (normalized to 3 April 2011); (b) map derived from soil sampling and laboratory based analysis, including values derived from measurements of ^{129}I (normalized to 14 June 2011)

The different physicochemical forms of iodine and caesium resulted in different behaviour of these two elements in the atmosphere following release. As a result, a different deposition pattern from that of radiocaesium is expected and can be observed in the ^{131}I maps. Although the same pattern of high levels in the evacuated areas is evident, higher levels of ^{131}I relative to those of radiocaesium have been measured in areas to the south of the plant. It is not clear whether the different deposition pattern for ^{131}I and ^{137}Cs in the southern area compared with the north-western area is due to different deposition processes for these two elements or the result of different release times based on variations of reactor core temperatures.

Maps of the deposition densities of ^{129m}Te, ^{110m}Ag, ^{89}Sr and ^{90}Sr, and ^{238}Pu and ^{239,240}Pu are shown in Appendix I. In general, the deposition pattern of ^{129m}Te was similar to that of ^{137}Cs. This was to be expected given the similar chemical form and behaviour of caesium and tellurium in the atmosphere. However, a larger concentration of ^{129m}Te relative to that of ^{137}Cs was measured south of the plant. The different isotopic ratio may be the result of differences in the deposition process or differences in the time trend of the releases of ^{129m}Te and ^{137}Cs.

The deposition pattern of ^{110m}Ag is different from that of caesium, reflecting potential differences in release, transport and deposition behaviour. The concentrations were relatively low (a maximum value of 89 kBq/m^2 was measured from a grid square in Futaba Town).

A map of deposition densities of ^{89}Sr and ^{90}Sr is shown in Appendix I. Values of ^{89}Sr and ^{90}Sr of greater than 15.5 and 3.7 kBq/m^2, respectively, were measured in grid squares in Futaba Town and Namie Town. As previously noted, the measured levels of these strontium isotopes were three to four orders of magnitude lower than those of radiocaesium, reflecting the relatively low amounts released owing to the low volatility of this element.

Plutonium isotopes (^{238}Pu and ^{239,240}Pu) were measured in a number of samples from Fukushima Prefecture as shown in Appendix I. Isotopic ratios (^{240}Pu/^{239}Pu atom ratio ~0.32 and ^{238}Pu/$^{239+240}$Pu activity ratio of 1.1–2.9) were found to be distinct from those of global fallout and subsequently shown to have been characteristic of the fuel from Fukushima Daiichi Unit 3 [18, 72]. The activity concentrations measured are very low — close to, or often below, the limit of detection — and are not of any radiological significance. It is difficult to discern a clear pattern in the distribution of the measured levels of plutonium isotopes. The density of detected values is higher in the evacuated areas. However, where detected, the measured levels are similar throughout the survey up to an 80 km radius of the Fukushima Daiichi NPP. It is somewhat surprising that plutonium was detected so far from the release point and at levels comparable with those measured close to the site but this may be due to the importance of wet deposition at greater distances. There is no convincing evidence of hot particles (fuel fragments), which were ubiquitous following the Chernobyl accident [72, 73]. This is expected given the different nature of the events leading up to releases from the Fukushima Daiichi NPP compared with those at Chernobyl.

The maps in Appendix I provide a useful high level overview of the deposition footprint. However, there is significant inhomogeneity at smaller scales. This is reflected in the designation of several hundred 'Specific Spots Recommended for Evacuation', which were defined by Japanese authorities outside of the two main evacuation areas. These are small areas, often just tens of square metres, where the annual dose from deposited radionuclides was expected to exceed 20 mSv.

Rates of deposition of radionuclides are known also to be strongly influenced by surface cover and structure and, hence, different land uses such as forests, agricultural lands, water bodies and urban settlements.

As a consequence of the accident at the Fukushima Daiichi NPP, there was significant deposition of radionuclides on agricultural land in the prefectures of Fukushima, Iwate, Miyagi, Ibaraki, Tochigi, Gunma and Chiba. Agriculture systems including paddy fields for rice cultivation, fields for various agricultural products and livestock feed, and storage reservoirs were affected by deposited activity. In the period from the accident until the early summer 2011, direct deposition of ^{131}I, ^{134}Cs and ^{137}Cs on the surface of products, especially on leafy vegetables and trees, was observed. Owing to its short half-life, ^{131}I was not detected in agricultural products beyond that date, and radiocaesium incorporated in plants by root uptake became dominant. Agricultural lands with activity concentrations exceeding 1000 Bq/kg are found in a wide area in the eastern part of Fukushima Prefecture, in a narrow area in the central part of the prefecture, and widely scattered in areas of the northern part of Tochigi Prefecture. The distribution of radiocaesium concentration in the soil on agricultural lands is further described in Annex III.

As the accident occurred before the period of rice planting (which is usually carried out in May in Fukushima Prefecture), the national Government issued a policy of restrictions on planting and cultivating rice in paddy fields where concentrations of ^{134}Cs and ^{137}Cs in soil exceeded 5000 Bq/kg, as described in Technical Volumes 3 and 5. Although concentrations higher than 25 000 Bq/kg were found in fields within the evacuated areas, no activity concentrations exceeding 5000 Bq/kg were found in paddy fields outside these areas. Thus, rice planting and cultivation was restricted only within the evacuation zones.

Beef contaminated with radioactive caesium levels exceeding 500 Bq/kg, which was the provisional regulation value at the time, was found in July 2011. The cause of these high levels was found to be rice straw, which had been contaminated during outdoor drying and distributed to the market to feed beef cattle [74].

Kato et al. [75] measured the depth distribution of ^{137}Cs, ^{134}Cs and ^{131}I in Kawamata Town, 40 km north-west of the Fukushima Daiichi NPP. The results of this study demonstrated that, at the time of the measurements (April 2011), more than 86% of the total radiocaesium and 79% of the total ^{131}I were in the upper 2.0 cm of the soil profile. The relaxation mass depth (kg/m^2), which quantifies the radionuclide penetration into the soil (the greater the value, the deeper the penetration of the radionuclide), derived from the depth distribution of radiocaesium and ^{131}I in the soil profile at the study site were 9.1 kg/m^2 and 10.4 kg/m^2, respectively.

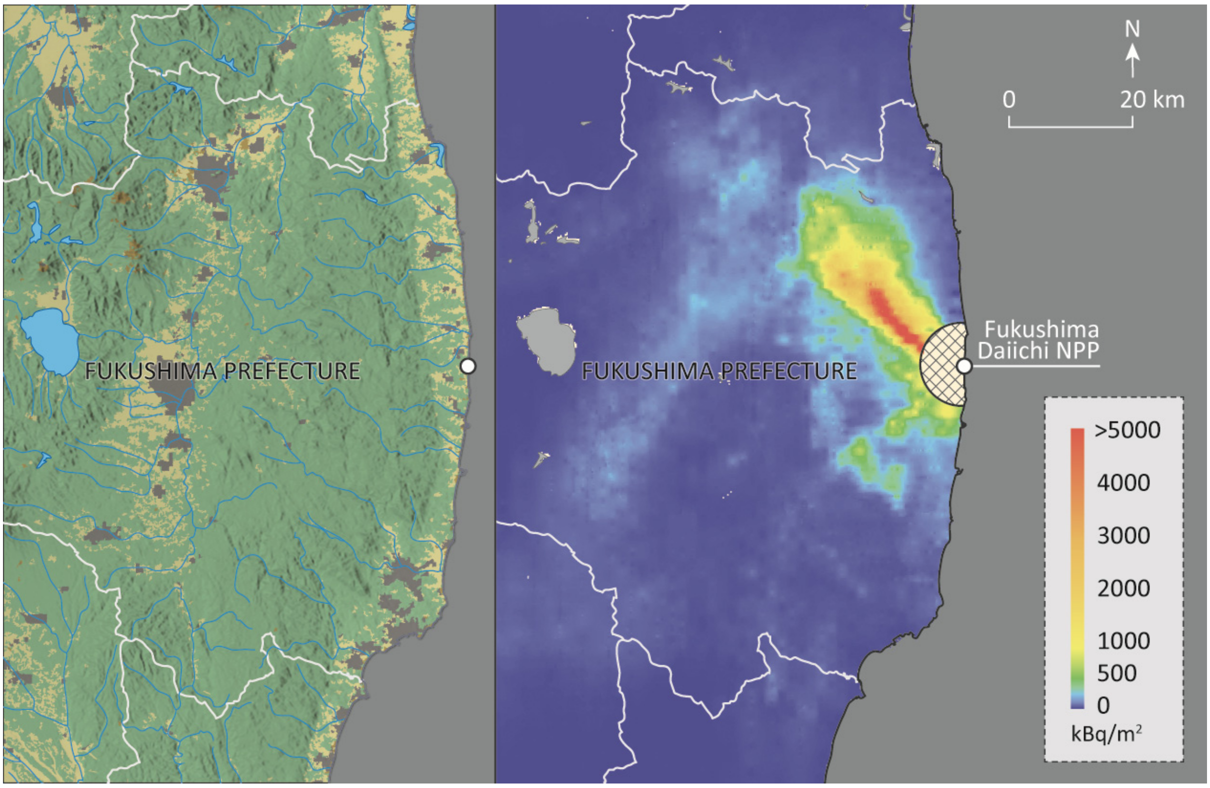
Tanaka et al. [76] carried out leaching experiments on different soil samples and revealed that most of the ^{137}Cs was attached to soil particles. In contrast, ^{131}I was leachable using an acidic solution, and the dissolved fraction of ^{131}I increased in an alkaline solution.

Relatively high levels of ^{137}Cs and ^{131}I were found in grass samples in Yagisawa (Iitate Village) just after the rainfall (snowfall) owing to direct deposition. However, for rice, the most important staple food in Japan, the major transfer process for radiocaesium is considered to have been uptake from the soil, because rice was not planted until after the main accidental releases from the Fukushima Daiichi NPP had ceased.

Forest covers approximately 70% of the land area of Fukushima Prefecture, so a significant part of the radionuclides deposited on the terrestrial environment entered the forest ecosystem. The surface of the canopy differs depending on the forest type and the season. At the time of the accident, deciduous forests were without leaves and deposition on the canopy was limited; radionuclides were deposited directly onto the litter and forest floor. However, analyses of ^{137}Cs, ^{134}Cs and ^{131}I in rainwater, throughfall and stemflow in coniferous forests indicated that more than 60% of the total deposited radiocaesium remained in the forest canopy after 5 months, while ^{131}I moved through the canopy with rainwater [75]. Ten months after the accident, radiocaesium was concentrated at the floor of coniferous forests, and high transfer factors were observed in undergrowth plants [77]. By 2014, around 99% of the total inventory of ^{137}Cs was found in soil within the top 10 cm, in which organic matter content was greater than 10%. This suggests that subsequent distribution will be dependent on the turn-over of organic matter.

The distribution of radiocaesium in tree stems of a conifer (Japanese red pine) and a broad leaved species (Japanese konara oak) was investigated 1.5 years after the accident. The activity concentrations were highest in the outer bark, followed by the inner bark and the wood. The vertical distribution varied with species [78]. The impact of releases on the forests is described in more detail in Annex III.

The distribution of radionuclides in the environment is strongly influenced by topography. The deposition density of radiocaesium measured by an aerial survey in October 2011 [60] in the Tohoku and Kanto regions is shown in Fig. 4.1–16, adjacent to a topographical map of the area. Elevated levels can be clearly observed in the mountainous regions, i.e. the Ou Mountains, Iide Mountains, Echigo Mountains and Kanto Mountains. The mountains seem to have formed an effective barrier, preventing significant further transport of radioactive material further westward.



(a) (b)

FIG. 4.1–16. (a) Topographical map of Fukushima Prefecture; (b) map showing total deposition density of ^{137}*Cs* *(kBq/m*^{2}*) estimated based on the results of aerial monitoring [60, 79](decay corrected to 13 October 2011) illustrating the influence of the mountains to the west of Fukushima Prefecture on deposition pattern.*

4.1.3. Deposition and releases to the marine environment and radioactivity in the aquatic environment

4.1.3.1. Deposition and releases into the Pacific Ocean

As described in Technical Volume 1, Section 1.4, radionuclides were introduced to the Pacific Ocean from the Fukushima Daiichi accident. Several processes have contributed, or are still contributing, to levels of radionuclides in the ocean as a result of the accident:

- Deposition on the ocean surface of radionuclides released to and transported by the atmosphere (12–30 March 2011);
- Unintentional release of highly contaminated water from pit near the intake channel of Unit 2 (1–6 April 2011);
- Planned discharge of low level radioactive accumulated water from storage tanks (4–10 April 2011);
- Unintentional release of water containing moderate amounts of radionuclides (10–11 May 2011);
- Inflow of contaminated water (including groundwater and treated retained water from the site) (May 2011–present).

There is also likely to be runoff of deposited radioactive materials following rain, typhoons, tides and so on.

The most significant of these sources are thought to be atmospheric deposition on the ocean surface and the direct release of highly radioactive water from a pit adjacent to Unit 2. Key factors leading to radionuclides entering the marine environment are summarized below [5]. Further information on the events leading to these releases is given in Technical Volume 1 (Section 1.4).

Atmospheric deposition on to the ocean

Before 25–26 March, the most significant source of radionuclides in the ocean arising from the Fukushima Daiichi accident was deposition of radionuclides released to the atmosphere. For example, Ref. [80] considers that, before the end of March 2011, the concentrations of radioactive material in the sea were mainly influenced by deposition. As indicated in Section 4.1.1, the dominant weather pattern for much of the period when the larger releases from the Fukushima Daiichi NPP occurred was associated with westerly winds, i.e. moving eastwards and leading to the wet and dry deposition of the airborne radionuclides (notably ^{137}Cs, ^{134}Cs and ^{131}I) over the Pacific Ocean. There were no measurements of dose rate above the ocean surface during the first weeks of the accident (the first aerial survey over the sea took place on 5 April). The estimates of radioactivity deposited are therefore uncertain.

The amount of ^{137}Cs released to the atmosphere was estimated to have been between 7 and 20 PBq, of which between 0.18 and 10 PBq has been estimated to have been deposited onto the ocean [1, 81–84], as described in more detail in Technical Volume 1, Section 1.4. Atmospheric deposition of ^{137}Cs on land and ocean has been estimated with large scale atmospheric transference models in the intercomparison exercise [35] (see Annex IV).

For the purpose of the assessment in their 2013 report [5], UNSCEAR estimated the range of indirect releases to the ocean due to atmospheric dispersion and deposition to be between 5 and 8 PBq for ^{137}Cs and between 60 and 100 PBq for ^{131}I.

Direct release of contaminated water

There were no observations of the concentration of radionuclides in sea water until 21 March 2011, near the southern outlet of the NPP, and 23 March, near the northern outlet of the Fukushima Daiichi NPP. Therefore, it is difficult to evaluate the direct release from the site to the ocean during the first few weeks of the accident. The evaluated values of ^{137}Cs directly released to the ocean ranged from around 2.3 to 26.9 PBq [80, 84–88]. Additional information is presented in Annex IV.

The main source of the direct releases of radionuclides to the ocean was the large amounts of sea water injected to cool the reactors and the structural damage that some of the pressurized containment vessels had suffered. Progressively larger amounts of heavily contaminated water accumulated inside the reactor and turbine buildings over time. As of September 2013, the total radioactivity of water inside the basements, trenches, and shafts was evaluated at 12.6 PBq [89]. During 2011–2013, three main events led to direct releases of some of this water containing radionuclides to the ocean:

(1) The first event was discovered at around 09:30 on 2 April 2011, when TEPCO found that water with a dose rate reading of over 1000 mSv/h was leaking directly into the sea through a 20 cm crack in the wall of a pit that was storing electric cables, near the intake channel of Unit 2 [90]. During the following days, several measures were taken to stop the release of water, which was eventually achieved at 05:38 on 6 April. Based on the calculated leakage flow and sampling results, TEPCO assessed the total inventory of radioactive material released with water at 4.7 PBq [91].
(2) An outflow of contaminated water into the sea occurred through a leak from a pit near the intake channel of Unit 3 and was discovered at 16:05 on 11 May 2011. It was stopped at around 18:45 on the same day. The total amount of radioactive material discharged into the sea was estimated at 0.02 PBq.
(3) The third event was an intentional discharge of wastewater with relatively low levels of radionuclides into the ocean in April 2011. This was to prevent a possible leakage of radioactive wastewater with high levels of radionuclides, which had accumulated in the basement floor of the turbine building of Unit 2. TEPCO decided to discharge the low level radioactive water accumulated in the radioactive waste treatment facilities and sub-drains of Units 5 and 6 and replace it with the highly active radioactive wastewater from Unit 2. About 10 393 t were discharged from 4 to 10 April 2011. The total amount of radioactive material released to the ocean is estimated to have been about 1.5×10^{11} Bq [92].

The total quantity of ^{137}Cs released directly to the ocean has been estimated with oceanic dispersion simulation models in an intercomparison experiment (see Annex IV).

Based on the available information, UNSCEAR used a range for the direct discharge of ^{137}Cs to the ocean of 3–6 PBq and about 10–20 PBq for ^{131}I, noting that the larger range was based on other studies [5]. As described in Annex IV and Technical Volume 1, Section 1.4, the direct releases and discharges of ^{137}Cs are generally estimated to be 1–6 PBq, but there are assessments that have reported estimates of 2.3–26.9 PBq [35]. Measurements of activity concentrations in ocean water close to the Fukushima coast show that, although the release rate has decreased, radioactive materials are still entering the ocean. The possible sources of continued releases are likely to be the drainage of groundwater transferring radioactive materials from the basements of reactors or trenches or, to a lesser extent, leakage from storage tanks, as well as runoff of radionuclides from sediments and the ground during rain.

As explained above, a long term source of radionuclides released to the ocean is through the transfer of radionuclides to groundwater and to rivers and hence to the oceans. The levels released in this way are significantly lower than those discharged in March to May 2011 but these environmental transport processes would be expected to continue for a period determined by radioactive decay and other physical and chemical processes.

4.1.3.2. Dispersion of radionuclides in the marine environment

The Fukushima Daiichi NPP is located adjacent to the Kuroshio-Oyashio Transition Area, which is the region of confluence of two wind-driven western boundary currents of the North Pacific: the Kuroshio, which transports warm, saline waters northwards along the south coast of Japan and then eastward; and the Oyashio, which transports cold, less saline water southwards [93]. The convergence of the two currents is marked by the creation of several intense mesoscale eddies. Another characteristic of the region is the Tsugaru Warm Current, flowing from the Sea of Japan through the Tsugaru Strait north of Honshu [94] and then southwards along the slope of its east coast.

Further information on the bathymetry and predominant currents during the time of the main release events in April 2011 are presented in Annex IV.

Marine dispersion and deposition

The dispersion of radionuclides released to the ocean depends on a number of factors, including the movement of the ocean currents illustrated above. Mixing of radionuclides with the ocean water is also influenced by the interaction of mesoscale structures and coastal waters where they meet on the shelf break, generating flows across the shelf break [85]. The dispersion in the shallow shelf waters is primarily driven by winds, tides and freshwater inputs. There are two regions with different dominant physical processes related to the dispersion of radionuclides released directly to the ocean. Before reaching the open ocean, where large scale currents and mesoscale structures will transport and disperse them, the radionuclides are transported by the coastal circulation on the continental shelf. The coast creates a blocking effect that reduces dispersion and induces a dominant alongshore transport. In 2011, during the three months following the Fukushima Daiichi accident, the strongest winds blew predominantly toward the south (south-east or south-west) and towards the north. In the first case, the wind induced downwelling, with surface waters pushed against the coast, and the emergence of a coastal jet flowing southwards. In the case of winds blowing north, the wind produced an upwelling. The resulting alongshore component of the transport was northward, but an additional perpendicular drift tended to spread coastal waters toward the external shelf and the slope. This dispersal favoured interaction with the offshore currents flowing southward along the slope, the Tsugaru and Oyashio Currents, as well as the residual tidal current.

Some 80% of the deposition of radionuclides from atmospheric releases from the Fukushima Daiichi NPP was spread on the ocean surface beyond the continental shelf [35]. Thus, these radionuclides were entrained by mesoscale structures characteristic of the region and by large scale currents, which enhanced their dispersion. The major surface current systems in the Pacific Ocean are the subpolar (subarctic) Gyre, the North Pacific Gyre and the South Pacific Gyre (Fig. 4.1–17). In the western North Pacific, the main currents are, as described above, the Oyashio and the Kuroshio, which are of primary importance for the dispersion of radionuclides released from the Fukushima Daiichi NPP. It has been shown that the North Pacific Current can transport radionuclides eastwards at a velocity of about 200 km/month [95]. In the eastern North Pacific, the main currents are the counter-clockwise Alaska Current in the north and the California Current, which is part of the North Pacific (subtropical) Gyre, flowing southwards along the western coast of North America. The Pacific equatorial current system is complex and consists of the North Equatorial Current, the North Equatorial Countercurrent and the South Equatorial Current. Significant equatorial subsurface flows include the Northern Subsurface Countercurrent, the Equatorial Undercurrent and the Southern Subsurface Countercurrent. Notwithstanding the complexity of the equatorial current system, the equatorial flow is predominantly eastward [96]. The dominant large scale structure in the South Pacific Ocean, the South Pacific (subtropical) Gyre, includes the East Australian Current and the Peru Current. South of the Gyre, the Antarctic Circumpolar Current transports water eastwards.

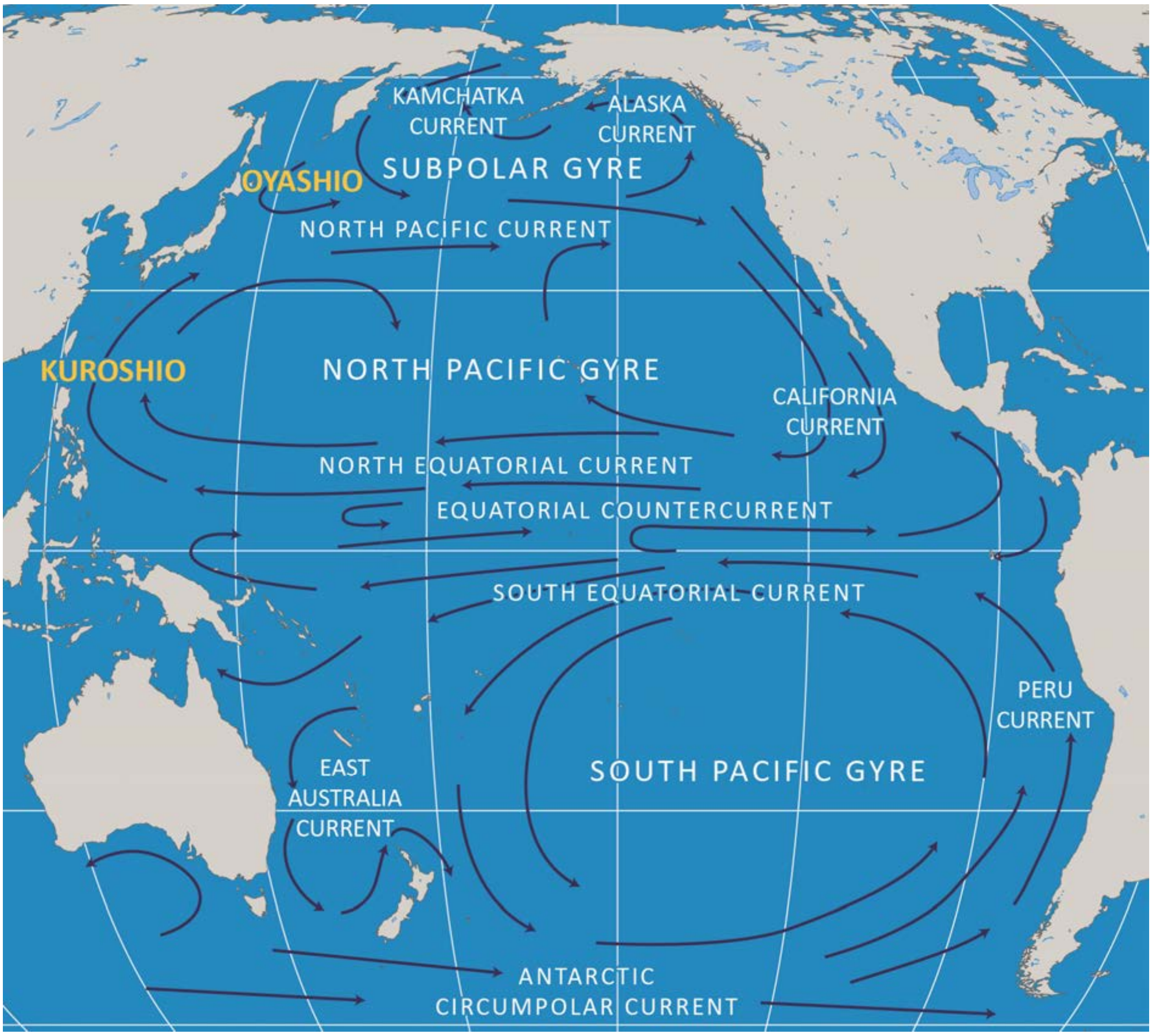


FIG. 4.1–17. The major surface currents in the Pacific Ocean (adapted from [99]).

The even larger scale global circulation ('conveyor belt' system) transports cold and salty Antarctic Circumpolar Bottom Waters from the South Pacific to the North Pacific, upwelling to shallower depths in the North Pacific Ocean. Warmer surface waters in the western North Pacific Ocean then move across the Pacific to the Indian Ocean through the Indonesian Straits [97].

The vertical profiles of temperature and salinity (density) in the ocean are indicators of vertical mixing processes and are a signature of the water masses at the respective point. A surface mixed layer with constant temperature and salinity, with a seasonally and geographically variable thickness of 10–200 m over most of the tropical and mid-latitude belts, results in downward mixing of any radionuclides deposited on the ocean surface. Relatively uniform distributions of radionuclides can be expected down to the bottom of the mixed layer (thermocline), followed by a sharp decrease below that. The mixed layer is deepest in winter, and further downward penetration of radionuclides originating at the surface can take place depending on the structure and flows of intermediate and deep water masses. In the North Pacific, besides the eastward transport of radionuclides by surface currents, the formation and subduction of subtropical mode waters and central mode waters result in southward and westward subsurface transport [95, 98].

The mixing of waters brought by the Kuroshio and the Oyashio currents, formation of eddies and further sinking of surface water masses can also entrain different dispersal patterns for radionuclides released from the Fukushima Daiichi NPP.

There are a large number of rivers flowing into the coastal waters around the Fukushima Daiichi NPP. These rivers are drivers of coastal circulation, through their input of fresh, less dense waters. They also act as secondary sources of radionuclides initially deposited then later remobilized, washed off and entrained from the catchment area to the coastal waters. Radionuclides deposited on fine particles in various sections of rivers can also be entrained by high waters in the rainy or snowmelt seasons and reach the river mouth. Important geochemical and depositional processes take place at the mouths of the rivers (estuaries), where fresh and salty waters mix. This can result in areas with higher concentrations of radionuclides. The main rivers in the region are the Natori and Abukuma Rivers flowing into the Sendai Bay, to the north of Fukushima. Their average flows into the sea are 190, 17 and 67 m^3/s, respectively [85].

The interaction of radionuclides with sediments suspended in the water mass and with bottom sediments is a process that can deplete radionuclides from the water column and increase their inventories in bottom sediment. These processes are important for particle reactive radionuclides, especially in the coastal zone, where there are more particles in suspension. The degree to which radionuclides interact with sediments is influenced by the nature of the sediments (composition) and grain size; coarse sands and silts exhibit the lowest affinity for interaction, while fine clays have the highest. Movement of fine sediments on the seafloor because of the action of waves and currents, combined with the influence of the bottom topography, can result in a very patchy pattern of bottom sediment radioactivity, with areas of high concentration on the scale of 1–100 m [100]. Deposition and mixing through physical and biological processes can reduce the concentrations of radionuclides in the surface layer of bottom sediment.

The complexity of oceanographic processes combined with the complex source term (including direct liquid releases to the coastal ocean and atmospheric deposition further offshore) renders the understanding and the prediction of distributions and dynamics of radionuclides released from the Fukushima Daiichi NPP challenging. A number of models have been applied to estimate the dispersion of ^{137}Cs in the North Pacific Ocean and the results of some of these are illustrated in Fig. 4.1–18. This shows the estimated activity concentration of ^{137}Cs in water as a function of time and uses the original code of colours employed in each particular reference. As in the case of atmospheric dispersion, small changes in the degree or tone of the colours correspond to a one order of magnitude change in the activity concentration. This illustrates that the activity in the ocean decreased significantly with distance from the Fukushima Daiichi NPP. The first graphic, Fig. 4.1–18(a), presents an example of modelling the dispersion of ^{137}Cs in sea water from 21 March 2011 to 29 June 2012 [101, 102]. The second, 4.1–18(b), presents an example of simulated horizontal distribution of ^{137}Cs in surface waters between 14 and 26 April 2011 [103]. The third graphic, 4.1–18(c), presents an example of the horizontal distribution of the ^{137}Cs concentrations averaged over a ten day period from 21 to 30 April 2011 [35]. All models show that the activity of ^{137}Cs in the ocean was very low. Some further information on the models is given in Annex IV.

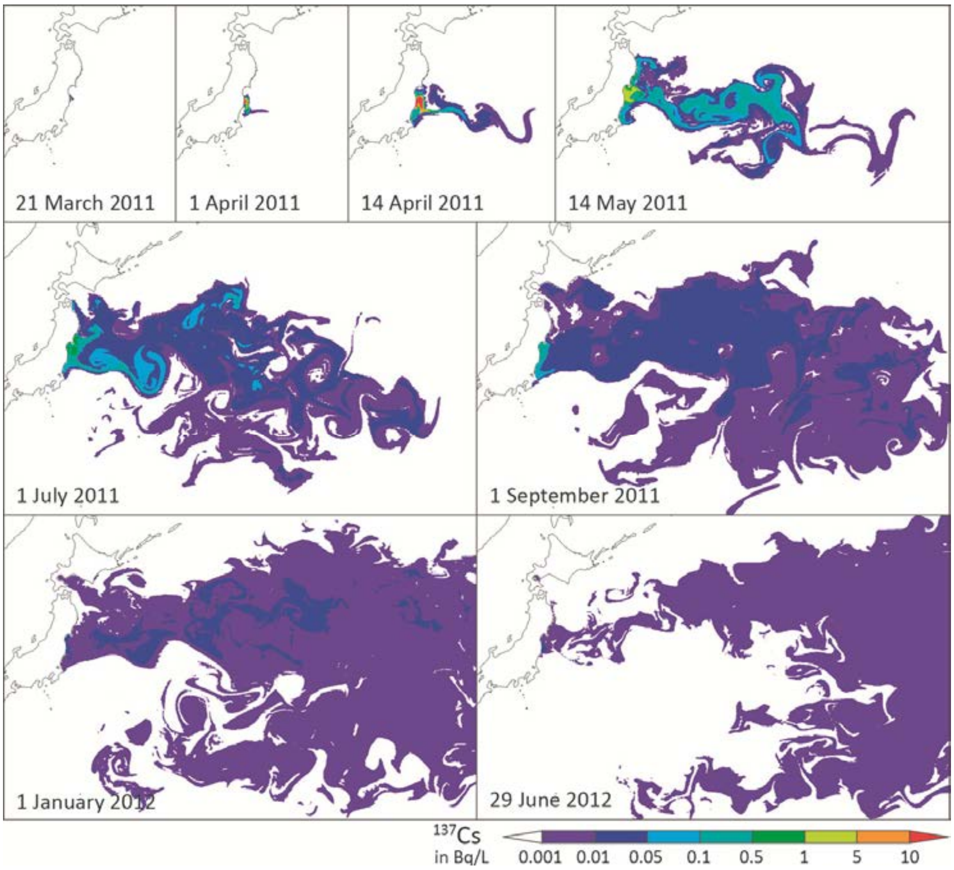


FIG. 4.1–18 (a). An example of the distribution of the activity concentration of ^{137}Cs in sea water obtained from an oceanic model for the period from 21 March 2011 to 29 June 2012 [104, 105];

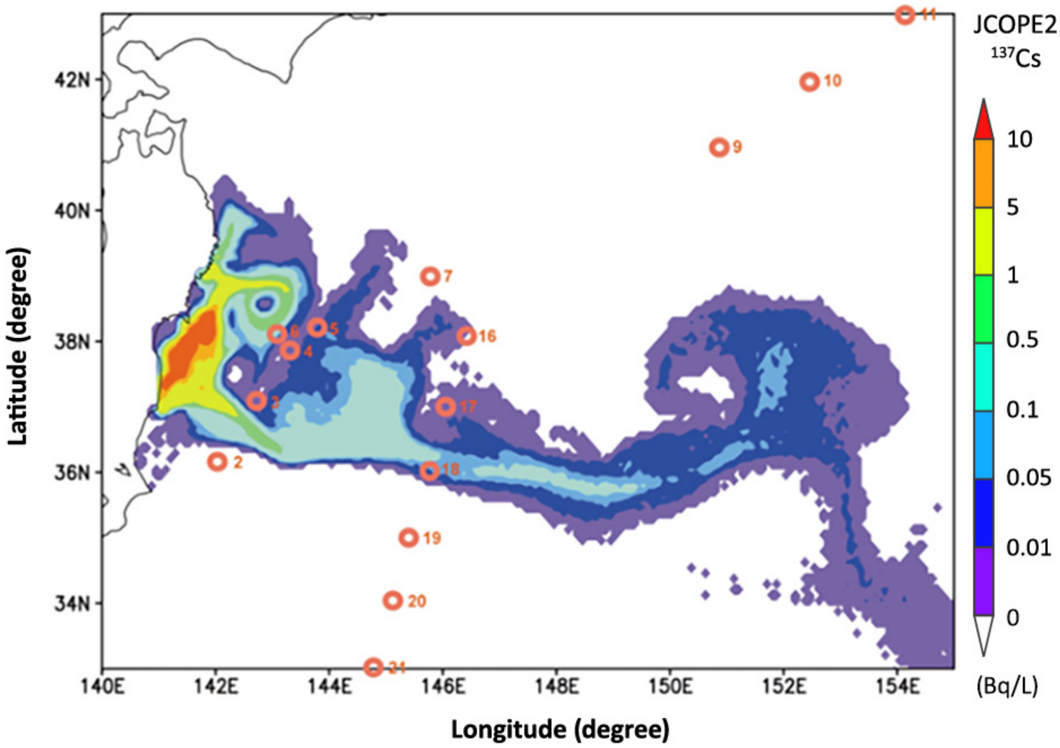


FIG. 4.1–18 (b). An example of the distribution of the activity concentration of ^{137}Cs in sea water obtained from an oceanic model for the period 14 and 26 April 2011 [103].

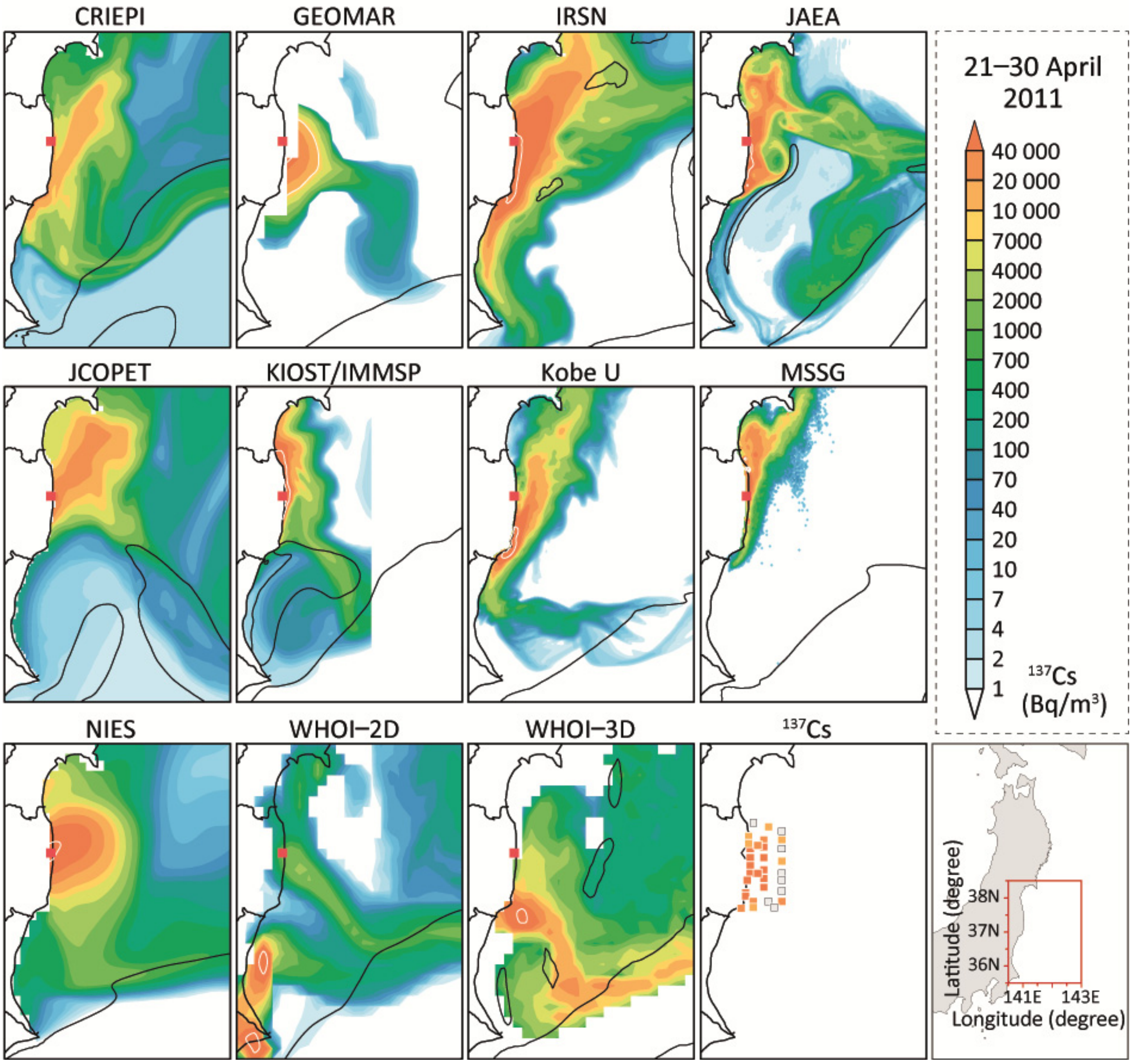
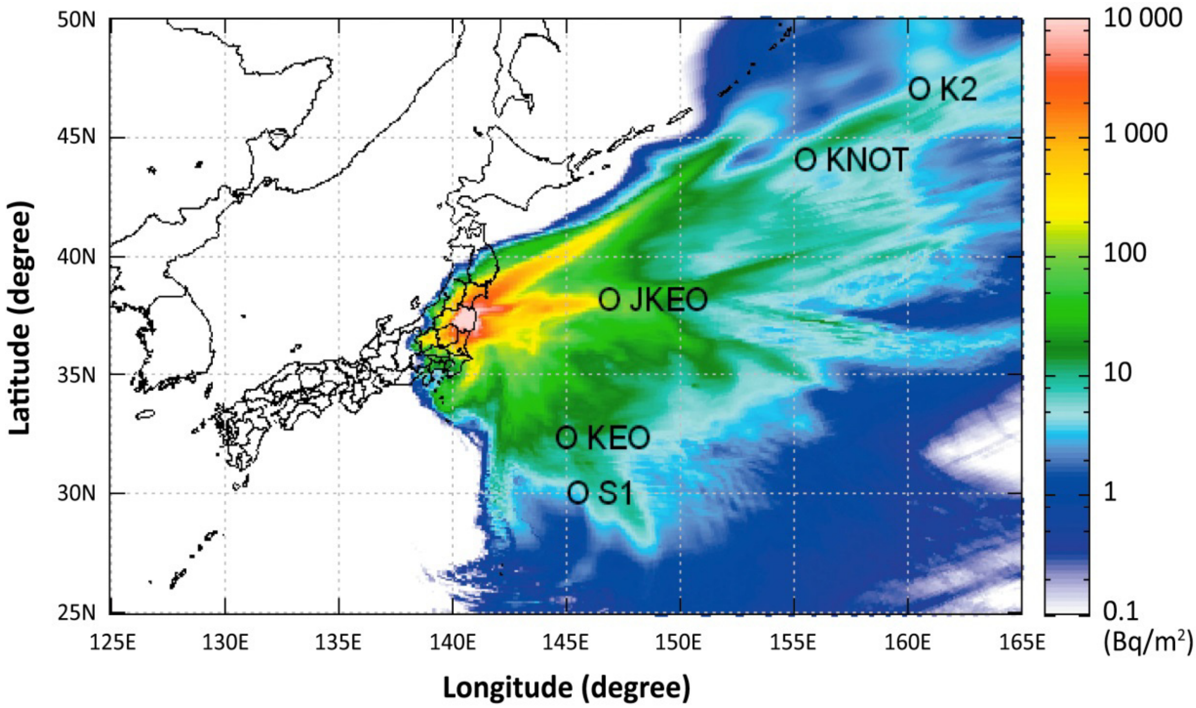
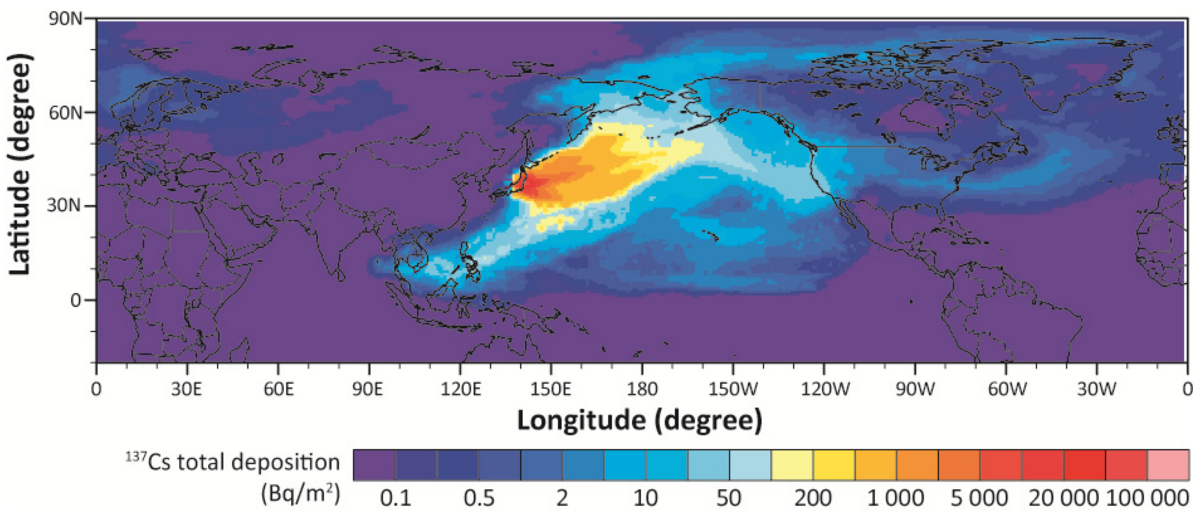


FIG. 4.1–18 (c). An example of the distribution of the activity concentration of ^{137}Cs in sea water obtained from oceanic models averaged over a ten day period from 21 to 30 April 2011 [35].

The deposition of ^{137}Cs onto the ocean has also been studied using various models. Figure 4.1–19 illustrates examples of modelling the cumulative Aeolian input (i.e. the accumulated deposition relating to or arising from the action of the wind) from 1 April 2011 [103] and of the ^{137}Cs deposition averaged over the estimates from a series of models from 11 to 31 March 2011 [35]. As explained above, it is challenging to produce an accurate estimate of the amount of the ^{137}Cs released to the atmosphere that was deposited on the ocean surface (see also Ref. [106]), but the results shown in Fig. 4.1–19 below illustrate the likely pattern of the deposition. The estimated total deposition of ^{137}Cs on the ocean surface due to the accident at the Fukushima Daiichi NPP is about 5–8 PBq, and this can be compared with the total global pre-accident deposition of ^{137}Cs (as of 1970), which is estimated as 290 ± 30 PBq, and the typical background level of ^{137}Cs in the North Pacific Ocean of about 69 PBq [43, 107].



(a)



(b)

FIG. 4.1–19. Various models have been used to estimate the oceanic deposition density of ^{137}Cs (the units used are Bq/m^2). (a) Modelling the cumulative Aeolian input up to 1 April 2011 [103]; and (b) an example of the ensemble averaged ^{137}Cs deposition (11–31 March 2011) [35].

4.1.3.3. Monitoring of radionuclides in the marine environment

The marine environment was thus affected by atmospheric releases and subsequent deposition of airborne radioactivity on the sea surface of the Pacific Ocean and by direct releases from the Fukushima Daiichi NPP. Despite these two pathways involving similar total activities, the atmospheric deposition has not led to significant concentrations, although it is detectable. The direct releases from the site caused high levels of radionuclides in the local marine environment. It is the nature of the huge ocean volume that persistent substances introduced into the oceans are dispersed through the ocean currents over large distances and diluted accordingly to significantly lower concentrations (as described above).

Measurements of ambient dose equivalent

The aerial surveys of ambient dose equivalent, described in Section 4.1.2 and Appendix I, measured levels of radioactivity over the land and over the sea. Measurements over the sea are presented in Refs [108, 109]. Figure 4.1–20 illustrates the results of one such survey showing the pattern of the ambient dose equivalent rate over the Pacific Ocean near the Fukushima Daiichi NPP in April 2011.

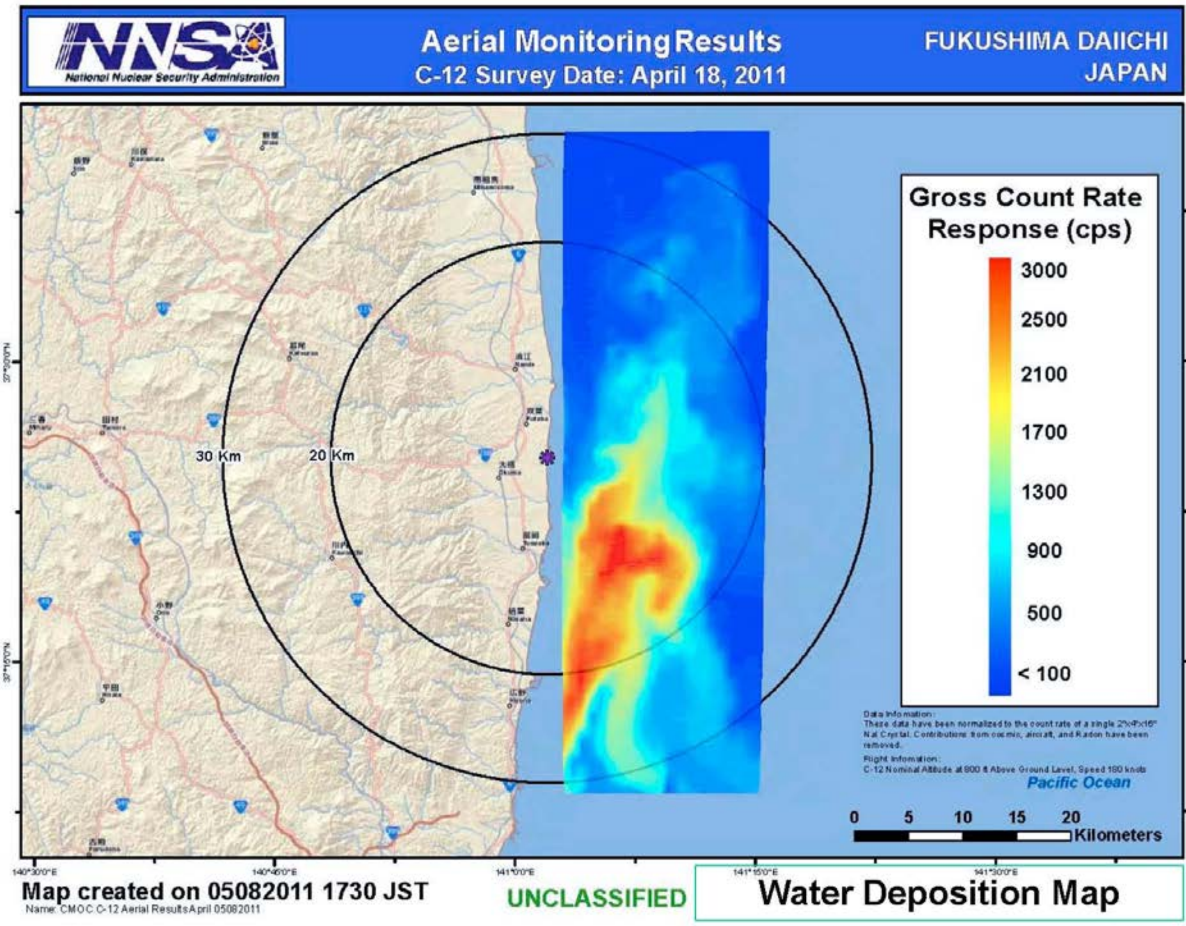


FIG. 4.1–20. The pattern of ambient dose equivalent rate over the Pacific Ocean as measured by aerial monitoring conducted by US DOE/NNSA, indicated by the gross count rate in counts per second [110].

After the initial phase of the accident and releases into the ocean, specific monitoring programmes were set up to follow the temporal and spatial trends of radionuclides in marine waters, sediments and biota.

Measurements of sea water

Marine monitoring began on 21 March 2011. On this date, radionuclides were detected in sea water around the discharge canal to the south of the Fukushima Daiichi NPP. This information was included in a press release on the following day [90] (see Table 4.1–4).

TABLE 4.1–4. INFORMATION INCLUDED IN THE TEPCO PRESS RELEASE OF 22 MARCH 2011

Time and date of sample collection	14:30, 21 March 2011			
Place of collection	Around the discharge canal (south) of Fukushima Daiichi NPP (approximately 330 m south of the discharge canal of Units 1–4)			
Manner of measurement	500 mL sample measured using germanium semiconductor detector			
Measurement time	1000 s			
Radionuclide	Measured activity concentration (Bq/cm^3)	Detection limit (Bq/cm^3)	Statutory limit[a] (Bq/cm^3)	Ratio of sample/statutory limit
^{58}Co	5.96×10^{-2}	3.35×10^{-2}	1	0.1
^{131}I	5.07	4.25×10^{-2}	4×10^{-2}	126.7
^{132}I	2.14	1.93×10^{-1}	3	0.7
^{134}Cs	1.49	4.03×10^{-2}	6×10^{-2}	24.8
^{136}Cs	2.13×10^{-1}	2.36×10^{-2}	3×10^{-1}	0.7
^{137}Cs	1.48	4.20×10^{-2}	9×10^{-2}	16.5

[a] The statutory limit is the allowable concentration of the listed nuclide in water discharged from the reactor.

The sea area within a 30 km zone of the Fukushima Daiichi NPP was monitored by TEPCO until 20 September 2011. After that date, TEPCO continued to monitor within a 20 km radius of the site, while other areas have been monitored by other organizations, including: the Nuclear Regulation Authority, the Ministry of the Environment, the Fukushima Prefectural Government, the Ministry of Land, Infrastructure, Transport and Tourism, Fisheries Agency and the Japan Coast Guard. Some research institutions and universities have also performed measurements of radioactivity in sea water, sediments and marine biota [111]. Marine monitoring results have been made available to international organizations and nuclear regulatory bodies [112], as well as on web sites of the monitoring organizations. These data indicate an improving situation in the sea areas over time (e.g. in sea water in coastal areas) [95, 98, 108, 113–117].

Relatively high levels of ^{137}Cs were detected close to the Fukushima Daiichi NPP directly after the accident and release in April 2011. The activity concentrations of ^{137}Cs in sea water at a range of monitoring points close to the Fukushima Daiichi and Daini NPPs and at a distance of 30 km offshore for the period 21 March–31 July 2011 are presented in Fig. 4.1–21. This figure also places these data within the context of the baseline activities in Japan in the period of 1960–2010 and peaks in activity in the Baltic and Black Seas resulting from the Chernobyl accident in 1986. The figure illustrates the relatively rapid decline in concentrations in the first few weeks. Since that time, there has been a continuous decrease in the activity concentrations of ^{137}Cs (see Annex IV). It also demonstrates that the radionuclide ^{131}I was only relevant and detectable during the first few months (until July 2011) in sea water [117].

Figure 4.1–21 indicates that the highest releases to the marine environment occurred from the end of March to the beginning of April 2011, resulting in concentrations of ^{137}Cs, ^{134}Cs and ^{131}I of up to 10^3 to 10^5 Bq/L in sea water near the reactors.

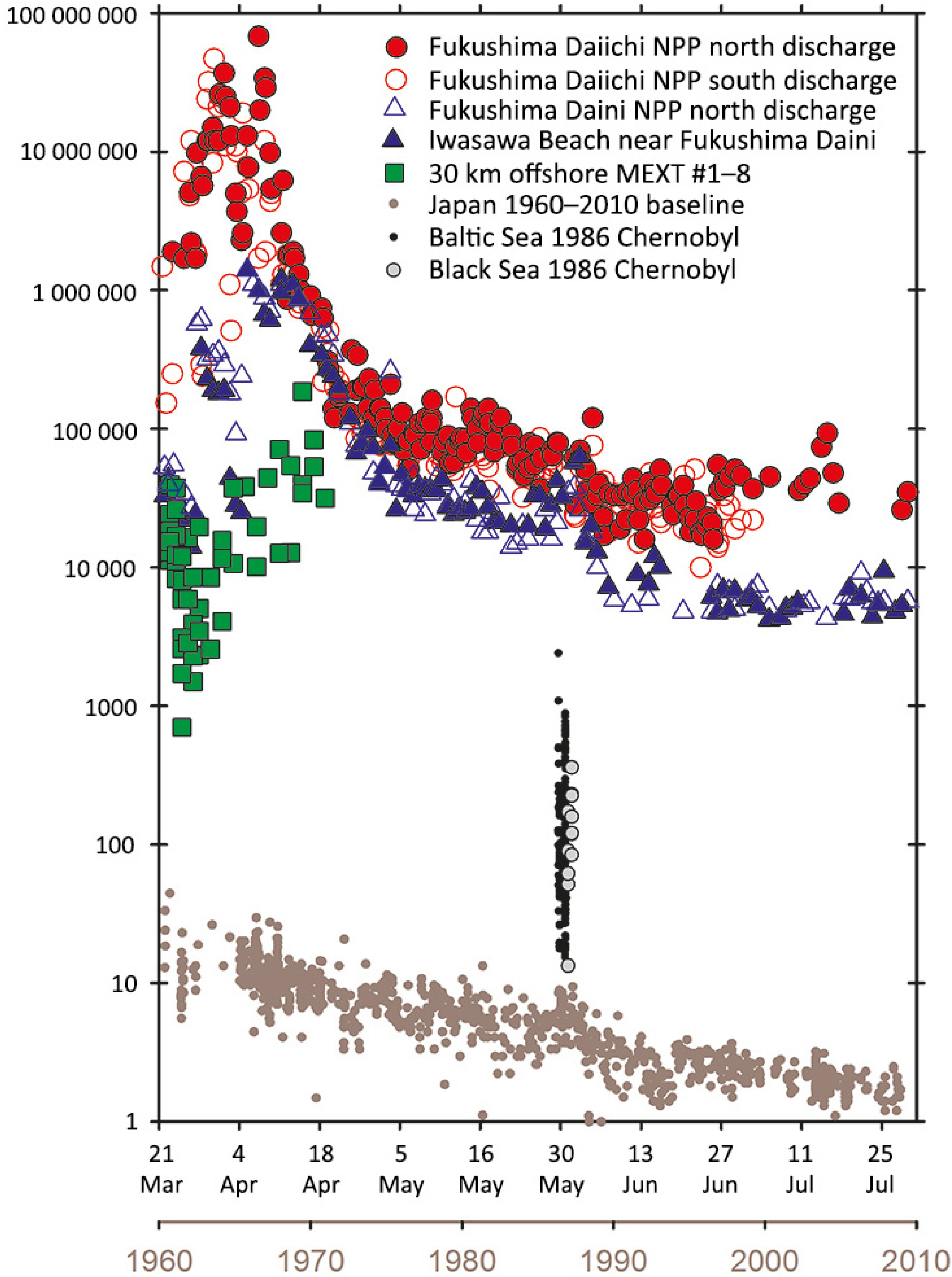


FIG. 4.1–21. Surface ocean concentrations of ^{137}Cs (in Bq/m^3) from 21 March to 31 July 2011 for two sites near the Fukushima Daiichi NPP, Fukushima Daini NPP, Iwasawa Beach near the Fukushima Daini NPP and 30 km offshore. These are compared on the lower x axis (1960–2010) to the historical record of ^{137}Cs off the east coast of Japan and to waters influenced by the Chernobyl accident in 1986 in the Baltic and Black Seas [118].

As explained earlier, following the initial phase of the accident, radionuclides released to the atmosphere were dispersed over the North Pacific Ocean. This activity, and the activity released directly to the sea from the Fukushima Daiichi NPP, is being transported along the Kuroshio extension in an eastern direction across the Pacific Ocean and will be diluted to lower levels over the years to come. More information can be found in Annex IV.

An ongoing intensive sea area monitoring programme was established following the accident. The monitoring of the sea is routinely carried out in five areas[5], and the resulting measurements have been published [117]. This programme comprises collection and measurement of sea water, sediment and marine biota, primarily fish [119]. Recent results in the sea area around the Fukushima Daiichi and Fukushima Daini NPPs have indicated that the levels of radionuclides outside the port or in the open sea have been relatively stable at lower levels.

Measurements of marine sediments

Caesium can be adsorbed by suspended particulate matter in the water column to some extent and is therefore partly accumulated in the sediment. Contamination of sediments depends mainly on the type of the sediment and is therefore highly variable. Resuspension and mixing of sediments will decrease the initial activity in the surface layer, but the remobilization of radionuclides from the sediment near the Japanese coast will act as a source of ^{137}Cs to the water column during the coming years [120].

Monitoring of environmental radioactivity levels has been carried out by local governments, some research institutes and ministries and government offices in Japan since before the 1960s [121]. The temporal variation of ^{137}Cs concentrations in surface sediments collected from the Pacific Ocean off the Fukushima Daiichi NPP prior to 2011 (1984–2010) is shown in Fig. 4.1–22. The concentrations of ^{137}Cs measured after the accident were at most two orders of magnitude greater than those measured in 2010 at eight sampling stations off Fukushima Prefecture [122], and almost 1 Bq/kg (dry weight) just before the accident in 2011. The spatial and temporal variations of ^{137}Cs concentrations in sediments following the accident are shown in Fig. 4.1–23. Early in the sampling period (May–June 2011), the concentrations varied considerably with the sampling date, especially for the stations in the southern portion of the monitoring area. After September 2011, however, there was generally much less temporal variation [123] which suggested that radiocaesium is transported laterally by resuspended sediments.

The concentration of ^{90}Sr in surface sea water was measured from August to November 2011, and showed a two- to fourfold increase compared with pre-accident values. Strontium-90 was not detected in the sediments collected from May to July 2011. This may have been owing to the relatively high detection limit. Other detected nuclides were ^{95}Nb, ^{110m}Ag, ^{129}Te, ^{129m}Te and ^{125}Sb; however, the activity ratios of ^{137}Cs were less than 1 in sediments. There, activity ratios to that of ^{137}Cs varied, indicating fluctuations in the temporal profiles of their release into, and their transport through, the environment. The complexity of the variation of isotope ratios in the sediments may have been due to temporal changes in the activity ratios from the Fukushima Daiichi NPP and the fluctuating pathways by which these nuclides reached the sediments [124].

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[5] Area 1: sea area close to the Fukushima Daiichi NPP; Area 2: coastal area; Area 3: offshore area; Area 4: outer sea area; Area 5: Tokyo Bay area.

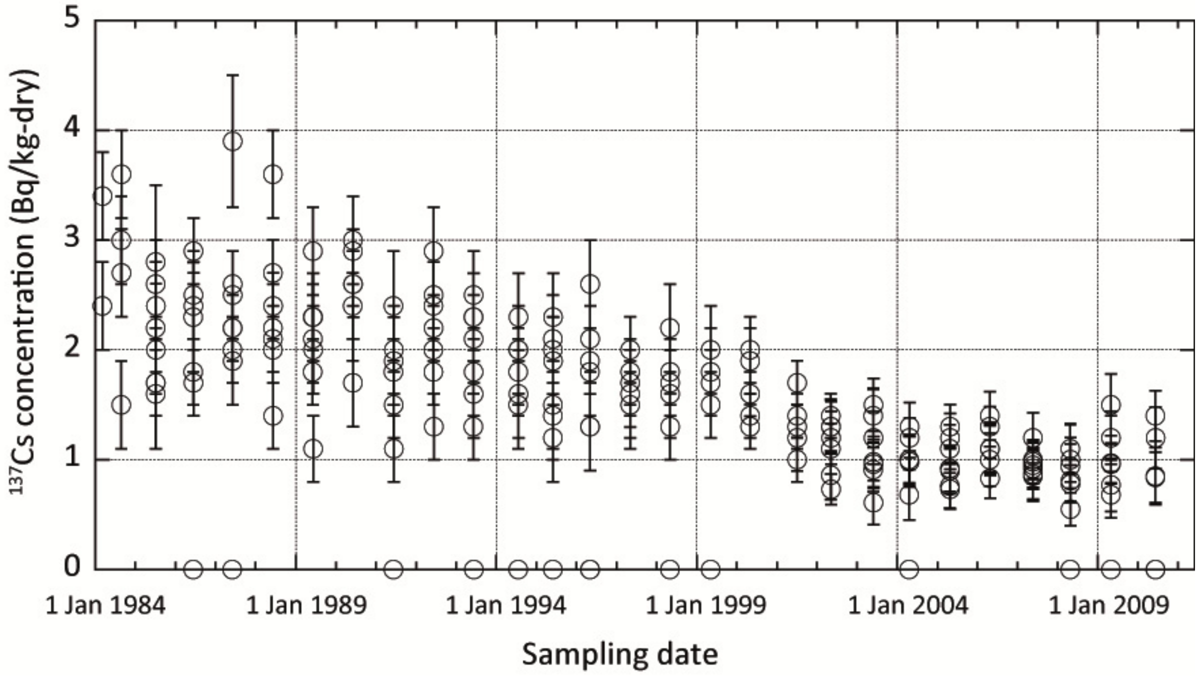


FIG. 4.1–22. Temporal variation of ^{137}Cs concentrations in surface sediments collected from the Pacific Ocean off the Fukushima Daiichi and Fukushima Daini NPPs prior to 2011 (1984–2009). The data plotted in the figure were obtained from the Ministry of Education, Culture, Sports, Science and Technology [125]. Eight sampling stations were located about 30 km off the coast. The open circles on the x axis indicate the concentrations that were below the detection limit [124].

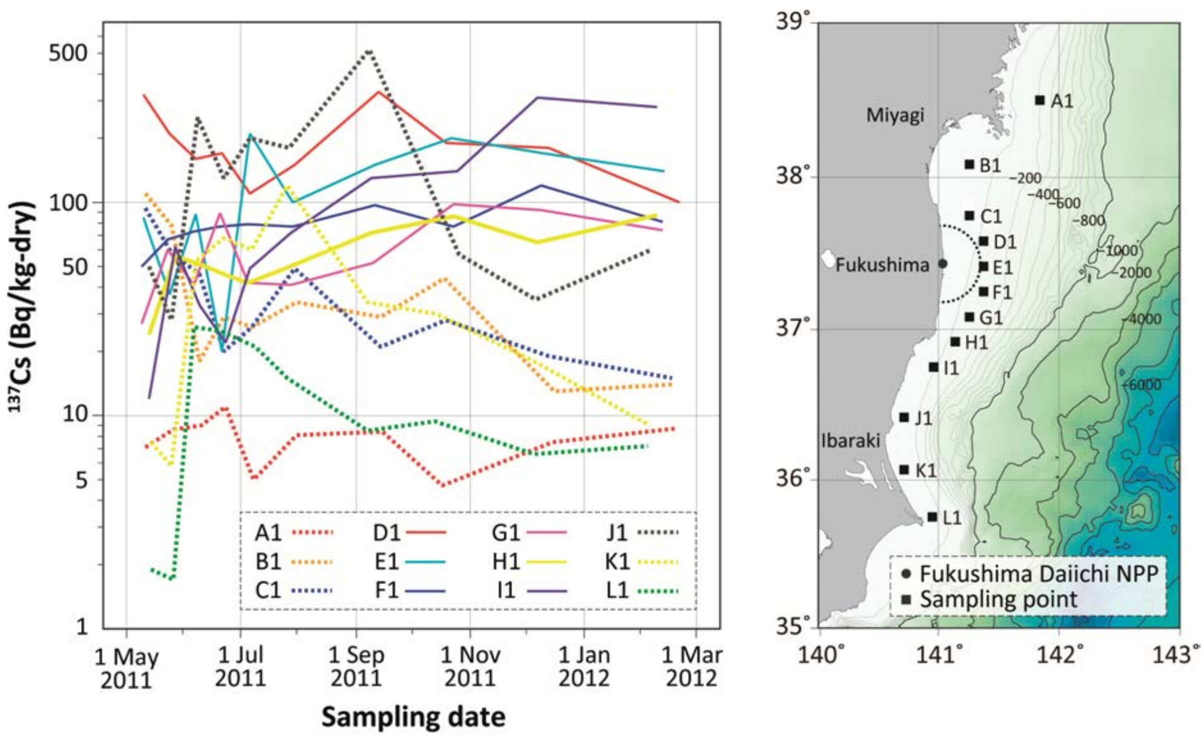


FIG. 4.1–23. Spatial and temporal distribution of ^{137}Cs concentrations in sediment samples collected on the dates indicated [124].

The activities of $^{239,240}Pu$ and ^{241}Pu in the sediments containing radiocaesium released from the Fukushima Daiichi NPP accident were low compared with the background level before the accident. Thus, the release of isotopes of plutonium from the accident to the marine environment was negligible [126].

A routine monitoring programme was established, on the basis of which monitoring results for sediment are presented for four areas[6] [127].

Measurements of marine biota

Surveys of radioactivity in fish and shellfish (as foods) were started after the detection of radionuclides such as ^{131}I, ^{134}Cs and ^{137}Cs in sea water around the Fukushima Daiichi NPP on 22 March 2011 [128]. All monitoring data from local governments, various research institutes and ministries and government offices are publicly available [129]. The main focus of measurements on marine biota as part of the monitoring programme has been on commercial fish species. As indicated in Section 4.3, Japan adopted a limit of 100 Bq/kg for combined ^{134}Cs and ^{137}Cs for food products on 1 April 2012, which also applies to the marine fishery products. The measurements of radionuclides in fish are described further in the section on food and drinking water below.

The levels of total caesium (^{134}Cs and ^{137}Cs) were found to have remained elevated one year after the accident in many fish collected in the coastal waters off Japan [129]. The levels in demersal, or bottom dwelling, fish close to Fukushima were particularly elevated, with over 40% exceeding the current Japanese regulatory limit of 100 Bq/kg (wet weight) in seafood, and no statistically significant decrease in caesium concentration was seen during 2011. However, in the analysis to the end of 2012, there is a slow reduction in caesium levels in these bottom dwelling fish off the coast of Fukushima Prefecture, equating to an ecological half-life of 330 days, much slower than initially predicted [130]. The activities of ^{134}Cs, ^{137}Cs and ^{110m}Ag in other marine biota off the coast of Fukushima Prefecture were investigated after the Fukushima Daiichi accident. Silver-110m was observed in many marine biota; Mollusca and Crustacea have a tendency to concentrate silver in the visceral parts. Fluctuations in the concentrations in plankton are a result of both radioactivity in sea water and sediment resuspension [131].

Overall, radiocaesium concentrations in marine products have decreased significantly since 2011. However, the time series trends differ greatly among taxa, habitats and spatial distributions. Higher concentrations have been observed in shallower waters south of the Fukushima Daiichi NPP. Radiocaesium concentrations decreased quickly or were below detection limits in pelagic fish and some invertebrates, and continue to decrease in seaweed, surf clams and other biota. However, in some demersal fishes, the declining trend was much more gradual, and concentrations above the regulatory limit (100 Bq/kg, wet weight) were frequently found, indicating continued uptake of radiocaesium through the benthic food web. The main continuing source of radiocaesium to the food web is expected to be detritus in sediment containing radiocaesium [132]. Comparison of ^{137}Cs concentrations in the invertebrates and those in sea water and sediments suggest that contaminated sediments are the major source of continuing contamination in benthic invertebrates, especially in Malacostraca and Polychaeta. Simulation studies using the data obtained, together with rearing experiments aimed at investigating invertebrates' mechanisms of ^{137}Cs uptake from contaminated sediments and further transfer from contaminated invertebrates to demersal fish, will be important to estimate how, and the degree to which, radioactive caesium near sediments moves up the benthic food web [133]. Information on the trend of ^{137}Cs activities in marine biota before the accident are presented in Ref. [134].

[6] Area 1: area close to the Fukushima Daiichi NPP; Area 2: coastal area; Area 3: offshore area; Area 4: Tokyo Bay area.

TEPCO installed a fence at the entrance of the port in the Fukushima Daiichi NPP in June 2013 to prevent the entry of fish from the coastal area [135]. Radiocaesium concentrations of more than 100 000 Bq/kg (wet weight) have been found in fish collected inside the port of the Fukushima Daiichi NPP [136]. Elsewhere in Fukushima Prefecture, only a small percentage exceeded the regulatory limit of 100 Bq/kg (wet weight) in November 2014 [129], and the highest ^{137}Cs activity in fish landed in Fukushima Prefecture in the period from June 2013 until November 2014 was 740 Bq/kg (wet weight) [137].

Madigan et al. [138] have reported that Pacific blue-fin tuna (*Thunnus orientalis*) have transported radionuclides derived from the release from the Fukushima Daiichi accident across the North Pacific Ocean at low levels. Gamma emitting radionuclides were found with ^{134}Cs concentrations of 4.0 ± 1.4 Bq/kg (dry weight) and ^{137}Cs concentrations of 6.3 ± 1.5 Bq/kg (dry weight) in 15 Pacific blue-fin tuna. These levels are very low, and the associated radiation dose from ingestion would be negligible compared with that dose from naturally occurring radionuclides, particularly ^{210}Po, in seafood.

4.1.3.4. Radionuclides in groundwater and surface freshwater systems

Rivers, lakes and reservoirs in Fukushima Prefecture have been described in detail in Section 4.1.1, which deals with the natural environment of the Fukushima Daiichi NPP. As mentioned above, numerous rivers flow into the coastal waters in the area around the plant.

Releases of groundwater and cooling water

As described in Technical Volume 1, from the early stages of the accident, water was injected into the reactor pressure vessels of Units 1–3 to provide cooling; at the time of writing, this process is still continuing. Some of this water drains into the lower levels of the reactor buildings and, as it comes into contact with melted fuel, it contains radionuclides. Currently, the flow rate of injected water is about 350–400 m^3 per day [136]. The topography of the Fukushima Daiichi NPP is such that groundwater flows from the hills to the west of the site down to the eastern shore of the Pacific Ocean. Some of this groundwater enters the reactor buildings and turbine buildings of Units 1–4 and also passes into auxiliary buildings. TEPCO estimates that the daily contribution of groundwater to the flooding of these buildings is about 400 m^3 [139].

These two sources of water (groundwater and cooling water) have resulted in large pools of water with ^{137}Cs activity concentrations of between 4 and 36 GBq/m^3 [140]. As reported in November 2013, the total volume of the water pool from all four units is approximately 75 000 m^3 [128]. The water flows into underground areas where, as reported in July 2013, there are approximately 11 000 m^3 of water with a ^{137}Cs activity concentration of 1.6 TBq/m^3, a beta activity concentration of 0.75 TBq/m^3 and a tritium activity concentration of 8.7 GBq/m^3 [141, 142]. These combined amounts of water are gradually infiltrating the ground through the layer of crushed stones, with radionuclides entering the clean groundwater that bypassed the basements of buildings; the contaminated groundwater is likely to flow toward the Pacific Ocean (see Fig. 4.1–24).

In order to reduce the infiltration of radioactivity into the groundwater and the ocean, TEPCO installed a water treatment and storage system coupled with a water injection system. It also built an impermeable wall along the harbour front, in an attempt to limit the discharge of contaminated groundwater into the ocean. The system includes the treatment of the stored water and its reuse as cooling water. However, owing to the additional groundwater entering the buildings, the total daily flow of water into the buildings (~800 m^3) exceeds the necessary flow rate to cool the reactors (~400 m^3), and each day a surplus of ~400 m^3 accumulates on the site. This excess of low level activity salt water is collected in tanks and stored on-site. As of January 2014, the total storage capacity of these tanks was approximately 410 000 m^3 and the volume of contaminated water stored on-site was 350 000 m^3 [143]. The storage capacity is foreseen to double in the future (i.e. to 820 000 m^3), as the processing capacity of the current water treatment is approximately 750 m^3 per day.[7] Further information is presented in Technical Volume 5, Section 5.3.

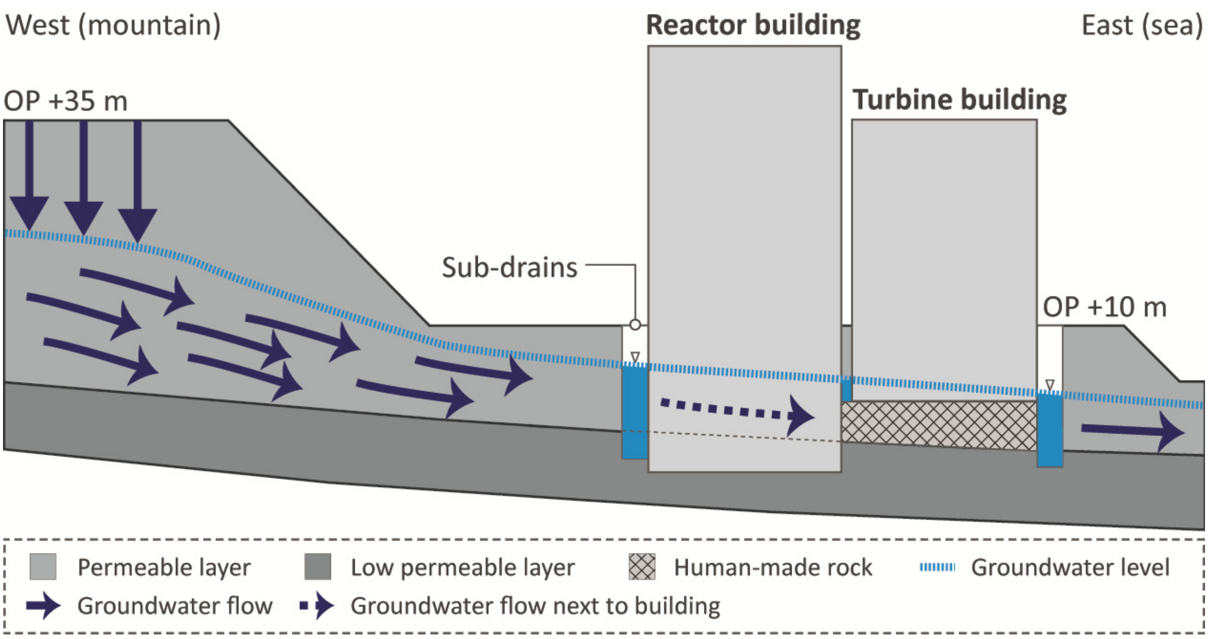


FIG. 4.1–24. On-site groundwater flowing in one direction from the mountain to the sea.

On two occasions, TEPCO announced the release of water containing radionuclides into the local on-site environment from the storage tanks. The first release was in August 2013 [144], and consisted of approximately 60 TBq of beta emitting radionuclides, 0.7 TBq of tritium and 0.06 TBq of combined ^{125}Sb, ^{134}Cs and ^{137}Cs [145]. A second leakage from a storage tank was announced by TEPCO in February 2014 [146]; it consisted of approximately 23 TBq of beta emitting radionuclides, an undisclosed amount of tritium and 6 GBq of combined ^{54}Mn, ^{60}Co, ^{125}Sb, ^{134}Cs and ^{137}Cs [146].

Measurements of activity in groundwater

With the exception of groundwater that flows through the Fukushima Daiichi NPP, groundwater bodies in Fukushima Prefecture have not been influenced by the radionuclides releases from the accident. The Ministry of the Environment has undertaken monitoring surveys of radionuclides (^{131}I, ^{134}Cs, ^{137}Cs, ^{89}Sr and ^{90}Sr) in groundwater in Iwate, Miyagi, Fukushima, Ibaraki, Tochigi, Gunma and Chiba prefectures and has found no radionuclides related to the accident in samples other than those at the Fukushima Daiichi NPP [147].

In order to monitor the on-site situation, multiple boreholes have been dug in locations between Units 1 and 4, storage tank locations and the harbour front. TEPCO has been reporting results for ^{90}Sr, ^{134}Cs, ^{137}Cs, gross beta and tritium levels in groundwater at these locations on a regular basis since 2013 [45]. The maximum ^{137}Cs results vary relatively widely with location, from values below 1 Bq/L to 93 kBq/L. There is a similar spread for gross beta (i.e. maximum values of below 20 Bq/L up to 3.1 MBq/L). For tritium, the corresponding range of maximum values is less than 200 Bq/L up to 0.6 MBq/L. Other reported radionuclides in groundwater are ^{90}Sr , ^{54}Mn, ^{60}Co, ^{106}Ru and ^{125}Sb. It is

[7] For a detailed description of these activities, see Technical Volume 5, Section 5.3 and Section 5.4.

important to note the relative differences between radionuclide ratios (e.g. the ^{137}Cs/tritium or ^{137}Cs/beta ratios) and activity concentrations (in some cases spanning several magnitudes) between locations relatively close together, suggesting an inhomogeneous distribution of the radioactive material, and multiple source terms.

Following the first of the reported leakages mentioned above, most of the sea water sampled near the Fukushima Daiichi NPP remained under the detection limits, and no significant changes were observed before and after the leakage. After the second event, the highest activity concentrations from water taken from these wells were measured in October 2013 for tritium and in November 2013 for all beta activity [148]. Significant levels of tritium in groundwater and sea water have been reported inside and outside the port of Fukushima Daiichi NPP. The activity concentration of tritium in groundwater collected in mid-April 2011 at the eastern side of the turbine building of Units 1 and 2 varied between less than 100 Bq/L and 270 000 Bq/L. The tritium concentration in sea water at the location near the water intake of Units 1 and 2 varied from about 100 Bq/L to about 3000 Bq/L during the monitoring period from June 2013 to April 2014. The concentrations in sea water collected in mid-April 2014 at a location outside the port ranged from less than 1.8 Bq/L to 6.5 Bq/L.

Measurements of radionuclides in rivers and other freshwater bodies

A series of surveys has been conducted to assess temporal variations in activity concentrations of radionuclides derived from the Fukushima Daiichi NPP in river water, riverbeds and suspended sediments [149].

Suitable sampling locations for ongoing monitoring were identified in 2011 using two selection criteria:

— Areas of relatively high radiocaesium deposition densities, determined by land based monitoring and aerial monitoring surveys;
— Locations with sufficiently high flow volumes to facilitate the assessment of the migration of radionuclides in the future.

Based on these criteria, 50 sampling locations were identified. River water sampling has been conducted over six periods in June 2011, August 2011, December 2011, February 2012, August 2012 and November 2012. The latter two sampling periods were selected specifically to assess activity concentrations before and after that year’s typhoon season. In the initial surveys, river water samples were analysed at all 50 locations for the gamma emitting radionuclides ^{131}I, ^{134}Cs and ^{137}Cs. Samples from a subset of 10 locations that were evenly spread out were chosen for analysis of strontium (^{89}Sr and ^{90}Sr) and plutonium (^{238}Pu and ^{239,240}Pu) using low background beta ray counters and silicon semiconductor detectors, respectively, following radiochemical separation. In later surveys, samples were not analysed for plutonium or ^{89}Sr owing to the very low levels of these radionuclides measured previously. In 2012, samples were collected from an additional 7 locations in the vicinity of the Fukushima Daiichi NPP. The sampling locations and the distribution of activity concentrations of ^{137}Cs in river water in August 2012 are shown in Fig. 4.1–25.

The maximum activity concentrations of ^{134}Cs and ^{137}Cs measured were less than 5 Bq/kg, with some evidence of a general downward trend toward background levels over the period monitored [150]. The maximum activity concentration of ^{131}I was 0.15 Bq/kg. Measured activity concentrations of strontium and plutonium were much lower. Measured levels of ^{90}Sr were comparable with background levels measured before the accident [150].

