

**FINAL SUMMARY REPORT
(2013–2022)**

**Cooperation between the
International Atomic Energy Agency
and Fukushima Prefecture**

Radiation Monitoring and Remediation

**Vienna/Fukushima May 2023
(Approved)**

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1. INTRODUCTION

1.1. BACKGROUND

The 11 March 2011 earthquake off the Pacific coast of Tohoku and the subsequent tsunami and accident at Tokyo Electric Power Company's Fukushima Daiichi Nuclear Power Plant (hereinafter referred to as 'Fukushima Daiichi accident') resulted in radioactive contamination deposited in various areas of Japan, including Fukushima Prefecture (hereinafter referred to as 'the Prefecture'). Following the accident, the Prefecture and the IAEA concluded a Memorandum of Cooperation. Radiation monitoring, remediation, decontamination and human health were identified as areas for cooperation. Concrete projects, as well as ways and means to implement them, were discussed between the IAEA and the Prefecture.

A memorandum titled, Practical Arrangements between the Prefecture and the International Atomic Energy Agency on Cooperation in the Area of Radiation Monitoring and Remediation (hereinafter referred to as 'Practical Arrangements'), which elaborated further on the objectives and scope of future cooperation, was agreed by the IAEA and the Prefecture. Practical Arrangements were signed on December 2012 and were valid for a period of five years after signature and were extended and modified by the mutual consent of both sides in April 2016 and December 2017 and continued until 2022.

The main role of the IAEA in implementation of these projects is the provision of effective technical assistance and support to the Prefecture based on international experience and best practices.

1.2. OBJECTIVES AND SCOPE OF THE COOPERATION

Practical Arrangements and Modification No. 1 and Modification No. 2 to the Practical Arrangements were signed by representatives of the Prefecture and the IAEA in December 2012, April/May 2016, and December 2017, respectively. The objective of the Practical Arrangements is to set forth the framework for cooperation between the Prefecture and the IAEA, and to provide broad and extensive assistance in the Prefecture in areas related to radiation monitoring and remediation in order to ensure ongoing protection of people and the environment from ionizing radiation resulting from the Fukushima Daiichi accident.

1.3. TOPICS OF COOPERATION

Section 2 of the Practical Arrangements (as revised in Modification No. 1 in 2016) identified the following areas and activities in which cooperation may be pursued:

- Research and study on radiation monitoring to include: application of environmental mapping technology by using unmanned aerial vehicles; long term monitoring of radioactive material in the forest and associated countermeasures and the IAEA's assistance in the use of radiation monitoring data to develop maps to be made available to the public;
- Research and study on off-site decontamination including the IAEA's assistance in analyses of results of environmental monitoring and exploration of exposure pathways in order to reduce or avoid exposure; and
- Research and study on the management of radioactive waste including IAEA's assistance in the study on management methods of low level radioactive waste from the above referenced decontamination activities.

Section 2 of the Practical Arrangements was further revised in December 2017 (Modification No. 2 to the Practical Arrangements) identifying further areas and activities in which cooperation may be pursued:

- Research and study on remediation of environment in the Prefecture;
- Research and study on management of radioactive waste from decontamination activities; and
- Research and study on radiation monitoring, including application of environmental mapping technology by using unmanned aerial vehicles, long term monitoring of radioactive materials in the forest areas, and associated countermeasures.

Information dissemination interlinks with and is in line with all the areas and activities of cooperation under the Practical Arrangements. To strengthen efforts in information dissemination, the IAEA and the Prefecture have organized several activities under the scope of each of the topics of cooperation. These were based on international examples of best practices in informing the public about the effects of radiation.

Cooperation under the Practical Arrangements is designed to complement existing Japanese activities and to provide immediate assistance and support which will be of direct benefit to residents of the Prefecture as well as visitors to the Prefecture.

1.4. PROVISION OF ASSISTANCE AND STRUCTURE OF THIS REPORT

After signature of the Practical Arrangements, work on the cooperative projects has been implemented primarily through a series of bilateral meetings — two meetings held in the Prefecture and one in Vienna annually. During each meeting, the representative of the Prefecture, experts from Japanese institutions, international experts identified by the IAEA, and IAEA staff members gathered together for discussions related to the subjects under the Practical Arrangements. International experts and IAEA staff members (herein referred to as the ‘IAEA team’) provided technical advice related to the planning, implementation and evaluation of the results of activities conducted by the Prefecture, which was based on the IAEA Safety Standards and good international practices. During several missions to the Prefecture, site visits were made to various locations such as temporary storage facilities, freshwater demonstration projects, and forest monitoring and management projects. Additionally, software developed by the IAEA was modified so that it could be used by the Prefecture to evaluate the safety of temporary storage sites for radioactive waste.

This Final Summary Report summarizes the current status and progress made in the activities conducted under the Practical Arrangements from 2013 through 2022. The Final Summary Report updates and replaces ‘Mid Term Summary Report (2013–2020)’ and the ‘SUMMARY REPORT (2013–2017); Cooperation between the International Atomic Agency and Fukushima Prefecture and activities undertaken by Fukushima Prefecture’. The body of this report is organized in 5 main sections that correspond to the main points of Section 2 of the Practical Arrangements (as revised in 2016). Sections 2, 5 and 6 cover activities in area 1, Section 3 covers activities under area 2 and Section 4 covers activities under area 3. The work undertaken on the further areas and activities identified in Modification No. 2 to the Practical Arrangements in 2017 are included in the respective Sections of the report.

In January 2023, a workshop was held in the Prefecture to present a summary of the activities and the key outcomes of the cooperation during 2013–2022 under the Practical Arrangements. A brief summary of the key outcomes is given in an Annex to this report.

2. LONG TERM MONITORING OF RADIOACTIVE MATERIAL IN FORESTS AND ASSOCIATED COUNTERMEASURES

2.1. BACKGROUND AND OBJECTIVES

Forests cover approximately 70% of the surface area of the Prefecture; an example of a coniferous forest is shown in Figure 2.1. They are used extensively for leisure activities and are also an important economic resource as they provide timber used in the construction of dwellings. Forests also help to prevent sediment discharge, landslides and other natural disasters. Many Japanese families live within or on the immediate outskirts of forests, which gives rise to specific challenges in terms of countermeasures to reduce external dose rates due to gamma radiation (hereinafter referred to as ‘air dose rate’). The forests in the Prefecture differ from European forests in terms of annual rainfall, temperature and topography. These differences result in faster decomposition of the litter layer in the Prefecture, which is consequently thin compared to European forests. However, in comparing European and Japanese forests, the more general movement of both nutrients and radionuclides are expected to be similar.

In Japan, berries, wild mushrooms and wild meat are not as widely consumed by the public as they are in Europe. However, some Japanese forests are a source of ‘forest vegetables’ (*sansai*) which are collected for human consumption.

From studies undertaken in the aftermath of the Chernobyl accident it is known that forests have a high interception capacity for all airborne pollutants. From the time when the Practical Arrangements were established in 2012, the most important exposure pathway for people is external radiation emitted by caesium-137 (^{137}Cs) and caesium-134 (^{134}Cs) (collectively referred to herein as radiocaesium), which is present in both the terrestrial and aquatic ecosystems. The half-life of ^{134}Cs is approximately two years; ^{137}Cs decays more slowly with a half-life of approximately 30 years. Both ^{137}Cs and ^{134}Cs were released to the environment in approximately equal amounts following the Fukushima Daiichi accident. ^{137}Cs was also released into the environment as a result of the above ground testing of nuclear weapons that took place in the 1950s and 1960s. Due to ^{137}Cs having a much longer half-life than ^{134}Cs , in December 2017 the ratio of $^{137}\text{Cs}/^{134}\text{Cs}$ was about 8:1 and by December 2019 this had changed to 16:1. Radiocaesium levels in the environment, and associated doses to people will decline without intervention as a result of the radioactive decay of radiocaesium, and the removal of radiocaesium by weathering from surfaces and vertical migration down soil and sediment profiles. Once deposited within forests, radiocaesium is retained and recycled within the forest ecosystem. The distribution of radiocaesium within the different components of the forest floor, vegetation and living organisms changes with time.

The Practical Arrangements have allowed the IAEA team to share international experience with the Prefecture on longer term monitoring of radiocaesium in forests and associated countermeasures. Issues discussed since 2012 included characterizing the distribution and long term accumulation of radiocaesium in various components of the forest ecosystem, establishing effective radiation monitoring programmes, reviewing the effectiveness of countermeasures and assessment of the *Satoyama* Rehabilitation Model Project. Other topics considered were countermeasures for reducing radiation exposures of forest workers and assessing the radiological impact of forest fires. International experience in the management of radiation doses from wild foods was reviewed and discussed in detail during a number of meetings.



FIG. 2.1: Coniferous forest in Tokiwa District, Tamura City (Image credit: Fukushima Prefecture).

2.2. MONITORING PROGRAMMES

A long term monitoring programme in forests has been established to track the rate of reduction of the air dose rate from radiocaesium and to better understand radiocaesium movement between the different components of the forest. The monitoring programme is also evaluating the distribution of radiocaesium within different components of trees (wood, bark and leaves), and how that changes with time.

2.2.1. Air dose rate

The number of monitoring points in forests for air dose rate has been extended each year since the accident and at the end of 2017 totalled 1300 (see Table 2.1). Air dose rate is measured at all monitoring points and, at 80 of these, sampling of soil and the leaves and wood of trees is carried out annually. The monitoring locations are within forests administered by the Prefecture including Prefecture and privately owned forests.

The air dose rate in the forest continues to fall in line with the physical half-life of radiocaesium. Considering only the 362 monitoring points established in the first year, the average dose rate has fallen from 0.91 $\mu\text{Sv/h}$ in August 2011 to 0.17 $\mu\text{Sv/h}$ at the end of 2021 i.e. a reduction of 81%, entirely by natural processes (see Figure 2.2). While a significant proportion of the prefecture's total area is now showing air dose rates less than the target value for decontamination in residential areas (0.23 $\mu\text{Sv/h}$), there are still a small number of sites close to the evacuated area which exhibit higher air dose rates is $>2.5 \mu\text{Sv/h}$. The data suggest that forests with air dose rates exceeding 0.23 $\mu\text{Sv/h}$ will still remain in 2036, 25 years after the accident.

In March 2011 the ratio between ^{137}Cs and ^{134}Cs was 1:1. By December 2019, that had changed to approximately 16:1, primarily due to the radioactive decay of ^{134}Cs , which has a half-life of 2.06 years compared to the much longer half-life of 30.07 years for ^{137}Cs . This means that the rate of reduction of air dose rate due to natural processes will slow considerably in future years and year to year reductions will be much more difficult to quantify.

Table 2.1. Forest monitoring sites established by Fukushima Prefecture

Fiscal Year	Number of Monitoring Sites Added	Total Number of Monitoring Sites
2011		362
2012	563	925
2013	81	1006
2014	187	1193
2015	37	1230
2016	20	1250
2017	50	1300
2018	–	1300
2019	–	1300
2020	–	1300
2021	–	1300

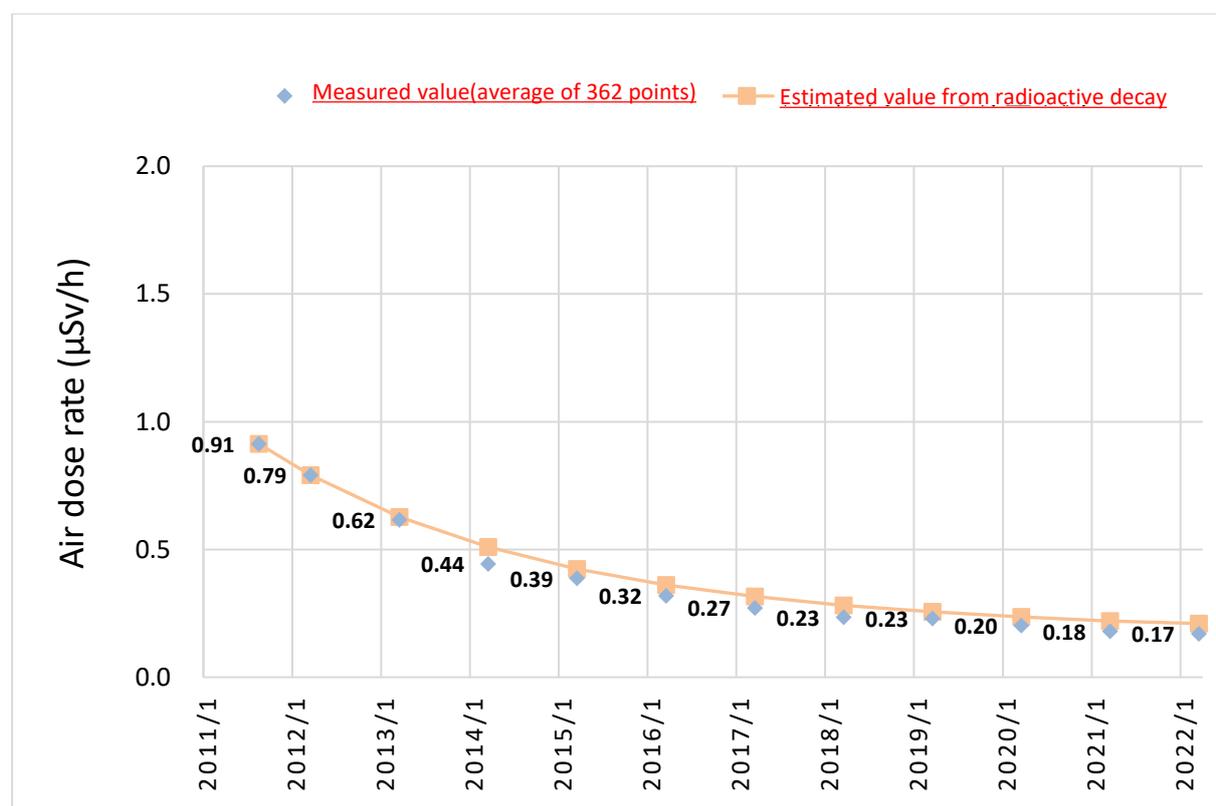


FIG. 2.2: Measured air dose rates at 362 monitoring points in forests within the Prefecture and estimated air dose rates based on radioactive decay of radiocaesium, (Image: based on data from Fukushima Prefecture).

The combination of mountain terrain and rainfall tends to increase the mobility of radionuclides and these will quickly move downhill (both physico-chemically and mechanically) and future radiation monitoring efforts may need to be adjusted for such processes.

Dynamic processes affecting the movement of radionuclides in the environment were relatively rapid in the initial years following the Fukushima Daiichi accident, but they have slowed down with time. Monitoring programmes should be continued at least until a stable situation is reached, but it is difficult to predict when that might be; some fixed sites established after the Chernobyl accident are still being monitored and continue to provide new and important information.

The IAEA team advised that, due to expected lower rate of decrease in air dose rate, a reduction in the frequency of monitoring to once every two, three or even five years, in particular at those sites furthest inland from the coast, would be justified from a technical viewpoint. The monitoring programme could be designed to ensure that measurements are carried out in each municipality, but not at every monitoring location, every year.

2.2.2. Distribution of radiocaesium in forests

Radiocaesium that is present in coniferous and deciduous forests is distributed mainly between among soil and the litter layer and trees. Through ecological cycling of materials within forests, radiocaesium has been redistributed such that by 2016, approximately 97% of the radiocaesium in the forests of the Prefecture was located in the soil and litter (fallen needles or leaves) layers, (see Figure 2.3). This observation still applies at the end of 2021. The results of the study have shown the positive effect of the removal of fallen leaves in 2012 on the radiocaesium concentration in young trees, as well as confirming that the litter and 0–5 cm of topsoil are the main sources of ^{137}Cs in trees. By 2021, the data collected suggest that the activity concentration of ^{137}Cs in the forest environment is approaching a quasi-equilibrium between the source (litter and soil) and trees. The percentage of the total inventory of radiocaesium present in understory vegetation, mushrooms and wild animals is less than 1% of the total. Therefore, any measures to reduce the air dose rate is best focused on managing the soil component. Another conclusion that can be drawn is that the harvesting of trees is unlikely to significantly reduce the ambient air dose rate. Large scale removal of soil would be expected to reduce the overall productivity of the forest and could have an overall negative impact; it would also create additional waste that would need to be managed.

A soil survey undertaken in forests in the Prefecture has identified the presence of illite and vermiculite in all samples collected. Both are clay minerals that are known to strongly bind radiocaesium in a non-reversible form. This observation probably explains the relatively low transfer of radiocaesium from soil to forest plants and animals. However, if there are any parts of the Prefecture where these clay minerals are absent, much higher transfer factors, and consequently higher concentrations in trees, understory vegetation and animals, would be expected.

Experiments undertaken by the Prefecture have shown that radiocaesium is recycled within the forest ecosystem and losses of radiocaesium are a fraction of a percent per year. Measurements have shown that the quantity of radiocaesium in water flowing into reservoirs with urban catchment areas is four times higher than water from forested catchment areas.

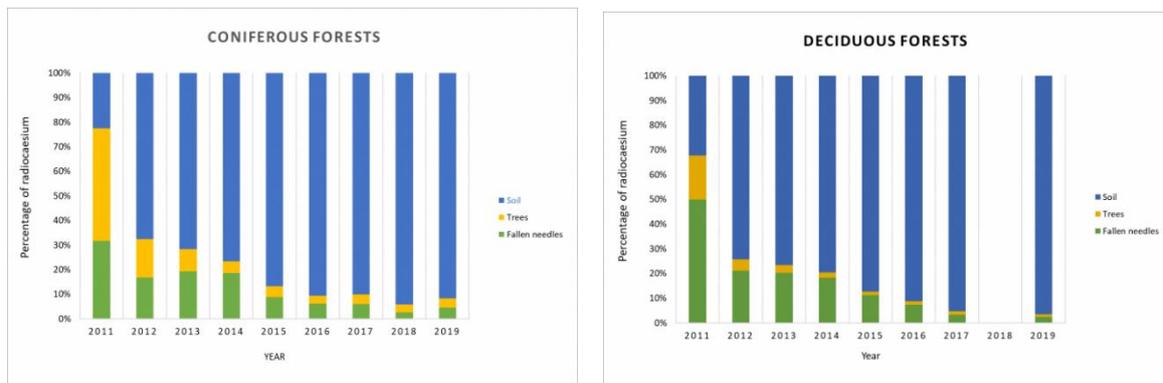


FIG. 2.3: Change in distribution of radiocaesium in the Prefecture's coniferous forests and deciduous forests from 2011 to 2019 (Adapted from cooperation with the Ministry of Agriculture, Forestry and Fisheries, and the Fukushima Prefectural Forestry Research Centre).

Some outflows do occur through sediment transport, with the radiocaesium being attached to the clay minerals in these sediments. (Additional information about the behaviour of radiocaesium in the environment including the importance of sediment transport is provided in Sections 3.2 and 3.3). Research has also shown that the greater the vegetation cover, the lower the outflow of sediment. This underlines the importance of forest management, whereby regular thinning encourages the growth of understory vegetation, which in turn reduces the likelihood of sediment outflow and landslides.

2.2.3. Radiocaesium in forest trees

The sampling programme for radiocaesium in timber includes separate measurements of bark, sapwood, heartwood, old leaves and new leaves. At a number of sites, soil is also collected and measured for radiocaesium. An example of collecting samples of wood for analysis is shown in Figure 2.4.

For the various species of trees in both coniferous and deciduous forests, the highest radiocaesium concentrations are found in bark, followed by wood and branches/leaves. In some species the activity concentration is higher in sapwood than in heartwood, and the reverse in others, for example Japanese cedar. This difference is believed to be linked with the processes of potassium uptake and its (re)distribution within the trees.

Over time, radiocaesium attached to old leaves is gradually shifting to the forest floor due to leaves falling from trees. The air dose rate that would result from trees having radiocaesium concentrations exceeding 8000 Bq/kg was estimated¹. The value that resulted from this process, measured at a height of 1 m, was 1.57 μ Sv/h. It should be noted that these estimated values have significant uncertainties associated with them. This is discussed further in Section 2.3.5 'Managing the timber industry'.

¹ Japanese National legislation requires any material that exceeds an activity concentration of 8000 Bq/kg of radiocaesium to be managed as radioactive waste, and such waste is considered 'designated waste'.

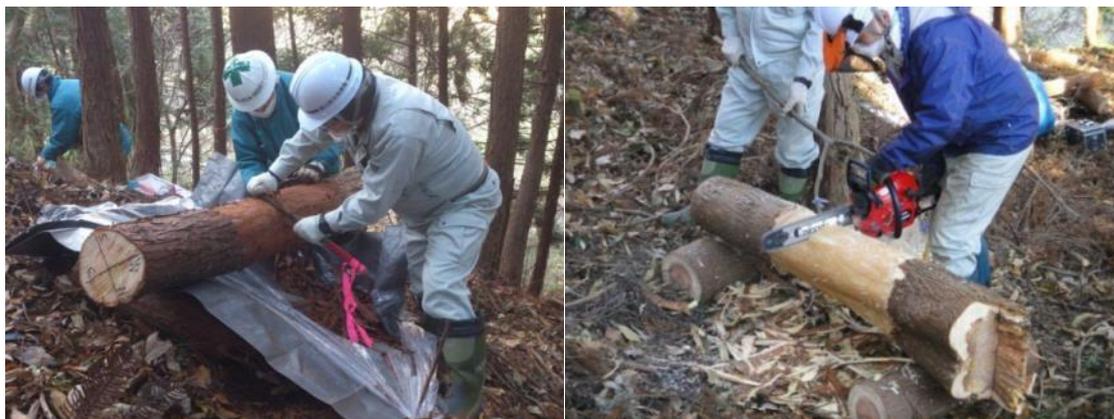


FIG. 2.4: Collecting samples of wood for analysis (Image: Fukushima Prefecture).

The radiocaesium content of saplings planted in 2013 has been evaluated. The saplings were planted at a depth of about 10 cm. Until 2015, no correlation was observed between the radiocaesium content of the wood and the air dose rate in the planting area. As the root system develops, the transfer of radiocaesium to the wood may increase in future years, so these experiments should be continued. While it is believed that much of the radiocaesium may be attached to clay minerals in the soil, some percentage of the radiocaesium is always likely to be available for uptake. (See Section 3.2 of this report for further information about the behaviour of radiocaesium in the environment.)

At the request of the Prefecture, IAEA experts gave an overview of different models available for predicting future activity concentrations of ^{137}Cs in forest trees and wild mushrooms. Six models were presented that can be applied for different situations and ranging in different levels of complexity and parameterization. The presented models and the data requirements for their application indicated that long term monitoring data will still be needed to compliment and validate the model predictions but the frequency and extent of monitoring could be reduced (see Section 2.2.4).