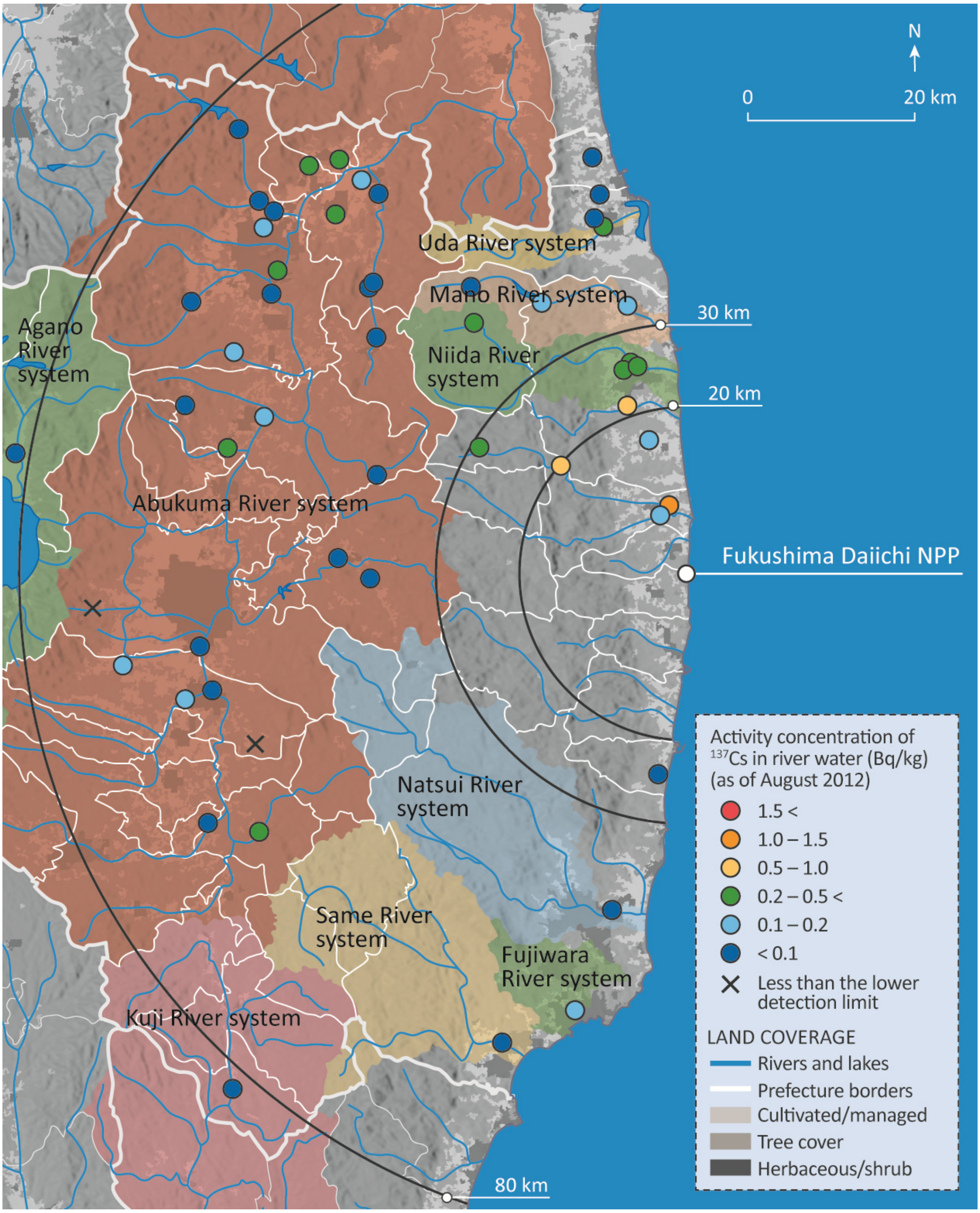
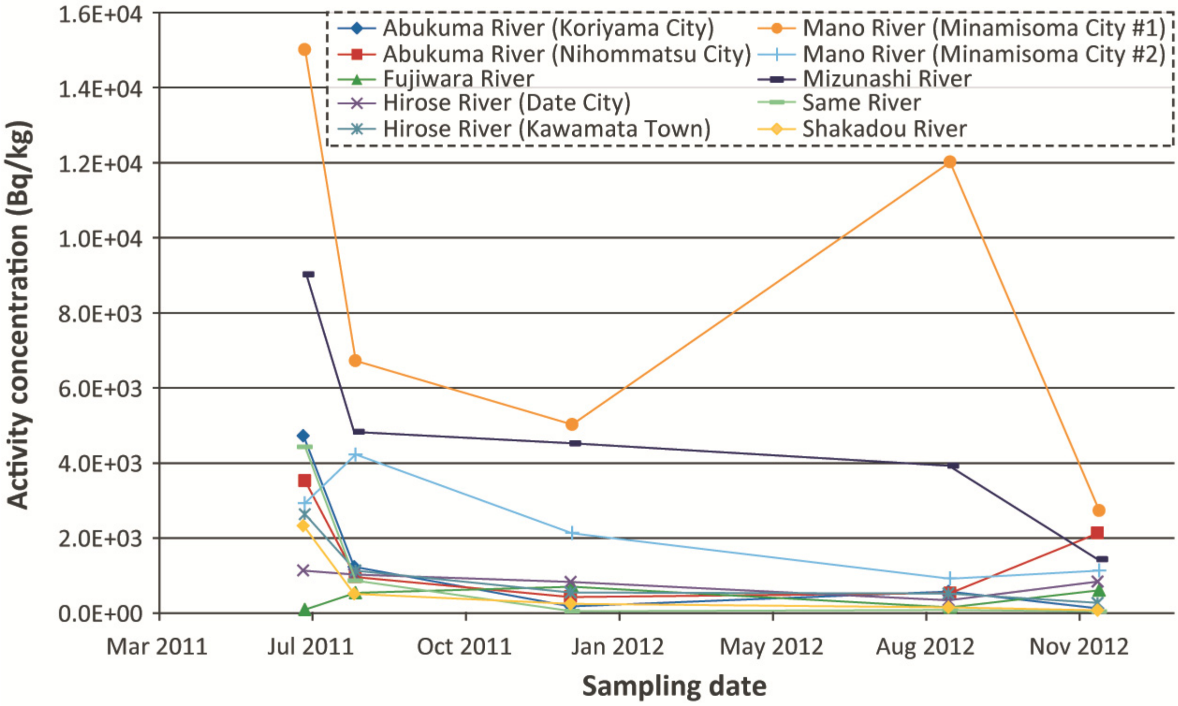
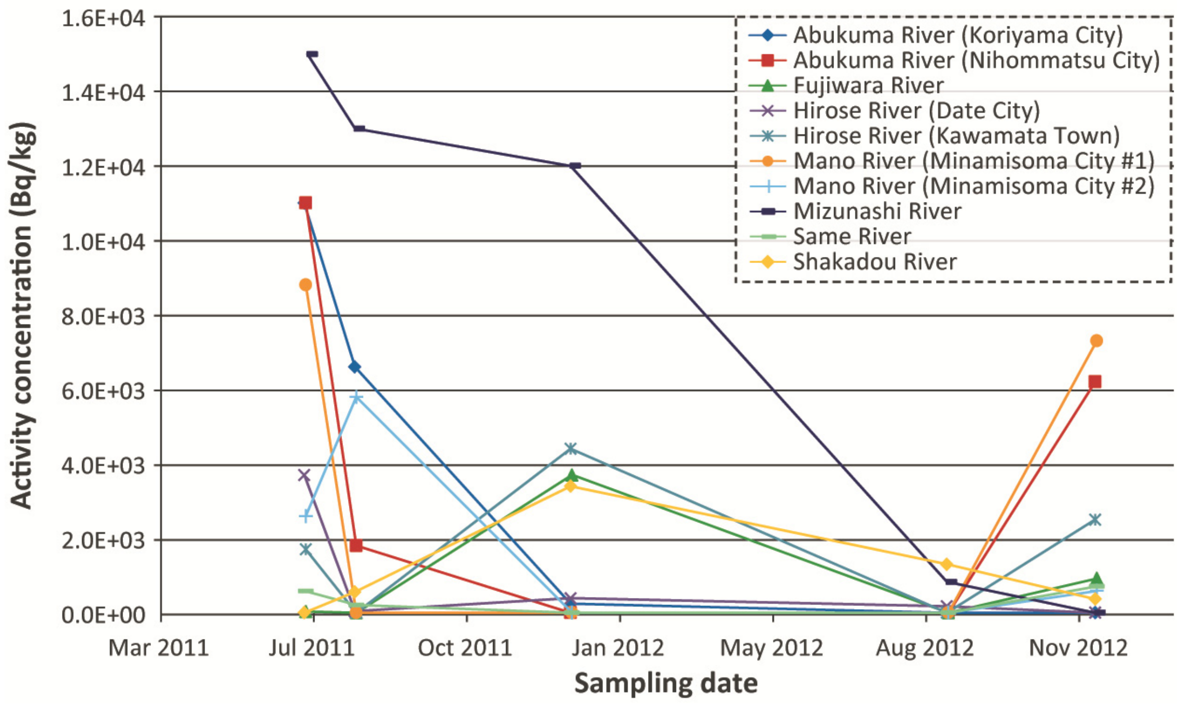


FIG. 4.1–25. Map of river sampling locations.

Riverbed sediment sampling has so far been conducted at the same ten locations from which river water samples were analysed for strontium and plutonium over five periods in July 2011, August 2011, December 2011, August 2012 and November 2012. As with the sampling of river water, the latter two sampling periods were selected specifically to assess activity concentrations before and after the typhoon season. The samples were analysed by HPGe gamma spectrometry for activity concentrations of ^{131}I, ^{134}Cs, ^{137}Cs, ^{110m}Ag, ^{129m}Te and ^{136}Cs. The results for ^{137}Cs and ^{131}I for the ten sampling locations are shown in Fig. 4.1–26.



(a)



(b)

FIG. 4.1–26. Results of measurements of (a) ^{137}Cs and (b) ^{131}I in riverbed samples for ten sampling locations in Fukushima Prefecture from July 2011 to November 2012 [151].

Suspended sediment sampling has been conducted over eight periods between August 2011 and February 2013. Samples were initially collected from the same ten locations as for riverbed samples and analysed by HPGe gamma spectrometry for activity concentrations of ^{131}I, ^{134}Cs, ^{137}Cs, ^{110m}Ag, ^{129m}Te and ^{136}Cs. Between December 2012 and February 2013, five surveys were performed which included sampling at an additional 30 sites, mainly located near gauging stations in the Abukuma River basin and in the Hamadori area of Fukushima Prefecture. These samples were analysed for radiocaesium only.

Maximum activity concentrations measured in ^{137}Cs and ^{131}I were of the order of 15 000 Bq/kg and 20 Bq/kg, respectively.

The higher activity concentrations of radiocaesium in the sediments of the Abukuma River system (over 10 000 Bq/kg, dry weight) were usually observed in the same period (September-October 2011). However, 80% of the measurements of ^{137}Cs concentrations in the sediments of the rivers, and 60% in those of the lakes, of Iwate, Yamagata, Miyagi, Fukushima, Ibaraki, Tochigi, Gunma and Chiba Prefectures were less than 1 000 Bq/kg (dry weight). About 50% of the coastal sediment measurements were less than 50 Bq/kg (dry weight) [151].

Soil erosion and subsequent sediment transport in rivers play a major role in the global biogeochemical cycles and in the dispersion of contaminants within the natural environment. As with other particle borne pollutants, radionuclides emitted after the Fukushima Daiichi accident are strongly sorbed by fine particles, and they are therefore likely to be redistributed by hydro-sedimentary processes across catchments.

Various studies have estimated the amounts of radionuclides, particularly ^{137}Cs, from rivers where levels of radioactivity are affected by heavy rainfall and soil erosion. For example, in 2013, Nagao et al. [152] showed that heavy rain during Typhoon Roke on 21–22 September 2011 transferred large amounts of particulate ^{134}Cs and ^{137}Cs deposited on the land to river watersheds (namely, the Natsui and Same rivers) and coastal marine environments. The value of that flux was estimated to 0.020–0.026 TBq/d in the Natsui River and 0.007–0.009 TBq/d in the Same River. This amounts to 30–50% of the total annual flux for these rivers from 11 March to 31 December 2011. Kanda [153], estimated the discharge of ^{137}Cs from small rivers in April–September 2012 to be not more than 0.32 TBq/month. Larger rivers, such as the Abukuma River, would be a larger source of ^{137}Cs of up to 0.87 TBq/month [154].

Typhoons and snowmelt during 2011 and 2012 also led to intense soil erosion from hill slopes by runoff processes in the upper parts of water catchments, reservoirs, lakes, floodplains and outlets, with a selective export of fine particles containing radionuclides derived from the Fukushima Daiichi accident. The main dams are found in the upper parts of the Mano River and Ota River catchments, and their reservoirs form a potential sink for radioactive sediments. The $^{110m}Ag/^{137}Cs$ ratio provided a tracer for the dispersion of sediment in the Nita catchment area, which is affected by the areas with the highest levels of radionuclides. The system was very reactive to the succession of summer typhoons (2011) and spring snowmelt (2012). The 2012 typhoons were less violent than the ones in 2011 and led to less intense erosion; however, they were sufficiently powerful to increase river discharges and to export the sediment stored in the river channel [100, 155].

Measurements of radionuclides were also taken at 20 lakes and dams in Fukushima Prefecture; all results in water were below detection limits for ^{131}I, ^{134}Cs and ^{137}Cs. For sediments, some lakes and dams had activity concentrations above the detection limit. For three locations, measured values exceeded 100 Bq/kg at Lake Hatori and 1000 Bq/kg at Komachi Dam and Hokkawa Dam.

4.1.4. Levels of radionuclides in terrestrial and aquatic foods

The Ministry of Health, Labour and Welfare (MHLW) has responsibility for monitoring the levels of radionuclides in food and drinking water in Japan. On 4 April 2011, MHLW confirmed that provisional regulation values for radioactive material in food and drinking water set on 17 March 2011 were effective in ensuring the safety for consumption, domestic distribution and export. At the same time, the Nuclear Emergency Response Headquarters issued policies for monitoring and enforcement of restrictions on the distribution and/or consumption of milk, vegetables, seafood, bottled water and other foods.[8]

4.1.4.1. Terrestrial food products

Extensive monitoring of food was carried out in Japan starting a few days after the initial accidental releases from the Fukushima Daiichi NPP, mainly by the municipalities under the Food Sanitation Law[9]. The monitoring was organized by the Ministry of Agriculture, Forestry and Fisheries (MAFF) and MHLW, and the information was used by the Food and Agriculture Organization of the United Nations (FAO) and the IAEA to compile a database in collaboration with MAFF and MHLW in Japan. This FAO/IAEA database includes data for over 500 types of food samples in all 47 prefectures and comprises activity concentrations in both terrestrial and aquatic foods. These measurements were mainly intended to ensure compliance with regulatory levels. Thus, the data do not provide information on the distribution of activity concentrations in food. The database only includes measurements for ^{131}I, ^{134}Cs and ^{137}Cs and contains data for immature crops and for areas where restrictions were in place; such foods would, therefore, not have been eaten. However, it is possible to select from the database results for those foods that were marketed and could have been consumed. Relatively high limits of detection were used in determining levels in food, and, in the database, it was assumed that any values below limits of detection were equal to 10 Bq/kg for each of the three radionuclides. However, for ^{131}I, this was only done for the first four months following the accident, and subsequently levels of ^{131}I below detection limits were taken to be zero. The information in the database formed the basis for the assessment carried out by UNSCEAR [5] of ingestion doses in the first year following the accident. Only results for foods as marketed were used in the assessment, and it was assumed that people obtained their food from a wide area, with doses estimated for Fukushima Prefecture, for five nearby prefectures (Miyagi, Tochigi, Gunma, Ibaraki and Chiba — using the means of all data for these prefectures) and for the rest of Japan. Rice is an important component of the Japanese diet, and, as a result, the database contains many measurements for immature crops. Therefore, in the UNSCEAR assessment, only measurements in rice taken six months or more after the accident were used to estimate the ingestion doses.

The initial concern following the accidental release of radionuclides to the atmosphere is the transfer of radionuclides to leafy vegetables through direct deposition from the atmosphere onto the edible part of the plant. Generally, the transfer of radionuclides, particularly ^{131}I, to milk is also of concern in the short term following accidental releases to the atmosphere, owing to the short transfer time for iodine from grassland to milk and the relatively high amounts of the radionuclide that reach milk. However, as the initial releases to atmosphere occurred in March, when cows would have been housed indoors and given stored feed, this transfer to milk was not as marked as it was following the accident at the Chernobyl NPP.

The results from the database show that ^{131}I was detected on edible leafy vegetables (cabbage, broccoli, lettuce and spinach) from eight prefectures in the first few months after the accident (Table 4.1–5). It should be noted that this includes all the measurement data and not just those from food that was marketed.

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[8] For detailed discussions, see Technical Volume 3, Section 3.3, and Technical Volume 5, Section 5.2.

[9] Food Sanitation Law, Law No. 233, December 24, 1947, as amended by Law No. 87 of July 26, 2005 (Japan).

TABLE 4.1–5. CONCENTRATION OF ^{131}I IN LEAFY VEGETABLES (Bq/kg) FROM MARCH TO MAY 2011 BY PREFECTURE [156]

Prefecture	*N*	Average	Standard deviation	Geometric mean	Geometric deviation	Minimum	Maximum
Chiba	11	963	1 123	226	12	<10	3 500
Fukushima	85	1 799	3 670	79	22	<10	19 000
Gunma	27	410	660	98	7.6	<10	2 630
Ibaraki	30	8 867	11 484	1 291	21	<10	54 100
Kanagawa	12	299	467	28	13	<10	1 300
Miyagi	2	185	153	150	2.6	77	294
Nagano	21	7.5	12	5.6	1.7	<10	58
Saitama	38	231	467	22	9.0	<10	1 900
Tochigi	16	2 345	2 250	299	22	<10	5 700
Tokyo	10	135	410	8.7	5.8	<10	1 300
All values	252	1 954	5 222	74	19.4	<10	54 100

The highest levels were found for spinach (see Table 4.1–6) during March 2011. Activity concentrations on leafy vegetables decreased significantly in subsequent months, as is to be expected after an accidental release of ^{131}I, owing to its short half-life and the removal of activity from the surface of the plants by weathering processes (see Table 4.1–7). These results also confirm that no further significant release of ^{131}I to the atmosphere occurred after the first few days following the accident.

TABLE 4.1–6. CONCENTRATION OF ^{131}I IN LEAFY VEGETABLES (Bq/kg) FROM MARCH TO MAY 2011, BY TYPE OF VEGETABLE [156]

Food tested	*N*	Average	Standard deviation	Geometric mean	Geometric deviation	Minimum	Maximum
Broccoli	28	1587.857	3 565.347	82.001 63	20.317 71	<10	17 000
Cabbage	39	203.7949	851.4137	12.301 29	5.870 361	<10	5 200
Lettuce	28	61.1	213.9948	9.200 975	3.989 963	<10	1 100
Spinach	157	2 791.45	6 273.575	165.744 4	20.874 81	<10	54 100
All leafy vegetables	252	1 953.875	5 222.332	74.330 66	19.381 14	<10	54 100

TABLE 4.1–7. CONCENTRATION OF ^{131}I IN LEAFY VEGETABLES (Bq/kg) FROM MARCH TO MAY 2011, BY MONTH [156]

Period	*N*	Average	Standard deviation	Geometric mean	Geometric deviation	Minimum	Maximum
March	129	3 800.733	6 814.398	672.289 6	12.425 6	<10	54 100
April	41	39.482 93	59.998 02	14.790 05	3.939 035	<10	230
May	82	5.646 341	4.701 909	5.214 407	1.321 011	<10	46
All leafy vegetables	252	1 953.875	5 222.332	74.330 66	19.381 14	<10	54 100

About 2950 samples of milk and dairy products were analysed in the first year after the accident. Of the 2636 samples of cattle milk, 207 contained levels above the limits of detection, all from samples taken in March and April 2011, with the exception of the results of two samples in May, where a lower detection limit was used. The average concentration of ^{131}I in milk for samples above detection limits was 190 Bq/L (range: 0.1–5300). Detection limits, however, varied from 0.1 Bq/L to about 10 Bq/L among different prefectures and towns. Average values for results above detection limits were 247 Bq/L in March 2011, 10 Bq/L in April and 0.5 Bq/L in May; of these, about 65% were from Fukushima Prefecture. However, these samples represent only about 10% of measured samples and include samples from areas where milk was not marketed due to restrictions.

A summary of data on the concentration of radiocaesium in agricultural products provided by MAFF for different types of food is presented in Table 4.1–8 [129].

TABLE 4.1–8. SUMMARY OF COUNTRYWIDE MEASUREMENTS OF RADIOCAESIUM IN AGRICULTURAL PRODUCTS [129]

Product		Total number of reported samples	Per cent of vegetable samples		
			<50 Bq/kg	50–100 Bq/kg	>100 Bq/kg
March 2011–31 March 2012					
Wheat and barley		557	95.15		4.85
Vegetables		12 671	96.96		3.04
Fruits		2 732	92.31		7.69
Pulses	Soy bean	534	97.00		3.00
	Other pulses	155	100.00		0.00
Other cultivated plants		498	96.79		3.21
Mushrooms and wild edible plants		3 856	79.80		20.20
1 April 2012–31 March 2013					
Wheat and barley		1 818	100.00	0	0
Vegetables		18 570	99.92	0.05	0.03
Fruits		4 478	98.37	1.34	0.29
Pulses	Soy bean	4 069	97.75	1.68	0.57
	Other pulses	329	97.26	2.13	0.61
Other cultivated plants		3 094	96.77	2.78	0.45
Mushrooms and wild edible plants		6 588	82.21	8.61	9.18
1 April 2013–31 March 2014					
Wheat and barley		592	100.00	0	0
Vegetables		19 657	99.99	0.01	0
Fruits		4 243	99.34	0.66	0
Pulses	Soybean	4 716	98.37	1.19	0.45
	Other pulses	447	99.10	0.90	0
Soy bean harvested in FY 2012		1 564	85.49	12.08	2.43
Other cultivated plants		1 618	99.81	0.19	0
Mushrooms and wild edible plants		7 581	93.23	4.21	2.56

Rice is a staple food in Japan, and the FAO/IAEA database includes about 2800 results for rice in 2011. Of these, only 62 are above the detection limit of 20 Bq/kg. Two samples had concentrations greater than 100 Bq/kg, one in Fukushima City and the other in Nihonmatsu City, both in Fukushima Prefecture. In 2011, rice planting was restricted in paddy fields in which activity concentrations of radiocaesium in soil of 5000 Bq/kg or more were measured. However, close examination of the rice produced in that year revealed that radiocaesium concentrations in rice did not follow a simple proportional relationship to those in soils. Food restrictions and agricultural countermeasures are explained in more detail in Technical Volume 5, Section 5.2.

Radionuclides can be transferred to animal products by an animal's ingestion of grass, other vegetables and water, and also by inhalation. In addition, grazing animals may ingest radionuclides together with soil by inadvertent ingestion. A summary of data for the concentrations of radiocaesium in animal derived products is periodically reported by MAFF; a summary of these data is presented in Table 4.1–9 for raw milk and in Table 4.1–10 for meat and eggs [157].

TABLE 4.1–9. SUMMARY OF MEASUREMENTS FOR RADIOCAESIUM IN RAW MILK FOR ALL PREFECTURES IN JAPAN

Period	Total no. of samples	Per cent of samples in ranges		
		<50 Bq/kg	50–100 Bq/kg	>100 Bq/kg
11 March 2011–31 March 2011	173	95.38	4.05	0.58
1 April 2011–31 March 2012	1 764	100	0	0
1 April 2012–31 March 2013	2 453	100	0	0
1 April 2013–31 March 2014	2 052	100	0	0

TABLE 4.1–10. SUMMARY OF COUNTRYWIDE MEASUREMENTS OF RADIOCAESIUM IN MEAT AND EGGS FOR ALL PREFECTURES IN JAPAN

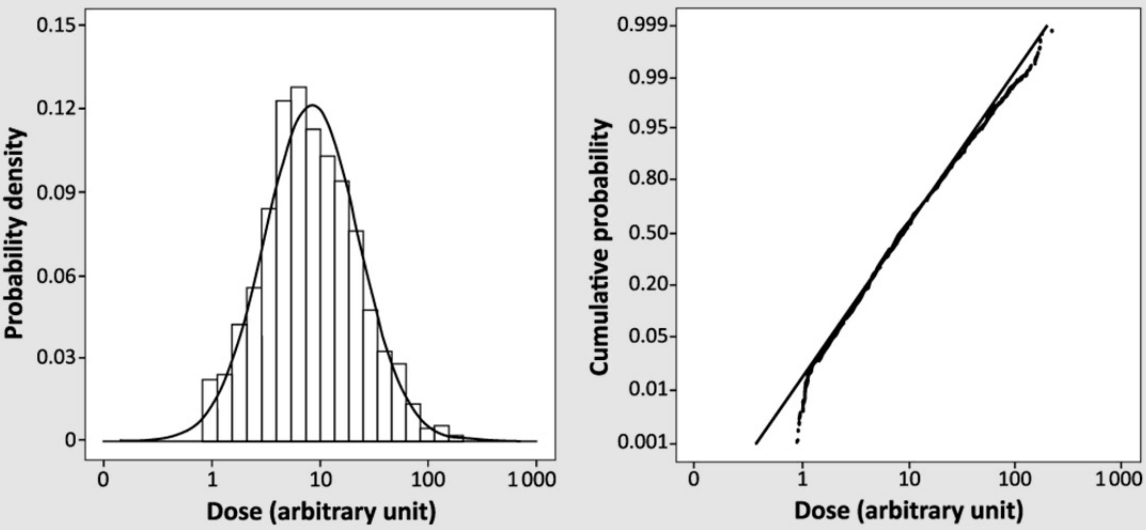
Period		No. of samples	Per cent of samples in ranges		
			<50 Bq/kg	50–100 Bq/kg	>100 Bq/kg
11 March 2011–31 March 2012	Beef	91 973	98.81		1.19
	Pork	538	98.88		1.12
	Chicken	240	100.00		0
	Egg	443	100.00		0
	Other	23	100.00		0
1 April 2012–31 March 2013	Beef*	74 168	99.97	0.02	0.01
	Beef**	113 008	99.99	0.01	0
	Pork	984	99.70	0.20	0.10
	Chicken	472	100.00	0	0
	Egg	565	100.00	0	0
	Other	99	97.98	1.01	1.01

* 1 April–September 2012
** October 2012–March 2013

Box 4.1–1. Statistical analysis of estimated and measured data

Some relevant data used in this report — notably data on personal doses and on activity in food — were analysed statistically. The values of the variable quantity (e.g. values of activity or dose) were classified according to their frequency distribution. For this, the whole range of data was *binned*, that is grouped together in *bins,* or a series of small interval ranges of numerical values, into which the data were sorted for analysis. The data in each bin were displayed adjacent to one another in a *histogram*. The histogram was then normalized, multiplying the values of the rectangles by a factor that makes the total area of the rectangles equal to 1. When sufficient data are available and the intervals become very small, the histogram tends towards a smooth curve termed *probability density function* that describes the relative likelihood for the quantity (e.g. the activity in food or the dose incurred by people) to have a given value.

While the most common distribution is the *normal* (or Gaussian) distribution, represented by a bell shaped probability density function that is symmetrical with respect to the maximum probability, the most relevant distribution for the purpose of the report is the *logarithmic-normal*, or *log-normal* distribution. The log-normal distribution is a probability distribution of a quantity, such as the activity or the dose, whose logarithm is normally distributed. Thus, the log-normal probability density function is symmetrical with respect to the maximum only when displayed as a function of the logarithm of the quantity (e.g. the logarithm of the activity or the logarithm of the dose) rather than as a function of the quantity. An example of such a log-normal probability distribution, showing an idealized histogram and its probability density function, is illustrated on the left hand side of the figure below.



The probability density function can be *integrated*, meaning that the values of the bins in the normalized histogram can be summed, from the lower to the higher values of the quantity. This summation, as a function of the quantity, is termed the *cumulative probability function* and describes the likelihood that a quantity with a given probability distribution will be found to be less than or equal to the value in question.

The *log-normal cumulative probability function* can be plotted as a straight line in a coordinate plane of abscissas representing the quantity (e.g. the dose) calibrated logarithmically versus ordinates representing the cumulative probability calibrated as a *normal* function. An example of such a representation is shown on the right hand side of the figure above, where the integral of the actual experimental data of the bins in the left figure is plotted vis-à-vis the straight line.

A statistical analysis was carried out on some of the data collected by FAO and the IAEA [156] of activity concentrations in different foods. Log-normal distributions were calculated using the approach described in Box 4.1–1. Figure 4.1–27 shows the log-normal probability distribution of ^{131}I in milk in the first month following the accident and in leafy vegetables in the first three months after the accident. As noted earlier in relation to the data given in Table 4.1–5, the results shown in Figure 4.1–27 include all measurement data and not just those from food that was marketed. The calculated mean level of ^{131}I in leafy vegetables of 4.3 Bq/kg and in milk of 34 Bq/kg are well below the levels at which restrictions were required by the Japanese authorities. However, the 95th percentiles of 7300 Bq/kg for leafy vegetables and 1800 Bq/kg for milk show that it was important that the restrictions were introduced. However, the initial limiting values on activity concentrations in foods, established by the Japanese authorities, were subsequently reduced [158]. This cautious approach created difficulties for producers and consumers.

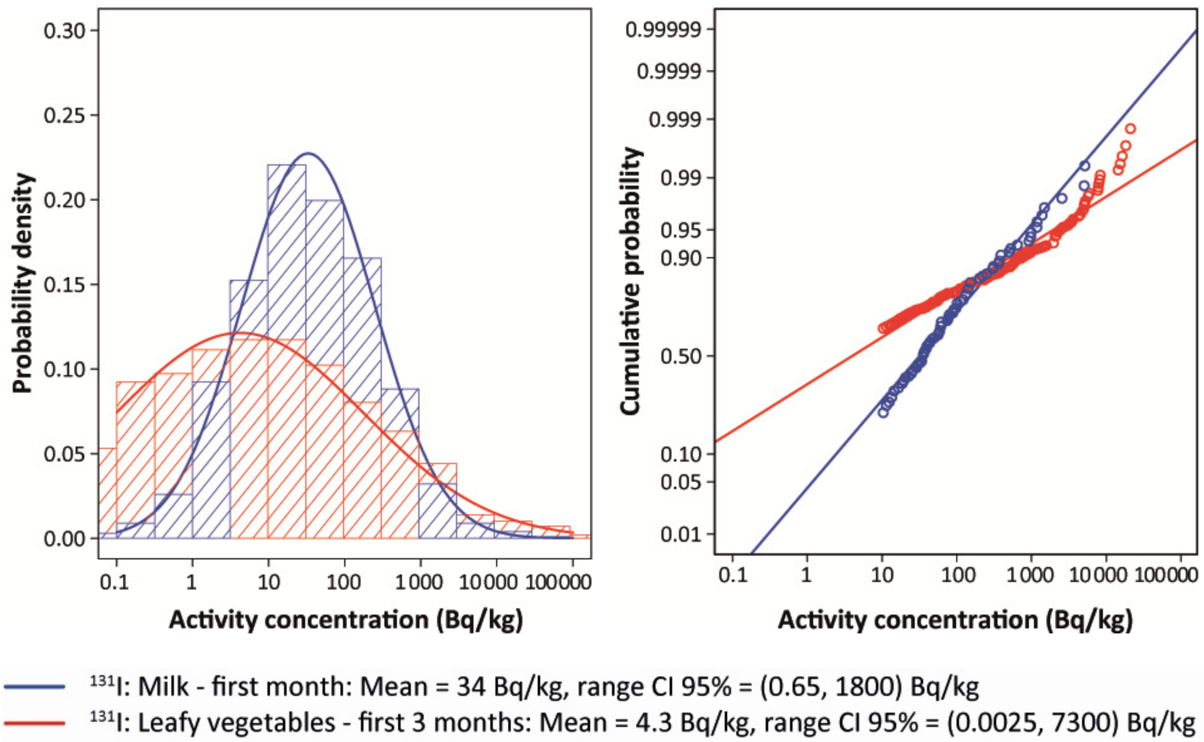


FIG. 4.1–27. Log-normal probability distribution of ^{131}I activity concentration in milk in the first month after the accident and in leafy vegetables in the first three months after the accident (normalized idealized probability density distribution and the cumulative probability distribution; a nominal detection limit of 10 Bq/kg was used) (CI: confidence interval) [156].

4.1.4.2. Wild foods

In addition to the farmed foods listed above, wild foods may contain radionuclides released from the Fukushima Daiichi NPP. Measured activity concentrations are available for wild boar, other game animals, mushrooms and berries.

Levels of caesium isotopes were measured in adult wild boar hunted in Fukushima, Miyagi, Tochigi and Ibaraki prefectures between May 2011 and March 2012. The range of measured levels of ^{134}Cs and ^{137}Cs in the muscle of wild boar is shown in Fig. 4.1–28. The two highest levels measured were 14 600 and 13 300 Bq/kg; more than half of the measurements from boar captured in Fukushima Prefecture had levels >500 Bq/kg, as did many animals from the neighbouring prefectures [159]. The boar forages for small animals and plants by digging through the litter on the ground and in the soil, which contains relatively high levels of ^{134}Cs and ^{137}Cs, hence the greater levels in wild boar than in farmed animals.

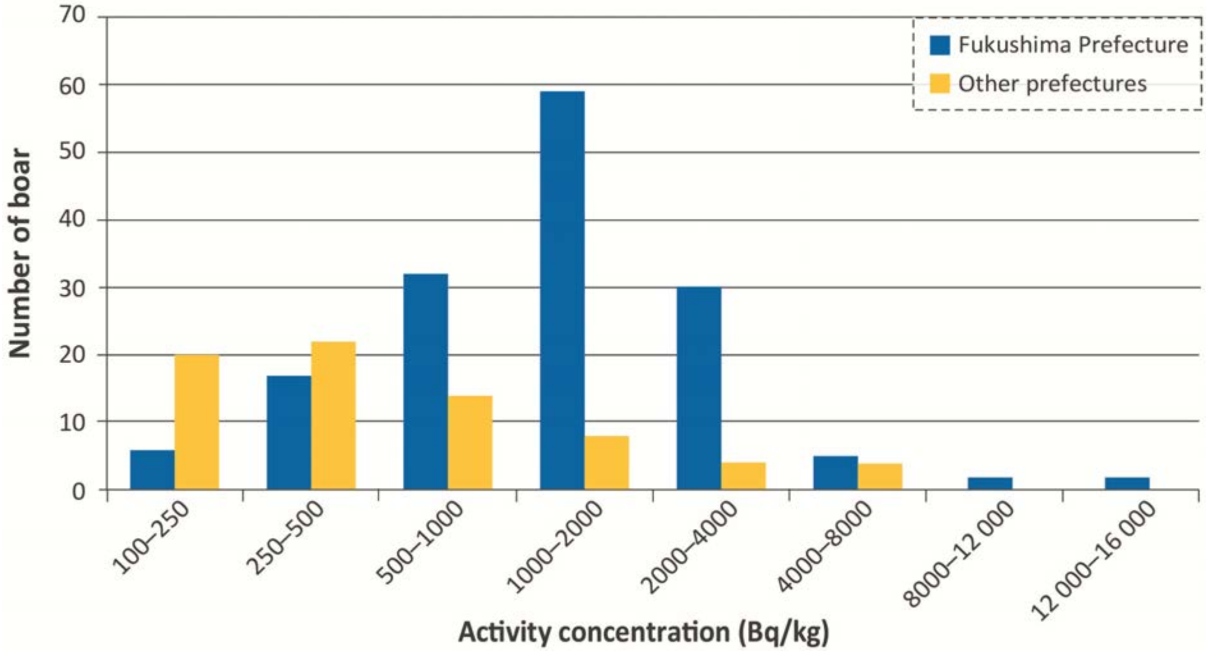


FIG. 4.1–28. Distribution of activity concentrations of radiocaesium in wild boar hunted in Fukushima, Miyagi, Tochigi and Ibaraki prefectures between May 2011 and March 2012 [159].

Concentrations of ^{134}Cs and ^{137}Cs were measured in about 400 samples of mushrooms from Fukushima Prefecture in the first year after the accident. A statistical analysis has been carried out of these measurement data, as shown in Fig. 4.1–29. Although the measurements fit a log-normal distribution, it can be seen from Fig. 4.1–30 that it was only after June 2011 that levels of ^{137}Cs started to be measurable (assumed detection limit about 10 Bq/kg). The concentrations reached a peak in September 2011 and then fell below the detection limit. In 2013, only three samples with concentrations above detection limits were found, with one sample having a concentration of ^{137}Cs of 9 Bq/kg. The average concentration in 2012 was below 15 Bq/kg. However, the number of samples is small, and the analysis of the annual change in radiocaesium concentration may be biased. It should be noted that this figure does not show the seasonal change of a single species, but presents the variation of species collected in different seasons of the year. The concentration of radiocaesium in wild mushrooms and wild edible plants is higher than in agricultural products. According to the food monitoring data, many samples exceeded 100 Bq/kg even after the first year (2.56%, as seen at the bottom of Table 4.1–8). This is consistent with the results of studies conducted after the Chernobyl accident. Collection, consumption and transportation of wild mushrooms are regulated in many areas of Fukushima Prefecture. From the analysis shown in Fig. 4.1–29, the calculated mean concentration of ^{137}Cs in mushrooms is 16 Bq/kg and there is a likelihood of around 90% that concentrations were below the Codex Alimentarius level for ^{137}Cs of 1000 Bq/kg (see Section 4.3 and Annex VIII for an explanation of the Codex Alimentarius). This figure illustrates the mean and 95% confidence interval (CI).

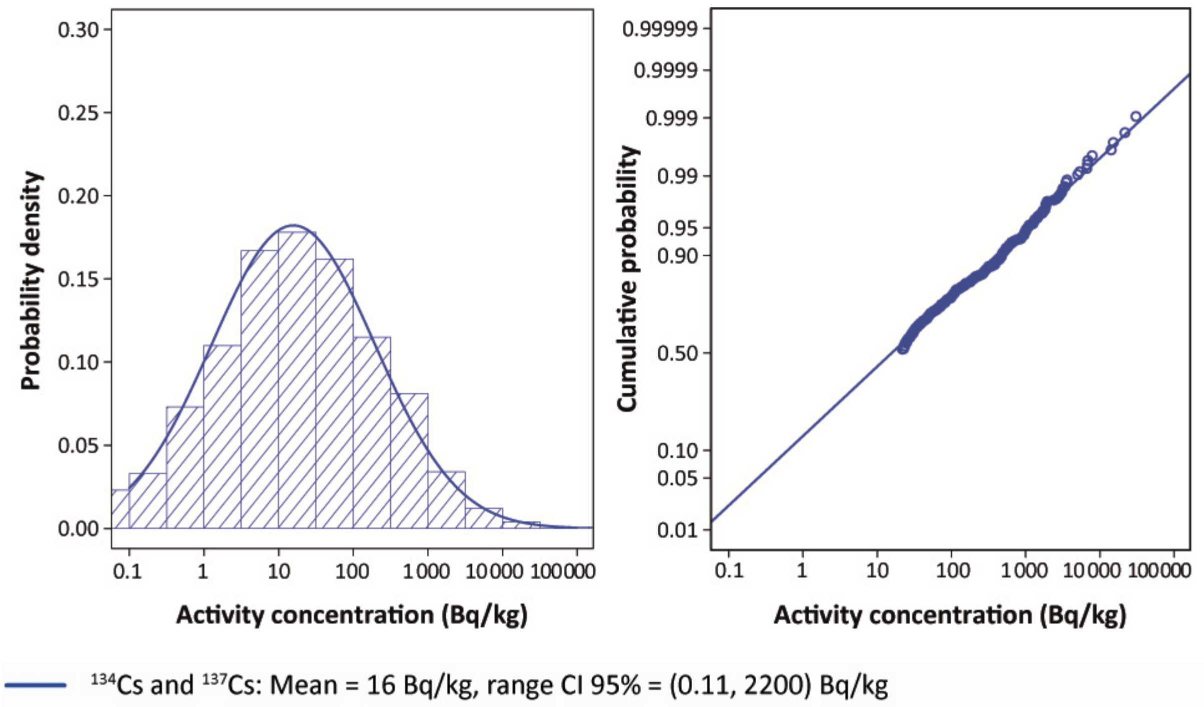


FIG. 4.1–29. Log-normal probability distribution of ^{134}Cs and ^{137}Cs activity concentration in mushrooms during the 12 months after the accident (normalized idealized probability density distribution and the cumulative probability distribution; a nominal detection limit of 10 Bq/kg was used) [156].

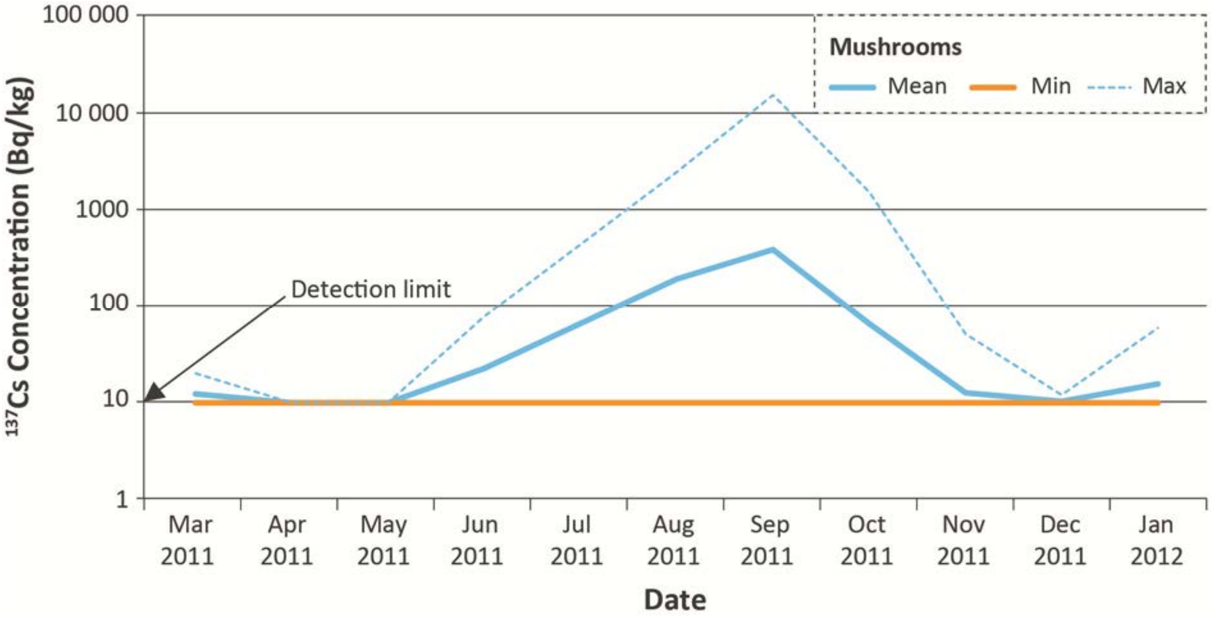


FIG. 4.1–30. Time trend of measured values of ^{137}Cs in mushrooms with different species collected in Fukushima Prefecture [156].

Only five samples in March 2011 contained measurable levels of ^{131}I, with an average concentration of 25 Bq/kg. Iodine-131 was not detected in any other sample, with detection limits varying from 5 to 10 Bq/kg.

From a total of nearly 250 samples of berries taken in the first year after the accident in Fukushima Prefecture, only 13 contained measurable levels of ^{131}I, with detection limits ranging from 5 to 10 Bq/kg. All these 13 samples were measured in March and April 2011. A statistical analysis of these data was carried out and is shown in Table 4.1–11.

TABLE 4.1–11. STATISTICAL SUMMARY OF CONCENTRATIONS OF ^{131}I IN BERRIES AT THE TIME OF MEASUREMENT [156]

Period	Number of samples	Arithmetical average	Standard deviation	Geometric average	Geometric deviation	Minimum[a]	Maximum
March 2011	23	92	293	18.4	3.7	10	1400
April 2011	22	18.0	23.6	13.0	1.9	10	110
2011–2012	247	18.4	91.0	10.8	1.6	10	1400

[a] Limit of detection assumed to be 10 Bq/kg, according to the FAO/IAEA database.

Although about 75% of samples contained levels below detection limits (about 10 Bq/kg), the monthly average activity concentrations were fairly constant during the first year after the accident, varying from less than 10 to 27 Bq/kg; some higher activity concentrations of ^{137}Cs were seen in March, July and October, as shown in Fig. 4.1–31. The highest measured concentration of ^{137}Cs was 170 Bq/kg. All samples taken in 2012 in Fukushima Prefecture had concentrations of less than the detection limits. The average concentration (arithmetical mean) of ^{137}Cs for the 240 samples of berries measured in the first year after the accident was around 18 Bq/kg, with a standard deviation of 24.

In addition to berries and mushrooms, wild plants such as ferns (collected mainly in the spring) are important forest products for people in Japan. The tendency for wild plants to accumulate caesium preferentially, compared with cultivated agricultural products, makes the monitoring of such products important. According to the food monitoring data, many of the samples exceeded 100 Bq/kg even after the first year (see Table 4.1–8). The collection and distribution of wild plants is regulated in areas of 12 prefectures in Japan.

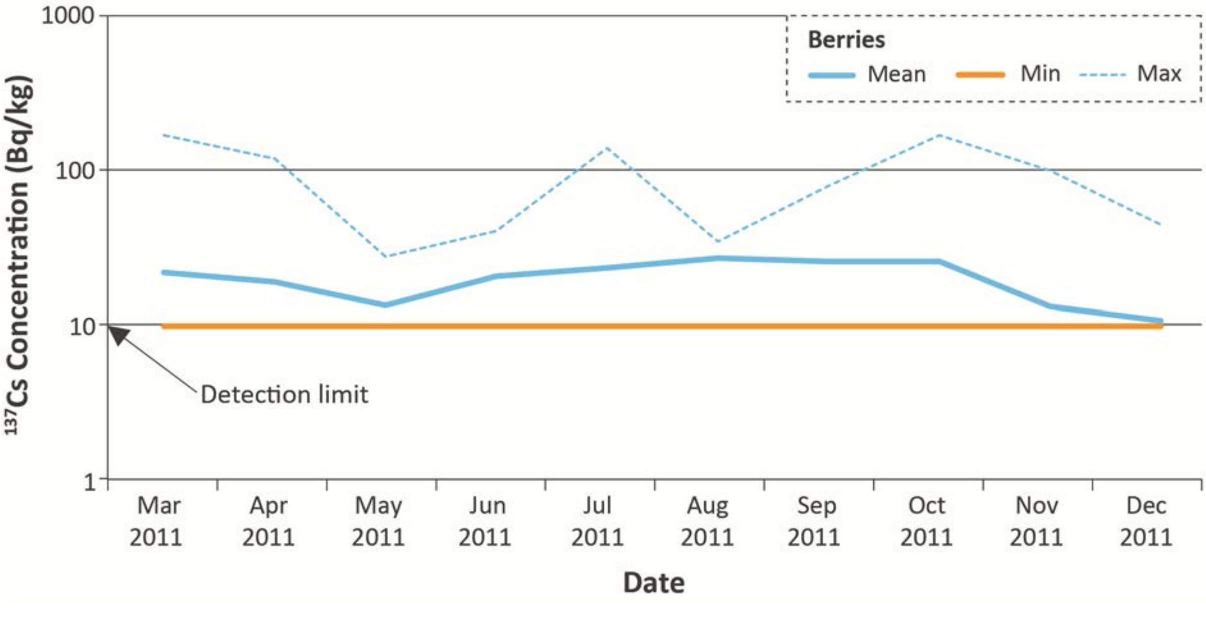


FIG. 4.1–31. Time trend of measured values of ^{137}Cs in berries in Fukushima Prefecture in 2011 [156]. These results may include data from the measurement of cultivated berries.

4.1.4.3. Fish

To supply safe fishery products to consumers, prefectural governments, in close cooperation with relevant ministries and industries, conducted monitoring of major marine fish species in each prefecture on a weekly basis [160].[10] If measurements approach the relevant standard, monitoring of the relevant products is strengthened [160]. The regulatory limits for combined ^{134}Cs and ^{137}Cs in food products also apply to seafood.

Commercial sea fishing activities were severely curtailed by the earthquake and tsunami, which damaged boats and ports. All sea fishing activities in Fukushima Prefecture were suspended for some time. A 20 km radius exclusion zone was established around the Fukushima Daiichi NPP, and some trial fishing beyond this area targeted 64 specific species, as of 30 April 2015 [129]. According to data published by the Fisheries Agency [129], 25 912 samples of marine fishery products were analysed from April 2011 to March 2015 in Fukushima Prefecture. Of these samples, 8% had a combined ^{134}Cs and ^{137}Cs level of more than 100 Bq/kg. The percentage of samples containing more than 100 Bq/kg dropped from 58% (average value for the period of April to June 2011) to 0.2% in the period of July to September 2014. In prefectures other than Fukushima, 32 852 samples of marine fishery products were analysed from March 2011 to March 2015 [129]. Only 0.5% of these samples had levels of combined ^{134}Cs and ^{137}Cs of more than 100 Bq/kg. The percentage of samples containing more than 100 Bq/kg in prefectures other than Fukushima dropped from 4.7% (average value for the period of March to June 2011) to effectively zero in the period of January to March 2015.

In the period of March 2011 to March 2012, the highest reported activity concentrations of ^{134}Cs and ^{137}Cs for freshwater fish in rivers and lakes was 18 700 Bq/kg (landlocked masu salmon, wild; Fukushima Prefecture). The highest reported value for these radionuclides in oceanic fish outside the 20 km radius exclusion zone in this period was 14 400 Bq/kg (Japanese sand lance; caught off the shore of Fukushima Prefecture) [161]. In the subsequent year (April 2012 to March 2013), the highest reported value for ^{134}Cs and ^{137}Cs was 1400 Bq/kg in fish in rivers and lakes (landlocked masu salmon, wild; Fukushima Prefecture). The highest reported value for these radionuclides in oceanic fish in this period was 3300 Bq/kg (Japanese black porgy; caught off the shore of Miyagi Prefecture) [162]. From April 2013 to March 2014, the highest reported values for ^{134}Cs and ^{137}Cs for fish in rivers and lakes was 600 Bq/kg (white spotted char, wild; Fukushima Prefecture). The highest reported value for oceanic fish in the period was 1700 Bq/kg (fat greenling caught off the shore of Fukushima Prefecture) [163]. In the period April 2014 to March 2015, the highest reported value for ^{134}Cs and ^{137}Cs in fish in rivers and lakes was 740 Bq/kg (white spotted char, wild; Fukushima Prefecture). The highest reported value for these radionuclides in oceanic fish was 510 Bq/kg (Japanese black porgy; caught off the shore of Fukushima Prefecture) [164]. However, inside the 20 km radius zone, and especially within the Fukushima Daiichi NPP harbour, much higher levels of ^{134}Cs and ^{137}Cs in fish were reported by TEPCO. To date, the highest reported value for these radionuclides in fish inside the harbour was 740 000 Bq/kg (greenling, caught in February 2013) [165], while outside the harbour, the highest value reported was 25 800 Bq/kg (greenling, caught in August 2012, 1 km offshore of the river Ota) [166]. TEPCO also reported values for other radionuclides (i.e. ^{110m}Ag and ^{90}Sr), mainly in shellfish, with levels not exceeding 69 Bq/kg and 1.5 Bq/kg, respectively [166]. As noted, these fish are not available for consumption.

If radioactive caesium close to or exceeding the standard is detected in a sample, fishermen stop the fishing and shipping of the species, and/or prefectural governments request distribution restrictions on the species. If any expansion of the contamination is observed (e.g. detection in more than one area in a prefecture of fishery products exceeding the standard), the Director General for the Nuclear

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[10] In accordance with the relevant policies, including the ‘Concepts of Inspection Planning and the Establishment and Cancellation of Items and Areas to which Restriction of Distribution and/or Consumption of Foods concerned Applies’, established by the Nuclear Emergency Response Headquarters.

Emergency Response Headquarters (i.e. the Prime Minister) issues an instruction ordering the suspension of the distribution of the fishery products affected. For instance, in some prefectures, including Miyagi and Ibaraki, fishermen stopped the fishing and shipping of fishery products which exceeded or could exceed the standard, in accordance with the request from the prefectural government. In addition, the Director General of the Nuclear Emergency Response Headquarters instructed the relevant governor to order the suspension of the distribution of the fishery product that exceeded the standard.

As for the area off the shore of the Fukushima Prefecture, since the accident, all coastal and bottom fisheries have been suspended. The fishery products caught in the area after the accident were captured as samples for monitoring, and were not distributed at the markets (except for 55 species caught by trial fisheries on 30 November 2014). Skipjack and Pacific saury fisheries, on the other hand, are operated in the Pacific Ocean, including off the shore of Fukushima Prefecture, and the fish have landed at ports in the prefecture. These species migrate mainly through areas far from the Fukushima Daiichi NPP, where the effects of radioactive materials are considered to be small. This is confirmed by the results obtained from monitoring them.

Restrictive measures, including distribution suspension orders, have been introduced for fish in rivers and lakes where radioactive caesium exceeding the standard has been detected. Such information is publicized on the web sites of the national and prefectural governments [129].

4.1.4.4. Levels of radionuclides in drinking water

Monitoring of radionuclides in bottled and tap water began throughout Fukushima Prefecture on 17 March 2011, as described in more detail in Technical Volume 3, Section 3.3. Iodine-131 was detected in samples from a number of locations in Fukushima Prefecture in March and April 2011. The measured levels of ^{131}I exceeded the provisional regulation value (of 100 Bq/kg for radioiodine in drinking water for infants) in several locations in the first three weeks following the accident, which required restrictions on the intake of tap water to be imposed for this age group. The highest levels of ^{131}I were recorded in Iitate Village: the maximum activity concentration recorded was 965 Bq/kg in a sample taken from a small scale water supply on 20 March 2011. Restrictions on consumption of tap water were imposed for all age groups in this municipality. The levels of ^{131}I measured in water sampled from supplies in Fukushima Prefecture where restrictions on intake were imposed are shown in Fig. 4.1–32.

In total, the provisional regulation value for radioiodine in drinking water for infants was exceeded for 20 water supplies in six prefectures. The maximum levels of ^{131}I detected, and the period for which restrictions on intake were imposed, are summarized for these prefectures in Table 4.1–12.

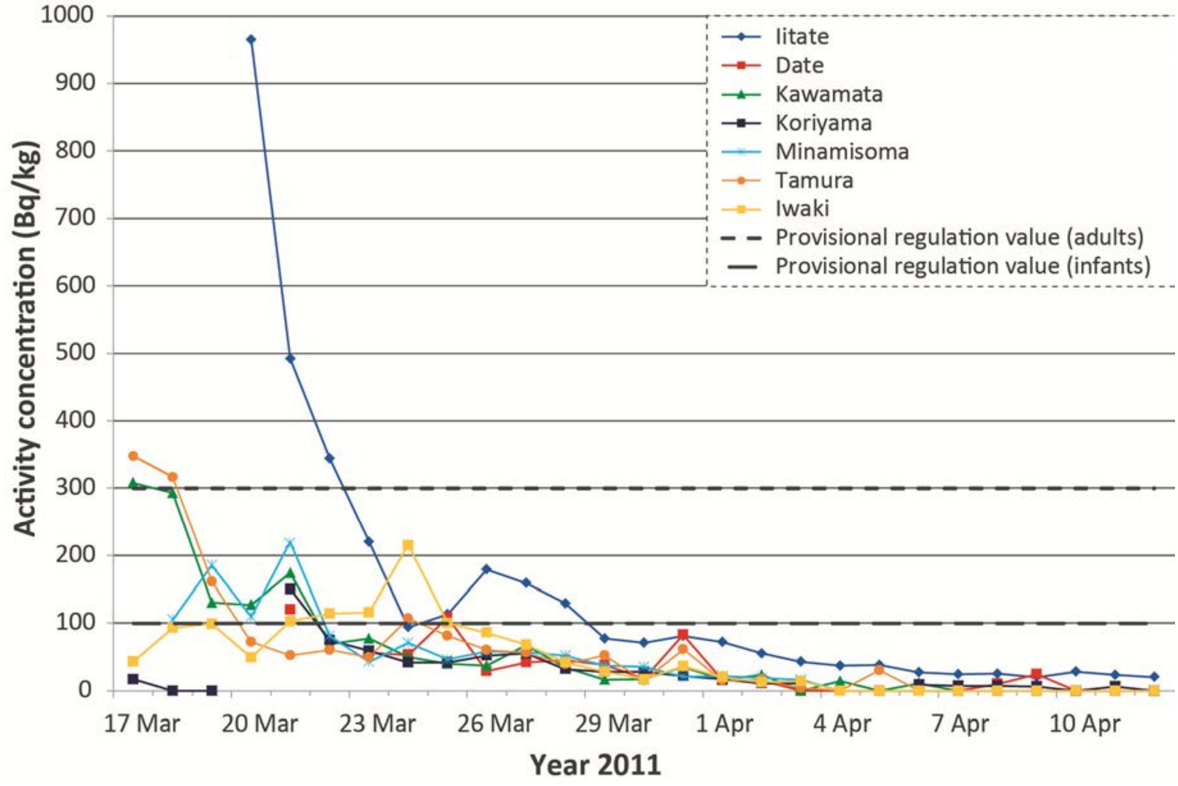

FIG. 4.1–32. Levels of ^{131}I measured in tap water supplies in Fukushima Prefecture [167].

TABLE 4.1–12. MAXIMUM LEVELS OF ^{131}I DETECTED IN DRINKING WATER[a] AND THE PERIOD FOR WHICH RESTRICTIONS ON INTAKE WERE IMPOSED
(adapted from Hamada and Ogino [168]).

Prefecture	Date ^{131}I levels first exceeded 100 Bq/kg	Maximum level of ^{131}I in tap water		Restrictions on consumption of drinking water by infants[b]	
		Activity concentration (Bq/kg)	Sample date	Date announced	Date lifted
Fukushima	16 March 2011	965	20 March 2011	21 March 2011	10 May 2011
Ibaraki	22 March 2011	298	23 March 2011	23 March 2011	27 March 2011
Chiba	22 March 2011	370	22 March 2011	23 March 2011	27 March 2011
Tokyo	22 March 2011	210	22 March 2011	23 March 2011	24 March 2011
Tochigi	23 March 2011	142	24 March 2011	25 March 2011	26 March 2011
Saitama	22 March 2011	120	22 March 2011	—	—

[a] These data relate to water available from the tap (not bottled water).
[b] In Iitate Village, restrictions for adults were also imposed. In Fukushima Prefecture, restrictions were lifted on 1 April 2011 in all locations except Iitate Village, where they were maintained in force until 10 May 2011.

The short lived radionuclide ^{132}I was also detected in a small number of samples taken from water supplies in Fukushima Prefecture in the first few days following the start of monitoring. The measured concentrations in tap water ranged from 50 to 150 Bq/kg. Radiocaesium was detected in a number of samples at levels far below the provisional regulation value of 200 Bq/kg. The highest levels were measured in samples taken on 31 March 2011 from water supplies in Date City (69 Bq/kg and 53 Bq/kg of ^{134}Cs and ^{137}Cs, respectively) and in Tamura City (60 Bq/kg and 81 Bq/kg of ^{134}Cs and ^{137}Cs, respectively). Other radionuclides, including ^{51}Cr, ^{54}Mn, ^{58}Co, ^{59}Fe, ^{60}Co, ^{65}Zn, ^{95}Zr, ^{106}Ru and ^{144}Ce were monitored, but values were below detectable levels. Levels of other gamma emitting radionuclides, including ^{132}Te, ^{133}I, ^{134}I and ^{135}I, were not monitored. Levels of ^{89}Sr and ^{90}Sr were also not monitored. It is of interest to note that after April 2012, measured levels in Japan were below WHO guidance values for permissible levels of radionuclides in drinking water, although these are intended for normal circumstances (see Section 4.3).

Daily monitoring of tap water by prefecture was also undertaken from 18 March 2011 until the end of 2011 [169].

Samples from groundwater supplies (wells and springs) were collected at 101 locations in Fukushima Prefecture and at 9 locations in Iwaki City in June and July 2011. Levels of ^{131}I and radiocaesium ^{134}Cs and ^{137}Cs were monitored, but no values above the detection limit of 10 Bq/L were recorded [170].

Since early 2012, extensive surveys of tap water have been carried out for three month periods in all 47 prefectures. The detection limit is very low, about 1 mBq/L. Measurable values for ^{137}Cs were found in 12 prefectures, and the highest value measured was 0.012 Bq/L, which was measured in the period of July–September 2012 in Tochigi Prefecture. Apparently, there was a peak for most prefectures in the same period, as shown in Fig. 4.1–33, which gives a summary of the measured levels of ^{137}Cs in tap water for the periods of July–September 2012 and January-March 2013.

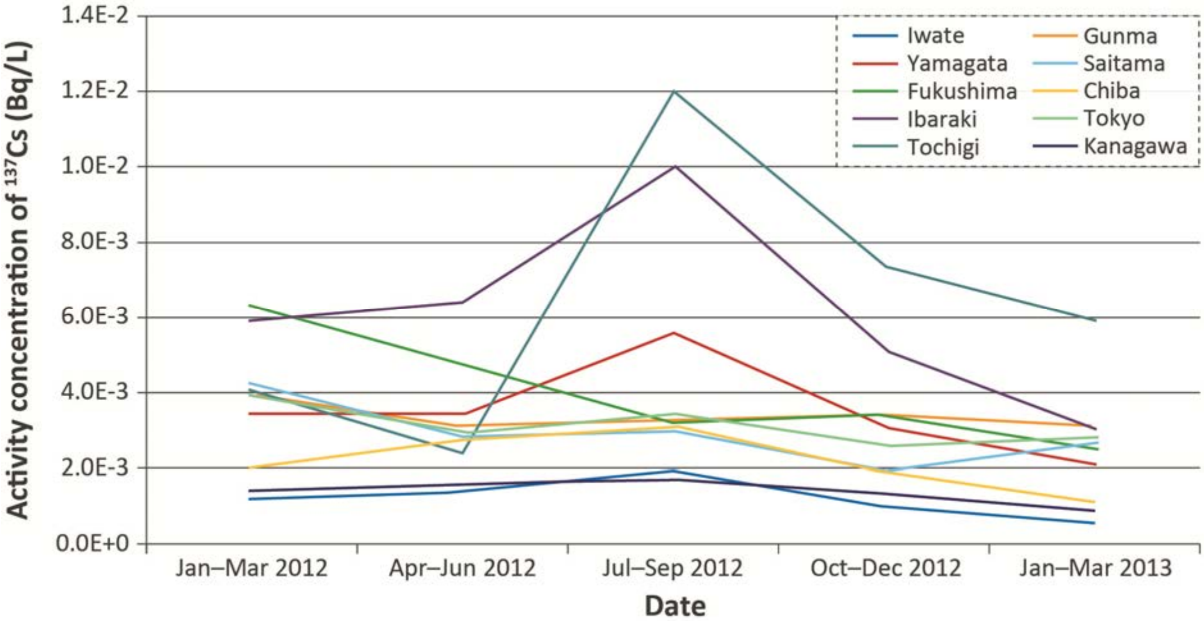

FIG. 4.1–33. Variation of ^{137}Cs activity concentration in tap water over time [171].

Although the concentrations of ^{137}Cs in tap water were very low, the increase from 2012 to 2013 observed in Fig. 4.1–33 may represent wash-off of radionuclides deposited on the land and transferred to surface waters used as a source for public supply (see Section 4.1.2).

Well water was also monitored. All the measurements made in July and August 2011 in about 80 wells in Fukushima Prefecture showed values below detection limits for ^{131}I, ^{134}Cs, ^{137}Cs, ^{89}Sr and ^{90}Sr [172], thus indicating that well water was not affected by the accident.

4.1.5. Levels of radioactivity worldwide

Radionuclides released to the atmosphere as a consequence of the Fukushima Daiichi accident were transported around the globe, resulting in very low but detectable concentrations above background levels in many regions. Atmospheric dispersion modelling results and environmental monitoring results, e.g. activity concentrations in air and rainwater, have been used to track the transport of the releases around the globe.

As explained in Section 4.1.2.2, radionuclides released to the ocean were also dispersed throughout the Pacific Ocean. Again, very low concentrations in sea water above the normal background have been detected, for example, in sea water sampled from the coasts of Alaska, Canada and California in 2013 and 2014.[11]

This section gives a brief overview of the global dispersion of the releases from the Fukushima Daiichi accident to the atmosphere and the resulting concentrations of radionuclides in environmental media.

4.1.5.1. Atmospheric transport modelling

A number of computer simulations have been carried out to model the dispersion of radionuclides released to the atmosphere from the Fukushima Daiichi NPP and to estimate the levels of radionuclides in other countries. Atmospheric dispersion modelling is subject to uncertainties in the amount of radionuclides released at different times and in other aspects of the source term as described in Section 4.1.2, together with the variable meteorological conditions and other factors affecting the modelling. The calculations suggest that the predominant long range transport of radionuclides was to the east of Japan, but that countries throughout the world received radionuclides from the Fukushima Daiichi accident releases, although at low levels. This long range transport was modelled in the preliminary dose estimation carried out by WHO in order to estimate global radiation exposures [173]. Calculations of the air mass trajectories were also performed by various other groups, using, for example, the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model [174] and the global aerosol transport model SPRINTARS [33].

To illustrate the type of results obtained, Fig. 4.1–34, which is reproduced from Thakur et al. [13], shows calculated air mass trajectories initially starting at 500, 1000 and 1500 m above ground level, from 10:00 UTC[12] on 12 March 2011, approximately three hours after the first explosion. All of the trajectories were estimated to follow the winds from a westerly direction toward the Pacific Ocean and North America. The patterns of trajectories were then different, depending on the height of the release. It was estimated that the lower altitude trajectory followed a cyclonic system over the Bering Sea, reaching the eastern part of the Russian Federation on 16–17 March 2011 before entering north-eastern China. From 23 to 26 March, the air mass was transported from north-eastern China to the coastal region of southern China [13].

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[11] CENTER FOR MARINE AND ENVIRONMENTAL RADIATION, WOODS HOLE OCEANOGRAPHIC INSTITUTION, Current Results (2015),

http://ourradioactiveocean.org/results.html

[12] Universal Time Coordinated, which is nine hours behind Japan Standard Time.

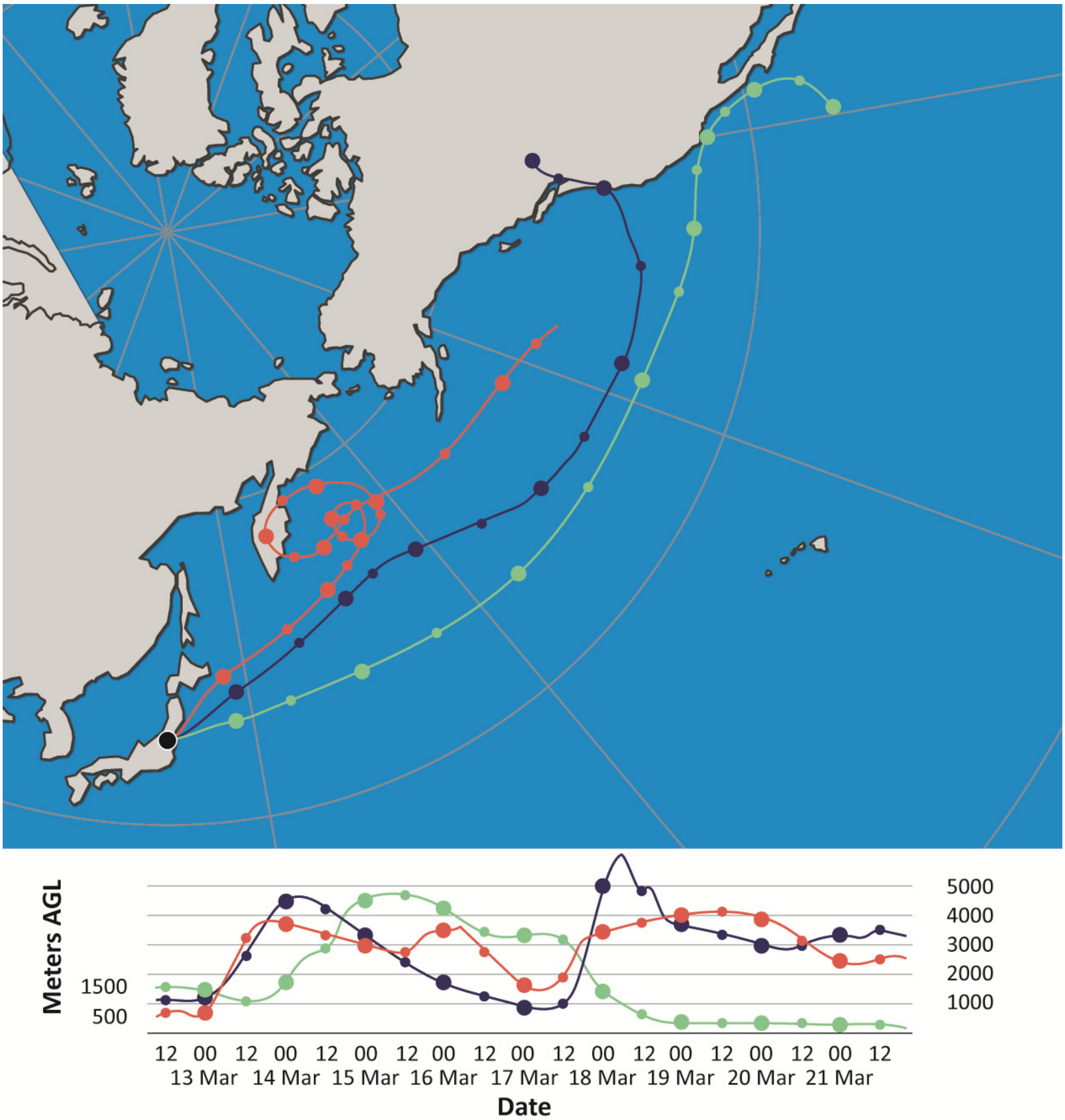

FIG. 4.1–34. Trajectories of air masses released from the location of the Fukushima Daiichi NPP calculated using the HYPSLIT model on the basis of GDAS Meteorological data and starting at 10:00 UTC on 12 March 2011 [13].

Similar results were obtained by Takemura et al. [33] using the SPRINTARS model to predict the long range transport of radioactive material from Fukushima Daiichi to the United States of America and to Europe within five days. These studies showed the importance of certain features, such as storms that lift material vertically, the action of jet streams and the removal of radionuclides by wet deposition. The results of the SPRINTARS model are illustrated in Fig. 4.1–35, which shows the global transport of material in air released continuously from the Fukushima Daiichi NPP for different periods (it should be noted that this does not reflect the actual releases). The complex nature of the dispersion can be seen, together with the possible mechanism by which radionuclides were dispersed to Europe. The model of Takemura et al. [33] also predicted the arrival of the radionuclides from the Fukushima Daiichi NPP in Asian countries in late March, as reported in various publications, including Refs [175, 176]. This suggests that the radionuclides were transported at two different altitudes along different trajectories with different speeds of transport.

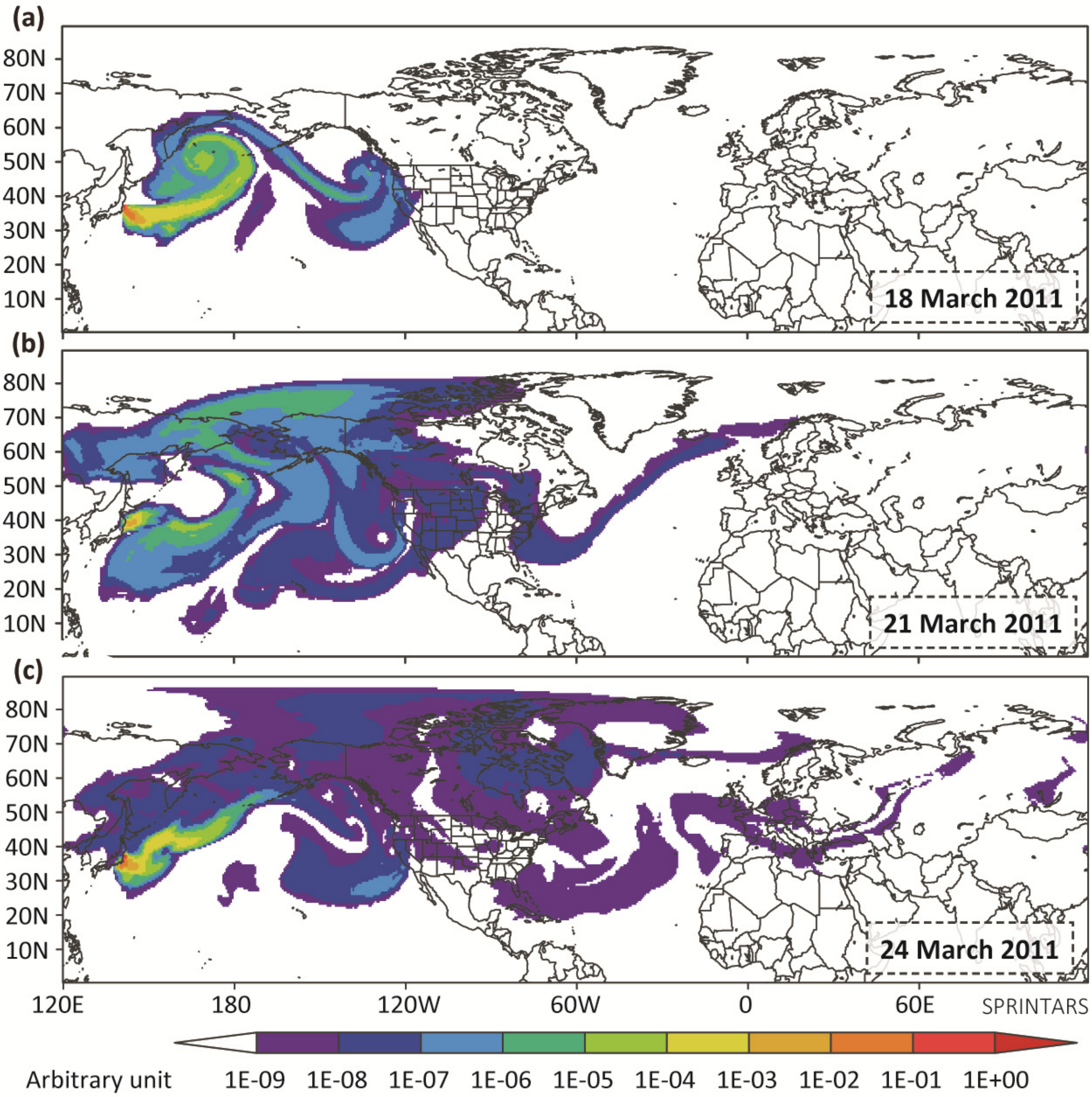

FIG. 4.1–35. SPRINTARS simulation of the global transport of material in near surface air masses emitted continuously from the Fukushima Daiichi NPP since 14 March, 12:00 UTC, for (a) 18 March, (b) 21 March and (c) 24 March 2011. The concentration indicated is relative to the concentration within a few tens of kilometres around the NPP. Each range of colour contours corresponds to one order of magnitude [33].

4.1.5.2. Global measurements of radionuclides released to the atmosphere

Following the events at the Fukushima Daiichi NPP in March 2011, the monitoring of radionuclides in the environment was increased throughout the Northern Hemisphere. The network of the CTBTO monitoring stations detected enhanced levels of isotopes of xenon, iodine and caesium in the air. Some additional radionuclides — isotopes of tellurium, ^{140}Ba/^{140}La, ^{90}Mo/^{99m}Tc, ^{110m}Ag and ^{111}Ag — were also detected in air samples collected across the USA and Europe. However, these measured activity concentrations were considerably (more than a thousand times) lower than the activity concentrations observed in Japan. Radionuclides from the releases from the Fukushima Daiichi NPP were detected in most of the countries in the Northern Hemisphere, but, as expected, there was little activity detected in the southern hemisphere, owing to the low exchange of air masses across the equator [13].

The measured activity concentrations in air throughout the Northern Hemisphere were evaluated by Thakur et al. [13]. They note that levels varied over time at the same location, reflecting the complex pattern of global dispersion, and also between locations. The measured activity concentrations in air were found to follow a log-normal distribution with higher values observed in North America, followed by countries in Asia, and lower values in Europe. They report that the highest activity concentrations in air measured outside Japan were 31 mBq/m^3 for ^{131}I; 8 mBq/m^3 for ^{134}Cs; and 10 mBq/m^3 for ^{137}Cs.

Radionuclides from the Fukushima Daiichi NPP were also detected in other environmental materials at many locations in the Northern Hemisphere, notably in rainwater, grass, milk and vegetables. Again, levels of these radionuclides were significantly lower than those measured in Japan. These measurements have been used to assess radiation exposures in many countries. UNSCEAR collected information from Member States on levels of radionuclides in environmental materials and on exposure assessments as part of a study to determine the levels and effects of radiation exposure due to the releases [5].

4.1.6. Summary

As a consequence of the Fukushima Daiichi accident, radioactive material was released into the environment, both to the atmosphere and into the ocean. This resulted in relatively high ambient radiation levels around the Fukushima Daiichi NPP. A proportion of the radioactive material reached the human habitat, including foods and drinking water. Some of this radioactive material was globally circulated.

The events leading to these releases were complex and variable. The main part of the releases occurred over a period of about one month and continued, albeit at very much lower levels. Of particular note were the releases that took place on 12 March 2011 following a hydrogen explosion in Unit 1, those on 14 and 15 March and those over the period from 20 to 23 March.

The radiological impact of the relevant releases to the atmosphere was dominated by the radionuclides of the elements caesium and iodine (including, ^{131}I, ^{134}Cs and ^{137}Cs). Different theoretical estimates of the releases have been performed by specialist institutions around the world. The estimates of the release of ^{131}I were in the range of 100–400 PBq. The amount of ^{137}Cs released is estimated to have been in the range of 7–20 PBq. A statistical analysis of the source term data using Bayesian techniques was carried out for the purposes of this report; it indicates that the mean of the distribution could be estimated to have been between 140 and 200 PBq for ^{131}I and between 12 and 16 PBq for ^{137}Cs.

One method of estimating an accident source term is to measure the levels of radionuclides deposited on the ground and calculate the amount of the release, using atmospheric dispersion models. However, in the case of the Fukushima Daiichi accident, part of the releases to the atmosphere took place when the wind was blowing in an eastward direction from the Fukushima Daiichi NPP towards the sea. Consequently, most of the radioactive material deposited onto the ocean and dispersed could not be measured, making it impossible to corroborate the amount of radionuclides released on the basis of measurement of deposition in the terrestrial environment. Nevertheless, it can be judged with sufficient confidence that the releases were lower than those from the accident at the Chernobyl NPP in 1986. The total release of ^{131}I is estimated to have been 20% of the release from the Chernobyl accident, while the total release of ^{137}Cs is estimated to have been 35% of the release from the Chernobyl accident. Unlike the Chernobyl accident, the Fukushima Daiichi accident is estimated to have led to only negligible releases of radionuclides such as ^{90}Sr and ^{239}Pu.

The weather conditions during the period of the releases were very variable, and, in spite of the fact that much of the released material was initially blown over the sea, some of the key releases were blown over the land. Some of the released radioactive material encountered rainfall, leading to enhanced levels of deposition on land in some areas. The variable weather conditions and the complex nature of the releases led to a distribution pattern of radionuclides in the terrestrial environment that was very inhomogeneous, with some areas being affected to a greater extent than others. Notably, some areas to the north-west of the Fukushima Daiichi NPP were subject to the highest levels of deposition of radionuclides. A further factor that influenced the pattern of deposition in the terrestrial environment was the prevalence of different physical and chemical characteristics of the radionuclides of iodine and caesium.

Extensive monitoring of the terrestrial environment was carried out in Japan by the relevant national authorities, supplemented by international expertise. This monitoring provided information on the type and the levels of radioactive material in the environment in Japan. Of particular importance were the aerial surveys of ambient dose carried out jointly by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and the United States Department of Energy (DOE), as well as the comprehensive measurements of radionuclides in soil across the whole of Japan. These two sets of measurements (which formed the basis for the UNSCEAR estimates of the consequences of the accident) confirmed the radiological significance of the radionuclides ^{131}I, ^{134}Cs and ^{137}Cs. Although other radionuclides were also detected during these measurements, they were found at relatively low levels. There is good agreement between the different measurements carried out by the Japanese authorities and other organizations, including measurements undertaken by the IAEA, which provides confidence in the results presented in this report.

Releases to the Pacific Ocean and levels of radionuclides in the aquatic environment

There were two main routes by which radionuclides reached the Pacific Ocean. Firstly, as mentioned above, because of the prevailing weather conditions, a component of the radionuclides released to the atmosphere was transported over the ocean and deposited on the ocean surface. Secondly, water containing radionuclides was released directly into the ocean. The direct releases took place in March and early April 2011. These two routes by which radionuclides reached the ocean seem to have been broadly similar in terms of the total amount released, although for direct releases of radionuclides to the ocean, there is a higher degree of uncertainty. Most estimates for the release of ^{137}Cs are in the range of 1–6 PBq; some estimates are as high as 27 PBq. The direct releases of ^{131}I are thought to have been in the range of 10–20 PBq. Other releases into the ocean included mainly ^{134}Cs and small amounts of other radionuclides, notably ^{90}Sr. Relatively low levels of radionuclides continue to be released to the ocean owing to transfer from groundwater and rivers.

The dispersion of radionuclides in the vast quantity of ocean water means that the levels of radioactive material measured in the Pacific Ocean were generally very low, although the radionuclides could be detected at large distances from Japan. The chemical characteristics of caesium are that it is soluble in sea water and is carried over very long distances by marine currents and widely dispersed throughout the water masses of the ocean. However, some of the caesium was bound to suspended particles and will eventually deposit on the sea floor.

Large volumes of water containing significant amounts of radionuclides are stored in tanks at the Fukushima Daiichi NPP. In addition, the damaged reactor buildings contain high levels of radionuclides, and large volumes of water have been transferred to the groundwater system around the site. As a consequence of the topography of the site, groundwater flows from the western side of the site to the eastern shoreline. Groundwater enters the damaged buildings and contributes to an increase in the amount of water containing radionuclides that needs to be treated, stored or discharged.

Radionuclides in food and drinking water

An extensive programme of monitoring of food and drinking water was implemented by the relevant authorities following the accident, and this programme is continuing. Measurements of ^{131}I, ^{134}Cs and ^{137}Cs on some terrestrial and aquatic foods identified levels that required restrictions on the sale and distribution of some foods. Measurements were also carried out on other sources of food, such as wild boar, mushrooms and berries, and, in the initial period after the releases, these were also found to have relatively high concentrations of the significant radionuclides.

Global circulation of radionuclides released from the Fukushima Daiichi accident

The transport of the atmospheric radioactive releases was directed mainly to the east and north of Japan, following the prevailing wind direction, and then around the globe. The transport of the releases to the Pacific Ocean is influenced by the complex recirculation patterns and the potential for the interaction of radionuclides with sediments and other physical and chemical processes.