2.2.4. Future monitoring of forests

There are uncertainties (estimated at several orders of magnitude) on measurements of radiocaesium concentrations in trees and important forest products, including Shitake logs and edible mushrooms, which add the uncertainty on the requirements and decisions on future monitoring of forests. The Prefecture's experts have identified that future monitoring needs to be able to evaluate the activity. The Prefecture scientists discussed with the IAEA experts ways in which further analysis and evaluation of existing data could be used to establish relationships between forest compartments and trends that can then be used to inform future monitoring. The topics of how best to monitor standing trees to provide representative concentrations, the spatial and temporal scales of monitoring and the focus of monitoring in areas where evacuation is to be lifted in the near future, as well as collecting data for research, were discussed. The advice of the experts was that a good first step would be to specify well formulated and traceable new questions that need to be answered by the forest monitoring programme before defining a future monitoring programme, especially if the initial objectives have already been met. The support of statisticians in this task would be beneficial.

2.3. SPECIFIC STUDIES

2.3.1. Radiocaesium transfer to wild mushrooms

The Prefecture is the principal producer of Shiitake and Nameko mushrooms in Japan. These mushrooms are saprophytes and artificial cultivation is carried out using rotting wood, enabling radiocaesium concentrations to be controlled.

Shiitake mushrooms

There are presently restrictions in place in the Prefecture on the distribution of open-field *Shiitake* mushrooms from 17 municipalities, bamboo shoots from 27 municipalities and wild mushrooms from 55 municipalities.

Prior to 2011, the Prefecture was the main producer of oak logs for growing shitake and other types of mushrooms. Many of the main production areas were close to the reactor site and high concentrations of radiocaesium were present in the logs, making it impossible to grow mushrooms that complied with the 100 Bq/kg distribution limit for radiocaesium in food to be sold commercially.

In an effort to regain market share, research has been undertaken to predict the activity concentration in the tree trunk by either measuring the exchangeable potassium in the soil or the radiocaesium concentration in fresh growth (leaves and twigs). Both approaches have shown some promise. However, most of the scientific knowledge on the relationship between potassium and caesium comes from plants and agricultural crops, with considerably less data from forests. The IAEA experts recommended that further research be undertaken to better quantify the relationship under different circumstances.

The IAEA experts also proposed to investigate if aggregated transfer factors would be a useful predictive tool. The experts suggested that large areas of Aizu province might be suitable for log production. It was noted that the scientific literature suggests a 1:1 ratio between the activity in the wood and that in the mushrooms grown on it. The index value of 50 Bq/kg for radiocaesium in oak logs destined for mushroom production therefore appears to be conservative.

Wild mushrooms

Prior to the Fukushima Daiichi NPP accident, forest mushrooms were collected and sold in local markets and roadside stalls to the local population and to visitors, some of whom travelled to the Prefecture specifically to purchase this local produce. At the end of 2019, there is still a full restriction on 'distribution' (i.e. sale) of forest mushrooms in place in 55 of the 59 municipalities. In three municipalities there is a ban on the collection of wild mushrooms while in some of the other municipalities, people are asked to refrain from collection.

The restrictions in place apply to all species of mushrooms. To lift a restriction on one species in any given municipality, 60 samples (700g or more for each sample) must be collected within the municipality for at least 3 years and all of the activity concentrations need to be below 50 Bq/kg. Once a species is de-restricted, samples must be collected at the beginning of each season, and all activity concentrations must be below the 100 Bq/kg limit. If one of the samples exceeds 100 Bq/kg, the restriction is again imposed for all mushroom species in that municipality.

Currently the range of radiocaesium activity concentrations in forest mushrooms is 10 to 82 000 Bq/kg fresh weight — the highest levels are observed in mycorrhizal species and the activity concentrations reduce with distance as you move inland from the coast. Large variability is also observed within the same species. The samples analyzed so far have been provided by the local population and therefore represent the most popular edible species. The IAEA team noted that higher concentrations are often found in poisonous (to man) species which may be a food source for wild animals, and that some saprobic species also have very high concentrations.

Between 2017 and 2019, no reductions have been observed in the concentrations of ^{137}Cs in wild mushrooms. The IAEA team commented that in the first eight years after the Chernobyl accident, concentrations in wild mushrooms in some European countries were reasonably constant, but subsequently fell with an effective half-life of six to eight years. For this reason, it is important that monitoring programmes should be maintained. As the forest soils and mushroom species are different between Europe and Japan, it cannot be assumed that the observations in Europe will apply in Japan and some comparative studies on the same species of mushroom were recommended by the IAEA team. By the end of 2021, the frequency of monitoring for fungus bed growing mushrooms is being reduced through the time, due to stable results of the monitoring being demonstrated. However, there has been no change for log-grown mushrooms or wild mushrooms.

The current policy of the Prefecture is to de-restrict ‘distribution’ (i.e. sale) on a species/municipality basis. It was agreed that a restriction for some species in some municipalities is likely to be in place for many years. The IAEA team underlined the importance of providing advice and information to the general public on the likely concentrations of radiocaesium in different mushroom species across the Prefecture.

Following on from the conclusion presented by the Prefecture that radiocaesium concentrations of ^{137}Cs in wild mushrooms will remain above 100 Bq/kg for many years, an overview of several studies conducted in Russian Federation on mushrooms after the Chernobyl accident were presented by an IAEA expert. Based on the study in 2020 in several different regions of the country, even 35 years after the accident, there were several types of mushrooms measuring over 600 Bq/kg (wet weight) of ^{137}Cs . It was discussed that consumption of privately collected mushrooms is not forbidden in Russia; instead, the population is advised to measure the sampled products in the local sanitary hygiene laboratories, apply different cooking methods to reduce ^{137}Cs concentration in products and decide on consumption themselves (self-support actions). This is further discussed in Section 2.5.

2.3.2. Radiocaesium in bamboo shoots

A year on year reduction in the radiocaesium concentration in bamboo shoots has been observed but this reduction does not appear to be related to the activity concentration of the soil.

The IAEA team commented that older bamboo plants may have deep roots that are therefore located in soil with low radiocaesium content. The radionuclide content in bamboo might be expected to increase with time as radiocaesium diffuses into the rooting zone, although chemical fixation by clay minerals will also need to be considered. Some surveys and verification experiments might be helpful in identifying long term issues of concern.

2.3.3. Radiocaesium in freshwater fish

For the vast majority of river systems, radiocaesium concentrations in fish are below 100 Bq/kg. However, there are still some restrictions on some fish species in some areas and distribution of fish and recreational fishing are not allowed. As of the end of 2022 some restrictions were still in place in four rivers for five species.

In selected river systems in the Hamadori region (along the east coast of the Prefecture where the Fukushima Daiichi Nuclear Power Plant is located) some species continue to show exceptionally high concentrations. For example, activity concentrations of ^{137}Cs up to 16 000 Bq/kg were measured in Masu salmon in the Ukedo river system north west of the Fukushima Daiichi NPP. A relationship of increasing activity concentration with fish size was established.

Laboratory experiments with dace carried out by the Fukushima University have established a concentration ratio (CR) for ^{137}Cs transfer from water to fish of ~10. By contrast, the CR values observed in the field are 1240 to 12 900, clearly demonstrating that the ^{137}Cs in the water is not the source of the ^{137}Cs in the flesh. Analysis of the gut content of fish caught in the wild showed that the diet includes both terrestrial insects and aquatic insects. Further work showed much higher concentrations of ^{137}Cs in the forest insects, correlated with the much higher concentrations of ^{137}Cs in the flesh of fish inhabiting forest streams. These insects are known to feed on forest litter and on mushrooms.

Some fish have a diet of algae rather than insects. The algae have ^{137}Cs concentrations similar to those observed in forest insects, but much lower concentrations are present in the flesh of those fish that consume large amounts of algae. This has been shown to be because the ^{137}Cs in algae and attached silts is much less bioavailable than that from digested insects and hence there is a lower transfer from the gut to the flesh. The Prefecture has indicated that it wishes to lift the remaining restrictions as quickly as possible but the currently available information suggests that some restrictions may need to be retained for a long time in some areas. The IAEA team provided information on the situation regarding freshwater fish in the Ukraine where, as a result of the Chernobyl accident, the concentrations of both ^{137}Cs and strontium-90 (^{90}Sr) remain very high in some water bodies and in many species of fish.

Information has also been provided by the IAEA team on restrictions on fishing in parts of the United States because of concerns about mercury contamination. Fishing is still allowed, but consumption is forbidden. The experience is that, once the fishermen understand the basis for the decision, it is accepted. However, where such fishing is for commercial purposes, there is a continuing economic impact of the restrictions. The Prefecture has a large aquaculture (fish farming) industry for freshwater fish. In order to ensure compliance with the distribution limit for radiocaesium of 100 Bq/kg, a limit of 40 Bq/kg has been established for the concentration of radiocaesium in fish feed. This value, relating the activity concentration in the feed with that in the edible portion of the fish, were developed through research at Japanese government research institutions. The IAEA team noted the conservative nature of the value used.

2.3.4. Radiocaesium in wild vegetables

Fukushima Prefecture scientists have carried out studies to measure the radiocaesium concentrations in wild vegetables. Samples of different wild growing vegetables and plants in several different municipalities of the Prefecture have been analyzed. Most of the plants demonstrate a decreasing trend in radiocaesium concentrations. In a study to investigate ways to reduce ^{137}Cs concentrations in cultivated bracken, the use of reversed tillage combined with fertilization with potassium has proven most effective. Further discussions on ways to manage wild vegetables and mushrooms exceeding the standard value of 100 Bq/kg were requested by the Prefecture and are summarized in Section 2.5.

2.3.5. Effectiveness of forest countermeasures

Various countermeasures to reduce the exposure due to radiocaesium in forests have been evaluated to determine their effectiveness and potential applicability, with the following results:

- (1) The thinning of coniferous trees in 2011 resulted in a reduction of air dose rates of 9–12%.
- (2) The removal of deciduous trees to aid in the regeneration of understorey vegetation in 2012 resulted in a reduction of air dose rates of 11–21%.
- (3) The addition of 3 cm of uncontaminated soil (in ‘liquid’ form) or wood chips resulted in a reduction of air dose rates of approximately 20% that was observed at 24 months after application. However, the introduction of an additional 3 cm of wood chips had very limited additional impact.
- (4) The removal of fallen leaves resulted in a reduction of air dose rates on the order of 10%, but there was a negative impact of increased erosion.

Countermeasures (1) and (2) are normal forest management practices; the thinning of trees increases the amount of sunlight reaching the forest floor, thereby encouraging the growth of understory vegetation. This in turn helps to bind the soil and prevents erosion. In 2011 and 2012, both of these countermeasures were shown to be highly effective in reducing air dose rates when a significant percentage of the deposited radiocaesium was still located in the trees. In the ensuing years, when most of the radiocaesium content of forests had migrated to the soil and litter layers, this practice was less effective in reducing air dose rates.

The experiment involving the addition of uncontaminated wood chips (countermeasure (3) above), and illustrated in Figure 2.5, was continued after the initial two year period and annual measurements of dose rate were made. At the end of 2019, the Prefecture reported that the initial reduction in air dose rate had been maintained for a fifth consecutive year. The IAEA team noted that the uncertainty estimates for each of the measurement points overlapped with the technical calculation of dose rate due to radioactive decay and therefore it was not possible to say with certainty that there is any effect. They also questioned why the addition of fallen leaves on top of the wood chips in each of the five years had apparently made no contribution to increasing the dose rate. Finally, it was commented that, over a period of five years, one might reasonably expect some form of disturbance by animals or decomposition of the wood chips, but that seems not to be the case.

The Prefecture concluded that the implementation of countermeasures involving the addition of liquid soil or wood chips is expensive and unlikely to be justified for widespread application. However, it is realistic to apply them over smaller areas with high air dose rates, especially if such areas are close to inhabited areas. Presently, these countermeasures are not in routine use.

The Prefecture is investigating the movement of radiocaesium from the forest ecosystem before, during and after the thinning of trees. While the overall losses are believed to be low, local farmers are still concerned about radiocaesium being transferred to agricultural land and rice paddies. The Prefecture is also investigating the effectiveness of log fencing and sandbags in reducing sedimentation rates and losses of radiocaesium from the ecosystem. Preliminary results indicate that such measures are effective in preventing soil erosion and runoff, particularly when the slope of the terrain is 30 degrees or greater. Any radiocaesium lost through sedimentation is likely to be bound with clay minerals and, as such, may not be available for transfer to agricultural soils. At the same time, air dose rates may increase in areas where sediment accumulates.



FIG. 2.5: Application of wood chips as a countermeasure to reduce the air dose rate in a forest (Image: Fukushima Prefecture).

Air dose rates near inhabited areas may be reduced through a combination of litter removal, branch removal and topsoil removal. A priority is to install log fencing on higher ground to prevent soil erosion and subsequent recontamination of decontaminated areas.

2.3.6. Managing the timber industry

National legislation requires any material that exceeds an activity concentration of 8000 Bq/kg of radiocaesium to be managed as ‘designated waste’. This is a concern in relation to forest management. An initial step in the processing of felled trees is the removal of bark, which is commonly used as a fertilizer and as a fuel for biomass plants. It is important to ensure that the timber industry is effectively managed as the wood is an important economic resource used for the construction of new housing, as well as window frames, household furniture, etc.

Measurements have been made in an attempt to correlate air dose rates with the radioactivity concentration in bark. As would be expected, wide variability in such measurements was observed. An air dose rate of 1.69 $\mu\text{Sv/h}$ roughly corresponds to a radiocaesium concentration of 8000 Bq/kg in bark. The Prefecture has adopted a rule whereby, in areas where the air dose rate is below 0.5 $\mu\text{Sv/h}$, the measurement of activity concentrations in bark is not required and logging and transportation of trees can be performed without restriction. If the air dose rate exceeds this value, a sample of the bark must be analyzed to determine the actual activity concentration of radiocaesium. This is a conservative approach, but it seems to work well.

An index value has been set of 40 Bq/kg for the activity concentration of radiocaesium in firewood to ensure that the radionuclide concentration of the ash does not exceed 8000 Bq/kg. The concentration factor between wood and ash is normally 100 Bq/kg or less so this is again a relatively conservative approach.

For newly planted trees, the uptake of radiocaesium would be expected to be greater than for existing trees; however, experts from the Prefecture presented the results of experiments indicating that the radiocaesium content of newly planted saplings was only a few hundred Bq/kg. As the time for trees to reach maturity is around 50 years, any possible increased uptake

will be more than compensated for by reductions due to the radioactive decay of radiocaesium over that time period.

As the radiocaesium in forests in the soil and litter layers migrates deeper into the soil, it will come within the rooting zone of trees, but one would expect that it will be effectively bound to the clay minerals present. This downward movement will result in changes in the uptake/transfer factor, but it is difficult to be specific at this stage about the onset and duration of these changes.

The highest concentration of radiocaesium measured to date in wood is 5500 Bq/kg. Using the methodology outlined in IAEA-TECDOC-1376 [1], if such wood were used for house construction, the annual dose to occupants is estimated to be 0.132 mSv. Scaling up, at 8000 Bq/kg, the annual dose would be about 0.2 mSv. Due to the conservative nature of the models used, any differences in Japanese house design would not be expected to significantly increase these estimated doses. Therefore, no additional restrictive measures are deemed necessary at this time to allow timber from the forests of the Prefecture to be used for house construction.

While radiocaesium concentrations in timber are currently low and well within international standards, it is important that the research studies which have commenced on the translocation of radiocaesium within trees and the transfer to newly planted saplings are continued.

2.3.7. Protection of forest workers against radiation

Forest workers are potentially at risk of exposure to radiation doses. Currently these workers are provided with gloves and face masks to help minimize their exposure. They are not classified as occupationally exposed workers and their work is restricted to those areas in which the air dose rate does not exceed 2.5 μ Sv/h. This corresponds to an annual dose on the order of 5 mSv, which is the value adopted by the Prefecture for protection of forest workers. The annual dose limit for workers that are occupationally exposed to radiation is 20 mSv.

In order to reduce doses to workers, tree harvesting machines are being introduced to replace manual cutting; the operator is higher above the ground and the machine further shields the operator from radiation. Also, cabins on certain forest machinery that enclose the operator provide shielding that reduces worker doses by about 35–40%.

2.3.8. Forest fires

According to IAEA-TECDOC-1240 [2] “There is thought to be some risk of radionuclide dispersion onto the adjacent territories as a result of forest fires. However, the available data on radionuclide transfer during forest fires are contradictory.” The TECDOC also states “The main problem produced by forest fires is the resuspension of contaminated ash in the atmosphere.”

While elevated radiation levels do not increase the likelihood of forest fires, they often contribute to reduced forest management activities so that the regular thinning of trees is not performed, which leads to an increase in the amount of material available for combustion. Following a fire, radionuclides can be transported over several hundred kilometres through the dispersion in the atmosphere of ash to which radioactive material is attached. The radiation exposure pathways are external radiation and plume inhalation (firefighters and the public); external radiation from deposited radionuclides (public); ingestion of contaminated food products (public); and inhalation of radionuclides in resuspended ash at the site of the wildfire (forest workers and the public).

The amount of radionuclides available for transportation as a result of a forest fire is relatively low. Experimental studies have shown that only a few percent of the radiocaesium in the litter layer is mobilized during a forest fire. Considering that as of 2016, only about 7% of the radiocaesium present in the Prefecture's forests was located in the litter, it would be expected that only a very small percentage of the total radiocaesium inventory would be mobilized in the event of a forest fire. For example, following a fire involving vegetation and litter only, about 0.1 to 0.5% of the radionuclides that are present could be mobilized; however, in the case of a crown fire, this amount could increase to 10%. Most of the radiocaesium that would be mobilized would be expected to be deposited within a few hundred metres of the location of the fire, so increases in air dose rates at large distances from the fire would not be expected. While forest fires may not disperse large amounts of radionuclides, fires may damage the capability of the forest to retain soil that may be lost through erosion and fallen leaves and needles that may be more readily washed away in the absence of understorey vegetation.

High temperatures resulting from forest fires may vaporize some of the radiocaesium that is present, which could be transported in the atmosphere. The remainder of the radiocaesium will be found in the ash. Even if deposited in rivers and streams, the radiocaesium will be quickly fixed to solid matter and the impact on biota is likely to be minimal. The impact of forest fires is usually evaluated through modelling, in part because the collection of real time data is problematic due to the hazards associated with, and the unpredictable nature of, forest fires. A number of different models for this purpose already exist. It was noted by the IAEA team that most models overestimate the actual impact of forest fires and therefore it is important to perform sensitivity analyses by varying parameters and associated assumptions. It was noted that differences in soil type and topography may lead to a forest fire in the Prefecture having a lower radiological impact than in the areas affected by the Chernobyl accident.

A number of forest fires have occurred in the Prefecture since 2011, which resulted in public anxiety. Prefecture experts presented information about three forest fires that took place in 2016 and 2017: (1) a fire near Date City that affected about 38 ha that burned during 30 March–1 April 2016; (2) a fire near Minami-soma City that affected about 32 ha and burned during 3–4 April 2016; and (3) a fire that occurred inside the Evacuation Designated Zone near Namie Town that affected about 75 ha and burned during 29 April–10 May 2017.

To examine the radiological impact of the 2016 fires, the Prefecture established a monitoring programme that measured air dose rates and the radiocaesium content of surface stream water and mountain stream water. An increase in air dose rates was not observed. A minor amount of radiocaesium was detected in surface stream water in the Minami-soma District. Radiocaesium was not detected in mountain stream water downstream of the areas affected by the fires. The amount of sediment outflow from the area affected by fire was three to five times greater than that in unaffected areas.

As of July 2017, the preliminary assessment of radiation survey results from the Namie Town fire indicated that the fire did not have a significant radiological impact in that only slight increases were observed in air dose rates at nearby measuring points. Further work was planned to assess the extent to which ash may have been deposited in the river passing close to the burnt area and the transportation of radiocaesium downstream.

The IAEA team noted that had the fires in 2016 and 2017 taken place soon after the Fukushima Daiichi accident when a larger percentage of the radiocaesium was in the litter layer, a greater amount of radiocaesium could have been redistributed.

2.4. SATOYAMA REHABILITATION MODEL PROJECT

Satoyama is the border zone or area between mountain foothills and arable land and usually consists of forests, grasslands, rice paddies, etc. The people who live in or close to these areas are often self-sufficient and may cultivate mushrooms in the forest. The aim of the Satoyama Rehabilitation Model Project, which was initiated in 2016, is to allow people to return to live in these areas as they did before the Fukushima Daiichi accident. Communities within the evacuation zones and neighbouring municipalities were selected for participation in the project between September and December 2016. At this time, people were starting to return or were considering returning to the identified municipalities. This is a joint project between a number of local and relevant Government of Japan Ministries and 14 of the 17 municipalities in the Hamadori and Nakadori Regions are participating.

The project has three main components: forest maintenance; decontamination; production of radiation dose maps; and performance of personal dosimetry surveys.

The project is driven primarily by the need for public reassurance and once completed, the Prefecture intends to share results from all 14 sites with local communities.

In 2017, the IAEA assistance in the following activities became the part of the modified Practical Arrangements:

- Creation of radiation dose maps;
- Decontamination of forests and surrounding areas used on a daily basis;
- Forest maintenance.

After the formal agreement was in place, the implementing staff of the Prefecture described the project to the IAEA team, who were impressed with the attention to detail of the work and noted that all necessary information to undertake a cost effectiveness study are available. For example, the radiation doses received by workers have been recorded and the dose reduction achieved takes account of what would be expected in any case due to radioactive decay alone. The IAEA team also noted that the effectiveness of countermeasures in the selected areas may be limited and that consideration should be given to defining how the success of the project would be evaluated.

In order to familiarize the IAEA team with the local environment and the nature of the remediation work, in July 2019 a site visit was organized to Iitate Village. In February 2020, another site visit was organized to Okuma Town and Kawauchi Village.

At both Okuma Town and Kawauchi Village, tree thinning and selective cutting of trees has been undertaken. In Okuma, which is a relatively high dose rate area (up to 2 $\mu\text{Sv/h}$), the observed reduction in dose rate was an average of 8% above that due to radioactive decay. In Kawauchi, where the annual dose rate is only marginally above background levels, no reduction above that due to radioactive decay was observed. Figure 2.6 shows the results of maintenance work on trails in Kawauchi Village and Okuma Town.