Many countries have developed and implemented highly sensitive monitoring networks that can detect very low levels of radionuclides in the environment. The measurement results from these networks have been widely reported, and they have demonstrated that, although radionuclides have been detected at large distances from Japan, their levels have been extremely low and the impact of the Fukushima Daiichi accident on existing global levels has been negligible.

4.1.7. Observations and lessons

— **Prompt quantification and characterization of the amount and composition of radioactive material released to the environment are needed following an NPP accident. For significant releases, a comprehensive and coordinated programme of long term environmental monitoring is necessary to determine the nature and extent of the radiological impact on the environment at the local, regional and global levels.**
The quantification and characterization of the source term of the accident at the Fukushima Daiichi NPP proved to be difficult. Prompt monitoring of the environment provides confirmation of the levels of radionuclides and establishes the initial basis for protecting people. The results can be used to inform the public and to develop strategies for response and recovery activities. It is also important to continue environmental monitoring to verify that there are no further significant releases of radionuclides and to provide information to decision makers and other stakeholders on the possible redistribution of radionuclides in the environment over time.

— **Groundwater surveillance needs to continue.**
Radioactivity in groundwater is a local problem restricted to the Fukushima Daiichi NPP. However, continued surveillance is needed to confirm that this continues to be the case in the longer term.

4.2. RADIATION EXPOSURE

The assessment of radiation exposures of people is an important aspect of determining the radiological consequences of accidental events and releases of radioactivity. Information on the levels of radiation doses received by workers and members of the public is necessary to construct a picture of the pattern of exposures for different groups in order to determine whether there are likely to be any observable radiation induced health effects among the population. Furthermore, it is important to determine the different routes of exposure, and the time dependence of the exposures, when using them as inputs for the planning and implementation of appropriate protection measures and for emergency planning and response purposes.

This section provides dose estimates that are as accurate as currently possible, making use of direct personal measurements where available. It builds on previous assessments, particularly the most recent international assessment, which was completed by UNSCEAR in 2014 [5]. It takes into consideration additional measurement data that have become available since that assessment was undertaken. Particular attention is paid to personal measurements from dosimeters worn by individuals and the results of thyroid measurements and whole body counting. This information has been provided by the Japanese Government, TEPCO and from available reports and sources collected up to December 2014.[13]

Section 4.2.1 focuses on occupational exposures and summarizes the doses received by workers in the more than three years since the accident. Section 4.2.2 provides a review of effective doses and thyroid equivalent doses incurred by the public in Fukushima Prefecture and neighbouring prefectures. Where possible, effective doses and thyroid equivalent doses are categorized by the appropriate location, namely the municipality in which the residents were living before the accident, and by the appropriate time period. Not all data for all prefectures are contained in this report. However, the data presented provide information for a range of municipalities for which such data were available.

4.2.1. Occupational exposures

This section provides a summary of the radiation doses received by workers engaged in on-site and off-site emergency work activities during and immediately following the accident at the Fukushima Daiichi NPP. It also provides information on the doses subsequently reported for on-site workers who have been involved with longer term stabilization and cleanup activities since the accident, for the period until December 2014. In order to place this information in context, it is helpful to provide some introductory information on the limits in place, the protective measures available at the time of the accident and the methods used to assess doses.

4.2.1.1. Dose control and dosimetry

To protect workers, other responders and the public, countries and organizations have established exposure guidelines, which are explained in greater detail in Section 4.3. Regulations and guidelines typically provide exposure limits for emergency workers that are different from those for normal radiation workers or the public. These guidelines balance the risks and benefits, considering the individual's training, the duties that require the individual to be close to radiation or radioactive sources, and the activities that need to be undertaken. The guidelines may differ between countries; they can also be changed. During the response to the Fukushima Daiichi accident, the Japanese guidelines evolved over time.

As explained further in Section 4.3, an effective dose limit of 100 mSv was initially applied for male workers involved in the radiation emergency.[14] This value was increased to 250 mSv with effect from 14 March 2011 to allow emergency workers to undertake tasks that it was necessary to perform, in particular tasks relating to controlling and stabilizing the reactors [177]. The lower level was reinstated for new workers after 1 November 2011, except for those working on reactor cooling and release suppression systems, where the higher value was retained for those workers who were already on-site [178, 179] (see Section 4.3 and Technical Volume 3 for more details). TEPCO staff and contractors and members of the police, firefighters and the Japan Self-Defense Forces (SDF) were also involved in on-site emergency activities.

[13] In some cases, information was available for the period until May 2015. This information was included in this volume, where possible.

[14] An effective dose limit of 5 mSv over three months remained in place for female workers.

Workers from the various emergency services and from other organizations were also involved in off-site emergency activities, including within the evacuation zone. Information on the doses reported for each of these groups of workers during the emergency is presented where it is available. Male SDF workers and firefighters were subject to an annual limit of 50 mSv effective dose (100 mSv in 5 years), while female workers with reproductive capacity (i.e. those who did not complete a form declaring that they did not have reproductive capacity) who served as emergency workers were subject to the normal effective dose limit of 5 mSv over three months. Other workers who offered assistance were typically subject to the guidelines of the agency for which they worked.

Table 4.2–1 shows the different organizations that responded and the organizations that had authority to issue exposure guidelines. The different sources of guidance can lead to different guidelines, as is also shown in Table 4.2–1. Note that the dose limits are associated with specific activities, reflecting the need to balance risks and benefits.

TABLE 4.2–1. RESPONDING ORGANIZATIONS AND THE ENTITIES ESTABLISHING APPLICABLE EXPOSURE GUIDELINES

Responding organization	Regulatory organization	Dose limits and criteria
TEPCO	Ministry of Health, Labour and Welfare (MHLW)	250 mSv (limiting effective dose criterion for emergency action) [a] 100 mSv (limiting effective dose criterion for emergency action)
SDF	Ministry of Defense	50 mSv/year, (100 mSv/5 years) (male); 5 mSv/3 months (female) [180]
Police	National Public Safety Commission and National Police Agency	50 mSv/1 year (100 mSv/5 years) (male), 5 mSv/3 months (female)
Fire Department	Ministry of Internal Affairs and Communications (MIAC)	50 mSv/year (100 mSv/5 years) (male); 5 mSv/3 months (female)
Municipal workers	Fukushima Prefecture	—
IAEA	IAEA Safety Standards	50 mSv/year
Australian military, urban search and rescue	Australian Radiation Protection and Nuclear Safety Agency (ARPANSA)	50 mSv/year (in ARPANSA RPS1) [181]
US urban search and rescue	US Occupational Safety and Health Administration	50 mSv/year
US Department of Energy (DOE)	DOE	50 mSv/year
US military	United States Pacific Command (USPACOM), derived from United States Nuclear Regulatory Commission occupational limits	3 mSv during Operation Tomadachi response[182]; ≤10 mSv but documentation of mitigating factors necessitated; only upon approval by Unit Commander; >10 mSv only with USPACOM approval
Volunteers (i.e. the public)	MHLW	1 mSv/year

[a] Applicable to a limited number of workers over a short period of time.

Different guidelines among responders from other countries and international organizations created challenges for personnel from different organizations working together.

4.2.1.2. Measurements of external dose

Worker protection, and the associated legal requirements, generally necessitates the use of dosimeters or other forms of workplace instruments to measure the external exposure that individuals receive. A variety of dosimeters are available; some provide real time information (known as electronic personal alarm dosimeters (PADs) or electronic personal dosimeters (EPDs)), while others capture the information for later retrieval (passive dosimeters). The former type of dosimeter enable individuals to act on the information in real time and to modify their activities or leave the exposure situation on the basis of the information provided. However, passive dosimeters can be more accurate and are more commonly used to provide a record of exposure.

Before the accident, TEPCO used EPDs for radiation dose measurements for the purposes of both dose control and for statutory monitoring and reporting. Immediately after the tsunami, many of the EPDs were damaged by flooding and were rendered inoperable. As a result of the shortage of EPDs, a single EPD was provided per work group during the period 15–31 March 2011 [183], when groups were working under conditions where exposure was expected to be almost constant. The reactor operators were provided with individual PADs, where possible, although they were not available on an individual basis in the main control rooms. During the first month, external doses for workers inside the seismic isolation building were estimated on the basis of measured external exposure rates in the work area and worker occupancy times. From 1 April 2011, a sufficient number of dosimeters of different types were available [184, 185].

A number of organizations involved in off-site assistance activities also used EPDs of various types for tracking doses in real time and for record keeping purposes.

4.2.1.3. Measurements of internal dose

During the immediate response to the accident, TEPCO estimated internal worker doses on the basis of assessments of external exposure and assuming an intake of gamma emitting radionuclides. However, no bioassays[15] were performed by TEPCO for workers during the emergency phase. The release was known to consist predominantly of iodine and caesium. Since these radionuclides are easily measured with a whole body counter (WBC), TEPCO decided to determine internal dose from the WBC measurements. This process, later approved by MHLW, is described in detail on the TEPCO web site [186]. When an individual incurred an external dose of 100 mSv, a WBC measurement was performed and the internal dose was estimated.

WBCs are widely used to measure the amount of radioactivity in people. The principles governing their use are presented in Annex I. High background radiation levels and elevated levels of contamination at the Fukushima Daiichi NPP meant that on-site WBC equipment could not be used to monitor workers. Other WBC facilities were therefore used, as described in Annex I.

In addition to WBC measurements, in vivo measurements of radionuclides in the thyroid were also carried out. These measurements started in 22 March 2011. However, owing to emergency response activities and a lack of WBCs, many workers were not measured until mid to late May 2011, with the exception of three of the most highly exposed workers, for whom measurements began in mid-April [185]. As indicated below, this delay increased the uncertainty in the assessment of doses from ^{131}I and other short lived radioisotopes of iodine and tellurium.

TEPCO later instituted a policy to detect internal contamination and exposure to beta emitting radionuclides in certain areas of the Fukushima Daiichi NPP (e.g. the reactor building area and

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[15] A bioassay is a measurement of the concentration or potency of a substance by its effect on living cells or tissues.

contaminated water storage tank locations) where the total beta and gamma exposure was expected to exceed the gamma-only exposure by approximately four times. Each worker wore an EPD (which measured gamma and beta radiation)[16] and a full face respirator in these areas. When workers left the work area, they were screened. If contamination was detected on the nose or mouth, a nasal smear was conducted. If the nasal smear was positive, the intake of beta nuclides was estimated and if the estimated committed effective dose exceeded 2 mSv, a bioassay was required. Workers with doses exceeding 250 mSv were referred to the National Institute of Radiological Sciences (NIRS) for detailed dose assessment and checkups. NIRS performed cytogenetic biodosimetry, usually by dicentric chromosome assay (DCA).

DCA is an accurate, yet time consuming, method which involves taking a blood sample, processing it in a laboratory, looking at it under a microscope, and counting chromosomal abnormalities, which can be calibrated to indicate radiation exposure. The process takes approximately two days. By the end of 2013, NIRS had performed assays for 12 workers for dose assessment purposes; ten of these workers agreed for their data to be incorporated in the study [187], and their data indicated that the estimated doses for all individuals were lower than 300 mGy, with a mean value of about 100 mGy. The results by DCA were consistent with those obtained by physical dosimetry based on personal measurements and thus primarily provided reassurance and confirmation to workers of their assessed exposures.

4.2.1.4. Protection measures

Time, distance and shielding can protect workers from external exposure. However, internal exposures tend to arise from intakes of radionuclides from ingestion or inhalation, which can lead to exposures over extended periods following intake. Personal protective equipment (PPE) is generally used to protect workers from receiving such intakes. Following the release of radioactive material from the Fukushima Daiichi NPP, virtually all of the on-site workplaces were contaminated with airborne or particulate radioactivity; thus, the greatest source of intake of radionuclides was through inhalation. Airborne contamination remained elevated until approximately the end of July 2011, as demonstrated by measurements of activity concentrations in air at the site perimeter. Emergency workers used a range of respiratory protection equipment, from filtering respirators to self-contained breathing apparatus. However, in the main control rooms, charcoal filtering PPEs were not properly distributed and used during the early phase of the accident [185, 188].

In addition to respiratory protection, gloves, shoe covers and protective suits were issued to on-site workers, depending on workplace conditions. For many off-site workers, shoe covers and gloves provided sufficient protection, although some used full PPE for particular operations such as decontaminating aircraft. Some assistance workers were measured using WBC and bioassay in their country of origin after completion of their work in Japan.

As explained in more detail in Technical Volume 3, from 13 March 2011, potassium iodide tablets were provided to some emergency workers, for the purpose of blocking the uptake of radioactive iodine by the thyroid.

4.2.1.5. Training

From the time of the accident until around 30 May 2011, TEPCO and the primary contractors conducted training for newcomers at J-Village (the coordination centre for response action located in the south of Fukushima Prefecture). The half-hour course developed by TEPCO covered worker training and education on the effects of radiation, how to control radiation dose, and the use of PPE.

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[16] Since 1 July 2013, all on-site radiation workers, including those conducting decommissioning activities, have worn dosimeters that measured both beta and gamma radiation.

The course was originally designed for 20–30 participants at a time, but with an increasing number of emergency workers, revisions to the TEPCO educational and training programme were made beginning on 19 May 2011 [183]. Later, on 8 June 2011, a special education programme was initiated at J-Village for both TEPCO staff and contractors. TEPCO started a compulsory seven hour training course in the summer of 2011, approximately five months after the accident [185].

Table 4.2–2 identifies some of the organizations that participated in the response to the Fukushima Daiichi accident and their general levels of radiological awareness and dosimetry. Many of the responders had been trained to work in environments with elevated levels of radiation or contamination. They typically worked under informed consent, their exposure was tracked, and they followed exposure guidelines.

Apart from TEPCO employees, only personnel from the SDF, police, Fire Department and Nanmei Kosan (a private firefighting company and a subsidiary of TEPCO) worked on-site. Firefighters from the municipalities were involved in the off-site response. The Tokyo firefighters were members of a specially trained unit who received annual refresher training in radiation protection. These individuals wore dosimeters and their dose was recorded.

However, some firefighters, specifically the employees of Nanmei Kosan, did not receive radiation protection training. During the accident, this group operated fire engines and other equipment on-site.

TABLE 4.2–2. OVERVIEW OF ORGANIZATIONS AND RADIOLOGICAL AWARENESS (11 MARCH 2011–16 DECEMBER 2011)

Organizations	No. of workers on-site	No. of workers off-site	Radiation safety training	Dose tracking
TEPCO (including contractors)	~20 000	—	Extensive	Required
TEPCO subsidiary Nanmei Kosan	~20 (15 March) ~130 (16 December)	—	No training	Required
Firefighters –Municipal off-site	—	Varied	Awareness	Available
Police	13	Varied	Awareness	
SDF	147	~100 000	Awareness	Required
Medical personnel	—	Varied	Awareness for those who received just in time training; otherwise, none	Unknown
IAEA	—	16	Extensive	Required
Australian military, urban search and rescue	—	72	Awareness	Required
DOE	—	100	Extensive	Required
US military	—	~90 000 (~1000 within 45 km)	Awareness; extensive for some	Required
US urban search and rescue	—	150	Awareness; extensive for subset	Required
Other volunteers	—	Varied	Varied	Varied

Police officers, firefighters, members of the SDF and other first responders were an essential component of the response, facilitating evacuations and providing assistance and performing other tasks off-site. In conducting these activities, they often entered areas with elevated levels of radioactivity which residents were being asked to leave, thus increasing their potential for radiation exposure. Their training was typically designed to give them the knowledge to minimize their exposure.

Many volunteers participated in the response and recovery work. Some of them were experienced radiation workers and others were not, but they were not designated workers. They included central and local government workers, staff at medical institutions, construction workers, university staff (e.g. Kyoto University Research Reactor Institute) and non-profit organization workers (e.g. Safecast, Greenpeace). The majority were from the affected area, but several hundred people came from other parts of the country or from other countries.

Individuals responding to the Fukushima Daiichi accident and the earthquake and tsunami performed a range of activities, including reactor stabilization, search and rescue, evacuation, medical treatment, environmental monitoring, decontamination, and providing support for these activities.

Specific on-site operations in the early phase included diagnosing the plant conditions and maintaining the important safety functions of criticality control, cooling and confinement. Initially, these were performed by TEPCO employees, with TEPCO contractors providing more support as time progressed. After the on-site situation had stabilized and major releases had ceased, the intermediate phase activities involved restoring enough control to the site to facilitate on-site operations, performing off-site contamination surveys and mapping, and mitigating the flow of heavily contaminated water into the sea. The recovery phase began in December 2012[17] and is continuing. Recovery activities include site restoration, cleaning heavily contaminated water in the basement of the plants, limiting the flow of contaminated groundwater to the sea, carrying out surveys to refine the off-site contamination maps, and decontaminating of residential areas off-site. These activities may lead to radiation exposure or contamination; thus, it is important that the people performing these activities have appropriate training, protection, and exposure monitoring. Tables 4.2–1 and 4.2–2, in combination, provide information on the people who performed the tasks, their level of training and the protection levels applied.

4.2.1.6. Reported doses to on-site workers

This section presents an overview of the reported doses to on-site workers during the emergency phase and, in the longer term, until December 2014. These data have been provided by TEPCO through the Japanese Government for the purposes of this technical volume. These data have not been independently validated. However, it should be noted that, in their 2013 report, UNSCEAR reviewed the methodologies used in Japan for assessing doses and undertook independent assessments of the doses for defined groups of workers, which were then compared with the reported values [5], as is described in more detail in Section 4.2.1.3.

Figure 4.2–1 shows the variation and decline in the annual effective doses (external plus internal dose) to on-site workers (TEPCO and contractors) from March 2011 to October 2014.

[17] As explained in Technical Volume 1, on 16 December 2011, the Government–TEPCO Integrated Response Office announced that the conditions for a ‘cold shutdown state’ had been achieved in Units 1–3. This officially brought the accident phase to an end, according to the criteria set by the Government of Japan at the time.

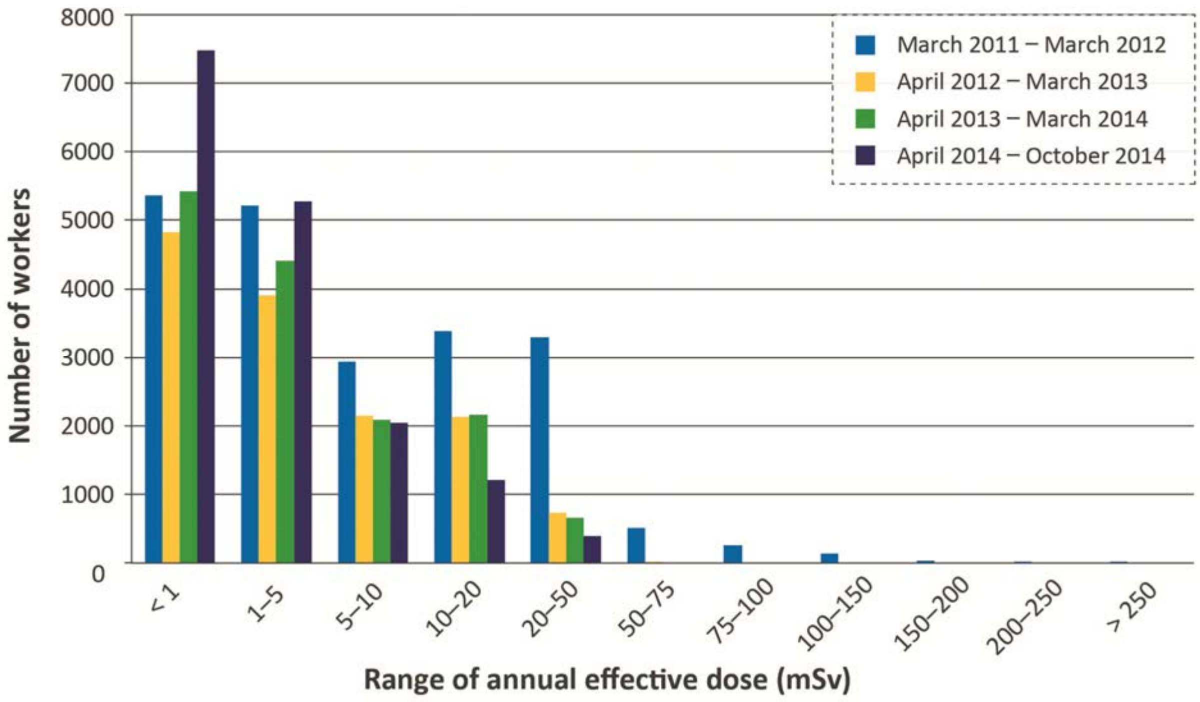

FIG. 4.2–1. The annual effective dose to workers between March 2011 and October 2014 [101].

In March 2011, 3971 workers were involved in the early on-site response, half of whom were TEPCO employees and the other half contractor employees. The number increased quickly to reach a peak workforce approaching 8000 in July 2011. Most of the additional workers were contractors who worked on a range of activities, from site restoration to technical work on the plant systems. The number of workers per month decreased gradually and remained at around 6000 for the following two years. The number increased towards the end of 2013, with a total of about 8000 workers employed at the end of March 2014 (see Fig. 4.2–2).

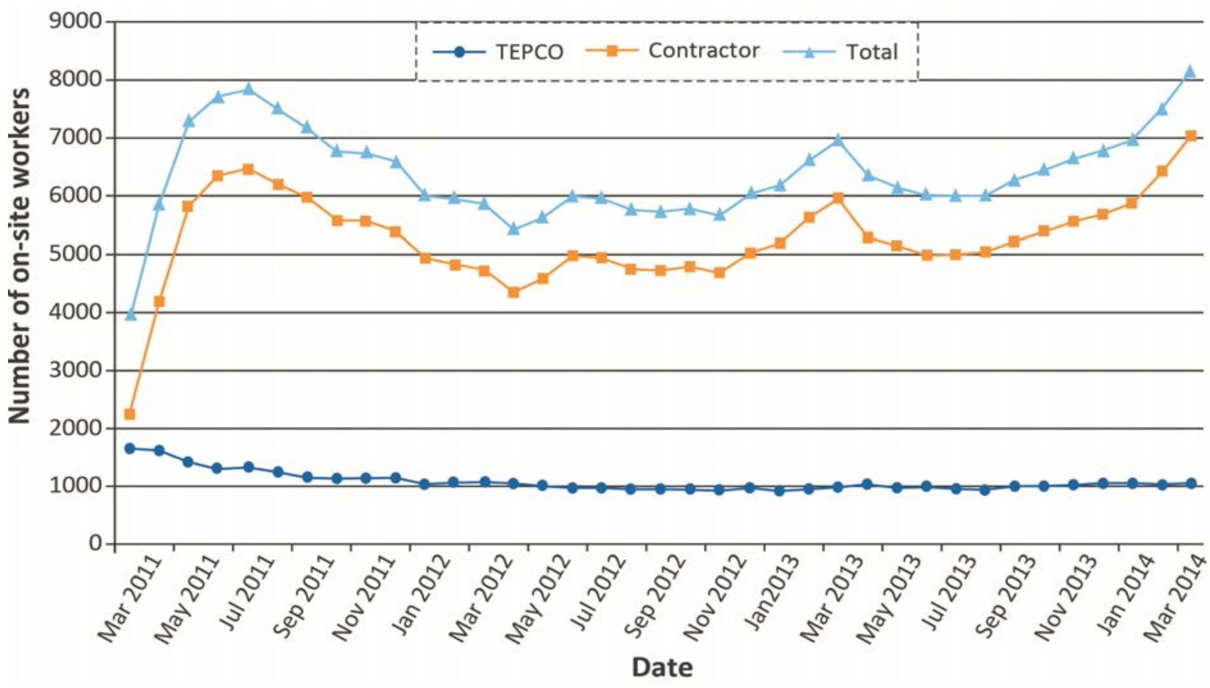

FIG. 4.2–2. The number of on-site workers after the accident [101].

On-site workers were subjected to the harshest work conditions and the highest radiation fields during the accident. Under these circumstances, six TEPCO workers exceeded the temporarily revised annual effective dose limit for emergency workers of 250 mSv, and 174 workers in total exceeded the original 100 mSv emergency dose limit during 2011. The reported external effective doses to TEPCO workers and contractors over the period March 2011–December 2014 are presented in Table 4.2–3. The reported committed effective doses from internal exposures in the period March 2011–March 2012 are presented in Table 4.2–4. In subsequent years, all reported committed effective doses were in the lowest dose category (2 mSv or less). As Table 4.2–3 indicates, no workers exceeded either of these dose limits in subsequent years and one worker exceeded an annual effective dose of 50 mSv in the period from March 2012 to December 2014.

Figure 4.2–3 illustrates the distribution of cumulative doses for the period from March 2011 to June 2014 by age groups for the on-site workers (TEPCO employees and contractors). The reference year of age is 2013. This figure illustrates that the higher doses were not reported for workers in the younger age groups. It also shows that most of the on-site workers were, and continue to be, between the ages of 30 and 60.

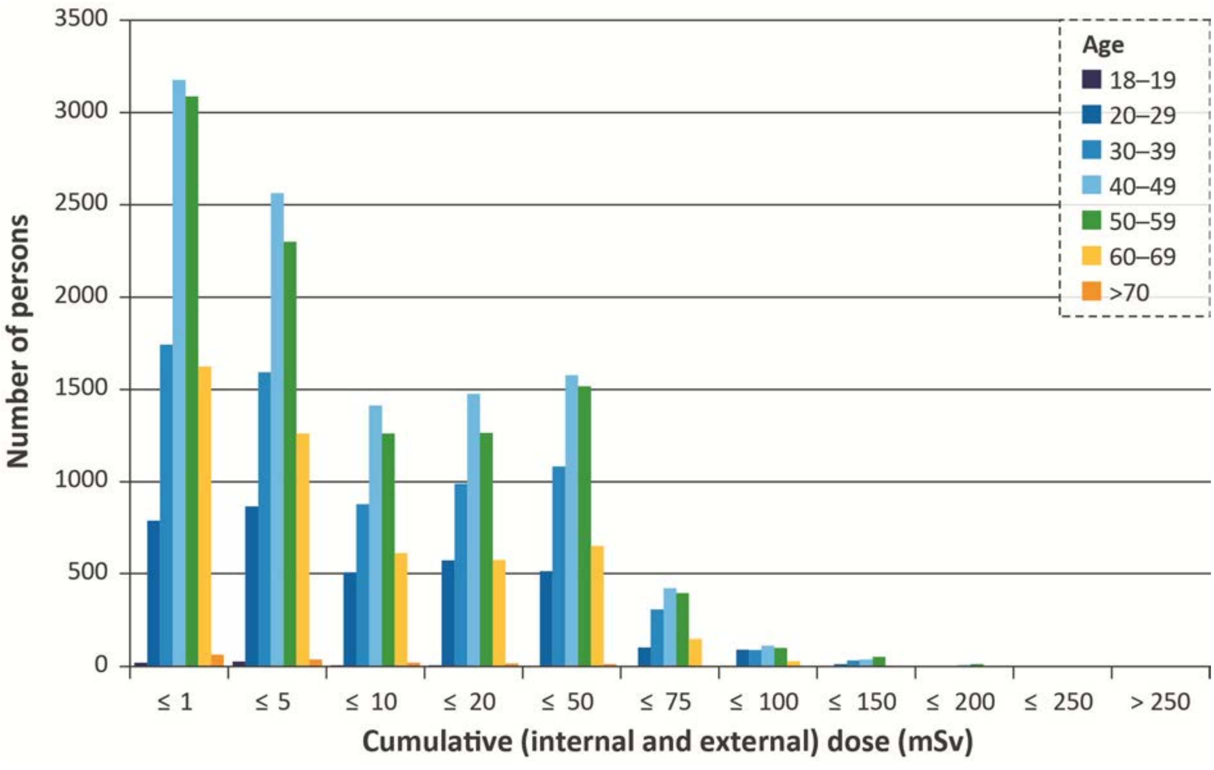

FIG. 4.2–3. Age and dose distribution of occupational exposure at the Fukushima Daiichi NPP for all workers (TEPCO employees and contractors). Cumulative (internal and external) dose from March 2011 to 30 June 2014.

TABLE 4.2–3. EFFECTIVE DOSE (EXTERNAL EXPOSURE) DISTRIBUTION TO TEPCO AND CONTRACT WORKERS (MARCH 2011–DECEMBER 2014) [189]

Classification (mSv)	March 2011–March 2012			April 2012–March 2013			April 2013–March 2014			April 2014–December 2014		
	TEPCO	Contract workers	Total	TEPCO	Contract workers	Total	TEPCO	Contract workers	Total	TEPCO	Contract workers	Total
Over 250	0	0	0	0	0	0	0	0	0	0	0	0
200–250	0	0	0	0	0	0	0	0	0	0	0	0
150–200	7	3	10	0	0	0	0	0	0	0	0	0
100–150	58	8	66	0	0	0	0	0	0	0	0	0
75–100	107	29	136	0	0	0	0	0	0	0	0	0
50–75	231	195	426	1	0	1	0	0	0	0	0	0
20–50	674	2 457	3 131	62	675	737	31	629	660	5	604	609
10–20	554	2 845	3 399	129	2 000	2 129	95	2 067	2 162	17	1 651	1 668
5–10	428	2 586	3 014	266	1 875	2 141	195	1 897	2 092	130	2 340	2 470
1–5	599	4 734	5 333	579	3 326	3 905	670	3 739	4 409	573	5 015	5 588
1 or less	758	4 852	5 610	588	4 240	4 828	701	4 722	5 423	898	6 954	7 852
Total	3 416	17 709	21 125	1 625	12 116	13 741	1 692	13 054	14 746	1 623	16 564	18 187
Max. (mSv)	188.14	199.42	199.42	54.10	43.30	54.10	41.90	41.40	41.90	24.18	39.85	39.85
Average (mSv)	19.14	9.16	10.77	4.49	5.90	5.74	3.24	5.51	5.25	1.74	4.27	4.05

TABLE 4.2–4. COMMITTED EFFECTIVE DOSE (INTERNAL EXPOSURE) DISTRIBUTION TO TEPCO AND CONTRACT WORKERS (MARCH 2011–MARCH 2012) [189]

Classification (mSv)	TEPCO	Contractor	Total
Over 250	5	0	5
200–250	1	0	1
150–200	1	0	1
100–150	7	0	7
75–100	11	11	22
50–75	27	17	44
20–50	191	125	316
10–20	399	311	710
5–10	280	411	691
2–5	223	685	908
2 or less	2 271	16 149	18 420
Total	3 416	17 709	21 125
Max. (mSv)	590.00	98.53	590.00
Average (mSv)	6.00	0.90	1.73

[a] Sum of effective dose from external radiation and the committed effective dose.

Table 4.2–5 summarizes the details relating to the doses received by the six on-site workers, out of a total of several hundred working in the elevated radiation exposure environment of the main control rooms, who exceeded emergency dose limits. In all cases, internal exposure from the intake of radionuclides was the predominant contributor to doses received. This was a consequence of challenges associated with respiratory protection during the emergency phase of the operations, notably with the availability and functioning of appropriate respiratory protection. Some issues with the fit of protective equipment were also noted [185, 188].

After the early phase of the recovery work in March 2011, workers were examined by WBCs operated by TEPCO. The six workers who had been involved in emergency work from 11 March were referred to the NIRS. The first worker visited the NIRS clinic on 30 May 2011 and the sixth worker came to NIRS on 1 July 2011, around 11 to 15 weeks after the estimated period of exposure to radionuclides. They are being followed up medically, including checking of their thyroid using ultrasound. Results at the time of writing indicate that none had developed deterministic effects such as hypothyroidism, as explained in more detail in Section 4.4.

To put these numbers in context, among the 20 most highly exposed workers, 11 received a total dose (internal and external dose) of less than 200 mSv. For this larger group, exposure from intake of radionuclides was not always the predominant contributor. This may reflect the nature of the work undertaken and the availability and functioning of proper respiratory protection in these cases [5].

TABLE 4.2–5. EXPOSURE OF SIX TEPCO EMERGENCY WORKERS IN THE MAIN CONTROL ROOMS (MCRs) OF UNITS 1–4 THAT EXCEEDED EMERGENCY DOSE LIMITS OF 250 mSv
(from Ref. [40])

Worker	Total effective dose[a]	Work period	Respiratory protection	Potassium iodide administration	Duties
A	680 mSv (590 mSv committed effective dose)	11 March–14 April	Particulate only until the Unit 1 explosion, and charcoal thereafter	No record	Plant operation and data collection in the MCR
B	650 mSv (540 mSv committed effective dose internal)	11–15 March	Particulate only until the Unit 1 explosion, and charcoal thereafter	Total:10 tablets 14 March: 2 2 May: 2 3 May: 1 12 May: 2 20 May: 2 21 May: 1	Plant operation and data collection in the MCR
C	350 mSv (240 mSv committed effective dose)	11–31 March	Charcoal	Total: 3 tablets after 14 March	Plant operation and data collection in the MCR
D	310 mSv (260 mSv committed effective dose)	11 March–15 June	Particulate only until the Unit 1 explosion, and charcoal thereafter	Total: 2 tablets after 28 March	Instrument restoration in the MCR (Units 1 and 2)
E	480 mSv (430 mSv committed effective dose)	11 March–4 June	Particulate only until the Unit 1 explosion, and charcoal thereafter	Total: 2 tablets after 21 March	Instrument restoration in the MCR (Units 1 and 2)
F	360 mSv (330 mSv committed effective dose)	11 March–7 June	Charcoal	Total: 15 tablets after 24 March	Instrument restoration in the MCR (Units 1 and 2)

[a] Rounded to 2 significant figures.

Absorbed dose to the thyroid

The reported dose results from the WBCs revealed that inhalation of ^{131}I was the predominant contributor to the internal doses of the workers at the Fukushima Daiichi NPP [190, 191]. Table 4.2–6 shows the reported internal doses to those most highly exposed group of workers, where $E50_{all}$ and $E50_{I\text{-}131}$ denote the committed effective doses from all radionuclides detected and from ^{131}I only, respectively. The fact that the values of the ratio $E50_{all}/E50_{I\text{-}131}$ are close to 1 indicates that ^{131}I is by far the most important component of the internal exposure. Absorbed doses to the thyroid can therefore be roughly estimated from the committed effective dose given in Table 4.2–6 by applying the tissue weighting factor for the thyroid of 0.05. This implies that the highest absorbed doses to the thyroid received by two emergency workers at the Fukushima Daiichi NPP are estimated to be around 10 Gy [192].

TABLE 4.2–6. COMPARISON OF COMMITTED EFFECTIVE DOSES FROM ALL RADIONUCLIDES AND FROM ^{131}I ONLY TO THE WORKERS MOST HIGHLY EXPOSED TO INTERNAL RADIATION*

Worker ID	Reported dose (mSv)		Ratio
	$E50_{all}$**	$E50_{I\text{-}131}$**	$E50_{all}/E50_{I\text{-}131}$
1	590	580	0.98
2	540	540	1.00
3	433	433	1.00
4	328	327	1.00
5	260	259	1.00
6	242	240	0.99
7	166	166	1.00
8	137	136	0.99
9	120	120	1.00
10	120	119	0.99
11	117	116	0.99
12	101	100	0.99
13	110	109	1.01
14	137	100	1.37

* This table includes information from a re-evaluation of TEPCO worker doses.
** $E50_{all}$: committed effective dose from all nuclides detected; $E50_{I\text{-}131}$: committed effective dose from I-131 only.

The reported total absorbed doses to the thyroid for 19 561 workers who worked on the Fukushima Daiichi NPP from 11 March–31 December 2011 are summarized in Table 4.2–7. The majority of these workers (17 804) were estimated to have received absorbed doses to the thyroid of less than 100 mGy, including those for whom measurement results were below the limit of detection. Some 1757 workers received thyroid equivalent doses above 100 mGy, among whom 17 workers were considered to have exceeded an absorbed dose to the thyroid of 2000 mGy (equivalent to 100 mSv effective dose if the contribution from other radionuclides and organs is not included), while two workers received thyroid equivalent doses in excess of 12 000 mGy [101]. All of these workers were performing emergency activities related to reactor stabilization operations [102]. The higher equivalent doses were a consequence of intake; 75 workers were estimated to have received an external dose to the thyroid exceeding 100 mSv (and in the range of 100–200 mSv).

TABLE 4.2–7. DISTRIBUTION OF TOTAL ABSORBED DOSE TO THE THYROID FOR WORKERS FROM 11 MARCH 2011 TO 31 DECEMBER 2011 [101][a]

Classification of dose (D) (mGy/y)	Internal dose		External dose		Total[a]	
	TEPCO employees	Contract workers	TEPCO employees	Contract workers	TEPCO employees	Contract workers
15 000 < D	0	0	0	0	0	0
10 000 < D ≤ 15 000	2	0	0	0	2	0
2 000 < D ≤ 10 000	13	0	0	0	15	0
1 000 < D ≤ 2 000	39	13	0	0	44	13
500 < D ≤ 1 000	109	64	0	0	129	67
200 < D ≤ 500	233	260	0	0	286	305
100 < D ≤ 200	338	383	64	11	416	480
≤100	2 549	15 558	3 219	16 267	2 391	15 413
Total	3 283	16 278	3 283	16 278	3 283	16 278

[a] Total dose (internal + external)[18].

TEPCO analysed the contributions of ^{131}I, ^{132}Te/^{132}I, ^{137}Cs and ^{134}Cs to effective dose [186]. The contribution from ^{132}Te/^{132}I was considered by TEPCO to be negligible, and the contribution from ^{133}I was not considered [193, 194]. UNSCEAR estimated that the additional contribution to effective dose from the intake of short lived radionuclides (such as ^{132}Te and ^{133}I, "may have been in the order of 20% relative to the contribution of ^{131}I" [5]. There are thus uncertainties associated with the dose contribution from short lived radionuclides.

4.2.1.7. Dose verification and re-evaluation

There are several uncertainties associated with the estimates of the workers' radiation doses due to internal exposure, particularly the thyroid equivalent doses. There was some time lag in undertaking thyroid measurements owing to the emergency operations and conditions. In addition, the estimated doses are dependent on the scenario that was assumed for the incorporation of radionuclides into the body (e.g. the timing). MHLW has since investigated the significant discrepancies between the internal dose assessments of emergency workers made by TEPCO and those reported by primary contractors. MHLW conducted a re-evaluation of internal dose assessments from March to June 2013 and concluded that some of the internal dose assessments of committed doses of 479 workers had been adjusted [193, 194]. In addition, TEPCO voluntarily re-evaluated the doses of hundreds of employees [195].

UNSCEAR undertook an independent evaluation of the 12 TEPCO employees with the highest reported internal exposure and a sample of workers with lower internal exposures who were randomly selected. In those cases where it had been possible to measure ^{131}I in the thyroid, the internal doses estimated by UNSCEAR were in reasonable agreement with those reported by TEPCO. For example, the largest absorbed dose to the thyroid was estimated to be 12 Gy by TEPCO, while the UNSCEAR independent assessments by different institutions ranged from 9.7 to 12.6 Gy, with the variation

[18] The thyroid equivalent dose was evaluated as follows: 20 × internal effective dose (^{131}I) + internal effective dose (^{134}Cs) + internal effective dose (^{137}Cs) + external effective dose. When the internal radionuclides were not identified, the thyroid equivalent dose was assumed to be equivalent to 20 × internal effective dose + external effective dose.

depending on the assumptions made, particularly the timing of the main intakes of ^{131}I. However, for many of the other workers considered (TEPCO and contract workers), ^{131}I was not detected in the thyroid owing to the time between exposure and the measurement and resulting radioactive decay. UNSCEAR identified the uncertainties associated with using a ratio approach to estimate doses to the thyroid in these cases, with the possibility that the resulting total effective dose “could, in extreme, have been underestimated by a factor of up to about 30, or overestimated by a factor of up to about 5” [5]. The reliability of assessments for those workers where ^{131}I was not detected in the body could not be confirmed, as it was considered that the two methods used did not provide a reliable estimate of the true intake and there was a significant uncertainty associated with the results, including that due to the influence of a high level of background doses in early whole body measurements. The delay in starting WBC or thyroid monitoring also meant that it would not have been possible to detect short lived radionuclides such as ^{132}Te and ^{132}I; the additional contribution to the effective dose from these radionuclides may have been of the order of 20%, but there could be large variations between individuals [5].

Since March 2014, MHLW has closely examined data for 6245 emergency workers, excluding those covered by the previous re-evaluation, from a total of 7529 emergency workers engaged in the period March–April 2011. This examination revealed that the data for 1536 emergency workers may have been obtained by methods other than the standard assessment methods. TEPCO and its primary contractors have re-evaluated these data and the committed effective doses for 142 emergency workers were revised accordingly [196].

Organizations in Japan are working to reduce further the existing uncertainties in the occupational dose assessment, specifically in the internal exposure assessments. In its re-evaluation of internal dose, MHLW recognized that, given the uncertainty of the chemical form of ^{132}Te, the contribution from ^{132}Te to the committed effective dose may be up to approximately 10% of the contribution from ^{131}I. However, given the conservative assumption of the intake date as the first work day and the use of the acute intake scenario, this contribution from ^{132}Te to the committed effective dose contribution was assumed to be within the margin of safety of conservative estimation [194].

4.2.1.8. Statistical analysis of recorded dose information

Further analysis has been carried out of the data available on worker doses as part of this study. In particular, log-normal distributions have been fitted for the different sets of data. The approach adopted is described briefly below. The results of this analysis are then presented.

Analysis approach using log-normal distribution

When a population is exposed to radiation, it is important to estimate the ‘dose distribution’, namely how many people are exposed to a certain amount of radiation. The whole range of the data can be binned by grouping data together in intervals (or bins) covering a specific range of doses. The approach used is described in more detail in Box 4.1–1 in Section 4.1.4. As indicated earlier, the probability density illustrates the probability that a member of the exposed population will incur a certain dose. If the curve is approximately bell shaped, it approximates the normal distribution.

The analysis of dose distribution in the exposed population can be taken further by summing the tops of the bars as the dose increases and then representing the resulting partial summations as a function of the dose. The ensuing function is termed cumulative probability because it represents a summation of probabilities that a certain dose incurs as a function of the dose. Figure 4.2–4 illustrates, in orange, a probability density function, f(x), and, in blue, the corresponding cumulative probability function, F(x), both versus variable values of dose, x. It can be observed that, as the dose, x, increases, the cumulative probability function approaches a value of 1, which corresponds to a probability of 100%, because it is certain that above a given doseall people will incur a dose lower than such a value.

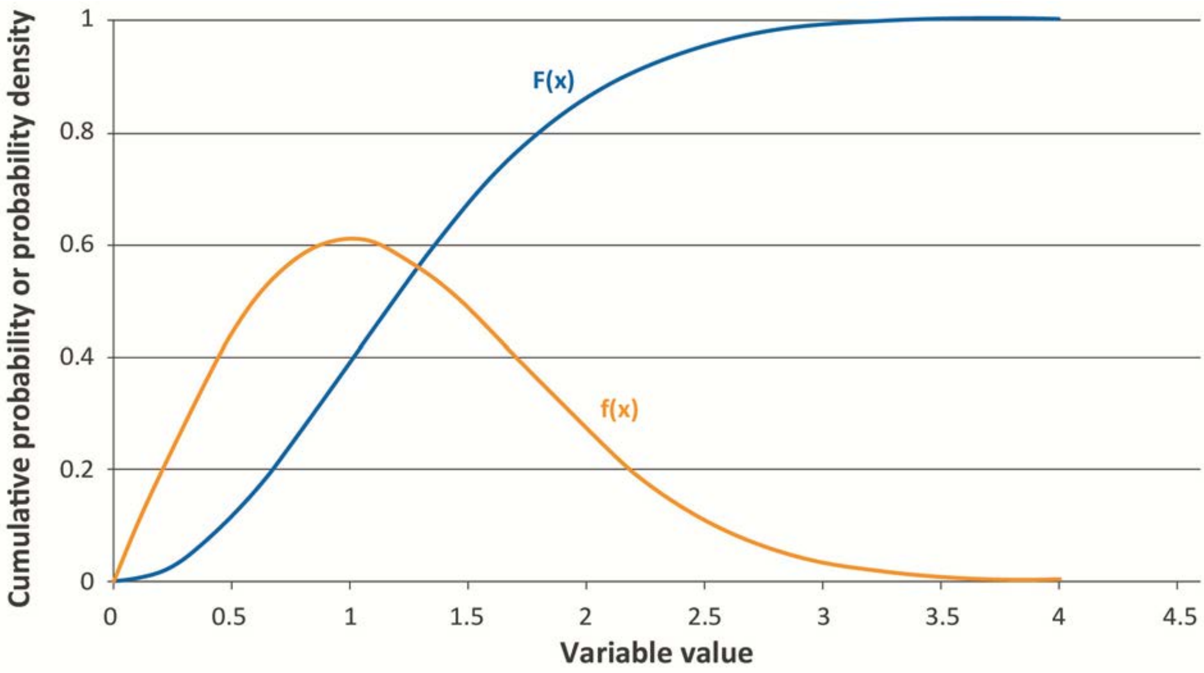

FIG. 4.2–4. Illustration of the relationship between the probability density function (orange) and the cumulative probability function (blue).

There is a large quantity of data at the international level on how the doses incurred by exposed populations are statistically distributed among their members, namely on the more common probability density and cumulative probability functions. This experience has been applied to the statistical analysis of dose data of exposed people as a result of the accident at the Fukushima Daiichi NPP. The relevant previous knowledge is from the UNSCEAR dose estimates and also from the analyses of public doses from the Chernobyl accident (which were performed by international organizations, including the IAEA). This experience has shown that, when the exposures are reasonably uniform, the distribution of doses follows a log-normal function.

Many radiation dose distributions exhibit a log-normal distribution, which can be identified as a straight line in a cumulative probability distribution. These log-normal graphs show the median value of the doses, along with an understanding of their distribution around the median such as the doses associated with a cumulative probability of 95% and 5%.

Data provided by the Japanese authorities were analysed following this approach and were often a reasonable fit to a log-normal distribution. There were, however, some issues with assigning log-normal distributions, which are summarized in Box 4.2–1.

Box 4.2–1. Issues with log-normal distribution of the data

While the binning of datasets usually results in a relatively smooth distribution, for some datasets this was not the case. For these datasets, the bin distributions appear distorted, usually owing to the accumulation of a large amount of data in a particular bin. For instance, in some datasets all the data near the detection limit were accumulated in one (initial) bin without discrimination while higher data were properly discriminated. In some of the statistical analyses, the decision was made to distribute this misleadingly accumulated data according to a probability density distribution derived from the actual data (using its relevant statistical values, such as mean and standard deviation) and, on this basis, building up a conjectural, randomly created, distribution including a larger number of bins. The result is a conceptual histogram which is tailored to the statistical values of the real data and to which a smooth density probability curve can be fitted. This idealized probability density function, which illustrates how the distribution would look if the data were sufficiently detailed and discriminated, is then presented together with the cumulative probability function in the relevant figures of the report. In some cases, the actual distribution of bins is also presented for comparison.

While exact adherence to the log-normal distribution may be not observable across the full range of data, explanations of the deviations, in particular, deviations from the straight line in the cumulative probability, can usually be elaborated, and they form an important part of the analysis. A cause of deviation is uncertainty originating both in the measurements themselves and in the statistical nature of the sampling process. A particular problem in the analyses of incurred doses, which is typical of accident situations, was the likely inhomogeneous nature of the cohorts of exposed people. Other causes included constrained distribution in the data; for instance, at high doses, there might be higher than expected cumulative probability (namely, fewer people than expected are incurring high dose) with the most likely explanation that dose restrictions have been applied successfully. If the cumulative probability is higher than expected in the low dose range (namely, more people than expected are incurring low doses), a plausible explanation is that a dose equal to the detection limit has been (misleadingly) assigned to all people with doses below these levels. Conversely, if the cumulative probability is lower than expected, it might mean that a zero dose has been assigned (again misleadingly) to all those with doses below the detection level. Sometimes deviations from the straight line became ostensible due to the high level of inconsistency in the local data; for example, when two different population groups were mixed, such as evacuees with residents that remained in the area, there may be evidence of the change in the slope of the cumulative probability distribution, with each sector reflecting the doses received in each area. Sometimes the collection of information was protracted and this distorted the data, for example, owing to radioactive decay over time. Deviations from linearity in a log-normal cumulative probability plot may be used to make plausible inferences about the underlying data.

Analysis of worker doses

Figures 4.2–5 to 4.2–7 show the normalized idealized probability density and cumulative probability plots for different doses to workers at the Fukushima Daiichi NPP [101].

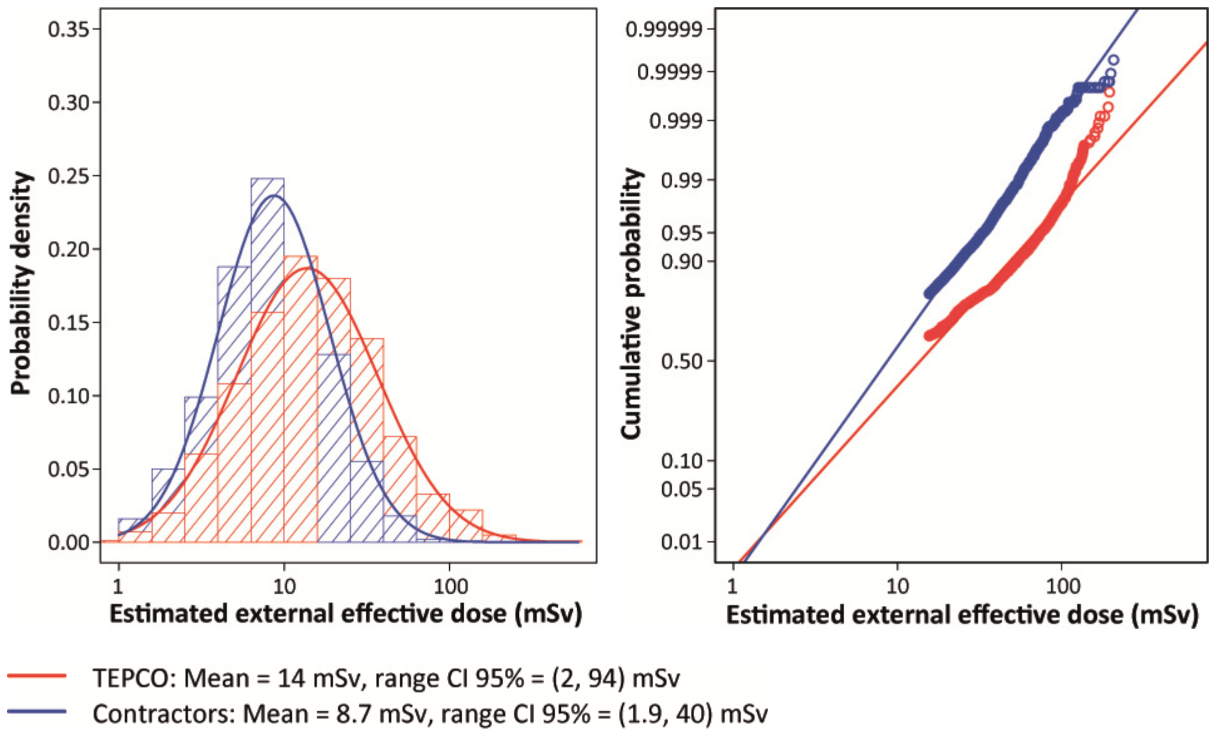

FIG. 4.2–5. Normalized idealized probability density distribution and cumulative probability distribution of personal dose equivalent monitored for workers from TEPCO and contracted workers for 2011 [101].[19]

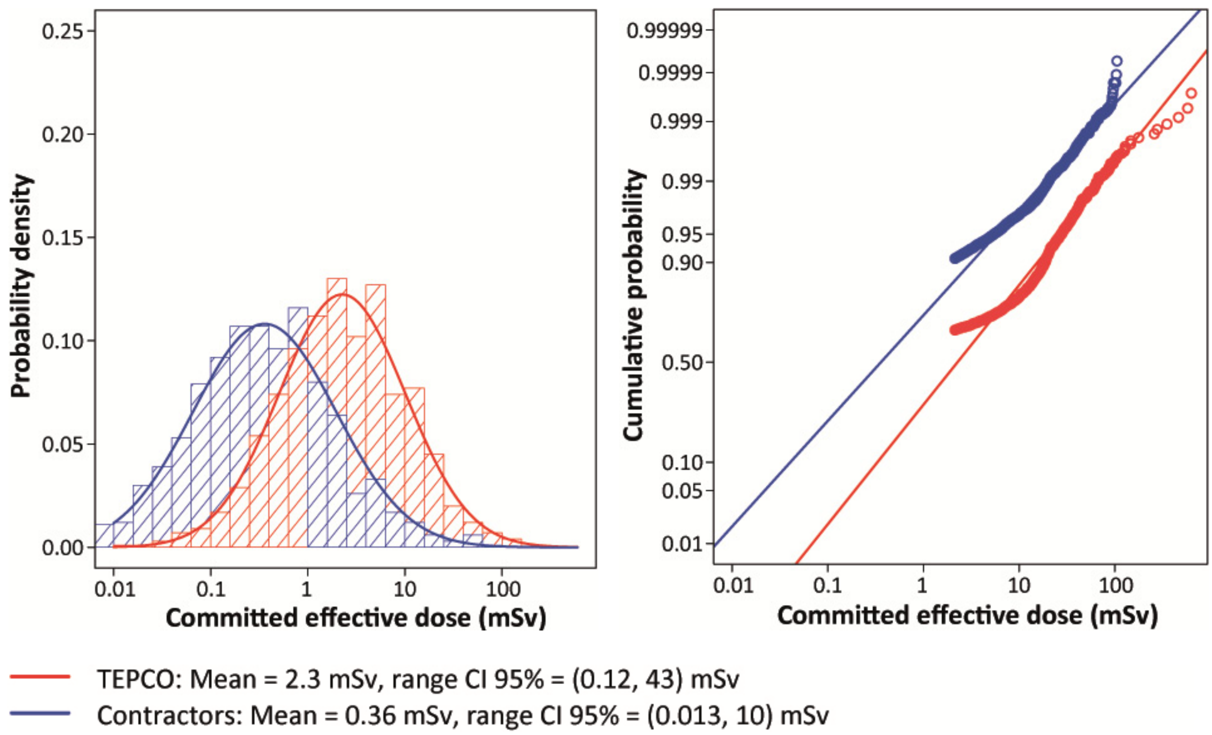

FIG. 4.2–6. Normalized idealized probability density distribution and cumulative probability distribution of committed effective dose from internal exposure [101].

[19] The effective doses from external exposure are estimated on the basis of personal dose equivalent, Hp(10), factually monitored in the exposed population, assuming that Hp(10) may be used as an approximation of the effective dose from external exposure to penetrating radiation.

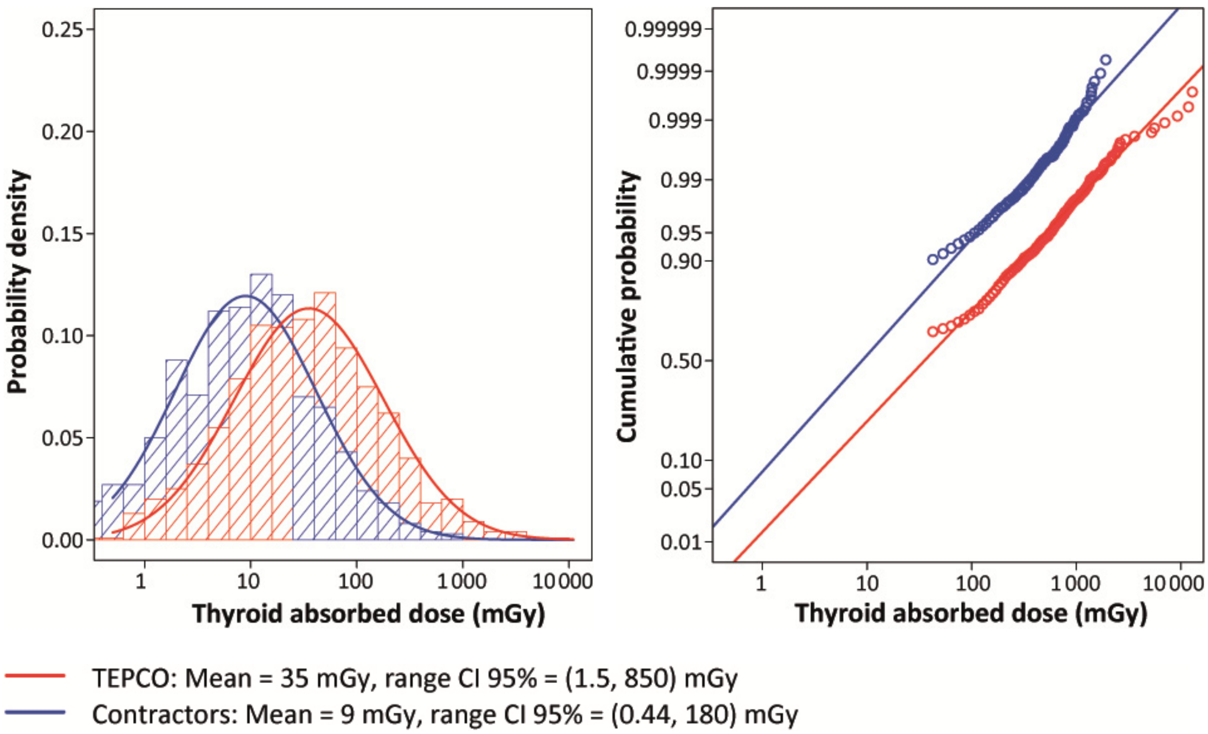

FIG. 4.2–7. Normalized idealized probability density distribution and cumulative probability distribution of thyroid absorbed dose [101].

These statistical analyses support the reported levels of radiation doses received by on-site workers presented above. Cumulative probability distributions for internal and external doses in subsequent years are presented in Appendix II.

4.2.1.9. On-site exposure of firefighters

From 18 to 25 March 2011, 260 firefighters engaged in on-site operations associated with cooling the spent fuel pools. The Fire and Disaster Management Agency (FDMA) has made available information on the range of doses received by this group for the purposes of this report. External doses received by this group were generally below 5 mSv, as indicated in Fig. 4.2–8.

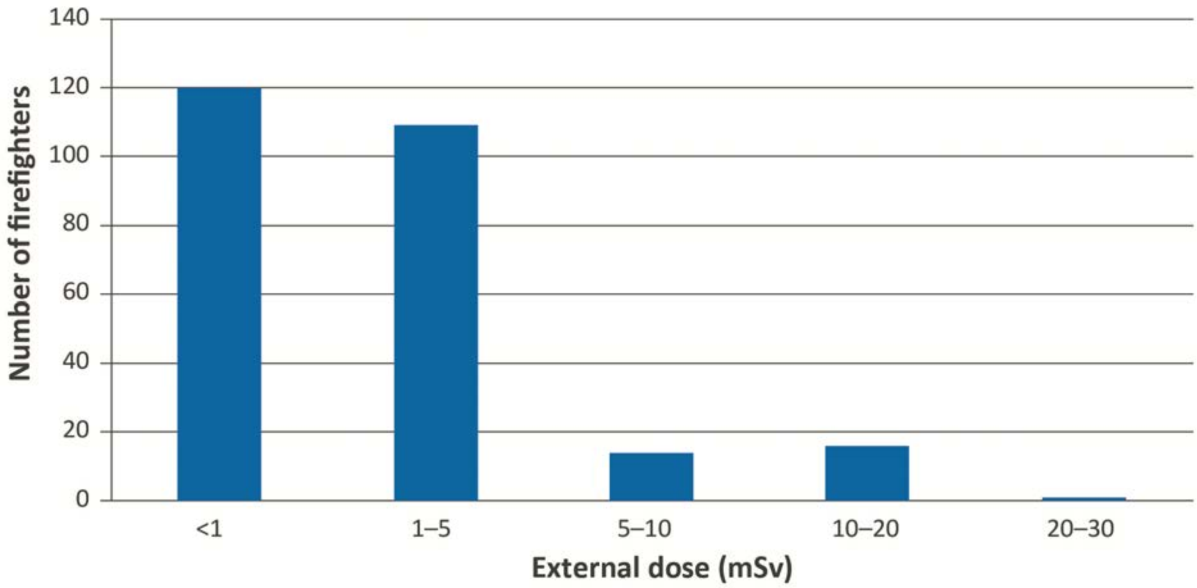

FIG. 4.2–8. Reported external doses of firefighters involved in on-site emergency activities from 18 to 25 March 2011 [197].

Of this group, 259 agreed to provide their internal exposure data for this report. The committed effective dose due to internal exposure was less than 1 mSv in all cases. The effective doses received by the firefighters working on-site were thus significantly lower than the dose limit values presented above.

All the firefighters working on-site during this period wore personal protection equipment, including a full face mask, gloves and fire boots with shoe covers. In making their assessment of doses to the skin and the lens of the eye, FDMA did not take account of these protective measures. The estimates presented in Fig. 4.2–9 are therefore likely to be conservative. These dose estimates were based on the personal dosimeter readings, modified for the depth of the skin and the lens of the eye and the relative height of the eye and the most exposed area of skin above the ground [197].[20] UNSCEAR considered that there was insufficient information on beta irradiation to make an assessment of doses to the lenses of the eyes of workers [5].

[20] Heights and depths assumed: Dosimeter height, 130 cm; lens of the eye, 160 cm, and skin 50 cm above the ground (above the height of boots). The depth assumptions: dosimeter 10 mm, lens 3 mm, skin 0.07 mm dose. The modification factors for gamma and beta dose equivalent to the lens of the eye applied were 0.1 and 0.95, respectively. For skin, the modification factors for gamma and beta dose equivalent were 10 and 1.2, respectively.

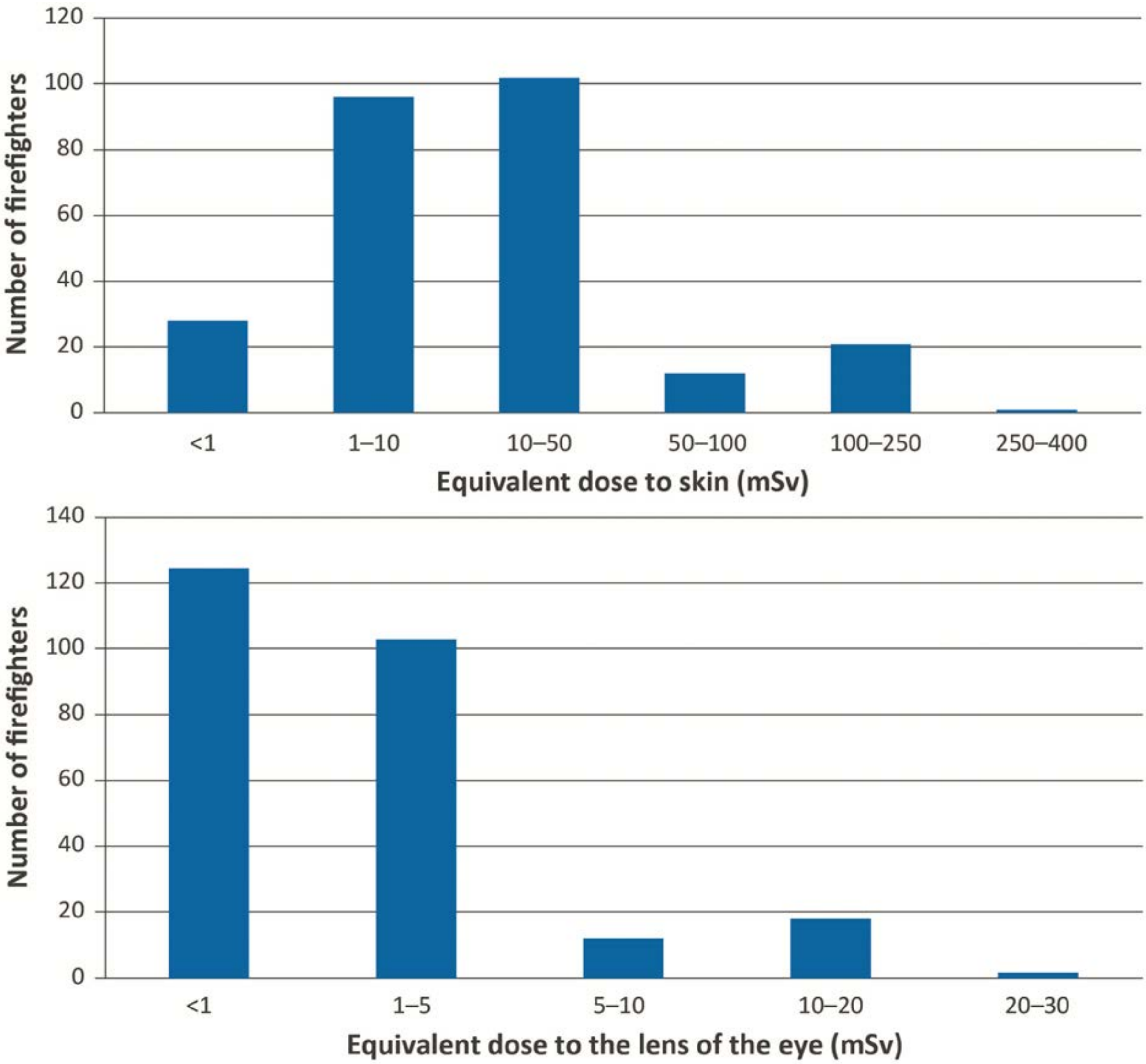

FIG. 4.2–9. Estimated equivalent doses to the skin and the lens of the eye of firefighters involved in on-site emergency activities from 18 to 25 March 2011 [197].

Japanese regulations concerning the prevention of radiation hazards due to ionizing radiation stipulate that exposure limits of workers to the skin and eye lens are 500 mSv/year and 150 mSv/year, respectively. However, in the case of an emergency, those limits are raised to 1 Sv/year for skin and 300 mSv for the lens of the eye. It can be seen from the data above that the reported doses received were significantly below these values [198].

4.2.1.10. On-site exposures of police and SDF personnel

A total of 13 police officers were involved in on-site operations related to the cooling of the reactor. The cumulative doses received by members of this group in the period until 17 March 2011 were less than 10 mSv.

UNSCEAR additionally presented reported doses to the 147 members of the SDF personnel, provided by the Government of Japan. No members of this group received an effective dose greater than 100 mSv, and 132 of this group received doses of less than 10 mSv [5].

4.2.1.11. Off-site workers

As explained previously, many organizations participated in a variety of activities during the immediate response. However, these activities were not considered to be emergency work, so dose limits for emergency work were not applicable to these activities. Personnel of some of these organizations were highly trained to work in radiation environments and operated under higher dose guidelines. Some workers were considered volunteers and operated under dose guidelines established for the public. Although different dose guidelines governed their activities, the workers remained well within the applicable limits, which were set as internal rules corresponding to the dose limits for radiation workers, which are prescribed in law.

As mentioned earlier, a number of police officers were also involved in off-site response activities in Fukushima Prefecture during 2011. A total of 290 000 person-days were spent in Fukushima Prefecture on such work in the period until 31 December 2011. The maximum external dose reported for this group was less than 5 mSv in the period up to 30 June 2011. During the period 21 July–23 August 2011, 33 police officers were monitored by whole body counting and the maximum committed effective dose recorded was around 10 μSv [199].

Information on the effective doses received by 8458 SDF personnel working off-site was provided by the Government to Japan to UNSCEAR. Of this number, five received doses in excess of 10 mSv, within a range of 10–20 mSv [5].

Almost 99% of the approximately 350 officials of Fukushima Prefecture involved in aiding various emergency measures for whom dose data are available received a dose of less than 1 mSv. The maximum dose recorded for this group was around 2.3 mSv [199].

Among the United States personnel who assisted or performed environmental monitoring in the Fukushima area, the maximum effective dose received was 0.12 mSv for the US military personnel [200] and around 0.07 mSv for personnel from the DOE. A total of 21 IAEA staff members participated in environmental monitoring and the provision of advice on nuclear safety and food restrictions. One member of this group received an effective dose of around 2.5 mSv from external exposure, while the mean dose was around 0.5 mSv.

4.2.2. Public exposures

In this section, the main routes by which people are exposed to radiation following an accidental release of radionuclides to the environment are reviewed. In addition, the estimated effective doses and thyroid equivalent doses incurred by adults and children in Fukushima and neighbouring prefectures are analysed.

4.2.2.1. Background and exposure pathways

The main exposure pathways relevant to a nuclear accident, such as that at the Fukushima Daiichi NPP, are illustrated in Fig. 4.2–10.

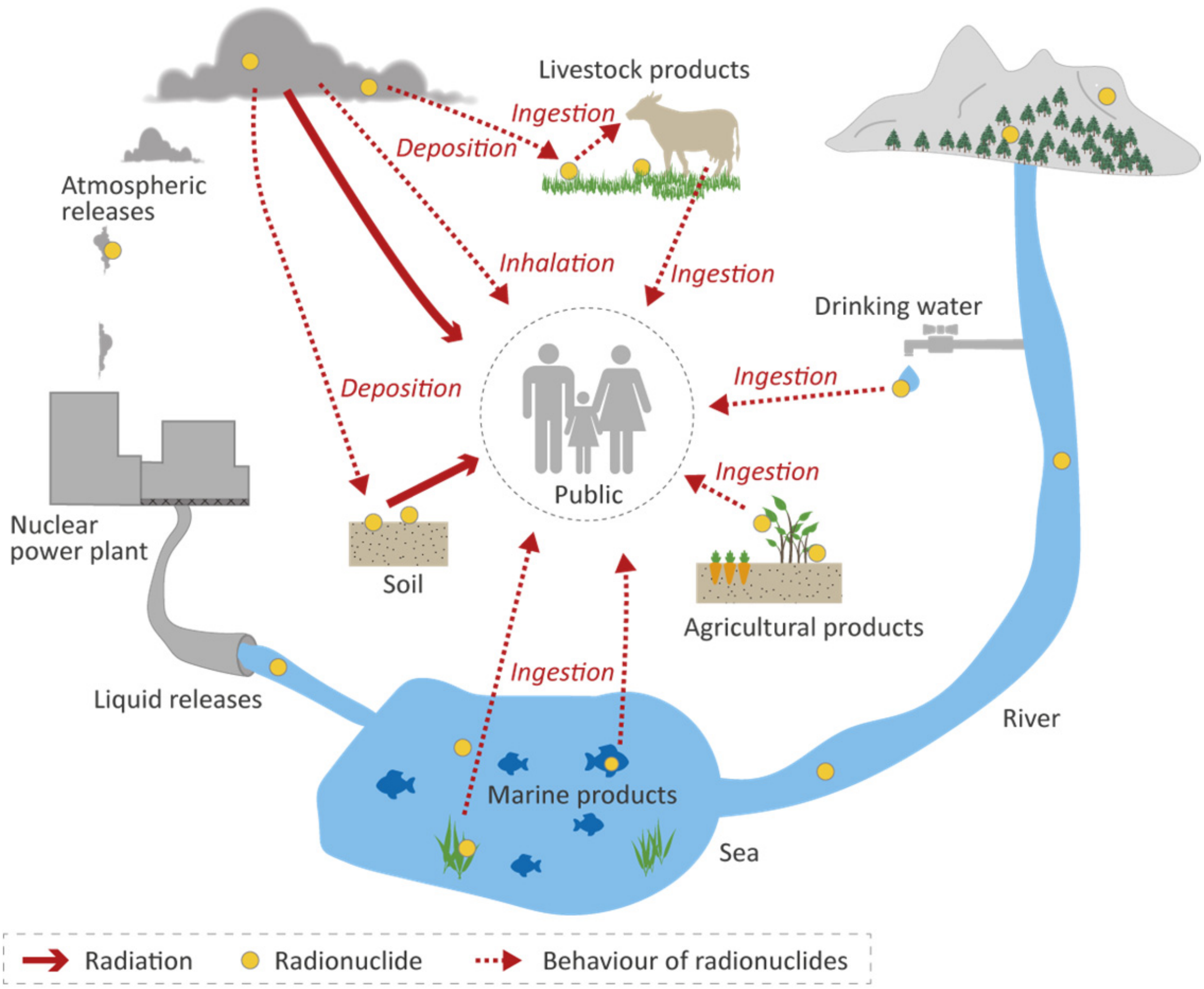

FIG. 4.2–10. Main exposure pathways relevant to a nuclear accident.

The most important exposure pathways are:

— External exposure from immersion in elevated concentrations of radioactive material in the air;
— External exposure from radionuclides deposited on the ground following the passage of radioactive material in the air;
— Internal exposure from inhalation of radioactive material in the air;
— Internal exposure from ingestion of radionuclides in food and drink.

The assessment of doses to the public from each of these main exposure pathways is explained in the following sections.

The focus of this report has been on gathering and interpreting data that have become available since the publication of previous assessments by WHO and UNSCEAR [5, 173]. The assessments by WHO and UNSCEAR were undertaken using the progressively more extensive databases that have become available (covering the time until September 2011 and March 2012, respectively).

Where possible, dose estimates in the present report have been based on direct measurements of people: measurements of external exposure rate, measurements of radionuclides incorporated in people (by whole body counting) and assessment of ^{131}I in the thyroid (by measurements of the dose rate close to the thyroid). This includes newly obtained data provided to the IAEA for this report by

Japanese Government institutions, and publicly available reports and sources collected up to December 2014.[21]

The general approach is to summarize doses by appropriate locations, for example, for the municipality in which residents were living before the accident, and by appropriate time periods. Where possible, these results have been compared with those in the most recent and comprehensive assessment, undertaken by UNSCEAR [5]. For ease of reference, background information on the two major international assessments of doses to the public arising from the Fukushima Daiichi accident is presented before further analysis of dose information.

Previous international assessment of dose to the public from the Fukushima Daiichi accident

WHO assessment of public exposures

WHO published two reports on the Fukushima Daiichi accident: Preliminary Dose Estimation from the Nuclear Accident after the 2011 Great East Japan Earthquake and Tsunami, in 2012; and Health Risk Assessment from the Nuclear Accident after the 2011 Great East Japan Earthquake and Tsunami, in 2013 [173, 201]. These reported estimated potential health consequences of human exposure to radiation during the first year after the Fukushima Daiichi accident. The assessment covered infants, children and adults living in Fukushima Prefecture, nearby prefectures, the rest of Japan, neighbouring countries and the rest of the world.

To the extent possible, measurements of radioactive material in the environment (e.g. levels of different radionuclides on the ground) and activity concentrations in foods were used. The estimated doses relied on measurements available in the first few months after the accident (until mid-September 2011). When direct monitoring data were not available, estimates based on simulations were used as input for dose models. The approach used for assessing doses within Fukushima Prefecture is summarized briefly below.

Surface activity densities were the environmental measurement data used as the primary input to the assessment, and gamma dose rates were also available from a wide range of monitoring locations in Fukushima Prefecture. External doses from the radioactive cloud were reconstructed by modelling, because measured dose rates were not available for sufficient locations for the first few days after the release; ground deposition levels were therefore converted to time integrated activity concentrations in air. These values were also used for assessing intakes by inhalation. External effective and thyroid doses from radionuclides deposited on the ground were based on measured ground deposition levels (surface activity densities).

The assessment of doses resulting from the ingestion of food containing radionuclides requires estimates of activity concentrations in food as a function of time, together with levels of consumption of the various foods for different age groups. Several scenarios were used in this assessment to estimate the dose from food consumed during the first year. WHO assumed that the measured activity concentrations in each food category were representative of the entire food market for Fukushima and neighbouring prefectures. Analytical results for radionuclides of iodine and caesium reported to be below the limit of detection were assumed to be 10 Bq/kg, except for ^{131}I, which was assumed to be close to zero after four months. Three scenarios were considered for the population living in Fukushima Prefecture, using median, mean and 90th percentiles of the distribution of concentrations in food in the prefecture for each of the relevant food categories.

[21] In some cases, notably for the results of the Fukushima Health Management Survey, information up to May 2015 was available and was included in this volume.

Given the limited information available at the time, it was acknowledged that the assessment contained a number of conservative assumptions, for example radioactive cloud composition and dispersion, time spent indoors/outdoors, consumption levels and the implementation of protective measures, leading to an overestimate of doses. The committed effective doses during the first year for individuals in two locations (Namie Town and Iitate Village) were estimated to be within a dose band of 10–50 mSv; in other areas of Fukushima Prefecture, doses in the range 1–10 mSv were estimated. Within Fukushima Prefecture, external exposure from deposited radionuclides was found to be the major contributor to the effective dose.

The typical thyroid doses in most locations in Fukushima Prefecture were estimated to be within a dose band of 10–100 mSv. In one particular location, the assessment indicated that the characteristic thyroid dose to one year old infants would be within a dose band of between 100 and 200 mSv, with the inhalation pathway being the main contributor to the dose. Thyroid doses in the rest of Japan were within a dose band of 1–10 mSv, and in the rest of the world, doses were estimated to be below 0.01 mSv and usually far below this level.

The WHO health risk assessment concluded that no discernible increase in health risks from the Fukushima Daiichi accident was to be expected outside Japan [201]. With respect to Japanese residents, the WHO assessment estimated that the lifetime risk for some cancers might be somewhat higher than baseline rates in certain age and sex groups that were in the areas most affected. This was based on assessment models that were derived from previous radiation events and experience, which did not match the pattern of exposure seen following the Fukushima Daiichi accident, owing to the generally conservative approach taken in the WHO preliminary dose estimation [173].[22]

UNSCEAR assessment of public exposure

The UNSCEAR evaluation of exposure and dose for the public [5] made use of a wide range of measurements of radionuclides in the environment, together with the necessary modelling to link these measurements to the doses received. Some limited measurements of radionuclides in people were also used for comparison purposes. UNSCEAR assessed doses to various groups of people living in different regions of Japan and also provided exposure information for other countries. Three different age groups were considered: one year old children, ten year old children and adults. Consideration was also given to doses to fetuses and breast-fed infants, but these were not explicitly evaluated as they would be similar to the doses to the other age groups. The four groups of people considered in Japan were: members of the public who were evacuated in the days and months after the accident; members of the public living in the non-evacuated districts of Fukushima Prefecture; members of the public living in Miyagi, Gunma, Tochigi, Ibaraki, Chiba and Iwate prefectures; and members of the public living in the remaining prefectures of Japan. The emphasis was on estimating the exposures of individuals who were representative of the average of the population, assuming typical habits such as average food intakes. Radiation doses were estimated for the first year following the accidental releases from the Fukushima Daiichi NPP and also integrated over the period of the first ten years. Committed doses were assessed for three age groups by integrating doses from incorporated radionuclides to age 80. Effective doses were estimated, together with absorbed doses to the thyroid and some other organs, notably the breast and the red bone marrow. The UNSCEAR report also described the variability in radiation doses for the public together with the main uncertainties in the assessment.

In later sections of this volume, the different aspects of assessing doses to members of the public are described, and a brief overview of the UNSCEAR assessment is given, together with further analysis

[22] Given the limited information available at the time, the assessment contained a number of conservative assumptions. WHO indicated that "All efforts were made to avoid any underestimation of doses" and that "some possible dose overestimation may have occurred" [173].

based on direct measurements of people carried out for the present volume. The key results of the UNSCEAR dose assessment of the public are reproduced in Annex V to provide some overall context for comparison with personal dosimetry information presented later in this volume.

The UNSCEAR report also provided estimated doses to people who were evacuated, taking into account the doses that were received before and during the evacuation and the doses at the evacuation destination from all exposure pathways to obtain estimated settlement averaged effective doses and absorbed doses to the thyroid for the first year following the accident. The results are presented in detail in Annex V and indicate that, in the evacuated areas with the highest average estimates, the effective dose estimated to have been received by adults before and during the evacuation was, on average, less than 10 mSv, and about half of that level for those evacuated early. Adults living in Fukushima City were estimated to have received, on average, an effective dose of about 4 mSv in the first year following the accident; estimated effective doses to one year old infants were about twice as high. Those living in other areas within Fukushima Prefecture and in neighbouring prefectures were estimated to have received comparable or lower effective doses; even lower effective doses were estimated to have been received elsewhere in Japan. However, UNSCEAR emphasized that there was considerable variation between individuals around this value, depending on their location and the type of food they had consumed.

Doses from releases of radionuclides to the marine environment were low due to the restrictions on fishing and access to the shore-line near the Fukushima Daiichi NPP. For the first year, marine foods were included in the estimated ingestion doses, but made a minor contribution [5]. In subsequent years, the doses from radionuclides in the marine environment were estimated to be very low (less than 1 μSv/y), and they were lower than those from radionuclides in the terrestrial environment.

Doses were also estimated by UNSCEAR for exposure over future years, which found that generally the district average or prefecture average effective doses integrated over ten years were likely to be up to twice the first year's effective dose, while the effective dose integrated to age 80 was likely to be three times higher than the first year's effective dose. UNSCEAR estimated the average lifetime effective doses to adults in Fukushima Prefecture to be of the order of 10 mSv or less [5]. However, this estimation did not make any allowance for the effects of remediation, and it was therefore recognized that in many cases the actual doses could be lower. The effectiveness of remediation is discussed further in Technical Volume 5. UNSCEAR also considered doses to other countries and concluded that the average effective doses to populations living outside Japan were less than 0.01 mSv in the first year.

Approach adopted in this assessment

As noted, the focus of this assessment was to gather further information to assess radiation doses for the public using personal dosimetry data, where available. These values were then compared with those estimated by UNSCEAR, where possible. To do this, a distinction was made between external and internal radiation exposure pathways (see Fig. 4.2–10). The emphasis was on the doses to those people who were evacuated following the start of the accident at the Fukushima Daiichi NPP and those living in the areas with elevated levels of radionuclides in Fukushima and other prefectures.

External exposures of people can be assessed directly by the use of personal dosimeters[23] or from measurements of external dose rate in the environment (using in situ dose rate meters or instruments mounted on vehicles or aircraft). In the latter cases, doses need to be reconstructed by accounting for an individual's location and movements. Following the accident at the Fukushima Daiichi NPP, a

[23] Personal dosimeters are those worn by individuals and which allow the external dose received during the period they are worn to be measured.

large number of residents were evacuated and therefore moved, sometimes a number of times, to different locations, which complicates assessments of external doses. In the first few months following the accident, personal dosimeter results were not available for the public, and therefore an approach based on environmental measurements had to be used.

A questionnaire, distributed in the context of the Fukushima Health Management Survey (FHMS) (see Section 4.4.2.1), provided information that is relevant here [202]. Around 2 056 000 residents and visitors in Fukushima Prefecture from 11 March 2011 were contacted to provide information on their movements in the four months following the nuclear accident. Around 26% of the total population (about 532 000 people) had responded to the postal survey by 31 March 2014, but response rates were higher in areas of greater radionuclide deposition. In the Soso area[24], the response rate was 45.1%.

In order to estimate the exposure levels of the external doses to the residents, NIRS developed a series of 18 representative evacuation scenarios to model the movement of residents from different locations following the accident [203]. These scenarios were also used in the UNSCEAR study to estimate doses for people in the evacuated communities.

Detailed studies were carried out later focusing on people living in specific locations in Fukushima Prefecture using personal dosimeters, which also allowed the results from the two approaches to be compared.

For assessing internal exposures, there are three main measurement methods for determining the intake of radionuclides to the body and hence estimating radiation doses. These are whole body counting, thyroid monitoring (primarily for radioiodine uptake) and analysis of radionuclides in urine. Annex I gives further information on these techniques. The key points are summarized here. In addition to these measurement methods, atmospheric dispersion simulations are also useful to construct maps of radionuclides in air for different times and locations for use when the available data are not sufficient.

WBCs are widely available and have the advantage that the levels of some radionuclides present in the body are measured directly and the results are available quickly. They are used for determining the levels of radionuclides that emit gamma radiation of sufficient energy to be measured. Following the releases from the Fukushima Daiichi NPP, whole body counting examinations were used primarily to detect ^{134}Cs and ^{137}Cs. These counters cannot differentiate between internal and external contamination, so care must be taken to ensure that individuals are free from external contamination on the body or clothing before measurements are performed.

For accidental releases of radioiodine, such as that following the Fukushima Daiichi accident, thyroid monitoring was also conducted to directly measure ^{131}I content in the thyroid. Calibration factors were developed to convert measured count rates to activity in the thyroid for children and adults. Factors were also developed to convert the measured count rate to committed effective dose and thyroid dose equivalent for various age groups. With regard to whole body counting, it is necessary to take into account the time and route of intake. Because of the short half-life of ^{131}I of eight days, it is desirable for measurements to be taken as soon as possible after intake. It is again important that individuals are free from external contamination before measurements and that suitable allowance is made for background radiation levels, which is not always straightforward.

[24] An area in eastern part of Fukushima Prefecture, consisting of Soma City, Minamisoma City, Hirono Town, Naraha Town, Tomioka Town, Kawauchi Village, Okuma Town, Futaba Town, Kazurao Village, Namie Town, Shinchi Town, Iitate Village, many of which were within the designated evacuation zone or the Deliberate Evacuation Area.

The estimation of doses from incorporated activities obtained from WBC or thyroid measurements requires knowledge of the time and route (i.e. whether by inhalation or ingestion) of intake. If such knowledge is not available, assumptions need to be made regarding these factors. Some uncertainty arises in the dose estimate if the mode and timing of intake are not well known.

As described in the following sections, a number of studies have been carried out which produced results used in this assessment. However, there are some limitations of the measurements used to estimate public exposures, including the fact that:

- Measurements were carried out by many different organizations and public bodies without a common monitoring protocol. In particular, there were different approaches to dealing with low doses below the limits of detection. In some cases, they were ignored, while in others they were all grouped together (e.g. in a range of 0–1 mSv).
- Measurements were carried out at different times, over different periods and using different measurement techniques. However, measurements were carried out in many, but not all, affected areas.
- Results above limits of detection were sometimes grouped by dose ranges, which might not be ideal for a subsequent log-normal analysis.
- An average background dose was usually subtracted from the measurement data, which were often close to background. For statistical analyses, it may be better to report the total doses and then the likely range in background doses for comparative purposes.

These limitations reflect the fact that the majority of the measurements were carried out for screening purposes that aimed to reassure the public and not to generate data for subsequent dose assessment studies.

Laboratory measurements may also be performed to determine if radioactive material has been absorbed, ingested or inhaled. This typically involves collecting samples of urine to determine the presence of a particular radionuclide. For individuals who received higher radiation exposures in a very short period of time, blood tests such as chromosome analyses may be conducted to determine if any biological effects from exposure, such as abnormalities in chromosomes, are detected. Such techniques are only appropriate for relatively high doses, and they were not appropriate for members of the public following the accident at the Fukushima Daiichi NPP. Some chromosome analyses were performed for a number of workers considered to have received the highest doses, as described in Section 4.2.1.

4.2.2.2. Assessment of external exposures

External doses from Fukushima Daiichi NPP releases to the atmosphere have two components: irradiation from radionuclides in the air and irradiation from radionuclides deposited onto the ground. Any measurements of ambient dose equivalents made during the period when releases were continuing included doses from both components. Personal dosimetry of members of the public is not normal practice, and the nature of the reactor accident and tsunami made such measurements particularly difficult. Estimates of external doses to the public have been based on a combination of modelling, particularly for the early period, and personal measurements, where such data are available. The studies that are of particular relevance for external doses are summarized in Table 4.2–8. The results of these studies are presented below.[25]

[25] The results of these studies have not been independently validated for the purposes of this volume.

TABLE 4.2–8. STUDIES TO DETERMINE EXTERNAL DOSES

Item	Survey type	Dates/locations/subjects	Key points	References
1	Personal dosimetry		— Glass badge (Chiyoda Technol. Corporation; radio photoluminescence) used in Fukushima City and Date City — Quixel badge (Nagase Landauer Ltd; optically stimulated luminescence) used in Nihonmatsu City, Tamura City and Koriyama City — Detection limit 0.01 mSv — Summary of measurements, measurement periods, results, etc. (see Table 2 of Ref. [204]) — Fukushima City: ○ 36 767 infants, schoolchildren, pregnant women ○ 1 September–30 November 2011 ○ Frequency distribution of individual accumulated external doses for three month period ○ 87.2% < 0.5 mSv; 99.7% < 1 mSv — Date City ○ Accumulated doses to 9 443 residents of all ages over three months by district ○ 1 September–30 November 2011 ○ Lowest: Yanagawa District (0.17 mSv) ○ Highest: Ryozen District (0.72 mSv) — Tamura City ○ Accumulated doses to 4 559 children up to junior high school age and pregnant women over 103 days gestation by district ○ 30 September 2011–10 January 2012 ○ Lowest: Ohgoe, Takine (0.1 mSv) ○ Highest: Miyakoji (0.17 mSv) — Nihonmatsu City ○ Accumulated doses to 8 725 pregnant women over three months gestation and children by age group ○ 1 September–30 November 2011 ○ Dose range 0.28–0.41 mSv	Results of individual doses as cited in Ref. [204] (in Japanese): Date City [205] Nihonmatsu [206] Tamura City [207] Koriyama City [208] No source for residents of Fukushima City Results of measurements made using personal dosimeters in 22 municipalities omitting names of cities, towns and villages [209]

TABLE 4.2–8. STUDIES TO DETERMINE EXTERNAL DOSES (cont.)

Item	Survey type	Dates/locations/subjects	Key points	References
			— Koriyama City ○ 24 115 school children ○ 7 November 2011–9 January 2012 ○ Frequency distribution of individual accumulated external doses for a 64 day period ○ 91.9% in range of 0.01–0.29 mSv ○ Maximum dose: 1.31 mSv; average dose: 0.17 mSv	
2.	External dose estimate, behaviour logging (FHMS)	12 March–11 July 2011	NIRS external dose estimation system — maps of gamma dose rate by MEXT and calculations by the System for Prediction of Environmental Emergency Dose Information (SPEEDI) combined with behaviour data derived from survey. 554 241 residents (27.0%) of a total of 2 055 383 residents who resided in Fukushima Prefecture at the time of the accident responded to the questionnaire. External doses in four months were estimated for 477 121 residents: ○ 279 118 (62.2%) < 1 mSv ○ 421 462 (93.9%) < 2 mSv ○ 446 059 (99.4%) < 3 mSv ○ The maximum dose was 25 mSv Results of individual external doses for four months in the Soso area: ○ 55 144 (77.6%) < 1 mSv ○ 67 521 (95.0%) < 2 mSv ○ 1 647 (97.3%) < 3 mSv ○ The maximum dose was 25 mSv	Fukushima Medical University [210] See also Ref. [203] for methods.

Assessment of external doses based on measured ambient dose equivalents

NIRS developed an external dose estimation system for residents of Fukushima Prefecture after the Fukushima Daiichi accident. The system has been used for the basic FHMS. In this system, the external exposures of the residents can be calculated based on information on the movements of the residents after the accident as recorded in the survey sheets, and on the dose rate maps of days in the four months following the accident, constructed from the measured dose rates and simulation data. Information on the shielding effects of houses or buildings from the radioactive plumes and from the radionuclides on the ground was based on Ref. [211]. The background exposure before the accident was estimated based on the available data and was subtracted from the calculated external exposures. For babies or children, the smaller body sizes compared with those of adults were considered, and the conversion coefficients for effective doses were applied.

As noted above, in the basic FHMS (see Section 4.4.2.1), information was collected on locations of residences, dates of moving and patterns of activity of Fukushima Prefecture residents and, combined with environmental dose rate maps, the individual integrated external exposures in the first four months following the accident were estimated. To examine the range of doses, 18 evacuation scenarios for the residents were assumed by considering actual evacuation information, as described above.

The doses to the residents from the Deliberate Evacuation Area were elevated compared with those from the area within the 20 km radius of the Fukushima Daiichi NPP. The estimated cumulative effective doses from external exposure for the four month period between 11 March and 11 July 2011 have been published on the Fukushima Prefecture's web site. Ninety-five per cent of residents were estimated to have received doses of less than 2 mSv. Natural radiation background of an average of 0.03 µSv/h (about 0.27 µSv/y) was subtracted from the estimated external exposure rates.

The estimated individual effective doses from external pathways received in the first four months following the accident have been published [212] and the results for Fukushima Prefecture are shown in Fig. 4.2–11. It can be seen that for the majority of people in Fukushima Prefecture external doses are low. A number of estimates of the individual effective doses due to external exposure in the first four months have been published [204, 210, 213, 214]. For example, in the Soso area (which includes the evacuation zone and the Deliberate Evacuation Area), these doses were below 5 mSv for 98.7% of residents (with a maximum effective dose of 25 mSv). In Fukushima Prefecture as a whole, including the evacuation zone and the Deliberate Evacuation Area, the doses were below 3 mSv for 99.4% of the residents surveyed [210].

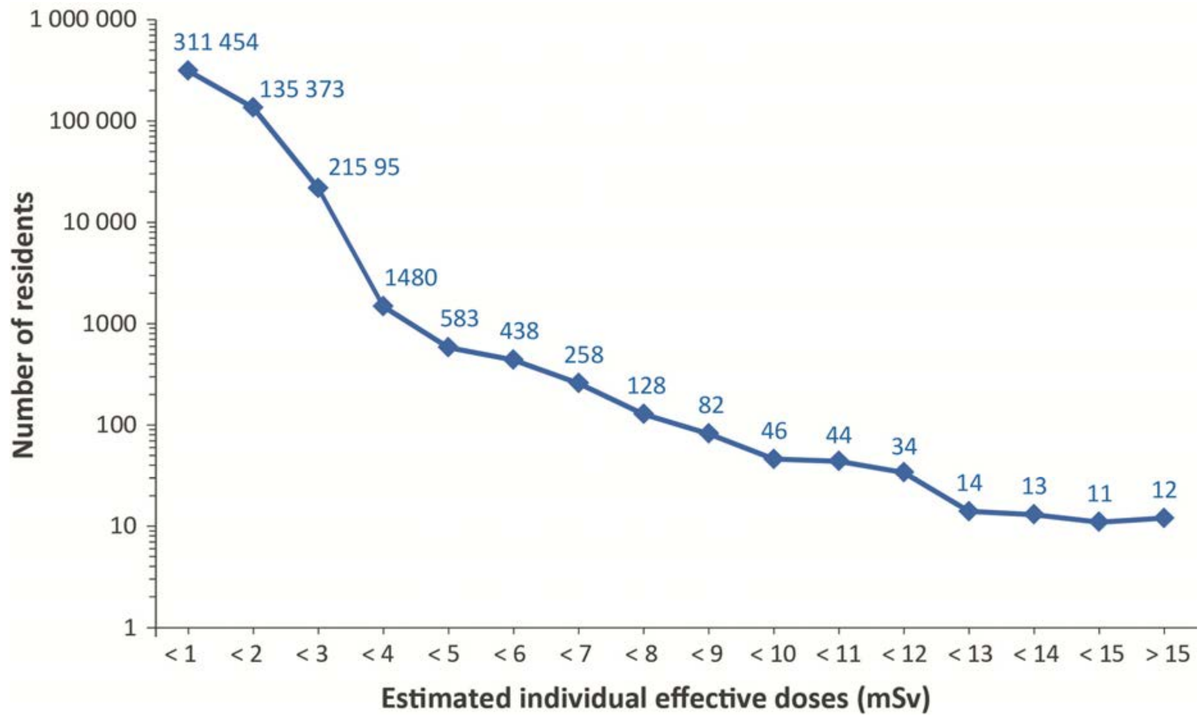

FIG. 4.2–11. Estimated individual effective doses from external radiation for all residents of Fukushima Prefecture for the first four months following the accident [212].

These results were further analysed using a log-normal fitting process (see Section 4.2.1.8 for details of this process), as illustrated in Fig. 4.2–12 for some settlements. The upper figures are for cities located within 20 km of the Fukushima Daiichi NPP, while the lower figures are for cities outside this area. This analysis took account of the fact that:

— Some measurements were aggregated in such a way that the datasets reflected the number of people who received a dose within specific intervals (bins).
— For many datasets, the majority of measurements were either around or below the limit of detection.

Therefore, a probability density function as well as the cumulative distribution were calculated. The measurements that were below the limit of detection (1 mSv) were particularly marked for Hirono Town and Iwaki City, where 97% and 99%, respectively, of the data were 1 mSv or less. The resulting distribution for Hirono Town was affected to such an extent that it is not included in Fig. 4.2–12. There were other difficulties in interpreting the data as discussed earlier, particularly the treatment of background radiation and the approach adopted for dealing with low doses. Nevertheless, it is possible to obtain useful information from these measurements and the analysis.

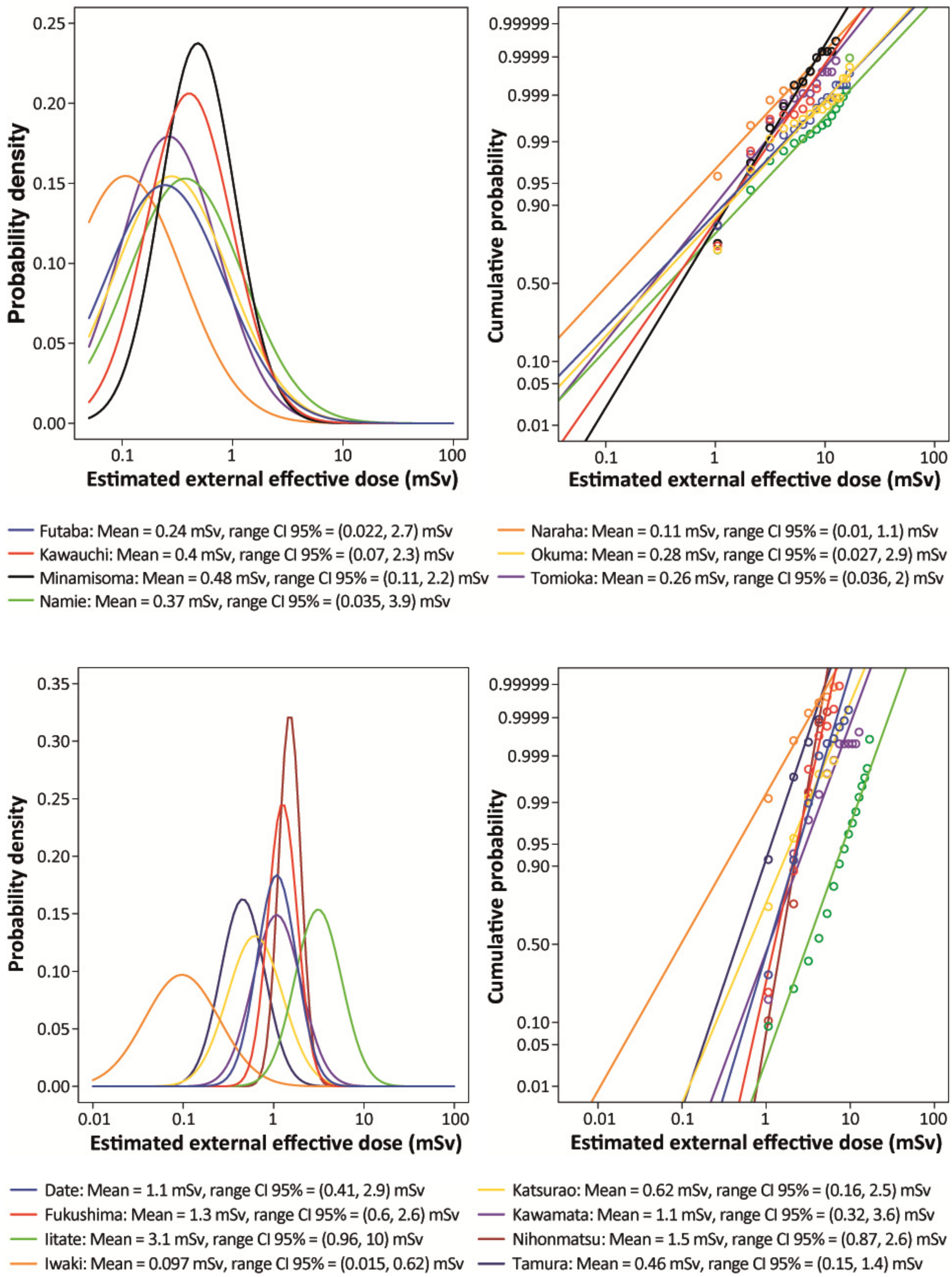

FIG. 4.2–12. Log-normal normalized idealized probability density and cumulative probability distributions of the estimated external effective doses in various cities, towns and villages of Fukushima Prefecture for the four months following the accident on the basis of Fukushima Health Management Survey data. The upper part of the figure presents the analysis for places located in the area within the 20 km radius and the lower part of the figure for places outside this area.

For people originally located within 20 km of Fukushima Daiichi NPP (the upper part of Fig. 4.2–12), the estimated mean doses range from 0.24 mSv to 0.4 mSv in the first four months after the accident. The highest 95th percentile dose is estimated to have been 3.9 mSv in Namie Town. As seen from lower part of Fig. 4.2–12, the estimated doses tend to be higher outside the 20 km zone, reflecting the effects of the prompt protective actions within 20 km. There is also a greater range in doses for people living outside the 20 km area, as would be expected from the variation in levels of radioactivity at different locations. For these cities and towns, the estimated mean doses range from 0.46 mSv in Tamura City to 3.1 mSv at Iitate Village (excluding Hirono Town and Iwaki, where the estimated mean doses are lower but where there are difficulties with the analysis as explained above). The highest estimated 95th percentile dose was about 10 mSv for Iitate Village, where evacuation took place later than in other locations [215]. The estimated 95 percentiles for other cities and towns ranged from 1.4 mSv for Tamura to 3.6 mSv for Kawamata Town (excluding Hirono Town and Iwaki City).

It should be noted that the spread of doses at Namie Town is wider than for other municipalities. This appears to be because the evacuation from Namie Town took place in two stages about a week apart, so that part of the population was exposed in the locality for a longer period, giving rise to an overall dose distribution which is effectively the combination of two distributions [215].

The results illustrated in Figure 4.2–12 are all reasonable fits to a log-normal distribution following the normalization process described in Section 4.2.1.8. Differences between the various locations reflect the extent and timing of evacuation as well as the levels of radioactivity experienced. The results within the 20 km zone tend to show wider distributions than the locations outside 20 km. This is due to the effects of evacuation of the same community to different locations and the further movements that took place in many cases. This complicated pattern was modelled by NIRS using 18 evacuation scenarios, as explained earlier. Appendix II presents some additional analysis of the data for various locations.

Despite significant inhomogeneity in the mean doses estimated for the individual municipalities, the distribution obtained for the Soso area as a whole is also well described by a log-normal probability density function. These results can be compared with those estimated by UNSCEAR using the same 18 scenarios and a similar methodology for estimating external doses, but with a different dispersion model and source term. These dose estimates also included other exposure pathways. For example, for Iitate Village, UNSCEAR estimated a total dose before and during evacuation of 5.7 mSv, which includes contributions from inhalation and ingestion. This is higher than the mean dose given above, but lower than the 95th percentile. UNSCEAR compared the external doses with the results obtained by NIRS and found that the two sets of doses were reasonably consistent [5]. UNSCEAR also estimated lower doses for those people who were evacuated in the first few days following the start of the accident than for those who were evacuated later.

Assessment of external doses from personal dosimetry

There are uncertainties associated with the use of interviews with residents, environmental measurement and dose estimation models for assessing public doses. Personal radiation monitoring of members of the public is therefore important for a reliable reconstruction of radiation doses. Personal dosimeters were distributed to large numbers of people living in different regions, as summarized in Table 4.2–8. Residents in Fukushima City were provided with dosimeters to be worn for a three month period from September 2011. The results were summarized by Nagataki et al. in 2013 [204]. For 36 767 infants, schoolchildren and pregnant women in Fukushima City, the accumulated dose in the three month monitoring period was less than 1 mSv in 99.7% of the measurements. The results are presented in the form of log-normal cumulative probability plots in Appendix II.

Further analyses have been carried out on the data for Date City[26] and Iwaki City[27], for which annualized doses derived from measurements in two settlements towards the end of 2011 and early 2012 are available. The results are presented in Fig. 4.2–13 [216–218].

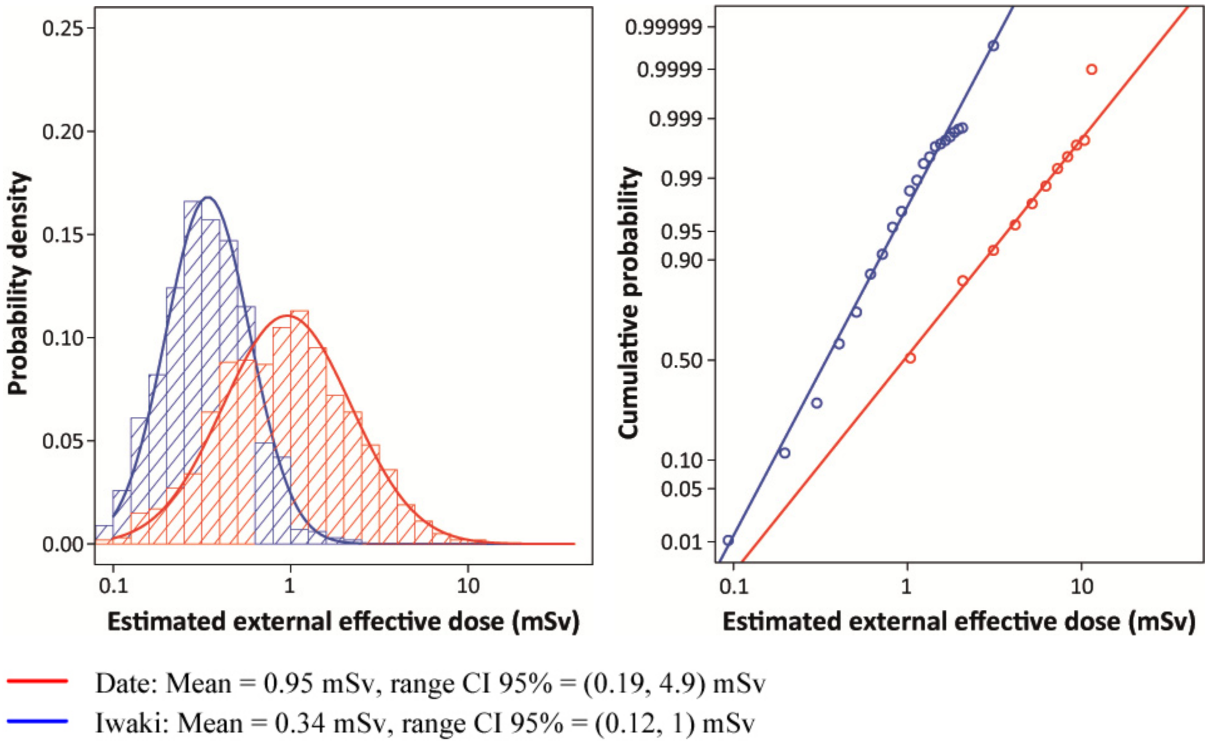

FIG. 4.2–13. Probability distribution of monitored personal dose equivalents of members of the public during 2011 for two cities in the affected area, Date City and Iwaki City, for which annualized data were available.The normalized idealized probability density function and the cumulative probability distribution is illustrated for each city.

Figure 4.2–13 indicates that personal dose equivalents received by members of the public in these two cities were low, with averages below 1 mSv per year, providing 95% confidence that individuals who incurred effective doses in those cities sustained doses below 5 mSv [216–218]. For Date City, the estimated mean external personal dose equivalent is 0.95 mSv for the first year following the accident with the 95th percentile being 4.9 mSv [216]. For Iwaki City, external doses are lower, reflecting the lower levels of radioactivity in the area. The estimated mean personal dose equivalent was 0.34 mSv in the first year and the 95th percentile is 1 mSv [217].

A number of studies were carried out in Date City with people in various locations within the area being provided with dosimeters to be worn over the period September 2011 to February 2012. Additional information is presented in Appendix II.

In Date City, personal dosimeters were also provided for a large number of schoolchildren attending various schools over the period April–June 2012. The average doses measured over the period ranged from 0.4 to 0.9 mSv, but the variation for different schools was greater (0.4–1.4 mSv) [216]. A further

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[26] For Date City, individual dose measurement with personal dosimeters (glass badges) was carried out for six months from September 2011 to February 2012. The cumulative dose was doubled to calculate the annualized dose, as described in Ref. [216].

[27] For Iwaki City, personal dose measurements were carried out for three months, from November 2011 to January 2012. The cumulative dose was multiplied by 4 to calculate the annualized dose, as described in Ref. [217].

set of measurements was obtained during the period from July 2012 to June 2013, and for these a comparison was carried out between the results of the personal dosimeters and estimates of external doses based on measurements of ambient dose equivalent. This is shown in Fig. 4.2–14 [219].

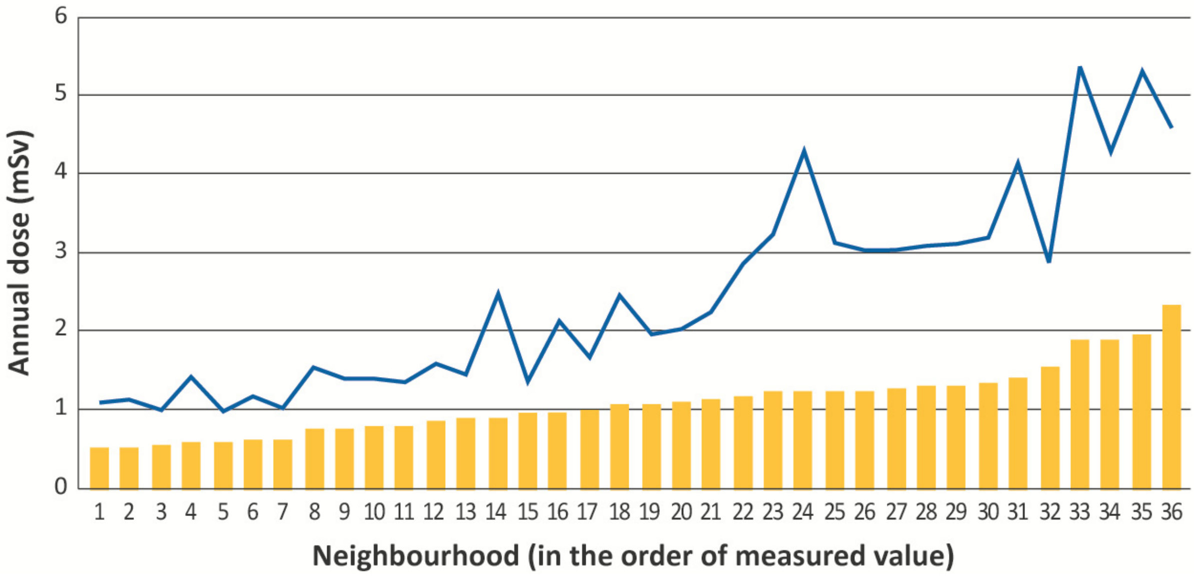

FIG. 4.2–14. Comparison of external individual dose estimates with measurements in Date City between July 2012 and June 2013. The effective doses are assessed by estimation (line), assuming indoor occupancy and shielding for 16 h, outdoors for 8 h, and by personal monitoring (bar) of personal dose equivalent, in various neighbourhoods of the city (numerated) [219].

These results indicate that the doses based on data from personal dosimetry are lower than those based on measured ambient dose equivalent rates, habit information and modelling. It is also possible to compare the results with those obtained using the UNSCEAR method for projecting external doses over time. From the beginning of April 2012 to the end of March 2013, the UNSCEAR assessment approach would imply a district averaged external dose of 1.2 mSv for a representative person[28] living in the wider Date City area, which is consistent with the dosimeter results [216].

Log-normal distributions were also produced for some other locations where the available information is sufficiently detailed to obtain ranges in external doses, and this information is presented in Appendix II.

Comparison with UNSCEAR estimates of external dose

Although measurements of external doses using personal dosimetry are generally performed for a maximum period of three months, these data may be used to derive a rough estimate of the dose in one year that can be compared with the projected additional annual effective doses from external pathways, estimated using the UNSCEAR methodology. This involved using time weighted district averages of soil measurements performed in 2011 to determine initial dose rates. Projections of the additional external dose rates at subsequent times were then estimated using information on the reduction in dose rate with time arising from natural processes, such as radioactive decay and weathering, from post-Chernobyl studies.

[28] A representative person is an individual receiving a dose that is representative of the dose to the more highly exposed individuals in the population [220].

Figure 4.2–15 shows the estimated reduction with time of external dose rates due to gamma emitting radionuclides from 2012 to 2015, with no allowance for any remediation of the land [221]. Thus, over the three year period 2012–2015, the external doses would be projected to decline by a factor of 4 owing to radioactive decay, natural weathering from surfaces and vertical migration in soil.

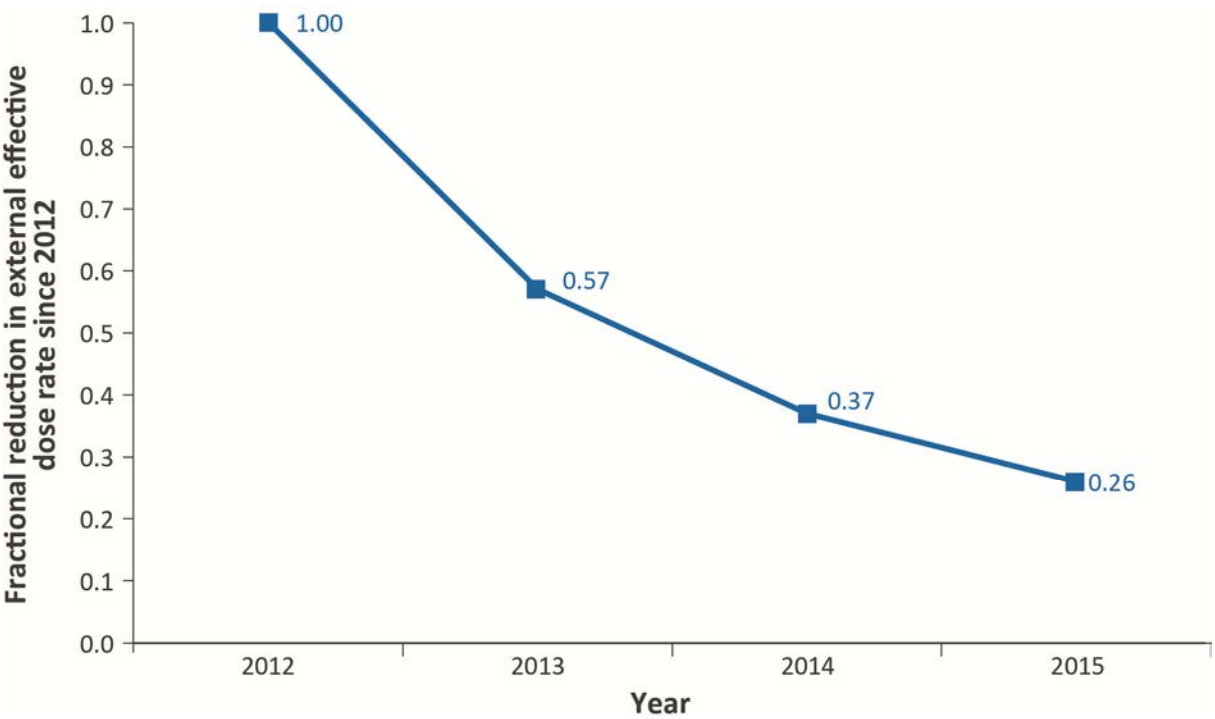

FIG. 4.2–15. Fractional reduction in external effective dose rates relative to 2012 from gamma emitting radionuclides. [221].

The projected external effective doses estimated for 2012 indicate that the district averaged doses to a representative person would have been less than 1 mSv in all prefectures except Fukushima Prefecture. Figure 4.2–16 is a map of the projected district averaged external effective doses for the representative person in Fukushima Prefecture in 2012. The projected annual effective dose in 2012 for representative persons returning to an area currently evacuated was estimated to be 10–17 mSv, in Okuma Town, Futuba Town and Namie Town, and below 6 mSv in the remaining areas of Iitate Village, Katsurao Village and Kawauchi Village. By 2015, this approach would suggest that the maximum district averaged effective dose to a representative person would be less than 5 mSv in that year based on natural processes and assuming no remediation. These district averaged estimates do not allow for spatial variation in radiocaesium deposition within each municipality. Actual doses will therefore vary below and above the district averaged estimate. For comparison with the effective doses to a typical person reported above and by UNSCEAR [5], the dose to a representative person, based on district average dose rate information, is estimated to be within a factor of 1.4 to 1.5.

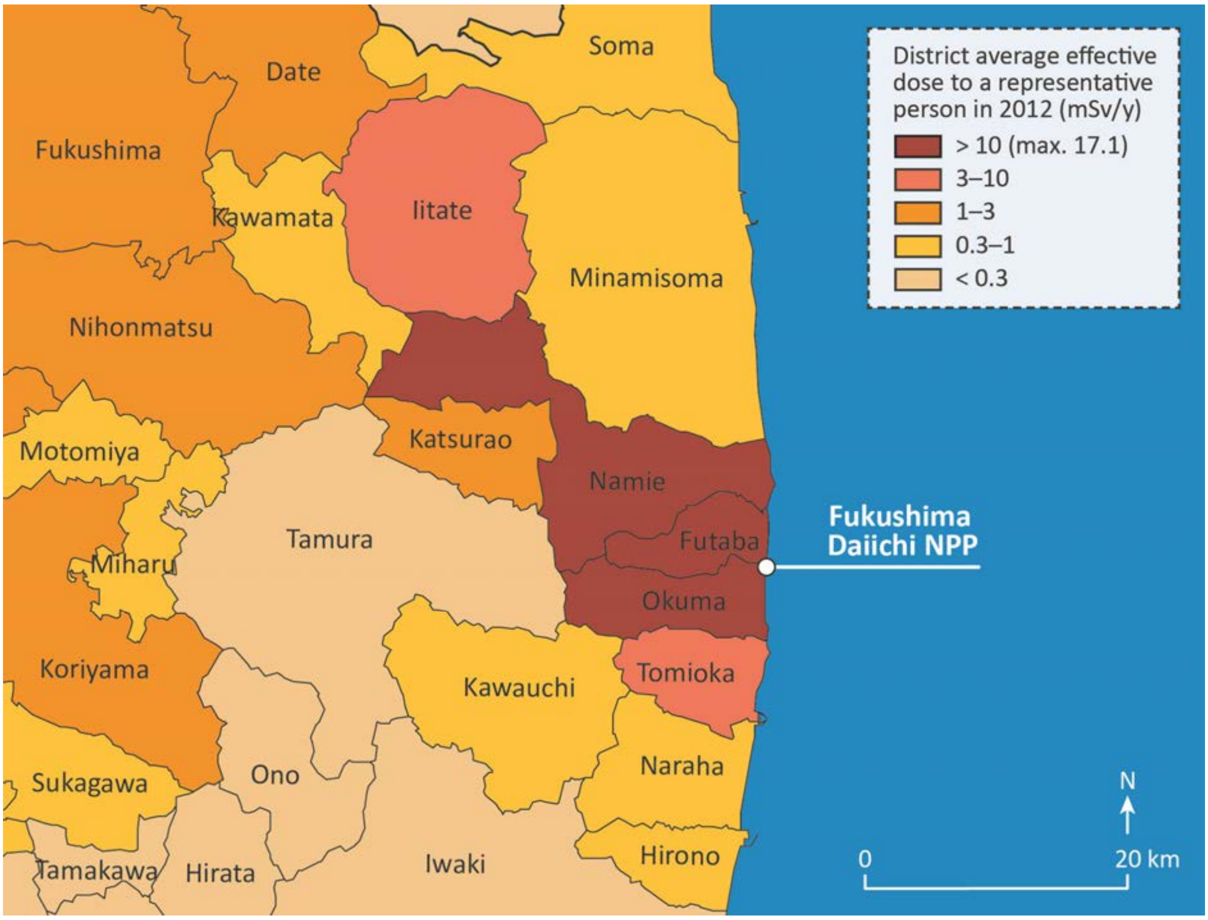

FIG. 4.2–16. Predicted district average external effective dose for a representative person in 2012.

Table 4.2–9 presents a comparison of personal dosimetry results with the projected additional external effective doses in 2012 from deposition measurements performed in 2011, using the methodology applied in the UNSCEAR assessment. Projected doses are generally assessed for the purpose of prospective decision making and do not reflect the doses received by any individual. By their nature, such estimates are based on some form of environmental and dosimetric modelling and are subject to the associated uncertainties. Dose estimates based on personal dosimetry represent more closely those received by individuals, but are also subject to the uncertainties associated with such measurements.

Although the measurements and modelled doses are of a different nature and cover different time periods, they are generally in good agreement. However, it is clear that there will be variability in individual doses, due to local variations in deposited activity together with variations in people's behaviour. It should be further noted that the modelled values presented in Table 4.2–9 are intended to be representative of those who are likely to receive higher doses (the representative person), while the measured values presented in this table are mean values and therefore more indicative of typical exposures.

TABLE 4.2–9. COMPARISON OF PERSONAL DOSIMETRY RESULTS WITH EXTENDED ANALYSIS USING UNSCEAR METHODOLOGY FOR ASSESSING PROJECTED ADDITIONAL EXTERNAL DOSE FROM DEPOSITION

Location	Measurement period	Doses estimated from measurements (mSv)		Annual doses (mSv)	
		Mean	Range[a]	Measured mean	Projected dose[b]
Fukushima City	1 Sep. 2011–30 Sep. 2011	0.06	0.01–0.26	1.2	1.8 (2012)
Fukushima City	1 Oct. 2011–30 Nov. 2011	0.11	0.03–0.46		
Fukushima City	1 Nov. 2012–31 Jan. 2013	0.08	0.02–0.33	0.3	1.0 (2013)
Iwaki City[c]	1 Nov. 2011–31 Jan. 2012	0.34[d]	0.12–0.99	0.34	0.2 (2012)
Tamura City	30 Aug. 2011–30 Sep. 2011	0.04	0.02–0.13	0.5[d]	0.28 (2012)
Tamura City	30 Sep. 2011–10 Jan. 2012	0.12	0.04–0.36		
Tamura City	11 Jun 2012.–11 Sep. 2012	0.07	0.02–0.24	0.28	0.28 (2012)

[a] The range is the 5th and 95th percentile; a simple method of multiplication by the number of months is not applicable, and comparison with data for 2012 is not strictly appropriate.
[b] Projected additional effective dose to the representative person based on environmental measurement data from 2011.
[c] Measured values for schoolchildren.
[d] These are annualized doses and not for the three month period of the measurement.

4.2.2.3. Assessment of exposures from intake of radionuclides

As explained in Section 4.2.2.1, there are two main routes for exposures from intakes of radionuclides: inhalation of radionuclides released to air and ingestion of radionuclides in food and drinking water. It is possible to assess the doses arising from intakes from either direct measurements of the body content of radionuclides, where such measurements are possible, or by an estimate of intake and the use of dose coefficients based on biokinetic models. The results of each type of analysis are presented below.

Assessment of committed effective doses by measurement of incorporated radionuclides

The measurement of radionuclides in people provides a direct source of information on their internal exposures. Two main sets of data are available, the first from measurements of ^{131}I in the thyroid and the second from whole body measurement for ^{134}Cs and ^{137}Cs. In order to assess dose from internal exposure of incorporated radionuclides, assumptions have to be made regarding when and where intakes took place and how much of the intake was by inhalation and how much by ingestion. The use of whole body counting does not take into account, or provide any measure of, any external radiation exposures.

The number of measurements of people in the vicinity of the Fukushima Daiichi NPP immediately after the accident is quite limited owing to the severe effects of the tsunami, organizational and transportation difficulties, elevated background radiation and contamination of radiation measuring devices. However, a large number of WBC measurements were later carried out at different settlements. Information on these was provided by the municipalities, through the Government of Japan, for this study and was also obtained from other published sources.

A summary of the distribution of committed effective doses among residents of Fukushima Prefecture, measured by WBC, is presented in Table 4.2–10.

TABLE 4.2–10. COMMITTED EFFECTIVE DOSE DISTRIBUTION OF FUKUSHIMA PREFECTURE RESIDENTS MEASURED BY WBC IN INDIVIDUAL MUNICIPALITIES FROM 27 JUNE 2011 TO 31 JANUARY 2012 [222]

Municipality	Committed effective dose (mSv)				Total
	<1	1–1.5	1.5–2.5	2.5–3.5	
Kawamata	632	0	0	0	632
Namie	3 043	5	2	0	3 050
Iitate	1 425	0	0	0	1 425
Hirono	645	0	0	0	645
Naraha	1 067	1	2	0	1 070
Tomioka	1 814	0	1	0	1 815
Kawauchi	302	0	1	0	303
Okuma	1 960	3	1	0	1 964
Futaba	1 155	2	2	2	1 161
Katsurao	181	0	0	0	181
Soma	2	0	0	0	2
Minamisoma	21	0	0	0	21
Date	1 208	2	1	0	1 211
Iwaki	799	0	0	0	799
Tamura	200	0	0	0	200
Shirakawa	10	0	0	0	10
Fukushima	430	0	0	0	430
Sukagawa	490	0	0	0	490
Total	15 384	13	10	2	15 409

The data presented in Table 4.2–10 were measured using a WBC with sodium-iodine detectors installed at NIRS, JAEA and other organizations. The measurements conducted by NIRS were measured using a bed type WBC with four sodium iodide detectors. The measurement time was 3 minutes [223]. The minimum detectable activity was 320 Bq ^{134}Cs and 570 Bq ^{137}Cs.

Some additional information was provided by the municipalities, through the Government of Japan, for the purposes of this assessment, as indicated in Table 4.2–11. It generally was not possible to undertake detailed statistical analyses of these data; most measurements were at or below the limits of detection.

As can be seen from Table 4.2–11, WBC measurements were carried out on tens of thousands of people from various locations, particularly in Fukushima Prefecture. Where it was possible to convert measurements to dose, making assumptions about the timing and nature of the intake, the estimated effective dose commitments from measurements of ^{134}Cs and ^{137}Cs were reported to be lower than 1 mSv for 99% of residents [204]. The aim of many of the studies was for screening or public reassurance purposes. Many measurements were below detection limits and serve to demonstrate that doses were less than 1 mSv. However, it is not possible to carry out any detailed statistical analyses, such as fitting log-normal distributions, for these data.

In many cases, the WBC measurements were carried out several months or more after the accident and therefore provide information on the levels of ^{134}Cs and ^{137}Cs incorporated, but do not provide information on ^{131}I, which would have decayed by this time. Given the importance of intakes of ^{131}I both by inhalation and ingestion in the first month following the accident, this makes comparison between the measurement data and the dose assessment carried out by UNSCEAR difficult.

Inhalation doses varied from place to place and included a component arising from the intake of ^{131}I, which would not have been detected in many of the WBC measurements. The highest estimated effective doses measured were 1 mSv, corresponding to an absorbed dose to the thyroid of 20 mSv (mGy). Without information about the locations in Fukushima Prefecture where the people monitored spent their time and the time of the measurement, it is not possible to compare these results in detail with those estimated by other organizations, although the overall magnitudes may be compared. UNSCEAR estimated that the committed effective dose from inhalation of the population of Fukushima Prefecture who were not evacuated was between about 0.01 mSv and 0.3 mSv, depending on location [5]. The first month's committed effective dose from ingestion for an adult was estimated to be about 0.8 mSv. These results are broadly consistent with those presented above.

TABLE 4.2–11. SUMMARY OF THE WHOLE BODY COUNTER (WBC), MEASUREMENTS CARRIED OUT

Study	Survey type	Dates/locations/subjects	Key points	References
1	WBC thyroid and urine analysis	27 June and mid-July 2011 Residents of Iitate Village, Namie Town and Yamakiya District of Kawamata Town (from Deliberate Evacuation Area) 122 subjects	— Pilot study performed by NIRS — Results reported for 109 of 122 residents — Significant levels of radiocaesium detected in 50% of subjects (max values 3 100 and 3 800 Bq of ^{134}Cs and ^{137}Cs, respectively) Ref. [224] — ^{134}Cs detected in 47.8% of subjects, ^{137}Cs in 29.4% and both in 23.9% — Estimated combined dose from radiocaesium (^{134}Cs and ^{137}Cs) <1mSv — ^{131}I not detected	Ref. [224]
2	WBC	11 July 2011–end January 2012 (reported here — measurements continuing) Residents of 11 municipalities in Fukushima Prefecture (at time of accident) 9 927 subjects aged 4–adult	— JAEA measurements of residents started — Measurements build on pilot study (item 3) and form part of the Fukushima Prefectural government's study, Health Examination for Citizens in Fukushima Prefecture — Details on efficiency calibrations/phantoms provided — Maximum concentrations for children <8 years and for adults were 2 700 and 14 000 Bq, respectively — 99.8% of committed effective dose (CED) estimates below 1 mSv (but does not include contribution from short lived radionuclides ^{131}I, ^{132}I, ^{132}Te) — 22 subjects had CED estimated >1 mSv; maximum CED = 3 mSv. All children or teenagers apart from one adult (who had worked at the damaged Fukushima Daiichi NPP) — $^{134}Cs/^{137}Cs$ ratio 0.89–0.79	Refs [224, 225]
3	WBC	June 2011–February 2013 118 930 residents of Fukushima Prefecture at the time of the accident (includes current residents and evacuees in Niigata Prefecture)	— Report entitled Health Examination for Citizens in Fukushima Prefecture — Estimated committed effective dose of 118 904 (99.9%) residents <1mSv based on the assumption that intake was by inhalation in March 2011 — Maximum estimated committed effective dose: 3 mSv	Monthly updates of statistics based on results of this WBC initiative are published (in Japanese) on the Fukushima Prefectural government web page. The monthly results as of February 2013 were used. See Refs [224, 226] up to end of January 2012 and Refs [204, 226] for results up to February 2013.

TABLE 4.2–11. SUMMARY OF THE WHOLE BODY COUNTER (WBC), MEASUREMENTS CARRIED OUT (cont.)

Study	Survey type	Dates/locations/subjects	Key points	References
4	WBC	7 October 2011–30 November 2012 Residents of Fukushima and neighbouring prefectures 32 811 subjects aged 4–93	— Distinct from the Fukushima Prefectural government measurement campaign (Item 3) — No information provided on efficiency calibration of WBC — Initial measurements (11 026 subjects between October 2011 and February 2011) eliminated owing to possible surface contamination of clothes — Of the remaining measurements (21 785 subjects between March 2012 and November 2012), $^{134}Cs/^{137}Cs$ detected in 1.0% of adults and 0.09% of children ≤15 years — $^{134}Cs/^{137}Cs$ ratio approximately 1, gradually decreasing with time — High concentrations in small groups of elderly subjects (maximum 184 Bq of ^{137}Cs; 108 Bq of ^{134}Cs) who had eaten banned wild foods — Possible sampling bias investigated and discounted	Ref. [227]
5	WBC	26 September 2011–31 March 2012 9 484 residents of Minamisoma City (including returned evacuees)	— WBC of residents (offered to all, 24% were measured) — Radiocaesium detected in 34.6% of subjects (16.4% of children, 37.4% of adults) — 1 432 children aged 6–15: 210–2 953 Bq (median 590 Bq); 2.8-57.9 Bq/kg (median 11.9 Bq/kg) — 3 051 adults 210–12 771 Bq (median 744 Bq); 2.3–196.5 Bq/kg (median 11.4 Bq/kg) — All doses <1 mSv in all but one resident	Ref. [228]
6	WBC	15 March 2011 onwards 173 subjects who were in Fukushima Prefecture between 11 March and 10 April 2011	— ^{131}I, ^{134}Cs and ^{137}Cs detected in >30% of subjects — ^{132}I and ^{132}Te detected in some measurements — Measured ranges: • ^{131}I: 0.42–140 kBq • ^{134}Cs: 0.13–16 kBq • ^{137}Cs: 0.13–16 kBq — Maximum dose estimated assuming acute inhalation of three radionuclides (levels from SPEEDI estimates) = 1 mSv (maximum thyroid dose, 20 mSv) — Reconstruction of doses for 16 evacuees for whom ^{131}I, ^{134}Cs and ^{137}Cs were detected by Matsuda et al. (2013) [229] and comparison with SPEEDI predictions of airborne activity concentrations	Ref. [229]; additional information in Ref. [230]

TABLE 4.2–11. SUMMARY OF THE WHOLE BODY COUNTER (WBC), MEASUREMENTS CARRIED OUT (cont.)

Study	Survey type	Dates/locations/subjects	Key points	References
7	WBC	2011–2013 residents of Date City 9 305 children and pregnant women to the end of 2011 6 377 (to end of September 2012) 17 577 in 2013	In 2011, 99.96% received <1 mSv; 33 of group from areas in spots recommended for evacuation — In 2012, 1091: 4–6 years old; 119 pregnant women 5167 people >19 years old from four districts — All <1 mSv — 1091: 4–6 years old; 2 779 students of elementary and junior high school; 507 high school students; — 13 765 people >19 years — All <1 mSv	Newsletter published on 26 July 2012 [231] (Municipality in Fukushima Prefecture)
8	WBC	Residents of Fukushima City, measurements for 2011–2013 117 measurements from 25 November 2011 to 20 December 2011 (no age information available) 24 598 measurements of adults and children in 2012 41 258 measurements of adults and children in 2013	— 2011: All ^{134}Cs levels were below detection limits and only ten ^{137}Cs levels were above detection limits — 2012 levels nearly all below detection limits — 2013 levels nearly all below detection limits	Ref. [226] (Municipality in Fukushima Prefecture)
9	WBC	Residents of Hirono Town for 2012–2014; September–December 2012, (1044 measurements) January 2013–January 2014, (514 measurements)	— Summary of WBC measurements — data not presented — 90% not detected, 2% only ^{134}Cs detected, 5% only ^{137}Cs detected and 3% both Cs isotopes detected. Distribution of effective dose where caesium was detected presented	Ref. [226] (Municipality in Fukushima Prefecture)
10	WBC	Koriyama City 2013 only	— 14 data points that exceeded detection limit (age and gender; with the exception of one man of 29 years, all >59 years) — CED between 0.009 and 0.07 mSv	Ref. [226] (Municipality in Fukushima Prefecture)

TABLE 4.2–11. SUMMARY OF THE WHOLE BODY COUNTER (WBC), MEASUREMENTS CARRIED OUT (cont.)

Study	Survey type	Dates/locations/subjects	Key points	References
11	WBC	Motomiya City In 2011, 3 035 children (by school type) and 81 pregnant women In 2012, 11 281 people, including 43 pregnant women, 416 workers (restorative construction), 7 986 general public — rest schoolchildren In 2013, 4 799 (1 584 general public), remainder children (by school age)	— No doses >1 mSv found	Ref. [232] (Municipality in Fukushima Prefecture)
12	WBC	Namie Town 26 April 2012–29 March 2013, 7 645 subjects (age information available) 1 April 2013–18 March 2014, 4 470 subjects	— Raw individual data — body burden and estimated effective dose (assumed to be derived from chronic ingestion) — Most measurements below limits of detection and all doses estimated to be less than 1 mSv	Ref. [226] (Municipality in Fukushima Prefecture)
13	WBC	Tamura City Raw data, 7361 subjects, June 2012–9 March 2014 Raw data for 4 681 subjects for 27 August–14 January 2014	— Body burden and effective dose from radiocaesium assuming chronic ingestion — Most measurements below limits of detection and all doses estimated to be less than 1 mSv	Ref. [226] (Municipality in Fukushima Prefecture)
14	WBC	Iwaki City, total of 62 071 measurements in the period November 2011–27 February 2014	— In the year March 2011–March 2012, 490 people were measured, with a detection rate of 28.8% — In 2012 and 2013, over 30 000 measurements were performed, with a detection rate of 2.3% and 0.3%, respectively	Ref. [226] (Municipality in Fukushima Prefecture)
15	Thyroid screening (scintillation survey meters)	26–30 March 2011 Iwaki City, Kawamata Town, Iiate Village 1 080 children, 0–15 years at time of accident	— Screening survey of children living in areas where thyroid doses were predicted to be high — Chronic intake rates and constant calibration factor used — Screening level of 0.2 μSv/h corresponds to a thyroid equivalent dose of 100 mSv (1 year old) — No significant signal detected in 55.4% of cases (<0.01 μSv/h) — Maximum thyroid equivalent dose measured was 43 mSv (1 year old)	Ref. [233] See also Ref. [234]

TABLE 4.2–11. SUMMARY OF THE WHOLE BODY COUNTER (WBC), MEASUREMENTS CARRIED OUT (cont.)

Study	Survey type	Dates/locations/subjects	Key points	References
16	Thyroid screening (scintillation survey meters)	12–16 April 2011 Residents of Namie Town (Tsushima district) Evacuees from coastal areas including Minamisoma City 62 subjects aged 0–83 years	— Thyroid measurements of 62 residents/evacuees — ^{131}I detected in 46 subjects — Mean thyroid doses for children and adults were 4.2 mSv and 3.5 mSv, respectively — Maximum thyroid doses for children and adults were 23 mSv and 33 mSv, respectively	Ref. [235]
17	WBC and thyroid measurements	196 residents and short term visitors to Fukushima, 11 March–20 April 2011	— Thyroid doses and effective doses were estimated using the measurement results from WBC — ^{131}I, ^{134}Cs and ^{137}Cs detected in 49 of the 196 people — Committed effective doses from caesium <1 mSv — Maximum thyroid equivalent dose was 18.5 mSv — Mean thyroid dose 3 mSv and committed effective dose of 0.06 mSv estimated	Ref. [230]
18	WBC, thyroid	734 Russian citizens in Tokyo in three trips in 2011–2012, the first one was from 8 to 20 April 2011	— In April 2011, 3 of 268 people exceeded the minimum detectable level of ^{131}I in the thyroid (100 Bq of ^{131}I) — Maximum estimated dose equivalent to the thyroid was 2 mSv for an adult and 4 mSv for a 1 year old child — Average thyroid equivalent dose estimated as 0.2 mSv for an adult and 0.4 mSv for a 1 year old child — None of 784 people exceeded the minimum detectable level of 1 800 Bq ^{137}Cs and ^{134}Cs in the body	Ref. [236]
19	Urine analysis	15 residents of Iitate Village and Kawamata Town between 54 and 78–85 days after 11 March 2011	— Estimated equivalent doses to the thyroid were between 27 and 66 mSv	Ref. [237]

Other assessments of doses from intake of radionuclides from ingestion

The assessment of exposure from the possible ingestion of radionuclides in food and drinking water requires information on the concentrations of radionuclides detected in food and drinking water over the period of assessment, as well as on the appropriate age dependent intake rates and dose coefficients of the radionuclides. Information on the average quantity of particular foods consumed per capita of the population, based on surveys carried out in Japan, has been provided by the Government of Japan. The most extensive data were available for adults, but these data also include information for infants and children.

Market basket analyses

Data on concentrations of ^{134}Cs, ^{137}Cs and ^{131}I in foods and in drinking water are described in Section 4.1.4. Market basket samples in more than ten areas across Japan were surveyed in September–October 2012, and the estimated annual committed effective doses for radiocaesium were derived from standard meals. Foods were purchased in 15 areas in Japan, including three areas in Fukushima Prefecture. Locally grown products were selected wherever possible. Using this approach, the annual committed effective doses from radiocaesium in food were found to be less than 0.01 mSv/y, as shown in Table 4.2–12. Subsequent surveys showed that doses continued to be less than 0.01 mSv/y. From the information given in Annex V, this is consistent with the estimated doses from ingestion beyond the first year given in the UNSCEAR study.

A detailed study of early doses due to the ingestion of radionuclides is being carried out by the Mitsubishi Research Institute, Inc., for the Ministry of the Environment, and some findings have been reported [238]. Field research was conducted to collect data on food distribution in the period following the accident and the intakes of food and water by the population during evacuation. Concentrations of radionuclides in water and foods were determined and ingestion doses calculated taking into account the quantities consumed for the period to the end of March 2011, when ^{131}I concentrations in water fell to below 10 Bq/L. Consumption of water is understood to be the primary contributor to ingestion doses. Concentrations in water were measured or assessed from ground deposition measurements. Owing to disruption in the distribution of food supplies, it is likely that few of these foods would have been eaten by the people who were evacuated.

The researchers confirmed that exposure from the consumption of milk was expected to be very low, as locally produced milk was not distributed. In addition, researchers determined that only bottled water was used to make infant formula food, as parents were concerned about the potential health effects of using tap water. Exposure from consumption of vegetables was noted to be low as very few vegetables were growing outside (owing to the cold weather at that time of the year) and that effectively the only locally produced vegetables consumed were those grown in greenhouses [239].

On 5 September 2013, the Fukushima Prefectural Government published ^{90}Sr radioactivity concentrations in food in Fukushima [240]. Strontium-90 was detected in 3 of 78 samples. The measured levels were 0.016 Bq/kg, in the diet of a child from 1 to 12 years of age, residing in the northern part of Fukushima Prefecture; 0.034 Bq/kg for a person over 13 years of age in the same area; and 0.026 Bq/kg for a child from 1 to 12 years in the central part of Fukushima Prefecture. The contribution of ^{90}Sr to doses is minor compared with that from ^{137}Cs and ^{134}Cs.

The concentrations of radionuclides in foods included marine species. Only foods available in markets complying with government standards were included.

TABLE 4.2–12. ANNUAL RADIATION DOSE FROM RADIOCAESIUM IN MARKET BASKET SAMPLES OF FOODS (COMMITTED EFFECTIVE DOSE BASED ON DIETARY SAMPLES) [241]

Area (Prefecture)	^{134}Cs and ^{137}Cs (mSv/year)
Hokkaido	0.0010
Iwate	0.0040
Miyagi	0.0057
Fukushima (Hamadori)	0.0018
Fukushima (Nakadori)	0.0038
Fukushima (Aizu)	0.0038
Tochigi	0.0032
Ibaraki	0.0035
Saitama	0.0024
Tokyo	0.0022
Kanagawa	0.0021
Niigata	0.0017
Osaka	0.0012
Kochi	0.0013
Nagasaki	0.0009

Assessment of thyroid equivalent doses from thyroid uptake measurements

A limited number of direct measurements of ^{131}I activity in the thyroid were reported for the weeks following the accident. These are summarized in Table 4.2–11, and a description of these studies is given in Annex VI.

A thyroid dosimetry survey was performed from 26 March to 30 March 2011 using a NaI (Tl) scintillation survey meter. The screening level was set under the assumption that a reading of 0.2 µSv/h on the survey meter corresponds to 100 mSv in the case of one year old infants, which is based on experiments by NIRS [233]. Using this method, the radiation doses to 1080 children under the age of 15 were measured in Iwaki City (134 children), Kawamata Town (631) and Iitate Village (315) in Fukushima Prefecture on the advice of the Nuclear Safety Council (NSC). None of the children showed a level of 0.2 µSv/h or higher, and the highest level was 0.1 µSv/h. Of these children, 55% showed background levels, and 99% had levels of less than 0.04 µSv/h [242]; data were expressed later as mSv with the intake (inhalation) scenario from 12 March to the day before measurement [233].

Figure 4.2–17 shows the distribution of measured thyroid equivalent doses estimated from the screening survey.

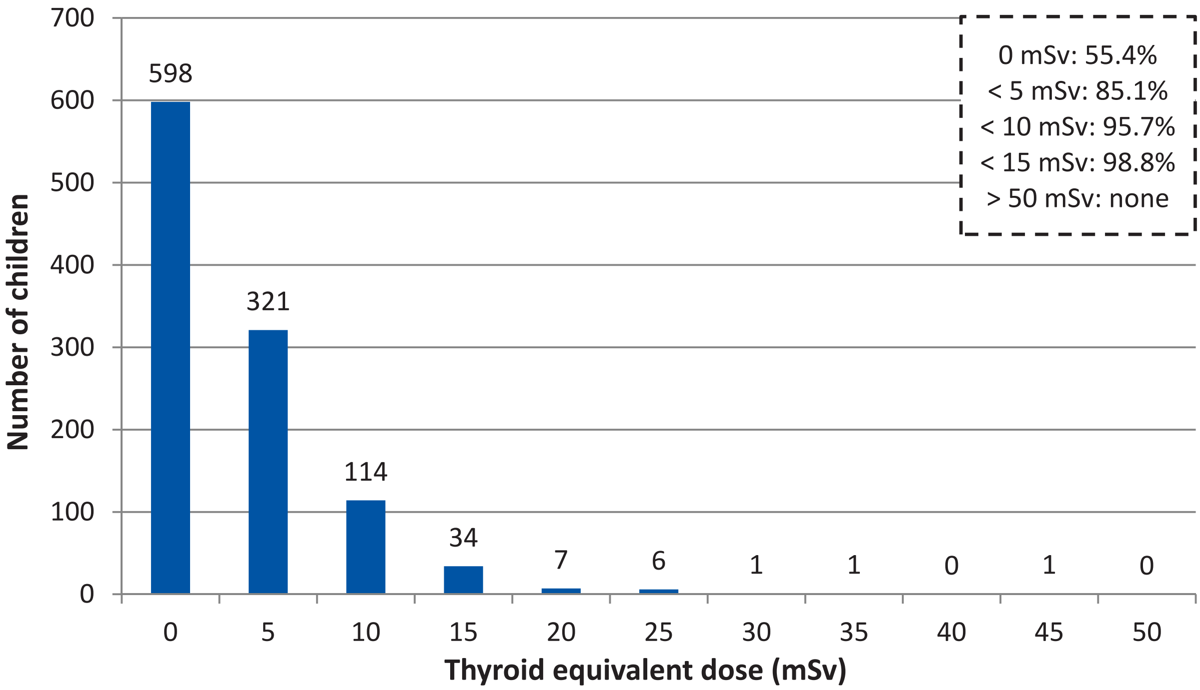

FIG. 4.2–17. Distribution of thyroid equivalent doses estimated by the results of the screening survey and intake scenario from 12 March 2011 to the day before measurement [233].

These doses indicate the range in the measurements and the fact that for the majority of the children the dose rates from the thyroid were low (less than 5 mSv).

For the purposes of this assessment, the data from this study were analysed further to investigate the relationship between the ratio of ^{131}I content in the thyroid derived from these measurements and those associated with theoretical assumptions on intakes by inhalation and ingestion. A comparison of the data for Iwaki City (see Fig. 4.2–18) clearly indicates that the measured data are closer to those for intakes by inhalation than ingestion, suggesting that the former was the predominant route of intake in this case. This analysis is presented in more detail in Annex VII.

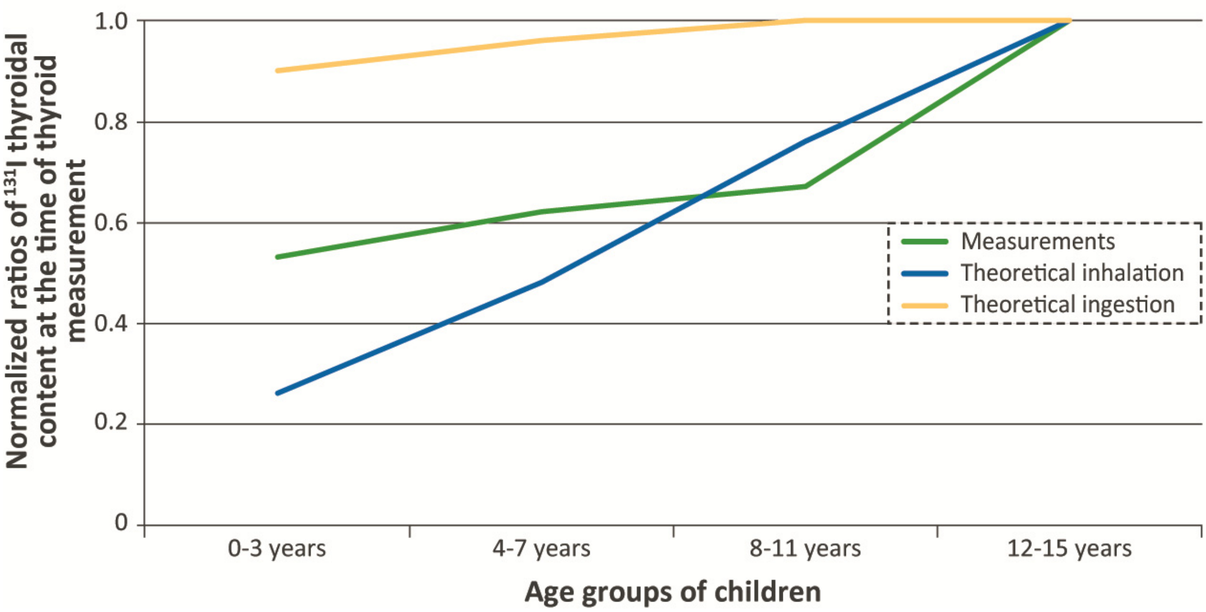

FIG. 4.2–18. Ratios of the estimates of the ^{131}I thyroidal content derived from direct thyroid measurements (green) and theoretically calculated on the basis of the assumption of (1) only inhalation intake (blue) and (2) only ingestion intake (yellow) in the form of normalization to the ^{131}I thyroidal content of group of older children for Iwaki City.

As a described in Annex VII, thyroid doses were estimated based on the assumption that inhalation occurred on 15 March 2011. The uncertainties associated with these data are described in Annex VII. It is necessary to recognize these uncertainties in interpreting the data and the corresponding cumulative log-normal probability distributions for Iwaki City and Iitate Village presented in Fig. 4.2–19. This figure suggests that the data for Iwaki City conform to a log-normal distribution, while those for Iitate Village do not. The distribution of individual doses in this village may include people who experienced different radiological conditions.

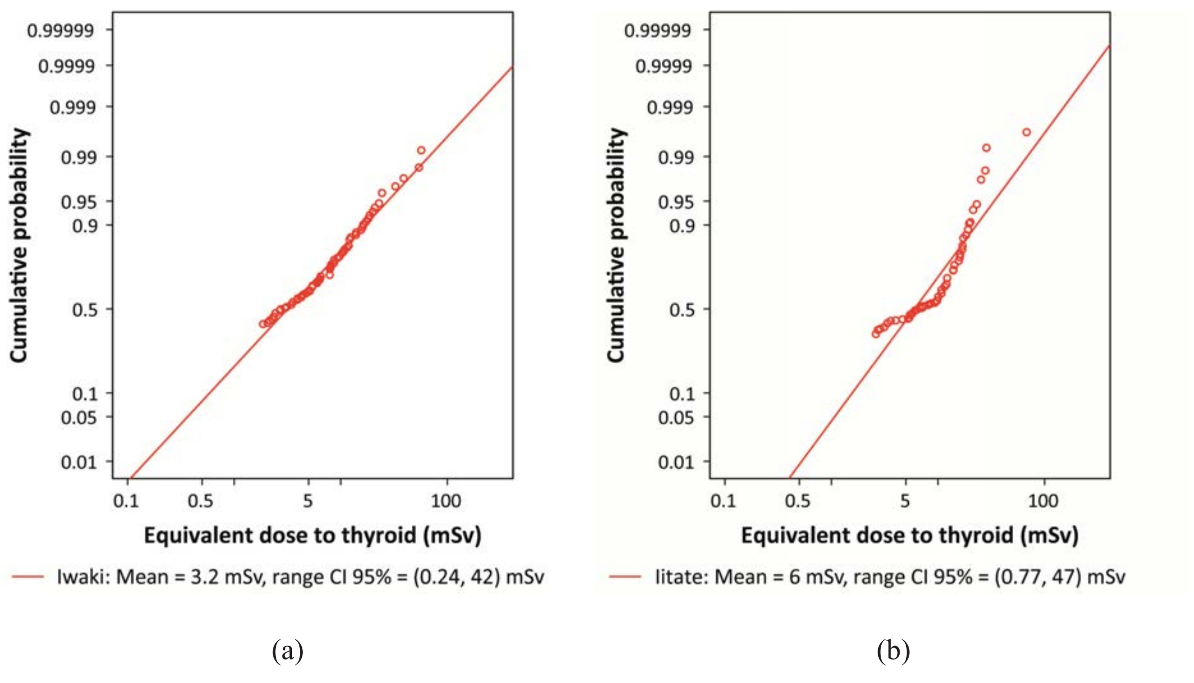

FIG. 4.2–19. Log-normal cumulative probability distribution of individual thyroid dose estimates for children of (a) Iwaki City and (b) Iitate Village, derived from direct thyroid measurements assuming inhalation intake.

A detailed analysis of the available direct thyroid measurements for the 1080 children aged up to 15 years from three settlements in Fukushima Prefecture indicated that inhalation intake of ^{131}I was the dominant intake pathway. This was partly a consequence of the fact that intakes by ingestion were largely avoided owing to the prompt notification and implementation of restrictions on foods by the Japanese authorities. This resulted in an average equivalent dose to thyroid from intakes of ^{131}I of the order of a few mSv among those children.

These results are in contrast to the situation following the Chernobyl accident, where ingestion was the dominant intake pathway of ^{131}I for children living in contaminated areas, mainly owing to consumption of fresh milk from cows grazing on pasture. People living in the contaminated areas were not immediately aware of the accident and continued to drink locally produced milk. This resulted in average equivalent doses to the thyroid of up to a few thousand mSv (with a maximum value of 50 000 mSv based on direct thyroid measurements).

It is important to recognize that the consumption of fresh cows' or goats' milk is potentially the most significant of the various ingestion pathways leading to intakes of ^{131}I. A cow grazing on pasture typically eats about 50 kg of grass (wet weight) per day. If this grass is contaminated with ^{131}I, the cow will produce milk that has higher volumetric activity of ^{131}I than that in grass. Furthermore, the typical daily intake of cows' milk is greater than that of leafy vegetables (by a factor of 10–100).

It was reported that thyroid equivalent doses determined in March 2011 using an NaI (Tl) scintillation survey meter in children in the evacuation zone and the Deliberate Evacuation Area were lower than around 10 mSv in 95.7% of children (with a maximum of 43 mSv) [233]. Effectively, all doses were lower than the generic optimized intervention value for iodine prophylaxis of 100 mGy of avertable committed absorbed dose to the thyroid due to radioiodine, established in the 1996 International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources:[29] [243], which were valid at the time of the accident, and lower than the projected dose of 50 mSv in the first seven days for iodine thyroid blocking established in the currently valid International Basic Safety Standards [220]. In comparison, the absorbed doses to the thyroid of children following the Chernobyl accident ranged up to several thousand mGy [244, 245], a factor of nearly 100 to 1000 times higher.

Thyroid radiation doses of evacuees from Fukushima Prefecture were determined by Hirosaki University. The thyroid dose was determined by NaI (Tl) scintillation spectrometer at the neck of the examinees during the period from 12 to 16 April 2011. The median thyroid equivalent dose in 62 evacuees was estimated to be 4.2 mSv for children and 3.5 mSv for adults, and the maximum values were 23 and 33 mSv, respectively. Five children under the age of 9 and a total of 8 under the age of 20 were included [235]. In Nagasaki, the internal radioactivity in evacuees and short term visitors to Fukushima was measured by WBC beginning on 15 March 2011. Internal radioactivity was measured in 173 people who stayed in Fukushima Prefecture between 11 March and 10 April 2011. The average length of stay was 4.8 days. Iodine-131, ^{134}Cs and ^{137}Cs were detected in more than 30% of examined individuals. The maximum committed effective dose and thyroid equivalent dose were 1 mSv and 20 mSv (mGy), respectively [229]. For comparison, the estimated dose range for thyroid dose to the evacuees from the Chernobyl accident was about 500 mGy (with individual values ranging from less than 50 mGy to more than 5000 mGy). For the more than six million residents of the contaminated areas of the former Soviet Union who were not evacuated, the average thyroid dose was about 100 mGy, while for about 0.7% of them, the thyroid doses were more than 1000 mGy [246].

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[29] Generally referred to as the International Basic Safety Standards (or by the acronym BSS).

Contribution to thyroid exposures of other short lived radionuclides

The contribution to thyroid exposures from short lived radioiodines (primarily from ^{133}I and ^{132}I due to intake of ^{132}Te) may be important, especially in the case of intakes by inhalation during the first few weeks following an accident. The contribution of short lived radioiodines to the thyroid equivalent dose to the public following the Fukushima Daiichi accident has been estimated by considering the ratio of the dose to the thyroid from short lived radioiodines to that from ^{131}I from inhalation. This contribution depends on three factors:

— Relative time integrated concentrations in the ground level air of radioisotopes of iodine in the form of gaseous and particulate aerosol;
— Relative time integrated concentrations in ground level air of ^{131}I, ^{133}I, and ^{132}Te;
— Age dependent ratios of the committed thyroid dose coefficients for inhalation for ^{131}I, ^{133}I and ^{132}Te.

Values for input parameters to assess thyroid exposures from short lived radioiodines as well as the estimates of the contribution of other short lived radioiodines to the thyroid doses from inhalation was not explicitly included in the thyroid dose estimates from radioiodines presented in the UNSCEAR study [5]. Table 4.2–13 presents separate assessments of the contribution of these short lived radionuclides based on input data used by UNSCEAR. The approach adopted takes account of the different deposition velocities of tellurium and iodine in aerosol form and iodine in its elemental form[30], as outlined in detail in Ref. [247].

TABLE 4.2–13. ASSESSING THYROID EQUIVALENT DOSES TO INFANTS FROM SHORT LIVED RADIOIODINES ASSUMING INHALATION INTAKE ON 15 MARCH 2011 [247]

Radionuclide		^{131}I	^{133}I	^{132}Te
Ratio to ^{137}Cs in soil (adjusted to 15 March 2011)*	All Japan except for the south trace***	11.5	1.39**	8
	South trace	74	8.95**	59
1-year-old child inhalation dose coefficient (Sv/Bq)	Particulate+	1.4×10^{-6}	3.5×10^{-7}	5.3×10^{-8}
	Elemental	3.2×10^{-6}	8.0×10^{-7}	—
Dose ratio to ^{131}I thyroid dose of 1-year-old child	All Japan except for the south trace	1.00	0.03	0.096
	South trace	1.00	0.03	0.11

* According to [5].
** Assuming a ratio of ^{133}I/^{131}I equal to 2.1 in the three reactors at time of shutdown (at 14:46 on 11 March 2011) [248].
*** UNSCEAR referred to a narrow region along the coast to the south of the Fukushima Daiichi NPP as the 'south trace'. This area was characterized by ratios for ^{129m}Te and ^{131}I that were significantly elevated.
+ The ratio of particulate to gaseous/elemental forms of radioiodine in air is equal to 0.67 (40% in particulate and 60% in gaseous forms) [247].

For the releases that occurred on 15 March 2011, the estimated additional contribution from short lived radionuclides is within 15% of thyroid equivalent doses to members of the public, which were calculated to have resulted from ^{131}I. The exposure to the thyroid from ^{132}I produced from ^{132}Te in the body is relatively more important than that due to ^{133}I (by a factor of up to 3) [247]. However, the

[30] Tellurium is assumed to be in aerosol form; 40% of iodine is assumed to be in aerosol form and 60% in its elemental form. The deposition velocity of elemental iodine is a factor of 10 greater than the aerosol form of iodine and tellurium.

contribution of short lived radioiodines to thyroid exposures decreases with time compared with that from ^{131}I.

The contribution of short lived radioisotopes of iodine to thyroid equivalent doses to the public in the case of inhalation intake that might have occurred as early as 12 March 2011 might be as great as 30–40% of that from ^{131}I. In this case, the relative importance of thyroid exposure from ^{133}I is greater than that from ^{132}I by a factor of up to 2 [247]. However, thyroid exposures from releases on 12 March would be much lower than those from releases on 15 March, because the amount of iodine released on 15 March was substantially higher and directed north-west, while on 12 March, the releases were primarily directed to the east (ocean).

For comparison with the situation following the Chernobyl accident, the contribution of short lived radioiodine to thyroid exposures for the vast majority of the public in the contaminated areas following the Chernobyl accident was much lower and did not exceed about 1–2% [244] because the primary intake pathway for those individuals was ingestion of locally produced cows' milk. Intake of radioiodines with contaminated milk following the Chernobyl accident resulted in much higher thyroid equivalent doses from ^{131}I (up to 50 Sv) than those following the Fukushima Daiichi accident [244, 245]. The thyroid equivalent doses from ^{131}I resulting from the Fukushima Daiichi NPP accident were lower than those at Chernobyl primarily because of government restrictions on food, and particularly milk products.

The results of the thyroid equivalent doses estimated from direct measurements performed on people from different age groups are summarized in Table 4.2–14. Where possible, the estimates from the UNSCEAR dose assessment have also been added for comparison (see Annex V for information on the UNSCEAR assessment).

TABLE 4.2–14. THYROID EQUIVALENT DOSES FROM DIRECT MEASUREMENTS

Dates and mode of measurement	Location of subjects	Number of subjects	Doses calculated from measured activities (mSv)	Reference and UNSCEAR estimates for comparison
26–30 March 2011 Thyroid uptake	Iwaki, Iitate, Kawamata	1080 children	Mean 2, Maximum 43	Ref. [233] 37–63 mGy during evacuation for a 1 year old
12–16 April 2011 Thyroid uptake	Namie, Minamisoma	62, aged 0–83 years	Median 4.2 for < 20 years, 3.5 for adults	Ref. [235] 6.4–52 mGy during evacuation for a 1 year old
Urine collection 54 and ~80 days after 11 March 2011	Iitate, Kawamata	15 adults	Maximum 27–66	Kamada et al. [237] 6.4–63 mGy during evacuation for a 1 year old
8–20 April 2011 Thyroid uptake	Tokyo	268 children and adults	Maximum 2 for adults Average 0.4 child, 0.2 adult	[236] For areas including Tokyo the ranges are: 0–0.4 adults external + inhalation + 0.5 ingestion 0–0.8 for 1 year old external + inhalation and 2.6 ingestion
11 March–20 April 2011 WBC	Residents in Fukushima and short term visitors in Fukushima	196	Committed effective dose: Median: ^{137}Cs: 0.004, ^{134}Cs: 0.003, Maximum: ^{137}Cs: 0.067, ^{134}Cs: 0.098; Thyroid: Median: 0.67, Maximum: 18.5	[230] Range for districts not evacuated Adult 0.1–9.6 external + inhalation plus 7.8 ingestion

Maximum thyroid equivalent doses in children in the more heavily exposed communities, based on these measurements, are several tens of mSv, with mean doses of a few mSv. The highest estimated dose was 66 mSv based on limited data. The most extensive dataset [233] found a 95th percentile dose of about 8 mSv [249] and a maximum recorded value of about 43 mSv. These doses would increase by 10–15% if contributions from shorter half-life iodines were included. It is difficult to compare these results with the estimates from UNSCEAR [5], but from the information presented above, there are no major differences between the two sets of estimated doses.

It is difficult to compare the estimated doses presented above with one other and with the UNSCEAR assessment as there are differences in the locations, the time periods considered and the exposure pathways included. There are also uncertainties in the results of all studies. For the results based on measurements of people, the numbers measured are often small compared with the total population, many of the early measurements were taken for screening purposes and there can be difficulties in accounting adequately for background radiation.

Assessments based on multiple pathways

Takahashi et al. [225] adopted a probabilistic approach to dose assessment based on the measurement data of the surface activity concentrations of ^{137}Cs and the results of the NIRS behavioural patterns of the population groups living in Fukushima Prefecture. The study assessed the doses to adults from external exposure to radionuclides deposited on the ground and radionuclides in the radioactive cloud, as well as the doses caused by internal exposure through inhalation of radionuclides from the radioactive cloud. Internal radiation doses from ingestion pathways were not included. The 95th percentile of the effective dose received by the inhabitants evacuated was mainly in the 1–10 mSv dose band in the first year after the accident. However, the 95th percentile of the dose received by some outdoor workers and inhabitants evacuated from highly contaminated areas was in the range of 10–50 mSv. It was assumed in the calculations that other protective actions such as sheltering and stable iodine uptake were not carried out.