FIG. 2.6: Examples of remediation work in the Satoyama Rehabilitation Model Project at Kawauchi Village (top) and Okuma Town (bottom) (Image: Fukushima Prefecture).

In Kawauchi Village, an area where the dose rate was $0.26 \mu\text{Sv/h}$ (just above the ‘target’ value of $0.23 \mu\text{Sv/h}$), 9 cm of litter and topsoil was removed, resulting in a reduction in the dose rate to $0.19 \mu\text{Sv/h}$. The experts commented that in a few months the dose rate would have reduced in any case to $0.23 \mu\text{Sv/h}$ and questioned whether or not this work was justified in terms of radiation protection.

The IAEA team underlined the importance of providing information on the results of the project to former evacuees to help inform their decision on whether or not to return.

At Ainosawa, Itate Village, it was reported in 2022 that, after the remediation work, a small number of the general public have visited Satoyama for recreational purposes. Combinations of remedial actions have been used: decontamination by litter removal; forest maintenance; and dose measurements/assessment. A major reason for the success of these projects has been the reassurance that they provide to the public through the establishment of a safer environment for local residents and visitors.

2.5. MANAGEMENT OF WILD FOODS

The IAEA team has provided information on the approach and philosophy in setting limits for radiocaesium in agricultural and wild foods in Belarus, Czech Republic, Norway and Sweden following the Chernobyl accident. In all cases, a considerably higher limit was applied to wild foods compared to agricultural foods. This is because wild foods are normally consumed in relatively small amounts and the associated radiation doses to consumers are not high, even though the activity concentrations may be much higher than is observed in agriculturally produced foods. National authorities also considered the societal implications, including

disruption of lifestyle, that would result if the consumption of wild foods was severely restricted and concluded that the associated radiation doses did not warrant such action.

A representative of the Prefecture has explained that the current limit of 100 Bq/kg for radiocaesium in wild foods that are sold into the marketplace is unlikely to be revised for two main reasons: firstly, it is a national limit and not within the control of the Prefecture to change and, secondly, an increase in the limit so many years after the accident would probably not be accepted by the public. Another important consideration is that the restrictions currently in place apply only to foods that are sold: those who wish to harvest wild foods for their own personal consumption are free to do so.

Given that the 100 Bq/kg distribution limit is likely to continue to apply to wild foods for at least the foreseeable future, in spring 2020, the IAEA team advised that greater focus needs to be given to reducing the doses to those who source wild foods — wild boar, mushrooms, sansei and freshwater fish — in the forest for their own consumption and to whom the distribution restriction does not apply. While there is a measurement service in place whereby people can have their foods measured for radiocaesium, it is mainly used more for checking locally produced agricultural foods such as cereals and vegetables but not game meat; people need to be encouraged to use this service also for wild foods. A list of plants and mushrooms is provided for the Fukushima Prefecture inhabitants, explaining which species are restricted in different municipalities (see also Section 6).

In the case of forest products such as wild boar, the IAEA team suggested to develop the ‘in vivo’ technology used widely after the Chornobyl accident. Such a measurement would provide a quick estimate of the radiocaesium content of the meat and allow the hunter to make an informed decision on whether or not to consume it or have it destroyed. The IAEA team gave two presentations as input to the discussions on this topic. The first was on ‘Monitoring programme of wild species in Fukushima Prefecture’, and the second was on ‘In vivo measurement of Cs in animals in Norway’. A description was given, based on the experience in Sweden, on how the Prefecture could build up a monitoring programme of the wild animals, including a representative sampling strategy, to ensure that measurement data sufficient for lifting the restrictions for hunters are available. It was also advised that, having undertaken a preliminary statistical evaluation of the measurement data in the Prefecture for wild boar, there will never be 100% certainty that concentrations of Cs will be <100Bq/kg in the near future and so dialogue with municipalities and hunters will be needed in order to lift restrictions and allow for taking personal decisions. The second presentation described how to perform monitoring of radionuclides in animals in vivo and the methods developed in Norway in the first few years after the Chornobyl accident in order to determine the Cs concentrations in sheep/cattle and reindeer and the experience of communication of the measurement results to interested groups based on the experience in Norway. Following the discussions on the two presentations, it was noted that the high concentrations of radiocaesium in the flesh of wild boar mean that restrictions are unlikely to be lifted in many of the Prefecture municipalities in the near future. However, relatively low concentrations are being observed in a small number of municipalities in Aizu district.

The experiences of monitoring game and wild mushrooms in Sweden were presented by an IAEA expert in the February 2022 meeting. The Swedish programme was designed in the late 1980s to provide the general public on the information about ¹³⁷Cs contamination of food. There have never been any restrictions on the consumption of game meat and mushrooms in Sweden based on the Cs concentrations; the measurement service available for the hunters allows them to make a decision on their personal consumption of hunted game meat and wild mushrooms.

To provide the population with the measurement results, a network of measurement laboratories was established in the countries and the measurements are subsidised by the government.

The Swedish Food Safety Authority provides a recommendation on the consumption of food containing ^{137}Cs [3]. The approach used is based on the combination of concentration of the ^{137}Cs in an individual product and the volume of the product that can result in doses above 1 mSv/a. The recommendations are:

- 300–1 500 Bq/kg: not more than a few times per week;
- 1 500–3 000 Bq/kg: not more than a few times per month;
- >10 000 Bq/kg: not recommended for consumption.

The limit for selling the meat and wild mushrooms is set at 1500 Bq/kg.

A new method that can be used for the non-destructive analysis (NDA) of the matsutake mushroom was presented by the Prefecture during the February 2022 meeting. The objective is to not destroy this valuable forest product after measurement so that it can be distributed and consumed, if the result of NDA allows it. The Prefecture plans to continue discussion with central governmental bodies regarding the extension of the NDA for matsutake mushroom and other species. If NDA can be applied to other wild mushroom species, this would allow the consumption and distribution of wild mushrooms collected in Prefecture municipalities and also, importantly, allow the population to return to traditional collecting and consumption of the wild plants and mushrooms.

The IAEA team noted that restrictions are likely to be necessary for certain wild foods in some parts of the Prefecture for many years or even decades. The IAEA team also noted that monitoring programmes will need to be maintained and it is essential to keep providing information on the trends of radicaesium concentrations in wild foods to the population, including hunters.

2.6. SECTION SUMMARY

The Prefecture has implemented an extensive monitoring and research programme to better understand and follow the behaviour of radiocaesium in forests. When comparing the situation with that which occurred following the Chernobyl accident, the more general mechanisms of recycling of both nutrients and radionuclides are expected to be similar. However, differences between the forests in the Prefecture and European forests in terms of annual rainfall, temperature, topography and soil characteristics have been shown to be important in influencing the movement and cycling of radiocaesium.

Some of the key conclusions from the work undertaken by the Prefecture are as follows:

Radiocaesium movement and cycling

- (1) Radionuclides deposited in the forests of the Prefecture are effectively retained within the ecosystem and the likelihood of transfers of radiocaesium to agricultural land appears to be low.
- (2) Forest maintenance procedures have helped to prevent erosion and soil loss and are also very effective at retaining radiocaesium within forests.
- (3) The presence of clay minerals in the underlying forest soils will chemically bind the radiocaesium and limit its transfer to vegetation. The result is that, for the same

deposition, the activity concentrations of radiocaesium in plants and animals in the forests in the Prefecture are considerably lower than those observed in European forests after the Chernobyl accident.

- (4) Based on experience with radiation monitoring in areas affected by the Chernobyl accident, radiation monitoring in forests may be necessary for many more years. Monitoring procedures for measuring air dose rates and the radiocaesium content of trees may need to be adjusted to account for changing conditions such as the movement of radiocaesium in the environment and the deposition of radiocaesium in waterlogged areas, where the uptake by vegetation would be expected to be higher. Based on the monitoring survey in forests up to 2022, the results indicate that 'background' dose rates have now been observed over several monitoring campaigns at a number of sites. The Prefecture is now considering the decrease in frequency and density of monitoring to reduce the number of measurements made based on clear objectives. However, it is recognised that some continued monitoring into the future will continue to be requested for public reassurance, even at sites where doses are very low.
- (5) All components of the forest ecosystem are interdependent: the forest insects eat mushrooms, which are in turn eaten by both wild boar and some freshwater fish. While not a part of this report, wild boar are believed to eat mushrooms directly. There do not appear to be any realistic remediation options that are cost effective and can be applied without causing damage to the environment. The available data suggests that restrictions will be in place in parts of the Prefecture for certain foods for many years, probably decades. In the meantime, monitoring programmes with high associated costs will be required.
- (6) Because future reductions in dose rates will be dominated by the radioactive decay of ^{137}Cs , the annual reductions will be low and, as such, the situation can be regarded as being more stable. In such circumstances, it may be justified, from a technical viewpoint, to reduce the frequency of monitoring without the loss of valuable information.

Possible countermeasures

- (7) Since 2012, most of the radiocaesium initially deposited in forests has been transferred from the trees to the soil and litter layers. The feasibility of removing large amounts of soil in order to reduce the air dose rate is not practical; it is expensive, produces additional waste material that must be managed, and has the potential to reduce the productivity of the forest.
- (8) Covering the forest floor with soil or wood chips that has studied as a potential measure to reduce air dose rates. A number of questions regarding the long term effectiveness of these measures remain. In the meantime, the Prefecture has already concluded that, because of the associated high costs, the application of such measures may be justified only over limited areas with high air dose rates, especially if such areas are close to inhabited areas.
- (9) To date there appears to be no need to restrict the production and use of the timber harvested from forests. However, monitoring of timber needs to continue, especially as logging work commences in areas which were affected by higher deposition of radiocaesium.

Protection of workers

- (10) Measures have been implemented to restrict the radiation exposure of forest workers; these include the use of harvesting machines and limitations on working hours. Overall, a conservative approach has been taken in order to reduce the radiation doses of these individuals.

Forest fires

- (11) Studies of forest fires in the Prefecture have not identified a significant radiological impact that resulted from these events. However, forest fires may have had a greater radiological impact if they had occurred soon after the Fukushima Daiichi accident when more of the radiocaesium inventory was in the litter layer and available to be redistributed as a result of forest fires.

Public information

- (12) The Satoyama Rehabilitation Model Project was concluded in fiscal year 2019. It is intended to publish the results obtained and make them widely available to the general public. This information is particularly important for former evacuees to help inform their decision on whether or not to return.
- (13) There are many similarities between the three monitoring programmes for wild foods. Apart from being interdependent, the data for wild mushrooms, freshwater fish and wild animals all show high concentrations of radiocaesium, many outlier values and a very slow reduction in levels. The activity concentrations in many of these foods will exceed the limit of 100 Bq/kg for general foods sold commercially that was established in April 2012 for the foreseeable future. A non-destructive analysis (NDA) has been developed for the matsutake mushroom to be able to distribute this valuable forest product for further consumption after the measurement. If NDA can be applied to other wild mushroom species, this would allow the consumption and distribution of the products collected in any municipality of the prefecture and allow the population to return to traditional collecting and consumption of the wild plants and mushrooms.
- (14) Ongoing attention needs to be given to providing more and better information on levels of radiation in the environment so that people can make informed choices on the radiation dose they are prepared to accept.
- (15) Also related to public information, as time progresses, monitoring programmes will identify more and more 'less than' or 'not detectable' results. These can be an important communication tool to show that the situation is improving, even if restrictions remain in place. A standard approach should be agreed and applied uniformly across all monitoring programmes.

3. MONITORING OF RADIOACTIVE MATERIAL AND ASSOCIATED REMEDIATION AND DECONTAMINATION IN TERRESTRIAL AND AQUATIC ENVIRONMENTS

3.1. BACKGROUND AND OBJECTIVES

Based on the data collected and an assessment conducted by the Prefecture, during the period of the Practical Arrangements, the most important exposure pathway for people is external radiation emitted by radiocaesium (see also Section 2.1 for further information on radiocaesium in the forest environment). Furthermore, the Prefecture has determined that radiocaesium levels in the terrestrial and aquatic environments and associated doses to people have declined due to decontamination activities, radioactive decay, the removal of radiocaesium by weathering from surfaces (including during extreme weather events, see Section 3.5) and vertical migration down soil and sediment profiles.

The need for remediation and decontamination depends to a large extent on the evolution of doses to members of the public over time. Decisions relating to remediation activities are based on an assessment of current doses, as well as future doses that would be achieved through remedial actions relative to those that would occur without intervention. It is, therefore, helpful to make predictions regarding temporal changes over time in air dose rates and doses to people with and without intervention.

The Practical Arrangements refer to the provision of assistance to the Prefecture on issues related to off-site decontamination, analyses of the results of environmental monitoring, and exploration of exposure pathways in order to reduce or avoid exposure. Under this activity, the cooperation has addressed the following topics:

- Behaviour of radiocaesium in the terrestrial and aquatic ecosystems, excluding forests (See Section 2), in the areas of the Prefecture affected by the Fukushima Daiichi accident;
- Effectiveness of remediation and decontamination measures in aquatic systems;
- Analysis of monitoring results to identify temporal trends in radiocaesium concentrations in environmental media (soil, water, sediments), and of air dose rate;
- Review of experience gained from remediation activities in order to elaborate input for the selection of appropriate and technically feasible remedial actions;
- Application of models to simulate radiocaesium flux in aquatic systems;
- Effectiveness of decontamination measures implemented in residential areas;
- Impacts of severe weather events, such as typhoons, on radiocaesium dynamics in freshwater environments;
- Dissemination of information on effectiveness of decontamination and remediation, doses to members of the public in the Prefecture, monitoring results and engagement of interested parties (this topic is covered in Section 6).

These topics are addressed in the following sections of this report.

3.2. BEHAVIOUR OF RADIOCAESIUM IN TERRESTRIAL AND AQUATIC ECOSYSTEMS

3.2.1. Global experience on radiocaesium in the natural environment

Radiocaesium has been released to the natural environment by atmospheric nuclear weapon tests, operations of nuclear facilities, and by accidental releases. In general, in the terrestrial environment, radiocaesium is strongly bound by mineral soil components, resulting in its slow migration and low uptake by plants from soil. Radiocaesium in soil is gradually bound to soil components, especially clay particles. This sorption may be reversible, constituting the fraction of exchangeable radiocaesium, or, largely irreversible, constituting the fixed fraction. However, in acidic, organic soils with low potassium content, radiocaesium uptake by plants is much higher. In tropical areas, where soils are subject to physical and chemical weathering over thousands of years, clay minerals have largely broken down and potassium has been depleted by leaching under acidic conditions; therefore, the uptake by plants may be much higher.

In freshwater ecosystems, radiocaesium binds strongly to suspended and bottom sediments, which causes a rapid decline in dissolved radiocaesium, and ultimately, deposition of radiocaesium in bottom sediments of surface waters. The transport of radiocaesium in rivers and lakes is largely due to the redistribution of sediments [4]. An increase in dissolved potassium concentration in fresh surface waters will result in a decrease in accumulation of radiocaesium by freshwater organisms due to competitive uptake between these two elements. In addition, following uptake, differences in the relative loss rates of caesium and potassium from freshwater organisms can lead to bioaccumulation of radiocaesium resulting in an increase in the activity concentration between each trophic level [5, 6]. Therefore, the physicochemical conditions in a water body that affect transport of particles and/or radiocaesium dynamics (e.g. pH, basin bathymetry, depth, concentrations of suspended sediments and potassium), as well as the length of the aquatic food chain, will influence the activity concentration of radiocaesium at the top of the aquatic food chain. Monitoring of radiocaesium in wild fish is described in more detail in Section 2.3.3 of this report.

3.2.2. Radiocaesium behaviour under the environmental conditions of the Prefecture

The behaviour of radiocaesium under the environmental conditions in the Prefecture has been the subject of many studies since 2011. Consistent with experience made after the Chernobyl accident and other contamination events [7, 8], these studies have shown that both the downward migration of radiocaesium in soil and the uptake of radiocaesium through crops from soil are very low due to the strong sorption of radiocaesium by soil.

According to studies conducted by Fukushima University, the proportion of exchangeable radiocaesium in soils and radiocaesium levels in crops in the Prefecture have contemporaneously decreased since 2011. For the prevailing soil types of the Prefecture, the Radiocaesium Interception Potential (RIP), which characterizes the ability of a soil to selectively adsorb radiocaesium, has been determined. Soils and sediments with a high RIP value strongly adsorb radiocaesium and, therefore, radiocaesium transfer from the soils to crops is small. This concept was widely applied after the Chernobyl accident to predict the radiocaesium uptake by crops based on soil parameters. In soils with a low RIP value, the application of clay can be effective in reducing radiocaesium transfer to crops.

Limited amounts of ^{90}Sr were released during the Fukushima Daiichi accident [9]. The deposition density of ^{90}Sr was 3–4 orders of magnitude less than for ^{137}Cs . In the immediate vicinity of the Fukushima Daiichi Nuclear Power Plant, ^{90}Sr deposition to the ground were

nearly equal to those resulting from fallout of atmospheric nuclear weapons testing in the 1960s. Resulting ^{90}Sr activities in foods were low as well; e.g. in 2012, ^{90}Sr was measured in foodstuffs in municipalities at a distance of 20–30 km from the FDNPP; in all cases the ^{90}Sr levels were below the level of detection [10]. In UNSCEAR (2013) [11] doses to the population outside the evacuated areas arising from ^{90}Sr are not explicitly estimated because they were considered as insignificant.

International experience on the behaviour of radiocaesium in the environment and environmental remediation projects was provided by the IAEA team. Following both the Chernobyl and Fukushima Daiichi accidents, it was observed that natural attenuation processes contributed to the reduction of radioactivity in the environment. However, the washoff of radiocaesium was found to be higher in the Prefecture than in areas affected by the Chernobyl accident due to:

- Greater rainfall precipitation from the occurrence of typhoons and higher temperatures;
- Greater biological activity due to higher precipitation and higher temperatures;
- Longer frozen periods in Chernobyl;
- Steeper slopes of hill sides.

These factors affected radiocaesium transport processes, as described in the following section.

3.2.3. Transport processes in catchments

The transport of radiocaesium from a catchment area via a river or river system is illustrated schematically in Figure 3.1. Radiocaesium is deposited in forests, agricultural and residential areas. Since radiocaesium is strongly adsorbed by mineral components in soil, it is transported via river flow and the associated redistribution of sediments. Figure 3.1 also depicts the interaction between terrestrial and aquatic ecosystems, including the possible transfer pathways to agricultural products. The following processes are important:

- Radiocaesium is removed from forests, residential and agricultural areas through runoff, which depends on the intensity of rainfall, the slope of the terrain and its surface characteristics (vegetated, paved, bare soil);
- River systems are connected to ponds, lakes and reservoirs, which might be used as drinking water or for irrigation purposes during the growing season;
- Following intensive rainfall or extreme weather events (e.g. typhoons), river flooding and turbulent flow can affect previous deposits of radiocaesium bound to sediments;
- Some radiocaesium will be transported to the ocean.

3.3. ANALYSIS OF RESULTS OF MONITORING PROGRAMMES

3.3.1. Monitoring of radiocaesium in water and sediments

In the Prefecture, river water is widely used as a source of water for the city water consumption, for agricultural activities and other purposes. Therefore, the Prefecture started monitoring radiocaesium in fresh surface waters and the campaign is conducted by the Fukushima Prefectural Centre for Environmental Creation (see Figure 3.2 and Table 3.1).

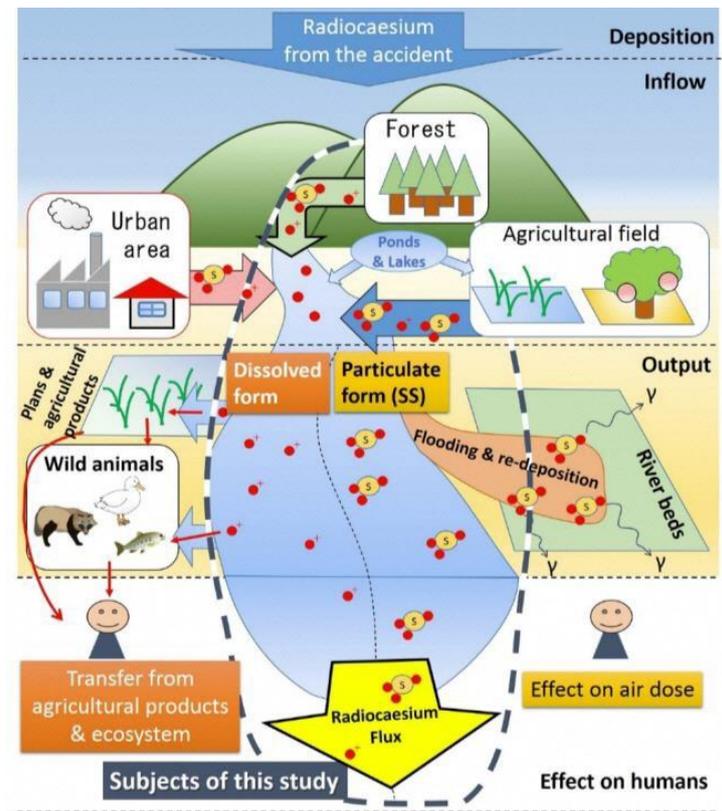


FIG. 3.1: Illustration of radiocaesium transport through a catchment area and interactions with terrestrial elements (Image: Fukushima Prefecture).

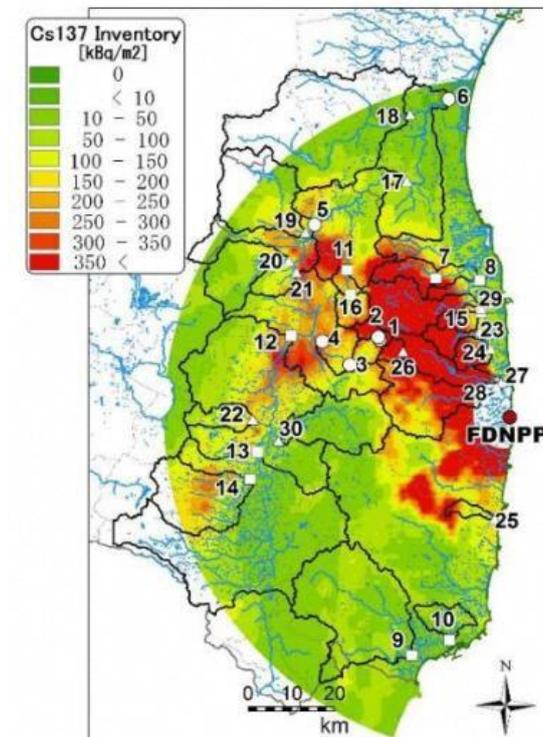


FIG. 3.2: Distribution of ^{137}Cs deposition in the Prefecture as determined during the Third Airborne Monitoring Survey (MEXT, 2 July 2011).

Table 3.1. Catchment area and average ^{137}Cs inventory in the wide area river survey [12]

Site No.	Site Name	Catchment drainage System	River Name	Catchment Area (km ²)	Average ^{137}Cs Inventory (kBq/m ²)
1	Mizusakai River	Abukuma River	Kuchibuto River	8	587
2	Kuchibuto River Upstream	Abukuma River	Kuchibuto River	21	408
3	Kuchibuto River Midstream	Abukuma River	Kuchibuto River	63	304
4	Kuchibuto River Downstream	Abukuma River	Kuchibuto River	135	248
5	Fushiguro	Abukuma River	Abukuma River	3645	102
6	Iwanuma	Abukuma River	Abukuma River	5313	96
7	Mano	Mano River	Mano River	76	521
8	Ojimadazeki	Mano River	Mano River	111	418
9	Matsubara	Same River	Same River	871	46
10	Onahama	Fujiwara River	Fujiwara River	70	45
11	Tsukidate	Abukuma River	Hirose River	84	222
12	Nihonmatsu	Abukuma River	Abukuma River	2380	88
13	Miyoda	Abukuma River	Abukuma River	1287	77
14	Nishikawa	Abukuma River	Shakado River	289	137
15	Kitamachi	Niida River	Mizunashi River	36	537
16	Kawamata	Abukuma River	Hirose River	57	226
17	Marumori	Abukuma River	Abukuma River	4124	113
18	Funaoka Ohashi	Abukuma River	Shiroishi River	775	27
19	Senoue	Abukuma River	Surikami River	313	51
20	Yagita	Abukuma River	Ara River	185	63
21	Kuroiwa	Abukuma River	Abukuma River	2921	109
22	Tomita	Abukuma River	Ouse River	73	117
23	Ota	Ota River	Ota River	50	1638
24	Odaka	Odaka River	Odaka River	50	750
25	Asami	Asami River	Asami River	26	197
26	Tsushima	Ukedo River	Ukedo River	25	813
27	Ukedo	Ukedo River	Ukedo River	153	2329
28	Takase	Ukedo River	Takase River	264	696
29	Haramachi	Niida River	Niida River	200	858
30	Akanuma	Abukuma River	Otakine River	243	57
31	Watari	Abukuma River	Abukuma River	5313	96

*The Watari Point (31) is on the bank opposite the Iwanuma Point (6) and was setup as a backup monitoring point.

The monitoring programme includes the measurement of radiocaesium dissolved in water, as well as radiocaesium bound to suspended sediments in rivers and lakes. In addition, samples are screened for highly enriched radiocaesium bearing microparticles (CsMPs) (see Section 3.3.4).

Due to the strong sorption of radiocaesium by suspended sediments and its deposition in the bottom sediments of water bodies, radiocaesium levels in river water have declined considerably with time, and within less than 7 years of the accident, were close to or below 0.05 Bq/L [13] for the measurement technique used (a level far below the criterion of 10 Bq/L for drinking water quality recommended by the World Health Organization (WHO) [14]).

There was also a clear decline in the activity concentration of radiocaesium in suspended sediments, especially when further erosion from contaminated catchment areas is limited.

Consistent with the international literature, radiocaesium activity concentrations in sediments have tended to increase with decreasing particle size.

The Prefecture monitoring programme has focused on studying the long term behaviour of radiocaesium in the catchment areas of the Prefecture, and specifically on three aspects:

- *Levels and the behaviour of radiocaesium associated with suspended particles*, including the deposition or removal of radiocaesium bound by sediments and floodplain soils during floods and extreme weather events (e.g. typhoons), and the corresponding effects on air dose rates;
- *Radiocaesium in its dissolved form*, i.e. transfer to agricultural products, wild animals and plants via the accessible ecosystem;
- *The dynamics of particulate and dissolved radiocaesium* in river catchments.

Concentrations of major ions (potassium, calcium, magnesium, and ammonium) are also measured to characterize the physicochemical properties of the water, which affects radiocaesium dynamics in aquatic systems (see Section 3.2). Tracer techniques are being applied in the Prefecture to gain further understanding of radiocaesium transfer between terrestrial catchment areas and surface water environments (see Section 3.3.5).

The measurements made by the Prefecture have focused on the catchment areas affected by the deposition of ^{137}Cs , see Figure 3.2 and Table 3.1. This included general surveys at monitoring points in multiple rivers to monitor temporal and spatial changes in radiocaesium activity concentrations and the influence of basin characteristics on radiocaesium dynamics. In addition, detailed surveys and studies were carried out in the basins of the Hirose and Kuchibuto Rivers to estimate radiocaesium transport and to compare measured data with estimates generated using a simulation model (see Section 3.4). Emphasis was placed on the Hirose River basin, where twelve monitoring points were established along the river and its tributaries, including the Takane River, the Nuno River and the Oguni River. In addition to the physicochemical attributes of the surface waters, the measurements included determination of water flow rates, turbidity of water and concentration of suspended sediments. As expected, rainfall events coincided — with some delay — with increases in the flow rate and concentration of suspended sediments. Although there are considerable fluctuations with time, the ^{137}Cs levels have decreased continuously in dissolved form and suspended sediments since 2011. Similar trends were observed in studies of radiocaesium transport in rivers within the Hamadori and the Nakadori Districts; the results for the suspended ^{137}Cs activity concentrations since 2011 at more than 30 points are shown in Figure 3.3. During a heavy rainfall event in September 2015 (Typhoon 15 Etau), suspended radiocaesium concentrations temporarily decreased.

These results are in accordance with a study conducted by Ueda, et al. [15] who measured the concentration of particulate and dissolved ^{137}Cs in the Hiso and Wariki River (two small rivers in the Soma District, Fukushima Prefecture) from 2011 to 2021. There is a continuous, relatively smooth decline during the whole observation period. The time dependence of the ^{137}Cs concentrations is shown in Figure 3.4. A fast component immediately after the deposition is followed by a slower component starting a few months after deposition.

The IAEA team and Prefecture experts have agreed that, in conducting monitoring to assess radiocaesium dynamics, it is important to apply standardized sample collection and storage procedures, and where relevant, standardized expression of monitoring results, to facilitate intercomparison between aquatic systems, which allows the results to be compared with international literature.

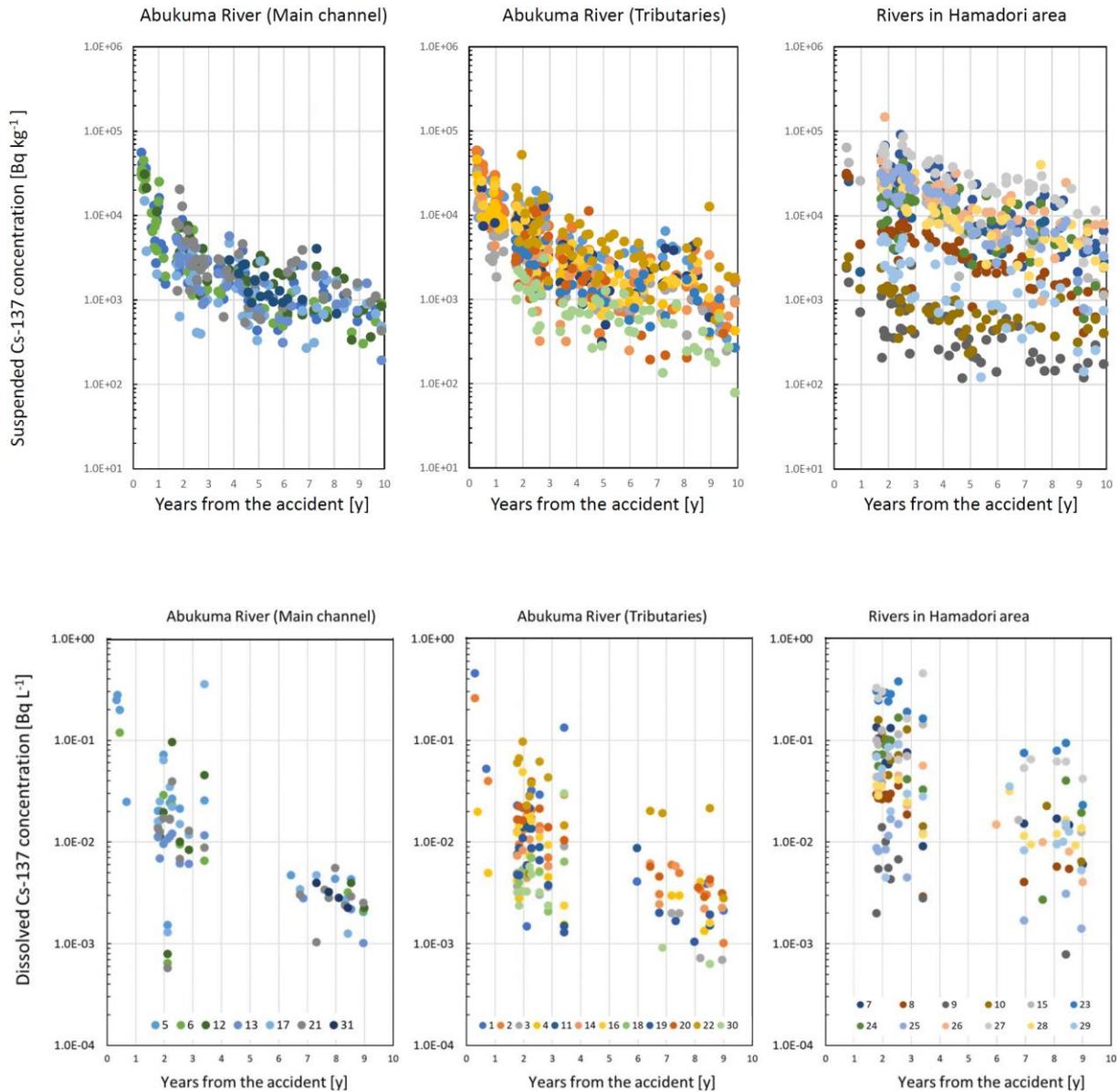


FIG. 3.3: Decline of ^{137}Cs in suspended matter (top) of dissolved ^{137}Cs (bottom) in water of rivers in the Prefecture from 2011 to 2021 (Image credit: Fukushima Prefecture) [16, 17].

The numbers represent the following rivers: 1 Mizusakai River, 2 Kuchibuto River, Upstream, 3 Kuchibuto River Midstream, 4 Kuchibuto River Downstream, 5 Fushiguro, 6 Iwanuma, 7 Mano, 8 Ojimadazeki, 9 Matsubara, 10 Onahama, 11 Tsukidate, 12 Nihonmatsu, 13 Miyoda, 14 Nishikawa, 15 Kitamachi, 16 Kawamata, 17 Marumori, 18 Funaoka Ohashi, 19 Senoue, 20 Yagita, 21 Kuroiwa, 22 Tomita, 23 Ota, 24 Odaka, 25 Asami, 26 Tsushima, 27 Ukedo, 28 Takase, 29 Haramachi, 30 Akanuma, 31 Watari (see Table 3.1).

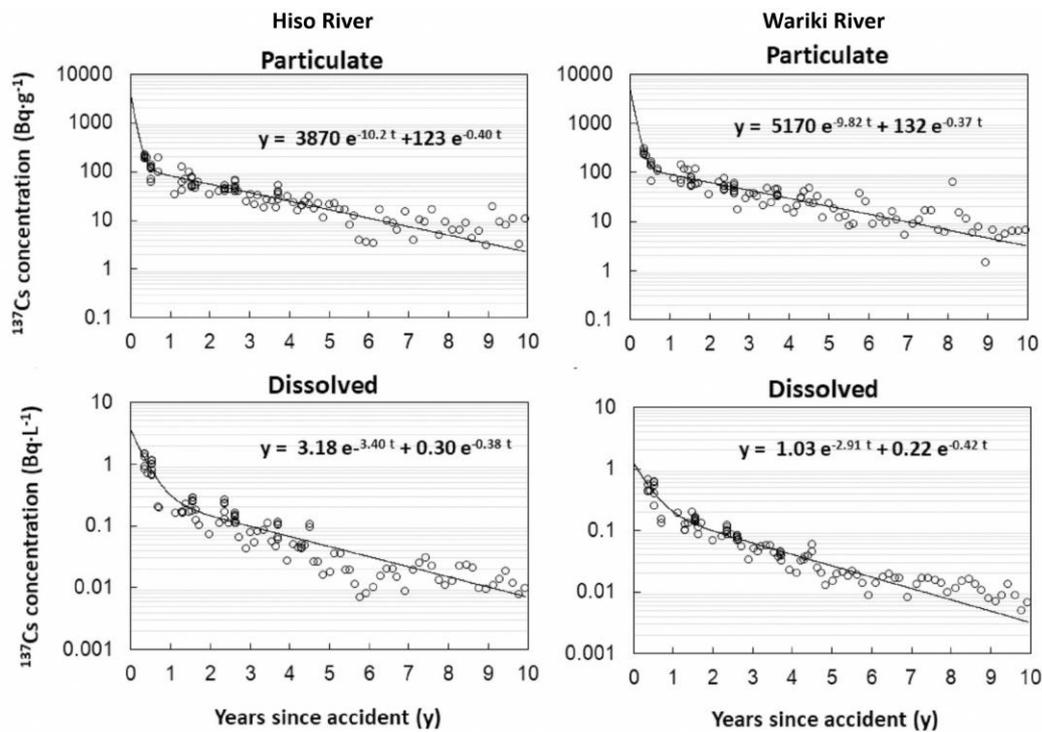


FIG. 3.4: Activity concentration of particulate and dissolved ^{137}Cs from 2011 to 2021 in the Hiso and the Wariki River (reproduced from Ref. [15]). (Please note: Some circles are on top of each other, so it looks like there are black circles, but there are only open circles).

3.3.2. Effective half-life of caesium-137 in Prefecture rivers

Since 2011, freshwater bodies have been monitored to study the dynamics of ^{137}Cs in water and in suspended and bottom sediments. The ^{137}Cs activity concentrations in water bodies and their time dependence are the results of an interaction of deposition density, catchment area, size of the water body, precipitation, rainfall intensity, slope, and land use.

Data obtained from monitoring of particulate and dissolved ^{137}Cs in water over time have been used to estimate the effective half-life (T_{eff}) of ^{137}Cs in each of these forms¹. Monitoring of ^{137}Cs in river water was also conducted in Europe after the accident in the Chernobyl nuclear power plant. To facilitate the comparison of the behaviour of ^{137}Cs in freshwater systems, the time dependence of radionuclides in sediments, suspended sediments or water is approximated by exponential functions with one to three components [18].

In long term studies, starting immediately after the Chernobyl deposition, a typical pattern of the long term decline of radiocaesium in water is characterized by 3 phases [18]:

- The first phase reflects the rapid decrease of activity due to dilution processes in the first weeks after deposition.
- The second phase is the result of fixation of radiocaesium to fine particles.

¹ The effective half-life (T_{eff}) is the time interval needed for the radioactivity of a certain amount of radioactive substance (in this case, ^{137}Cs in suspended and dissolved forms) to decrease to half its original value due to radioactive decay and other loss processes.

- The third phase represents the long term decline of radiocaesium in rivers due to the gradually reduction of radiocaesium runoff from the catchments.

However, in some cases, the observations started too late after the deposition, and as a result, the initial activity concentration in water could not be determined. In such cases, the rapid decline immediately after the deposition was not covered by the observation period. In other cases, the observation period was not long enough to identify the long term component of the decline. Therefore, in both Japanese and the European studies, the number of components of the exponential functions identified varies, depending on the observation period and the start of the observation period after the contamination event.

Data on half-lives on ^{137}Cs in water of Japanese and European rivers are summarized in Table 3.2 and Table 3.3, respectively. The half-lives are given for the short term, the intermediate and the long term component of the decline. If more than one component is given, the weighting factors for these components are given in brackets.

Most of the data are for suspended sediments. However, the effective half-lives observed for particulate and dissolved ^{137}Cs are in the same range. By and large, the temporal trends observed in Japan and other parts of the world agree quite well. From the results summarized in Tables 3.2 and 3.3, the following conclusions can be drawn:

Following both accidents, initially, activity concentrations in water decrease rapidly. The effective half-lives determined depend on the beginning of the measurement series after the deposition event, whereby:

- In water of European rivers, immediately after deposition, a decline of the ^{137}Cs was observed following an effective half-life of 5 days during a period of about 2–3 weeks.
- For measurements of ^{137}Cs in water, starting several days after deposition, effective half-lives in the range of 20–50 days were observed.
- In some cases, the measurements started later (in 1987 following the Chernobyl accident, in 2012 following the accident in FDNPP). In such cases, the very rapid immediate decline of concentrations is no longer reflected in the first component, and effective half-lives of 70–270 days were found; in one case, an effective half-life of 1.6 years was observed.
- The results achieved in Japan agree well with the global experience.

Many data sets do not include the initial phase with the fast decline, and instead, most data are available for the second component, which covers observation periods of 5–15 years starting several months after radionuclide deposition, as follows:

- For the Fukushima Prefecture, data on effective half-lives for 48 (data sets) are available, ranging from 0.7 to 16 years. Three values are below 1 year, and three values are above 5 years. Forty-two values are in the range of 1.1–4.6 years.
- These results agree very well with the effective half-lives observed in Ukraine, Russia, and Finland. For Ukrainian rivers, the effective half-lives found are in the range of 2.0–6.5 years. In two Finnish rivers, effective half-lives of 3.5 and 6 years were observed. In the Iput River (Russia), an effective half-life of 1.3 years was observed in the period 1987–1991.

Table 3.2. Summary of effective half-lives (T_{eff}) of ^{137}Cs in Japanese rivers affected by the FDNPP accident, half-lives are given — as available) for the short term, the intermediate and the long term component of the decline. If more than one component is given, the weighting factors for these components are given in brackets.

River or site name	Observation period	Medium	Effective half-lives (Weighting factors of components)			Reference
			$T_{eff,1}$	$T_{eff,2}$	$T_{eff,3}$	
			(short term)	(intermediate)	(long term)	
Ukedo	2015–2018	Dissolved	–	3.7 y	–	[14]
		Particulate	–	2.3 y	–	
Ota	2015–2018	Dissolved	–	2.4 y	–	[19]
		Particulate	–	1.6 y	–	
Koutaishi	2011–2013	Dissolved	–	0.69 y	–	[19]
Iboishi	2011–2013	Dissolved	–	0.69 y	–	
Ishidaira	2011–2013	Dissolved	–	1.5 y	–	
Fukushima Rivers	2012–2014	Dissolved	–	1.8±0.5 y	–	[20]
Odaka River	2012–2016	Sediment	–	4.7±1.3 y	–	[21]
		River water	–	3.7±0.6 y	–	
Ota		Sediment	–	1.5±0.4 y	–	[21]
		River water	–	2.1±0.6 y	–	
Niida		Sediment	–	1.8±0.6 y	–	[21]
		River water	–	1.0±0.2 y	–	
Mano		Sediment	–	2.1±0.2 y	–	[22]
		River water	–	0.9±0.1 y	–	
Mizusakai	2011–2016	Particulate	1.6 y (0.64)	2.7 y (0.36)	–	[22]
Kuchibuto_Upper	2011–2016	Particulate	135 d (0.79)	2.0 y (0.21)	–	
Kuchibuto_Middle	2011–2016	Particulate	120 d (0.74)	1.6 y (0.26)	–	
Kuchibuto_Down	2011–2016	Particulate	274 d (0.64)	1.4 y (0.36)	–	
Fushiguro	2011–2016	Particulate	66 d (0.96)	1.8 y (0.04)	–	
Iwanuma	2011–2016	Particulate	80 d (0.92)	1.5 y (0.08)	–	
Mano	2012–2016	Particulate	–	8.2 y	–	
Ojimadazeki	2012–2016	Particulate	–	4.6 y	–	
Matsubara	2012–2016	Particulate	–	3.7 y	–	
Onahama	2012–2016	Particulate	–	2.1 y	–	
Tsukidate	2012–2016	Particulate	–	1.1 y	–	
Nihonmatsu	2012–2016	Particulate	–	1.6 y	–	
Miyota	2012–2016	Particulate	–	2.9 y	–	
Nishikawa	2012–2016	Particulate	–	2.9 y	–	
Kitamachi	2012–2016	Particulate	–	1.5 y	–	
Kawamata	2012–2016	Particulate	–	1.1 y	–	
Marumori	2012–2016	Particulate	–	1.8 y	–	
Senoue	2012–2016	Particulate	–	2.4 y	–	
Yagita	2012–2016	Particulate	–	16 y	–	
Kuroiwa	2012–2016	Particulate	–	1.3 y	–	
Tomita	2012–2016	Particulate	–	1.5 y	–	
Ota	2012–2016	Particulate	–	3.8 y	–	
Odaka	2012–2016	Particulate	–	11 y	–	
Asami	2012–2016	Particulate	–	2.1 y	–	
Tsushima	2012–2016	Particulate	–	1.7 y	–	
Ukedo	2012–2016	Particulate	–	2.8 y	–	
Takase	2012–2016	Particulate	–	1.7 y	–	
Haramachi	2012–2016	Particulate	–	3.0 y	–	
Akanuma	2012–2016	Particulate	–	2.0 y	–	

River or site name	Observation period	Medium	Effective half-lives (Weighting factors of components)			Reference
			$T_{eff,1}$	$T_{eff,2}$	$T_{eff,3}$	
			(short term)	(intermediate)	(long term)	
Abukuma River	2011–2017	Particulate	0.14 y (0.96)	1.5 y (0.04)	–	[23]
Rivers coastal region of Fukushima Prefecture	2011–2017	Particulate	0.12 y (0.93)	2.6 y (0.07)	–	
Abukuma and rivers of coastal region	2011–2017	Dissolved	0.14 y (0.94)	2.6 y (0.06)	–	
Hiso River	2011–2021	Particulate	0.068 y (0.97)	1.7 y (0.03)	–	[15]
Hiso River	2011–2021	Dissolved	0.20 y (0.914)	1.8 y (0.086)	–	
Wariki River	2011–2021	Particulate	0.071 y (0.975)	1.9 y (0.025)	–	
Wariki River	2011–2021	Dissolved	0.24 y (0.82)	1.7 y (0.18)	–	

Table 3.3. Summary of half-lives of ^{137}Cs in European rivers affected by the Chornobyl accident.