4.2.3. Summary

Occupational exposures

Despite the accident and extreme work conditions, exposure and levels of contamination, doses beyond accepted limits were rare among the many emergency workers, first responders, and other workers. Of the approximately 23 000 workers on the site in the period from March 2011 to December 2011, six TEPCO workers exceeded the temporarily revised annual effective dose limit for emergency workers of 250 mSv, and 174 workers in total exceeded the initial 100 Sv emergency dose limit during 2011. No workers exceeded either of these values in subsequent years, and only one worker exceeded an annual effective dose of 50 mSv in the period of March 2012–June 2014. This worker was working under the emergency dose limit 100 mSv for those conducting troubleshooting tasks, such as those related to reactor cooling. Internal exposure from the inhalation of radionuclides was the predominant contributor to doses received by the six on-site workers who exceeded the emergency dose limit in 2011. This was a consequence of challenges associated with respiratory protection during the emergency phase of the operations.

The reported results of WBC measurements indicate that the internal doses to the workers at the Fukushima Daiichi NPP were mostly from inhaled ^{131}I. The highest absorbed doses to the thyroid received by two emergency workers at the Fukushima Daiichi NPP are estimated to be in the region of 10 Gy. However, there are uncertainties associated with these estimates (and the contribution from other short lived radionuclides) due to the high background levels associated with early WBC measurements, the delay in undertaking thyroid measurements and the lack of bioassay information.

Firefighters, police officers and SDF personnel were also involved in a range of on-site emergency activities. No members of this group received effective doses in excess of 100 mSv and the majority received doses of less than 10 mSv.

Of the more than 8000 members of the SDF personnel who worked off-site, and for whom dose information was available, 5 received effective doses in excess of 10 mSv, but less than 20 mSv. The maximum effective dose recorded for police officers working off-site was less than 5 mSv.

Public exposures

Following the accident at the Fukushima Daiichi NPP, the highest radiation exposures for the public occurred in the first months owing to external irradiation from deposited material, inhalation and, possibly, ingestion of foods. At later times, radiation exposures decreased significantly, and external irradiation from deposited material became the most significant exposure pathway. Effective doses received by the majority of people in Japan were less than 1 mSv in the first year following the accident and are estimated to be significantly less than this in subsequent years. For the people who were evacuated or who lived in the areas where levels of radionuclides in the environment were highest, effective doses in the first year are estimated to have ranged up to 10 mSv, and again, all indications are that doses in subsequent years are significantly lower. These estimated doses are low and generally comparable with the range of effective doses incurred owing to global levels of natural background radiation. Global natural background radiation delivers an annual average effective dose of 2.4 mSv, with a typical range of 1–13 mSv, and with sizeable population groups incurring up to 10–20 mSv, and in extreme cases, up to around 100 mSv [250].

In some locations with relatively high levels of radionuclides on the ground, people have been issued with personal dosimeters to measure their external radiation dose over extended periods. Although these measurements are very limited in the early period, they are generally in reasonable agreement with the estimates of the UNSCEAR 2014 study. Further calculations carried out using the UNSCEAR methodology demonstrate that external doses are falling significantly with time owing to radioactive decay, natural weathering and migration down the soil column. Remediation will reduce these doses further (see Technical Volume 5).

Internal doses were highest in the first month or so following the accident and are thought to be mainly due to the inhalation and possible ingestion of ^{131}I. There is also a contribution from the inhalation of short lived radionuclides. Later, when intakes by inhalation directly from radionuclides released to the atmosphere had ceased, intakes by ingestion became the most important source of internal exposure. However, the restrictions placed by the Japanese authorities on the distribution and marketing of food means that doses from ingestion of food are very low after the initial period. This is found both in the UNSCEAR assessment of doses and the analysis of measurements of caesium radionuclides in people by WBC and on measurements of the thyroidal content of ^{131}I in 1080 children carried out on 26–30 March 2011.

In the initial period after the accident, there were limited measurements directly on the levels in people, and the purpose of these measurements was to provide screening rather than for detailed dose assessment. However, from the limited measurements available, there is some indication that the doses estimated by UNSCEAR for the initial period for the people who were evacuated may have been overestimated, at least for the average person. Nevertheless, much depends on whether people ate locally produced food in the first few days after the accident, before restrictions were fully implemented, and whether tap water was consumed. As these doses were mainly due to intakes of ^{131}I, which has a half-life of eight days and therefore could not have been measured in the later measurements, uncertainties in the doses will remain.

The exposures to the public in the period immediately following the Fukushima Daiichi accident appear to have been dominated by the inhalation pathway, in contrast to the situation following the Chernobyl accident, when ingestion was the main contributor to dose.

4.2.4. Observations and lessons

— **Personal radiation monitoring of representative groups of members of the public provides invaluable information for reliable estimates of radiation doses and needs to be used together with environmental measurements and appropriate dose estimation models for assessing public dose.**

  The early estimation of doses was based on environmental dispersion modelling, resulting in some conservative assumptions on doses incurred and projected.

  Personal monitoring of ^{131}I in the thyroids of children needs to be undertaken as soon as possible following radioiodine releases to the environment, owing to the short half-life (eight days) of this radionuclide. Personal monitoring of external radiation and the internal presence of the longer lived radionuclides (e.g. ^{137}Cs) needs to be undertaken as soon as feasible and to continue over time, as appropriate.

  In the absence of personal radiation measurements, modelling of environmental and ambient data may be needed to estimate the radiation doses incurred by individuals. In these cases, the uncertainties associated with the assumptions used in the models need to be clearly explained, particularly if the results are being used to inform decision making on protective measures and actions or to estimate the potential for radiation induced health effects.

— **While dairy products were not the main pathways for the ingestion of radioiodine in Japan, it is clear that the most important method of limiting thyroid doses, especially to children, is to restrict the consumption of fresh milk from grazing cows.**

  The estimates of thyroid doses to children following the accident were low. This was the result of a combination of factors, including the time of year (before the growing season), agricultural practices in Japan, low consumption of cows' milk by infants and the controls on milk consumption that were immediately introduced. These factors contributed to the low level of intake of ^{131}I. This is in contrast to the situation following the Chernobyl accident, where the dominant intake pathway of ^{131}I for children living in contaminated areas was ingestion intake, mainly due to consumption of fresh milk from cows grazing on pasture. People in contaminated areas were not immediately aware of the accident and continued to drink locally produced milk. This resulted in average equivalent dose to the thyroid of up to a few thousand mSv.

— **A robust system is necessary for monitoring and recording occupational radiation doses, via all relevant pathways, particularly those due to internal exposure that may be incurred by workers during severe accident management activities. It is essential that suitable and sufficient personal protective equipment be available for limiting the exposure of workers during emergency response activities and that workers be sufficiently trained in its use.**

  Early and continued direct measurements of the radiation exposure and the levels of radionuclides incorporated by emergency workers are the most valuable approach for obtaining information for estimating radiation risks and potential health effects and for optimizing protection. There is a need to monitor and register occupational radiation doses through a robust system of personal dosimeters and measurements. Monitoring of ^{131}I in the thyroid needs to be undertaken as soon as possible.

  Immediately following the Fukushima Daiichi accident, the provision of personal protective equipment for restricting the exposure of workers and monitoring was difficult.

— **Clearer guidelines on occupational medical management of potentially overexposed workers would be beneficial. It is necessary that people responsible for workers' health have a clear understanding on how, when, for how long and to whom protective therapies need to be administered.**

  The timely application of potassium iodide for blocking the thyroid gland is helpful for controlling workers' thyroid doses. For some workers, taking potassium iodide is thought to have significantly reduced their thyroid exposures from inhalation of radioiodine. However, many workers used potassium iodide long after their intake had ceased.

— **Following an accident, it is essential to provide personal radiation monitors to the affected population, because direct personal measurements are much more reliable than reconstructing such doses through environmental modelling and assumptions about personal behaviour.**
Early and follow-up direct measurements of levels of dose and incorporation of radionuclides in members of the public are the most valuable way of obtaining information on the radiological impact of an accident and for providing public information. In particular, measurements of ^{131}I in thyroid should be taken as soon as possible following releases to the environment, owing to its short half-life. If direct measurements are not available, modelling and assumptions of transfer parameters may be required to estimate the doses received as long as its limitations in accuracy are recognized. When estimating doses using modelling techniques that are based on environmental measurements and estimates of the amount of radionuclides released, the relatively large uncertainties associated with these estimates should be recognized and clearly explained.

— **The comparisons of assessments from various organizations would be simplified if a common monitoring protocol were developed which included ranges of doses to report, how to report doses below detection limits and how to take background radiation into account**.

4.3. RADIATION PROTECTION

Over many decades, an international system of radiation protection and safety has evolved based on scientific information, recommendations and standards developed by a number of organizations. A distribution of responsibilities has been established in which UNSCEAR, established in 1955 by the United Nations General Assembly, assesses and reports levels and effects of ionizing radiation. Taking account of such information, ICRP produces recommendations on radiological (or radiation) protection, primarily on its principles and aims. Guided by UNSCEAR estimates and ICRP recommendations, safety standards are set by a number of United Nations and international bodies, in particular by the IAEA.

Several international conventions were agreed through the International Labour Organization (ILO) and by the IAEA. The International Basic Safety Standards are developed under the aegis of the IAEA and co-sponsored by the Food and Agriculture Organization of the United Nations (FAO), the ILO, the United Nations Environment Programme and the World Health Organization (WHO), as well as by several non-United-Nations bodies. In addition, FAO and WHO jointly issue food standards through the Codex Alimentarius Commission, and WHO establishes drinking water guidelines.

The information, recommendations, conventions and standards of these various bodies comprise the system of radiation protection and safety, which is reflected in national legislation worldwide. The Fundamental Safety Principles [251], developed by the IAEA and other international organizations, specify that "The fundamental safety objective is to protect people and the environment from harmful effects of ionizing radiation" [251]. The currently valid International Basic Safety Standards (BSS) state that "the system of protection and safety aims to assess, manage and control exposure to radiation so that radiation risks, including risks of health effects and risks to the environment, are reduced to the extent reasonably achievable" [220].

Planning, preparedness and response for nuclear and radiological emergencies are determined by radiation protection and other considerations. The International Emergency Preparedness and Response (EPR) Framework that was in place at the time of the Fukushima Daiichi accident comprised international legal instruments, IAEA safety standards and operational arrangements, as described in detail in Technical Volume 3. This included requirements for the Preparedness and Response for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GS-R-2 [252], which was jointly sponsored by the FAO, IAEA, ILO, the OECD Nuclear Energy Agency (OECD/NEA), the Pan American Health Organization (PAHO), the United Nations Office for the Coordination of Humanitarian Affairs (OCHA), and WHO.

Like many countries, Japan has its own system of radiation protection, implemented by national legislation and regulations, which takes account of the international system. Japan is a signatory to a number of legally binding international conventions that address radiation protection issues. Furthermore, Japan is a Member State of the IAEA, the ILO, UNSCEAR and WHO, and Japanese experts participate in the work of the ICRP, UNSCEAR and the standard setting organizations.

As described in Technical Volume 3, the accident at the Fukushima Daiichi NPP severely tested the system of radiation protection and emergency preparedness and response arrangements. There were many contributing factors, including the fact that decisions regarding urgent protective actions had to be taken in the context of the destruction resulting from the preceding earthquake and tsunami.

This section is structured as follows. Firstly, the major relevant elements of the international system of radiation protection that were in place at the time of the accident are set out. The information, recommendations, standards and guidance available from UNSCEAR, the ICRP and international intergovernmental organizations, notably the IAEA, are outlined. The most important aspects of Japan's system are then introduced. Finally, specific aspects of radiation protection of workers and of members of the public related to the response to the accident in Japan are described. Issues that emerged during the emergency and recovery phase are identified, and lessons learned that may be of interest to the wider radiation protection community are described.

4.3.1. International organizations, recommendations and standards

4.3.1.1. UNSCEAR

The mandate of UNSCEAR is to assess and report on the levels and effects of exposure of people to ionizing radiation. The reports of UNSCEAR constitute an important input to the recommendations of the ICRP and to the international safety standards, developed under the aegis of the IAEA. Several of its recent reports are directly relevant to the analysis of the Fukushima Daiichi accident. This applies in particular to the ICRP's annex on hereditary effects in the UNSCEAR 2001 Report [253], the annex on epidemiological studies of radiation and cancer in the 2006 Report [254], the annex on health effects due to radiation from the Chernobyl accident in the 2008 Report [246] and the summary of low dose radiation effects on health in the 2010 Report [250]. An annex on the levels and effects of radiation exposure due to Fukushima Daiichi accident was published in April 2014 as part of UNSCEAR's 2013 Report [5]. The present volume was produced in close consultation with UNSCEAR in order to utilize the information compiled in that annex.

The UNSCEAR 1996 Report included a compilation [255] of the effects of radiation on non-human biota. This was updated in the 2008 Report [246], showing that information on the effects of ionizing radiation on non-human biota has accumulated over the years, although many investigations are limited to external radiation and high dose rates. The results from studies performed in areas contaminated by accidental releases of radionuclides, such as the Chernobyl accident, are valuable for understanding the long term impact of the Fukushima Daiichi accident on the natural environment. The April 2014 annex of UNSCEAR's 2013 Report [5] reviewed the consequences of the accident until March 2012 based largely on measurements performed in the environment.

4.3.1.2. Recommendations of the ICRP

The ICRP is an independent, non-profit-making advisory body that develops radiation recommendations and principles. The recommendations of the ICRP are a key input to international standards and national regulations addressing radiation protection.

Aims and principles of the ICRP recommendations

The recommendations of the ICRP aim at contributing to an appropriate level of protection for people and the environment against the detrimental effects of radiation "without unduly limiting desirable human actions" associated with such exposure [256]. The human health objectives of this aim are to prevent deterministic effects[31] and to reduce the probability of stochastic effects[32] to the extent reasonably achievable (see Section 4.4 and Annex X on health consequences). The environmental protection objective is to achieve negligible radiation impact on the maintenance of biological diversity, the conservation of species, and the health and status of natural habitats, communities and ecosystems.

Fulfilling these aims and objectives requires scientific knowledge on radiation exposure and its health and environmental effects, consideration of societal and economic aspects of protection, and making value judgments about the relative importance of different kinds of detrimental effects and about the balancing of detriments and benefits.

For instance, there may be a trade-off between controlling radiation doses to members of the public and controlling occupational radiation doses, for instance, in an emergency exposure situation. Remediation after an accident may also raise questions concerning the distribution of potential health effects between population groups and between generations.

The System of Radiological Protection developed by the ICRP contains three basic principles, described as follows in the 2007 ICRP Recommendations [256]:

Two principles are source related and apply in all exposure situations[33]:

- *Justification*: Any decision that alters the radiation exposure situation should do more good than harm;
- *Optimization of protection*: The likelihood of incurring exposures, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors.

The remaining principle is related to the individual and applies in planned exposure situations:

- *Application of dose limits*: The total dose to any individual from regulated sources in planned exposure situations, other than medical exposure of patients, should not exceed the appropriate limits.

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[31] Deterministic effect: a health effect of radiation for which generally a threshold level of dose exists above which the severity of the effect is greater for a higher dose. Such an effect is described as a severe deterministic effect if it is fatal or life threatening or results in a permanent injury that reduces quality of life.

[32] Stochastic effect: a radiation induced health effect, the probability of occurrence of which is greater for a higher radiation dose and the severity of which (if it occurs) is independent of dose.

[33] In its 2007 Recommendations, the ICRP defined the following exposure situations: planned (involving the planned introduction and operation of sources of radiation), emergency (e.g. as an unexpected development of a planned situation) and existing (where the radiation is already present when decisions on control are being contemplated).

The system of radiation protection applies to all ionizing radiation exposures from any source, whether natural or human-made, and to all exposure situations. However, dose limits can only apply in planned situations. In some cases, neither the source of radiation nor the pathway from the source to doses to individuals can be controlled (e.g. natural ^{40}K in the human body). Such exposures are *excluded* from regulatory control. In some other cases, the effort to control exposures would be unwarranted and excessive compared with the associated probability of detrimental health effects; such exposures are *exempted* from some or all regulatory requirements.

The ICRP recommendations are reviewed and revised at intervals of about 15 years and supplemented with more specific recommendations provided in several reports each year. New recommendations generate reviews and revisions of the documents of standard setting bodies such as the IAEA, a process that usually takes several years.

At the time of the Fukushima Daiichi accident, legislation related to radiation protection in Japan and worldwide was generally based on the 1990 ICRP Recommendations [192] and was generally aligned with the safety standards of the IAEA, in particular the 1996 International Basic Safety Standards (BSS) [243]. However, a new set of ICRP Recommendations was issued in 2007 [256]; revised international safety standards were in the final stages of being completed at the time of the accident. These standards were approved in September 2011, and an interim version of the revised BSS was published in November 2011 [257].

The 1990 and 2007 ICRP Recommendations are based on the three fundamental principles listed above, but in 2007, the principles had been condensed and simplified to the wording above, in order to clarify their scope and validity to different exposure situations. The 1990 Recommendations used a process based on distinction between *practices* (that add doses) and *interventions* (that reduce doses). The 2007 Recommendations evolved from the previous process based protection approach (using practices and intervention) to an approach based on the exposure situation.

The 2007 ICRP Recommendations reinforced the principle of optimization of protection subject to restrictions on individual doses and risks (i.e. probabilities of exposure): dose and risk constraints for planned exposure situations, and reference levels for emergency and existing exposure situations. Constraints and reference levels are not intended to be interpreted as (legally enforceable) limits.

Recommendations on protection of the environment

The principles of environmental protection derived from, among other things, the Rio Declaration of 1992 [258], have been laid down through multilateral environmental agreements defining the general objectives of environmental protection and how it may be achieved. Protection of the environment is now recognized as an integral part of sustainable development, and strategies are formulated for that purpose. One of the aims of protection of the environment[34] identified in ICRP Recommendations is “the maintenance of the integrity of ecosystems, which depends on surviving and reproducing populations”. The 2007 ICRP Recommendations [256] endorsed this aim and subsequently provided practical guidance in a series of reports on the subject [259, 260] (see Annex VIII). Thus, people are protected at the level of the individual, while the living components of the environment (flora and fauna) are generally protected at the population level.

[34] Protection of the environment includes the protection and conservation of: non-human species, both animal and plant, and their biodiversity; environmental goods and services such as the production of food and feed; resources used in agriculture, forestry, fisheries and tourism; amenities used in spiritual, cultural and recreational activities; media such as soil, water and air; and natural processes such as carbon, nitrogen and water cycles [220].

ICRP recommendations at the time of the accident

The dose limits for planned exposure situations recommended by the ICRP were the same in 2007 as in 1990 (Table 4.3–1). These limits refer to the total (additional) dose from regulated sources (in addition to natural background) to any individual in planned exposure situations other than the medical exposure of patients.

TABLE 4.3–1. DOSE LIMITS RECOMMENDED FOR PLANNED EXPOSURE SITUATIONS [192, 256]

Type of limit	Occupational	Public
Effective dose	20 mSv per year, averaged over defined periods of five years, and not exceeding 50 mSv in any single year[a]	1 mSv in a year (in special circumstances a higher value could be allowed in a single year provided that the average over five years does not exceed 1 mSv per year)
Annual equivalent dose to the:		
Lens of the eye[b]	150 mSv	15 mSv
Skin (averaged over 1 cm[b])	500 mSv	50 mSv
Hands and feet	500 mSv	—

[a] Additional restrictions apply for pregnant women.
[b] Reduced in 2011 [261, 262] for occupational exposure to 20 mSv in a year averaged over defined five year periods, with no single year exceeding 50 mSv.

Accidents, by definition, are not controllable, nor are they planned exposure situations. Consequently, dose limits do not apply. The ICRP presented principles for intervention for protection of the public in a radiological emergency in its Publication 63 [263]. It included recommended intervention levels as a range of optimized intervention values. Subsequently, in 1999, the ICRP published recommendations on the protection of the public in situations of prolonged exposures [264] (which could result from accidents). Generic reference levels for intervention were provided. They established a range from a total existing annual dose of ~100 mSv, above which intervention would almost always be justifiable, to ~10 mSv, below which intervention was not likely to be justifiable.

These *generic reference levels* of *existing annual dose* were specified for intervention in prolonged exposure situations. This position was based on several considerations, including natural background radiation levels and the detriment expected at such radiation levels. It is acknowledged that sometimes intervention will be justified below an annual dose of 10 mSv, and that radiation protection considerations are one input to decision making.

Concerning occupational exposures in emergency exposure situations, the ICRP recommends no dose restrictions for informed volunteers in life saving actions. For other urgent rescue operations, the 1990 ICRP Recommendations suggested an intervention level of about 500 mSv, while the 2007 Recommendations indicated reference levels[35] of at most about 1000 or 500 mSv, depending on circumstances. Reference levels of dose for other rescue operations should, according to the 2007 Recommendations, be selected at or below 100 mSv. Additional advice on occupational exposure in emergencies is given in ICRP Publication 96 [265]. Reference levels are not dose limits (see Section 4.3.2.1 concerning the use of dose limits in Japanese regulations). However, it is recommended that those undertaking recovery and restoration work in a later phase, after the termination of an emergency, should be protected according to normal occupational radiation

[35] Reference levels are defined in the 2007 ICRP Recommendations as: "the level of dose or risk, above which it is judged to be inappropriate to plan to allow exposures to occur, and below which optimization of protection should be implemented" [256].

protection standards, i.e. for such occupational exposure, the recommended dose limits for planned exposure situations should apply.

The various dose criteria recommended for public exposure in emergency exposure situations are complicated, because they refer to a multitude of different exposure pathways and possible actions (some of which are disruptive) to reduce exposures. Pertinent ICRP reports are enumerated in Annex VIII. The 2007 ICRP Recommendations suggested that, in planning for emergency situations, a reference level for the highest planned residual doses[36] in emergency situations would be selected typically between an acute or annual effective dose of 20 and 100 mSv, depending on the situation.

The existing exposure situation that develops after an emergency poses challenging questions concerning public exposures. Even if it is technically possible to reduce doses due to accident residues to below the public dose limit of 1 mSv/y, the actions required could be prohibitively disruptive. Thus, the ICRP does not recommend that the dose limit for the public be applied to existing exposure situations.

In Publication 82 [264], the ICRP concluded that interventions to reduce doses after an emergency event were unlikely to be justifiable, in the radiation protection sense, for existing doses (i.e. the total dose due to the accident and due to other causes) to members of the public below about 10 mSv/year. Interventions would almost always be justifiable for doses approaching 100 mSv/year. The 2007 ICRP Recommendations proposed that in existing exposure situations, a reference level of *residual dose* (after the application of protective strategies) to members of the public be selected between 1 and 20 mSv/year, according to the situation. The main factors to be considered for setting the reference levels are the feasibility of controlling the situation and past experience with the management of similar situations. While this allows for optimized actions that are adapted to the prevailing situation, regulatory authorities as well as members of the public often tend to favour the lowest number in any dose band. ICRP Publication 111 [266] suggested that a typical long term reference level of residual dose would be 1 mSv in a year. However, it is also recommended that the prevailing circumstances should be taken into account and that intermediate reference levels be adopted to improve the situation progressively.

These reports stress, in general terms, the importance of the optimization of radiological protection. Techniques are well developed for balancing the adverse health effects of radiation and different kinds of costs of protective measures [267–269]. However, little international guidance is available on optimization in emergency and existing exposure situations. Such situations will usually require the assessment of possible adverse health effects associated with the actual protective actions, and the cost implications will usually go beyond the expertise of radiation protection specialists. Further details concerning the 1990 and 2007 ICRP Recommendations, and several guidance reports supplementing these two sets of recommendations, are provided in Annex VIII.

4.3.1.3. International safety standards issued by the IAEA

The IAEA safety standards have their foundation in the IAEA's Statute, which authorizes the organization:

> "to establish or adopt, in consultation and, where appropriate, in collaboration with the competent organs of the United Nations and with the specialized agencies concerned, standards of safety for protection of health and minimization of danger to life and property ... and to provide for the application of these standards" [270].

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[36] Residual dose: the dose expected to be incurred after protective actions have been terminated (or after a decision has been taken not to take protective actions) [220].

A decision by the IAEA Board of Governors in 1960 states that:

> "The Agency's basic safety standards ... will be based, to the extent possible, on the recommendations of the International Commission on Radiological Protection (ICRP)." [271]

The standards include the International Basic Safety Standards (BSS) [220, 243, 257] established jointly by several United Nations and other international bodies and published by IAEA; the IAEA safety standards; and standards from other standard setting organizations, including FAO, the ILO and WHO.

The IAEA safety standards are a system of fundamental safety principles, safety requirements (including the BSS) and safety guides. As the primary publication in the IAEA Safety Standards Series, the Fundamental Safety Principles establishes the basic safety objectives and principles of protection and safety for ensuring the protection of the public and the environment, now and in the future, from the harmful effects of ionizing radiation. Safety requirements publications, such as the BSS, establish the requirements that must be met to ensure the protection of people and the environment, both now and in the future, in accordance with the objective and principles of the Safety Fundamentals. Safety guides provide recommendations and guidance on how to comply with the safety requirements, indicating an international consensus on the measures recommended.

While regulating safety is a national responsibility, international standards and harmonized approaches to safety promote consistency, help to provide assurance that nuclear and radiation related technologies are used safely, and facilitate international technical cooperation, commerce and trade. The methodology used in this and other technical volumes is to use IAEA safety standards in force at the time of the accident as the basis of assessment; they are considered to represent international consensus regarding requirements and guidance that is necessary to ensure radiation protection and nuclear safety. However, the use of these standards does not imply that Member States are required to follow them or that they are the only means of ensuring protection and safety.

The IAEA Statute makes the safety standards binding on the IAEA in relation to its own activities. They are not by default binding on Member States, but any State entering into an agreement with the IAEA concerning any form of IAEA assistance is required to comply with the requirements of the safety standards that pertain to the activities covered by the agreement. Many States chose to use the IAEA safety standards as templates for their own legislation and regulations. Many other States, including Japan, use legislation and regulations adapted to their own situation and traditions. While Japanese regulations are not explicitly based on the BSS, the regulations related to radiation protection at the time of the Fukushima Daiichi accident were consistent with the 1996 BSS then in force [243], which reflected the ICRP 1990 Recommendations [192].

IAEA safety standards in force at the time of the accident

The key safety standards addressing radiation protection and emergency response in place in March 2011 were:

— The Safety Fundamentals, IAEA Safety Standards Series No. SF-1: Fundamental Safety Principles [251];
— Safety Requirements: Safety Series 115: International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS) [243] (now superseded by GSR Part 3 [257]);
— Safety Requirements: IAEA Safety Standards Series No. GS-R-2: Preparedness and Response for a Nuclear or Radiological Emergency [252];

— Safety Guide: IAEA Safety Standards Series No. GS-G-2.1: Arrangements for Preparedness for a Nuclear or Radiological Emergency [272].[37]

The Fundamental Safety Principles, established by the international organizations mentioned above and issued by the IAEA, underpin the relevant safety conventions and were formulated following the previous ICRP Recommendations, including their basic principles of justification, optimization and limitation [251].

A relevant fundamental safety principle is that of emergency preparedness and response, which require that arrangements must be made for emergency preparedness and response for nuclear or radiation incidents. According to this principle, the primary goal of emergency preparedness is to ensure that arrangements are in place for a timely, managed, controlled and effective response at the scene, and at the local, regional, national and international level to any nuclear or radiological emergency [252].

The BSS in force at the time [243] were published in 1996 and were based primarily on the 1990 ICRP Recommendations. The BSS established basic requirements for the protection of people and the environment against the risks of exposure to ionizing radiation, and for the safety of sources that deliver such exposure.

The 1996 BSS incorporated the concepts of practices and interventions from ICRP Publication 60. They included emergency situations and requirements for intervention. The radiation protection requirements for intervention include justification of intervention; optimization of intervention; and action levels of dose, as explained in more detail in Annex VIII.

An intervention is justified if it is expected to achieve more good than harm, with regard to health, social and economic factors. Regarding the protection of workers undertaking an intervention, the 1996 BSS required that:

> "When undertaking intervention…, all reasonable efforts shall be made to keep doses to workers below twice the maximum single year dose limit, except for life saving actions, in which every effort shall be made to keep doses below ten times the maximum single year dose limit in order to avoid deterministic effects on health. In addition, workers undertaking actions in which their doses may approach or exceed ten times the maximum single year dose limit shall do so only when the benefits to others clearly outweigh their own risk." [243]

The Safety Requirements on Preparedness and Response for a Nuclear or Radiological Emergency [252] were published in 2002 and were sponsored by the FAO, IAEA, ILO, OECD/NEA, OCHA, PAHO and WHO . These standards establish requirements for an adequate level of preparedness and response for a nuclear or radiological emergency in any State. They provide a structure and comprehensive details for all the requirements relating to emergency preparedness and response established in other IAEA safety standards. The Safety Guide on Arrangements for Preparedness for a Nuclear or Radiological Emergency [272] is intended to assist Member States in the application of the Safety Requirements [252] and to help in fulfilling the IAEA's obligations under the Convention on Assistance in the Case of a Nuclear or Radiological Emergency.

Further details on the international framework on emergency preparedness and response in the event of a nuclear or radiological emergency are given in Technical Volume 3.

[37] General Safety Guide: IAEA Safety Standards Series No. GSG-2: Criteria for Use in Preparedness and Response for a Nuclear or Radiological Emergency [273] was available on the IAEA website on 17 March 2011.

At the time of the Fukushima Daiichi accident, the 1996 edition of the BSS [243] was in the final stages of revision. The revised BSS was published in November 2011 as an interim version [257] (see Annex VIII). The final version was published in 2014 [220]. The Safety Guide on Criteria for Use in Preparedness and Response for a Nuclear or Radiological Emergency (GSG-2) [273] was published on 17 March 2011, after the accident. The generic approach and criteria in this Safety Guide are consistent with GSR Part 3 (2014 BSS).

4.3.1.4. Radiation protection issues in international treaties and conventions

A number of international conventions are implicitly or explicitly connected to the international radiation protection standards established by relevant international organizations. For example, the ILO Radiation Protection Convention (ILO 1960 [274]) sets out legally binding requirements on occupational exposures to radiation. The Convention on Early Notification of a Nuclear Accident (Early Notification Convention) [275] and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (Assistance Convention) [276] were adopted in 1986, and place legally binding obligations related to nuclear and radiological accidents on the parties to these conventions and on the IAEA. Article 16 of the Convention on Nuclear Safety [277] and Article 25 of the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management (the Joint Convention) [278] establish legally binding obligations related to emergency preparedness for the parties to the conventions, while other articles relate to other aspects of radiation protection and safety.

Japan, like many other countries, is a signatory to a range of international conventions pertaining to radiation issues and is thus subject to certain obligations. More information is provided in Annex VIII. Information on the conventions directly related to emergency preparedness and response, notably the Early Notification and Assistance Conventions, is provided in Technical Volume 3.

ILO Radiation Protection Convention

The ILO is a specialized agency of the United Nations that promotes social justice and human and labour rights. Its structure is unique in that it is the only tripartite United Nations agency, with employer and worker representatives in addition to government delegations. Radiation protection is a component of the ILO mandate to protect workers against sickness, disease and injury arising from employment. Several requirements were established in its 1960 Convention Concerning the Protection of Workers against Ionizing Radiations (ILO Radiation Protection Convention) (Annex VIII) [274].

This convention sets out requirements: for ensuring the effective protection of radiation workers and other workers from exposure to ionizing radiation; for setting and reviewing dose limits and limits of intake; and for providing adequate warnings and information on potential health hazards due to radiation. It also defines requirements for follow-up action in the event of significant exposures of workers, including medical examinations, notification of competent authorities, workplace inspections and remedial actions. When assessing compliance with the convention's requirements, the ILO refers to the BSS.

Japan has been bound by the terms of the ILO Radiation Protection Convention [274] since 1973. Its Competent Authority for this convention is MHLW.

Convention on Nuclear Safety

The Convention on Nuclear Safety (CNS) [277], for which the IAEA is the Secretariat, is an incentive instrument based on the common interest of its Contracting Parties to achieve higher levels of safety. It obliges participating States operating land based nuclear power plants to submit reports for discussion at periodic review meetings of the Contracting Parties.

The obligations of the Contracting Parties are based to a large extent on the principles contained in the Fundamental Safety Principles (IAEA Safety Standards Series No. SF-1) [251]. The convention's criteria related to radiation protection are established in Article 15 (see Annex VIII) and include the principle that exposures to workers and the public from the nuclear installation be kept as low as reasonably achievable and that individual doses not exceed national dose limits. The convention also includes the requirement to "prevent accidents with radiological consequences and to mitigate such consequences should they occur" [277].

Japan has been bound by the terms of the CNS since 1996. For reporting purposes, the Competent Authority was the Nuclear and Industrial Safety Agency (NISA) and is now the Nuclear Regulation Authority (NRA). [38]

Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management

The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (the Joint Convention) [278], for which the IAEA is the Secretariat, focuses on the management of spent fuel and radioactive waste resulting from civilian nuclear reactors and applications. It also applies to spent fuel or radioactive waste from military or defence programmes, if so declared by the Contracting Party, and if and when such materials are transferred permanently to and managed within exclusively civilian programmes. The convention also applies to discharges, i.e. planned and controlled releases into the environment of liquid or gaseous radioactive material from regulated nuclear facilities, and radioactive waste management as defined by the Convention.

Relevant requirements are provided in Articles 24 and 25 of the convention (see Annex VIII). Article 24 relates to the safety of spent fuel management facilities and to the prevention and mitigation of unplanned and uncontrolled releases of radioactive material into the environment. In Article 25, the convention establishes the necessity of implementing and exercising adequate on-site and off-site emergency plans in spent fuel management facilities. The convention also makes reference to protection of the environment in Articles 4, 6, 11 and 13, as outlined in more detail in Annex VIII.

Japan has been bound by the terms of the Joint Convention since 2003. Its Competent Authority is the Ministry of Foreign Affairs.

4.3.2. Radiation protection regulations in Japan at the time of the accident

The Japanese legislation on radiation protection comprises primarily the Atomic Energy Basic Act [279], the Act concerning Prevention from Radiation Hazards due to Radioisotopes, etc.(hereinafter referred to as the Prevention Act [280]), and the Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors (hereinafter referred to as the 'Reactor Regulation Act') [281] (see Annex VIII). Several additional laws apply to the operation of nuclear installations (see Technical Volumes 1 and 2), for instance, the Act on Special Measures Concerning Nuclear Emergency Preparedness [282] and the Industrial Safety and Health Act [283]. Regulations and legislation applicable to the national emergency preparedness and response (EPR) system in Japan prior to the accident are described in Technical Volume 3.

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[38] In June 2012, the Establishment of the Nuclear Regulation Authority Act was passed. This established the NRA as an independent commission in charge of all of the nation's nuclear regulatory functions. The NRA replaced the organizations previously responsible for nuclear safety regulation, including NISA. This restructuring separated the government's nuclear regulatory function from that of nuclear power promotion. The reform also established the Nuclear Emergency Preparedness Commission under Japan's cabinet and required the new regulatory body to incorporate the latest scientific and technical knowledge into the nation's nuclear regulatory basis.

The Atomic Energy Basic Act [279] establishes a general framework for the regulation of nuclear activities, deferring specific aspects to subsequent separate acts. Radiation protection issues are governed by the Prevention Act and the Reactor Regulation Act.

The Prevention Act [280] authorizes the issuing of ordinances on radiation protection, prescribes occupational and public dose limits for facilities where radioactive material is used, and for the handling of radioactive material. The Reactor Regulation Act and other relevant legislation also prescribe regulations on radiation protection for facilities where nuclear materials are used. They were supervised at the time of the accident by NISA and the Ministry of Education, Culture, Sports, Science and Technology (MEXT); they are now supervised by the NRA, which also prescribes dose limits for ionizing radiation. The Regulation Law authorizes the issue of ministerial ordinances on radiation protection, such as the Ordinance on Dose Limits, which sets out occupational dose limits for personnel under the Industrial Safety and Health Act (staff of NPP operators and contractors working on-site). People working for public agencies had occupational radiation limits defined in specific regulations; for example, the Prefectural Nuclear Emergency Plans defined dose limits for off-site responders.

This set of laws, acts, ordinances, and other regulatory instruments defines the application of the system of radiation protection in Japan. It is not based explicitly on the international standards, but is generally aligned with them and with the recommendations of the ICRP.

4.3.2.1. Occupational exposures

Dose limits for occupational exposure to ionizing radiation during normal operation, i.e. in what is now termed planned exposure situations, are given in the MHLW Ordinance on Prevention of Ionizing Radiation Hazards [198] and, in the case of NPPs, the Ministry of Economy, Trade and Industry (METI) Ordinance on Installation of Commercial Nuclear Power Reactors [284], the METI Notification for Dose Equivalent Limits on the Basis of the Ministerial Ordinance [285] and the National Personnel Authority Rules 10–5 (Prevention of Radiation Injuries in Staff) [286]. They are in line with the 1990 Recommendations of the ICRP [192]. For example, a limit on effective dose of 20 mSv averaged over defined five year periods is stated, with the added provision that the dose must not exceed 50 mSv in any single year. Additional restrictions apply, as in the 1990 ICRP Recommendations, to equivalent dose in the lens of the eye, the skin and to female workers who have declared a pregnancy.

The regulations include an additional restriction on the effective dose rate to female workers who could potentially become pregnant of 5 mSv every three months, with the purpose of reducing the probability of the fetus receiving a dose in excess of 5 mSv [287]. This provision reflects older international recommendations issued at a time when the effective dose limit was 50 mSv/y. The 1990 ICRP Recommendations, as well as the 2007 ICRP Recommendations, considered that no special occupational dose limit was required for women in general [192, 256].

For emergency situations, the ordinance laid down a dose limit for workers of 100 mSv in an event. This was more restrictive than the ICRP Recommendations of 1990 [192] or 2007 [256], or the BSS of 1996 [243] and 2011 [257]. The ICRP Recommendations point out that dose limits are not intended for emergency situations. It may not be possible in a serious accident to undertake justified work within the dose limits permitted in normal conditions, and some relaxation of controls can be permitted without lowering the long term level of protection.

The ICRP recommendations and the 2011 Interim BSS [257] provide a reference level or guidance values for effective dose of up to 100 mSv.[39] While the numerical value equals the Japanese dose limit, the concepts are different, since exceeding a reference level is not necessarily an infraction of any laws or regulations. International guidance recognizes that there are situations where higher exposures could be justifiable, for example, if the exposure is unavoidable or occurs in exceptional situations, such as to save life or prevent serious accidents. For such situations, the guidance is that every effort should be made to keep effective doses below 500 mSv.

TEPCO had, and continues to have, a comprehensive set of internal rules and guidelines on radiation protection matters. These describe the applicable legislation and set out in detail the steps that TEPCO workers must follow in order to ensure compliance with the official regulations. They also cover legal requirements on the operator with respect to public exposures (see Annex VIII).

4.3.2.2. Public exposures

A dose limit for members of the public of 1 mSv in a year[40], consistent with ICRP Recommendations and the BSS, is provided for exposures due to radioactive sources in the Ordinance of the Prevention Act. The dose limits associated with nuclear installations are stipulated in the Ordinance of the Reactor Regulation Act. Discharge authorizations for nuclear installations in planned exposure situations, aimed at keeping doses to members of the public below 1 mSv in a year, were issued by NISA and are now issued by the NRA [288].

4.3.3. Aspects of radiation protection relevant to the response

This section discusses specific aspects of radiation protection associated with the accident at the Fukushima Daiichi NPP related to the limitation of doses to members of the public, limitation of doses to emergency workers and radiation protection lessons learned.

As indicated above, international safety standards addressing emergency preparedness and response and the transition from the emergency phase to an existing exposure situation were in place, notably in IAEA Safety Standards Series No. GS-R-2 [252], published in 2002. However, in their response to the accident, notably in the transition phase, the Japanese authorities decided to apply the recent ICRP recommendations in making radiation protection decisions. As explained above, around one year before the accident, the ICRP had issued specific recommendations for the application of the ICRP Recommendations to the protection of people in emergency exposure situations [289] and of people living in long term contaminated areas after a nuclear accident or a radiological emergency [289]. At the time of the accident, this guidance had not been applied in practice.

4.3.3.1. Radiation workers and others engaged in radiation emergency situations

There were major challenges encountered in the monitoring and controlling of doses for on-site emergency workers. These challenges were resolved in a staggered manner over an extended time period, which is described in detail in Technical Volume 3, Section 3.2. For example, electronic personal dosimeters (EPDs) and dose reading devices were unusable for a time, and appropriate personal protection equipment (such as protection masks) were not always available or were improperly used, resulting in workers receiving enhanced inhalation exposures (Section 4.2.1).

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[39] A guidance value of 100 mSv is specified for restricting exposure of emergency workers involved in tasks to avert a large collective dose [257].

[40] Additional dose, excluding background.

For workers engaged in a radiation emergency situation, a dose limit was specified in the pertinent ordinances of MHLW [198] and the Notification for Dose Equivalent Limits on the Basis of the Ministerial (METI) Ordinance, at an effective dose of 100 mSv, at an equivalent dose of 300 mSv for the lens of the eye and at an equivalent dose of 1 Sv (1000 mSv) for the skin. As indicated in Section 4.3.5, this differs from (and is more restrictive than) the approach included in international guidance, which recommends reference levels rather than dose limits.

The dose limit for workers engaged in a radiation emergency situation was revised from 100 mSv owing to the need to undertake specific tasks to prevent further worsening of the nuclear accident. An increased emergency dose limit of 250 mSv was selected in several successive decisions, with the overriding aim of keeping doses as low as reasonably achievable while still permitting required emergency actions to be carried out.

The details of the decisions are as follows:

- Through an Exemption Ordinance issued on 15 March 2011[41], the emergency dose limit was raised from 100 mSv to 250 mSv to allow necessary activities to continue on-site and within a radius of 30 km of the Fukushima Daiichi NPP [177, 290].
- On 1 November 2011, the Exemption Ordinance was revised. For workers who were first engaged in emergency work after this date, the emergency dose limit was decreased to the original 100 mSv level, except for certain tasks as specified by MHLW. These concerned work on troubleshooting tasks for reactor cooling systems and radioactive material release suppression systems, for which the 250 mSv level was retained [178].
- The 250 mSv level was also retained as a transitional measure for workers who had been engaged in emergency work before 1 November 2011.
- On 16 December 2011, the Exemption Ordinance was abolished. This meant that the dose limits for planned exposure situations applied to most workers, as recommended by international standards [290].
- Workers engaged in maintaining the functions of reactor cooling systems and radioactive material release suppression systems were still subject to emergency dose limits, but at the original 100 mSv level.
- The 250 mSv level was retained until 30 April 2012 for a group of some 50 TEPCO workers with highly specialized knowledge and experience of the cooling and release suppression systems. These workers had been engaged in emergency work before 1 November 2011 and had accumulated doses exceeding 100 mSv [290].

These decisions were in line with the reference levels suggested in the ICRP recommendations and generic criteria in the BSS. However, it would not have been necessary to change regulatory provisions during the accident had the approach and levels proposed in the BSS and ICRP Recommendations been adopted in advance.

MHLW issued administrative guidance on radiation doses for workers previously engaged in emergency work who were then engaged in non-emergency work, which nevertheless exposed them to radiation [291]. Also, the national Government issued instructions to TEPCO regarding exposure and dose management for workers, including internal exposure, through the implementation of temporary health examinations, and so on, as decided in the Policy for Immediate Actions for the Assistance of Nuclear Sufferers by the Nuclear Emergency Response Headquarters on 17 May 2011. The Government has also required TEPCO to report periodically on the implementation status [184].

[41] Retroactive to 14 March 2011.

In addition, certain emergency operational work is required to be reported in advance to the Labour Standards Inspection Office to have provisions for exposure control for workers confirmed. Moreover, the policy requires that a database be created for tracking doses over the long term for all workers who were engaged in emergency work, even after they leave their current jobs, for conducting long term health management [292]. On 20 May 2011, MHLW established the Promotion Office for the Measures for the Health Management of Workers of TEPCO Fukushima Daiichi NPP to promote the above measures.

Members of the SDF. The SDF are the unified self defense forces of Japan. By an order of the Minister of Defense on 12 March 2011, the SDF were engaged in a nuclear disaster relief mission. As such, the MHLW Ordinance on dose limits does not apply to national Government staff (including the SDF). However, the SDF have their own regulations with the same dose limits as those given in the MHLW Ordinance.

Members of the firefighting teams. Firefighters are local government employees and are subject to the MHLW Ordinance. However, the relevant supervisory organization is the personnel committee of the local government. The dose limits specified in the MHLW Ordinance for planned exposure situations were not exceeded (see Technical Volume 3 for more information).

4.3.3.2. Members of the public

As explained in Section 4.3.1, dose limits for the public do not apply during an emergency exposure situation or in the exposure situation following an accident. It may be impossible to keep doses following an accident below the limits for planned situations, or actions required to keep doses below limits might be unjustifiably disruptive and/or associated with other adverse impacts. In an emergency exposure situation, countermeasures (or protective actions) are implemented as described below, based on the dose averted by different actions (Tables 4.3–2 and 4.3–3). This may be complicated and disruptive in practice [256].

The protective actions applied to reduce exposures of members of the public, and the basis for decisions, are described in detail in Technical Volume 3. The doses received by members of the public after the Fukushima Daiichi accident are presented in Section 4.2.2 of this volume.

Urgent protective actions: Sheltering, evacuation, stable iodine intake, food restrictions

In the emergency phase, urgent protective actions may need to be considered in order to mitigate the exposure of members of the public. International recommendations on criteria for urgent protective actions have been published by the ICRP [192, 256] and, in the form of international safety standards, by the IAEA (co-sponsored by other international bodies) [243, 252]. At the time of the accident, the guidance used in Japan was expressed in terms of projected dose. Those recommendations are summarized in Tables 4.3–2 and 4.3–3. The actions taken in Japan are presented in Technical Volume 3, Section 3.2.

Sheltering involves remaining indoors while the radioactive plume is passing, with doors and windows closed, and ventilation systems shut off, to reduce inhalation and external irradiation doses from the radioactive plume and from radioactive material deposited on the ground. Sheltering can reduce external radiation doses by an order of magnitude or more. For example, sheltering in cellars can reduce inhalation doses by a factor of about 2 [263].

Evacuation involves the temporary removal of persons from a contaminated or potentially contaminated area to one which is free of contamination or contaminated to a lesser extent. Effective evacuation can prevent exposures from all significant pathways, including external exposure, and inhalation of airborne radionuclides. Evacuation is not recommended for a period of much longer than one week. For longer term protection, temporary relocation or permanent resettlement may be required.

TABLE 4.3–2. SUMMARY OF INTERNATIONAL RECOMMENDATIONS ON SHELTERING AND EVACUATION

Countermeasure	Organization	Intervention level[a] (mSv)	Integration time
Evacuation	IAEA[b]	50	No more than 1 week
	ICRP[c]	50–500	<1 week
Sheltering	IAEA[b]	10	No more than 2 days
	ICRP[c]	5–50	2 days

[a] Avertable dose (the dose that could be averted if a countermeasure or set of countermeasures were to be applied)
[b] IAEA, GS-R-2, (2002) [252]
[c] ICRP, Pub. 63 (1991), [263], ICRP, Pub. 103 (2007) [256]

National emergency arrangements at the time of the accident envisaged that decisions on protective actions would be based on estimates of the projected dose to the public that would be calculated when a decision was necessary using a dose projection model — the System for Prediction of Environmental Emergency Dose Information (SPEEDI). However, estimates of the source term could not be provided as an input to SPEEDI owing to the loss of on-site power (see Techical Volume 3, Section 3.3). Initial decisions on protective actions were made on the basis of plant conditions although the arrangements at the time did not envisage that decisions on urgent protective actions for the public would be based on predefined specific plant conditions, as recommended in IAEA safety standards such as Ref. [252].

Stable iodine tablets (prophylaxis) taken before the arrival of the radioactive plume or within a few hours of the arrival of the plume, can effectively reduce uptake of radioactive iodine by the thyroid following inhalation[42], and thus significantly reduce the probability of thyroid cancer [263]. This is particularly important if the normal diet is poor in stable iodine (as was the case in Chernobyl, but not in Japan).

TABLE 4.3–3. SUMMARY OF INTERNATIONAL RECOMMENDATIONS ON STABLE IODINE INTAKE

Countermeasure	Organization	Intervention level (mSv)[a]
Stable iodine intake	IAEA–WHO [252]	100 mSv
	ICRP [263]	50–500 mSv

[a] Equivalent dose to the thyroid [252, 263].

Restrictions on foods

Protective actions to restrict the distribution and sale of contaminated food aim to reduce its consumption and any consequential detrimental radiation health effects, especially to children. This involves preventing contaminated food from entering supply chains by restricting the harvesting, collection and distribution of affected food at the point of production and, if necessary, withdrawing foods from sale. These protective actions also ensure the availability of food supplies with measured

[42] Food restrictions, e.g. withholding contaminated milk, may be more effective in reducing exposure from radioiodine.

or predicted activity concentrations less than pre-defined action or guideline levels, and they assist in maintaining public confidence in the commercial food supply. Similar restrictions could apply to the public water supply and other drinks; to animal feed, for reasons of public health rather than animal welfare; and to non-edible commodities.

The control of activity concentrations in this range of commodities associated with international trade is governed at the international level by a complex set of standards and guidelines from different organizations.

The Codex Alimentarius Commission (a body set up jointly by FAO and WHO) has recommended guidance levels (GLs) for the maximum activity concentrations in food acceptable as commodities in international trade (see Annex VIII). The Codex General Standard for Contaminants and Toxins in Food and Feed [293] includes revised guideline levels that apply to radionuclides contained in foods destined for human consumption and traded internationally following a nuclear or radiological emergency. They apply to food after reconstitution or preparation for consumption, i.e. not to dried or concentrated foods, and are based on a dose criterion for ingestion of 1 mSv in a year. When radionuclide levels in food do not exceed the corresponding GLs, the food should, as far as radiation protection of consumers is concerned, be considered safe for human consumption [293]. When the GLs are exceeded, national governments may decide whether and under what circumstances the food should be distributed within their territory or jurisdiction. National governments may wish to adopt different values for internal use within their own territories where the assumptions concerning food distribution that have been made to derive the GLs may not apply, for example in the case of widespread radioactive contamination. For foods that are consumed in small quantities, such as spices, which represent a small percentage of the total diet and hence a small addition to the total dose, the GLs may be increased by a factor of 10.

Generic action levels for foods to be used within the Accident State, based on earlier (1991) Codex guidelines [294], are provided in IAEA Safety Standards Series No. GS-R-2, which was jointly sponsored by the pertinent international and United Nations organizations [252]. It should be noted that action levels serve a particular purpose in an intervention following an emergency and are not the same as GLs, although for coherence, they were made numerically consistent with the GLs current at that time. These action levels differ from the revised Codex GLs in the following respects:

- The use of the GLs was originally intended to be limited to the first year after a nuclear emergency (in 1991, the Codex agreed that the applicable timespan for these GLs should be extended for an indefinite period after an emergency) [294].
- The GLs are based on a dose criterion of 5 mSv in a year (the generic action levels for foods originate from optimized intervention levels based on considerations of the benefits and detriments for the withdrawal and substitution of foodstuffs) [295].
- The GLs only apply to food in international trade and assume an annual consumption rate of 550 kg/y for adults or 200 kg/y for infants, with only 10% of food derived from affected countries and containing radionuclides.

The 1996 BSS [243] include the same Codex guidelines. However, the 2011 version of the BSS [257] requires Member States to develop food intervention levels, taking into account the current 2006 Codex guidelines.

ICRP Publication 63 [263] recommends both restrictions on the consumption of contaminated water and actions limiting the transfer of radionuclides into the food chain (such as housing grazing animals). According to the ICRP, for any single food, an intervention level that is almost always justified is an averted effective dose of 10 mSv in a year. If alternative food supplies are not readily available, intervention may be justified only at much higher levels of projected dose.

WHO has issued guidelines for drinking water quality, the fourth edition of which was published in 2011 [296]. However, the WHO GLs for radionuclides do not apply to drinking water supplies contaminated during emergency exposure situations.

Guidance on commodities (other than foods and drinking water) is provided by the IAEA in Safety Standards Series No. RS-G-1.7 [297]. It includes specific values of activity concentration for both radionuclides of natural origin (table 1 in Ref. [297]) and those of artificial origin (table 2 in Ref. [297]) that may be used for bulk amounts of material for the purpose of applying exclusion or exemption. It also elaborates on the possible application of these values to clearance.

The Japanese restrictions on food are described in more detail in Technical Volumes 3 and 5. A discussion of the approach applied is provided by Hamada and Ogino [168].

Early protective actions: Relocation

Relocation differs from evacuation mainly in terms of the time over which this action is taken. It may be undertaken as an extension to evacuation or it may be introduced weeks or months after an accident to reduce doses from deposited radionuclides and to allow remedial measures to be carried out. The duration of relocation may be permanent or for a limited period.

International guidance at the time of the Fukushima Daiichi accident on intervention levels of avertable dose for relocation and resettlement is shown in Table 4.3–4.

TABLE 4.3–4. SUMMARY OF INTERNATIONAL RECOMMENDATIONS ON RELOCATION AND RESETTLEMENT*

Countermeasure	Intervention level of avertable dose (mSv)	Integration time
Initiating temporary relocation	30	1 month
Terminating temporary relocation	10**	1 month
Permanent resettlement	1000	lifetime

* Refs [243, 252]; ICRP Pub. 96 (2005) [265])
** from IAEA, GS-R-2 (2002) [252]

A generic effective dose criterion of 100 mSv per year (projected dose) is included in the revised BSS (2014) [220] and in IAEA Safety Standards Series No. GSG-2 [273] for taking early protective actions, such as temporary relocation, decontamination and replacement of food, milk and water, and for public reassurance.

Inconsistencies concerning commodities

The various criteria described in the previous section have given rise to questions among the Japanese public. For example, the WHO drinking water reference level for ^{137}Cs is 10 Bq/L [296], but the Codex Alimentarius GL for foods (including fruit juice, for example) is 1000 Bq/kg (Annex VIII, Table VIII-6) [293]. This variation is due to the different circumstances in which these levels are intended to be used. For example, drinking water is essential and cannot always be replaced (the WHO guidelines for drinking water are not applicable in an emergency), while the Codex values relate to foods and liquids that can be replaced and that are traded internationally. There are more examples of criteria and restrictions, the logic of which is not immediately clear and which could have benefitted from more explicit explanations or supplementary recommendations (see, for example, González et al. [298]).

4.3.4. Reactions to the situation for radiation protection in Japan and globally

In the aftermath of the accident, many radiation protection questions were raised, not only by members of the public and their representatives but also by specialists, including those in the radiation protection community. Thus, soon after the accident, the ICRP convened a Task Group to compile the lessons learned with respect to the system of radiological protection. Its report [299] is aimed at the ICRP itself rather than the radiation protection community.

The ICRP report [299] does not discuss in depth the level of protection to be selected for protection of the public in an existing exposure situation, although other ICRP documents consider different arguments on this issue. Arguments in favour of using the high end of the pertinent dose band (>1–20 mSv) for public dose reference levels (i.e. emphasizing the reasoning advanced in ICRP Publication 82 [264]) are put forth by Hedemann-Jensen and McEwan [300], who also point to some inconsistencies in ICRP guidance that may warrant updating. Several papers also stress the confusion caused by public misunderstanding of the concept of reference levels and their application (e.g. Kai [301] and Sakai [302]).

Issues encountered in remediation after the accident are described in Technical Volume 5, Section 5.2. Remediation also generates radioactive waste, as indicated in Technical Volume 5, Section 5.4 (see also Annex VIII).

Section 4.3.5 below demonstrates that the evacuation and temporary relocation efforts entailed significant adverse effects. An optimization assessment in order to alleviate these side effects may indicate that generic criteria for relocation should be set above 20 mSv effective dose received in the first year following an accident. According to the 2014 BSS, the optimization of a protection strategy including relocation should be considered with a reference level in the range of 20–100 mSv residual effective dose [252].

4.3.5. Social issues associated with protective actions

As described in earlier sections, a range of protective actions were taken by authorities in Japan after the Fukushima Daiichi accident. These actions were generally successful in reducing doses to those living and working in the vicinity of the Fukushima Daiichi NPP, but in many cases, they impacted negatively on the daily lives of individuals and on communities.

4.3.5.1. The impact of evacuation and sheltering

As described in detail in Technical Volume 3, Section 3.3, there were many practical issues associated with implementing the evacuation of a large number[43] of people [215] at the same time as dealing with the consequences of the earthquake and tsunami. Infrastructure — roads, railways, public transportation, telephone and internet, electricity, gas, drinking water, supplies of food, petrol, heating oil, and so on — was significantly damaged. This affected transport, communication and coordination activities. There were difficulties in arranging the transportation and accommodation of hospital patients.

The implementation of evacuation, especially within the 20 km zone, was stressful for many of the evacuees. Traumatic situations and deaths of hospital patients during the transport out of the 20 km zone were documented [303], as described in detail in Section 3.3 of Technical Volume 3. Healthy people also suffered. The evacuation orders, together with the earthquake and tsunami damage to the

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[43] At the peak, in June 2012, around 160 000 people were involved, including people from a number of different evacuation areas.

road and railway systems, led to an effective suspension of the supply and distribution of goods. Many evacuees were accommodated in temporary shelters, such as large school auditoriums or other local municipal buildings. Many evacuees lived in uncomfortable conditions for several months, as illustrated in Fig. 4.3–1(a).

(a) (b)

FIG. 4.3–1. The initial evacuation led to crowded conditions in shelters. (a) A senior TEPCO executive apologizes to evacuees at an evacuation centre on 22 March 2011 (Photograph courtesy of Koichi Nakamura/AP Images/picturedesk.com); (b) the normal living conditions of the people who were relocated were greatly affected (Photograph courtesy of Dr Yujiro Kuroda/Fukushima Medical University).

Sheltering is normally considered to be less disruptive than evacuation, and different dose criteria are consequently applied. However, it is also generally considered to be a short term measure, extending for a period of two days [252]. Following the accident at the Fukushima Daiichi NPP, sheltering continued for a longer period, during which living standards of residents deteriorated as a consequence of isolation and lack of supplies. More information is provided in Technical Volume 3, Section 3.3.

4.3.5.2. Impacts of relocation

The deliberate evacuation affected Iitate Village and parts of Katsurao Village, Kawamata Town and Minamisoma City, and amounted to about 10 000 residents. The inhabitants living in these areas were allowed around six weeks to move from their homes. This enabled people and the communities to be better prepared, and some employees and elderly people were permitted to remain.

Construction of temporary housing began in the summer of 2011, leading to an improvement in living conditions; however, as illustrated in Fig. 4.3–1 (b), these conditions were still not ideal. In addition, there is the continued isolation of evacuees from their home community life. Opportunities for employment and for participation in community activities have been limited, and the temporary and uncertain situation has made planning for the future very difficult. As a consequence, evacuees have suffered psychologically and physically. More information on these issues is provided in Section 4.4.

Long term evacuation has also affected family structures. Before the accident, many residents lived in large farmhouses, often with three generations living together. After the accident, the number of households increased, because temporary housing units are generally too small to accommodate all family members. More information is presented in Technical Volume 5.

Local communities effectively disintegrate when their members move. Additionally, relationships within a community can and have been affected by inequities in the application of measures within it, due to zoning and the monetary compensation policies [304, 305] (see Technical Volume 5 for further information on compensation policies).

4.3.5.3. The impacts of applying remediation criteria

The two level nature of internationally recommended reference levels has led to some confusion among local residents in the affected areas. An effective dose criterion of 20 mSv/y (residual dose) was specified for lifting evacuation orders [306], but the existence of a lower reference level that was numerically equivalent to the annual effective dose limit of 1 mSv[44] for planned exposure situations appeared to imply that the situation was not safe. There was also a lack of clarity in international advice on long term residual doses (see Section 4.3.3). The choice to return to the evacuated and relocated areas may imply accepting that radiation doses are higher than before the accident. It may be possible to improve the situation on return by following guidance to avoid radiation exposure by avoiding hot spots and foods that exceed the established criteria. See Technical Volume 5 for more information.

4.3.5.4. Food safety standards and their impacts

Prior to the accident, there were no specific regulatory limits that applied to radionuclides in foods produced in Japan, but the guidelines of food and water restrictions in the Nuclear Safety Commission Regulatory Guide [307] were broadly consistent with international guidance. However, these levels had not been adopted in the regulations prior to the accident, as explained in detail in Technical Volume 3. Many local governments were not equipped and some were reluctant to perform the necessary tests on food owing to concerns about the possible harm to their reputation. There were thus differences in monitoring programmes instituted by different local governments. Some private sector companies began to perform tests voluntarily and some retailers adopted voluntary standards that were lower than the standards set by the Government [215]. Although restrictions on products for public consumption were important and necessary, they caused economic damage and social disruption to local producers.

Four years after the accident, the level of radiocaesium in the food produced in Fukushima Prefecture has decreased to close to background levels; no radiocaesium has been detected in most commercially available food produce in Fukushima Prefecture. However, a substantial fraction of the general public still refuses to buy food produced in Fukushima Prefecture [308].

4.3.6. Summary

There is an internationally accepted system for the protection of people and the environment from the harmful effects of ionizing radiation. It is founded on basic principles formulated in the system of radiological protection recommended by the ICRP, which have been established by international intergovernmental standards. These principles include:

- Justification of facilities and activities, namely that facilities and activities giving rise to radiation risks must yield an overall benefit so that actions that might alter the extant radiation exposure situation should produce more good than harm;
- Optimization of radiation protection, namely that protection be the best under the prevailing circumstances;
- Limitation of risks to individuals, namely that measures for controlling radiation risks ensure that no individual bears an unacceptable risk of harm.

[44] Additional dose, excluding natural background.

The principles embed an overarching principle of protection of present and future generations, namely that people and the environment, present and future, must be protected against radiation risks.

An international framework of agreements and standards related to radiation protection and safety exists that is based on international legally binding undertakings, international safety standards and international provisions for the application of those standards. The exposure and risk estimates undertaken by UNSCEAR provide the scientific basis for these standards. The recommendations and guidance of the ICRP also provide an input to many international safety standards developed, under the aegis of the IAEA and specialized organizations of the United Nations system. The recommendations of the ICRP have influenced the development of many international safety standards.

At the time of the accident, international requirements related to preparedness and response for a nuclear or radiological emergency were available in the form of IAEA Safety Standards Series No. GS-R-2 [252], which covered both the emergency phase and the transition from the emergency to long term recovery. However, at the time of the accident, the general requirements on radiation protection (the international Basic Safety Standards, BSS) were being revised to take account of, among other things, the recently revised recommendations of the ICRP. A draft version of the new standards had been available since 2009. The interim version of the new BSS was not available until November 2011, several months after the accident. The Government of Japan decided to apply the ICRP recommendations in making decisions related to the transition phase.[45]

Radiation protection measures taken after the Fukushima Daiichi accident helped to limit the radiation doses to the public, but the complex nature of the distribution of doses across communities, within and beyond the 20 km evacuation zone, demonstrate the influence of evacuation timing, location and destination on the doses received. Furthermore, these measures have also had a variety of effects on the well-being of individuals and communities in the affected areas and severely disrupted the daily life of people. The impact of these protection measures may not always be commensurate with the benefits achieved by the protection.

4.3.7. Observations and lessons

— **Relevant international bodies need to develop explanations of the principles and criteria for radiation protection that are understandable for non-specialists in order to make their application clearer for decision makers and the public. As some protracted protection measures were disruptive for the affected people, a better communication strategy is needed to convey the justification for such measures and actions to all stakeholders, including the public.**

  There is a recognized need for simple explanations of a number of radiation protection issues, including:
  - Differences between the concepts of dose limits and reference levels and the associated rationale;
  - Criteria for the justification of protective measures and actions aimed at averting radiation doses in the long term, in particular when they involve significant disruptions to normal life;
  - Specific situations relating to the radiation protection of emergency workers.

  The principles of radiation protection are based not solely on science but also on value judgements based on ethical principles. In some circumstances, protective measures and actions involve protracted social disruption. Under these circumstances, the potential benefit from

[45] NUCLEAR SAFETY COMMISSION, Provisions for a Deliberate Evacuation Area and an Evacuation-prepared Area (2011),
http://www.nsr.go.jp/archive/nsc/NSCenglish/geje/20110410advise_1.pdf

avoiding radiation doses must outweigh the individual and social detriment caused by the protective measures and actions themselves. It is important to explain to stakeholders the justification for long standing radiation protection measures and actions.

— **Conservative decisions related to specific activity and activity concentrations in consumer products and deposition activity led to extended restrictions and associated difficulties. In a prolonged exposure situation, consistency among international standards, and between international and national standards, is beneficial, particularly those associated with drinking water, food, non-edible consumer products and deposition activity on land.**

  The current international system for controlling radioactivity in consumer products is governed by distinct guidance, e.g. the Codex Alimentarius for food (including bottled water) in international trade, IAEA safety standards for food and drinking water for use in an emergency, WHO guidelines for drinking water in existing exposure situations and IAEA safety standards for non-edible products for exemption purposes. There is a need for harmonization among the international standards for acceptable levels of radioactivity in products for public consumption in order to facilitate their application by regulatory bodies and their understanding by the public. National standards need to be in line with international standards, where this is feasible. Moreover, there is a need for criteria for dealing with the protracted presence of radionuclides on land.

  Guidance also needs to be developed for international trade to control of contaminated non-edible commodities. There is a need for transparency in the derivation and implementation of reference levels of activity in food and other commodities to facilitate understanding. The terminology used needs to be clarified. Moreover, existing guidelines do not fully address commodities assessed by measuring surface activity (there is a need for criteria in terms of Bq/cm^2). A review is needed to identify any gaps in existing international standards and to identify the work necessary to achieve an international consensus on such standards.

— **Education and training in radiation protection should be continuous for all stakeholders and should be regularly updated.**

  There is always room for even more preparation in radiation protection. While radiation protection was successful, given the scale of the earthquake and tsunami and the concomitant nuclear accident, some gaps in procedures occurred; the experience needs to be used to achieve further improvements and resilience should accident an accident occur in the future.

4.4. HEALTH CONSEQUENCES

Since the Fukushima Daiichi accident, one of the foremost concerns for the people of Japan has been the possible health consequences that might arise from the release of radioactive material from the damaged reactors. This concern has been especially important for those in the regions surrounding the Fukushima Daiichi NPP who have been directly affected by evacuation, and/or for workers from the plant who were present at the time of the accident or who have participated in emergency or remedial actions. This section provides a description of the possible health consequences of the accident in the light of the information available at the time of writing.

According to the WHO, *health* is “a state of complete physical, mental and social well-being, not merely the absence of disease” [309]. This section thus addresses two types of possible consequences: detrimental (physical) health effects that may be caused by exposure to radiation; and indirect effects arising from experiences due to the situation during and following the accident, including reactions to the presence of radiation, such as effects on mental well-being. The first type of effect is reviewed extensively in this section and the supporting annexes. However, only a preliminary discussion of information on the second type of health effect is available at the time of writing and can therefore be provided here. Societal consequences, as distinct from health consequences, are reviewed in Sections 4.3.5 of this volume and in Technical Volume 5, Section 5.5.

As indicated in Section 4.2 above, there have been two earlier international assessments of the possible health consequences of the Fukushima Daiichi accident: one by WHO [201] and one by UNSCEAR [5]. These are described in Section 4.4.1.

Section 4.2 of this report provides estimated radiation doses to workers and to the public as a result of the accident. In order to appreciate the health significance of these exposures, it is important to be aware of the current extent of scientific knowledge concerning the relationship between radiation dose and possible harmful consequences that can be attributed to radiation. Annex X summarizes the known effects of radiation on human health and how assessments of possible future risk from radiation exposure are made.

The health of people living in the regions surrounding the Fukushima Daiichi NPP and of workers who were engaged in emergency or remedial work following the accident is being monitored through ongoing studies. Section 4.4.2 reviews post-accident studies in Japan, including the FHMS, which is tracking the health of members of the public and the results of surveys of the health of workers at the Fukushima Daiichi NPP.

Section 4.4.3 presents the evidence on observable health effects of the accident, and Section 4.4.4 describes surveys of thyroid effects. The possibility of thyroid malignancies arising from exposure to ^{131}I released from the NPP is the most significant potential radiation related health issue associated with the accident. This is being dealt with in depth using primarily thyroid ultrasound surveys. Some background material to assist in understanding possible thyroid effects is given in Annex IX.

The possibility of delayed effects on health in the future is explained in Section 4.4.5. This is based on the dose estimates presented in Section 4.2 and modelling of risks as described in Annex X. A preliminary consideration of the effects of the accident on mental health is presented in Section 4.4.6, recognizing that there are consequences of the earthquake and tsunami in addition to those arising from the Fukushima Daiichi accident. Finally, the assessment of health consequences is summarized in Section 4.4.7, with observations and lessons presented in Section 4.4.8.

4.4.1. Previous international assessments

This technical volume builds on earlier publications by WHO [201] and UNSCEAR [5] and is able to make assessments based on information that has become available since the publication of these reports. To clarify the relationship between these international assessments, the earlier reports are summarized here. The WHO report was initiated soon after the accident in order to provide advice on potential human health consequences as early as practicable, based on radiation dose estimates available at the time. The UNSCEAR decision to conduct an assessment of the levels of exposure and radiation risks attributable to the accident was endorsed by the United Nations General Assembly in December 2011. The present technical volume originated from an undertaking by the IAEA Director General that the IAEA would prepare a report on the Fukushima Daiichi accident. He stated that this would be “an authoritative, factual and balanced assessment, addressing the causes and consequences of the accident, as well as lessons learned” [310].

4.4.1.1. Assessment by WHO

Soon after the Fukushima Daiichi accident, WHO initiated a health risk assessment “to support the identification of needs and priorities for public health action and to inform Member States and the public” [201]. Its declared aim was to estimate “at global level the potential health consequences of human exposure to radiation during the first year” [201] after the accident. It was designed to cover “infants, children and adults living in the Fukushima prefecture, nearby prefectures, the rest of Japan, neighbouring countries, and the rest of the world” [201].

Because the health risk assessment required estimates of radiation doses received by the population, WHO first established an International Expert Panel "to make an initial evaluation of radiation exposure of people both inside Japan and beyond, as a result of the accident". The panel's report, issued in May 2012 [173], while taking into account all major pathways of exposure, was based on the monitoring data that was available for about the first six months following the accident, and projections derived therefrom. As a result, it is acknowledged to be a preliminary assessment and subject to refinement as further information becomes available.

This technical volume, based on more extensive monitoring data collected over a longer period, has shown that doses incurred by the population affected by the accident are lower than the estimates of the WHO preliminary report. WHO issued a health risk assessment of the Fukushima Daiichi accident in 2013 based on its 2012 dose assessment report [173, 201]. The assessment was conducted by independent international experts who were selected by WHO for their expertise and experience in relevant scientific and public health disciplines, including radiation dosimetry and radiation risk modelling.

The WHO risk assessment involved the following elements:

— The lifetime risk of cancer was modelled for all solid cancers combined (not including leukaemia), and separately for the individual cancer sites most closely associated with radiation exposure and with a known dependence of the magnitude of risk on age at exposure (leukaemia, thyroid cancer and female breast cancer).
— The lifetime risks were inferred for both sexes and three different ages at exposure (1 year (infant), 10 years (child) and 20 years (adult)).
— Predictions of the cumulative risks for the 15 years following the accident were also made.
— Health risks for male emergency workers were inferred for three different ages (20 years, 40 years and 60 years).

The conclusion of the WHO health risk assessment for the rest of the world was that:

> "[N]o discernible increase in health risks from the Fukushima event is expected outside Japan. Outside the geographical areas most affected by radiation, even in locations within Fukushima prefecture, the predicted risks remain low and no observable (i.e., attributable) increases in cancer above natural variation in baseline rates are anticipated." [201]

The assessment estimated that, within the Fukushima region, the lifetime risk for some cancers may be elevated above baseline rates in certain age and sex groups that were in the areas most affected. In the highest dose locations, the WHO preliminary estimates of effective doses for the first year ranged from 12 to 25 mSv. Based on this, the estimated lifetime attributable risks (LARs) for the development of leukaemia, breast cancer, thyroid cancer and all solid cancers over baseline rates are likely to represent an upper bound of the risk, as methodological options were consciously chosen to avoid underestimation of risks.

With an understanding that the calculations were performed to avoid underestimation, the WHO report concluded that:

— For leukaemia, the LARs are predicted to increase by up to about 7% over baseline cancer rates in males exposed as infants.
— For breast cancer, the estimated LARs could increase by up to about 6% over baseline rates in females exposed as infants.
— For all solid cancers, the estimated LARs could increase by up to about 4% over baseline rates in females exposed as infants.

— For thyroid cancer, the estimated LARs could increase by up to about 70% over baseline rates in females exposed as infants.

The WHO report emphasizes that "due to the low baseline rates of thyroid cancer, even a large relative increase represents a small absolute increase in risk" [201]. It also recognizes that the assessments were based on preliminary estimates of radiation doses and that the calculated percentages "represent estimated relative increases over the baseline rates and are not estimated absolute risks for developing such cancers" [201].

4.4.1.2. Assessment by UNSCEAR

As noted in Annex X, the issue of attributability of health effects to ionizing radiation is complex. In 2007, the United Nations General Assembly requested UNSCEAR "to clarify further the assessment of potential harm owing to chronic low-level exposures among large populations and also the attributability of health effects" [311].

UNSCEAR provided an answer to this request in its 2012 Report to the United Nations General Assembly [312]. It reached, inter alia, the following conclusion:

> "Increases in the incidence of health effects in populations cannot be attributed reliably to chronic exposure to radiation at levels that are typical of the global average background levels of radiation, among other reasons because of the uncertainties associated with the assessment of risks at low doses, the current absence of radiation-specific biomarkers for health effects and the intrinsic insufficient statistical power of epidemiological studies." [312]

UNSCEAR therefore decided to discourage the multiplication of very low doses by large numbers of individuals to estimate the number of radiation induced health effects within a population exposed to incremental doses at levels equivalent to or lower than natural background levels. It also noted that theoretical calculations of hereditary effects were unsubstantiated, regardless of the dose incurred. It advised that "although demonstrated in animal studies, an increase in the incidence of hereditary effects in human populations cannot at present be attributed to radiation exposure".

However, UNSCEAR underlined that public health bodies need to allocate resources appropriately, and that this may involve making projections of the risk of health effects for comparative purposes. "This method, though based upon reasonable but untestable assumptions, could be useful for such purposes provided that it were applied consistently, the uncertainties in the assessments were taken fully into account, and it were not inferred that the projected health effects were other than notional" [311].

In 2014, UNSCEAR published a report [5] in which it addressed the attribution of health effects to chronic low levels of radiation exposure monitored in the population affected by the Fukushima Daiichi accident. The key questions to be addressed are summarized as follows:

— To what degree a health effect that has been observed, either in an individual or as an increased incidence of health effects in a population, can be attributed to the chronic low levels of radiation exposure received by the population affected by the Fukushima Daiichi accident (and, conversely, to what degree could a potentially observed decrease in the incidence of health effects in that population be attributed to the radiation exposure)?
— Is it correct to infer radiation risks from the situation caused by the accident and apply commensurate radiation protection measures?
— Is it valid to project absolute numbers of health effects following the radiation exposure caused by the Fukushima Daiichi accident, particularly at levels at which an increased incidence in radiation

induced health effects have not been observed in any other population subjected to similar exposure conditions?

In summary, the conclusions of UNSCEAR concerning the first issue, related to the observation of health effects of the accident, were:

— “No radiation-related deaths or acute diseases have been observed among the workers and general public exposed to radiation from the accident” [5];
— “The doses to the general public, both those incurred during the first year and estimated for their lifetimes, are generally low or very low. No discernible increased incidence of radiation-related health effects are expected among exposed members of the public or their descendants” [5].

UNSCEAR also noted that:

> “The most important health effect is on mental and social well-being, related to the enormous impact of the earthquake, tsunami and nuclear accident, and the fear and stigma related to the perceived risk of exposure to ionizing radiation. Effects such as depression and post-traumatic stress symptoms have already been reported.” [5].

With regard to the second and third of the questions above, UNSCEAR noted that its 2012 report [312] had advised that it is appropriate to make “projections of numbers for comparative purposes” [312] in the context of allocating public health resources, but specifically recommended against “multiplying very low doses by large numbers of individuals to estimate the numbers of radiation induced health effects within a population exposed to incremental doses at levels equivalent to or lower than natural background levels” [312].

4.4.2. Post-accident health surveys in Japan

A number of health surveys were initiated in Japan following the Fukushima Daiichi accident. The FHMS focuses on the general population. The health of workers involved in remediation of the accident is also being closely monitored. Two key surveys are reviewed below.

4.4.2.1. Public health: Fukushima Health Management Survey

Recognizing the public anxiety concerning the accident at the Fukushima Daiichi NPP, Fukushima Prefecture established a health monitoring and support programme — the FHMS — about three months after the accident. The primary purposes of the survey are: “to assess residents’ radiation dose, and to monitor residents’ health conditions, which result in disease prevention, early detection and early medical treatment, thereby to maintain and promote their future health” [313].

The FHMS comprises a survey of basic health indicators and four more detailed, specialized surveys. Two million residents of Fukushima Prefecture have been targeted in the basic survey, with smaller numbers participating in the detailed surveys [202]. The estimations of internal exposures from radioactive material ingested or inhaled were not directly included in the survey but assessed separately using WBCs, as explained in Section 4.2. Some of the observations from the survey are described below. A discussion of the evidence for observable effects of radiation is given in Section 4.4.3.

The basic survey began with self-administered questionnaires mailed out to people who met residential or location criteria for being possibly connected with the consequences of the accident. Respondents were asked to record their movements following the accident in order to allow the results to be used in estimating radiation exposure from assessments of the variations in ambient dose equivalent in time and location. The overall response rate was about 27% (about 554 000 respondents, including radiation workers), as of 31 December 2014. For the residents excluding radiation workers, the estimated external effective dose during the first four months of the accident was less than 2 mSv in 95% of individuals and less than 5 mSv in 99.8% of individuals surveyed. Similar figures were obtained for the subset of the population (about 74 000 respondents) in the Soso area: the estimated external effective dose over the first four months was less than 2 mSv in 95% of individuals and less than 5 mSv in 98.8% of individuals [214]. Doses estimated to have been received by workers and members of the public, based on all available sources of information, are presented in Section 4.2.

The four specialized surveys involved: ultrasonography thyroid screening of residents age 18 and under (target population: 370 000), termed the Thyroid Ultrasound Examination (TUE) Survey; comprehensive medical check-ups of evacuees (210 000); a mental health and lifestyle survey of the same evacuees; and a survey of pregnant women and nursing mothers (approximately 15 000 in each year).

Following an initial survey, the second screening of the TUE Survey revealed that, for the period until March 2015, over 99% of the results of about 299 233 respondents fell within a normal range [314]. For this group, no specific findings were identified during the screening; no suspicious nodules or small nodules with a diameter of less than 5 mm nor any small cysts with a diameter of less than 20 mm were found. These results were compared with ultrasonography screenings of thyroid nodules in three other prefectures in Japan [315], which revealed similar findings of 99% of individuals with results that fell within the same normal range. There were 2279 individuals in the TUE with results beyond the normal range who underwent further screenings. Of these, 112 were found to have malignant, or the suspicion of malignant, nodules and/or cysts, for which 99 individuals had a thyroid operation. Of these, 98 were malignant and one benign. Thyroid effects are explained in detail in Section 4.4.4 [314].

The comprehensive medical check-ups include tests for body mass index, glycated haemoglobin (HbA1c), liver function and blood pressure. Although it must be noted that, owing to evacuation, the population surveyed is not identical year after year, there was a marked increase in adverse test results for both men and women in 2011 and 2012. Notably, the percentages of men and women whose liver function test was over 51 units per litre in 2011 and 2012 are more than double the percentages of what they were before 2011 [316]. These results imply that the individuals have an increased risk of obesity related diseases, diabetes mellitus, liver diseases, and hypertension, among other things. Data for 1032 people examined in Iitate Village in 2011 and 2012 were compared with those of previous years, with results indicating rising obesity, hypertension and hyperlipidemia, and a small increase in diabetes [316].

In the mental health and lifestyle survey, questionnaires covered physiological and mental conditions, lifestyle changes, experiences of the earthquake and tsunami, and radiation related issues. A year after the accident, a significant proportion of residents of Fukushima Prefecture were observed to exhibit symptoms of post-traumatic stress disorder (PTSD) (about 20%) and general mental health issues (about 15%) [317]. General mental health issues in Fukushima Prefecture occurred at about twice the level of those in the other two prefectures severely affected by the earthquake and tsunami (about 7% in Iwate and Miyagi). Higher rates persisted two years after the accident, but to a lesser degree. Additionally, almost half of Fukushima Daiichi NPP workers were observed to have high scores for general mental health issues [317].

The survey of pregnant women and nursing mothers involved a questionnaire, sent out to all mothers who were given a Maternal and Child Health Handbook between 1 August 2010 and 31 July 2011, which was returned by about 15 000 respondents. This survey is being updated every year to take account of new data, particularly on pregnancy and births. When answers on the questionnaire indicated that consultation was needed, doctors provided telephone consultations in some cases. In other cases, pregnant women and nursing mothers called or sent emails directly to midwives and doctors at Fukushima Medical University. These telephone consultations covered health concerns about the effects of radiation, and general advice for the pregnant women and nursing mothers (including concerns about their children, issues of child rearing, life in evacuation centres and family matters). Between December 2011 and July 2012, 30% of the 1400 calls expressing the greatest concerns focused on the influence of radiation on health. Between October 2012 and May 2013, the greatest concern was health issues of pregnant woman or nursing mothers, representing about one third of over 1000 calls made in that period.