River or site name	Observation period	Medium	Effective half-lives			Reference
			$T_{eff,1}$ (short term)	$T_{eff,2}$ (intermediate)	$T_{eff,3}$ (long term)	
Pripyat (Ukraine)	May 1986, Week 1–3 after deposition	Dissolved	11 d			[24]
Dnieper (Ukraine)		Dissolved	9.0 d			
Glatt (Switzerland)		Dissolved	19 d			
Elbe (Germany)		Dissolved	18 d			
Po (Italy)	20 May to July 86	Dissolved	35 d			[25]
European rivers	1–15 May 1986		5 d			[26]
9 Ukrainian rivers	1987–1991	Dissolved	–	1.0–2.1 y	–	
5 Finnish rivers	1987–1991	Dissolved	–	1.7–4.3 y	–	
5 Belarussian rivers	1987–1991	Dissolved	–	1.0–1.4 y	–	
Dora Baltea (Italy)	1987–1991	Dissolved	–	1.9 y	–	
Rhine (Germany)	1987–1991	Dissolved	–	1.3 y	–	
Rhine (Germany)	1987–1991	Particulate	–	1.9 y	–	
Pripyat (Ukraine)	1987–1991	Dissolved	–	1.6 y	–	
Pripyat (Ukraine)	1995–1998	Dissolved	–	3.8 y	–	[24]
Dnieper (Ukraine)	1995–1998	Dissolved	–	3.6 y	–	
Desna (Ukraine)	1995–1998	Dissolved	–	9.9 y	–	
5 Finnish rivers	1995–2002	Dissolved	–	5.2–7.5 y	–	
5 Belarussian rivers	1994–1998	Dissolved	–	2.1–4.5 y	–	
Pripyat (Ukraine)	1995–1998	Particulate	–	8.2 y	–	
Dnieper (Ukraine)	1995–1998	Particulate	–	7.5 y	–	
Desna (Ukraine)	1995–1998	Particulate	–	2.6 y	–	
Pripyat (Ukraine)	1987–2001	Unfiltered water	–	3.0 y *	14 y *	
Pripyat (Chornobyl)	1987–2001	Unfiltered water	–	2.5 y *	15 y *	
Dnieper (Ukraine)	1987–2001	Unfiltered water	–	1.9 y *	8.3 y *	
Uzh (Ukraine)	1987–2001	Unfiltered water	–	2.6 y *	6.2 y *	
Teterev (Ukraine)	1987–2001	Unfiltered water	–	3.1 y	–	
Irpen (Ukraine)	1987–2001	Unfiltered water	–	2.8 y	–	[27]
Braginka (Ukraine)	1987–2001	Unfiltered water	–	5.3 y *	6.0 y *	
Ilya (Ukraine)	1987–2001	Unfiltered water	–	3.2 y	–	
Sakhan (Ukraine)	1987–2001	Unfiltered water	–	2.7 y *	16 y*	
Glimitsa (Ukraine)	1987–2001	Unfiltered water	–	2.0 y *	21 y *	
Pripyat (Ukraine)	1988–2018	Particulate	–	1.1 y *	10 y*	
Dnieper (Ukraine)	1989–2012	Particulate	–	3.6 y *	7.6 y*	[27]
Ukrainian rivers	1987–2001	Dissolved	–	2.0–6.5 y	–	
25 rivers in Asia and Europe	1987–2001	Unfiltered water	20 d (0.905)	1.6 y (0.09)	16 y (0.005)	[18]
Iput River (Russia)	1987–1991		–	1.3 y	–	[28]
Kymijoki (Finland)	1990–1996		–	6.0 y	–	
Kokemäenjoki (Finland)	1990–1996		–	3.5 y	–	[29]

* The data indicate that the decrease of ^{137}Cs in these rivers follows an exponential function with two components. However, the weighting factors for the 2 components are not given by the authors, since the uncertainty of the long term component is very high, and it was not considered reasonable to assign a specific value for the weighting factors. The values should therefore be considered as a first estimation of the long term component. The high uncertainty of the long term component is due to the short observation period compared to its ecological half-life.

If the observation period is long enough, in some cases a third phase can be identified. However, quantifying a third decline component requires observation times of at least 15 years, since the

overall contribution of a third exponential term is very small. So far, in the studies carried out in the Fukushima Prefecture, such long observation periods are not possible since only 12 years have passed since the accident in FDNPP. In an analysis of the time dependence of ^{137}Cs in water of 25 rivers in Europe and West Asia, a third component with an effective half-life of 16 years was identified. The contribution to the overall decline of this component was only 0.5 percent and the relevance in practice is of minor importance. Finally, it is important to note that the effective half-life of a radionuclide (in this case, for ^{137}Cs) can change over time reflecting timing aspects, as well as changes in both particle and radiocaesium dynamics in a river basin. For example, monitoring of ^{137}Cs in suspended sediments over time in areas in the Kuchibuto River basin have indicated that in areas where extensive decontamination was undertaken during spring 2014 (details on this observation are given in Figure 3.11 located in Section 3.5.3 below), ^{137}Cs in suspended sediments rapidly declined, with a corresponding decrease in the effective half-life (see Table 3.2).

3.3.3. Radiocaesium in phytoplankton and zooplankton

Radiocaesium levels in phytoplankton and zooplankton ('plankton') populations were investigated in the Yokogawa reservoir [30]. Measurements were performed at three sites of the reservoir. The contribution of plankton species to the total plankton (sum of phyto- and zooplankton) varied both temporally and spatially. The ^{137}Cs activity concentration in phyto- and zooplankton is approximately in the same range. Only a small fraction of the ^{137}Cs in the reservoir is bound to plankton. The ratio of ^{137}Cs bound to phytoplankton and ^{137}Cs in the reservoir water varies from 0.016% to 0.83%. The ratio for zooplankton is about a factor of 10 lower and varies between 0.0018% and 0.011%. This means that the total radiocaesium activity in phytoplankton and zooplankton represents only a small fraction of a percent of the radiocaesium present in a given water body [30].

3.3.4. Occurrence and characterization of radiocaesium-bearing radioactive particles (CsMPs)

In several investigations carried out in the Fukushima Prefecture, glassy particles containing radiocaesium were found by autoradiography methods in various materials as air filters, house dust, soils, plant leaves near the accident site, agriculture materials, feather of birds, and river water (e.g. see Refs [31–34]). The particles are usually called CsMPs and these particles were released from the reactors and dispersed in the atmosphere. So far, most CsMPs were found relatively close to the reactors.

Studies were carried out to investigate the chemical and isotopic compositions of the CsMPs, to identify the likely sources of the CsMPs and the processes generating CsMPs during the accident. The particles are classified into two categories, called Type A and Type B particles [33, 35]:

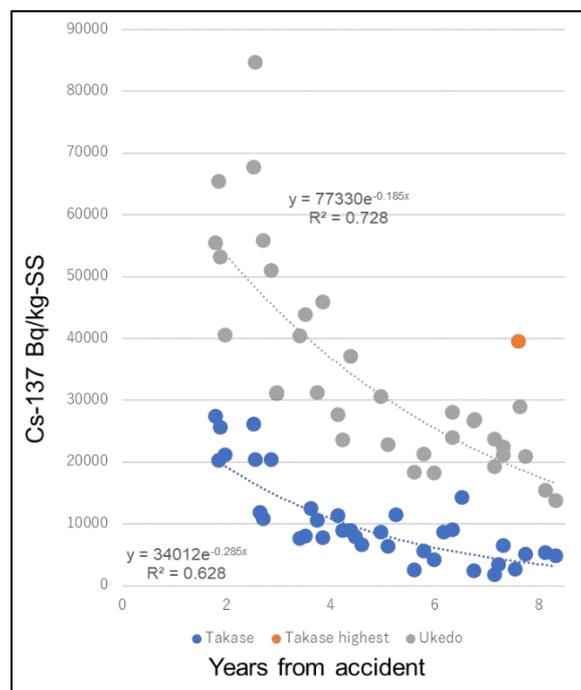
- Type A particles are usually nearly spherical and have a diameter of less than 5 μm . Typically, ^{137}Cs activities are on the order of a few Bq of ^{137}Cs per particle. However, Igarashi et al. [33] described a type A particle with a total ^{137}Cs activity of nearly 400 Bq. The $^{134}\text{Cs}/^{137}\text{Cs}$ ratio is above 1, reflecting the fuel burnup at the time of the accident in Units 2 and 3 of the FDNPP. Therefore, Type A particles are associated to the Units 2 and 3. Type A particles consist of silicate glass in which Cl, K, Rb, Cs, Mn, Fe, Zn, and Sn are dissolved.
- Type B particles have various shapes, with diameters of a few to up to 400 μm . Due to their larger size, they are predominantly found close to the FDNPP. These particles

appear to originate from fibre silicate, which is an insulation material used in the reactor. Activities are in general higher than for type A particles, activities are in the range of 30–19 000 Bq. The $^{134}\text{Cs}/^{137}\text{Cs}$ ratio is lower than 1. Type B particles are associated with Unit 1 of FDNPP.

During a monitoring campaign in October 2018, an elevated ^{137}Cs activity concentration was detected in one of the suspended sediment samples from a river in the Hamadori Region of the Prefecture (see Figure 3.5). It was determined that insoluble highly enriched radiocaesium microparticles (CsMPs) may have been entrained into the sample.

K_d values of ^{137}Cs and CsMPs

Since the sorption to suspended sediment plays a key role in the behaviour of radiocaesium in the natural environment, efforts were undertaken by the Prefecture to quantify the strength of radiocaesium sorption to soils and sediments. This is often characterized by the distribution coefficient (K_d), which is derived from measurements of radiocaesium in the particulate relative to the dissolved phase. For the investigated rivers, K_d values in the range of 10^5 to 10^7 L/kg dry sediment were measured, reflecting the strong sorption of caesium to particulates¹ (see Figure 3.6). The apparent distribution coefficient (K_d) normalized by particle size did not show any significant change throughout the first 4 years [22].



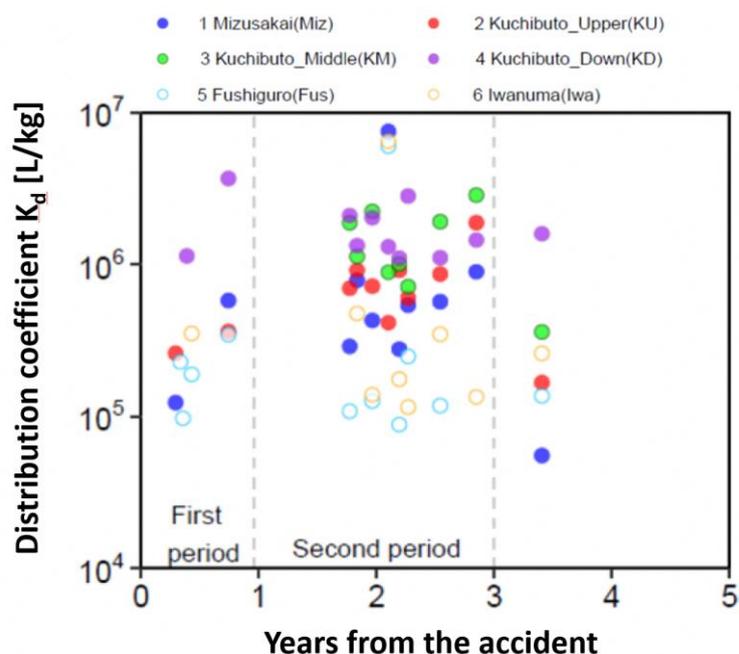


FIG. 3.6: Apparent¹ distribution coefficients K_d in dry suspended sediment samples collected from 2011 to 2014 at six river sites of the Fukushima Prefecture [22]. The different colours represent samples at different river sites.

Miura et al. [36] compiled the characteristics of CsMPs found in the Kuchibuto River during campaigns carried out from 2011 to 2016 (Table 3.4). The distribution coefficients K_d for ^{137}Cs in the suspended sediment samples were calculated based on the ^{137}Cs activity in the sample, both excluding and including the activity of the CsMPs. In all cases, the K_d values based on the total activity (including the ^{137}Cs activity of the CsMPs) are higher than those based the activity excluding the ^{137}Cs activity of the CsMPs, indicating the low solubility of the CsMPs. However, in both cases, the K_d values indicate strong sorption of ^{137}Cs to the suspended sediments.

The characteristics of 5 CsMPs deposited on a non-fabric cloth 50 km west of the FDNPP were investigated [34]. Diameters varied from 1.6 to 2.7 μm , the total ^{137}Cs activity ranged from 0.7 to 1.9 Bq, and $^{134}\text{Cs}/^{137}\text{Cs}$ ratios between 0.96 and 1.17 were found. Based on these properties, and the on ratios of $^{235}\text{U}/^{238}\text{U}$, all these CsMPs were classified as Type A originating from Unit 2.

The investigations of CsMPs in soil and suspended sediment samples [33, 36] indicate that only a minor fraction of the ^{137}Cs in the environment is associated with Cs-microparticles. CsMPs are slowly degraded. In solubility experiments using a CsMP with a radius of approximately 1 μm a lifetime for this particle of less than 10 years in seawater has been estimated. In pure water, the dissolution rate was estimated to be 10 times slower than in seawater, which indicates a low solubility and a slow degradation. The low solubility in the freshwater system indicates low bioavailability [37].

¹ The calculation of the K_d value requires equilibrium conditions. Since it is not known whether equilibrium conditions exist in the samples, the term apparent distribution coefficient is used in this context.

Table 3.4. Concentrations of ^{137}Cs in CsMPs collected in the Kuchibuto River; the number of CsMPs, and K_d values without and with consideration of the CsMP in the solid phase [36].

Sampling dat	Number of CsMPs	Caesium-137 in CsMPs (Bq)	Fraction of CsMPs on filter (%)	K_d excluding CsMPs (L/g)	K_d including CsMPs (L/g)
31 July 2011	17	4.3	15	1400	1700
3 Aug 2012	1	0.11	1.3	1910	1950
3 May 2014	6	4.1	36	1100	1700
22 November 2014	4	0.77	67	4600	14 000
22 November 2015	5	2.3	66	3200	9300
1 April 2016	3	0.48	36	850	1300

Following both accidents in Fukushima and in Chernobyl, particles with enhanced levels of radionuclides were detected. International experience on CsMPs, their occurrence and characterization was provided by the IAEA team. The Chernobyl hot particles are fuel fragments, and they are very different from the CsMPs which are found in the Fukushima deposited material. CsMPs are smaller and contain much lower activities than those released from the Chernobyl reactor.

The total number of CsMPs found so far is relatively small. In most cases, their total activity is a few becquerel per particle. So, they do not contribute significantly to the total environmental radiocaesium. Nevertheless, it was recognized that screening for such particles as part of existing monitoring programmes in freshwaters is important to provide reassurance that the situation does not change.

The CsMPs are generally very small and contain only a few becquerels per particle, so a large radioanalytical effort is required for their full characterization. Therefore, a screening method has been developed for easy detection and rapid radioanalytical characterization of CsMPs, which is based on Photo Stimulated Luminescence (PSL). Should a sample be suspected of containing a CsMP, the sample is spread on a plate with a material sensitive to high energies, producing an image showing the areas with enhanced radioactivity. The total activity of a CsMP is determined based on a calibration curve that links the PSL-signal to the amount of radioactivity in the CsMP.

3.3.5. Redistribution of radiocaesium in surface water catchments

Redistribution of radiocaesium can occur due to natural processes and/or anthropogenic disturbances that impact transport of particles and/or radiocaesium in catchments. Natural processes can include typical or extreme weather events, such as rainfall events, snowmelt, storms, or typhoons. Such events can cause increased runoff, flooding and radiocaesium washoff into downstream surface waters and/or erosion. This can lead to redistribution of soil and/or sediment particles onto which radiocaesium is bound or transport processes, such as senescence of vegetation and subsequent decomposition and remobilization of radiocaesium that has accumulated in plant tissues. Anthropogenic activities can include work resulting in physical disturbances in a catchment that alter exposure pathways and/or facilitate remobilization of radiocaesium through processes, such as runoff, erosion and/or washoff (see Figure 3.1 above).

When such events or disturbances occur, it is important to understand the sources and redistribution of material, such as suspended sediments, their influence on radiocaesium dynamics, and ultimately, on exposure. The application of environmental tracers, such as stable

isotopes, was discussed by the IAEA team, as they can provide important insight regarding the sources of suspended sediments (including organic matter and inorganic substances) and their influence on radiocaesium transport dynamics, for example, between forested catchments and surface waters. For example, stable carbon isotopic signatures ($\delta^{13}\text{C}$)¹ [38] are distinctive in different environmental media, as well as for different types of plants. Therefore, characterization of $\delta^{13}\text{C}$ signatures, in addition to ^{137}Cs activity concentrations in forest litter, forest soil as well as river sediments, and of total organic carbon (TOC) can serve as tools to gain a better understanding of radiocaesium dynamics in catchments.

3.3.6. Flux of caesium-137 with suspended sediments

Since most of the radiocaesium in water bodies is associated with suspended sediments in river water, the measurements of radiocaesium in rivers allowed the estimation of the total flux of radiocaesium from the catchment areas.

For the monitoring stations in Table 3.1, the transport of ^{137}Cs from the catchment with suspended sediments was estimated for the period June 2011 to March 2017 [22, 39]. The loss of ^{137}Cs from catchments via surface runoff was calculated from the average initial deposition in the catchment areas as of June 2011, the ^{137}Cs activity concentrations in suspended sediment, the concentration of suspended sediment in water, the flow rate of the river, the precipitation, and the topographical data (including elevation and land use data).

The total losses of ^{137}Cs from the different catchments are shown in Figure 3.7. The observation periods vary for the different monitoring points. In general, the losses of ^{137}Cs activity from the catchments due to runoff and river transport are low.

- Six monitoring points (stations 1–6, red columns) cover the whole observation period from June 2011 to March 2017, and their total ^{137}Cs fluxes vary from 0.4 to 3.3%;
- The blue stations cover the observation from October 2012 to March 2017. The total flux varied from 0.04 to 4.4%. Most values are well below 1% and there is no obvious reason for the relatively high values for station 22. Excluding the value for station 22, the range is from 0.4 to 1.1%;
- The observation period for station 20 (grey) is from October 2012 to March 2016, for station 26 (violet) from October 2012 to August 2015, and for station 12 (black) September 2015 to March 2017. The total flux during for the station 20, 26, and 12 during these observation periods are 1.1%, 0.1% and 0.08% respectively.

Due to radioactive decay, ^{137}Cs activity in the watershed was reduced by 12.4% and 9.7% during the periods from June 2011 to March 2017 and October 2012 to March 2017, respectively.

¹ Carbon-13 is a natural stable carbon isotope, about 1.1% of the global carbon is C-13. The $\delta^{13}\text{C}$ signature quantifies the deviation of the C-13/C-12 ratio from Vienna PeeDee Belemnite (VPDB) standard [38] in an environmental sample in permille; it is also called the $\delta^{13}\text{C}$ -signature. The $\delta^{13}\text{C}$ level is calculated from the concentrations of ^{13}C and ^{12}C in the samples and in the VPDB standard according to:

$$\delta^{13}\text{C} = \left[\frac{{}^{13}\text{C}_{\text{sample}}/{}^{12}\text{C}_{\text{sample}} - {}^{13}\text{C}_{\text{standard}}/{}^{12}\text{C}_{\text{standard}}}{{}^{13}\text{C}_{\text{standard}}/{}^{12}\text{C}_{\text{standard}}} \right] \times 1000.$$

The depletion of C-13 in organic material is due to the higher atomic mass of C-13 compared to C-12, this facilitates the uptake of $^{12}\text{CO}_2$ by plants during the photosynthesis, and it causes the depletion of C-13 in plant material.

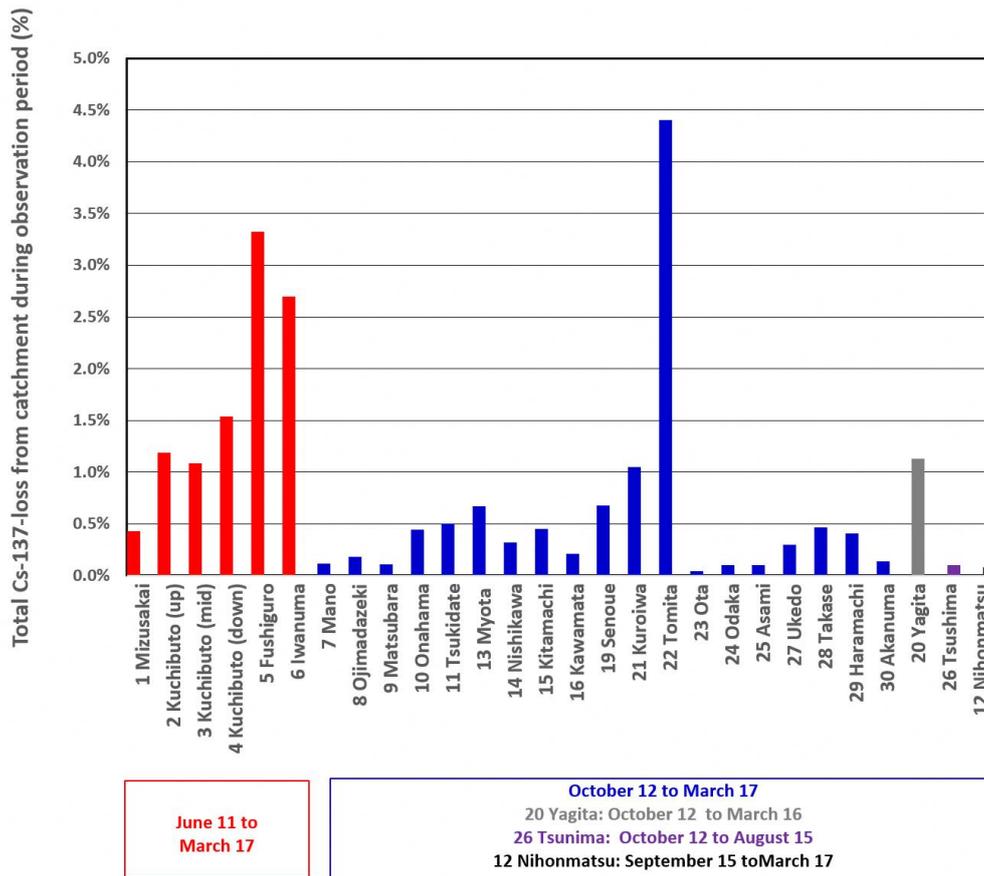


FIG. 3.7: Flux of ¹³⁷Cs in catchments of the Fukushima Prefecture.

These small percentages indicate that the reduction of the radiocaesium levels in the natural environment is mainly due to radioactive decay, and that runoff is only a minor contributor to the reduction of the overall radiocaesium inventory in these catchments (since washoff and erosion process affect only the very top surface layer of the contaminated soils in the water catchments). These results also indicate that the exchange of radiocaesium between different elements of the landscape is limited.

The increase of the cumulative loss of ¹³⁷Cs as function of time from the catchments to the Pacific Ocean for the period of 2011 to 2016 is shown in Figure 3.8. The increase in the cumulative loss (i.e. the amount of the radiocaesium transferred into the Pacific Ocean during a certain period) became less and less over time, as reflected by the decreasing slopes of the lines presented in Figure 3.8).

Assessment of the relative amounts of ¹³⁷Cs outflow from the Abukuma River in the suspended versus the dissolved forms indicated that 96.5% was in suspended form during the five year period after the Fukushima Daiichi accident [22] (Figure 3.9).

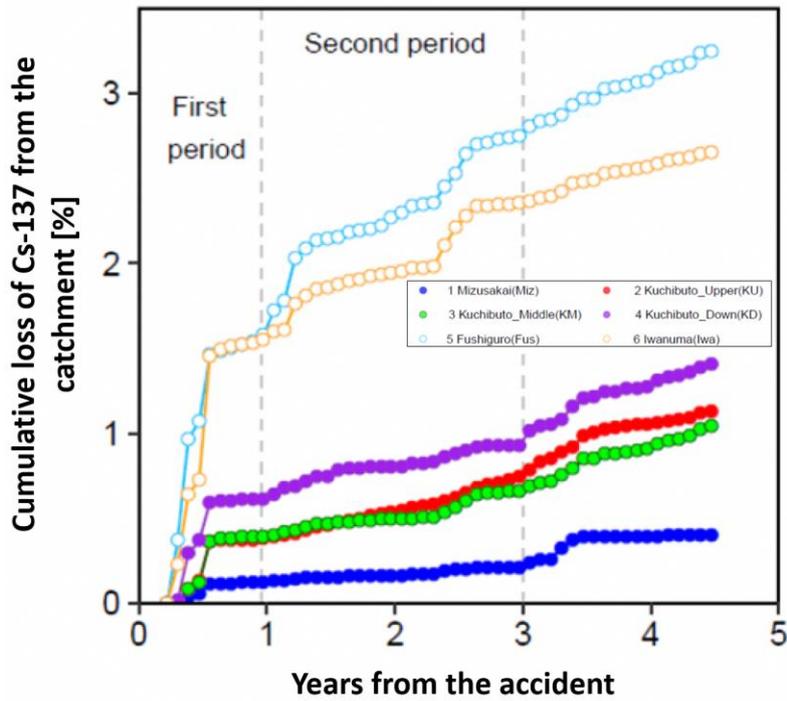


FIG. 3.8: Cumulative loss as function of time from the watersheds of sites 1–6 (Table 3.1) during the period 2011–2016.

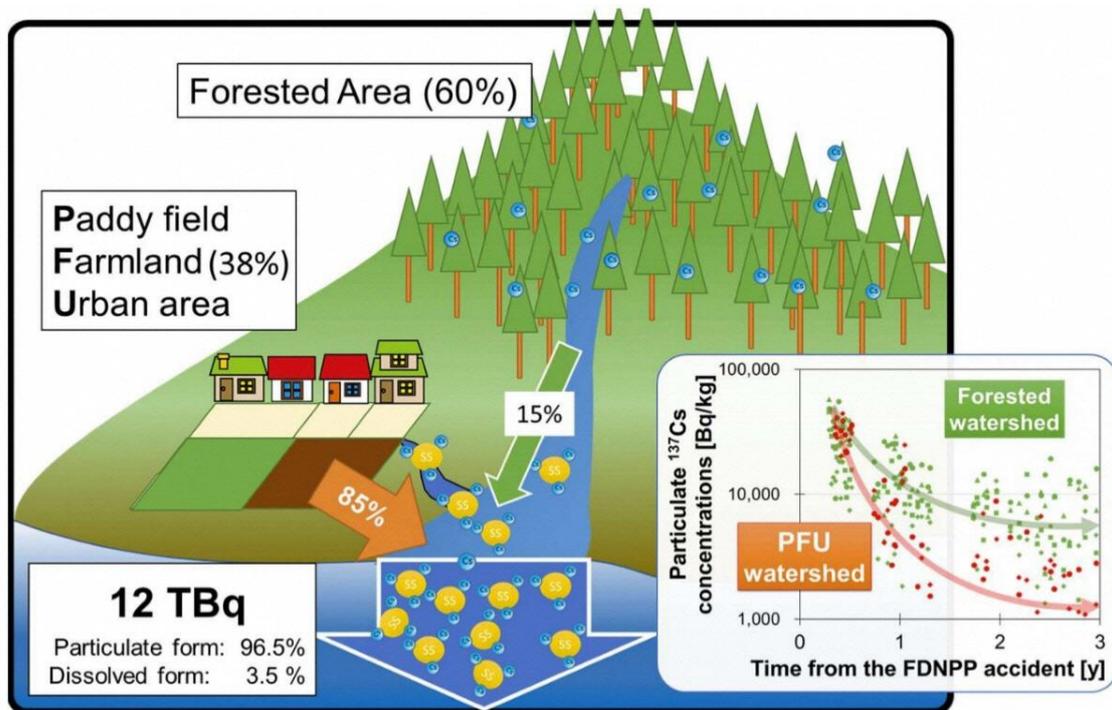


FIG. 3.9: Relative ^{137}Cs fluxes from forested areas relative areas of human activities (paddy fields, farmlands and urban, 'PFU', areas) of the Abukuma River during the five year period following the Fukushima Daiichi accident [22].

3.3.7. Influence of land use on surface runoff

The relationship between the activity concentration and flux of suspended ^{137}Cs and the land coverage ratio was evaluated for different land uses in the Imanuma catchment with a total ^{137}Cs inventory of 470 TBq. From 2011 to 2015, in total 12 TBq ^{137}Cs were lost from the catchment with surface runoff. The study considered forest areas and areas with high human activities (e.g. paddies, farmland, urban areas, 'PFU') (Figure 3.9) It was concluded that the reduction rate for the ^{137}Cs activity concentration and the outflow rate were low in forested areas, but were high in areas of human activities (e.g. paddies, farmland, urban areas) (see Figure 3.9). Areas with human activities contributed a total of 85% of the 12 TBq ^{137}Cs flux from the watershed and forested areas contributed the remaining 15%. These results were reported in a peer reviewed scientific paper in the Journal of Environmental Science and Technology [22].

The flux of ^{137}Cs flux from forest and PFU areas in different time periods was studied as well. The flux in the 9 month period from June 2011 to February 2012 was compared against the 3.5 year period from March 2012 to August 2015 [22]:

- In the first period (i.e. the 9 month period), 0.38% of ^{137}Cs in forests was lost with surface runoff, whereas 4.3% was lost with surface runoff from PFU areas. These results are equivalent to annual fluxes of ^{137}Cs of 0.51%/year and 5.7%/year for forests and PFU areas, respectively.
- In the second period (i.e. the 3.5 year period), the ^{137}Cs flux from forests is like that in the first period. However, the ^{137}Cs flux from PFU areas is lower than in the first period by a factor of 2. The annual fluxes for this period are 0.1%/year and 0.6%/year for forest and PFU areas, respectively.

The data show that the ^{137}Cs flux with surface runoff declines with time. In total, during the whole observation period from 2011 to 2015, approximately 2.5% of the total ^{137}Cs inventory of the catchment was transported out of the catchment with surface runoff from both forests and PFU areas; so, there is significant movement of ^{137}Cs with sediments in the riverbed. However, compared to the total ^{137}Cs inventory of the catchment, runoff is of minor importance in reducing the total ^{137}Cs inventory in the catchment. During the observation period from 2011 to 2015, the ^{137}Cs inventory decreased by approximately 10% due to radioactive decay.

Dissolved and suspended radiocaesium were measured in the Yokokawa dam reservoir in 2014 by the Japan Atomic Energy Agency (JAEA) and National Institute for Environmental Studies (NIES) in the Prefecture in 2014 [40]. The total activity of dissolved radiocaesium in the inflow relative to the outflow of the reservoir were very similar. However, the amount of particulate radiocaesium in the outflow was much less than in the inflow, since the particulate radiocaesium is subject to sedimentation in waters with a very low flow velocity, as is the case for reservoirs and lakes. In this way, reservoirs act as a kind of sediment trap.

3.3.8. The carbon-13/carbon-12 ratio as tracer for identifying the origin of suspended matter in rivers

Since the deposition of radiocaesium in March 2011, dissolved and particulate ^{137}Cs levels have steadily declined as the amounts of radiocaesium entering rivers via surface runoff from watersheds have also been decreasing. However, due to the variations of rainfall, surface runoff is not a continuous process. For a better understanding of the ^{137}Cs transport with surface runoff, the relationships between water level, concentration of suspended sediments and the ^{137}Cs levels in suspended sediments were investigated in the catchment of the Hirose River [41] from

September 2017 to October 2019. Water samples were also taken during and after typhoons to cover both base flow and high flow conditions¹; the following quantities were determined:

- Particulate ¹³⁷Cs in river water (activity concentration per unit volume)
- Particulate ¹³⁷Cs in suspended sediments (activity concentration per unit mass of sediment);
- Concentration of suspended sediments (sediment load in the river water);
- Total organic carbon (TOC) in water and in suspended sediments;
- Caesium-137 and TOC levels in adjacent forest soil, forest litter, riverbank soil and river sediments;
- The ratio of carbon-13 (¹³C) to carbon-12 (¹²C) in forest soil, forest litter, riverbank soil and river sediments. This ratio is quantified by the $\delta^{13}\text{C}$ -signature¹;
- In addition, the fractions of forest soils, forest litter, forest soils, and river sediments in suspended sediments were determined based on the concentrations of ¹³⁷Cs, TOC, and $\delta^{13}\text{C}$ -signature in these media. The fractions were estimated by means of a mixing model for base flow and high flow conditions.

Comparison of ¹³⁷Cs activity concentrations in suspended sediments between base flow versus high flow conditions indicated that ¹³⁷Cs levels were higher during base flow periods. This is consistent with results of work conducted in the Prefecture, which indicated that a dilution effect had occurred when large amounts of sandy particles became suspended in rivers of the Prefecture during a heavy rainfall event in September 2015, resulting in reduced activity concentrations of ¹³⁷Cs in suspended sediments. Additionally, it was found that with increasing concentration of suspended sediments in river water:

- the concentration of particulate ¹³⁷Cs in river water increased;
- the concentration of organic matter in water increased;
- the concentration of particulate ¹³⁷Cs in suspended sediment declined;
- the total organic carbon in suspended sediments decreased; and
- the $\delta^{13}\text{C}$ -level in suspended sediments decreased.

The $\delta^{13}\text{C}$ -signatures, the TOC concentration in water and the ¹³⁷Cs activity concentration in suspended sediments were used to determine the source of carbon in a sample. The $\delta^{13}\text{C}$ -signatures in different media and forest soil samples indicate the origin of the increased amounts of suspended matter in river water. Table 3.5 summarizes the $\delta^{13}\text{C}$ -signatures, the ¹³⁷Cs concentrations and the TOC concentrations in various samples in the study site. There is a clear difference of the $\delta^{13}\text{C}$ -signatures among river sediments, riverbank soil, forest soil, and forest litter. The $\delta^{13}\text{C}$ -signatures for material from the river vary from -25.4 to -26.4‰, whereas the $\delta^{13}\text{C}$ -signatures in forest soil and litter vary from -26.4 to -30.0‰.

¹ Base flow conditions are defined, if the sampling of water was carried out at least 2 days after the last precipitation, TSS concentration varied from 1.5 to 4.2 mg/L.

Sampling under high flow conditions was carried out during and after typhoons, SS concentrations varied from 5 to 930 mg/L.

Table 3.5: $\delta^{13}\text{C}$ -signatures, ^{137}Cs activity concentration, total organic carbon and for river and forest samples [41].

Material	$\delta^{13}\text{C}$ signature (‰)	Caesium-137 activity concentration (Bq/kg)	Total organic carbon (mgC/mg)
Forest soil	-26.9	5400	0.11
Forest litter	-30.0	240	0.47
Riverbank soil	-26.4	470	0.018
River sediment	-25.4	110	0.001

The decline of the $\delta^{13}\text{C}$ signature with increasing concentrations of SS in water — and with a tendency to increasing flow velocities — indicates that the relative contribution of forest soil and forest litter declines. At the same time, the relative contribution of riverbank soils and river sediments to SS increases with increasing concentrations of SS in river water. A simulation of the different contributors to SS confirms this hypothesis:

- Under base flow conditions forest soil contributes nearly 70% to the SS. Riverbank soil and river sediments together contributed approximately 7%.
- At high flow, the TOC concentration in river water increased. However, the relative contribution of forest soil to SS decreased to 48%, while the input of both riverbank soil and river sediments to SS in total increased to about 50%.

3.4. APPLICATION OF SIMULATION MODELS

To facilitate the interpretation of monitoring results, models were applied to simulate the transport of radiocaesium from catchment areas through the river system to the Pacific Ocean. For this purpose, the TODAM model (Time dependent, One dimensional Degradation And Migration) [42] was applied to simulate the ^{137}Cs flux in the Ukedo-Takase River and in the Ogaki Dam reservoir. This model has been applied previously to several other large, medium and small rivers around the world. Previous applications of the TODAM model involved assessments, analysis and evaluation of the transport of radionuclides following releases to the environment as a result of the Chernobyl accident, and from nuclear facilities in Mayak (Russian Federation), Hanford and Savannah River (USA).

The TODAM model can be used to estimate the transport of ^{137}Cs with sediments and water in rivers, taking account of the possible influence of water flow, topography, land use and other factors on radiocaesium dynamics, for example, in the evaluation of the:

- Possibility of using the water for domestic and agricultural purposes;
- Effectiveness of remediation measures to be applied in rivers in support of decision making;
- Effect of recontamination of rivers, which is important for evaluating the persistence of remediation measures;
- ^{137}Cs flux from the catchment area to the ocean.

The TODAM model was applied by the Japan Atomic Energy Agency (JAEA) to simulate the transport of ^{137}Cs in the Ogaki Dam Reservoir and to investigate the role of the dam in the dispersion of radiocaesium. It was determined that the dam reservoir can retain about 90% of the suspended radiocaesium. This result is similar to observations made for the Yokokawa Dam reservoir. The very low water flow rate in such reservoirs favours the sedimentation of suspended sediments.

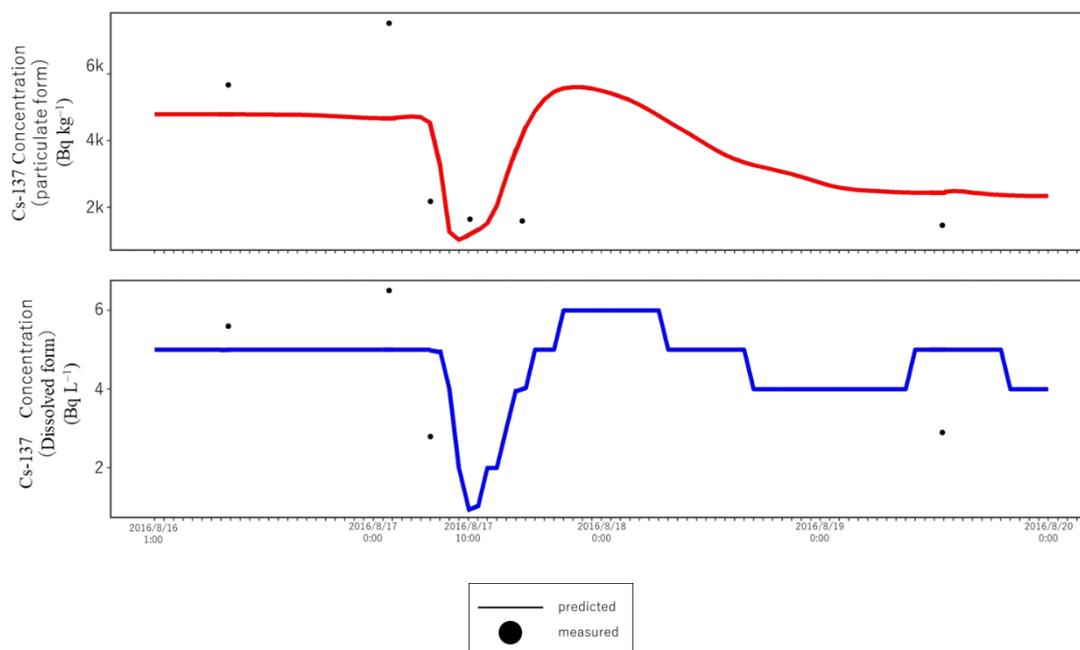


FIG. 3.10: Comparison of ^{137}Cs activity concentration measurements in dissolved and particulate forms over time relative to TODAM model predictions at the lowest downstream monitoring station in the Hirose River during conditions of high water level (Image: Fukushima Prefecture).

In addition, measured ^{137}Cs activity concentrations were compared to those estimated using the TODAM model in the Hirose River basin under conditions of normal and high water levels (see Figure 3.10). In general, there was reasonable consistency between measured and modelled values.

Several workshops involving the IAEA and the Prefecture experts from different Japanese and other international institutions were held, during which experts discussed their experiences in the use of different types of models for radiocaesium prediction in aquatic ecosystems.

3.5. EXPERIENCE WITH REMEDIATION AND DECONTAMINATION IN RIVER AND LAKES

3.5.1. Global experience

In recent decades, a number of areas worldwide have been affected by the deposition of radionuclides. In many cases, freshwater ecosystems were impacted. Examples include the Chernobyl accident, as well as the releases of radionuclides from nuclear facilities in Mayak (Russian Federation), and from the Savannah River Plant and the Hanford site (USA). These global experiences were presented by the IAEA team.

All of these cases were unique; they varied in terms of the areas affected, level of contamination, relevance of different exposure pathways (including aquatic pathways) with regard to exposure of people living in those areas, the magnitudes of doses to people, and the measures taken in the aquatic system to mitigate radiological and social consequences. Following the release of contamination, the IAEA team identified two types of countermeasures that were applied:

- (1) *Technical measures*, such as:
 - removal of sediments from contaminated water bodies;
 - construction of dams to reduce the further dispersion of radionuclides with water;
 - application of substances to increase pH of a water body to reduce bioaccumulation; and
 - construction of sediment traps to accelerate sedimentation of particle bound radionuclides.
- (2) *Administrative measures*, such as:
 - restriction of access to contaminated areas;
 - restrictions for fishing and for withdrawing drinking water and irrigation water and;
 - guidance to the public.

One lesson derived from the analysis of past releases of contamination is that technical measures have only a limited potential to control the dispersion of radionuclides in water bodies and the potential to have significant adverse effects on aquatic habitat. Freshwater systems are often characterized by a pronounced time dependence of water flow rates, mixing dynamics and water levels, which can be associated with significant variation in flow velocities and transport of radionuclides occurs predominantly during temporary periods of high water flow, usually associated with resuspension, displacement and redeposition of contaminated sediments. Such processes are difficult to control; therefore, the sustainability of technical measures often remains limited.

The control of exposures to the public arising from the use of rivers and lakes through administrative measures, such as restriction of access and the implementation of guidance is less complicated. Such measures can be relatively easy to implement and have been proven effective in reducing radiation exposure through aquatic pathways; however, clear instructions and guidance are necessary for successful implementation. Experience shows that the public must be kept informed about such administrative measures as long as they are in place.

Due to the dynamic nature of freshwater systems, once radioactive contamination has occurred, monitoring of radionuclides may be a long term commitment in order to: (1) determine time trends of radiocaesium in water, sediments and as relevant, biota; (2) identify new contamination patterns, which may be created through displacement of material and sediment during high flow and floods; and (3) verify the effectiveness of any applied remediation measures.

3.5.2. Countermeasures to reduce radiocaesium in irrigation ponds

The Prefecture determined radiocaesium activity concentrations in water and sediments in about three thousand irrigation ponds inside and outside the evacuation designated zones in 2014. Since radiocaesium binds strongly to clay particles, the activity concentrations of dissolved radiocaesium in the water of these ponds are orders of magnitude lower than those in sediments. This finding agrees very well with the observations made by the Prefecture for rivers and lakes. In 1% of the water samples collected from irrigation ponds, the activity concentrations of radiocaesium in the dissolved phase were above 1 Bq/L, and these ponds are mainly found inside the evacuation designated zones. The number of ponds with dissolved radiocaesium exceeding 1 Bq/L decreased between 2013 and 2014.

The Prefecture government tested technologies to reduce the activity concentrations of dissolved radiocaesium in pond water. The technologies were selected through open recruitment in 2014 and 2015 and were as follows:

- Separation of the sand, gravel and the clay fractions by means of an underwater device, which takes advantage of the fact that the radiocaesium activity concentrations in sand and gravel particles are much lower than in clay minerals. The sand and gravel fractions remain in the pond, whereas the clay fraction is removed;
- Removal of sediments from ponds and storage in bags, where the material is dehydrated, which reduces the volume of the waste material;
- Installation of silt fences in ponds, which reduces the flow velocities in irrigation ponds and enhances sedimentation. This procedure prevents the outflow of the radiocaesium from the pond;
- Removal of water from the pond and fixation of the sediment in place by adding cement, which binds the sediment together and prevents the outflow of radiocaesium.

The Japanese government developed a manual for countermeasure techniques based on these test results. In the Prefecture, the countermeasures have been implemented in accordance with this manual.

3.5.3. Decontamination measures in riverside areas in the Prefecture

The Prefecture experts presented work on decontamination measures tested in three riverside areas in the Prefecture to reduce air dose rates. These projects are described below and are ongoing.

Evaluation of effect of decontamination on ^{137}Cs in suspended particles

A wide area, multiple point survey was undertaken in the ‘upstream’ section of the Kuchibuto River in the Special Decontamination Area (SDA) of the Prefecture where ^{137}Cs activity concentrations were relatively high, and at ‘midstream’ and ‘downstream’ locations. Radiocaesium survey data for suspended particles was evaluated during the ‘Pre-decontamination’ period prior to February 2013, the ‘Ongoing decontamination 1’ period from March 2013 to March 2014, the ‘Ongoing decontamination 2’ period from April 2014 to December 2015, and the ‘Post-decontamination’ period after January 2016 (see Figure 3.11). Based on this survey, it was determined that the concentration of ^{137}Cs reduction rate increased during decontamination at both upstream and midstream locations, whereas no change was measured at the downstream location.