A study by Fujimori considered six geographical regions (Kenpoku, Kenchu, Kennan, Soso, Iwaki and Aizu), and the response rate for the survey was greatest in the regions most affected by the accident (Soso, Kenpoku and Kenchu) [318]. The results in 2011 and 2012 showed that the rates of premature birth and low birth weight were similar to the national averages, and the ratios of congenital anomalies and other abnormalities were also approximately similar to the general incidence rates [318]. By area, there were no significant differences in the rate of stillbirth or preterm delivery, but the incidence of low birth weight was significantly lower in Kenpoku and higher in Iwaki than in the other regions. The study concluded that “although it is possible to underestimate incidences when using a self-administrated questionnaire with variable response rate, we could conclude no significant adverse outcomes from the pregnancy and birth survey over the whole Fukushima prefecture after the disaster” [318].

Health consultations were also carried out when medical check-ups took place. Doctors and public health nurses gave advice on the prevention of primary and secondary diseases, such as hypertension, diabetes mellitus and cancer related to lifestyle changes. This was to provide support for deterioration of access to medical services due to the necessity of evacuation. Care for mental health issues was also provided for residents and their families, as well as consultation and explanations of the thyroid screening results.

4.4.2.2. Worker health: TEPCO emergency workers at the Fukushima Daiichi NPP

For the long term health care of emergency workers who were engaged at the Fukushima Daiichi NPP, various programmes, including regular health check-ups, are being conducted, depending on the effective doses to workers according to the guidelines of MHLW [292]. In addition, TEPCO independently provided ultrasound examinations of the thyroid for emergency workers whose thyroid equivalent dose (during emergency work in addition to ordinary radiation work) was more than 100 mSv in 2011. Taking into account the age of these workers, several symptoms can be expected to be detected for some workers by an ultrasound examination regardless of their radiation exposures. In order to examine the possible effect on the thyroid, an ultrasound examination with the same procedure has been conducted for a control group of the workers with lower exposure to the thyroid (100 mSv or less of thyroid equivalent dose). An interim report of this survey was available at the time of writing of this volume [319].

A total of 2064 workers were enrolled (672 in the more highly exposed group and 1437 in the control group). The majority of the participants were TEPCO employees, with 2.2% of participants being employed by subcontractors. All of the examinees were men with a mean age of 43 for the exposed group and 41.7 for the control group. The categories used to describe the results were the same as those for the FHMS TUE carried out in children. There were no significant differences between the groups with respect to the different categories.[46] The initial findings suggest no effect on the thyroid of exposure to radioiodine, which is consistent with the relatively low doses received by these adults (see Section 4.2.1), and the short time interval between exposure and examination.

[46] Smoking and alcohol consumption was not significantly different between exposed and control groups.

MHLW called an expert committee to discuss perspectives on a future epidemiological study for the emergency workers, and a report of the committee has been published [320]. It pointed out the importance of a long term prospective cohort study for the approximately 20 000 emergency workers who worked until 16 December 2011. The committee suggested the desired study design, including end points, dosimetry, follow-up methods, and so on. The decision to implement this large scale study was reached by the study group (in which the Radiation Effects Research Foundation played key role) in November 2014.

4.4.2.3. Worker health: Follow-up survey of other workers

In cooperation with experts in various fields from research institutes and universities in Japan, NIRS initiated a follow-up study for those workers involved in emergency and recovery operations after the Fukushima Daiichi accident. In the follow-up, results of regular and special health examinations will be collected periodically from each organization and stored in the secured database at NIRS. Based on the lessons learned from studies of recovery operation workers after the Chernobyl accident and other occupational studies, which have often shown mixed results, lifestyle factors, including smoking and other possible factors will be taken into account. The ongoing study will collect such data using a questionnaire at the beginning of the follow-up and subsequently every few years. Information on disease history for both cancer and other diseases is also being collected through the same questionnaire. Various sources, including national vital statistics, cancer registry data, and so on, will be used to ascertain the disease outcomes.

4.4.3. Evidence of observable health effects

Radiation induced health effects depend on the dose received and can be divided into tissue reactions (the severity of which increases with dose) and stochastic effects (likelihood of effect related to dose).

4.4.3.1. Tissue reactions

Tissue reactions (also known as deterministic effects) are those for which there is a threshold of dose below which they do not occur and for which the severity of the effect increases with increasing dose. The threshold is necessary, since a critical number of cells need to be damaged before an injury becomes clinically evident. Below the threshold, there may be sufficient redundancy, so that any cellular loss is inconsequential. Damaged cells may be removed and/or gradually replaced, maintaining normal tissue or organ function. Tissue reactions may often occur soon after exposure, particularly for rapidly dividing tissues, such as bone marrow, skin, the cells lining the gastrointestinal tract and mucous membranes. However, symptoms appear after a latency period. For some organs, tissue reactions may not become evident for months or even years. The thresholds vary for different organs and tissues of the body and are generally well above 100 mSv. One of the lowest thresholds adopted by the ICRP for protection purposes is 0.5 Gy, whether delivered over a short or protracted period, for induction of cataracts in the lens of the eye [262, 321, 322].

Based on the doses estimated to have been received by members of the public (Section 4.2.2), no tissue reactions are expected, and none has been observed to date. A small number of workers have received effective doses in excess of 100 mSv [194]. Most of this dose came from internal exposure — from radioactive material taken into the body — which would not have significantly exposed the lens of the eye.

Three workers received dose to the feet and lower leg, but the corresponding data have not yet been published. However, these workers were evaluated by NIRS: two were found to have received skin equivalent doses of less than 500 mSv, while the third wore boots and received almost no dose. The skin equivalent dose of the two most exposed workers were reported to be lower than the estimated threshold for deterministic effects [262]. [47] None of these workers developed beta burns as confirmed by medical follow-up [323].

A 'prenatal (or antenatal) effect of exposure' is the term used to refer to effects of radiation on the embryo and fetus. At absorbed doses under 100 mGy, lethal effects of irradiation in the pre-implantation period of embryonic development are considered to be very infrequent, and there is an absorbed dose threshold of around 100 mGy for the induction of other effects [324–326]. Absorbed doses to the embryo and fetus that could be attributable to the accident were much lower than the threshold absorbed dose for the occurrence of these effects.

4.4.3.2. Stochastic effects

Stochastic radiation induced health effects are those for which the probability of their occurrence depends on dose. If such an effect occurs, its severity is independent of dose [256, 327]. The category of stochastic effects includes malignant diseases in exposed individuals and heritable effects in their offspring, although the latter effects have been observed only in animals and not in humans [312]. It is thought that stochastic effects are initiated by non-lethal transformations in somatic or germ cells, which may contribute, after a latency period, to malignant diseases or heritable effects, respectively. Some non-cancer health effects that may be connected with exposure to radiation are not sufficiently understood to determine whether they are stochastic responses [256].

The potential for radiation effects in children is an issue of special concern. International recommendations and standards for radiation protection take account of children in an exposed population. For radiation protection purposes, they postulate a potential nominal radiation risk for an entire population, i.e. a population including children that is about 30% higher than the postulated risk for an adult population (such nominal risks have been estimated on the basis of epidemiological studies of populations exposed to high radiation doses) [256, 328]. Following the lessons learned from the Chernobyl accident, the possibility of radiation induced thyroid cancer, particularly in children, has been a key consideration in the aftermath of the accident at the Fukushima Daiichi NPP. For this reason, effects on the thyroid are described in a separate section (Section 4.4.4).

As explained in the previous section, the dose received by an individual is the sum of doses from external and internal radiation. With respect to internal dose, there is an important interplay between the biological and physical half-life that affects the dose of radiation received by individual tissues in the body. While iodine is concentrated in the thyroid gland, caesium is neither actively taken up nor bound preferentially in any particular tissue in the body. Therefore although the two isotopes of caesium, ^{134}Cs and ^{137}Cs, have physical half-lives of around 2 and 30 years, respectively, caesium has a relatively shorter biological half-life of 70 days. It is likely that most of a single dose intake of ^{134}Cs and ^{137}Cs will be excreted from the body before emitting its radiation. Therefore, the dose received by the tissues from an intake of these two radioactive elements (iodine and caesium) will be markedly different, and for comparable intakes, the dose, and therefore the probability of radiation induced health effects, of ^{131}I is likely to be greater than that of ^{137}Cs.

In comparison with the general population, the workers at the Fukushima Daiichi NPP received higher whole body doses (see Section 4.2.1). A total of 174 received doses of greater than 100 mSv, with six receiving doses of above 250 mSv, including two workers with a whole body dose in excess of

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[47] ICRP estimates for the exposure of the skin is that an early response, as early transient erythema, is seen a few hours after doses of >2000 mGy when the exposed area is relatively large. It also estimates that the approximate threshold doses are as follows: early transient erythema — 2000 mGy, main erythema reaction — 6000 mGy, temporary epilation — 3000 mGy, permanent epilation — 7000 mGy, dry desquamation — 14 000 mGy, moist desquamation — 18 000 mGy, secondary ulceration — 24 000 mGy, late erythema — 15 000 mGy, ischaemic dermal necrosis — 18 000 mGy, dermal atrophy (first phase) — 10 000 mGy, telangiectasia — 10 000 mGy and dermal necrosis (late phase) — >15 000 mGy [262].

600 mSv, the majority of which was due to internal radiation. The high contribution of the internal dose to the overall dose was due to inhalation of radioactive material [185]. The health of these workers is being closely monitored. However, given the level of doses received, the number of people involved and other factors, it is unlikely than any increase in cancer will be discernible (see Section 4.4.5).

Regarding effects other than cancer, two recent studies have suggested that there may be an increase in the risk for heart disease and stroke at moderate dose levels. Analysis of the participants in the lifespan study of the atomic bomb survivors showed an increased risk for both heart disease and stroke at doses over 500 mGy, but the authors stated that at lower doses it was difficult to be certain of any excess risk [329]. In a large study of nuclear workers exposed to radiation in the course of their normal work, an excess risk for circulatory disease was noted at doses over 350 mSv [330]. However, there are significant contradictory points in these studies and both suggest that there are insufficient data to draw conclusions for lower doses.

In addition, recent review papers have concluded that, despite evidence in animal models, there is no evidence for transgenerational effects in the human of exposure to radiation at any dose level [331, 332].

4.4.4. Studies of effects on the thyroid

Regarding thyroid cancer, children are more radiosensitive than adults. For a given intake of radioiodines, the dose to the thyroid for infants is eight or nine times larger than adults. A substantial environmental presence of ^{131}I can result in thyroid cancer in children. The normal incidence of some types of thyroid cancer in children is low, and the sensitivity of children's thyroid glands to radiation is high. Owing to this higher sensitivity, in the aftermath of the accident it was important to undertake screening follow-up in order to detect at an early stage any potential increase in the incidence of this type of cancer [333].

High doses of radiation can result in significant killing of cells in the thyroid that can reduce the function of the gland to such a level that hypothyroidism ensues. Hyperthyroidism can also occur, but again at high doses (exceeding 15 Gy). Effects at low and medium doses have been difficult to quantify, and the magnitude of the effect remains unclear [334]. As with the effects of radiation on thyroid cancer incidence, the effect is most pronounced in those who were exposed in childhood. Hypothyroidism can occur in adult patients treated with radiotherapy for head and neck cancer, but the radiation dose to the thyroid is much higher (of the order of 50 Gy) than that which has been recorded in the worker population at Fukushima Daiichi NPP. Where hypothyroidism does occur, it is usually transient.

Section 4.2 provides more detailed information on radiation doses received following the accident at the Fukushima Daiichi NPP. Some information of specific relevance to possible thyroid effects is reviewed here (see Annex IX).

4.4.4.1. Monitoring for thyroid health effects

The FHMS is introduced in Section 4.4.2. It was known that one of the major concerns for the exposed population was the possibility of long term effects of radiation on the thyroid. Consequently, the TUE Survey [202, 335] is an integral part of the FHMS and is directed at all inhabitants of Fukushima Prefecture who were aged between 0 and 18 years on 11 March 2011. Modern ultrasound equipment, such as that used in the TUE study, is able to detect thyroid carcinomas as small as a few millimetres in size, long before these may come to clinical attention (if ever, because some may remain asymptomatic during a whole lifetime). Thus, it is to be expected that more thyroid abnormalities will be identified through this screening procedure than would occur through normal clinical procedures — this screening effect is well known.

An ultrasound examination of children will continue to be carried out biennially until the participants reach the age of 20 years, and every five years thereafter. The protocol of the TUE is carefully designed to establish a standardized examination procedure that is the most appropriate for the circumstances. The examinations are being conducted by Fukushima Medical University using modern, highly sensitive ultrasound equipment (10 MHz frequency probe for initial evaluation and 18 MHz frequency probe for confirmatory examination) [202, 335]. The first round of examinations started in October 2011 and was completed in March 2014. Based on current knowledge about the minimum latency of 4 to 5 years for radiation related thyroid cancer [246], cancers diagnosed at the initial TUE Survey, i.e. within three years of the Fukushima Daiichi accident, would not be expected to be radiation related; therefore, the initial survey will provide baseline data on the spectrum and frequency of thyroid abnormalities in children under the conditions of intense screening.

The adult thyroid is substantially less sensitive to the carcinogenic effects of ionizing radiation for the same received dose as that for children [336]. In addition, maximum dose estimates of external and internal thyroid exposure in Fukushima Prefecture residents are low (see Section 4.2.2), making the likelihood of developing thyroid cancer following adult exposures low. Thus, no special thyroid examination for those over 18 years at the time of the accidents is conducted or included as part of the Comprehensive Health Check [202, 337, 338] unless a patient has thyroid symptoms or concerns.

As of 31 March 2015, 299 543 children, or 81.5% of the TUE targeted population, have received an initial thyroid examination, and results are available for 299 233 children. The most common ultrasound findings are thyroid cysts, found in 143 268 (47.9%) children, followed by thyroid nodules found in 3968 (1.3%) children. It is important to note that 94.9% of cysts are ≤20 mm and 43.0% of nodules are ≤5.0 mm and would not have been detected without a sensitive screening tool. The majority of screened children (99.2%) had no thyroid abnormalities requiring additional testing, while 2279 (0.8%) had to be referred for confirmatory testing or required immediate attention [314]. The confirmatory testing includes advanced ultrasound examination, thyroid function testing, analysis of urinary iodine and fine needle aspiration biopsy (FNAB), where indicated. Functional thyroid tests and urinary iodine measurements are only performed in children suspected of having thyroid abnormalities. The results may not be applicable to the entire screened population.

A final diagnosis of papillary thyroid cancer (PTC) was confirmed in 95 children of 99 who underwent thyroid surgery. Of the four other cases, three were confirmed as poorly differentiated thyroid cancer and one is confirmed as a benign thyroid nodule. The mean age of individuals who presented with nodules that were suspicious for malignancy was 17.2 years (standard deviation: 2.7, range 8–22). These individuals were on average 14.8 years old (SD 2.6, range 6–18) at the time of the Fukushima Daiichi accident. The male to female ratio was 38 to 74 (1:1.95) and estimated median quantity of iodine in urine was 230 µg/day (the maximum among the 1917 other individuals surveyed was 35 700 µg/day). Because a number of patients are awaiting FNAB or surgery (N = 13), an accurate estimate of the baseline thyroid cancer prevalence is not yet possible.

To evaluate if there is an excess of thyroid cancer or other thyroid diseases following the Fukushima Daiichi accident, preliminary prevalence data for children in Fukushima Prefecture ideally need to be compared with the respective rates in Japanese children not affected by the accident but screened according to the same protocol and comparable in terms of age, sex and other risk factors. Comparison with rates derived from cancer registries in Japan or other countries should be avoided as misleading because the majority of cases reported to cancer registries are diagnosed by clinical methods and not by screening. Thus far, one relatively small study of approximately 4400 children from Aomori, Yamanashi, and Nagasaki prefectures is available for comparison with TUE findings [339]. The number of individuals with cancer or suspicion of cancer on FNAB, if there were any, was not reported by Hayashida et al.[339]. Comparison of prevalence for several outcomes in two paediatric populations suggests that thyroid lesions, for example small thyroid cysts and nodules (≤5 mm), are common among children screened with sensitive ultrasound equipment. The limited size of the three prefecture study means that it provides an estimate of thyroid cancer rate for comparison with the Fukushima Prefecture findings only for common thyroid abnormalities such as nodules and cysts.

The results of the second screening examination (the first screening of the full scale survey) are available. As of 31 March 2015, 148 027 children of the TUE targeted population (about 385 000), have had received a TUE and test results are available for 121 997 children [340]. The most common ultrasound findings are thyroid cysts, found in 70 531 (57.8%) of the children, followed by thyroid nodules found in 1846 (1.5%) of children. It is important to note that 95.4% of cysts are ≤20 mm and 43.7% of nodules are ≤5.0 mm and would not have been detected without a sensitive screening tool. The majority of screened children (99.3%) had no thyroid abnormalities requiring additional testing, while 1043 (0.9%) had to be referred for confirmatory testing or required immediate attention.

A final diagnosis of PTC was confirmed in 5 children of 5 who underwent thyroid surgery. The mean age of individuals who presented with nodules that were suspicious for malignancy was 16.8 years (SD 3.5, range 10–22). These individuals were on average 13.1 years old (SD 3.5, range 6–18) at the time of the Fukushima Daiichi accident. The male to female ratio was 6 to 9 (1:1. 5) and estimated quantity of iodine in urine was 190 µg/d (the maximum among the 472 other individuals surveyed was 11 800 µg/d). Because the full scale TUE survey has not been completed and a number of patients are awaiting FNAB or surgery (N = 10), an accurate estimate of the baseline cancer prevalence is not yet possible [340].

The examinations use highly sensitive ultrasound sonography equipment for the screening of the thyroid gland, which has detected asymptomatic thyroid abnormalities (nodules, cysts and cancers) that would have gone undetected if asymptomatic children had been screened using standard equipment. Similar results were obtained when the same screening was carried out on children living far away from the areas affected by the accident [341]. The latency time for radiation induced thyroid cancer is also longer that the four years since the accident. In many cases, thyroid cancers were found in children in the late teenage years and no case was found in the most vulnerable group of children who were at the age of 0–5 years as of 11 March 2011. The proportion of suspicious or malignant cases was almost the same among regions in Fukushima Prefecture in the first screening conducted in 2011–2013 [342]. These factors suggest that the thyroid abnormalities detected in the survey are unlikely to be associated with radiation exposure due to the accident.

4.4.4.2. Health monitoring of workers

Although the vast majority of workers at the Fukushima Daiichi NPP received thyroid equivalent doses below 100 mSv, 1709 individuals received doses above this level, with 12 workers receiving doses above 2 Sv and 2 doses in excess of 12 Sv (see Section 4.2.1). As noted earlier, the risk from thyroid cancer from exposure to radiation in adult life is very much lower than that from radiation exposure in childhood, and it is therefore unlikely that an increase in thyroid cancer in this population will be discernible. As described above, a survey of thyroid effects among the emergency workers of the Fukushima Daiichi NPP is ongoing to evaluate the possible association between thyroid doses and ultrasound examination results.

Since October 2011, MHLW, based on ministerial guidelines, has required TEPCO and employers to conduct cancer screening surveys including ultrasonic examination of the thyroid gland annually for emergency workers who were exposed to more than 100 mSv effective dose during emergency work. MHLW is responsible for conducting the tests for retired workers [292]. In 2013, MHLW sponsored a cross-section study on health effects of radiation exposure on thyroid glands. The research conducted ultrasonic examination of thyroid glands for 627 emergency workers in the exposed group (exposed to more than 100 mSv thyroid equivalent dose) and the 1437 workers in the control group (exposed to not more than 100 mSv in thyroid equivalent dose) in early 2014. The results of the research can be used as a baseline result on ultrasonic examination of the thyroid gland for further epidemiological research [319].

4.4.5. Inference of future risk

No health effects among workers or members of the public that could be diagnosed by a physician and confirmed by pathology can be attributed to exposure to radiation arising from the Fukushima Daiichi accident (see Sections 4.4.2 and 4.4.3). In short, there are no discernible early health effects of radiation arising from the accident. However, it is important to consider whether there may be later (stochastic) health effects, in particular, the development of malignancies (cancer). Such effects appear after a delay that is different for different malignant diseases. For thyroid cancer, the latency period is estimated to be four years or more; for most solid cancers, it is typically longer [254]. So, even if an increase in the incidence of malignant diseases would be observable in principle in the future, it would be too early to see any evidence at the time of this analysis.

As explained in more detail in Annex X, for moderate and high doses of radiation, there is sufficient evidence from epidemiological studies to predict with a fair degree of confidence the future consequential increase in incidence of cancer in an exposed population. However, for low doses and very low doses (at the level generally reported following the Fukushima Daiichi accident), there is insufficient epidemiological evidence to demonstrate an increase in incidence of cancer in exposed populations. Observed effects cannot be unequivocally attributed to radiation, partly because other causes of the effect cannot be ruled out without the existence of an associated biomarker, and partly because the studies have insufficient statistical power to draw conclusions with confidence owing to the high natural incidence of cancer and associated uncertainties. Predictions based on the application of risk coefficients at such levels of dose are scientifically untestable with current knowledge.

Since the accident occurred, several hypothetical estimates of future incidence of cancer have been reported in the media, sometimes basing predictions on calculations of collective dose or its computational equivalent. Such predictions are inappropriate (see Annex X) and may lead to anxiety and emotional distress among exposed populations.

It is recognized, however, that estimates of possible incidence may serve a role in decision making. For example, such information is necessary in comparative analyses (e.g. selecting which is the preferred option from a range of possible preventative or remediation measures) and for resource allocation for health care purposes. Such an assessment may also help people to place the hypothetical risk of harm from radiation in context with other risks with which they are more familiar. This section therefore provides theoretical predictions of a statistical indicator of risk and projections of the hypothetical future incidence of various types of malignancies that could be associated with available estimates of radiation doses from the Fukushima Daiichi accident. These values are based on risk models that reflect the most widely held consensus of opinion in the scientific literature. It is necessary, however, to recognize that such estimates are notional and subject to uncertainties (see Section 4.4.1.2 and Annex X).

Some studies related to Chernobyl accident emergency workers that provide a useful comparison are referenced in Annex XI.

4.4.5.1. Risk models

One of the indicators used by epidemiologists in order to facilitate the theoretical inference of prospective radiation risks on a human population exposed to ionizing radiation is the so called

LARF. LARF is used to express the fraction of the total cancer incidence (both radiation associated and non-radiation associated) that is radiation induced for a population exposed to radiation. LARF is commonly expressed as a percentage. Risk models and approaches have been developed for calculation of LARF on the basis of experience and conclusions from epidemiological studies and taking account of medical and demographic features of the population of Japan. The mathematical basis for the selection of radiation risk models used in the following analyses is explained in Annex X.

Two mathematical models have been used to estimate the risks (expressed as LARF) and the nominal incidence of malignant diseases that might be inferred from the radiation doses reported for workers and members of the public (see Sections 4.2.1 and 4.2.2). These models are referred to as the ICRP model [256] and the WHO model, which is described in the WHO report on health effects from the Fukushima Daiichi accident [201]. This section presents summary information; more detailed information for each year and for different population groups is presented in Annex X.

4.4.5.2. Inferred risks for workers

At the time at which the risk calculations presented in this section were performed, information on worker doses was available for the period up to August 2013. More recent data have become available in the interim, and are presented in Section 4.2.1. The updated data include revised estimates of the doses received in the first year. However, these differences in dose are not considered to be sufficient to significantly affect the overall magnitude of the inferred risks or nominal estimates of the incidence of malignancies, or the relative magnitude of these values to the spontaneous (natural) incidence of health effects.

Table 4.4–1 presents the LARF for various forms of malignancy associated with the reported doses to workers at the Fukushima Daiichi NPP for the period March 2011–August 2014, derived using both risk models. It will be seen from this table that the inferred LARF is, in all cases, less than 1%, and that the values derived using the WHO model are higher. Tables 4.4–2 and 4.4–3 provide estimates of the nominal incidence of thyroid cancer cases associated with various ranges of radiation exposure, the inferred spontaneous incidence of thyroid cancer within each group of workers and the associated LARF, derived using the ICRP and WHO models, respectively. These tables indicate that the LARF for thyroid cancer varies significantly among the groups of workers, according to the thyroid dose received. The LARF for the whole worker population for which thyroid doses are available is of the order of 3% or less, depending on the risk model used (with the WHO model giving the higher estimates).

TABLE 4.4–1. LARF FOR FUKUSHIMA DAIICHI NPP EMERGENCY WORKERS, CALCULATED USING THE ICRP AND WHO MODELS.

(Summary follow-up period from March 2011 to August 2013)

	LARF (%) ICRP			LARF (%) WHO		
	Solid cancers	Leukaemia	All cancers	Solid cancers	Leukaemia	All cancers
TEPCO	0.13	1.37	0.15	0.26	0.95	0.27
Contractors	0.06	0.76	0.07	0.13	0.49	0.14
Total	0.07	0.85	0.08	0.15	0.56	0.16

TABLE 4.4–2. INFERRED NUMBER OF THYROID CANCER CASES AND LARF AMONG FUKUSHIMA DAIICHI NPP EMERGENCY WORKERS, CALCULATED WITH THE ICRP MODEL

Thyroid equivalent dose (mSv)	No. of workers	No. of radiation induced cases	No. of spontaneous cases	LARF (%)
>10 000	2	0.01	<0.01	65.05
2 000–10 000	10	0.02	0.02	42.67
1 000–2 000	63	0.02	0.13	15.69
500–1 000	188	0.04	0.40	8.51
200–500	790	0.07	1.68	4.16
100–200	656	0.03	1.39	1.83
<100	17 883	0.24	37.93	0.62
Total	19 592	0.42	41.56	1.00

TABLE 4.4–3. INFERRED NUMBER OF THYROID CANCER CASES AND LARF AMONG FUKUSHIMA DAIICHI NPP EMERGENCY WORKERS, CALCULATED WITH THE WHO MODEL

Thyroid equivalent dose (mSv)	No. of workers	No. of radiation induced cases	No of spontaneous cases	LARF (%)
> 10 000	2	0.03	<0.01	86.59
2 000–10 000	10	0.05	0.02	72.09
1 000–2 000	63	0.08	0.13	39.24
500–1 000	188	0.12	0.38	24.41
200–500	790	0.24	1.61	13.10
100–200	656	0.09	1.34	6.07
<100	17 883	0.79	36.53	2.11
Total	19 592	1.40	40.03	3.39

These tables suggest that, among the almost 20 000 workers for whom thyroid dose information is available, of the order of one radiation induced case of thyroid cancer may be predicted among the 40 or so that would be likely to occur spontaneously in this population. Thus, given these doses, it is unlikely that an increase in the incidence in cancer will be discernible among this group of workers.

These results are also shown in Figs 4.4–1 and 4.4–2.

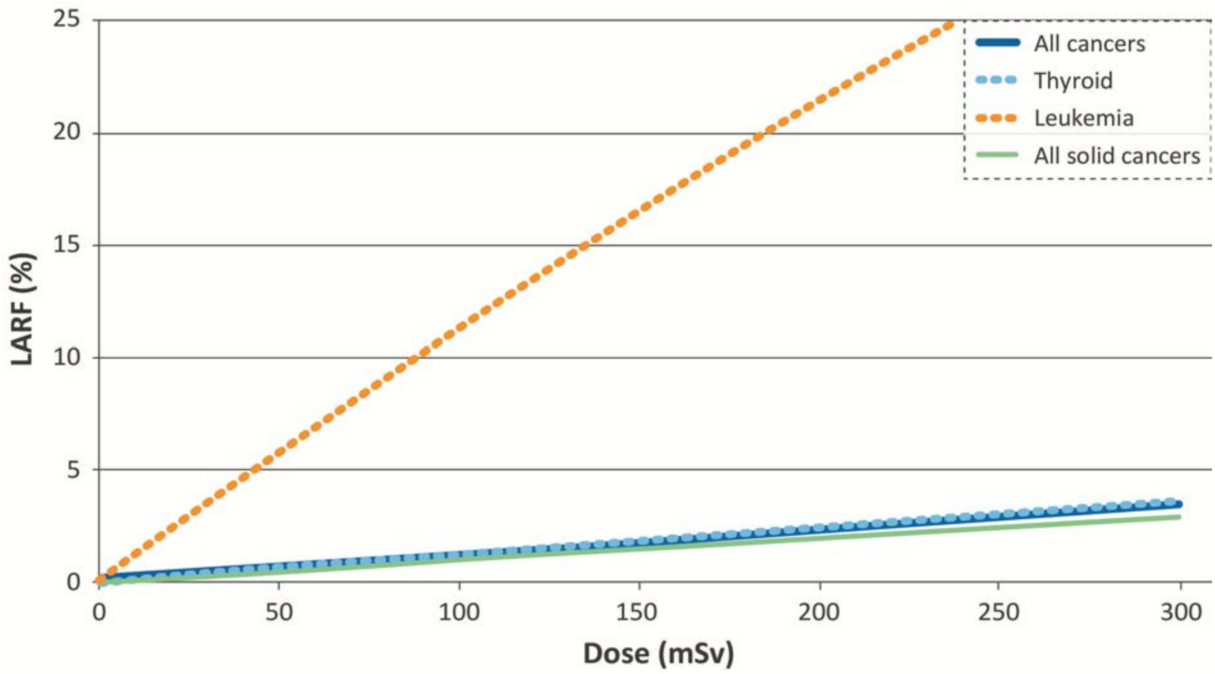

FIG. 4.4–1. Average age specific LARF (%) as a function of radiation dose, estimated with the ICRP model.

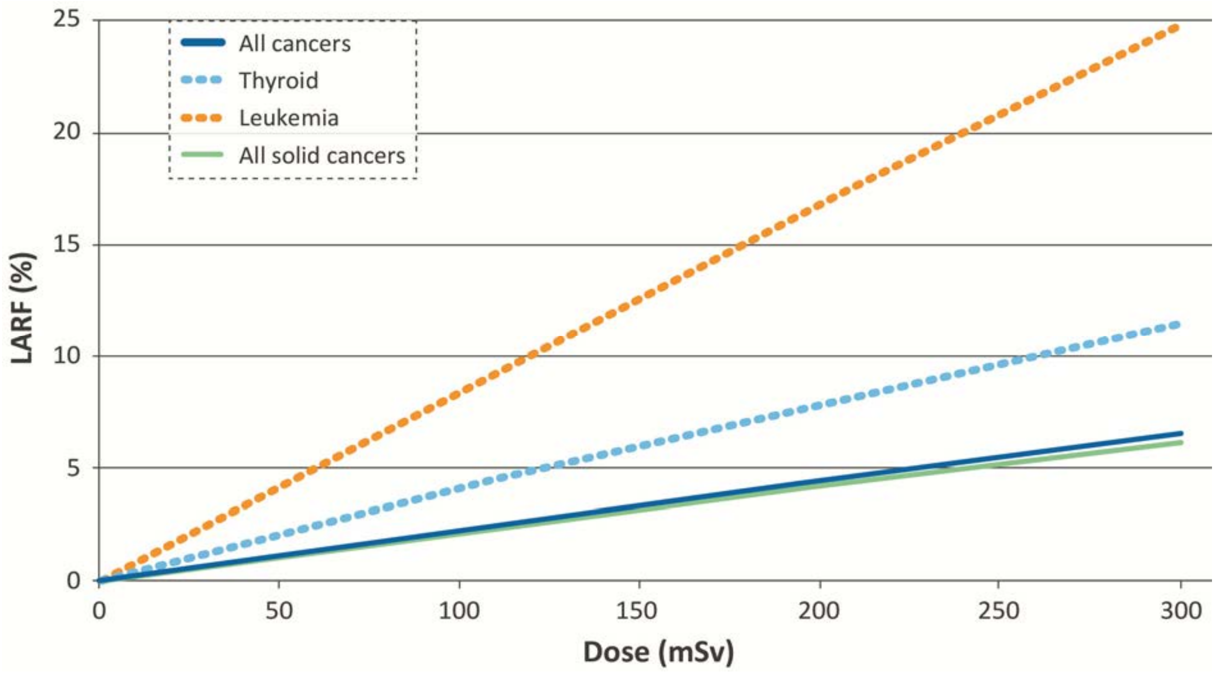

FIG. 4.4–2. Average age specific LARF (%) as a function of radiation dose, estimated with the WHO model.

4.4.5.3. Inferred risks for members of the public

LAR calculations have also been undertaken for the public at a range of locations and for various populations, including children in the areas where higher doses were received. These groups received lower doses than emergency workers, so the values of LARF are generally lower, at 1% or as low as 0.1%. The risk factors for thyroid cancer in young children are of the order of 1% for all of the areas for which thyroid dose information is available (see Annex X for more information). It is therefore unlikely that an increase in the incidence in cancer, including thyroid cancer in children, will be discernible among members of the public as a result of releases from the Fukushima Daiichi accident.

4.4.5.4. Inference of potential risks from the Fukushima Daiichi accident

The value of the LARF was found to be less than 1%. This result may be placed in context by considering that data obtained from large scale epidemiological studies carried out following the Chernobyl accident have not been able to confirm inference of risk for LARF lower than 5% [343, 344]. The prospective theoretical risk inferred from the range of doses that appear to have been delivered during and following the Fukushima Daiichi accident are small, and it will not be possible to verify such a level of risk by the results of epidemiological studies.

In the low dose range, increases in cancer incidence are not discernible and hence increases in the incidence of cancer are not attributable to radiation at such doses.

4.4.6. Non-radiation effects: Mental health

There is evidence that the Fukushima Daiichi accident, and the subsequent radiation protection measures taken, have resulted in observable health effects that are not related to the action of radiation on tissues and cells in the human body. The presence of radiation is a component of the complex and stressful situation that arose following the accident. These health effects include psychological effects that reflect an apprehension about radiation exposure, and a lack of public understanding of the scientific data on health effects of low dose radiation. They also arise as an indirect consequence of measures such as evacuation that were taken to reduce radiation exposures. These have been highlighted in both of the UNSCEAR reports following the Chernobyl accident [246, 250], and the WHO [201] and UNSCEAR [5] reports following the accident at the Fukushima Daiichi NPP.

The Three Mile Island (TMI), Chernobyl and Fukushima Daiichi accidents produced anxiety and uncertainty about short and long term health consequences. In the previous accidents, these uncertainties were exacerbated by contradictory information from scientists and government and industry authorities; loss of faith in experts, related to protective actions taken to minimize potential radiation exposure; information of uncertain validity on both formal and informal media; and the rapid spread of rumours about birth defects, heart disease and, especially, cancer [345–347]. Studies of atomic bomb survivors and populations affected by the accidents at TMI and Chernobyl show strong associations between these uncertainties and observations of anxiety, depression and post-traumatic stress responses (PTSR), as well as medically unexplained physical symptoms [348–350]. These symptoms were found to be persistent and disabling in vulnerable subgroups impacted by the TMI and Chernobyl accidents, such as mothers of young children and cleanup workers. As a general example, Table 4.4–4 illustrates the cardinal symptoms of anxiety, depression and post-traumatic stress disorder (PTSD), which are the most common psychological conditions that occur after such accidents.

The small but growing number of surveys on the psychological aftermath following the Fukushima Daiichi accident has largely focused on the possibly vulnerable subgroups of the population (pregnant women and mothers of infants, rescue and cleanup workers and the evacuees). Some psychological consequences have already been detected in the affected population [202, 317, 351–359]. The largest survey of evacuees is the Mental Health and Lifestyle Survey conducted as part of Fukushima Medical University's Health Management Survey [202]. Information about other health effects can be seen in the study by Yabe et al. [317].

TABLE 4.4–4. EXAMPLES OF SYMPTOMS OF ANXIETY, DEPRESSION AND PTSD

Psychological condition	Examples of symptoms
Anxiety	Excessive worry
	Feeling fearful
	Feeling tense or keyed up
	Easily alarmed about health status
	Preoccupation with having or acquiring a serious illness
Depression	Persistent depressed mood
	Contemplation of suicide
	Significant change in weight or appetite
	Insomnia or hypersomnia
	Trouble in concentration
PTSD	Flashbacks, intrusive memories
	Nightmares
	Hypervigilance
	Easily startled
	Avoidance of trauma related thoughts

For the Mental Health and Lifestyle Survey, questionnaires first mailed in January 2012 contained standard symptom measures of trauma symptoms, PTSD and psychological distress (anxiety), as well as questions on concerns about radiation exposure and adversities resulting from the earthquake and tsunami. The adversities considered included loss of family or relatives, house damage, loss of employment, decrease in income, and evacuation destination (within or outside Fukushima Prefecture). Two methods were used for assessing the mental health status of adult evacuees[48]; the Kessler K6 scale[49] [360] and the post-traumatic stress disorder checklist (specific version, PCL-S)[50] [361]. An additional survey, using the CAGE questionnaire, was used to assess the level of alcoholism [362]. These surveys indicate that, over the period covered by this volume, mental health symptoms were higher than would be expected from surveys of the general population [352]. Preliminary results indicate that rates of probable PTSD, based on scoring above a standard cut-off point on the PTSD symptom questionnaire, are ~20% for women and ~17% for men. In contrast, the rate of PTSD in a general population sample of Japan reporting trauma exposure is less than 2% [352].

Yabe et al. [317] note that many evacuee households were separated and had to move several times. As a measure of general mental health, a factor, K6, was used in the survey. It was found that the percentage of adults who scored above the K6 cut-off for general mental health (14.6% in the fiscal year (FY) 2011 and 11.9% in FY 2012) was higher than usual, indicating mental health problems among the evacuees. In addition Yabe et al.[317] report that the percentage of adults scoring above the cut-off for PTSD using a checklist was 21.6% in FY 2011 and 18.3% in FY 2012.

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[48] The target population was "the residents of evacuation zones including Hirono Town, Naraha Town, Tomioka Town, Kawauchi Village, Okuma Town, Futaba Town, Namie Town, Katsurao Village, Minamisoma City, Tamura City, Yamakiya district of Kawamata Town, and Iitate Village" [317], which numbered in total 210, 189 in 2011 and 211,615 in 2012 [317].

[49] The Kessler scale was designed to be sensitive around the threshold for the clinically significant range of the distribution of non-specific distress in an effort to maximize the ability to discriminate cases of serious mental illness from non-cases. The text refers to the K6 Keller scale, which is one specific screening measure for psychological distress.

[50] The post traumatic stress disorder checklist is a 17 item self-report measure of post-traumatic stress disorder that assesses severity of PTSD symptoms.

The status of children's mental health was assessed using the Strength and Difficulties Questionnaire[51]. The proportion of children aged 4–6 years and of primary school age (6–12 years old) who scored above the cut-off (≥16) of the questionnaire were 24.4% in FY 2011 and 16.6% in FY 2012. These findings indicated psychological difficulties in children, with relative improvement year by year. Because of differences in measurement and metrics, it is not known how this level of distress compares with that found in children exposed to the earthquake and tsunami [353]. However, a study of depressive symptoms in a large sample of 6–15 year olds in Japan found a similar percentage scoring in the high distress range [363], suggesting that, as in the cases of the TMI and Chernobyl accidents, the affected children are highly resilient [364, 365].

Mothers and pregnant women [354]. Several studies and review papers have shown that, after the TMI and Chernobyl accidents, the psychological well-being of mothers of young children and pregnant women was poorer than that of other women and was adversely affected by radiation related fears [354]. Consistent with these findings, the Health Management Survey conducted a Pregnancy and Birth Survey that reported a rate of depression among mothers of young children and pregnant women of 14.6% [202]. A survey of mothers attending a check-up for children at 18 months of age in Fukushima City in 2012 indicated that 10% of these mothers were found to be depressed. Moreover, the rate of depression was two times higher among mothers residing in higher priority cleanup areas of Fukushima City than in those living in lower priority cleanup areas [355]. The rates in these two samples from Fukushima City are two to three times higher than expected for similarly aged women in Japan [356].

Following accidents involving the potential for significant radiation exposure, some pregnant women seek medical advice on whether or not their pregnancy should be terminated. A study by the Obstetrics and Gynaecology Department of the Fukushima Medical University reported that no such elective terminations were carried out in the aftermath of the accident [366, 367].

Workers [368]. A study was carried out comparing the mental health of workers at the two nearby nuclear power plants, Fukushima Daiichi and Fukushima Daini. Shigemura et al. found significantly more general psychological distress (GPD) and PTSR among workers at the Fukushima Daiichi NPP compared with the Fukushima Daini NPP workers in April–June 2011 [357, 358] (see Fig. 4.4–3). In both groups, there was a statistically significant association between the more severe distress and PTSR responses and experiencing perceived discrimination and slurs.

First responders. In a study of first responders (doctors, nurses, coordination staff) conducted in April 2011, 4.0% of the surveyed responders reported distress and 21.4% scored high on a depression symptom scale. However, the response rate was very low, and the prevalence estimates, though believed to be comparable with general population rates, have uncertain reliability. More importantly for the radiation related impact, the authors found that first responders who expressed concerns about radiation exposure were significantly more symptomatic on both measures than responders who were not concerned [359].

Evacuees living in shelters. In October–November 2012, a pilot study was conducted of evacuees living in shelters in two areas of Fukushima Prefecture [351]. The participation rate was low (13.4%). However, this was the first study related to the Fukushima Daiichi accident that involved face to face structured diagnostic interviews. The rates of diagnosable PTSD, depression and anxiety were found to be two to seven times higher than in the general population of Japan [369, 370].

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[51] The Strengths and Difficulty Questionnaire is a brief child mental health questionnaire for children and adolescents aged 2–17 years, covering 25 attributes on symptoms related to mental health and behaviour divided between 5 scales: emotional symptoms, conduct problems, hyperactivity/inattention, peer relationship problems and prosocial behaviour.

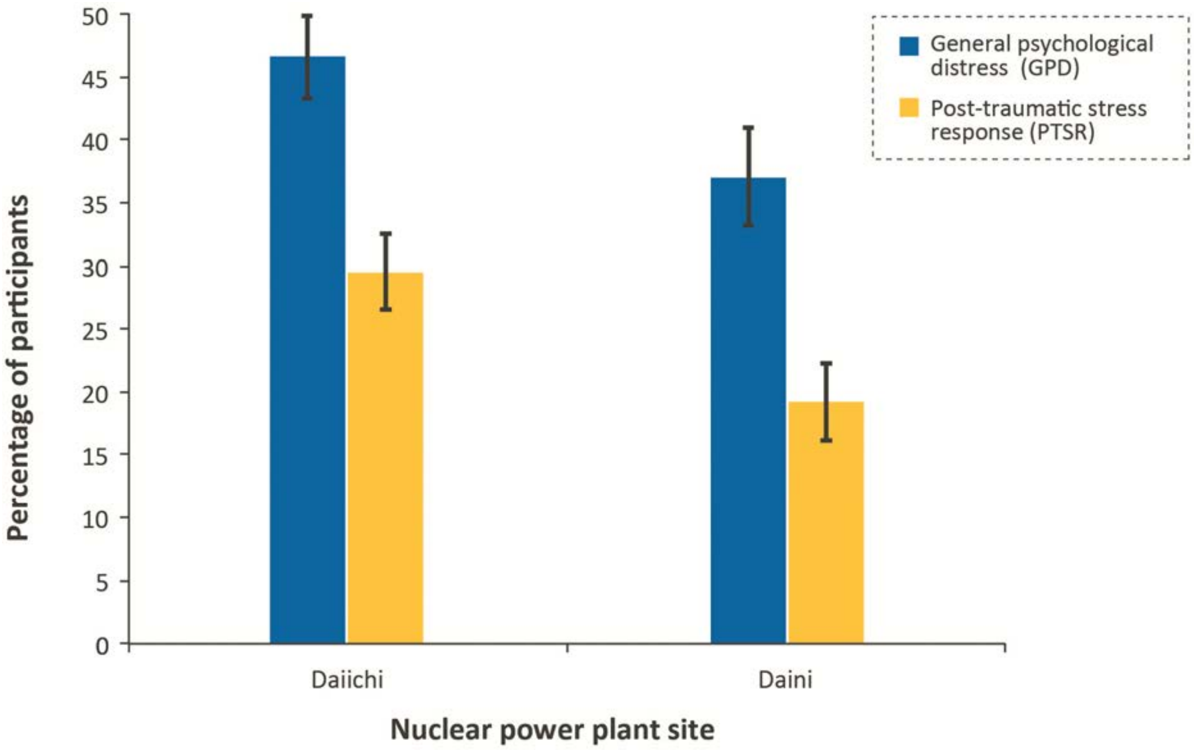

FIG. 4.4–3. Percentage of workers at the Fukushima Daiichi and Fukushima Daini NPPs reporting psychological distress, April 2011 [357].

Recent evidence suggests that concerns about radiation exposure similar to those that occurred after the TMI and Chernobyl accidents are widespread among Fukushima residents and evacuees. In the survey reported in Ref. [317] for residents and evacuees questioned in 2012, 3045 (9.5%) of residents reported that they felt an immediate effect of the accident was likely, for 19.5% a late effect was likely and 25.4% reported that a genetic effect was likely to occur as a result of exposure to releases from the Fukushima Daiichi NPP. This last finding is in spite of scientific evidence to the contrary. Two recent review studies of the data from the atomic bomb cohorts have shown that there is no transgenerational effect in people at any level of radiation dose [331, 332]. Thus, although the radiation doses received by the population are unlikely to result in discernible health effects, anxiety related to perceptions of exposure to radiation is very likely to lead to discernible psychological effects.

Communication and dissemination of accurate information received by the public at an early stage and during the development of the accident have helped to alleviate unwarranted psychological reactions [298].

4.4.7. Summary

The Fukushima Daiichi accident resulted in a large release of radioactive material to the environment, with the potential for exposing the local population to radiation. However, the affected population was largely protected against radiation exposure, and no one incurred a lethal dose of radiation or a dose sufficiently large to cause early health effects such as the tissue reactions often referred to as ‘deterministic effects’.

It should be noted, however, that there are health effects associated to radiation exposure that may be manifested after some latency time. These effects are commonly termed stochastic because of their probabilistic nature and are dominated by the induction of malignancies. The potential occurrence of such effects cannot be disregarded at the time of writing owing to the latency periods for such effects. However, taking into account the low radiation doses incurred by members of the public in the regions affected by the accident, it is not expected that health effects will be discernible among the exposed members of the public or their descendants in the future.

The stochastic health effect with the greatest potential to be manifested after a nuclear accident is thyroid cancer among children. This is the result of the preferential absorption and irradiation of the thyroid gland following the intake of radioactive iodine by ingestion or inhalation. Previous experience shows that the dominant route for such intake is the ingestion of contaminated milk. In the case of the Fukushima Daiichi accident, this route was generally prevented by the implementation of controls on consumption, and the estimates of thyroid doses suggest that they were generally low. It seems, therefore, that there should not be any future increase in thyroid cancers that could be attributable to radiation exposure from the Fukushima Daiichi accident. Hereditable effects have also been mentioned to have such potential; however, a recent UNSCEAR report to the United Nations General Assembly states that “although demonstrated in animal studies, an increase in the incidence of hereditary effects in human populations cannot at present be attributed to radiation exposure” [371].

The health screening of workers and residents of Fukushima Prefecture has detected asymptomatic thyroid abnormalities — nodules, cysts and cancers — that would have gone undetected if asymptomatic children had been screened using standard equipment. Similar results were obtained when the same screening was carried out on children living far away from the areas affected by the accident [339, 341]. The latency time for radiation induced thyroid cancer is longer than the four years that have elapsed since the accident at the time of writing. In many cases, thyroid cancers were found in children in the late teenage years, but no cases were found in the most vulnerable group of children who were under five years of age on 11 March 2011. The proportion of suspicious or malignant cases was almost the same among regions in Fukushima Prefecture in the initial screening conducted in 2011–2013 [314]. These factors suggest that the thyroid abnormalities detected in the survey are unlikely to be associated with radiation exposure due to the accident. Following such a combined catastrophe of earthquake, tsunami and nuclear accident, psychological consequences among the affected population have been widely reported. Some of these effects can be associated to the fear and stigma caused by radiation exposure. While the majority of people impacted directly or indirectly by past accidents and disasters have proved resilient to the potential psychological effects from the situation, some vulnerable groups have been identified, including mothers and pregnant women, workers, and long term evacuees.

In the case of the Fukushima Daiichi accident, the inferred lifetime risk values are extremely low and well below the levels for which effects have been observed, and the hypothetical numbers of cancer cases calculated by using the risk models are a small fraction of the expected number of spontaneous cases. There is little likelihood of discerning an increase in cancer due to radiation from the accident at the Fukushima Daiichi NPP in the general population or among emergency workers in the future.

4.4.8. Observations and lessons

— **The risks of radiation exposure and the attribution of health effects to radiation need to be clearly presented to stakeholders, making it unambiguous that any increases in the occurrence of health effects in populations are not attributable to exposure to radiation, if levels of exposure are similar to the global average background levels of radiation.**
  In the case of the Fukushima Daiichi accident, doses to members of the public were low and comparable with typical global average background doses. There is a need to clearly inform the public, particularly the people affected, that no discernible increased incidence of radiation related health effects is expected among exposed members of the public and their descendants as a result of the accident.

An understanding of radiation and its possible health effects is important for all those involved in an emergency, in particular for physicians, nurses, radiation technologists and medical first responders. This needs to be ensured through appropriate education and training of medical professionals in the topics of radioactivity, radiation and health effects associated with radiation exposure.

— **After a nuclear accident, health surveys are very important and useful, but should not be interpreted as epidemiological studies. The results of such health surveys are intended to provide information to support medical assistance to the affected population.**

The Fukushima Health Management Survey provides valuable health information for the local community, helping to ensure that any health effects are detected quickly, and that appropriate actions are taken to protect the health of the population. The overall results of health checks may provide important information, but they should not be misinterpreted as the results of an epidemiological assessment.

— **There is a need for radiological protection guidance to address the psychological consequences to members of the affected populations in the aftermath of radiological accidents. A Task Group of the ICRP has recommended that "strategies for mitigating the serious psychological consequences arising from radiological accidents be sought" [372].**

Psychological conditions have been reported as a consequence of the accident. This has been a repeated issue in the aftermath of accidents involving radiation exposure. In spite of its importance, these consequences have not been recognized in international recommendations and standards on radiological protection.

— **Factual information on radiation effects needs to be communicated in an understandable and timely manner to individuals in affected areas in order to enhance their understanding of protection strategies, alleviate their concerns and support their own protection initiatives.**

Arrangements at the national and local level need to be put in place to share information in an understandable manner with the public who may be affected by accidents with radiological consequences. The arrangements need to allow for person to person dialogue, so that individuals can seek clarifications and express their concerns. These arrangements will require the concerted efforts of the relevant authorities, experts and professionals in supporting and advising the affected individuals and communities. Sharing information is important when conveying decisions to protect these individuals, including the support of their own initiatives.

4.5. CONSEQUENCES FOR NON-HUMAN BIOTA

The releases of radionuclides to the environment as a result of the accident at the Fukushima Daiichi NPP not only raised concerns over the potential impact on humans but also over the possibility of any long term impacts on the living components of the environment.

Protection of the environment includes "the protection and conservation of: non-human species, both animal and plant, and their biodiversity; environmental goods and services". The term also includes "the production of food and feed; resources used in agriculture, forestry, fisheries and tourism; amenities used in spiritual, cultural and recreational activities; media, such as soil, water and air; and natural processes, such as carbon, nitrogen and water cycles" [220]. As explained in Section 4.3, environmental radiation protection objectives focus on populations. The ICRP has defined protection objectives as: to prevent or reduce the frequency of deleterious radiation effects on biota to a level where they would have a negligible impact on the maintenance of biological diversity, the conservation of species, or the health and status of natural habitats, communities and ecosystems [256] (see Section 4.3.1).

Although residents within a 20 km radius of Fukushima Daiichi NPP were evacuated in order to reduce their radiation exposures, the exposure of non-human biota inhabiting these areas was unavoidable. Given the scale and complexity of the releases, the spatial and temporal variations in the levels of deposited radionuclides, and the range of types of different terrestrial and aquatic biota affected, it has not been possible to obtain a fully comprehensive picture. Furthermore, the earthquake, the tsunami and the subsequent remedial work have given rise to physical and structural damage of the environment around the Fukushima Daiichi NPP, which also has consequences for the non-human biota.

The larger releases of radionuclides during the Chernobyl accident in 1986 led to the death of pine trees in the 'red forest' [373]. However, the release of radionuclides, and the corresponding doses to non-human biota occupying areas of high deposition in Japan, was much lower than in areas around Chernobyl. These facts indicate that severe detriments are not expected to have occurred and, in fact, acute effects were not observed immediately after the accident. Nevertheless, more subtle potential effects need to be investigated in the longer term.

4.5.1. Background to the assessment

4.5.1.1. The natural environment around the Fukushima Daiichi NPP

The location and characteristics of the environment around the Fukushima Daiichi NPP are described in Section 4.1.1. In the context of the present section, it should be noted that the terrestrial ecosystem structure is heterogeneous and contains many niches for wildlife. The Abukuma highlands contain a mixture of paddy fields, farmlands, secondary deciduous forest and evergreen coniferous trees, mainly cedar, where the biodiversity is high. Several coastal catchments extend from the coastal mountain range (at a distance of approximately 30 km from the coast) to the Pacific Ocean. The region is exposed to typhoons and spring snowmelt events, leading to severe soil erosion and subsequent export of sediment in rivers. There is a considerable range of birds and terrestrial mammals in the area[52], including the macaque monkey. The dominant natural species of trees include species of *Fagus*, *Carpinus*, *Zelkova*, *Aesculus*, *Pterocarpa*, *Acer* and *Abies*.

With regard to the marine environment, the local marine ecosystem is characterized by rich primary production, and the major primary producers are not only phytoplankton but also macro algae, especially brown algae. Such algae harbour rich fish and invertebrate fauna in the area [2].

4.5.1.2. The earthquake and the tsunami

The severe earthquake and tsunami caused significant environmental stress to the terrestrial and marine environments along the north-eastern coast of Honshu, far in excess of that caused by radiation exposure. The earthquake induced topographic changes to the sea floor, and inundation following the tsunami resulted in the transfer of large volumes of marine sediments onshore. Elevated deposition of sediment affected the abundance of several benthic biota and may have a major impact on the biological functioning of the sediments for years to come [376]. The Biodiversity Center of Japan [377] has conducted an investigation on the impact of this event on the environment, excluding the radiation impact from the Fukushima Daiichi accident[53].

4.5.1.3. Environments affected

The releases of radionuclides, dispersion and deposition and the resulting activity concentrations in a range of environmental media have already been described in detail in Section 4.1.

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[52] The Animal Distribution Atlas of Japan [374] and the Vegetation Map in Japan [375] describe the vegetation in Japan.

[53] Other reports of the effect of the tsunami on the ecosystems can be found in NAGAHATA, Y., How massive tsunami changed ecosystems (2012) [378]; NAKAJIMA, H. and KOARAI, M., Assessment of Tsunami Flood Situation from the Great East Japan Earthquake, Bulletin of the Geospatial Information Authority of Japan, Vol.59 December, 56–66 (2011) [379].

Terrestrial and freshwater environments

In the context of the terrestrial biota assessment in the initial phase, the MEXT soil survey described in Section 4.1 [380] is particularly useful. Samples for the first survey were collected between 6 June and 8 July 2011 from an area covering Fukushima, northern Ibaraki and southern Miyagi prefectures. The survey area comprised 2182 grid squares in total. A number of samples — normally five but ranging from one to seven depending on circumstances — were collected from each grid square. A consistent sample depth of 5 cm was used. All soil samples were analysed for gamma emitting radionuclides and the average deposition densities (Bq/m^2) were calculated. These measurements were used to construct accurate maps of activity concentrations in soil of each radionuclide measured.

Interception of ^{137}Cs, ^{134}Cs and ^{131}I by coniferous forest canopies were studied by Kato et al. (2012) [75] in Tochigi Prefecture, 150 km south-west of the Fukushima Daiichi NPP, with an estimated total deposition of ^{137}Cs in the area of less than 10 kBq. (See Annex III for more information.) Fresh water has been continuously monitored since the accident. Some aquatic species have also been measured. These data indicate that samples containing the highest activity concentrations were collected from rivers and lakes within Fukushima Prefecture. The information is presented in greater detail in Section 4.1.

Marine environment

Dispersed radionuclides in sea water may either be dissolved or adsorbed onto particulates that settle to bottom sediments, depending upon the chemical and physical characteristics of the radionuclides. A large fraction of radiocaesium is likely to remain in the water column and will follow the movement of the prevailing currents. When interaction with suspended material does occur, adsorption to clay is likely to be at least as important as adsorption (and presumably uptake) by plankton, which is often low [381]. Thereafter, transfer to bottom sediment can occur through processes such as the settling of particulate detrital products from plankton [382]. The highest activity concentrations of radionuclides were measured close to the Fukushima Daiichi NPP directly after the accident (in April 2011). The main radionuclides detected were ^{134}Cs, ^{137}Cs and, during the first few months, ^{131}I. The initially high levels of radiocaesium observed in proximity to the facility decreased significantly with time and space. According to UNSCEAR, the deposition of radiocaesium close to the coast was estimated to be around 10^4 Bq/m^2 and around 10^2–10^3 Bq/m^2 at a distance of 500 km [5]. However, the concentration of radionuclides in sea water was highly variable in both space and time, ranging from 1 to 50 kBq/L for ^{131}I and from 0.1 to 20 kBq/L for radiocaesium near the outlet in the coastal area within the first months following the accident. At greater distances, at locations in the open sea, the concentrations were much lower (>300 times). For the assessments in the initial phase, daily time series data of activity concentrations in sea water close to the Fukushima Daiichi NPP from TEPCO [118] and Vives-i-Batlle (2014) [383] were key sources of information.

Concentrations of radiocaesium in sediments from the surface of the seabed have been regularly measured in coastal areas. Close to the outlet of the Fukushima Daiichi NPP, the highest concentration of ^{137}Cs was detected in dry sediments (approximately100 kBq/kg dry mass) [5].

4.5.2. Dose assessment approaches, end points and benchmarks

To meet a growing demand for increased focus on the protection of the environment from ionizing radiation, several organizations have developed approaches to the assessment of radiation induced effects with the probability of causing long term consequences for non-human biota. These assessment methodologies tend to be based on simple assumptions. Uncertainties are thus usually taken into account by the use of conservative assumptions that tend to overestimate the radiological consequences [384].

The generally accepted approach has been to focus on the viability of biota populations and the integrity of ecosystems. Thus, it is assumed that, although individual biota may be harmed by radiation, it does not necessarily follow that this will have an impact on the survival of populations, nor on the structure and function of ecosystems.

The evaluation of potential impact is closely related to the assessments of the relevant biological end points. It is widely recognized that the most relevant biological end points in terms of potential environmental impact are those that could lead to changes in population size or structure and affect the ability of an organism to reproduce [385, 386].

Calculating radiation doses to biota is relatively simple, if certain simplifying assumptions are made. It is more difficult to relate the calculated doses to biological effects that can be attributed to the absorbed radiation. Naturally occurring radioactive material is ubiquitous in the environment, and in many cases, the natural background is the dominant source of exposure to any given organism [387].

The ICRP assessment approach has been adopted in this volume. This approach is based on a framework of an underlying set of twelve reference animals and plants (RAPs)[54] that relate exposure to dose, and dose to effect, for a limited number of biota that are typical of the major environments.

Numerical benchmarks have been developed that enable comparison with the estimated dose rates. The ICRP defined a set of reference values (Derived Consideration Reference Levels (DCRLs)) specific to each of the different RAPs, following a review of the effects of radiation on similar types of biota [260]. Each DCRL is a band of dose rates, spanning one order of magnitude, within which there is some chance of causing deleterious effects in individuals of a given RAP category arising from exposures to ionizing radiation according to the ICRP [260]. The relevant values and the list of reference animals and plants are given in Table 4.5–1.

TABLE 4.5–1. DERIVED CONSIDERATION REFERENCE LEVELS (DCRLs) FROM ICRP 108 (2008) [260]

DCRLs (mGy/d)	Reference animals and plants
0.1–1	Deer, rat, wild duck, pine tree
1–10	Frog, trout, flat fish, wild grass, brown seaweed
10–100	Bee, crab, earthworm

Other useful benchmarks have also been made available. In the scientific annexes to the 1996 and 2008 UNSCEAR reports [246, 255], published data on the exposures and effects on non-human biota

[54] RAPs are, by definition, points of reference, although other organisms could be identified similar to RAPs, relevant to each situation and geographical location. Reference data sets have been developed allowing exposures to be derived and placed in the context of dose effects information for RAPs [260]. For example, concentration ratios have been tabulated [260] by which whole body concentrations for the selected radionuclide concentrations in RAPs can be derived from corresponding radionuclide concentrations in ambient media. The explicit criterion for application of concentration ratios is that near steady state or equilibrium conditions exist between biotic and abiotic environmental compartments. However, this may not be valid for all types of radionuclides released to the environment and may have limited application for an emergency situation where ambient concentrations fluctuate rapidly with time. Once radionuclide activity concentrations in RAPs have been derived (or directly measured) and ambient media concentrations are known, dose rates can be calculated through the application of tabulated dose conversion factors [260].

have been evaluated[55]. The derived conclusions are that *"*chronic dose rates of less than 100 μGy/h to the most highly exposed individuals would be unlikely to have significant effects on most terrestrial communities" and that "maximum dose rates of 400 μGy/h to a small proportion of the individuals in aquatic populations of biota would not have any detrimental effects at the population level" [246]. These values are in agreement with the values reported elsewhere [246, 388, 389].

Other values have been identified for guidance on the environmental impact assessments. The research projects ERICA[56] and PROTECT [390, 391], funded by the European Commission, defined a generic dose rate of 10 μGy/h, to be used as benchmarks for screening assessment purposes during chronic exposure conditions.

All these reported values are primarily related to chronic rather than acute exposures. These facts have to be taken into account when interpreting the results following the assessment of the radiological consequences for non-human biota in the areas around the Fukushima Daiichi NPP. Furthermore, care must be taken in deciding about the impact to populations of animals or plants as opposed to small groups of individuals as reflected in the DCRL compilation. Population modelling approaches demonstrate that the linkage from radiation effects in individuals to population impacts is very complex and may be dependent on factors other than radiation doses and the dose–response relationships such as life history traits [392].

4.5.3. The dose assessment of non-human biota in the vicinity of the Fukushima Daiichi NPP

The dose assessment undertaken for the purposes of this volume comprises two distinct components. The first part concerns the application of activity concentration of radionuclides in environmental media, i.e. water, sediment and soil (or deposition) to calculate doses to adult RAPs following the releases from the Fukushima Daiichi NPP. The use of such data reflects the absence, or sporadic coverage, of direct radionuclide activity concentrations measurements in plants and animals for this period and requires the application of transfer models in deriving the levels of radionuclides associated with wildlife. Nevertheless, it gives an indication of the likely dose rates, and thus the effects, of biota generally in these areas.

Dose rates to biota have thus been estimated for defined time periods following the releases from the Fukushima Daiichi NPP. The source of the input datasets for this part of the assessment is the same as those used by UNSCEAR in its 2013 report [5]; however, the methodology applied, in particular the methodology for modelling transfer in the environment, is different and specific to the application of RAPs.

The second part of the assessment is based on data pertaining to directly measured activity concentrations in biota (and their habitats) from the review presented in this volume (see Section 4.5.3.2). These data provide the most precise estimates of doses, because the approach avoids the use of transfer models with their concomitant uncertainties. Reference dosimetric models for

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[55] UNSCEAR has repeatedly collated data on effects of radiation on non-human biota [246, 255] to provide, inter alia, a context for environmental impact assessments. Other compilations of data have also been made, of which the database FREDERICA, developed within the European Commission funded projects Framework for Assessment of Environmental Impact (FASSET), Environmental Risk from Ionizing Contaminants: Assessment and Management (ERICA) and Environmental Protection from Ionizing Contaminants in the Arctic (EPIC), is one of the more comprehensive. Data are structured as suggested by the ICRP.

[56] Several research projects have been supported by the EC during recent years, such as the FASSET, ERICA, Protection of the Environment from Ionizing Radiation in a Regulatory Context (PROTECT) and EPIC projects, which contributed to the ultimate goal of developing an integrated approach to assessing and managing the impact of radiation on the environment. In support of this aim, an assessment tool (ERICA) and a database on radiation effects in biota (FREDERICA) were developed. Work on the testing and intercomparison of the tools and methods developed in the aforementioned projects and elsewhere has continued at the IAEA through the EMRAS II and MODARIA programmes.

RAPs have been used in the exposure estimates for the second part of the assessment, whenever possible. In some cases, bespoke models were required where the biota differed considerably from those included in the list of RAPs. More details of the method used to calculate absorbed dose rates from activity concentration data are provided in Annex XII.

4.5.3.1. Assessment based on activity concentrations of radionuclides in environmental media

The assessment of the exposures resulting from the accident has been divided into three distinct periods in order to take into account the time dependence of the delivery of dose. The dose was estimated based on the time integrated activity concentrations in soil, fresh water and sea water (water and sediment) for the periods listed below:

- An early, acute period, during which exposures from short lived radionuclides, notably ^{131}I, occurred (30 days, mid-March–mid-April 2011);
- An intermediate period after 31–90 days (mid-May–mid-September 2011), when data on activity concentrations in the environment are available;
- Late period after 90 days (up to one year), when equilibrium is assumed, especially for radiocaesium (chronic exposures). [57]

These periods have been appropriately selected to address the time dependence of activity concentrations in the environment while removing an emphasis on ephemeral, very high values.

The radionuclides considered for the various assessments periods were:

- In the early and intermediate periods: ^{134}Cs, ^{137}Cs and ^{131}I;
- In the late period: ^{134}Cs, ^{137}Cs.

Other short lived radionuclides, particularly ^{132}I and ^{132}Te, may also have been important in the early acute period. However, the environmental measurements available for these radionuclides are too limited to allow a reliable estimate of dose rates.

Concentration ratios (CRs) can be used to derive activity concentrations in biota from activity concentrations in media. These values are strictly applicable in situations in which an equilibrium has been established between the levels of elements in different environmental media. These values are generally intended for application in assessing routine releases of radionuclides to the environment. However, the use of time integrated activity concentrations in media extends the applicability of this approach to situations where radionuclide concentrations are changing rapidly with time. Example calculations of CRs for biota in different environments are presented in Annex XII.

This approach has been used to calculate whole body concentrations of radionuclides in animals during the early and intermediate periods and in all biota types, including vegetation, during the late phase.

Terrestrial

The method of calculating the radionuclide content in vegetation at a specific time, accumulated via direct deposition from the air, is set out in Annex XII.

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[57] Equilibrium is unlikely to have been established on a timescale of 90 days for some RAPs (notably the pine), leading to additional uncertainties.

A single deposition event on 15 March has been assumed to simplify the assessment[58]. Further information regarding the assumptions and parameters used in this assessment is presented in Annex XII.

Soil activity concentrations as a function of time (to allow derivation of external dose rates and application of CR values) are also required for exposure estimates. The method of calculating the component of deposited radioactivity which becomes associated with soil is set out in Annex XII.

The time integrated activity concentration in vegetation and soil is calculated for 0–30 day and 31–90 day periods. The radionuclide concentrations in soil at one year were determined for the late period exposure calculations.

Concentrations for terrestrial RAPs are derived from soil concentrations using CRs for terrestrial RAPs (Annex XII). Thereafter, doses for all biota are derived using the methodology described above.

The highest activity of ^{137}Cs at a location in Okuma Town was used to provide an indication of exposures to the most highly exposed individuals in animal and plant populations [5]. Corresponding ^{131}I levels were based on ^{131}I:^{134}Cs ratios [69] (see Annex XII).

Dose rates for terrestrial RAPs during the initial phases of the Fukushima Daiichi NPP releases are presented in Fig. 4.5–1. Maximum dose rates in the range of 0.8–0.9 mGy/h (approximately 20 mGy/d) were calculated for the (wild) grass and (pine) tree RAPs in the initial 0–30 day period post-accident. These dose rates decreased rapidly to be in the range of 10–20 μGy/h (0.25–0.5 mGy/d) within the first year of the assessment. Substantially lower dose rates were calculated for animals. Maximum dose rates were estimated in the initial 0–30 day period reflecting the contribution of ^{131}I to total exposures.

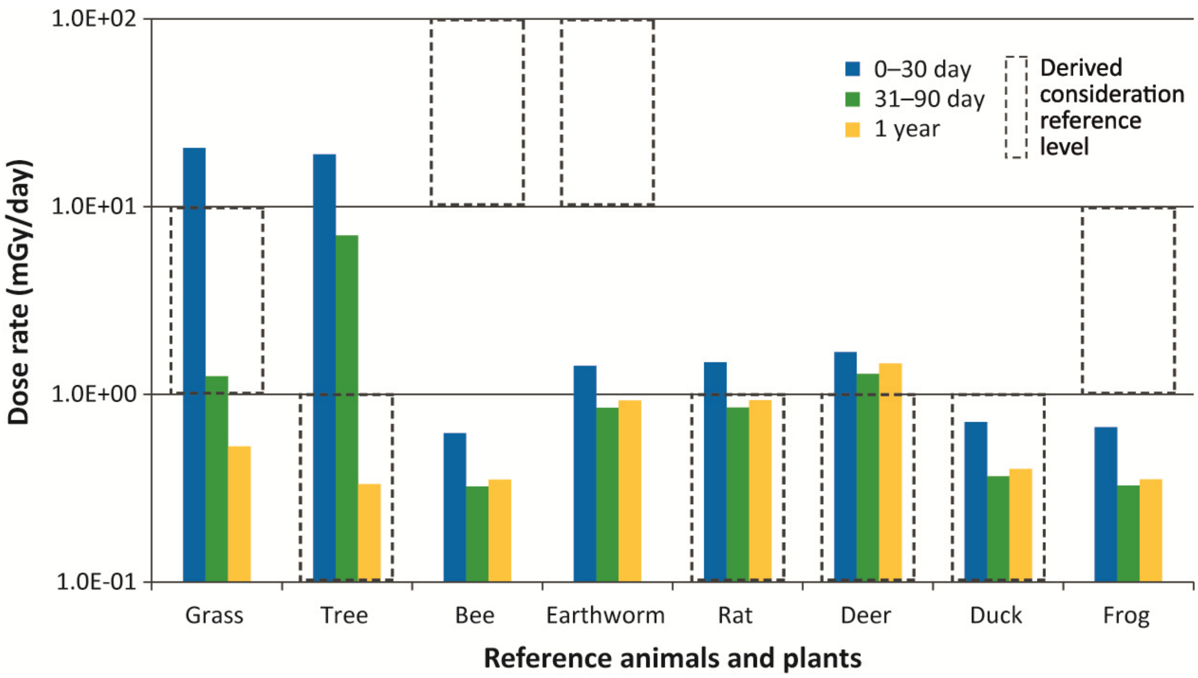

FIG. 4.5–1. Dose rates (mGy/d) for terrestrial RAPs versus time at Okuma Town.

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[58] This corresponds to the date at which the greatest proportion of the atmospheric release occurred, while the wind direction and weather conditions led to deposition onto the terrestrial environment.

The deer RAP exhibited the highest estimated exposures of the animals considered in the assessment: maximum dose rates of 70 µGy/h (1.7 mGy/d) were estimated, but this value decreased to 60 µGy/h (1.4 mGy/d) in the first year. Accumulated dose rates for terrestrial RAPs are also presented in Fig. 4.5–1. The highest accumulated doses were derived for vegetation, reflecting the relatively high dose rates calculated for the (wild) grass and (pine) tree RAPs in the initial period. A significant fraction of the dose was accumulated over the 0–30 day period for all RAP categories.

Marine

Exposures of biota to radiation in the marine environment vary according to the organism's habitat. All biota will be internally exposed via the contaminated food web, and benthic biota are likely to receive a substantial additional external exposure from contamination associated with seabed sediments. External exposures of pelagic biota are likely to be low in comparison. The dispersal of radionuclides over large spatial areas with time will therefore moderate the exposures to pelagic marine fish and other marine species.

The time integrated activity concentrations in sea water and sediment have been derived for the periods: 0–30 days and 31–90 days.

The datasets for a point 30 m north of the discharge channel of Units 5 and 6 of Fukushima Daiichi NPP and the south channel, approximately 1.3 km south of the discharge channel from Units 3 and 4, were selected from UNSCEAR (2014) [5]. These constitute the sampling locations where activity concentrations were at a peak and correspond to those values presented in Section 4.1.2 of this volume.

Radionuclide concentrations in marine biota are obtained from the concentrations in the dissolved phase in sea water, multiplied by the appropriate concentration ratios as described in Annex XII.

Dose rates for marine RAPs during the initial phases of the Fukushima Daiichi NPP releases are presented in Fig. 4.5–2, along with accumulated doses for the periods of 0–30 days and 31–90 days. Maximum exposures were derived for the brown seaweed RAP, for which dose rates exceeded 70 mGy/d (3 mGy/h) in the initial 0–30 day period. This elevated dose rate reflected the relatively high bioaccumulation of radioiodine by macroalgae from sea water. However, dose rates decreased rapidly for this RAP group, with dose rates approaching 2.4×10^{-3} mGy/d (0.1 µGy/h) after one year of elapsed time. Dose rates for the flatfish and crab RAPs were in the range of 1.7–3.4 mGy/d (70–140 µGy/h) in the initial high exposure period and deceased to dose rates around 0.12–0.14 mGy/d (5–6 µGy/h) in the intermediate period. The elevated dose rates for these RAP groups in the late period compared with macroalgae reflects the importance of external exposure from radiocaesium in the seabed for flatfish and crab, Brown seaweed is assumed to be externally exposed to radionuclides present in the water column only.

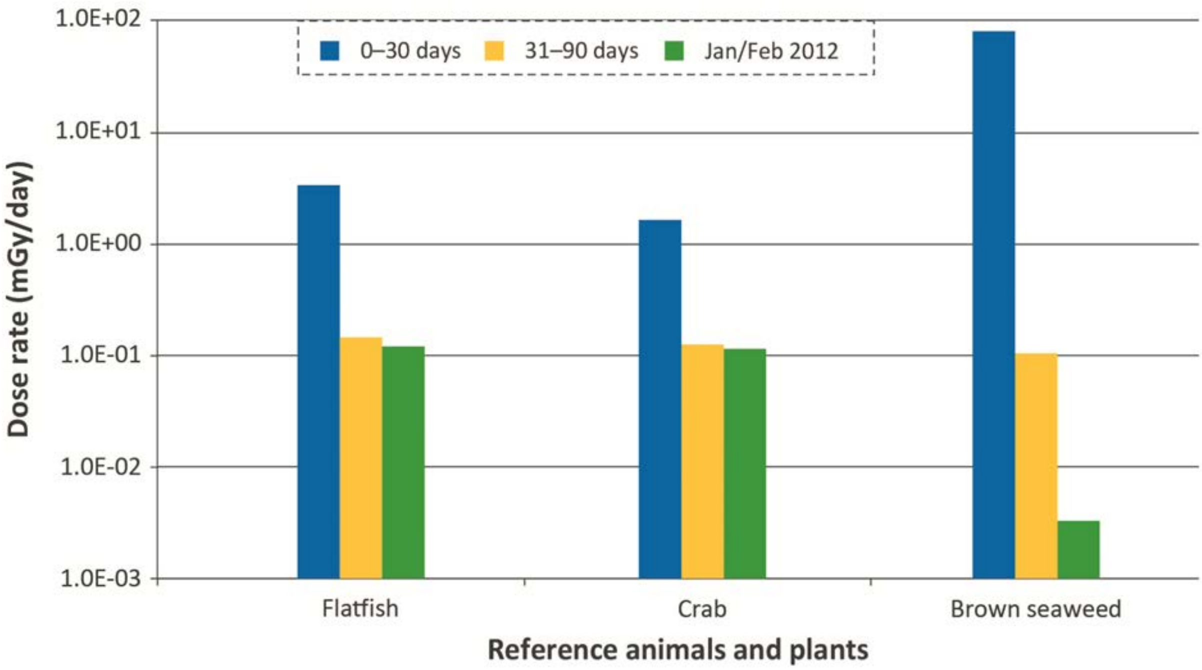


FIG. 4.5–2. Dose rate (mGy/d) for marine RAPs versus time at location 30 m north of discharge channel of Units 5 and 6 of the Fukushima Daiichi NPP.

4.5.3.2. Assessment based on directly measured activity concentrations in biota

Numerous papers have reported activity concentrations in biota that are said to arise from releases from the Fukushima Daiichi NPP. Data selected from information for radionuclide activity concentrations for biota presented in this volume have been used in conjunction with data on activity concentrations in the organism's habitat (i.e. in sea water, fresh water, sediments or soil) to provide a quantification of total exposures at the time of sampling. In practice, this was achieved by mapping each of the selected organism types onto an appropriate organism geometry and then using the corresponding dose conversion coefficients (DCCs) for internal and external exposures from ICRP Publication No. 108 [260] as described in Annex XII. In those cases where an appropriate geometry was not available, bespoke dose conversion coefficients were derived for what were effectively the representative organisms (RAPs)[59], using the ERICA tool [393, 394].

Concentrations of ^{134}Cs and ^{137}Cs in the muscle of Japanese monkeys (*Macaca fuscata*) inhabiting the forest area of Fukushima City were measured by Hayama [395]. Concentrations in muscle were in the range of 6000 to 25 000 Bq/kg for monkeys captured in areas with soil contamination levels in the range of 100 000 to 300 000 Bq/m^2. Levels decreased rapidly in May and June 2011 and reached an equilibrium value of around 1000 Bq/kg in monkeys captured during and after June, although there were substantial individual differences.

The concentration of radiocaesium in leaves of Japanese cedar, bamboo and *Clinopodium gracile* was measured by Tazoe et al. (2012) [396]. Samples of Japanese cedar leaves collected in April and June 2011, respectively, showed a much lower concentration of radiocaesium than leaves from the bamboo (approximately 450 kBq/kg), which might be due to the differences in overlapping branches (interception). Grass sampled from Namie Town showed a maximum activity concentration of approximately 350 kBq/kg of radiocaesium in April. Japanese mugwort showed very low

[59] The organism or group of organisms that are the actual ecological entity being assessed.

concentrations (<0.5 Bq/kg), despite relatively high concentrations of ^{137}Cs in the soil (6.3–27.1 kBq/kg).

Kuroda et al. (2013) [397] investigated the radiocaesium concentrations in the stemwood of three major Japanese tree species (oak, cedar and red pine trees) collected from five sites in Fukushima Prefecture. Half a year after the Fukushima Daiichi accident, radiocaesium was distributed in bark, sapwood and heartwood, indicating a very rapid translocation of radiocaesium into the wood. The concentration levels in the components of the tree depended on the radiocaesium deposition density. At all sites and for all species, radiocaesium activity concentrations were substantially greater in bark than they were in sapwood and heartwood.

The concentrations of earthworms in forests of Fukushima Prefecture were measured six months after the accident at three forest sites located at distances of 26 km–134 km from the site of the Fukushima Daiichi NPP [398]. Japan has a high diversity of terrestrial earthworms, especially those in the family *Megascolecidae*. Three plots were Japanese cedar plantations (*Cryptomeria japonica*), and one plot was a mixed forest of oak (*Quercus serrata*) and pine (*Pinus densiflora*). The deposition densities of radiocaesium ($^{134+137}Cs$) varied from 20 kBq/m^2 at a site located 134 km from the NPP to 1230 kBq/m^2 at a site located 26 km from the plant. The highest concentrations in earthworms were 61 ± 41 kBq/kg of ^{134}Cs; values of 70 ± 46 kBq/kg (dry weight) of ^{137}Cs were also found at this site. The lowest values — 1.26 ± 1.17 and 1.46 ± 1.17 kBq/kg (dry weight) for ^{134}Cs and ^{137}Cs, respectively — were obtained for soil invertebrates sampled at the distance of 134 km from the Fukushima Daiichi NPP. No substantial differences in $^{134+137}Cs$ concentrations were identified for different species of earthworms on the same plots [398].

The concentrations of radiocaesium (^{134}Cs and ^{137}Cs) were measured in large web spiders, *Nephila clavata L. Koch* (*Nephilidae: Arachnida*), collected at three sites at different distances from the Fukushima Daiichi NPP about 1.5 years after the accident [399]. The radiocaesium concentrations in spiders were highest in a streamside secondary forest 33 km north-west of the Fukushima Daiichi NPP with a mean of 2.4 ± 1.2 kBq/kg (dry weight) for ^{134}Cs and 4.0 ± 1.8 kBq kg^{-1} (dry weight) for ^{137}Cs. At a hillside secondary forest 37 km north-west of the Fukushima Daiichi NPP, the mean concentrations of ^{134}Cs and ^{137}Cs were 0.83 ± 0.25 kBq/kg (dry weight) and 1.5 ± 0.5 kBq/kg (dry weight), respectively.

In a pine forest 62 km west of the Fukushima Daiichi NPP, very low radiocaesium concentrations were detected. The concentrations of ^{134}Cs and ^{137}Cs in spiders collected at each site tended to correlate with the measured external air dose rate at each site. Spiders are key components of food webs in forests and, consequently, the relatively high concentrations of measured radiocaesium in these species may indicate that the deposited radiocaesium from the accident had reached higher trophic levels of the food chains [399].

An overview of radiocaesium in freshwater fish in Fukushima Prefecture and eastern Japan was based on data published in Mizuno et al. in 2013 [400]. An isogram map shows the radiocaesium contamination of the Ayu (*Plecoglossus*) captured between May and September 2011 in each prefecture in eastern Japan. At about 100 km from the Fukushima Daiichi NPP, the average concentration was about 200 Bq/kg and decreased with larger distances. However, no information is given in the study about uncertainties or variability. Nor is any information provided on where the fish were caught. The data do, however, indicate that the levels of concentration in fish were relatively low.

With regard to the marine environment, activity concentrations in pelagic fish and plankton were measured in samples collected at 50 stations at the Japanese coast in June 2011 [401]. The amount of radiocaesium ranged from below the detection point to about 56 Bq/kg (dry weight). Silver-110m was occasionally detected in zooplankton, with concentrations up to 23.6 Bq/kg (dry weight). The authors concluded that “radiation risks due to these radionuclides are below those generally considered harmful to marine animals and human consumers” [401]. The input datasets for the assessment are provided in Tables 4.5–2 and 4.5–3.