Demonstration at the Kami-Oguni River

Part of one side of the Kami-Oguni River (approximately 200 m long) is traversed by children as they walk to and from school and is used for recreational purposes by local inhabitants. In August and September 2014 (prior to decontamination), extensive monitoring was carried out by the Prefecture in this area, which included the measurement of air dose rates and radiocaesium activity concentrations in bottom sediments. Decontamination measures, such as weeding, removal of sediments in the low waterbed, and removal of vegetation and soil from the river dykes, were implemented in autumn 2014 (see Figure 3.12). Monitoring data collected before and after implementation of decontamination measures shows that the air dose rates were reduced by about 50% (see Figure 3.13).

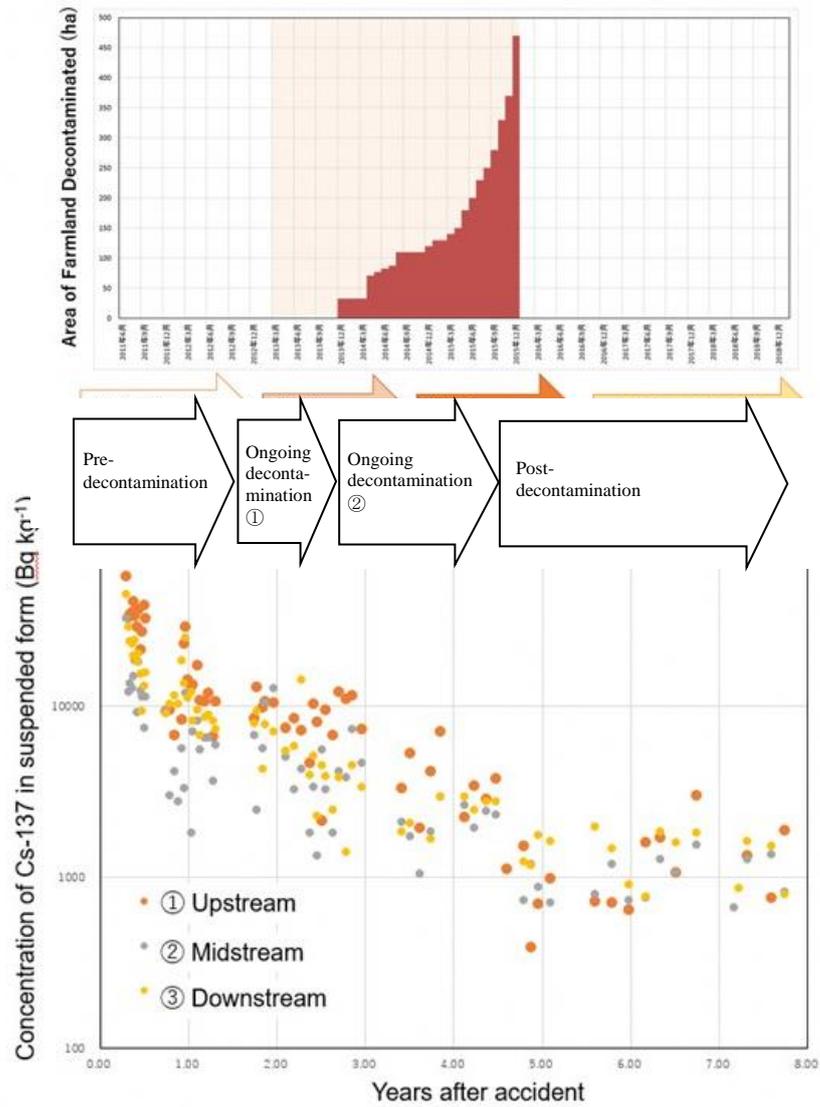


FIG. 3.11: Temporal changes in activity concentrations of ^{137}Cs in suspended sediments during pre-decontamination, ongoing decontamination 1, ongoing decontamination 2 and post-decontamination periods in the Kuchibuto River basin (Image: Fukushima Prefecture).



FIG 3.12: River bed before (left) and after (right) decontamination measures in the Kami-Oguni River [43].

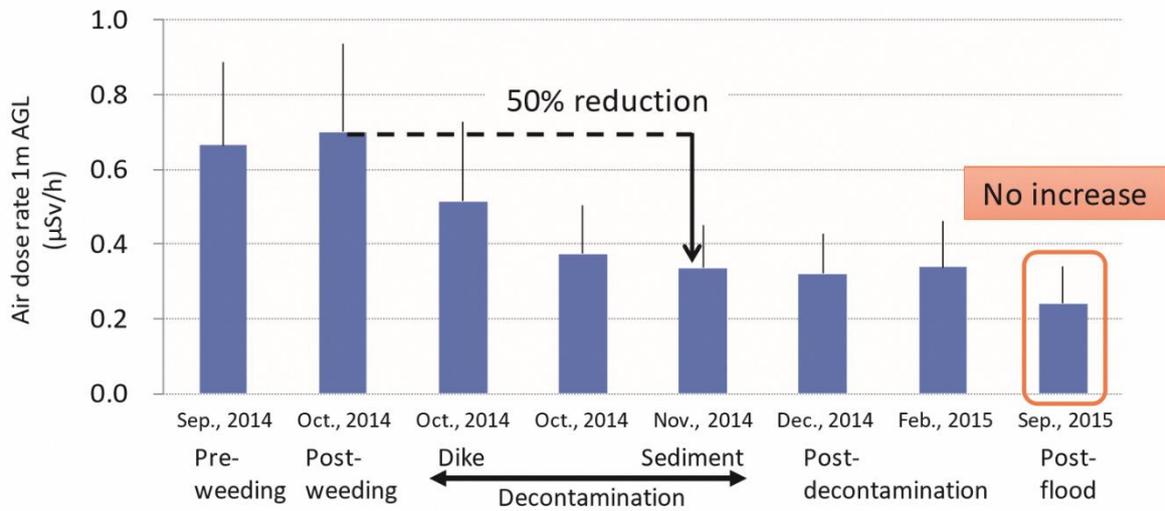


FIG 3.13: Air dose rate at 1 m height before, during and after the remediation and decontamination measures at a river in the Prefecture (Image: Fukushima Prefecture).



FIG. 3.14: Before and after pictures of 2019 excavation work (Sep 2019) and Typhoon No. 19 (12–13 October 2019) in the Kami-Oguni River. Photograph A was taken prior to excavation (27 August 2019) and Photograph B was taken after excavation (30 September 2019). Photograph C (30 September 2019) was taken after the excavation work and before Typhoon No. 19. Photographs D to G were taken after Typhoon No. 19 (18 October 2019). Photograph D was taken at approximately the same location as Photograph C (Images: Fukushima Prefecture).

The area was affected by a severe flood in September 2015, which caused intensive resuspension, displacement and sedimentation of radiocaesium associated with suspended particles. Sediments and vegetation in the river were removed and new material (mainly coarse material and stones) was deposited at this location. Measurements of air dose rate carried out after the flood by the Prefecture (see Figure 3.14) did not indicate significant change in the air dose rate as a result of the flood.

Waterside park at the Niida River

This park is close to a river which is used for leisure and recreational purposes. Air dose rates measured in 2015 by the Prefecture averaged approximately 0.6 $\mu\text{Sv}/\text{h}$. By comparison, air dose rates of 0.20 $\mu\text{Sv}/\text{h}$ were reported in mid-October 2019.

Model simulations performed for this area by the Prefecture indicated that decontamination measures may reduce the air dose rate by about 35% (Table 3.6). Without any decontamination measures, the air dose rate would be expected to decline by about 13% after one year due to radioactive decay. Further reduction of the predicted annual radiation doses due to decontamination measures was assessed by the Prefecture, as well, taking into account local habits and occupancy times for various activities, e.g. walking, cleaning and beautification, and playing in or near the water.

Calculations performed by the Prefecture showed that decontamination measures may reduce the annual effective dose to an individual by 1–15 $\mu\text{Sv}/\text{yr}$. Results of projected individual doses related to the use of this part of the Niida River are given in Table 3.2 above. This analysis underlines that doses resulting from activities at this particular location are quite low.

Flooding in 2015 had a considerable impact on the geometry of the riverbed. Parts of the riverbanks were removed, and at higher elevations of the riverbanks, where the water velocity during the floods was reduced, large amounts of coarse material (mainly sand) were deposited. The dynamic nature of the transport processes makes the assessment of the sustainability of decontamination measures very complex; however, even with the impact of flooding in 2015 on the geometry of the riverbed, measurements made by the Prefecture after these flooding events indicated that the effects of the remedial actions had not been affected significantly. Nevertheless, due to the likelihood of flooding in the coming years, it is important that monitoring of the effects of decontamination efforts are continued.

Table 3.6. Estimation of dose reduction at a demonstration site through decontamination

Item	Activity			
	Recreation	Walking	Cleaning/ beautification	Water activity
Dose rate after decontamination ($\mu\text{Sv}/\text{h}$)*	0.53	0.38	0.39	0.26
Occupancy (hours per year)	16 (4 h/d \times 4 d/y)	111 (1 h/d \times 111 d/y)	48 (1 h/d \times 48 d/y)	9 (1 h/d \times 9 d/y)
Annual additional dose (mSv/y):				
Before decontamination	0.008	0.038	0.017	0.002
After decontamination	0.005	0.023	0.010	0.001
After 1 y without decontamination	0.007	0.032	0.015	0.002

*Derived from air dose measurements over 15 minutes.

Impacts of anthropogenic disturbances and extreme weather events on the Kami-Oguni River

In 2019, the Kami-Oguni River was impacted by both anthropogenic and natural disturbances. The anthropogenic disturbance involved excavation work, which was undertaken to remove sediments and enhance the flow capacity during flooding, as part of routine maintenance (see Figure 3.14).

In addition to the anthropogenic disturbance due to the planned maintenance work, the Kami-Oguni River was also impacted by Typhoon No. 19, which hit Japan 12–13 October 2019 and caused collapse of the riverbank, deposition of sediment, cobbles and rocks, and flooding (see Figure 3.14, Photographs D–G).

Monitoring data collected following Typhoon No 19 indicate that air dose rates on riverbanks impacted by the typhoon have either decreased or remained the same, compared to pre-typhoon values (see Figure 3.15). Air dose rates (1 m above ground surface) measured on the shoreline of the Kami-Oguni River prior to the typhoon (31 January 2018) were $0.34 \mu\text{Sv/h}$, compared to $0.18 \mu\text{Sv/h}$ after the typhoon (17 October 2019).

Findings were similar in the areas of Niida River park ($0.30 \mu\text{Sv/h}$ before and $0.20 \mu\text{Sv/h}$ after Typhoon No. 19) and the Mizunashi River ($0.214 \mu\text{Sv/h}$ before and $0.156 \mu\text{Sv/h}$ after Typhoon No. 19). In both cases, increased air dose rates following Typhoon No. 19 were not observed. At these sites, natural processes have contributed to the reduction of doses and dose rates. Further work is being done to analyze ^{137}Cs in suspended sediments and river water downstream of areas impacted by the typhoon.

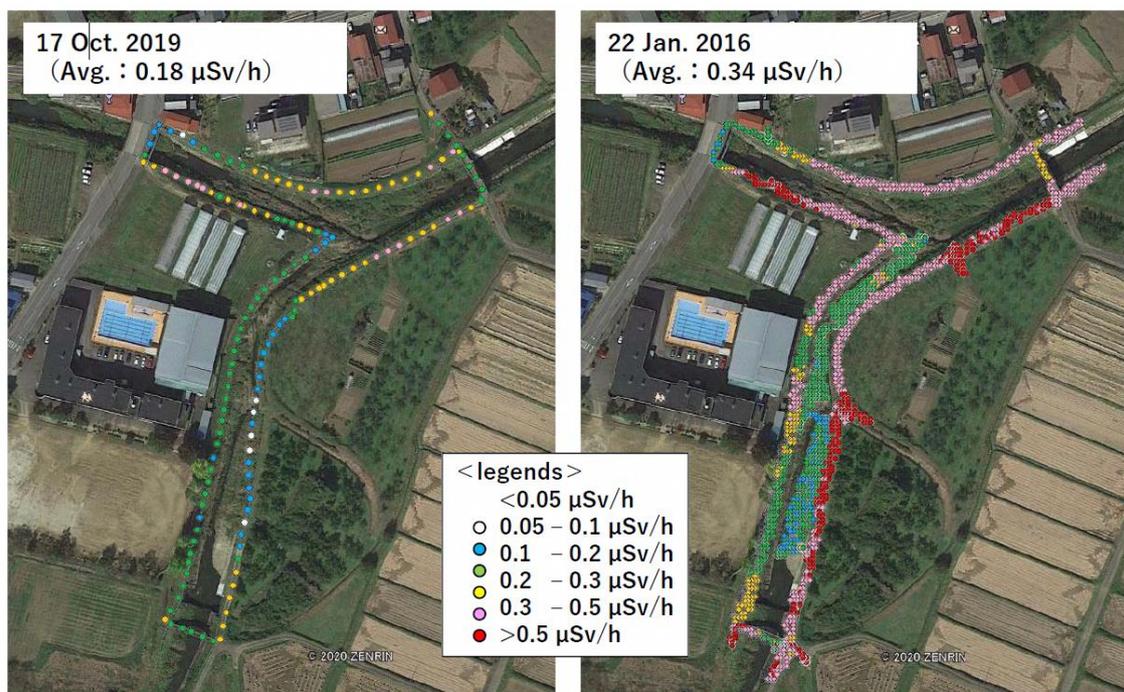


FIG. 3.15: Maps of air dose rates at 1 m height above the ground after and before Typhoon No. 19 (Hagibis) (Image: Fukushima Prefecture).

3.6. EXPERIENCE WITH REMEDIATION AND DECONTAMINATION IN RESIDENTIAL AREAS

In the Prefecture, houses, public facilities, farmland, and roads were decontaminated to reduce the effects of environmental contamination that resulted from the Fukushima Daiichi accident. Some of the most common decontamination techniques that have been applied in the Prefecture are shown in Figure 3.16.

By March 2018, the decontamination activities in the Prefecture (with the exception of the ‘Difficult-to-Return-Zones’) were terminated. In Table 3.7, the status of the effort to decontaminate different categories of buildings and areas within the Prefecture is summarized [44]. Remediation and decontamination activities in the Prefecture were focused on public areas, including routes traversed by children going to and from kindergarten and schools, and on recreational areas.

For assessing the effectiveness of the decontamination activities in residential areas, measurements of air dose rate were taken before and after decontamination. The effectiveness was quantified in terms of reduction of air dose rate in the areas that were subject to remediation.

Specific sets of remedial actions were applied to residential areas, public facilities, roads, agricultural land and forests, respectively. Depending on the type of area treated, air dose rates were reduced by approximately 20–50% (see Table 3.8); such reduction factors are very similar to those achieved by remediation measures in areas affected by the Chernobyl accident. Table 3.8 is based on measurements performed before and after decontamination work that was performed from June 2011 to February 2016. Further details on countermeasures implemented in forests are given in Section 2.

The effectiveness of decontamination work is shown in Figure 3.17 for the ‘Special Decontamination Area’ [45]. Depending on the land use, the average gamma dose rate immediately after the decontamination work was reduced by 44–60%. Six to twelve months after the decontamination work, the gamma dose rate was 55–76% lower than before decontamination; this decrease is due to ongoing attenuation processes relating to migration in soil, street cleaning, and radioactive decay (especially of the relatively short lived ^{134}Cs).

The distribution of the gamma dose rates before and after the decontamination work for the SDA is shown Figure 3.18 [44]. The measurements were performed before, immediately after, and a few months after termination of the decontamination activities. The average value of the gamma dose rate declined from 1.27 $\mu\text{Sv/h}$ (before) to 0.63 $\mu\text{Sv/h}$ (immediately after) to 0.44 $\mu\text{Sv/h}$ (a few months after), respectively. The ongoing decline of the gamma dose rate after the termination of the decontamination work confirms the persistence of the measures; the results indicate that recontamination is a phenomenon of minor importance, if it occurs at all.



Removal of topsoil



High-pressure washing



Removal of topsoil at a school



Removal of sediment from gutters

FIG. 3.16: Main decontamination techniques (Image: Fukushima Prefecture).

Table 3.7. Summary of decontamination completed in the municipalities [44]

Category	Decontamination completed
Residences (total no. of houses)	418 579 (418 897)
Public facilities (total no.)	11 627 (12 376)
Roads (km)	17 701 (20 476)
Agricultural land (ha)	31 196 (31 061)
Forests (in living areas) (ha)	4307 (4513)

Table 3.8. Reduction of the air doses rate due to decontamination work

Category	Number of measurements	Reduction of air dose rate (%)
Residences	117 949	42
School Park	7 783	55
Forests	11 603	21

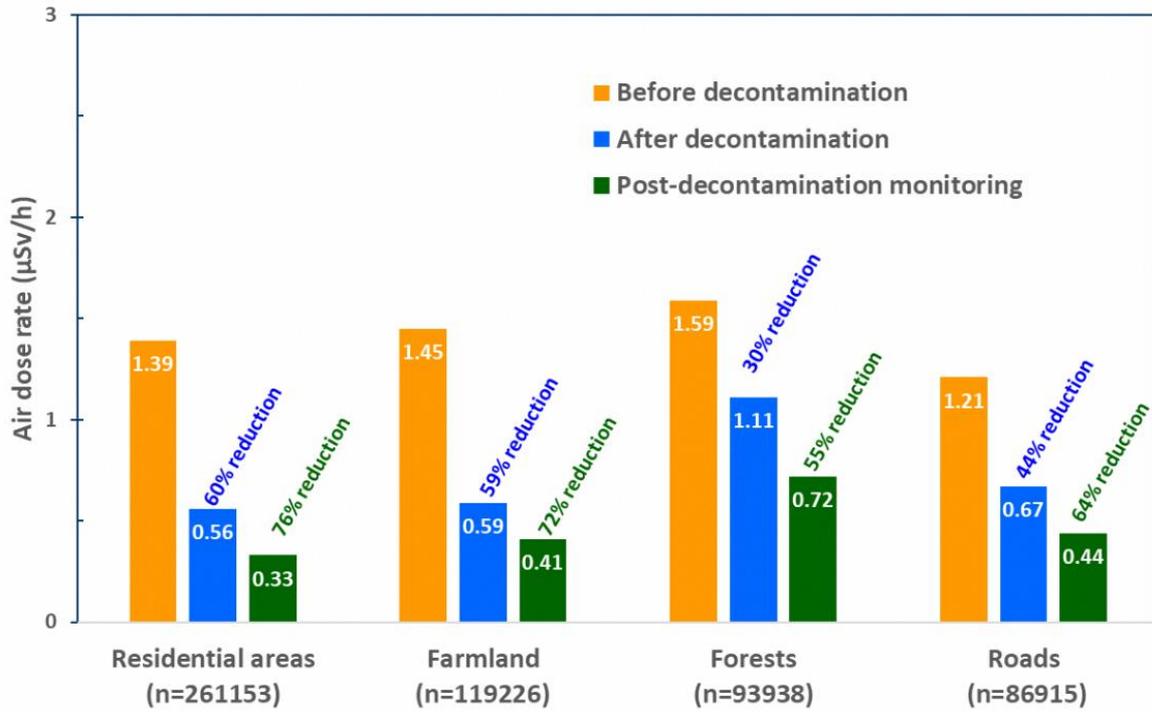


FIG. 3.17: Effect of decontamination work for different land uses in the Special Decontamination Area (redrawn using data in Ref. [45]).

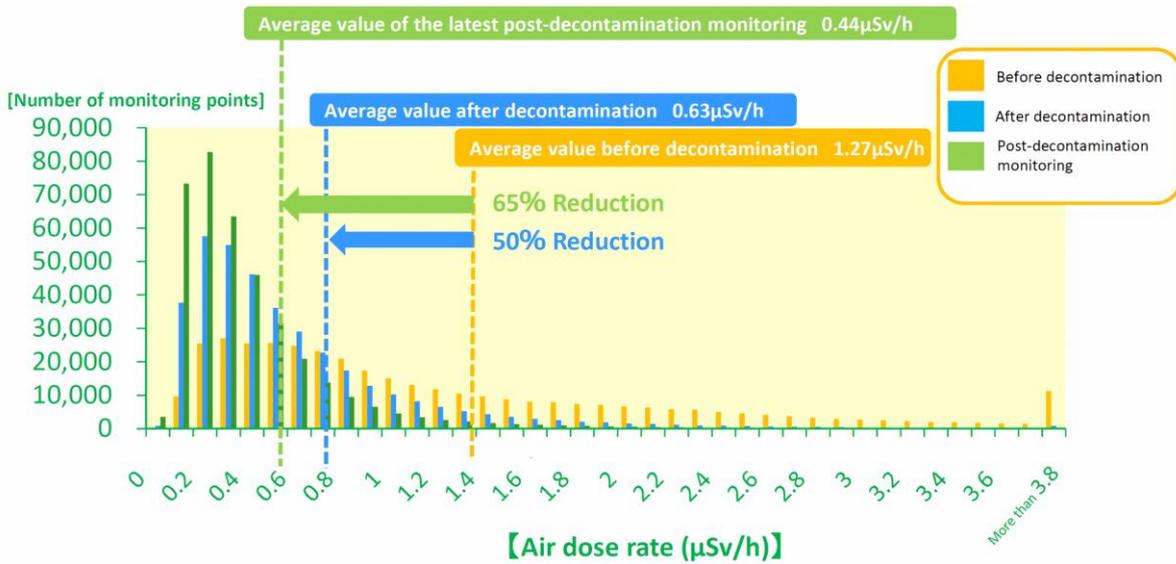


FIG. 3.18: Distribution of gamma dose rates in the Special Decontamination Area (SDA) before and after decontamination work [44].

3.7. SECTION SUMMARY

The behaviour of radiocaesium in ecosystems has been studied for the last several decades. In general, in the terrestrial environment, caesium is strongly bound by mineral soil components, which results in slow movement in soil and a low uptake by plants from soil. In freshwater ecosystems, caesium is in general strongly bound to suspended sediments, which deposits on the bottom of surface waters and causes a rapid decline of dissolved radiocaesium in the water column. Sorption of caesium to suspended sediments, therefore, plays a key role in its environmental behaviour.

The physicochemical conditions in surface waters (e.g. pH, basin bathymetry, depth, concentrations of suspended sediments and potassium) can also affect transport of particles which bind radiocaesium and radiocaesium dynamics. Such conditions might explain the generally stronger radiocaesium sorption onto soils and sediments that was measured under the conditions in the Prefecture compared to Ukraine and Russian Federation after the Chernobyl accident [46].