TABLE 4.5–2. INPUT DATA USED AND DOSE RATES DERIVED FOR THE ASSESSMENT BASED ON DIRECTLY MEASURED ACTIVITY CONCENTRATIONS IN TERRESTRIAL BIOTA

Species (RAP)	Activity concentration Bq/kg fresh weight biota (radionuclide)	Activity concentration Bq/kg dry weight or Bq/L (media)	Notes (date, location, methods)	Reference	Dose rate (mGy/d)
Japanese monkey, *Macaca fuscata*	2.5×10^4 (radiocaesium)	4.6×10^3 (soil)	April 2011; Fukushima City (>50 km NW of Fukushima Daiichi NPP); bespoke DCCs derived using the methodology outlined by Ulanovsky et al. (2008) [394] and bodyweight data provided in article	Hayama et al. (2013) [395]	0.2
Japanese monkey, *Macaca fuscata*	1×10^3 (radiocaesium)	4.6×10^3 (soil)	July 2011; Fukushima City (>50 km NW of Fukushima Daiichi NPP); bespoke DCCs derived as above	Hayama et al. (2013) [395]	0.03
Japanese cedar, *Cryptomeria japonica* (Pine Tree)	3.3×10^3 (Cs-137) 2.8×10^3 (Cs-134)		August 2011; Kawauchi Village (37°20′15″N, 140°48′34″E) approximately 20 km W of Fukushima Daiichi NPP; whole tree activity concentrations, weighted according to model tree	Kuroda et al. (2013) [397]	0.1
Earthworm, *Amynthas sp.* (Earthworm)	1.2×10^4 (Cs-137) 1.0×10^4 (Cs-134)	1.2×10^4 (Cs-137) 1.0×10^4 (Cs-134)	August 2011; Kawauchi Village (37°17′18 ″N, 140°47′47 ″E)	Hasegawa et al. (2013) [398]	0.4
Web spiders *Nephila clavata L. Koch* (Bee)	1.4×10^3 (Cs-137) 8.6×10^2 (Cs-134)	1.5×10^4 (Cs-137) 9.6×10^3 (Cs-134)	October 2012; streamside secondary forest dominated by broadleaved trees, about 33 km north-west of Fukushima Daiichi NPP; dry/fresh ratio = 0.36 for site. No soil data but appears to be in an area where soil deposition was approx. 1 MBq/m^2 from July 2011	Ayabe et al. (2014) [399]	0.1
Bamboo (Wild Grass)	2.0×10^5 (Cs-137) 2.0×10^5 (Cs-134) No data (I-131)	8.4×10^4 (Cs-137) 8.2×10^4 (Cs-134) 2.9×10^4 (I-131)	12 April 2011; Tetsuzan dam (37°34.5'N, 140°52.9'E), 21.8 km from Fukushima Daiichi NPP	Tazoe et al. (2012) [396]	2
Grass (Wild Grass)	1.9×10^5 (Cs-137) 1.6×10^5 (Cs-134)	9.0×10^3 (Cs-137) 9.0×10^3 (Cs-134)	13–14 April 2011; Namie Town (37°29′N, 141°00′E) approximately 20 km from Fukushima Daiichi NPP	Tazoe et al. (2012) [396]	1
Grass (Wild Grass)	5.9×10^3 (Cs-137) 6.0×10^3 (Cs-134)	8.5×10^3 (Cs-137) 8.5×10^3 (Cs-134)	June–July 2011; Keiko Park, Motomijya City (37°31′N, 140° 24′E), >50 km from Fukushima Daiichi NPP	Tazoe et al. (2012) [396]	0.1

TABLE 4.5–3. INPUT DATA USED FOR THE ASSESSMENT BASED ON DIRECTLY MEASURED ACTIVITY CONCENTRATIONS IN AQUATIC BIOTA

Species (RAP)	Activity concentration Bq/kg fresh weight biota (radionuclide)	Activity concentration Bq/kg dry weight or Bq/L (media)	Notes (date, location, methods)	Reference	Dose rate (mGy/d)
Ayu, *Plecoglossus altivelis altivelis* (Trout)	3.3×10^3 (radiocaesium)	7.8×10^3 (Cs-137) 6.9×10^3 (Cs134)	Biota, Mano River between May and September 2011, sediment 29 May 2011; Mano River in Minamisoma City at Majima bridge approximately 40 km from Fukushima Daiichi NPP. The paper refers to quasi Cs-137, which appears to equate to radiocaesium (Cs-134 + Cs-137). A 1:1 ratio has been used. Water concentrations are not given, but a rough estimate of external exposures can be attained by assuming exposure to sediment. Maximum value reported for Ayu.	Mizuno and Kubo [400]	0.1
Zooplankton mixed Copepods (Zooplankton)	1.1×10^1 (Cs-137) 8.2×10^0 (Cs-134)	2.4×10^{-3} (Cs-137) 1.0×10^{-3} (Cs-134)	4–18 June 2011; at least 30 km offshore Fukushima Daiichi NPP; values given as dry weight, converted to fresh weight using factor from Hosseini et al. (2008) [402].	Buesseler et al. (2012) [401]	5×10^{-5}
Fish – S. gracile (Flatfish)	2.8×10^0 (Cs-137) 2.7×10^0 (Cs-134)	3.9×10^0 (Cs-137) 3.8×10^0 (Cs-134)	4–18 June 2011; at least 30 km offshore from Fukushima Daiichi NPP; S. gracile appears to be a deep water species: note surface water activities used (likely to be conservative).	Buesseler et al. (2012) [401]	1×10^{-4}

Dose rates for terrestrial plants and animals for which direct activity concentration measurements in biota were available (Table 4.5–2) are presented in Fig. 4.5–3 for two periods corresponding to 0–90 days post-accident and the ‘chronic exposure’ (later than 90 days, i.e. equilibrium conditions) period following this. Maximum dose rates of approximately 1 to 2 mGy/d (50 to 90 µGy/h) were calculated for bamboo and grass in the 0–90 day period at sites located at around 20 km from the Fukushima Daiichi NPP. Although dose rates for grass appear to have decreased relatively sharply with time, falling to approximately 0.1 mGy/d (approximately 5 µGy/h) after the 90 day period, this might equally be explained by sampling location — the latter exposure estimate pertaining to a site exceeding a distance of 50 km from the Fukushima Daiichi NPP. For Japanese monkeys (*Macaca fuscata*) inhabiting the forest area of Fukushima City, absorbed dose rates of approximately 0.2 mGy/d (8 µGy/h) in the initial period (April 2011) can be derived. These values decrease to approximately 0.03 mGy/d (1 µGy/h) in the late period (post-July 2011). By the summer of 2011, and at a distance of approximately 20 km west of the Fukushima Daiichi NPP, dose rates for earthworms and cedar trees were approximately 0.4 mGy/d (15 µGy/h) and 0.1 mGy/d (5 µGy/h) respectively. Finally, dose rates for web spiders for a sampling site about 33 km north-west of Fukushima Daiichi NPP, were of the order of 0.1 mGy/d (5 µGy/h) in October 2012.

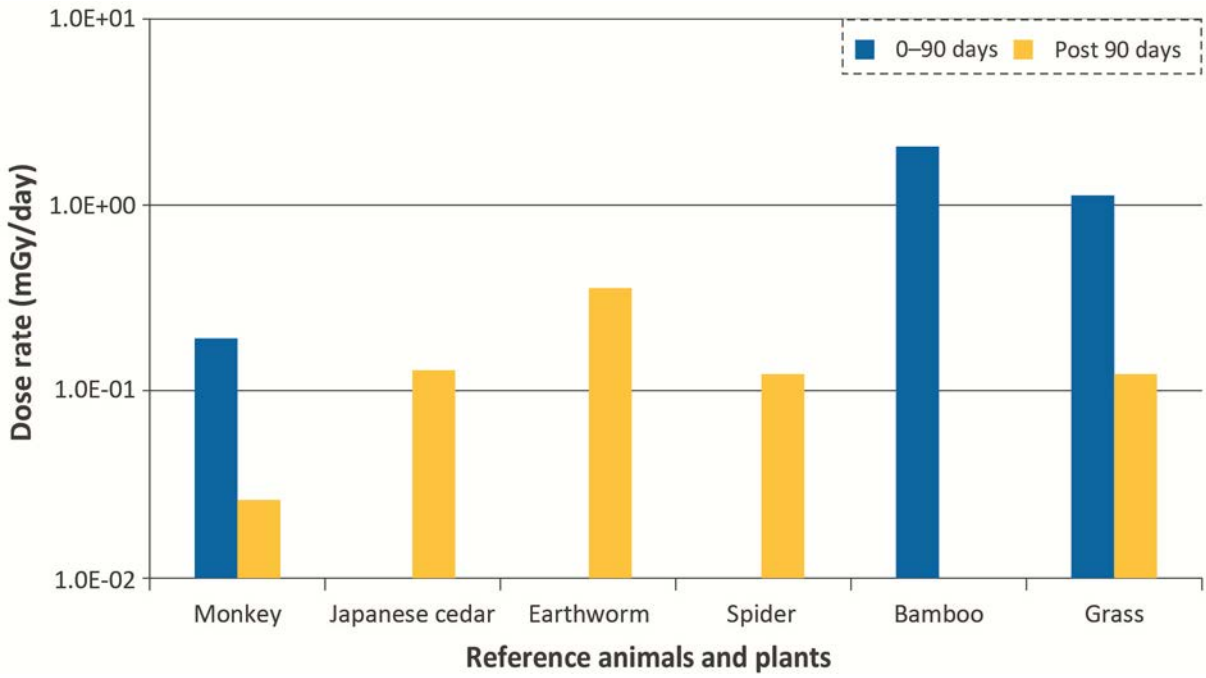


FIG. 4.5–3. Dose rates for terrestrial plants and animals for which direct activity concentration measurements in biota were available.

The dose rate for marine plants and animals for which direct activity concentration measurements in biota were available (Table 4.5–3) are presented in Fig. 4.5–4 for the period post-90 days following releases from the Fukushima Daiichi NPP. Bearing in mind that the marine samples were collected at least 30 km off the shore of the Fukushima Daiichi NPP, dose rates for marine fish and zooplankton fell substantially below 2.4×10^{-4} mGy/d (0.01 µGy/h). In contrast, dose rate for freshwater fish sampled at around 40 km from the Fukushima Daiichi NPP may have exceeded 0.1 mGy/d (4 µGy/h) in the chronic exposure phase.

Any assessment of the effects on non-human biota is inevitably subject to a high degree of uncertainty. In this particular assessment, it was difficult to account for short lived radionuclides in the initial post-accident period. Overall uncertainties associated with the types of models applied in this assessment, particularly those involving a biological transfer component (and as required in a large part of the most contaminated areas), are normally large — as typified by the observation that estimations using different models often differ from one another by more than an order of magnitude [403]. In contrast, where dose rates were estimated using directly measured concentrations of radionuclides in biota, uncertainties are much lower.

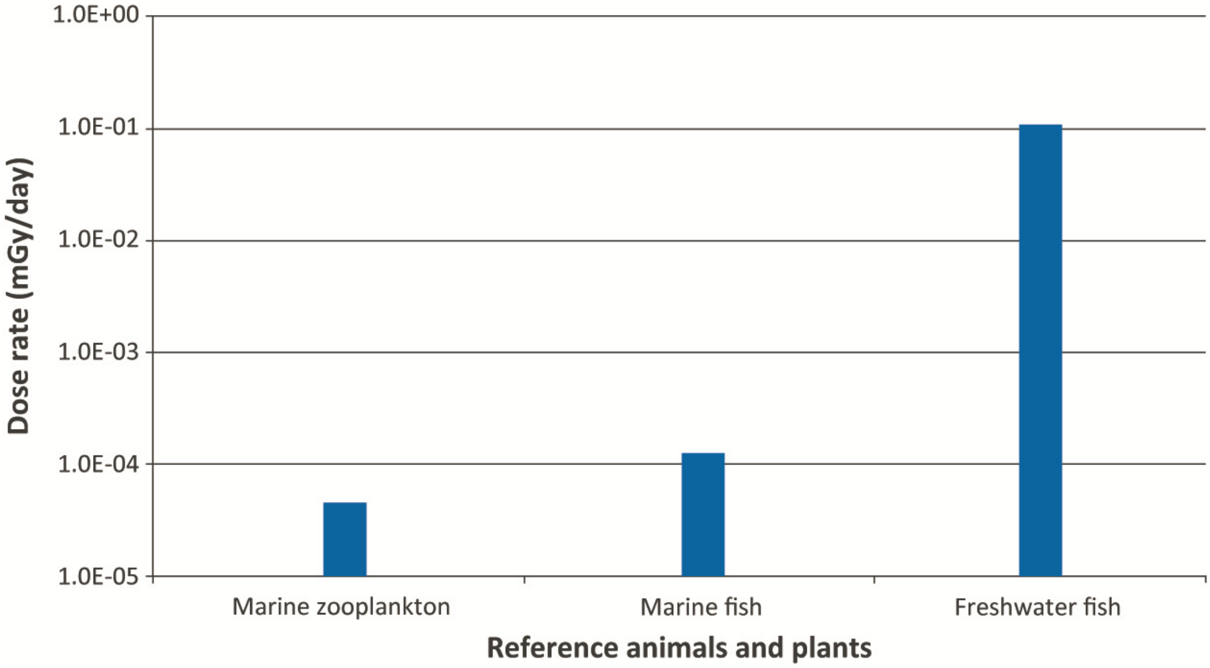


FIG. 4.5–4. Dose rates for freshwater and marine animals for which direct activity concentration measurements in biota were available (summer 2011).

The approach outlined does not account for inhomogeneity in radionuclide concentrations within biota, which may lead to elevated exposures for different tissues compared with the whole organism. In the case of acute doses, it is important to have a good estimation of the dose to the most radiosensitive tissues and organs of an organism — such as the apical meristem of trees. Although attempts have been made to simulate the dynamics of radionuclide retention and loss in vegetation, the approach presented above is largely based on an assumption of equilibrium between radionuclides in biota and their surrounding media. In the case of acute contamination situations, doses to radiosensitive organs of biota species, such as apical meristem of trees, are much higher compared with doses to the whole body, because they are the first forest compartments to be exposed to contamination and because of their tendency to intercept radionuclides from passing plumes. To take into consideration these effects, the FORESTLAND dynamic model [404, 405] was utilized for the same deposition data inputs as outlined in Annex XII. Although the FORESTLAND model was not developed specifically for the areas affected, it was well validated based on data from different areas and has a proven ability to provide reliable assessments [406]. The doses to the top of crowns calculated based on this approach are in a range of 200–400 mGy for the first 30 days after the deposition and in a range of 250–500 mGy for 90 days after the deposition. These values are similar to those given in Fig. 4.5–1 for the (pine) tree RAP.

Thyroid doses from inhalation of ^{131}I by mammals may be an important component of exposure in the early periods following the accident. This route of exposure is not modelled explicitly, nor does the methodology account for specific organ doses (as only whole body activity concentrations have been derived). Even if it were possible to derive ^{131}I thyroid concentrations and concomitant doses in the thyroid of wild mammals, the available dose rate benchmarks are based primarily on whole body exposures.

The experience gained after the accident at the Chernobyl accident clearly indicated that the radiation damage to grazing agricultural animals was caused by exposure of the thyroid from radioiodine accumulation. An impaired thyroid function in cattle was related to the dose received by the thyroid[60] [407], and the estimated thyroid doses at which no effects were observed were found to be about 20 Gy [373].

4.5.4. The radiological consequences for non-human biota

4.5.4.1. General considerations

In any exposure situation, spatial and temporal deposition patterns set the initial conditions for radiation induced effects in all living biota, but on an individual level. The response of an individual organism to initially induced damage is, in turn, dependent not only upon the physical parameters of the dose delivered but also upon the intrinsic radiosensitivity of the organism, relevant to the end point studied. Thus, understanding the dose and dose rate dependence of the response to radiation is the key aspect of interest for risk estimations in relation to radiation exposures.

Acute exposures to ionizing radiation are delivered within a limited time period, usually within minutes or hours, in contrast to chronic exposure, which may last for weeks, months or years. Concurrently, the effects and effect levels are commonly different between these exposure regimes, which may have implications for the long term consequences. There is a wide range of acute doses required to cause death in individual non-human biota. Lethal doses ($LD_{50/30}$) range from 2 to 10^4 Gy in the report by UNSCEAR (2011) [246], depending on factors such as the exposure conditions and the life stages of the biota, with early life stages generally considered to be more sensitive to acute radiation doses.

When doses that lead to death in an individual are delivered over a long period, the dose rate is much less than for fatal acute exposures [246]. Lowering the dose rates allows the recovery of tissues or organs and increases the tolerance to higher total doses. Similarly, partial body irradiation may increase the tolerance, since critical parts of vital organs may be unexposed.

There is, furthermore, a dilemma in that as the ecological relevance of a system increases, so does the complexity of the system, and, correspondingly, the difficulty in assessing or measuring the response(s) to a stressor. For this reason, toxicological investigations most often focus on simpler systems, or on tissue and individual effects. Attempts must then be made to extrapolate individual effects data to populations and the higher levels of organization. While most scientific data available to date on radiation dose–effect relationships concern individual animal and plant biota [255, 408, 409], these data lack information on special system level effects, as already stressed in radiological protection [410].

Direct effects on the variation of species and ecosystems that are induced by radiation are rare but could be observed in large controlled field studies where external irradiation was performed with gamma radiation sources at high and very high dose rates [411, 412]. For example, high dose rates have resulted in a reversible depletion of radiosensitive plants [413]. As for radiation accidents like the one at Chernobyl, ecological impact stems from the first acute period of exposure, when the releases of activity are the highest. At a later stage, indirect effects may become more pronounced but might not be explicitly related to radiation [414].

[60] A reduction of 69% in function with a thyroid dose of 50 Gy, and an 82% reduction in animals that received a dose of 280 Gy [407].

4.5.4.2. Observations from post-Chernobyl accident studies on the impact on ecosystems and populations

The time course of radiation impact on ecosystems following nuclear accidents has been described in relation to the Chernobyl and Kyshtym accidents [373]. Initially, the dose rates decreased rapidly due to the decay of short lived radionuclides (e.g. ^{131}I). Later, migration of the deposited radionuclides vertically and laterally in soil (e.g. ^{137}Cs) led to heterogeneous exposures and, in a longer time perspective, low exposures to the biota prevailed over comparatively long periods of time [414].

The area around the Chernobyl NPP has a temperate climate and flourishing flora and fauna. The complex time dependence of the released radionuclide composition and variable meteorological conditions over ten days of active emission caused an extremely inhomogeneous deposition pattern and a wide scatter of dose burden to the biota. The acute dose rates in the first 20 days following the start of the accident came mainly from short lived radionuclides which were deposited onto plant and ground surfaces. In the zone immediately surrounding the Chernobyl NPP, the deposition was more than 3.7×10^{13} Bq/km^{-2}, which caused numerous acute adverse effects in the biota. The pine forest was severely damaged up to 7 km from the reactor, and lethal doses to the pine needles amounted to 20–100 Gy (acute dose). The initial dose rate in the 'red forest' was 5 mGy/h (120 mGy/d). Leaf gigantism was observed in deciduous trees, while no visual effects on herbaceous plants were evident in 1986 in the 10 km evacuation zone. In addition, vertebrate animals also received high thyroid doses as a result of internal exposure from radioiodine during this early period.

Approximately 80% of the total radiation dose accumulated by animals and plants was received in the first three months following the accident, with 95% due to beta radiation. During the summer and autumn of 1986, the dose rate at the soil surface declined to less than 10% of the initial values as short lived radionuclides decayed, although damaging doses were still accumulated. A third, continuing phase of radiation exposure was characterized by chronic dose rates at levels less than 1% of the initial values, derived mainly from ^{137}Cs. The contribution to the total dose rate from gamma and beta radiation was comparable owing to the migration of much of the ^{137}Cs into the soil. Studies following the Chernobyl accident indicated that the coniferous plants and coniferous forest (ecosystem) are radiosensitive populations in the environment [373].

It has to be noted that the populations of biota around the Chernobyl NPP have recovered substantially during the years following the accident. But the nature and scale of the recovery has been confounded by drastic changes in human activity, including termination of agricultural and industrial activities and the accompanying environmental pollution in the most affected area. As a result, the populations of many plants and animals have expanded.

4.5.4.3. The radiological consequences for non-human biota in proximity to the Fukushima Daiichi NPP

Around the Fukushima Daiichi NPP, the releases of radionuclides and thus the doses to non-human biota were highest during the first weeks and months following the initial releases. For large accidental releases of radioactive material in general, it is during this period that the potential for acute damage in tissues and organs may arise. If the dose is high enough, death can occur due to failure of important organ systems.

The estimated doses to the terrestrial RAPs during the first weeks after the accident were highest for plants. The accumulated dose is approximately 0.6 Gy for the first 30 day period for both the (pine) tree and (wild) grass RAPs. From data collated for forest affected by deposition after the Chernobyl accident, UNSCEAR [246] reported that minor damage characterized by disturbances in growth, reproduction and morphology of conifers could be observed at doses from 0.5 to 1.2 Gy. More serious, sublethal damage, including destruction of meristems and partial death of conifers, was not observed until doses were in the range of 10–20 Gy. Herbaceous plants, including grasses, are considered to be more radioresistant, and after the Chernobyl accident, sterility of seeds was not observed at doses below 5 Gy [246]. From the assessed doses, it is possible to infer that any direct lethal effects in even relatively sensitive plants such as conifers would not have occurred. Comparison with the DCRLs shows that the calculated dose rates exceed the DCRL band for pine, grass and mammals during the first 90 days after the accident.

For the terrestrial deer RAP, the estimated dose rate of 1.7 mGy/d for the period of 0–30 days falls just within the range (1–10 mGy/d) where there is a potential for reduced reproductive success, owing to increased male sterility [260]. However, comparison with the $LD_{50/30}$ data for the deer RAP indicates that the calculated accumulated doses were orders of magnitude below levels at which lethal effects would be observed. In other words, the estimated total dose during the acute phase was such that no major acute radiation induced effects would have been expected at the calculated exposure levels. Similarly, limited impacts may be inferred from the second part of the assessment, in which experimental data on radionuclide activity concentrations measured directly in plants and animals have been used. To illustrate this, for grass, the calculated dose rate of 2 mGy/d in the 0–30 day period fell within the ICRP's DCRL band but below a dose rate where reduced reproductive capacity in these types of plants has been recorded [260]. Although not directly comparable, because ICRP's tabulated dose rates pertain to chronic exposure regimes, the comparison nevertheless suggests that exposures are unlikely to affect population viability. Similarly, dose rates for Japanese monkey at 0.2 mGy/d in the early phase fell in a DCRL band, considered for the related deer and rat RAPs, to constitute a very low probability of effects. In contrast, dose rates for earthworms (0.4 mGy/d) fell substantially below the corresponding DCRL (10–100 mGy/d) where effects are considered unlikely[61].

The marine biota category, brown seaweed received the highest exposures among the RAPs considered, with dose rates exceeding 70 mGy/d in the initial period of 0–30 days. The highest accumulated doses were observed for brown seaweed at 2.4 Gy, and thus within the same order of magnitude as the acute threshold value proposed at the ecosystem level for the marine environment of 4.84 Gy [415], also reported by UNSCEAR [246].

Dose rates in the range of 10–100 mGy/d have the potential to cause effects on reproduction and growth rate in (individual) macroalgae [260]. Nonetheless, these elevated exposures were limited in space — the values used in the assessment relate to a position 30 m from the main release area — and in time. The spatially limited and transient nature of the highly elevated exposure indicates that releases from the Fukushima Daiichi NPP were unlikely to have caused any substantial harm to regional populations of brown seaweed.

Dose rates for offshore marine biota in the late phase were extremely low, and the maximum dose rate for freshwater fish of 0.1 mGy/d fell substantially below the appropriately comparable DCRL band for trout (1–10 mGy/d). Nevertheless, short lived radionuclides, including ^{131}I, were generally not included in the assessment, based on measured activity concentrations in plants and animals; actual doses in the early phase may have been somewhat higher than those calculated. It is possible that dose rates may have exceeded corresponding DCRL bands in some cases, but they are unlikely to have been at a level that would cause detriment to populations of wild plants and animals.

Although the methods used for the assessments are simple, they are robust and encompass the main exposure pathways relevant for assessing exposures to wild plants and animals. Nonetheless, the

[61] It should be noted that the DCRLs have been defined in terms of bands of dose rates spanning one order of magnitude relevant to each RAP. In planned exposure situations, the ICRP advises that the lower boundary of the relevant DCRL band be used as the appropriate reference point for protection of different types of biota, while in emergency situations the upper boundary of the DCRL band is more appropriate as a reference [259].

treatment of heterogeneous distributions of some radionuclides, such as radioiodine, is subject to considerable uncertainty. The possibility that some individual biota received rather high local doses, for example to the thyroid[62], cannot be excluded, although a response at the population level would be unlikely given the short duration of elevated radioiodine levels in time and space.

Interactions between species and other constituents in the environment affected by radiation may have indirect implications for ecosystem function but are difficult to disentangle from effects on individuals.

It is possible to conclude that, although dose rates exceeded some reference values included in ICRP and UNSCEAR publications in the early phases of the accident, no impact on populations and the ecosystems (both terrestrial and marine environments) is expected. Furthermore, long term effects are not expected, given that the estimated short term doses were generally well below levels at which highly detrimental acute effects might be expected, and dose rates declined relatively rapidly after the accident.

4.5.5. Review of relevant studies on modelling of doses and field observations of effects in proximity to the Fukushima Daiichi NPP

4.5.5.1. Observations from assessment of the Fukushima Daiichi NPP by UNSCEAR

UNSCEAR examined the impact of the Fukushima Daiichi accident on non-human biota within the first year or so [5]. The main conclusion of the evaluation was that, although the existing benchmarks may have been exceeded in the terrestrial ecosystems for limited periods after the accident, population effects of major significance were unlikely. Furthermore, estimated doses to marine biota (in the intermediate phase) did not indicate the potential for effects on populations of these biota.

The investigation was, as far as practicable, based on measured radionuclide concentrations in biota and their habitat, but in many cases, transfer models starting from an input as media concentrations were applied. The ERICA methodology [393] was widely applied. Koriyama City was selected in its entirety as a representative area for the terrestrial assessment, covering relatively low to high contamination levels in locations where direct measurements of activity concentrations in biota were available. During June 2011, high percentile dose rates in a range between 1.2 and 2.2 μGy/h for terrestrial mammals and birds were estimated for Koriyama City at 50–100 km west of the Fukushima Daiichi NPP. Dose rates were also calculated by UNSCEAR using the mean deposition levels for Okuma Town and default transfer parameters. The dose rates estimated for mid-June 2011 were 71 μGy/h for deer/herbivorous mammals and 26 μGy/h for grass.

For the marine ecosystem, dose rates in the period 10 May 2011 to 12 August 2012, for coastal locations where biological samples were available, ranged from 0.10 to 0.25 μGy/h, i.e. much less than for terrestrial biota. UNSCEAR concluded that, for the late phase (months to years) after the accident, effects in individuals of certain species, especially mammals (terrestrial), may exist in areas of highest deposition. Predicted exposures derived by UNSCEAR for both marine and freshwater biota during the late phase were well below thresholds above which effects could be deemed likely. UNSCEAR thus concluded that “the possibility of direct effects of radiation exposure on non-human biota was geographically constrained and that, in areas outside of that considered by this assessment, the potential for such effects on biota may be deemed insignificant” [5].

Dose rates and accumulated doses in the intermediate phase of the accident (first months after the accident) were much higher than doses calculated for the later phases; terrestrial dose rates (including

[62] See, e.g., Refs [416, 417].

the short lived isotopes ^{132}Te and ^{132}I) may have been as high as 1 mGy/h in the terrestrial environment and exceeded 20 mGy/h for macrolagae in the marine environment. Accumulated doses over the intermediate phase were estimated to have fallen short of levels found to cause observable effects in non-human biota, as reported in reviews such as those concerning exposures in the aftermath of the Chernobyl accident. Estimated doses to marine biota during the intermediate phase did not indicate the potential for effects on populations of these biota, although effects on individual macroalgae (e.g. impacts on growth and reproduction) close to the discharge area may have occurred.

Table 4.5–4 provides a comparison of the maximum dose rates and accumulated doses for RAPs estimated in this assessment with those estimated by UNSCEAR [5]. There are some discrepancies between these dose rates that might be explained by considering what the maximum dose rates actually represent. Whereas the maximum (initial period) dose rates for this assessment are actually integrated values over the specified 30 day period, the values from UNSCEAR (2014) [5] represent dose rates for particular instantaneous moments in time within the 30 day period.

TABLE 4.5–4. MAXIMUM DOSE RATES AND ACCUMULATED DOSES FOR REFERENCE ANIMALS AND PLANTS IN THE INITIAL PERIOD FROM THIS ASSESSMENT AND UNSCEAR (2014) [5]

Reference animals and plants	Maximum dose rate — mGy/day (accumulated dose: mGy) in 0–30 day period: IAEA assessment	Maximum dose rate — mGy/day (accumulated dose: mGy) in 0–30 day period: UNSCEAR (2014) [9]
Wild grass	21 (600)	135 (500)[a]
Pine tree	19 (600)	34 (400)[a]
Earthworm	1.4	7
Bee	0.6	4
Rat	1.5	8
Deer	1.7 (50)	9 (200)[a]
Duck	0.7	4
Trout	N/A	N/A
Frog	0.7	4
Brown seaweed	80 (2400)	480 (6800)
Crab	1.6 (50)	3 (80)[b]
Flatfish	3.4 (100)	3.4 (120)[c]

[a]Using FASTer model (Avila et al., 2004).
[b]Using D-DAT model (Vives-i-Batlle, 2014) and accumulated dose for 90 days.
[c]Not assessed for this period.

4.5.5.2. Assessments based on other published model calculations and field observations

A number of studies of radiation induced effects following the accident at the Fukushima Daiichi NPP had been published by the end of 2014.

Soon after the accident, radiation doses to forest and marine biota during the first 30 days were assessed [418]. The methods were based on the application of equilibrium transfer models from measured radionuclide activity concentrations in soil and sea water. Maximum dose rates were estimated to be 210 mGy/d for marine birds, 2600 mGy/d for benthic biota and 4600 mGy/d for macroalgae. However, neither the applied assessment methods nore the selected deposition pattern is applicable to the non-equilibrium conditions existing at the time.

Radiation dose rates to fish, molluscs and algae were assessed for the first three months following the accident using dynamic methods [419]. The average dose rates, for example, to pelagic fish in the coastal zone, were estimated to be 0.9–1.2 mGy/d from March to May 2011. The estimated dose rates for fish and molluscs were below 10 mGy/d. Activity concentrations measured in tuna fish captured off the Californian coast in August 2011 [387] were used to reconstruct internal doses. The doses resulting from the Fukushima Daiichi accident were found to be more than two orders of magnitude lower than the lowest commonly applied screening benchmark of 10 μGy/h.

Some other studies of dose rates and of observed radiation induced effects following the accident have been published (e.g. [418, 420–422], from which it is difficult to draw firm conclusions for a variety of reasons, which include the dosimetry applied or the lack of reliable controls. There are difficulties involved in collecting radio-ecological information in accidental situations [246]. However, it is important to take account of potentially significant temporal variations in dose rates, especially in the early phase, and to ensure that radiological input data are sufficiently representative of the spatial coverage required to estimate effects at the population level [418]. Furthermore, it is necessary to confirm single observations of suspected impacts by using transparent and reliable statistical treatment of data; otherwise it is impossible to draw conclusions about dose–response relationships based on observations.

4.5.6. Summary

The assessment of the potential radiological impact of the accident on non-human biota comprises two distinct components: an estimation of dose rates based on activity concentrations of radionuclides in environmental media, i.e. water, sediment and soil (or deposition); and data pertaining to directly measured activity concentrations in biota (and their habitat) published in the literature.

For the first assessment, the ICRP approach of reference organisms was adopted. Three distinct time periods were considered: an early acute period with larger releases of particularly short lived radionuclides; an intermediate period up to 90 days after the accident; and a late period of chronic exposures. The estimated dose rates were then compared with the ICRP DCRLs and other relevant benchmarks. The second type of assessment also drew upon the ICRP approach using DCRLs and other relevant dose–response data to put the dose rates derived for specified non-human biota into perspective.

The estimated doses were highest for plants during the first weeks after the accidents but remained below levels at which acute effects would be anticipated. The DCRLs were exceeded for some terrestrial RAPs (such as pine, grass, deer and rat) in the early phases, which could imply a potential for harm (defined as a detriment to sensitive end points in this case) in some of the most exposed individuals. However, no impact on populations or the ecosystems would be expected. DCRLs were also exceeded for marine Brown seaweed, but the spatially limited and transient nature of the highly elevated exposures suggests that the releases from the Fukushima Daiichi accident were unlikely to have caused any substantial harm to regional populations of this biota group. Long term effects are not expected given that the estimated short term doses were generally well below levels where acute effects might be expected and dose rates in the environment declined relatively rapidly after the accident.

No observations of direct radiation induced effects in plants and animals have yet been reported, based on analyses undertaken using appropriate dosimetry and experimental designs. The long term consequences of the releases on the environment are considered to be insignificant, although the elapsed time since the accident is relatively short for making a decisive judgement.

4.5.7. Observations and lessons

— **During any emergency phase, the focus has to be on protecting people. Doses to the biota cannot be controlled and could be potentially significant on an individual basis. Knowledge of the impacts of radiation exposure on non-human biota needs to be strengthened by improving the assessment methodology and understanding of radiation induced effects on biota populations and ecosystems. Following a large release of radionuclides to the environment, an integrated perspective needs to be adopted to ensure sustainability of agriculture, forestry, fishery and tourism and of the use of natural resources.**

It may be difficult to substantially reduce doses to non-human biota because of the impracticability of introducing countermeasures. Impact assessments for plants and animals in the aftermath of accidents such as that at the Fukushima Daiichi NPP require consideration of numerous potential stressors — radiation exposure being one of many. Consideration also needs to be given to the potential for the buildup and accumulation of long lived radionuclides in the environment and how this might affect plants and animals over multiple generations.

APPENDIX I
MAPS OF LEVELS OF RADIOACTIVITY AND RADIONUCLIDES IN THE ENVIRONMENT

A range of environmental monitoring was undertaken during and following the Fukushima Daiichi accident, notably measurements of ambient dose equivalent rates for external exposures, activity concentrations in air and deposited on the ground, and levels of radionuclides in the terrestrial and marine environments, including activity concentrations in food and drinking water.

A Comprehensive Radiation Monitoring Plan was developed that included a comprehensive assessment of the distribution of radionuclides deposited on the ground and the migration of radionuclides through different media [423]. In addition to the large amount of government led environmental monitoring activities, many volunteer and other organizations gathered information to help understanding of the radiological situation in the environment in the area surrounding the Fukushima Daiichi NPP. An overview of information available for various types of measurements and materials is presented in Annex III.

This appendix provides a sample of measured data on the geographical distribution of radioactivity and key radionuclides in the environment, in the form of a series of maps.

I.1. AMBIENT DOSE EQUIVALENT RATE

The first aerial monitoring of ambient dose equivalent that provided a map of levels in the environment was performed by the US Department of Energy/National Nuclear Security Administration (US DOE/NNSA) from 17 to 19 March (see Annex III, Fig. III–2) [424].

Joint aerial surveys were carried out by MEXT and US DOE/NNSA of the area within 80 km of the NPP between 6 and 29 April and 18 and 26 May 2011. Since then, a number of repeat surveys of this area have been undertaken by MEXT. Additional surveys of the evacuation areas and of wider areas have also been performed. The aerial surveys performed for the period until March 2015 are summarized in Table I.1. The web site of the NRA of Japan contains information on all of the aerial surveys done to date [425].

TABLE I.1. AERIAL SURVEYS[a]

Survey name	Survey date	Decay date[b]	Issuing date	Area surveyed	References
The situation in Japan[c]	17–19 Mar. 2011			<30 km	Lyons and Colton (2012) [424]
First aerial monitoring survey[d]	6–29 Apr. 2011	29 Apr. 2011	6 May 2011	≤80 km	[57]
Second aerial monitoring survey[d]	18–26 May 2011	26 May 2011	16 Jun. 2011	≤100 km, plus parts of Ibaraki and Toshigi	[58]
Third aerial monitoring survey	31 May–2 Jul. 2011	2 Jul. 2011	8 Jul. 2011	≤80 km	[59]
Fourth aerial monitoring survey	22 Oct.–5 Nov. 2011	5 Nov. 2011	16 Dec. 2011	≤80 km	[60]

TABLE I.1. AERIAL SURVEYS[a] (cont.)

Survey name	Survey date	Decay date[b]	Issuing date	Area surveyed	References
Fourth aerial monitoring survey	22 Oct.–5 Nov. 2011	5 Nov. 2011	16 Dec. 2011	≤80 km	[60]
Aerial monitoring survey in the restricted areas and deliberate evacuation areas	6–10 Feb. 2012	10 Feb. 2012	24 Feb. 2012	Restricted and deliberate evacuation areas	[61]
Fifth aerial monitoring survey	22–28 Jun. 2012	28 Jun. 2012	28 Sep. 2012	≤80 km	[62]
Aerial monitoring survey beyond 80 km of the Fukushima Daiichi NPP	2 Apr.–7 May 2012	28 Jun. 2012	28 Sep. 2012	>80 km with dose rates ≥0.2 μSv/h (western Fukushima, Ibaraki, Gunma, Tochigi, Miyagi, southern Iwate, northern Chiba, and eastern Yamagata prefecture)	[62]
Sixth aerial monitoring survey	31 Oct.–16 Nov. 2012	16 Nov. 2012	1 Mar. 2013	≤80 km	[63]
Aerial monitoring survey beyond 80 km of the Fukushima Daiichi NPP	31 Oct.–28 Dec. 2012	28 Dec. 2012	1 Mar. 2013	>80 km with dose rates ≥0.2 μSv/h (western part of Fukushima, Ibaraki, southern part of Iwate, northern part of Chiba, Gunma, Tochigi, Miyagi, and the eastern part of Yamanashi)	[63]
Aerial monitoring in the evacuation-directed zones	4–11 Mar. 2013	11 Mar. 2013	13 May 2013	Areas under evacuation orders	[64]
Seventh aerial monitoring survey	27 Aug.–28 Sep. 2013	28 Sep. 2013	25 Dec. 2013	≤80 km	[65]
Eighth aerial monitoring survey	3 Sep.–19 Nov. 2013	19 Nov. 2013	7 Mar. 2014	>80 km; Fukushima and its neighbouring prefectures	[67]
Ninth aerial monitoring survey	1 Sep.–7 Nov. 2014	7 Nov. 2014	13 Feb. 2015	≤80 km	[68]

[a] Referred to as ‘airborne surveys’ in the referenced sources.
[b] The later date is used as the reference date for calculating physical decay.
[c] Carried out by US DOE.
[d] Carried out by MEXT and US DOE.

In these measurements, the non-terrestrial background (cosmic and aircraft) is removed on the basis of measurements over water (lake, not ocean). The terrestrial background is not removed, but is insignificant in the 80 km region (initial survey only). In later surveys, background subtraction had to be taken into account.

Maps of dose rates measured by aerial surveys are presented in Fig. 4.1–6.

Deposition densities of ^{134}Cs, ^{137}Cs and ^{131}I were also derived from these aerial measurements (see Section 4.1.2.2).

I.2. SOIL MEASUREMENTS

The MEXT Comprehensive Radiation Monitoring Plan included initiatives to assess the activity concentrations of radionuclides in soil using consistent sampling and analytical procedures. Samples for the first survey — Research on Distribution of Radioactive Substances Discharged by the Accident at TEPCO's Fukushima Daiichi NPP [380, 426] — were collected between 6 June and 8 July 2011 from an area covering Fukushima Prefecture, northern Ibaraki Prefecture and southern Miyagi Prefecture. Based on the results of aerial monitoring and other environmental monitoring, the area within 80 km of the Fukushima Daiichi NPP was divided into 2 km × 2 km grid squares. The area between 80 and 100 km and the areas in neighbouring prefectures were divided into 10 km × 10 km grid squares. The study area comprised in total 2182 grid squares. A number of samples — normally five but ranging from one to seven depending on circumstances — were collected from each grid square. A consistent sample depth of 5 cm was used.

All soil samples were analysed for gamma emitting radionuclides (such as ^{134}Cs, ^{137}Cs, ^{131}I, ^{129m}Te and ^{110m}Ag). An average deposition density (Bq/m^2) was calculated by dividing the sum of the results of measurements of each individual sample — including a zero value for those below the limit of detection — by the number of analyses performed. If all sample measurements were below the limit of detection, no value was reported. A subset of samples were also analysed for isotopes of strontium (^{89}Sr and ^{90}Sr) and plutonium (^{238}Pu, ^{239,240}Pu). This was due to the more time consuming procedures required for analysis of these radionuclides: priority was given to samples from grid squares where levels of radiocaesium had already been found to be highest. Ambient dose equivalent rates were also measured at a height of 1 m above the ground surface at one location in each grid square.

These measurements were used to construct maps of activity concentrations in soil of each radionuclide measured. This information, together with in situ measurements of ambient dose equivalent rates, was used in the UNSCEAR assessment to assess radiation doses to the public living in different locations [5].

The deposition density of ^{134}Cs is shown in Fig. I.1; the corresponding map for ^{137}Cs is Fig. 4.1–12. Maps of ^{137}Cs and ^{134}Cs deposition densities were also derived from aerial monitoring surveys and are shown in Figs 4.1–13 and 4.1–14.

As sampling for this survey was performed some three to four months after accidental releases from the Fukushima Daiichi NPP, the levels of ^{131}I had generally decayed to levels which were not detectable by gamma spectrometry. In fact, deposition densities could be reported for less than 20% of the grid squares described above owing to the number of measurement results below the limit of detection.

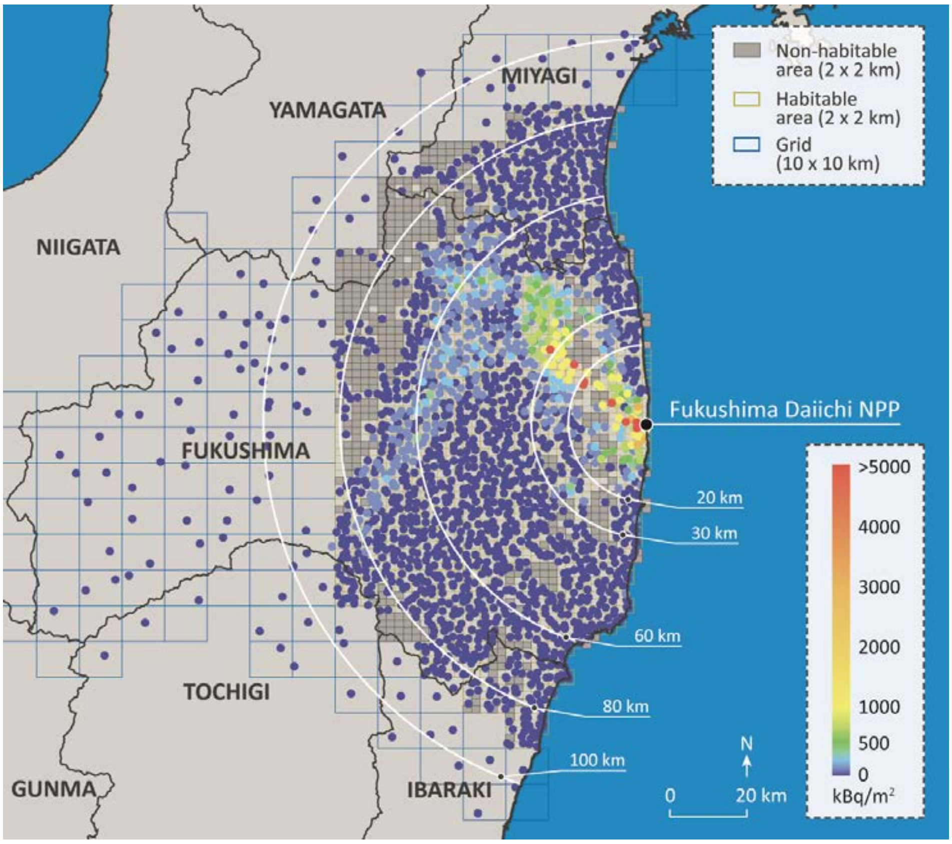


FIG. I.1. Map of deposition density of ^{134}Cs (kBq/m^2) based on the results of soil measurements.

To resolve this, values of ^{131}I were estimated from measurements of ^{129}I. A pilot study was first undertaken to measure ^{129}I using accelerator mass spectrometry (AMS) in a total of 82 samples from grid squares from which it had been possible to measure ^{131}I by gamma spectrometry [427]. These results were used to calculate a conversion factor between activity concentrations of ^{129}I and those of ^{131}I. The parallel measurement of ^{131}I by gamma spectrometry and ^{129}I by AMS carried out for 82 soil samples produced a good correlation (R^2 = 0.84), which gave confidence in the reliability of this method. The isotopic ratio of ^{129}I to ^{131}I, decay corrected to 11 March 2011, was around 21. This value is comparable with the ratio of around 16 obtained for rain water [70, 71] and 22.3 ± 6.3 for soil samples, and with the estimated ratio from the operational history of the reactor (18–21) [71].

In order to derive values of ^{131}I for 388 grid squares from which no value could be detected by gamma spectrometry, one sample from each was analysed for ^{129}I by AMS. Activity concentrations of ^{131}I for these samples were estimated by applying measured ^{129}I to ^{131}I conversion factor to the results. Iodine-127 (stable iodine) was also measured in the samples by inductively coupled plasma mass spectrometry in order to facilitate the subtraction of the contribution of ^{129}I from fallout from atomic weapons tests. A correction factor was also calculated (from ^{137}Cs) to account for the fact that only one sample from each location was analysed (due to time constraints). The resulting map of ^{131}I distribution, including both the original gamma spectrometry measurements and those derived from ^{129}I, is shown in Fig. 4.1–15.

A map of ^{131}I deposition density has also been estimated from the results of the first aerial survey, also shown in Fig. 4.1–15. In contrast to the earlier maps of ^{134}Cs and ^{137}Cs, which were derived from aerial surveys by applying constant conversion coefficients, the activity concentrations for the ^{131}I map were derived by fitting iodine photo peaks in the measured gamma spectra.

Maps of the deposition densities of ^{129m}Te and ^{110m}Ag are shown in Figs I.2 and I.3, respectively.

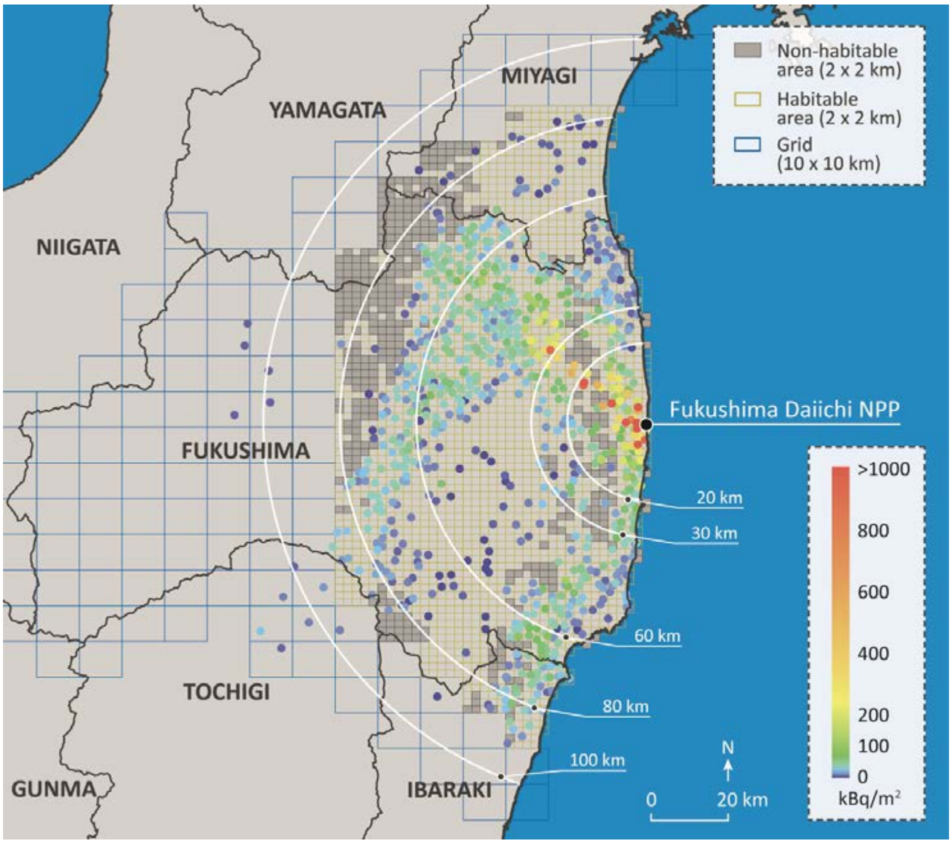


FIG. I.2. Deposition density of ^{129m}Te (kBq/m^2) based on the results of soil measurements.

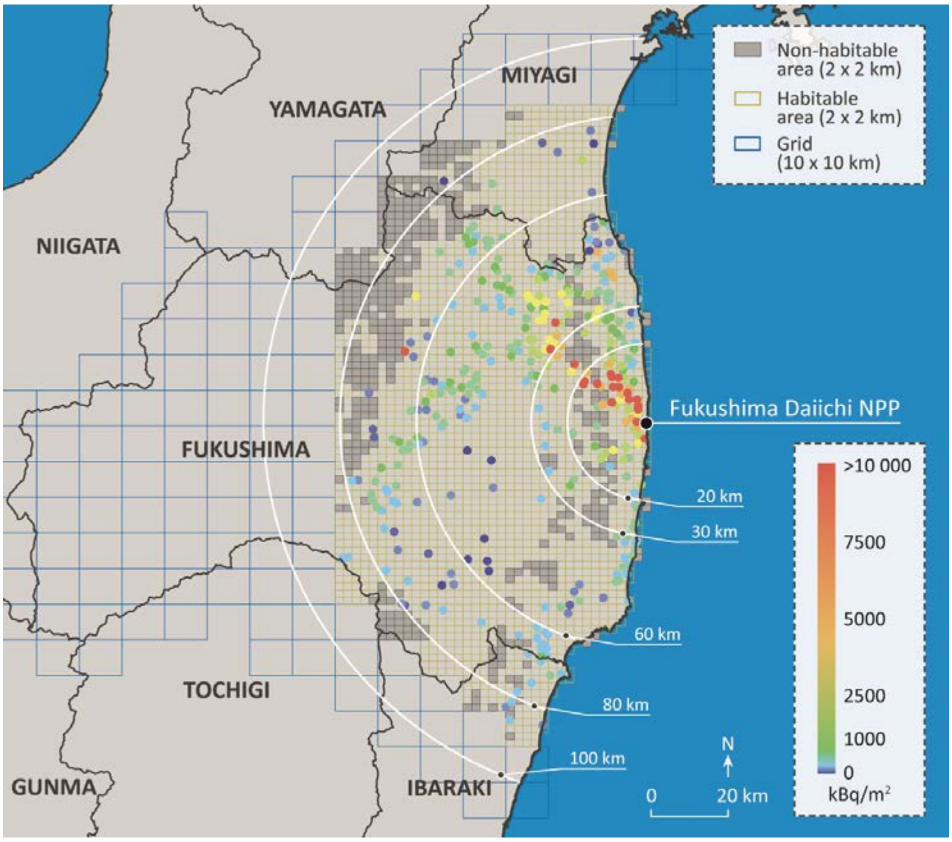
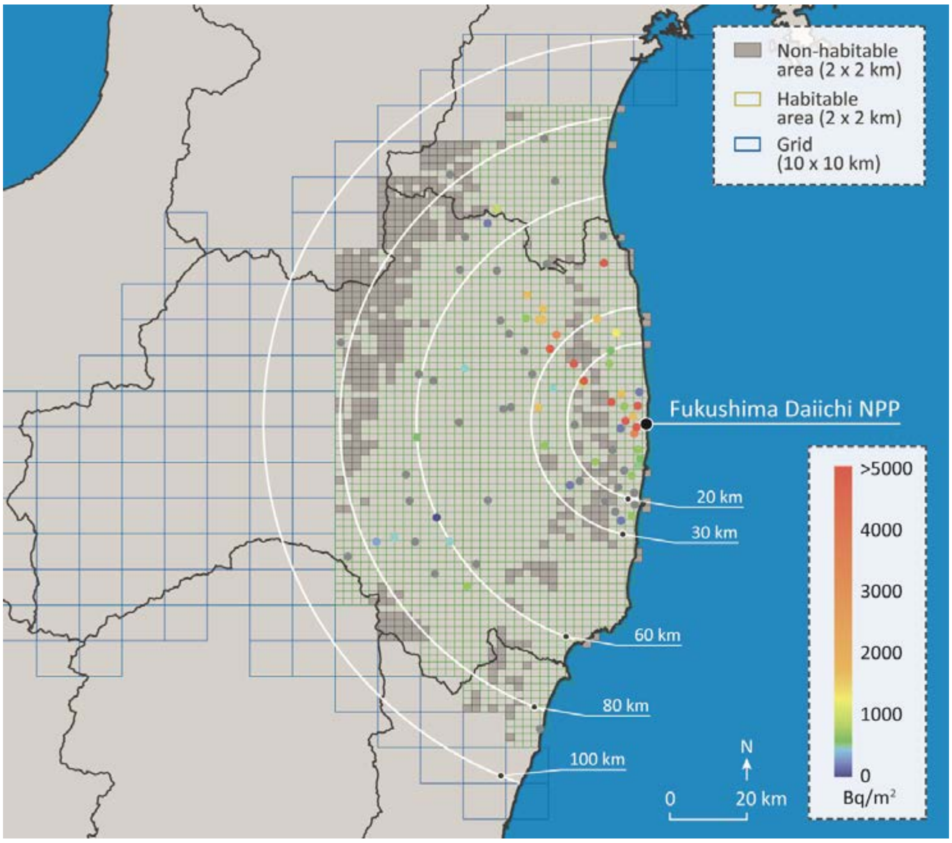
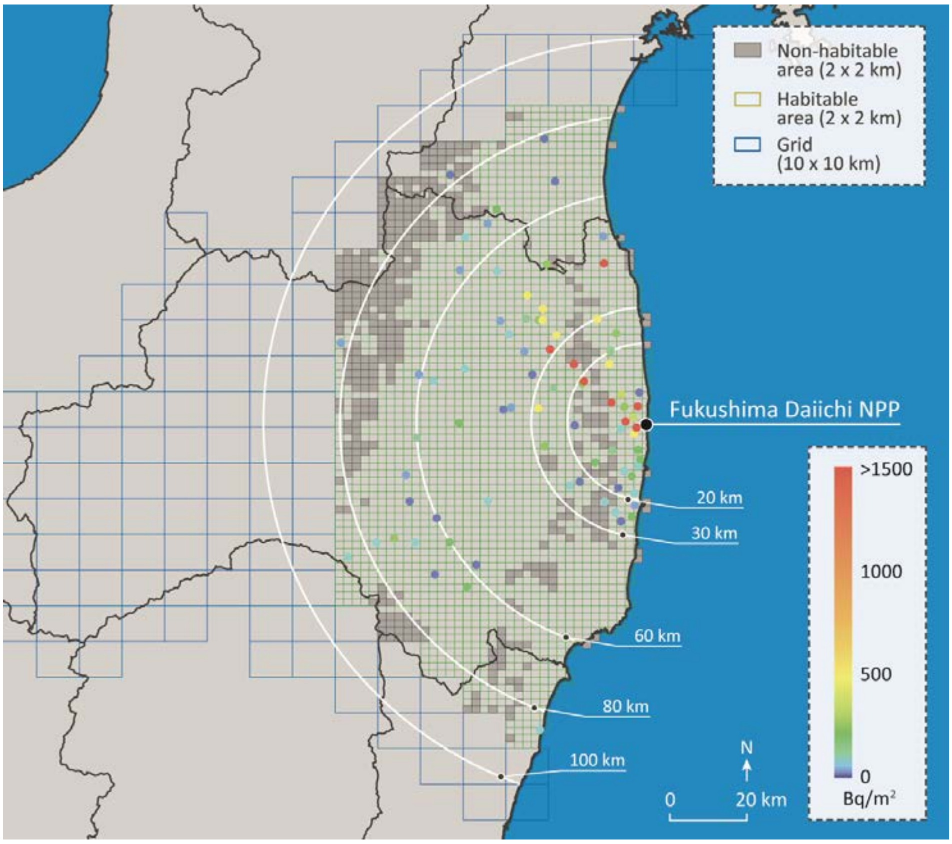


FIG. I.3. Deposition density of ^{110m}Ag (kBq/m^2) based on the results of soil measurements.

A map of deposition densities of ^{89}Sr and ^{90}Sr is shown in Fig. I.4. As previously noted, the levels of the strontium isotopes measured were three to four orders of magnitude lower than those of radiocaesium, reflecting the small amounts released owing to the low volatility of this element. Similar results were found by Steinhauser et al. [428], who measured activity concentrations of beta emitting ^{90}Sr and β/γ emitting ^{134}Cs and ^{137}Cs in soil and vegetation samples from several areas known to have been subjected to relatively high levels of deposition. The ^{90}Sr concentrations in the samples did not exceed 1000 Bq/kg and were up to four orders of magnitude lower than the respective levels of ^{137}Cs.



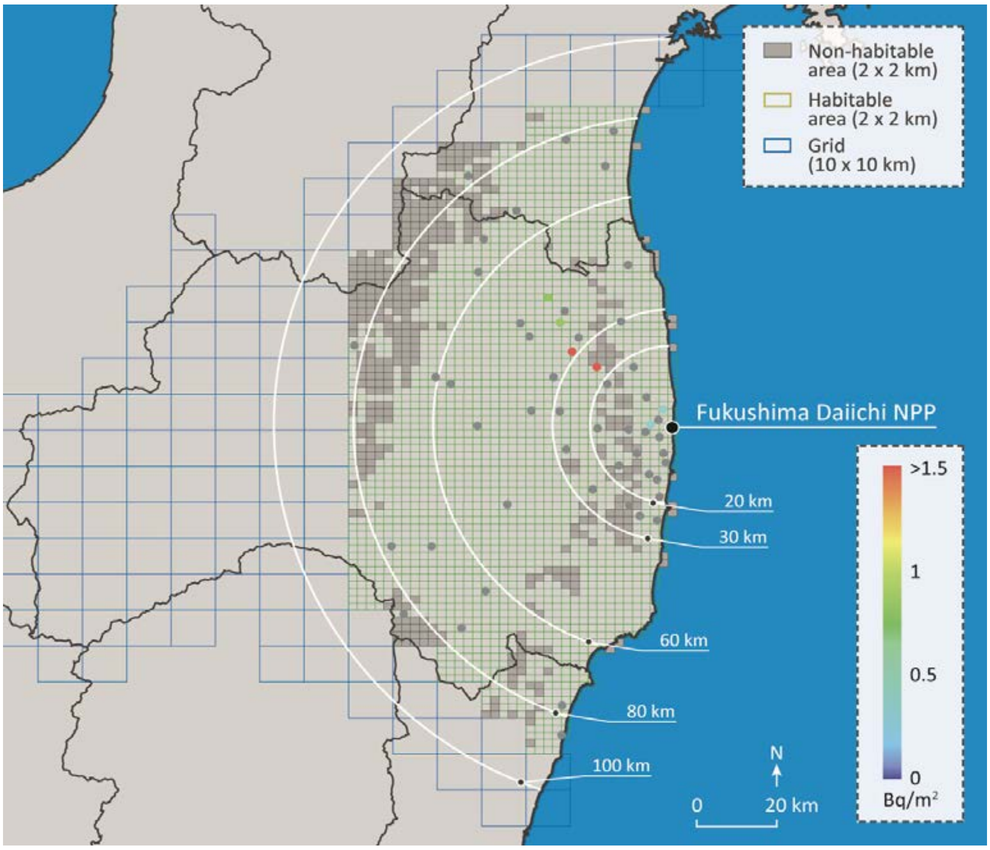
(a)



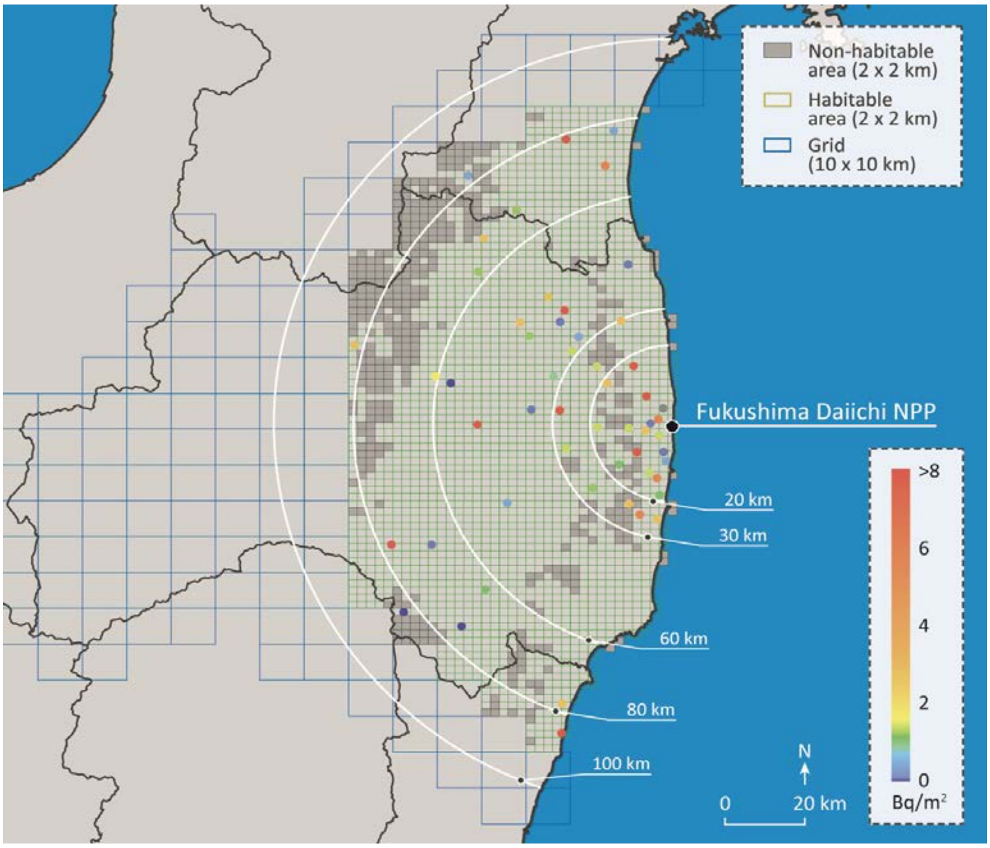
(b)

FIG. I.4. Deposition density of (a) ^{89}Sr and (b) ^{90}Sr (Bq/m^2) based on the results of soil measurements.

Plutonium isotopes (^{238}Pu and $^{239,240}Pu$) were measured in a number of samples relatively far from the Fukushima Daiichi NPP in Fukushima Prefecture, as shown in Fig. I.5. Isotopic ratios distinct from those of global fallout ($^{240}Pu/^{239}Pu$ atom ratio ~ 0.32 and $^{238}Pu/^{239+240}Pu$ activity ratio of 1.1–2.9) were found and subsequently shown to have been characteristic of the fuel from Unit 3 of the Fukushima Daiichi NPP [18, 429]. The activity concentrations measured were very low, close to or often below the level of detection. There has been no convincing evidence of the type of hot particles (fuel fragments) which were seen following the Chernobyl accident [73].



(a)



(b)

FIG. I.5. Deposition density of (a) ^{238}Pu and (b) $^{239+240}$Pu (Bq/m^2) based on the results of soil measurements.

APPENDIX II
STATISTICAL ANALYSIS OF INDIVIDUAL DOSE DATA

II.1. INTRODUCTION

The basic statistical methodology applied was to fit an appropriate theoretical statistical function to the distribution of the measurements (i.e. *N* versus the parameter measured), with the objective of assessing the extent of agreement or deviation from that function. The theoretical distribution assumed was the log-normal probability density function and the log-normal cumulative probability distribution (see Box 4.1–1 and Box 4.2–1).

As indicated below, due to the scarcity and inhomogeneity of data available, some additional analysis was necessary to determine whether the log-normal distribution was applicable. This included an analysis of the effect of different assumptions regarding the distribution of data within reported intervals (or bins). Cumulative probability distributions were developed for the purpose of determining the extent to which the available data fitted the log-normal function and to form the basis of analysing log-normal statistics, as appropriate. Normalized idealized probability density functions were also constructed for comparison purposes. A comparison of the results of these approaches will be the subject of a future publication. A summary of the analysis is presented in this appendix.

The log-normal mathematical function can generally be used to approximate positive–variant data of many types, including those related to radiation measurement [430–433]. For positive–variant data such as the number of people who were exposed to a certain dose, an asymmetric distribution can be expected. The log-normal distribution offers the simplest mathematical means of describing such distributions and is most commonly found in practice [434].

The cumulative probability distribution can be estimated simply by fitting a straight line to a plot of such data on normal probability scale versus log scale axes. A simple plot such as this will quickly show whether a log-normal function is an adequate representation of the data. If this is the case, descriptive statistics such as the geometric mean and geometric standard deviation can be derived.

This statistical procedure can also be used to check and validate datasets and to identify systematic deviations from the expected log-normal distribution pattern. Following the Chernobyl accident in 1986, this method was used successfully to assess the distribution of doses to the public [435]. Values greater than the fitted log-normal, especially in the higher dose tail, were investigated further because such deviations indicated a higher probability of occurrence than one would have expected from a log-normal distribution, and were generally due to enhanced external doses from ‘hot spots’ or additional ingestion doses due to non-adherence to restrictions on the consumption of certain foods.

The main goal of the analysis described in this appendix is to determine whether each dataset of measurements following the Fukushima Daiichi accident could be described by a log-normal distribution, as was generally the case for similar datasets compiled after the Chernobyl accident [435]. In order to enhance the precision of the analysis, an additional stage of investigating the fit of the log-normal probability density functions (PDFs) was used, in addition to the cumulative probability distribution. The main advantage of this process is that, if the log-normal function proves to be a reasonable fit for the distribution of data, log-normal statistics may then be used to describe the distribution of parameters, such as activity concentrations and doses.

In the case of the accident at the Fukushima Daiichi NPP, the analysis of certain datasets of measured radiation doses was complicated by two factors:

(1) Some measurements were aggregated as the number of cases N per measurement interval (or bin). For example, in the case of measurements of radiation exposures the datasets comprised the number of people who received a dose within specific intervals, the width of which depended on the type of dose measured and on the measurement techniques and instrumentation employed.
(2) For many datasets, the majority of measurements were either around or below the limit of detection.

Therefore, for these datasets, the application of more sophisticated methods of analysis was required. In order to thoroughly test for log-normality, the distribution of the probability over the width of the measurement interval was considered and the probability density function was used in addition to the cumulative distribution to determine whether the log-normal distribution was a suitable fit for the dataset and, thus, whether log-normal statistics could be applied. The details of this methodology are provided in the next subsection. The datasets analysed in this way include:

— Occupational doses received by TEPCO employees and contractors (internal, external and thyroid exposures);
— Thyroid doses of 1080 children resident in three municipalities in Fukushima Prefecture at the time of the accident;
— Estimates of external doses received by residents of Fukushima Prefecture in the first four months following the accident at the Fukushima Daiichi NPP;
— External exposures of residents of a number municipalities in Fukushima Prefecture assessed by personal dosimeters.

II.2. OVERVIEW OF THE METHODOLOGY

It was assumed that the measurements in each dataset could be described by a log-normal function and an analysis of the maximum likelihood was performed.

For a given dose D, logarithmic mean μ and standard deviation σ, the log-normal probability is given by:

$$P(D) = \frac{1}{(2\pi)^{1/2} D\sigma} \exp\left[-\frac{(\ln D - \mu)^2}{2\sigma^2} \right]$$

The data collected for a series of doses D_i are obtained with a total probability of:

$$P_{tot} = \prod_i P(D_i)$$

The objective of the analysis was to identify the optimal theoretical log-normal distribution, described by μ and σ, which gives rise to the maximum value of P_{tot}, corresponding to the best agreement with the measured values and their uncertainties.

For the data collected within intervals (bins) with a width of $\Delta = 2\delta$, the expected number of cases $N(D_i)$ within an arbitrary bin centred on D_i must thus be proportional to:

$$N(D_i) = \int_{D_i-\delta}^{D_i+\delta} \frac{1}{(2\pi)^{1/2} D\sigma} \exp\left[-\frac{(\ln D - \mu)^2}{2\sigma^2} \right] dD = \int_{zd}^{zg} \frac{1}{(2\pi)^{1/2}} \exp(-0.5z^2) dz$$

where

$$zd = \frac{\ln(D_i - \delta) - \mu}{\sigma}$$

and

$$zg = \frac{\ln(D_i + \delta) - \mu}{\sigma}$$

$N(D_i)$ should be scaled by a normalization factor A in order to fit the measured data. Therefore:

i^{th} measured value = $AN(D_i)$

Using the classical maximum likelihood methodology, the value of the misfit function (χ^2) is calculated: each term in this function is weighted by an inverse of appropriate variance of the measured data point. In fact, the fitting of a theoretical function to the data requires assignment of the combined statistical uncertainty of the values plotted on both the vertical and horizontal axes. In this case the variances used are:

$$\sigma_i^2 = N_i + \left[A \frac{dN(D_i)}{dD_i} \sigma_{D_i} \right]^2$$

where the second term describes the impact of the uncertainty of the measured dose. Because the probability of a dose within a bin with the width $\Delta = 2\delta$ is assumed to be uniform, the variance of the dose is:

$$\sigma_D^2 = \frac{1}{12}\Delta^2 = \frac{1}{3}\delta^2$$

The normalization factor, A, was calculated according to classical minimization of χ^2.

It is possible that by ignoring the fact that data has been binned, and by simply fitting the probability distribution function (PDF) using a single appropriate value of the dose, the maximum of the PDF may be significantly overestimated. Such maxima are likely to be artefacts resulting from the limitations of the analysis and are unlikely to have physical meaning. When the binning is required but has not been considered in the analysis, substantial differences between the parameters obtained from fitting the PDF and cumulative distribution may arise.

Care also needs to be taken in interpreting values obtained around the detection limit because it is not always clear if the value N given at, say, 1 mSv, reflects the number of persons who received the doses between 0.5 and 1.5 mSv, or between 0 and 1.0 mSv. These issues are considered below with specific reference to the available data on doses to workers and the population following the Fukushima Daiichi accident.

Probability plots were generated according to the same methodology used to analyse data measured following the Chernobyl accident [435].

As indicated elsewhere (see Box 4.2–1), owing to the scarcity and inhomogeneity of data, both the normalized bins of the available data and the resulting normalized probability density had to be 'idealized' into what was considered the most likely normalized distribution of bins and the corresponding probability density functions. These are represented in the figures on the left in the series of figures below. Conversely, the cumulative probability functions were constructed using the data directly and they are not based on the idealized probability distributions. These functions are shown on the right in the series of figures below. There is not, therefore, a direct correspondence between these two representations of the distributions; the curves on the left represent the most probable normalized distribution of bins and corresponding probability density function, and those on the right are the cumulative distribution functions derived directly from the available data.

II.3. OCCUPATIONAL EXPOSURE DATASETS

As an illustration of the characteristics of the data available on doses to worker doses, the frequency distribution of the external dose to TEPCO workers and contractors in 2012 is presented in Fig. II.1.

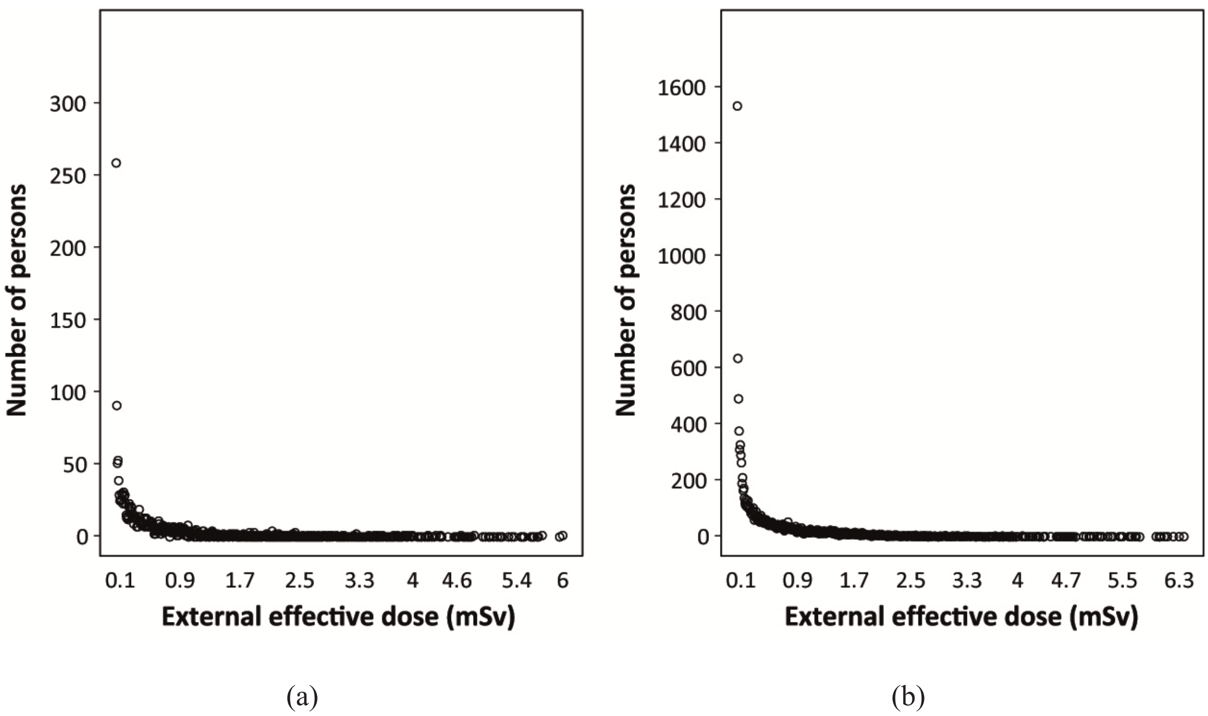


FIG. II.1. Frequency distribution of the reported external effective doses to (a) TEPCO employees and (b) contractors for the FY 2012.

The frequency distribution displayed in Fig. II.1 indicates that there are some deviations from a log-normal distribution. Inspection of the data shows two features which make detailed analysis difficult:

(1) Very high number of cases N associated with the first dose band,
(2) Very long tail with levels of N close to 1.

It is not immediately obvious how the reported doses should be interpreted. The first point indicates that the first dose interval (or bin) includes non-detected cases (i.e. where measurement values were below the levels of detection). In the following analysis it was assumed that:

— The first point is the cumulative number of persons who received the dose up to the lowest value.
— The next points represent the number of people within the dose interval (or bin). For example, the original numbers N for doses 20, 30, 40, etc., are treated as values obtained in bins 20±5, 30±5, 40±5, etc.

As explained earlier, such features of the data are not as problematic for the analysis which uses the cumulative distributions as this function is not as sensitive to the considerable variations in *N*. Furthermore, the assumptions related to binning do not significantly affect the fitted parameters.

Some of the data provided by TEPCO feature very small increments in the doses reported and, in addition, show larger scatter than might be expected. In such cases, the original data were aggregated into wider bins resulting in a smoother behaviour of the *N(D)* function.

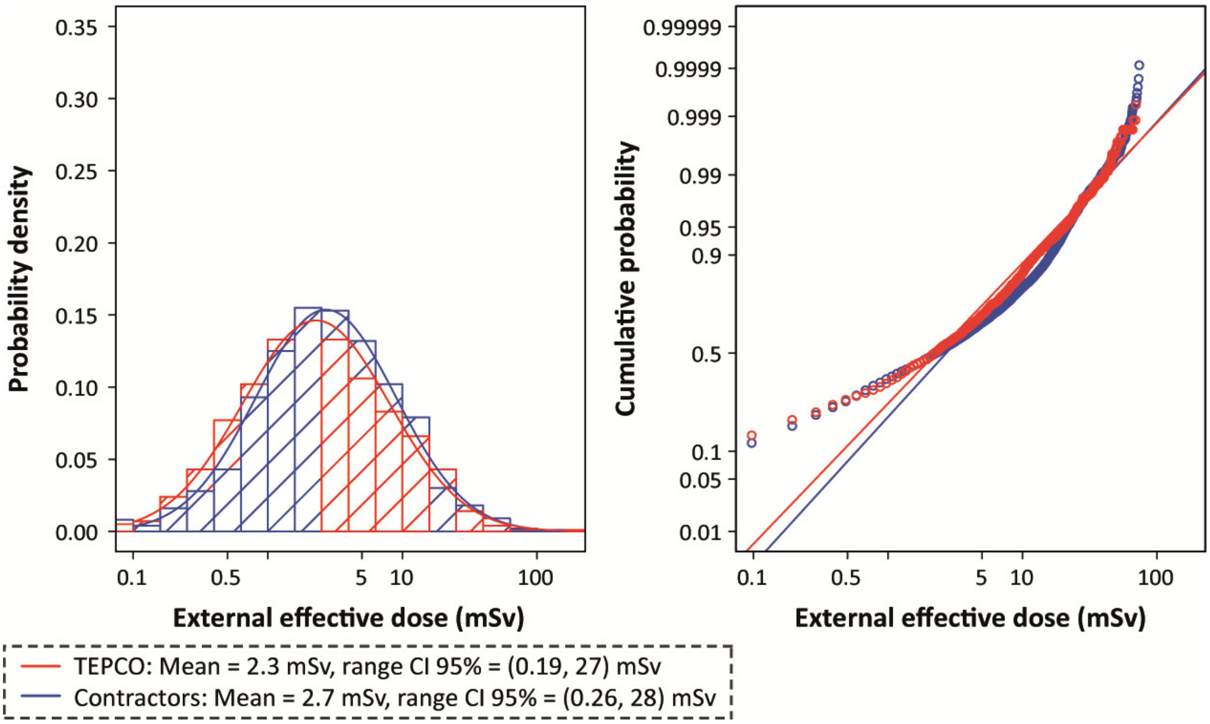
II.3.1. External exposures

For TEPCO employees in FY 2011 after binning the original data into 10 mSv intervals, the following statistics were obtained for the cumulative probability distribution and probability density function given in Table II.1.

TABLE II.1. COMPARISON OF THE ESTIMATED CUMULATIVE PROBABILITY DISTRIBUTION OF DOSES TO TEPCO WORKERS AND CONTRACTORS IN 2011 USING DIFFERENT LOG-NORMAL STATISTICAL METHODS

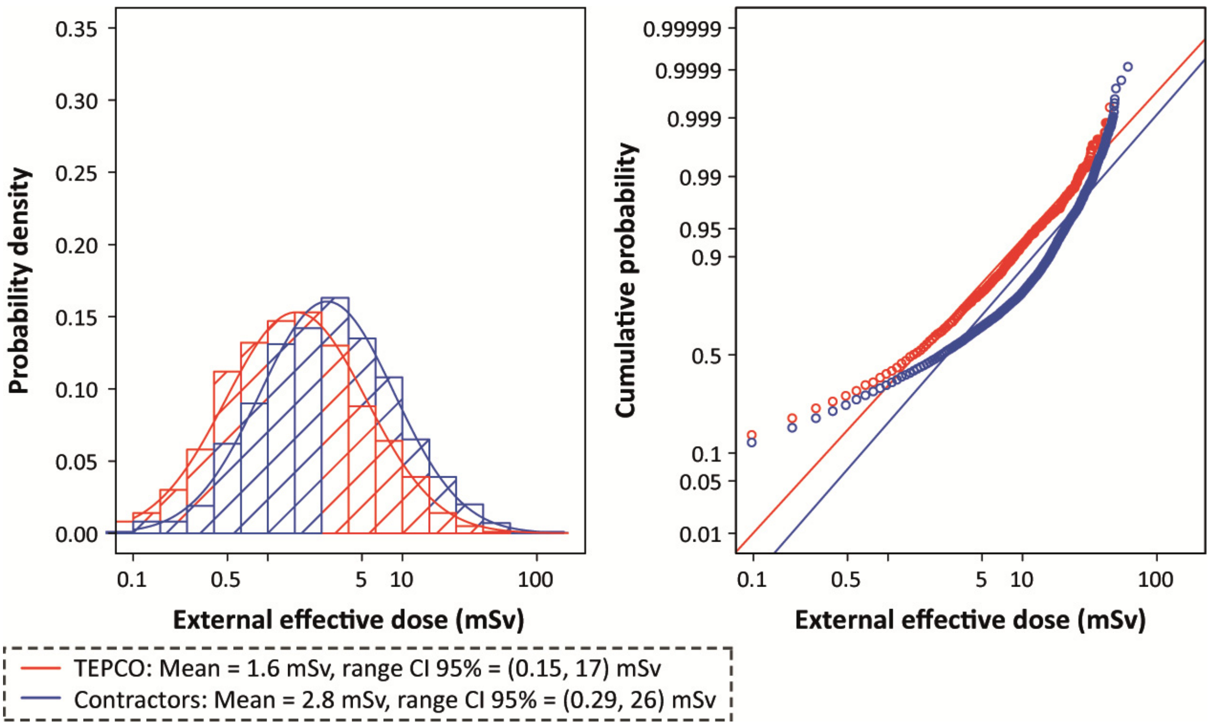
Statistic	Estimated doses to TEPCO workers (mSv)		Estimated doses to contractors (mSv)	
	Cumulative density function	Probability density function	Cumulative density function	Probability density function
Mean	16.8	10.6	7.1	7.8
67% confidence interval	5.9–48	3.42–33	2.8–18	3.6–17
95% confidence interval	2.1–134	1.11–101	1.1–45	1.7–36
χ^2	0.09	5.32	0.04	—

The results for the year 2011 are presented in Section 4.2.1 and the associated distributions are given in Figs 4.2–5 to 4.3–7. These data are consistent with those presented in Section 4.2.1 that were prepared according to the methodology used to analyse data following the Chernobyl accident. The results of the analysis for FY 2012, FY 2013 and FY 2014 are summarized in Table II.2. The data available for subsequent years are presented in Figs II.2–II.4. In these figures the normalized idealized probability density function is presented on the left and the cumulative probability distribution on the right.



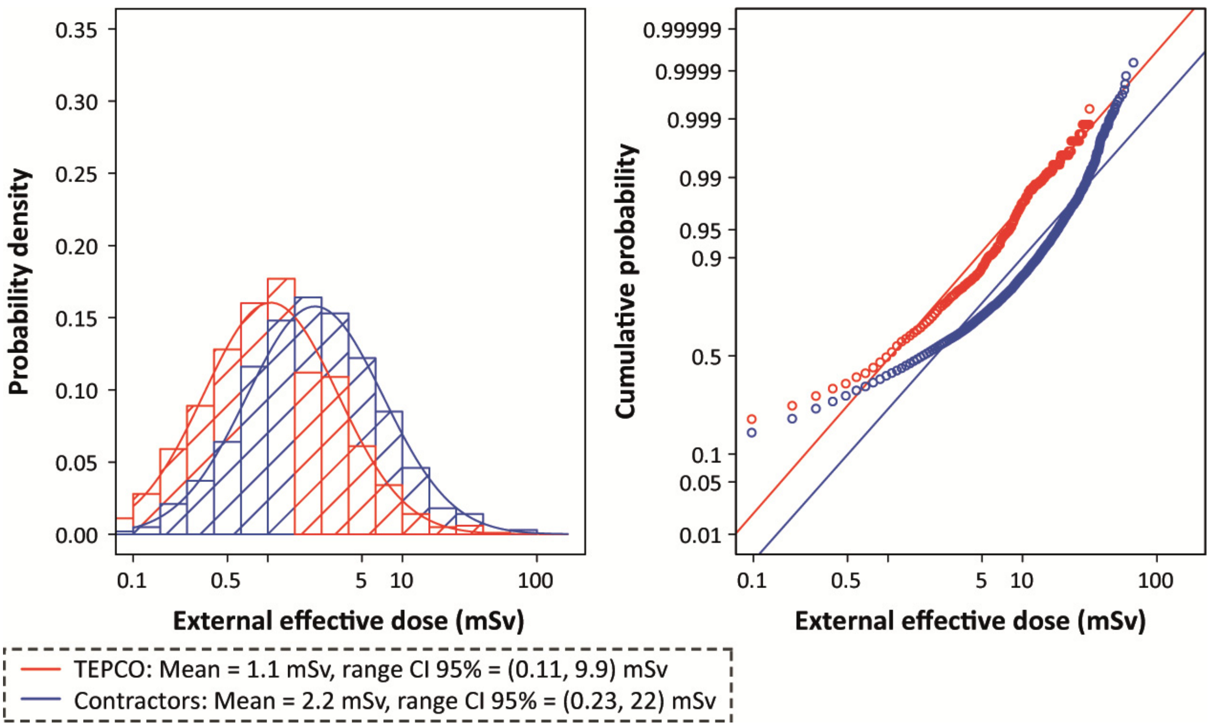
(a) (b)

FIG. II.2. (a) Normalized idealized probability density function and (b) cumulative probability distribution for the reported external effective doses to TEPCO employees and contractors for FY 2012.



(a) (b)

FIG. II.3. (a) Normalized idealized probability density function and (b) cumulative probability distribution for the reported external effective doses to TEPCO employees and contractors for FY 2013.



(a) (b)

FIG. II.4. (a) Normalized idealized probability density function and (b) cumulative probability distribution for the reported external effective doses to TEPCO employees and contractors for FY 2014.

TABLE II.2. SUMMARY OF THE ANALYSIS OF EXTERNAL DOSES RECEIVED BY TEPCO EMPLOYEES AND CONTRACTORS AT THE FUKUSHIMA DAIICHI NPP IN FY 2012 TO FY 2014

Year: best fit for cumulative distribution	Mean dose (mSv) CI 95%	
	Workers	Contractors
2012	2.3 (0.19, 27)	2.7 (0.26, 28)
2013	1.6 (0.15, 17)	2.8 (0.29, 26)
2014	1.1 (0.11, 9.9)	2.2 (0.23, 22)

Table II.2 demonstrates that the reported mean external effective doses received by TEPCO employees decreased progressively from around 2 mSv in 2012 to around 1 mSv in 2014. There is a similar order of reduction in the 95th percentile over this period, from 27 mSv to approximately 10 mSv. For contractors, the decrease in dose was less marked, and indeed the mean values for 2012 and 2013 are essentially the same. The 95th percentile values are also similar. There is, however, an indication of a reduction in 2014 to a mean value of around 2 mSv and in the 95th percentiles from 28 mSv in 2012 to 22 mSv in 2014. The probability density functions and the cumulative probability distributions (Figs II.2–II.4) also clearly illustrate a divergence in the distribution of doses received by TEPCO workers and contractors; in 2012 the distributions for the two groups are almost identical, while for 2014 two distinct distributions can be seen.

II.3.2. Internal exposures

The distribution of reported internal effective doses received by workers in 2011 is presented in Section 4.2.1 (Fig. 4.2–7). These data were also analysed by binning the values into dose intervals of widths 5 mSv and 0.5 mSv. The results obtained are shown in Table II.3.

TABLE II.3. COMPARISON OF STATISTICS FOR DIFFERENT LOG-NORMAL FITTING TECHNIQUES AND APPROACHES TO ALLOW FOR DATA AGGREGATION WITHIN DOSE INTERVALS (BINNING) FOR INTERNAL DOSES TO WORKERS (FY 2011)

Statistic	Estimated doses assuming dose interval of 5 mSv (mSv)		Estimated doses assuming dose interval of 0.5 mSv (mSv)	
	Cumulative density function	Probability density function	Cumulative density function	Probability density function
Mean	2.59	2.44	0.12	0.07
67% confidence interval	0.59–11	0.55–10.8	0.01–2.1	0.0–3.3
95% confidence interval	0.14–49	0.12–47.9	0.0–36	0.0–58
χ^2	0.11	2.68	0.31	2.56

The data estimated assuming a dose interval of 5 mSv are consistent with those presented in Section 4.2.1. These data illustrate the effect of assumptions regarding the dose intervals (or bins) and suggest that the fit of cumulative distribution data is good while the PDF is rather poor.

II.3.3. Doses to the thyroid

In the case of thyroid doses, the data tend towards an exponential decrease as a function of dose rather than a log-normal distribution. The extent of the deviation of these data from a log-normal distribution is illustrated in Fig. II.5, which presents the frequency distribution of the original measurement data and that based on log-normal fitting. While a reasonable agreement can be obtained with the cumulative log-normal distribution, a direct comparison of the PDF shows that such agreement cannot be considered to support an assumption of log-normality.

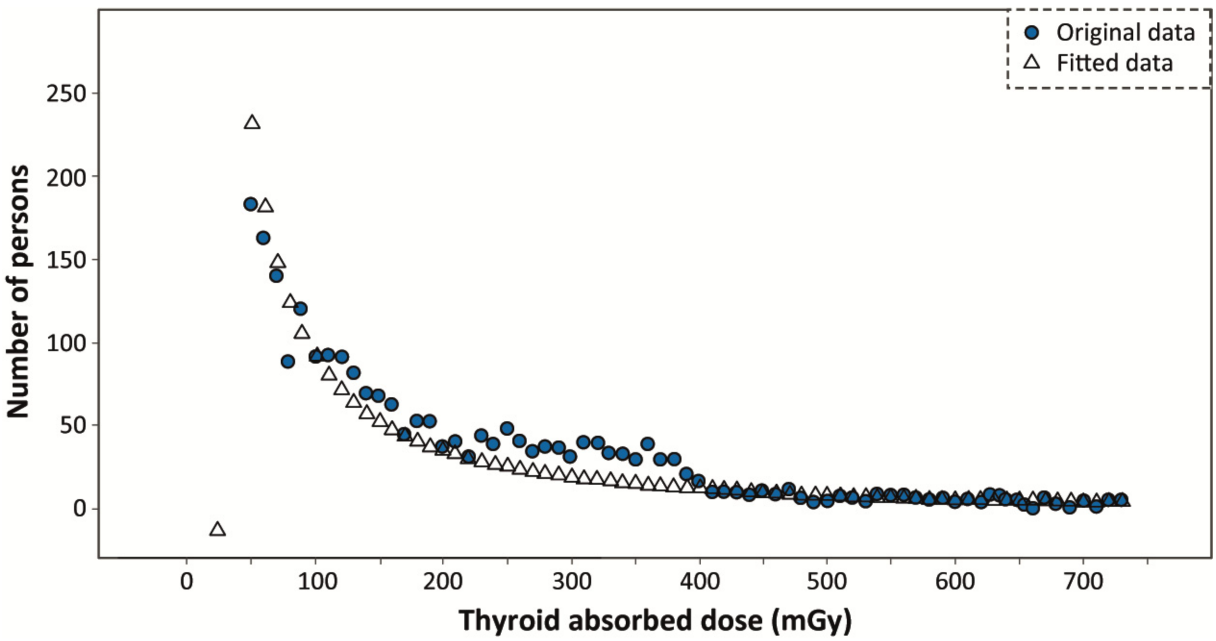


FIG. II.5. Frequency distribution of thyroid equivalent doses received by contractors at Fukushima Daiichi NPP in FY 2011 (March 2011–March 2012).

A normalized idealized probability density function and cumulative probability distribution of reported thyroid equivalent doses received by TEPCO workers and contractors in 2011 is presented in Fig. 4.2–8.

II.3.4. Summary of occupational exposure analysis

With the exception of thyroid dose measurements, the results derived are adequately described by a log-normal distribution, although there are some deviations from it. The differences in the parameters associated with the fit of the distributions are not significantly different between the application of the PDF and cumulative distribution approaches. These analyses provide a coherent set of statistical parameters.

II.4. THYROID DOSES RECEIVED BY CHILDREN RESIDENT IN THREE MUNICIPALITIES OF FUKUSHIMA PREFECTURE

A survey of thyroid exposure was conducted as screening to determine the need for further medical attention. A net screening level of 0.2 μSv/h was defined for this purpose. A statistical analysis of measured thyroid doses of 1080 children from three municipalities in Fukushima Prefecture cannot conclusively support or dismiss the assumption of a log-normal probability density function (PDF) to express the distribution of doses to the thyroid among the population of Fukushima Prefecture. Further analysis of the information and data from this survey is presented in Annex VII.

II.5. APPLICATION OF THE METHODOLOGY TO EXTERNAL DOSES TO RESIDENTS

The external effective doses received by residents of various municipalities in Fukushima Prefecture in the first four months following the accident at the Fukushima Daiichi NPP (11 March–11 July 2011) have been estimated by means of environmental dose rate measurements and responses to questionnaires on locations during that period. More information is presented in Section 4.2.2. The number of people receiving doses within bins of width 1 mSv has been reported for people from different municipalities and from specific regions of Fukushima Prefecture. The information for individual municipalities within and outside a 20 km radius of Fukushima Daiichi NPP is presented and explored in Section 4.2.2.2 and Fig. 4.3–13 and is not presented in more detail here. However, the frequency distribution of estimated external effective doses for people in Iitate Village provides an example of the difficulties and the value of evaluating the fit of reported data to a log-normal distribution (see Fig. II.6).

The following features are seen in Fig. II.6:

— The original data exhibit a double peak structure (one peak at about 1 mSv and the second at around 5 mSv), which is not compatible with the assumption of a log-normal distribution.
— Different parameters are obtained from fits using PDF and cumulative distributions.

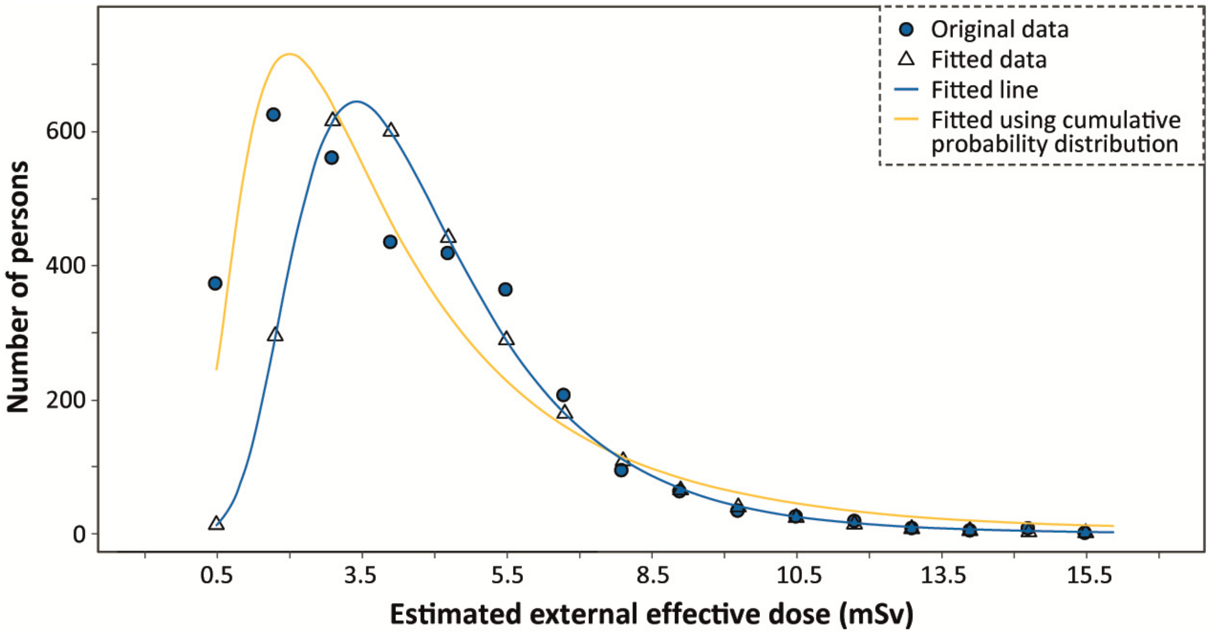


FIG. II.6. Estimated external effective doses received by residents of Iitate Village in the first four months following the accident at the Fukushima Daiichi NPP.

From this, it is apparent that the fitting of two different functions may result in a different evaluation of the weights denoted to individual points to the overall distribution. However, the deviation of the distribution from the log-normal is also valuable information from a radiation protection point of view. This distribution, with a double peak structure, may be indicative of the exposure of different groups of the population to different radiological conditions, for example, due to different patterns of evacuation and levels of radionuclides in the environment.

Figure II.6 also demonstrates that the lowest doses are underestimated by the fitting procedure when the PDF is used. This is due to treating the lowest bin in the same way as those for higher doses — by averaging over the dose interval — whereas it actually represents the cumulative values obtained between 0 and 1.0 mSv.

The distributions of estimated external effective doses received by residents of various regions in Fukushima Prefecture in the first four months following the accident are presented in Figs II.7–II.12, beginning with Soso, the region in which Iitate Village is located. In these figures the normalized idealized probability density function is presented on the left and the cumulative probability distribution on the right.

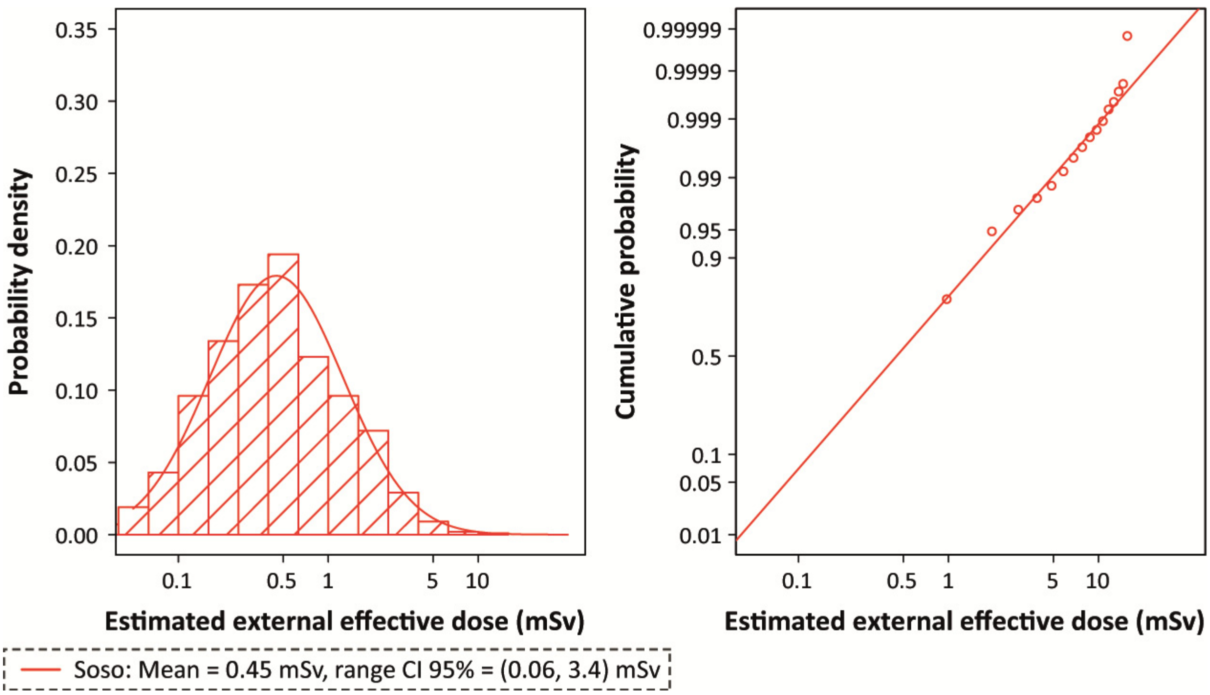


FIG. II.7. Estimated external effective doses received by residents of the Soso region in the first four months following the accident at the Fukushima Daiichi NPP.

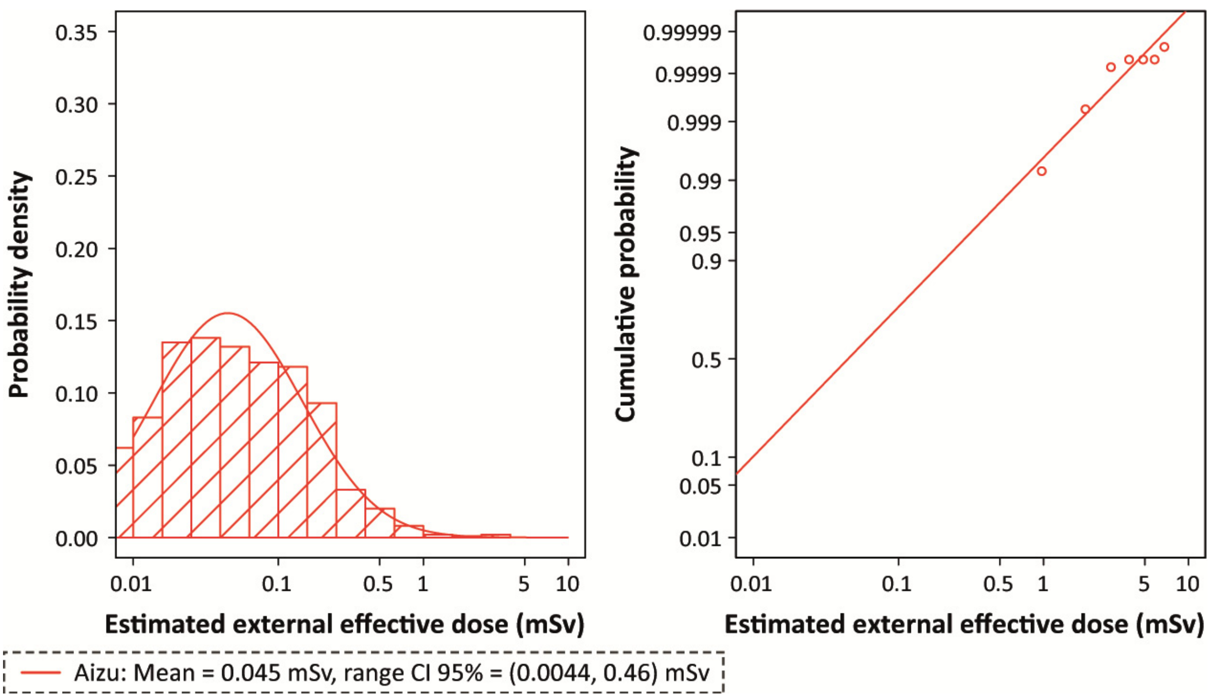


FIG. II.8. Estimated external effective doses received by residents of the Aizu region in the first four months following the accident at the Fukushima Daiichi NPP.

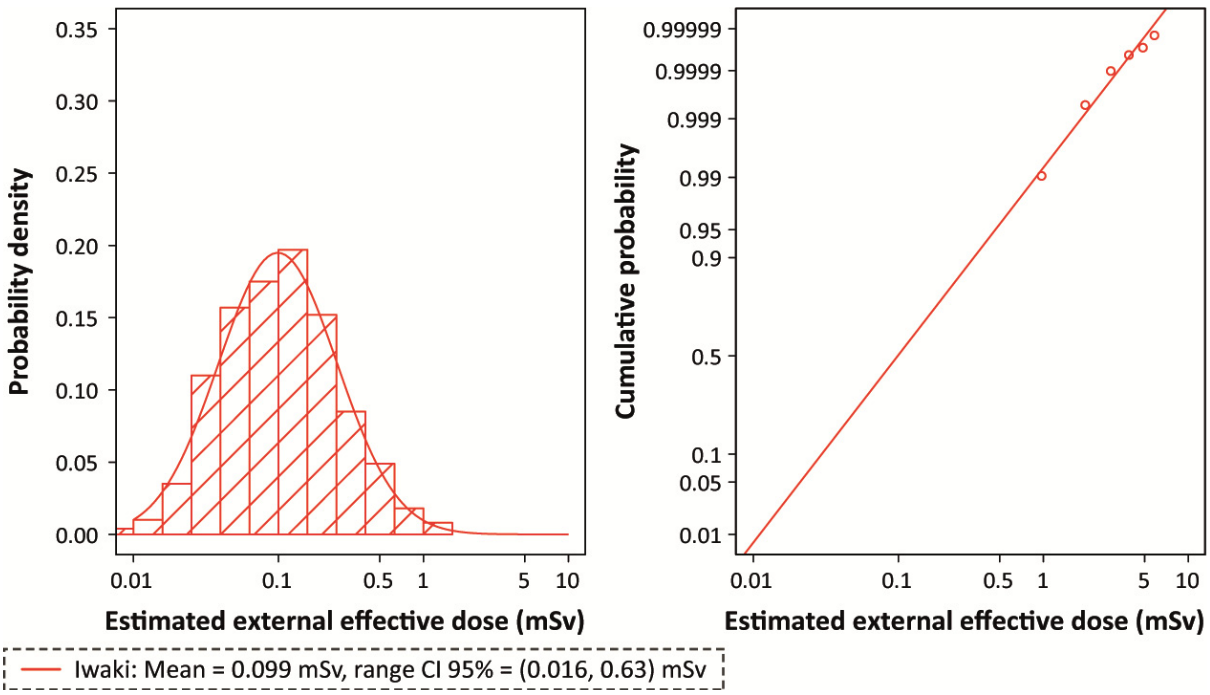


FIG. II.9. Estimated external effective doses received by residents of the Iwaki region in the first four months following the accident at the Fukushima Daiichi NPP.

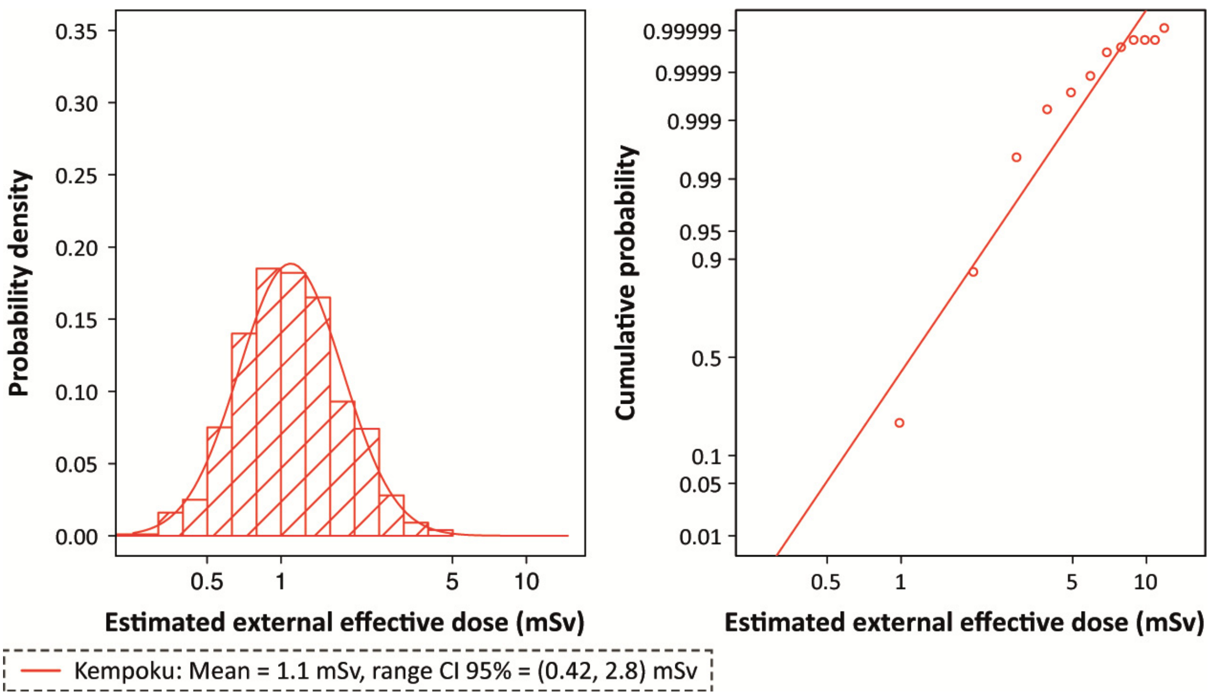


FIG. II.10. Estimated external effective doses received by residents of the Kempoku region in the first four months following the accident at the Fukushima Daiichi NPP.

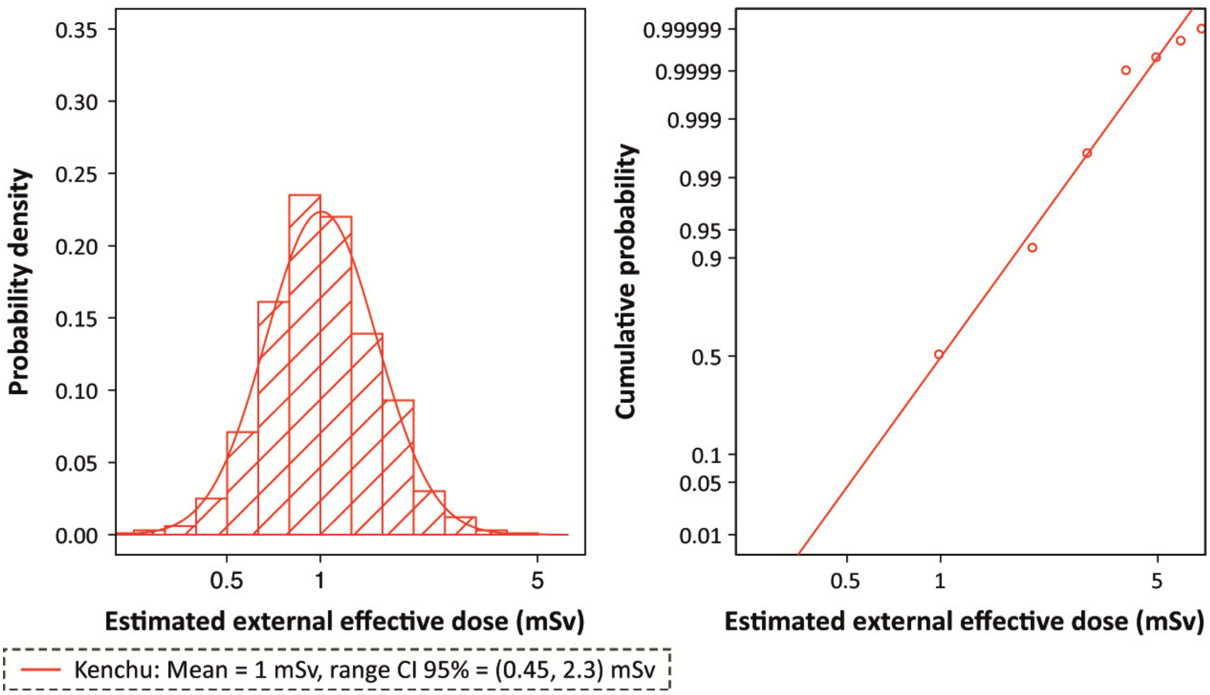


FIG. II.11. Estimated external effective doses received by residents of the Kenchu region in the first four months following the accident at the Fukushima Daiichi NPP.

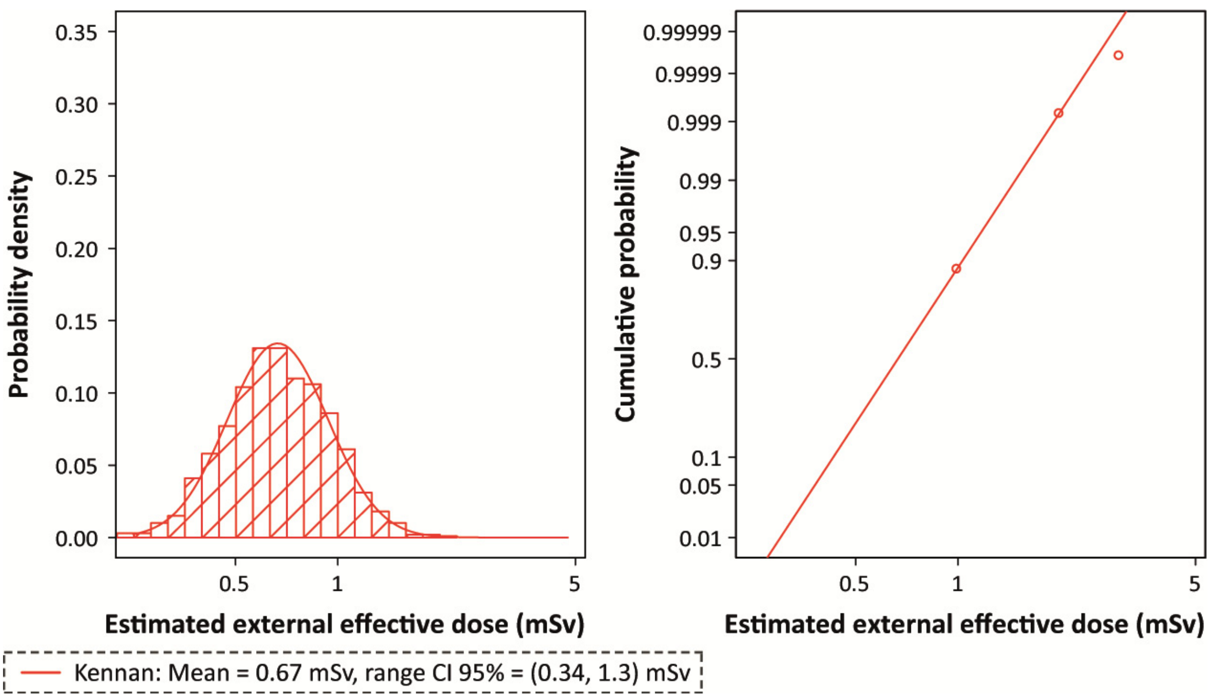


FIG. II.12. Estimated external effective doses received by residents of the Kennan region in the first four months following the accident at the Fukushima Daiichi NPP.

The mean external effective doses in the first four months following the accident, in all the regions in the figures, were estimated to be of the order of 1 mSv or below and the 95th percentiles were of the order of 3 mSv or below. This pattern of dose is also illustrated by the data presented for different age groups in Figs II.13–II.15. These figures demonstrate that there is no significant difference between the distribution of external effective doses for the different age groups for which information is available. In these figures the normalized idealized probability density function is presented on the left and the cumulative probability distribution on the right.

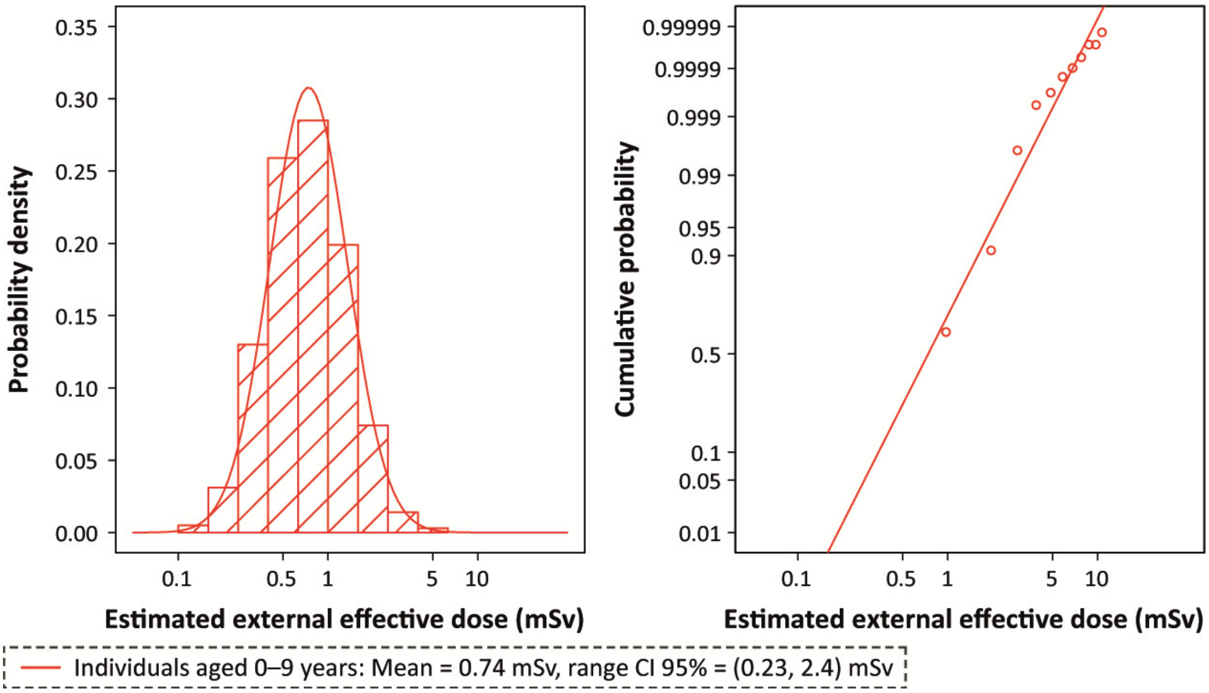


FIG. II.13. Estimated external effective doses received by children (aged 0–9 years) in Fukushima Prefecture in the first four months following the accident at the Fukushima Daiichi NPP.

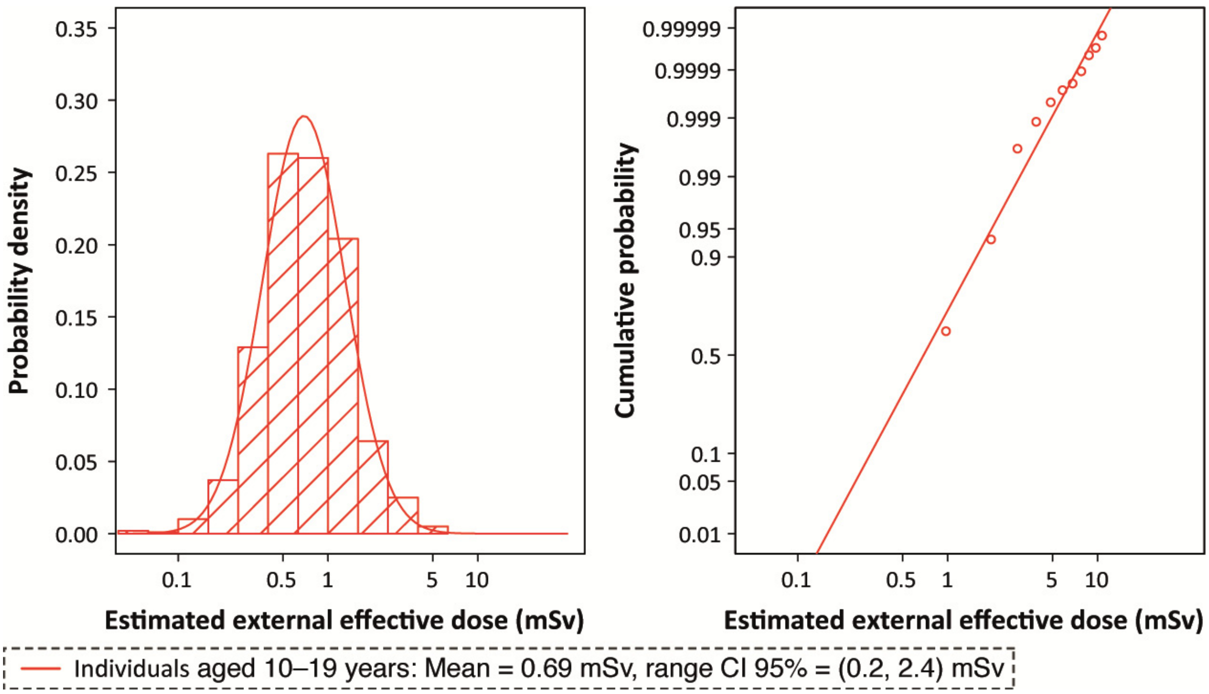


FIG. II.14. Estimated external effective doses received by young people (aged 10–19 years) in Fukushima Prefecture in the first four months following the accident at the Fukushima Daiichi NPP.

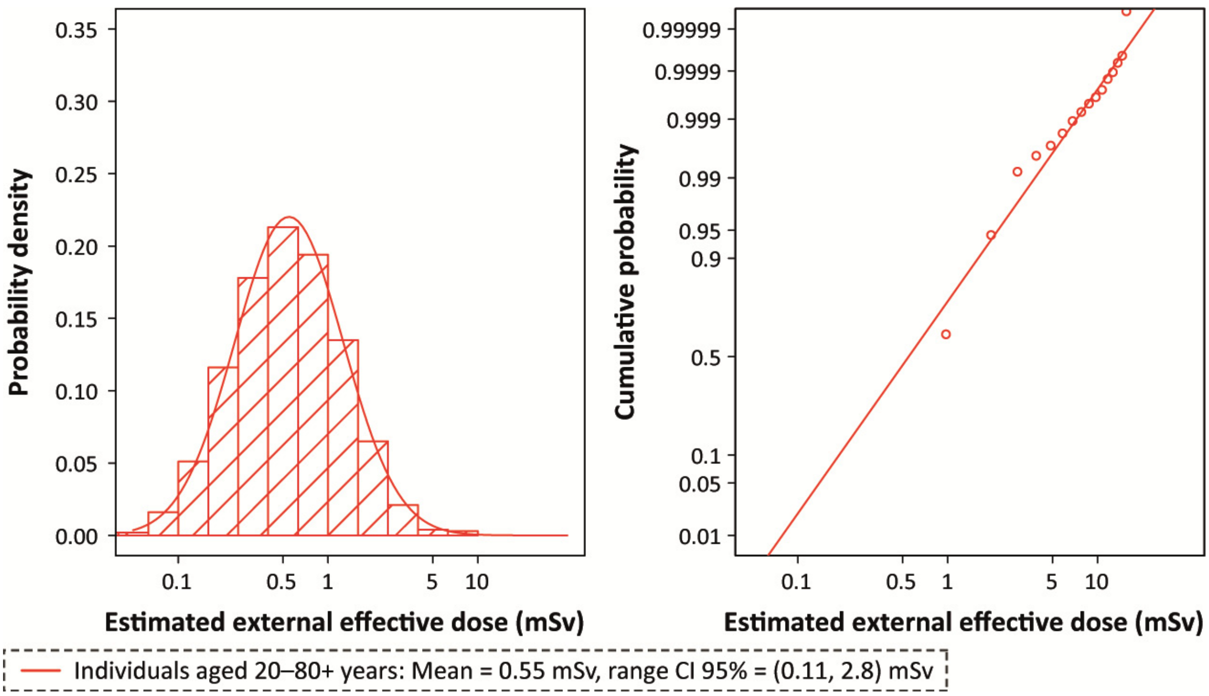


FIG. II.15. Estimated external effective doses received by adults (aged 20 years or older) in Fukushima Prefecture in the first four months following the accident at the Fukushima Daiichi NPP.

II.6. PERSONAL EXTERNAL DOSIMETRY DATA PROVIDED BY FUKUSHIMA PREFECTURE

Fukushima Prefecture made a range of datasets publicly available through its web site, including the results of personal dosimetry and WBC measurements undertaken in Fukushima Prefecture during and since 2011. These data are summarized in Table II.4 [226].

TABLE II.4. SUMMARY OF PERSONAL DOSIMETRY DATA PROVIDED BY FUKUSHIMA PREFECTURE [226]

Place	Date	Number of samples	Comments
Date City	Sep. 2011–Feb. 2012	8 982	Cumulative log-normal distribution function and probability density function presented in Section 4.2.2
	Jul. 2012 – Jun. 2013	36 721	Cumulative log-normal distribution function and probability density function for different occupational groups presented in this appendix
			Comparison of external doses estimated by different methods presented in Section 4.2.2.-
Fukushima City	Sep.–Oct. 2011 Oct.–Nov. 2011	5 750 and 5 580	Cumulative log-normal distribution function presented in Section 4.2.2 and probability density function presented in this appendix
	1 Nov. 2012–31 Jan. 2013	15 945 (< 15 years)	Cumulative log-normal distribution function and probability distribution presented in this appendix
Tamura City	30 Aug.–30 Sep. 2011	4 401	Cumulative log-normal distribution function and probability density function presented in this appendix
	30 Sep.–10 Jan. 2012	4 570	Cumulative log-normal distribution function and probability density function presented in this appendix
	11 Jun.–11 Sep. 2012	4 318	Cumulative log-normal distribution function and probability density function presented in this appendix
	11 Sep.–11 Dec. 2013	3 634	Cumulative log-normal distribution function and probability density function presented in this appendix
Iwaki City	1 Nov. 2011–31 Jan. 2012	30 910 (< 15 years)	Cumulative log-normal plot presented in Section 4.2.2. Additional information probability distribution information for different groups of schoolchildren presented in this appendix

The log-normal distribution is generally a good representation of these data, although there are some deviations, as represented by the normalized idealized probability density functions and cumulative distribution functions for each city for which data are available in the sections below.

II.6.1. Distribution of personal dosimetry data for Date City

The main survey periods for which data are available for Date City are summarized in Table II.5. The cumulative probability distribution and the idealized normalized probability density function appropriate for exposures in 2011 are presented in Section 4.2.2. The data from subsequent surveys also allow the doses estimated using different methods to be compared, as explored further in Section 4.2.2.

During the period July 2012–June 2013, over 35 000 workers in Date City took part in a survey of external doses. Information on their occupation was also recorded, so that the results of this survey can be used to investigate the effect of different occupations on the external doses received. The distribution of the doses received by different occupational groups from external exposure are presented in Fig. II.16.

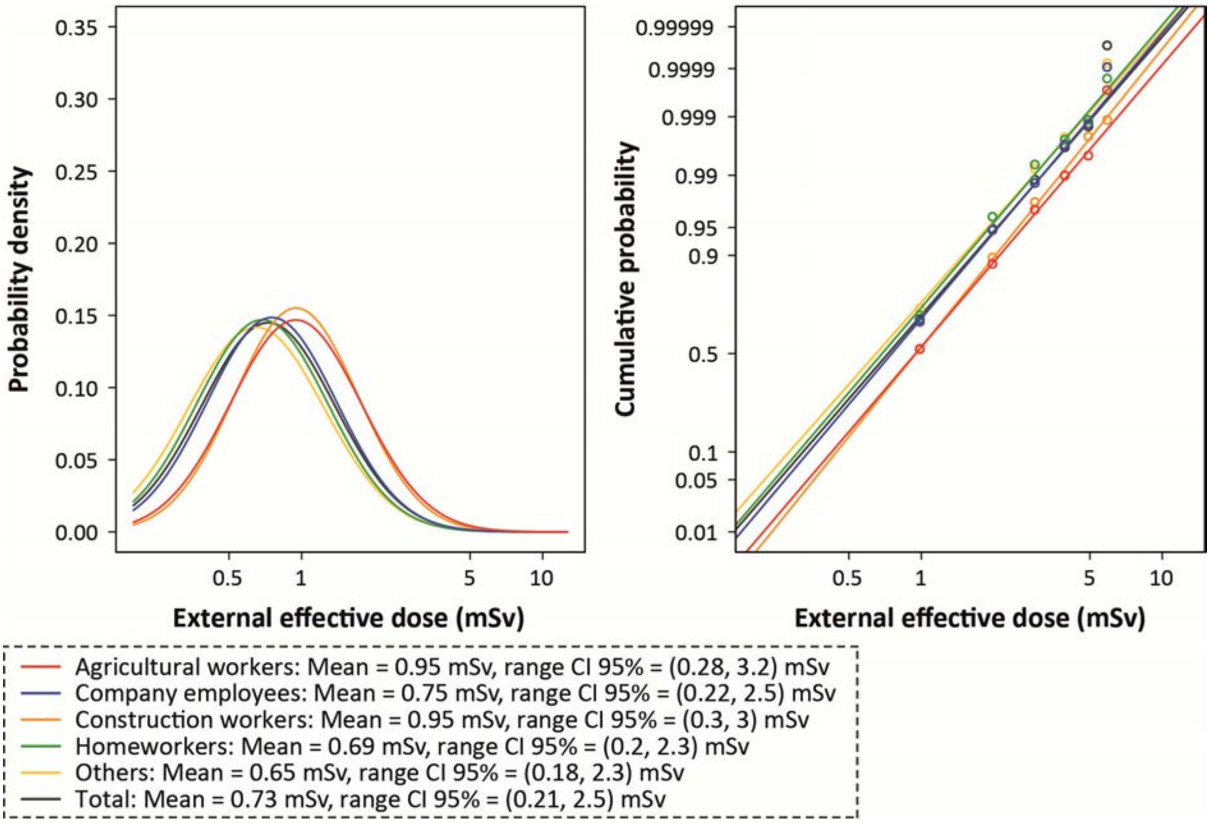
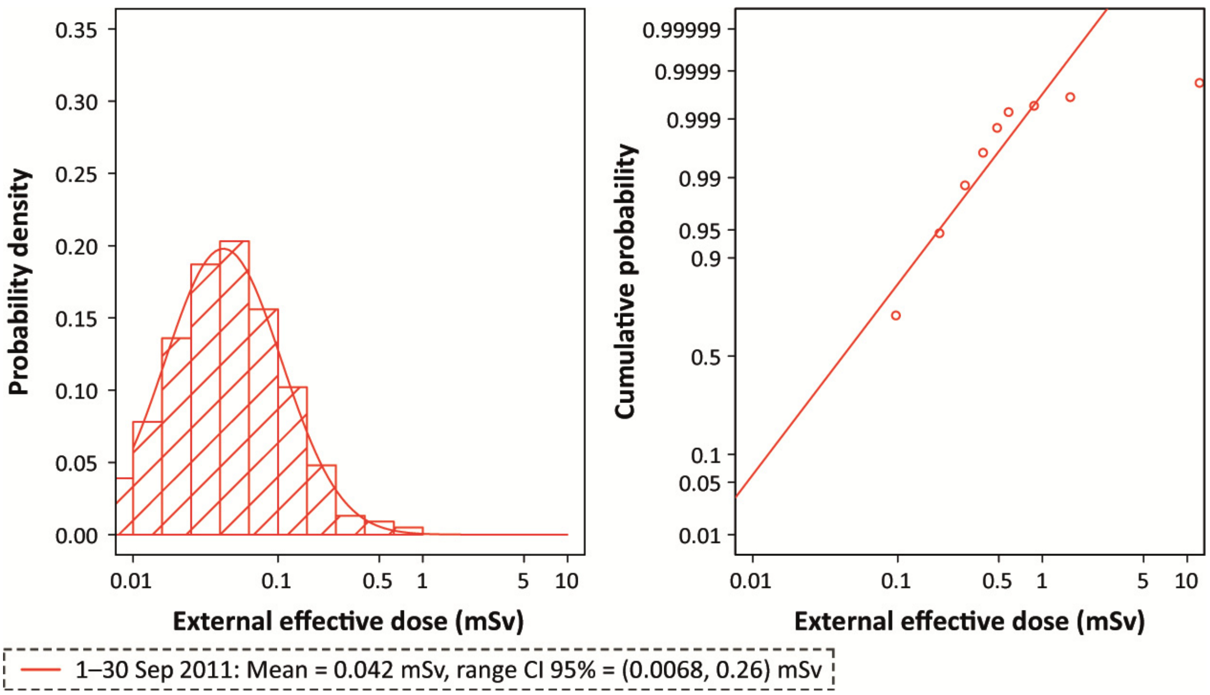


FIG. II.16. (left) Normalized idealized probability density function of external effective doses to different occupational groups in Date City; (right) log-normal cumulative probability distribution, based on personal dosimetry measurements for the period July 2012–June 2013.

Figure II.16 demonstrates that the distribution of doses to agricultural and construction workers are shifted towards higher doses in comparison to other workers, as a consequence of the greater time spent outdoors. Indoor workers and other groups of the population receive lower doses due to the shielding effect of buildings from radioactive material deposited on the ground.

II.6.2. Distribution of personal dosimetry data for Fukushima City

Information on the estimated external effective doses received by the population of Fukushima City is available for three measurement periods, beginning in September 2011. The normalized idealized probability density function and the cumulative probability distribution for the doses estimated for each period are presented in Figs II.17–II.19 [226].



(a) (b)

FIG. II.17. (a) Normalized idealized probability density function of external effective doses to residents of Fukushima City; (b) log-normal cumulative probability distribution, based on personal dosimetry measurements in Fukushima City for the period 1–30 September 2011.

These figures demonstrate that there is some deviation from the log-normal distribution towards the upper tail, associated with higher doses. These results indicate that a mean dose of around 0.04 mSv was received by residents of Fukushima City in September 2011 and that the 95% confidence interval is around 0.01–0.3 mSv. One outlying result exceeds 10 mSv, while others are around 1 mSv or below.

Figures II.18 and II.19 indicate that the cumulative probability distribution is closer to a straight line corresponding to the log-normal distribution, indicating that this distribution is a better fit for the personal dosimetry data measured in the later periods of measurement in the city (1 October–30 November 2011 and 1 November 2012–31 January 2013). The mean values and 95% confidence values for these periods are presented, together with those of those of the month of September 2011, in Table II–5.

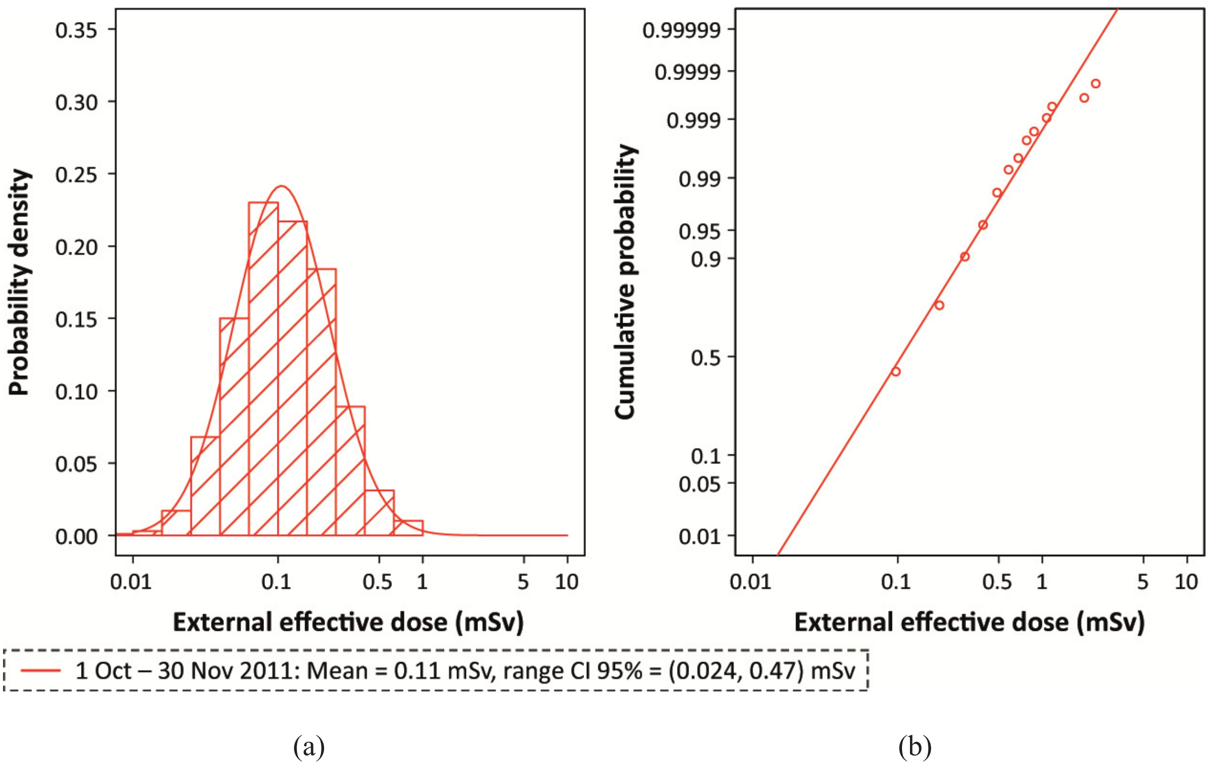


FIG. II.18. (a) Normalized idealized probability density function of external effective doses to residents of Fukushima City; (b) log-normal cumulative probability distribution, based on personal dosimetry measurements in Fukushima City for the period 1 October–30 November 2011.

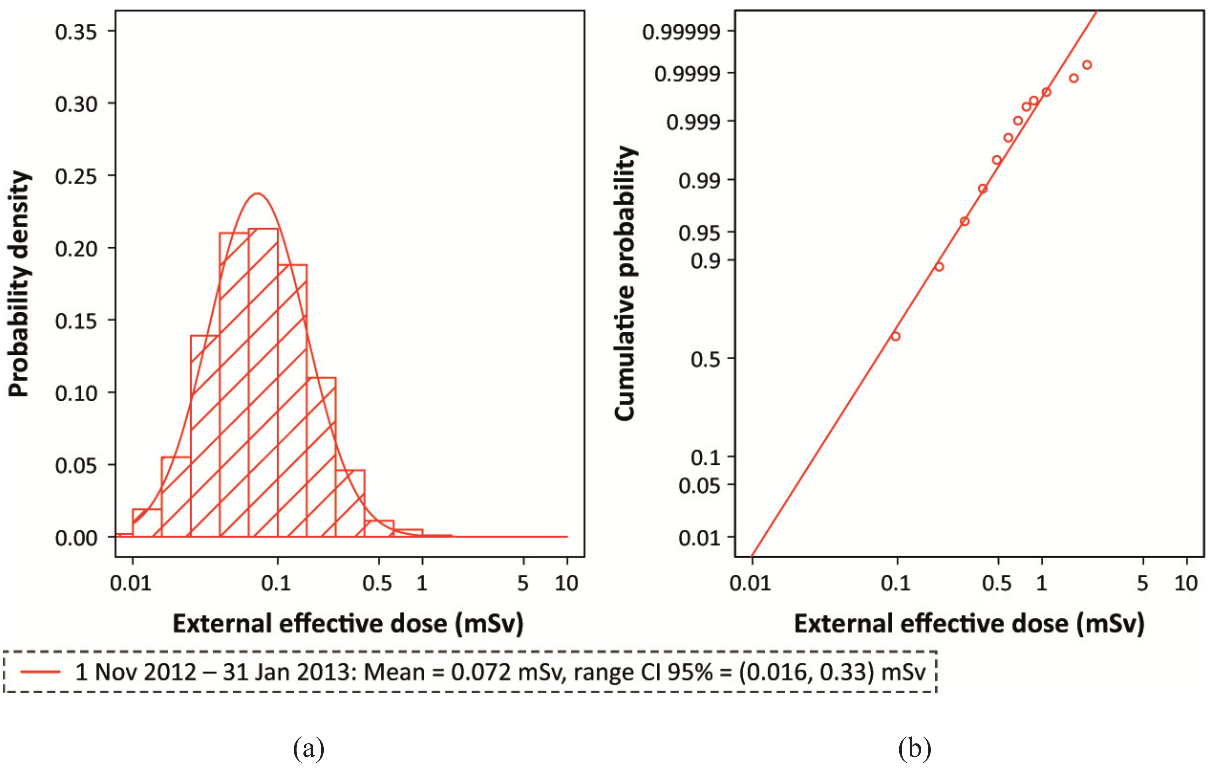


FIG. II.19. (a) Normalized idealized probability density function of external effective doses to residents of Fukushima City; (b) log-normal cumulative probability distribution, based on personal dosimetry measurements in Fukushima City for the period 1 November 2012–31 January 2013.

TABLE II.5. EXTERNAL DOSES MEASURED BY PERSONAL DOSIMETRY IN FUKUSHIMA CITY DURING THE SPECIFIED PERIODS (mSv) [226]

	1 September–30 September 2011	1 October–3 November 2011	1 November 2012–31 January 2013
Mean	0.04	0.11	0.07
95% confidence interval	0.07–0.26	0.02–0.47	0.02–0.33

II.6.3. Distribution of personal dosimetry data for Tamura City

The external effective doses received by the population of Tamura City were available for four measurement periods beginning at the end of August 2011 and extending until mid-September 2012. The normalized idealized probability density function and the cumulative probability distribution for the doses estimated for each period are presented in Figs II.20–II.23 [207].

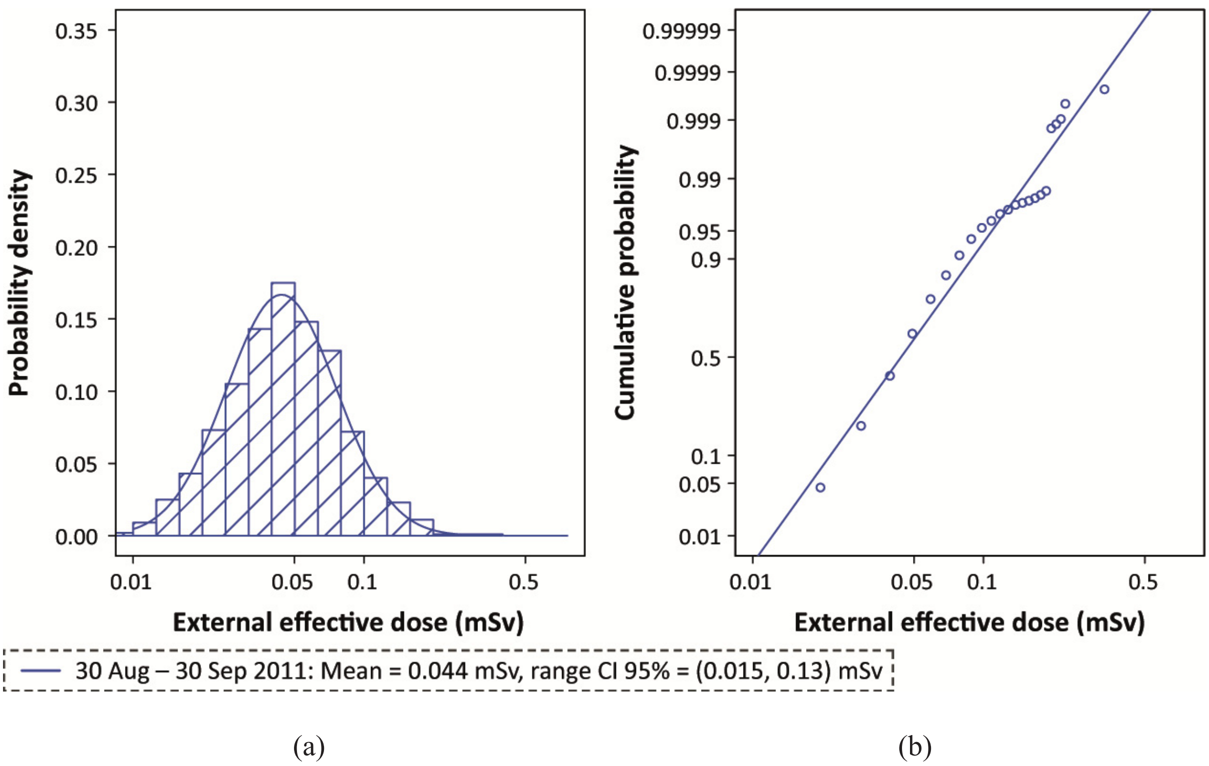
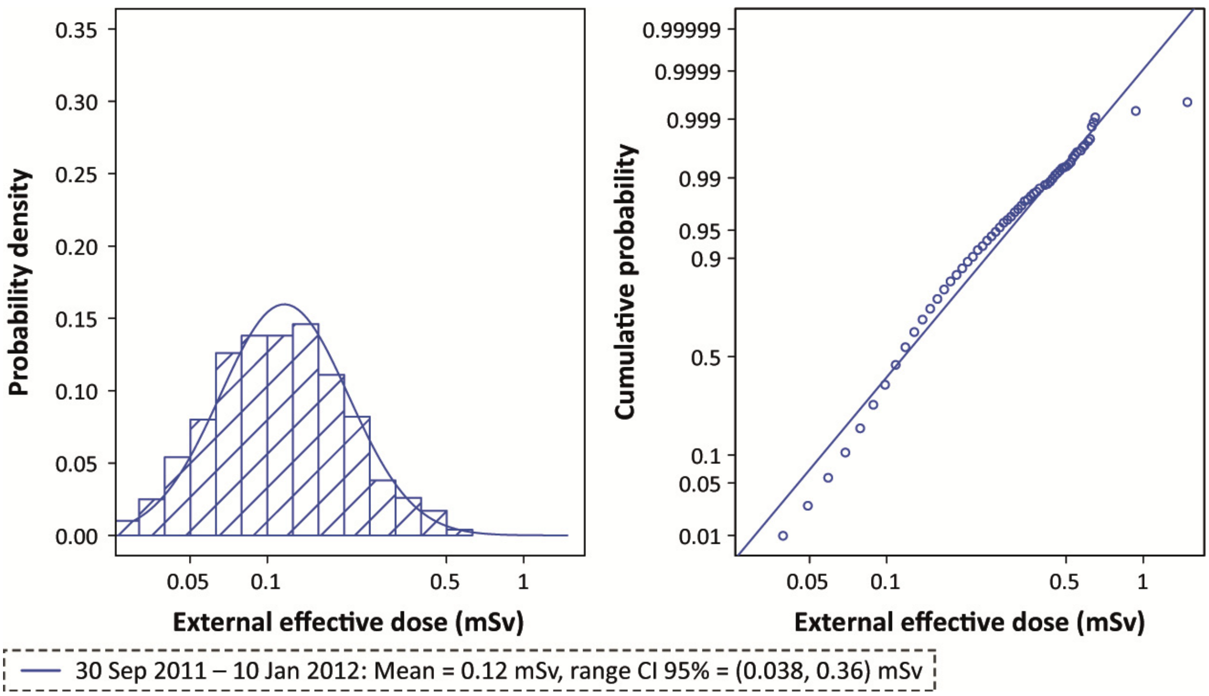


FIG. II.20. (a) Normalized idealized probability density function of external effective doses to residents of Tamura City; (b) log-normal cumulative probability distribution, based on personal dosimetry measurements for the period 30 August–30 September 2011.

Deviations from the log-normal are illustrated in the cumulative probability function and in the probability density function for the same dataset.



(a) (b)

FIG. II.21. (a) Normalized idealized probability density function of external effective doses to residents of Tamura City; (b) log-normal cumulative probability distribution, based on personal dosimetry measurements for the period 30 September 2011–10 January 2012.

The data for the later measurement period in 2011 (Fig. II.21) appear to fit the log-normal distribution, although there are some deviations. The personal dosimetry data for the subsequent period (11 June 2012–11 September 2012) also demonstrate a reasonable fit to the log-normal. These data also show a reduction in mean dose, consistent with radioactive and environmental decay processes (and possibly remediation measures).

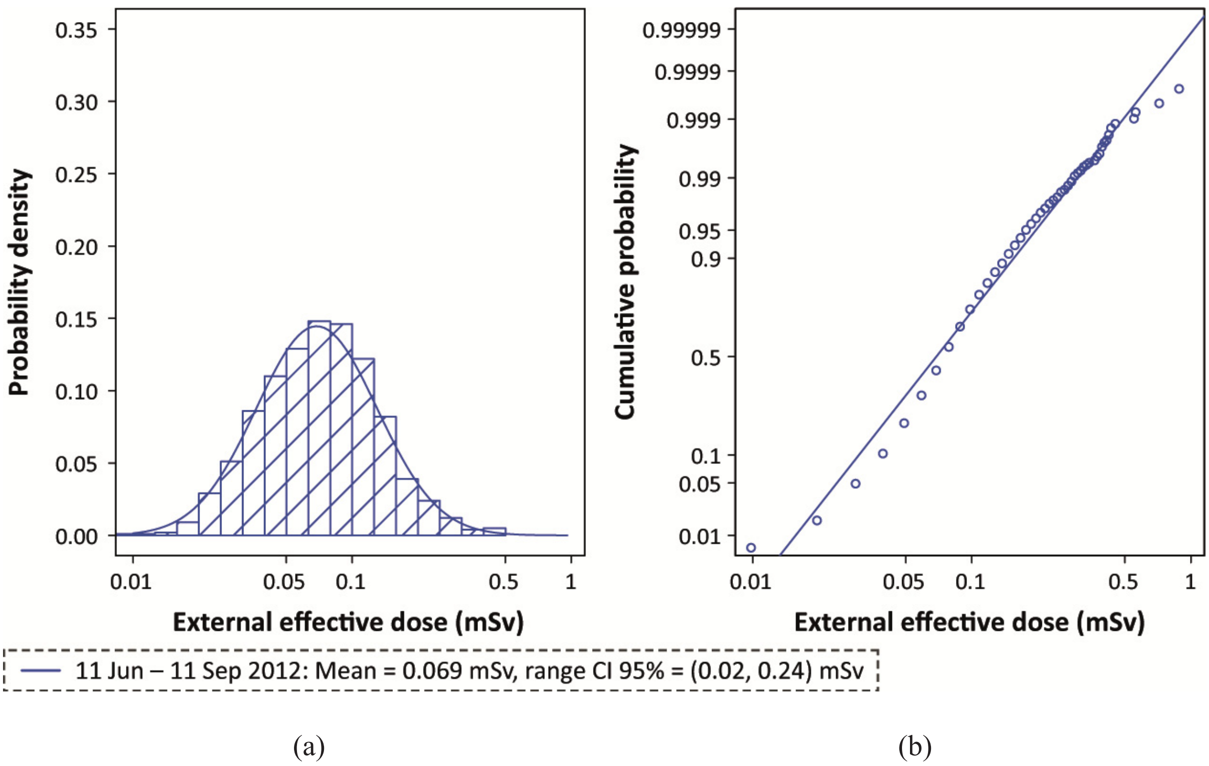


FIG. II.22. (a) Normalized idealized probability density function of external effective doses to residents of Tamura City; (b) log-normal cumulative probability distribution, based on personal dosimetry measurements for the period 11 June–11 September 2012.

The final dataset for Tamura City suggests some deviation from the log-normal distribution such that the confidence intervals should be treated with some caution (Fig. II.23). However, the mean values indicate a continued decrease due to decay mechanisms and possibly remediation. The statistics associated with external doses measured in Tamura City in different periods are summarized in Table II.6.

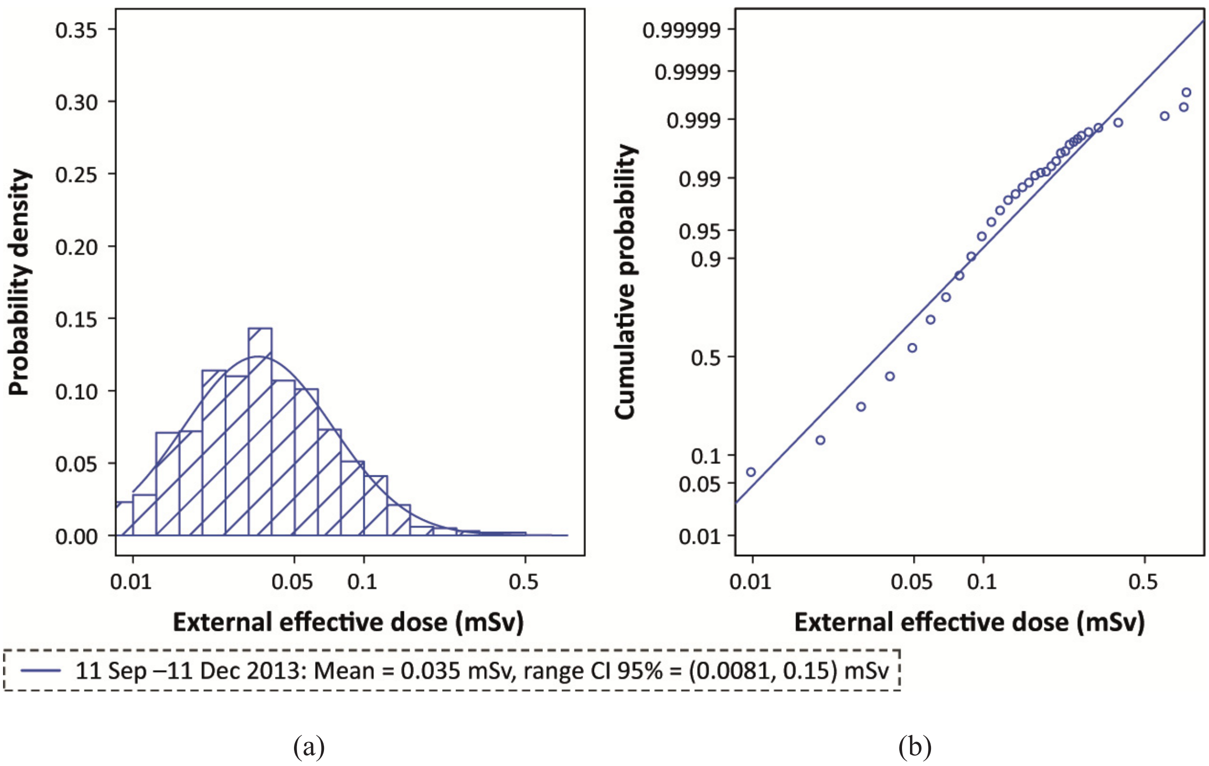


FIG. II.23. (a) Normalized idealized probability density function of external effective doses to residents of Tamura City; (b) log-normal cumulative probability distribution, based on personal dosimetry measurements for the period 11 September – 11 December 2013.

TABLE II.6. EXTERNAL DOSES MEASURED BY PERSONAL DOSIMETRY IN TAMURA CITY DURING THE SPECIFIED PERIODS (mSv) [207]

	30 Aug–30 Sep. 2011	30 Sep. 2011–10 Jan. 2012	11 Jun.–11 Sep. 2012	11 Sep.–11 Dec. 2013
Mean	0.044	0.12	0.069	0.035
95% confidence interval	0.015–0.13	0.038–0.36	0.002–0.24	0.008–0.15
χ^2	4.4	—	—	5.4

Note: The values of χ^2 are presented where the values indicate deviations from a log-normal distribution (illustrated by the high maximum values in the PDFs above).

II.6.4. Distribution of personal dosimetry data in Iwaki City

Approximately 30 000 school children in Iwaki City took part in a survey in which they wore personal dosimeters during the period 1 November 2011–31 January 2012. The results of these measurements have been made available [217, 218] and allow the distribution of external effective doses received by school children of different ages to be determined, as illustrated in Fig. II.24. The distribution of the effective doses is effectively the same for each of the age groups of schoolchildren, with a mean of around 0.4 mSv and a 95th percentile value of approximately 1.5 mSv or slightly less.

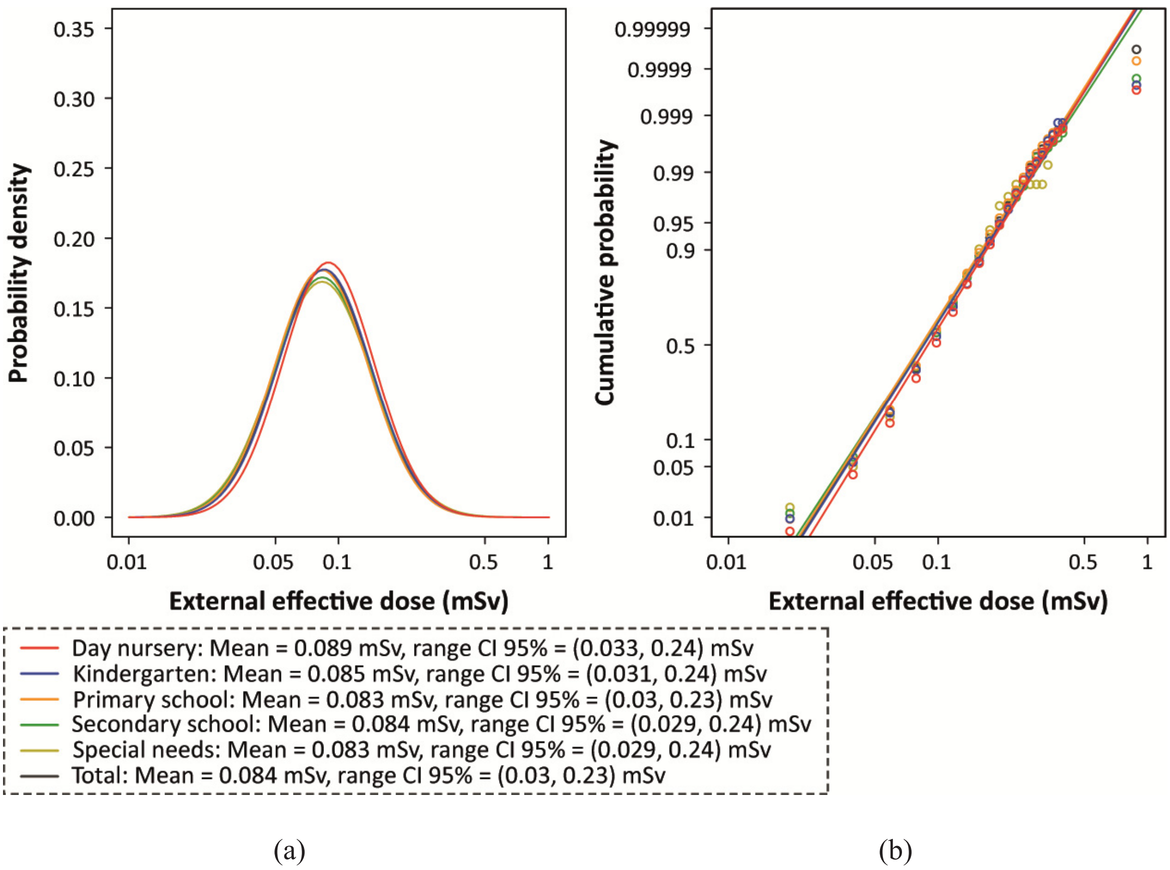


FIG. II.24. (a) Normalized idealized probability density function of external effective doses to children of various school ages in Iwaki City; (b) log-normal cumulative probability distribution, based on personal dosimetry measurements for the period 1 November 2011–31 January 2012.

II.7. INTERNAL EXPOSURES TO RESIDENTS OF MUNICIPALITIES IN FUKUSHIMA PREFECTURE MEASURED BY WHOLE BODY COUNTERS

The dataset of measurements of internal exposures of residents of Namie Town derived from WBCs (Namie 2012, 2013 for ^{134}Cs and ^{137}Cs) [226] does not allow an analysis of the probability distributions. The levels of incorporated radiocaesium are low relative to the relative detection levels of the WBCs so that almost all data points are within the first dose interval. Further analysis of the remaining results would lead to ambiguous results.

II.8. SUMMARY

A general feature of all of the datasets for which a statistical analysis has been attempted is that the levels of effective doses were, in general, extremely low. In most cases the measurement results are either below or broadly comparable with the limit of detection of the radioanalytical technique employed. The subsequent large dynamic range between the first and higher dose intervals restricts the effectiveness of this type of analysis. In the case of the Chernobyl accident, the levels of dose received by workers and the public were generally higher relative to the limits of detection.

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CONTENTS OF CD-ROM

The following annexes to Technical Volume 4 are included on the attached CD-ROM:

ABBREVIATIONS

AGL	height above ground level
AMS	accelerator mass spectrometry
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
BSS	Basic Safety Standards
CED	committed effective dose
CI	confidence interval
CNS	Convention on Nuclear Safety
CPS	counts per second
CRIEPI	Centre of the Central Research Institute of the Electric Power Industry
CR	concentration ratio
CTBTO	Comprehensive Nuclear Test-Ban-Treaty Organization
DCA	dicentric chromosome array
DCCs	dose conversion coefficients
DCRL	Derived Consideration Reference Level
DOE	United States Department of Energy
EPD	electronic personal dosimeter
EPIC	Environmental Protection from Ionizing Contaminants in the Arctic
ERIC	Environmental Risk from Ionizing Contaminants: Assessment and Management
FAO	Food and Agriculture Organization of the United Nations
FASSET	Framework for Assessment of Environmental Impact
FDMA	Fire and Disaster Management Agency
FHMS	Fukushima Health Management Survey
FNAB	fine needle aspiration biopsy
FY	fiscal year
GDAS	Global Data Assimilation System
GEOMAR	Research Center for Marine Geosciences
GLs	guidance levels
GPD	general psychological distress
Gy	gray
HPGe	High Purity Germanium
HYSPLIT	Hybrid Single-Particle Lagrangian Integrated Trajectory
ICRP	International Commission on Radiological Protection
ILO	International Labour Organization
IMMSP	Institute of Mathematical Machines and Systems Problems
IRSN	Institut de radioprotection et de sûreté nucléaire (Institute for Radiological Protection and Nuclear Safety)
JAEA	Japan Atomic Energy Agency
JCOPET	Tide-resolving regional nested subsystem of Japan Coastal Ocean Predictability Experiment
JKEO	Japan Agency for Marine–Earth Science and Technology Kuroshio Extension Observatory
KEO	Kuroshio Extension Observatory
KIOST	Korea Institute of Ocean Science and Technology
KNOT	Kyodo North Pacific Ocean Time-series
Kobe U	Kobe University
LARF	lifetime attributable risk fraction
LARs	lifetime attributable risks
LD	lethal dose
MAFF	Ministry of Agriculture, Forestry and Fisheries
MCR	main control room
METI	Ministry of Economy, Trade and Industry
MEXT	Ministry of Education, Culture, Sports, Science and Technology

MHLW	Ministry of Health, Labour and Welfare
MSSG	Multi-Scale Simulator for the GeoEnvironment
NIES	National Institute for Environmental Studies
NIRS	National Institute of Radiological Sciences
NISA	Nuclear and Industrial Safety Agency
NOAA	National Oceanic and Atmospheric Administration
NPP	nuclear power plant
NRA	Nuclear Regulation Authority
OCHA	United Nations Office for the Coordination of Humanitarian Affairs
OECD	Organisation for Economic Co-operation and Development
OECD/NEA	OECD Nuclear Energy Agency
OP	Onahama Port
PADs	personal alarm dosimeters
PAHO	Pan American Health Organization
PDF	probability density function
PPE	personal protective equipment
PROTECT	Protection of the Environment from Ionizing Radiation in a Regulatory Context
PTC	papillary thyroid cancer
PTSD	post-traumatic stress disorder
PTSR	post-traumatic stress response
RAPs	reference animals and plants
SDF	Self-Defense Forces
SPEEDI	System for Prediction of Environmental Emergency Dose Information
TEPCO	Tokyo Electric Power Company
TMI	Three Mile Island
TUE	Thyroid Ultrasound Examination
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
US DOE/NNSA	US Department of Energy/National Nuclear Security Administration
USPACOM	United States Pacific Command
UTC	Universal Time Coordinated
WBC	whole-body counter
WHO	World Health Organization
WHOI	Woods Hole Oceanographic Institution
WMO	World Meteorological Organization

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MEETINGS

Working Group (WG) meetings

18 March 2013
Initial meeting of the WG Co-Chairs, Vienna

21–22 March 2013
1st meeting of all WGs, Vienna

12–14 June 2013
2nd meeting of all WGs, Vienna

7–9 October 2013
3rd meeting of WGs 3, 4 and 5, Vienna

9–13-December 2013
4th meeting of all WGs, Vienna

10–14 February 2014
5th meeting of all WGs, Vienna

5–9 May 2014
6th meeting of WG 4, Vienna

International Technical Advisory Group (ITAG) meetings

21–22 March 2013
1st ITAG meeting, Vienna

10 June 2013
1st Joint ITAG/Co-Chairs meeting, Vienna

11 June 2013
2nd ITAG meeting, Vienna

6 December 2013
2nd Joint ITAG/Co-Chairs meeting, Vienna

7 May 2014
3rd Joint ITAG/Co-Chairs meeting, Vienna

23–24 October 2014
4th Joint ITAG/Co-Chairs meeting, Vienna

23–24 February 2015
5th Joint ITAG/Co-Chairs meeting, Vienna

Consultants services (CS) meetings

24–26 March 2014
CS on Radioactivity in the Environment, Monaco

20–21 May 2014
CS on Radiation and Log-Normal Distributions, Vienna

23–27 June 2014
CS on Radiation and Log-Normal Distributions, Vienna

Bilateral meetings in Japan

25–27 November 2013
CS to Discuss Issues Related to Radiological Consequences in Connection with the Preparation of Chapter 4 (Radiological Consequences) and Chapter 5 (Post-accident Recovery)

20–24 January 2014
CS to Discuss Issues Related to Regulatory Activities, Operating Experience and Waste Management Topics in Connection with the Preparation of the IAEA Report

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