The IAEA team and Prefecture experts have agreed that continuation of routine monitoring of radiocaesium in river catchments of the Prefecture is important to assess temporal and spatial changes. This includes monitoring within a river drainage basin, where water collects, as well as in the tributaries that carry radiocaesium from upstream of the basin into larger rivers downstream. In conducting such monitoring to assess radiocaesium dynamics through time and space, it was agreed that it is important to apply standardized sample collection and storage procedures, and where relevant, standardized expression of monitoring results, to facilitate intercomparison between aquatic systems, which in turn allows the results to be compared with international literature.

In the freshwater bodies of the Prefecture (within less than 7 years of the accident), dissolved radiocaesium levels in water were close to or below 0.05 Bq/L, a value far below the World Health Organization (WHO) [14] recommended quality criterion for ^{137}Cs in drinking water of 10 Bq/L. There also continues to be a clear decline of the concentration of radiocaesium in suspended sediments.

Usually, the time dependence of ^{137}Cs in river water can be described by exponential functions with one to three components representing different phases after the deposition, as follows:

- Immediately after deposition, a decline of ^{137}Cs in European rivers according to an effective half-life of 5 days during a period of about 2–3 weeks was observed. However, many data sets do not include the initial phase with the fast decline.
- Most data sets cover an observation period of 5–15 years starting several months after radionuclide deposition. For rivers in the Fukushima Prefecture, the values for the effective half-life of ^{137}Cs in rivers for 48 sites are ranging 0.7–16 years. Only 3 values were below 1 year, and only three values were above 5 years. Forty-two values were in the range 1.1–4.6 years.
- If the observation period is long enough, in some cases a third phase can be identified. However, quantifying a third decline component requires observation times of at least 15 years. For the studies in the Fukushima Prefecture, such long observation periods are not possible. In water of 25 rivers in Europe and West Asia, a long term component with an effective half-life of 16 years was identified. The contribution to the overall decline of this component was only 0.5 percent and the relevance, in practice, is of minor importance.

— By and large, the time trends observed in the Prefecture agree reasonably well with those observed in other parts of the world after the Chernobyl accident and the general pattern of the decline is quite similar.

The reduction of the radiocaesium levels in the environment is mainly caused by radioactive decay, whereas runoff of radiocaesium provides a further contribution to the reduction. The cumulative losses of ^{137}Cs activity between 2011 and September 2015 from the catchments of the Abukuma and the Kuchibuto tributary were about 3% (2.5–3.5%) and 1% (0.7–1.5%), respectively. The loss of ^{137}Cs due to runoff is influenced by the land use. The loss of ^{137}Cs increases with increasing fractions of rice paddies, farmland, and residential areas. Decontamination activities in catchment areas cause a higher runoff of soil and of ^{137}Cs sorbed to soil particles.

Measurements of radiocaesium in reservoirs have shown that the amount of suspended radiocaesium in the outflow is much less than in the inflow. This indicates that reservoirs act as a kind of sediment trap.

The density of plankton in freshwater bodies in the Prefecture was very low and the total radiocaesium activity incorporated into phyto- and zooplankton did not exceed a small fraction of a percent of the radiocaesium present in the water bodies studied.

To facilitate the interpretation of monitoring results, models were applied by the Prefecture to simulate the transport of radiocaesium from the catchment area through the river system to the Pacific Ocean. The Prefecture recognized that models were also very useful in selecting appropriate remedial options and assessing the effectiveness of remediation measures being applied in rivers. In addition, simulation models allowed the assessment of the effect of recontamination of rivers.

International experience shows that decontamination work in rivers is challenging due to the dynamic nature of flowing waters. Engineering measures are costly and often difficult to implement. Usually, the experiences shows that the overall impact on public doses remains low. To reduce exposures to the populations, restrictions on the abstraction of drinking water and fishing were most effective.

Following both the accidents in Fukushima and in Chernobyl, particles with enhanced levels of radionuclides were detected. The Chernobyl ‘hot particles’ are fuel fragments, and they are different from the CsMPs which are found in the Fukushima deposited material. CsMPs are smaller and contain much lower activities than those released from the Chernobyl reactor.

Since 2011, intensive remediation and decontamination work has been carried out by the Prefecture in private homes, public facilities, roads, agricultural land, and parts of the forests close to inhabited areas, with particular focus on public areas, including routes traversed by children going to and from kindergarten and schools, and on recreational areas. Depending on the type of area, the Prefecture observed that air dose rates were reduced by circa 20–50%, similar to results achieved by remediation in areas affected by the Chernobyl accident. Decontamination of residences (houses) in the Prefecture was completed by March 2018.

In addition, the Prefecture has initiated a number of projects in and around freshwater bodies to demonstrate the effectiveness of implementing decontamination measures. These measures have been found to reduce air dose rates. Based on international experience, the IAEA team indicated that administrative measures, such as restrictions and guidance to reduce exposure via freshwater pathways, are relatively easy to implement compared to technical measures (e.g. sediment removal) and tend to be more effective.

4. MANAGEMENT OF WASTE FROM REMEDIATION ACTIVITIES

4.1. BACKGROUND AND OBJECTIVES

As stated in Technical Volume 5, *Post-accident Recovery*, of the IAEA's *The Fukushima Daiichi Accident Report* [47]:

“According to the decontamination plan formulated by the MOE (Ministry of the Environment), contaminated soil and waste generated from remediation in the Prefecture are to be collected and stored at, or near, the sites undergoing remediation in temporary storage facilities. Afterwards, the material will be placed in the ISF (Interim Storage Facility). After interim storage for up to 30 years, final disposal will take place outside the Prefecture.”

The ISF is to be developed and operated by the central government. Temporary storage sites (TSS) were established in municipalities and the Prefecture based on laws and government guidelines. After the Fukushima Daiichi accident, the Prefecture performed a significant amount of work concerning remediation activities and the management of the resulting radioactive waste.

The radioactive waste that resulted from remediation activities required urgent but also safe and sustainable management. The IAEA team advised that the applicable IAEA Safety Standards should be used. When activities under the Practical Arrangements commenced in 2013, the Prefecture was faced with an urgent shortage of TSS in which to store waste from remediation activities. Furthermore, concerns were raised by the public about the safety of existing TSS, and prospective TSS that were to be established to accommodate radioactive waste generated by ongoing remediation activities. Later, it became necessary to store waste in TSS for greater time periods than was originally intended. TSS were established with the intention that waste would be stored in these facilities for only three years before being transferred to the ISF. However, it has become necessary to store waste in TSS for more than three years because the transportation of the waste from the TSS to the ISF has taken longer than expected. It has therefore become an issue that needed evaluation to ensure the safety of these facilities and to address public concerns.

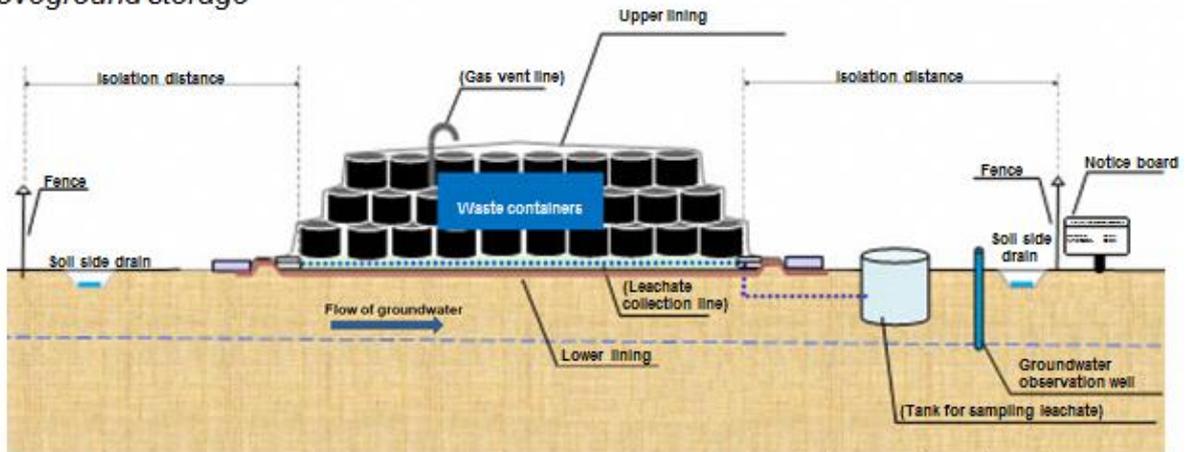
The activities concerning the management of waste from remediation activities under the Practical Arrangements consequently focused initially on providing assistance to the Prefecture in finalizing technical guidelines for the establishment of temporary storage facilities and assisting the Prefecture in demonstrating the safety of temporary storage facilities. As time has passed, the provision of assistance shifted gradually to focus more on the safety of the longer term operation of the TSS, on strategies for the retrieval of waste from the TSS, and on the remediation and long term safety of the former TSS. A key aspect of the assistance provided by IAEA has been to facilitate the sharing of expertise and experiences of relevant radioactive waste management practices from outside Japan.

4.2. TEMPORARY STORAGE SITES

Three main types of TSS have been established in the Prefecture: aboveground storage, semi-underground storage and underground storage, each of them having advantages and disadvantages with regard to ease of construction, transfer of waste to the ISF, stability, etc. Figure 4.1 provides conceptual diagrams of three types of design for TSS.

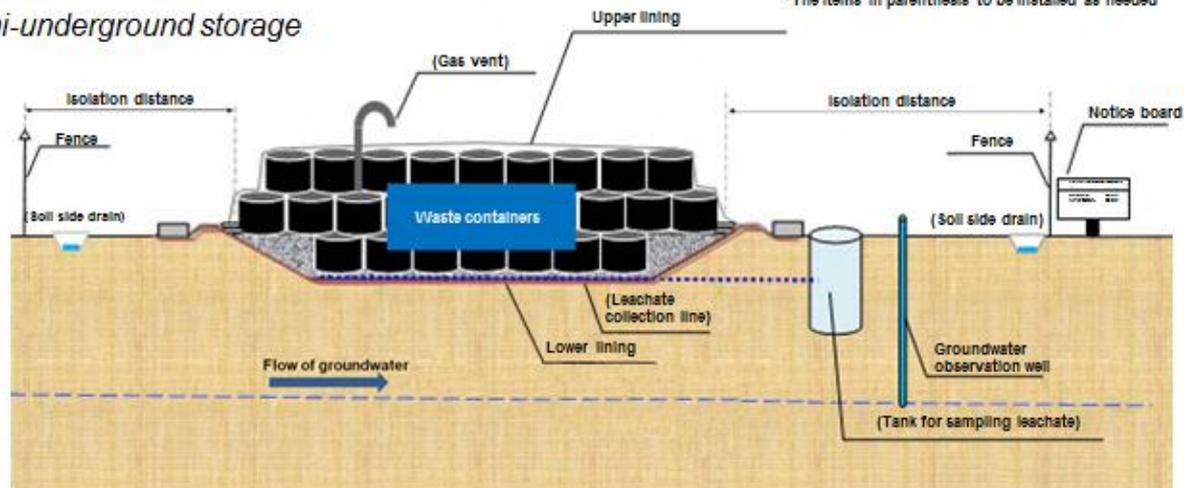
As of September 2022, 151 TSS remain in municipalities within the Intensive Contamination Survey Area. As indicated by Figure 4.2, the number of TSS increased rapidly from 2013 to 2014, peaked in 2015 and has since slowly decreased.

Aboveground storage



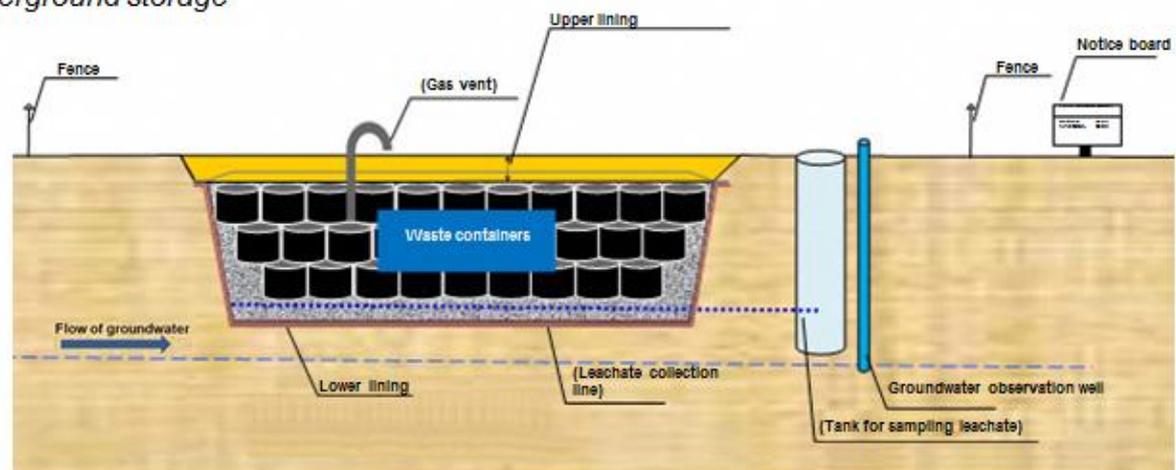
*The items in parenthesis to be installed as needed

Semi-underground storage



*The items in parenthesis to be installed as needed

Underground storage



*Items in parenthesis to be installed as needed

FIG. 4.1: Conceptual diagrams of three types of TSS (Image: Fukushima Prefecture).

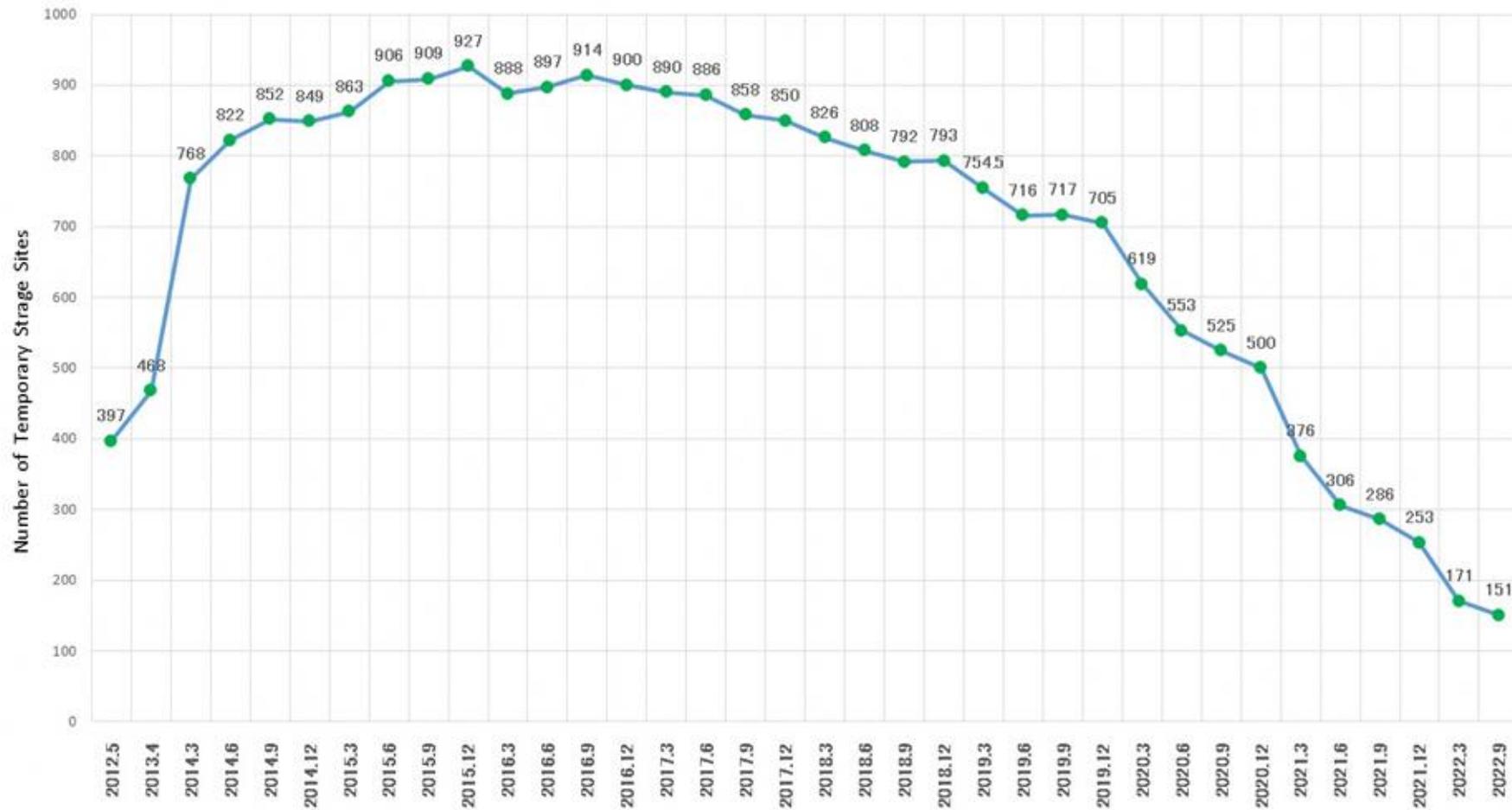


FIG. 4.2. Number of TSS in Municipalities from March 2012 to September 2022 (Image: Fukushima Prefecture).

After the emplacement in TSS of bags containing waste from remediation activities, various phenomena were observed and concerns were raised concerning some of the storage facilities including:

- Limitations on the number of waste bags that could be stacked;
- Effect on long term stability and integrity of stored waste bags resulting from lack of rigidity of the bags and voids between the bags;
- Uncertainty in the long-term stability of facilities established on sloping land;
- Potential leaching phenomena;
- Degradation of the organic matter in waste storage bags and potential impact on the integrity of the storage facility;
- Gradual caving in of the waste bags and accumulation of water in the resulting depressions in tarps covering the stored waste bags;
- Risks of fires due to auto-combustion of the contents of waste bags.

4.3. DEVELOPMENT OF TECHNICAL GUIDELINES FOR TEMPORARY STORAGE SITES

When the activities under the Practical Arrangements began in 2013, intensive remediation activities were being conducted in the Prefecture and many new TSS were being established to store the resulting waste. In 2013, the Prefecture had been developing a guidance document on the establishment and operation of TSS. At this time, as part of the further development of the guidance document, the IAEA team encouraged the Prefecture to take stock of their experience with the development and operation of TSS. Consequently, an analysis was conducted of the activities carried out so far regarding the development of TSS in the different municipalities. This analysis aimed at identifying the main issues affecting TSS, identifying good practices implemented, and comparing the different strategies for developing TSS in the different municipalities. The aim of this approach was that it would serve as a basis for development of an overall harmonized strategy for the development and operation of temporary storage sites in the Prefecture and for the eventual removal of waste from the TSS and the cleanup of the sites.

The IAEA team provided technical advice and feedback to the Prefecture experts concerning the development of the guidance document on TSS including reviewing the draft text and providing comments on its content. Version 1 of Technical Guidelines for Temporary Storage Sites was published in August 2013. Subsequent revisions to this document were issued in June 2014 (Version 2), March 2015 (Version 3), March 2016 (Version 4), August 2017 (Version 5) and September 2019 (Version 6).

Version 6 of the Technical Guidelines were presented, reviewed and discussed at the mission held in Fukushima during 1–8 February 2020. The IAEA team considered that the 6th Version was generally sensible and pragmatic and should help to optimize the waste management process. The IAEA team suggested:

- The need to further elaborate procedures for dealing with water removed from the waste bags.
- The need to further address the issue of whether underground tanks used for the collection of contaminated water at some of the TSS can be safely left in the ground, or whether the tanks should be removed.
- The need to ensure that the number of measurement points used to verify satisfactory cleanup of a restored site is appropriate for the size of the site.

- The need to further address the guidelines for the retention of records and the transfer of the sites of former TSS back to the landowners.

The Prefecture has considered these suggestions in the Technical Guidelines for the TSS.

4.4. DEVELOPMENT OF A SAFETY ASSESSMENT FOR TEMPORARY STORAGE SITES

When managing radioactive waste, the operator of relevant facilities and activities (e.g. TSS) is required to provide a demonstration that the facilities and activities are safe. The IAEA team advised that, according to the IAEA Safety Standards, this demonstration of safety should be used to support the authorization of the facilities and activities by the regulatory body. The demonstration of safety, in particular, aims at representing the various aspects of the site and the facility design to allow the regulatory body to have confidence that the facility or activity may be developed, operated and closed safely so that people and the environment are protected from harmful effects of radiation now and in the future. In accordance with the IAEA Safety Standards, the demonstration of safety should be supported by quantitative evaluation of the radiological impact (safety assessment) of the facility or activity at each stage, under normal operating conditions and accident scenarios.

The development of a safety assessment involves identifying all relevant features, event and processes that could affect safety, such as site characteristics, the designed safety features of the facility, the characteristics of the waste and its containers, and then using this information together with appropriate models and parameter values to quantitatively assess the impact of the temporary storage sites.

Prior to the commencement of the activities under the Practical Arrangements, the Prefecture experts had no experience in the performance of safety assessments as required by the IAEA Safety Standards. Therefore, training and assistance was provided on the development of safety assessment for the TSS. This proceeded in a stepwise fashion, beginning with an educational phase and followed by subsequent phases in which the IAEA Safety Assessment Framework software tool (SAFRAN)¹ was applied first to a ‘model’ site, then on a trial basis to a site in the Prefecture, and then to several selected TSS in the Prefecture. The safety assessment development process is presented schematically in Figure 4.3.

4.4.1. Safety Assessment Framework software tool

The IAEA methodology for safety assessment of the predisposal management of radioactive waste is provided in the General Safety Guide, GSG-3, The Safety Case and Safety Assessment for the Predisposal Management of Radioactive Waste [48]. GSG-3 [48] provides recommendations on meeting the safety requirements in GSR Part 5, Predisposal Management of Radioactive Waste [49]. In order to facilitate the application of this methodology, the IAEA developed a Safety Assessment Framework Software Tool, SAFRAN, to guide the user in performing a systematic and structured safety assessment of facilities and activities for the predisposal management of radioactive waste. As such, SAFRAN is suitable for used in developing a safety assessment for the TSS in the Prefecture. SAFRAN has various modules concerning site and waste stream characteristics, postulated scenarios, and regulatory requirements, as well as tools for performing quantitative analyses. The software has its own databases, which can be adjusted enhanced with further data according to available evidence and user needs.

¹ <http://safran.facilia.se/safran/show/HomePage>

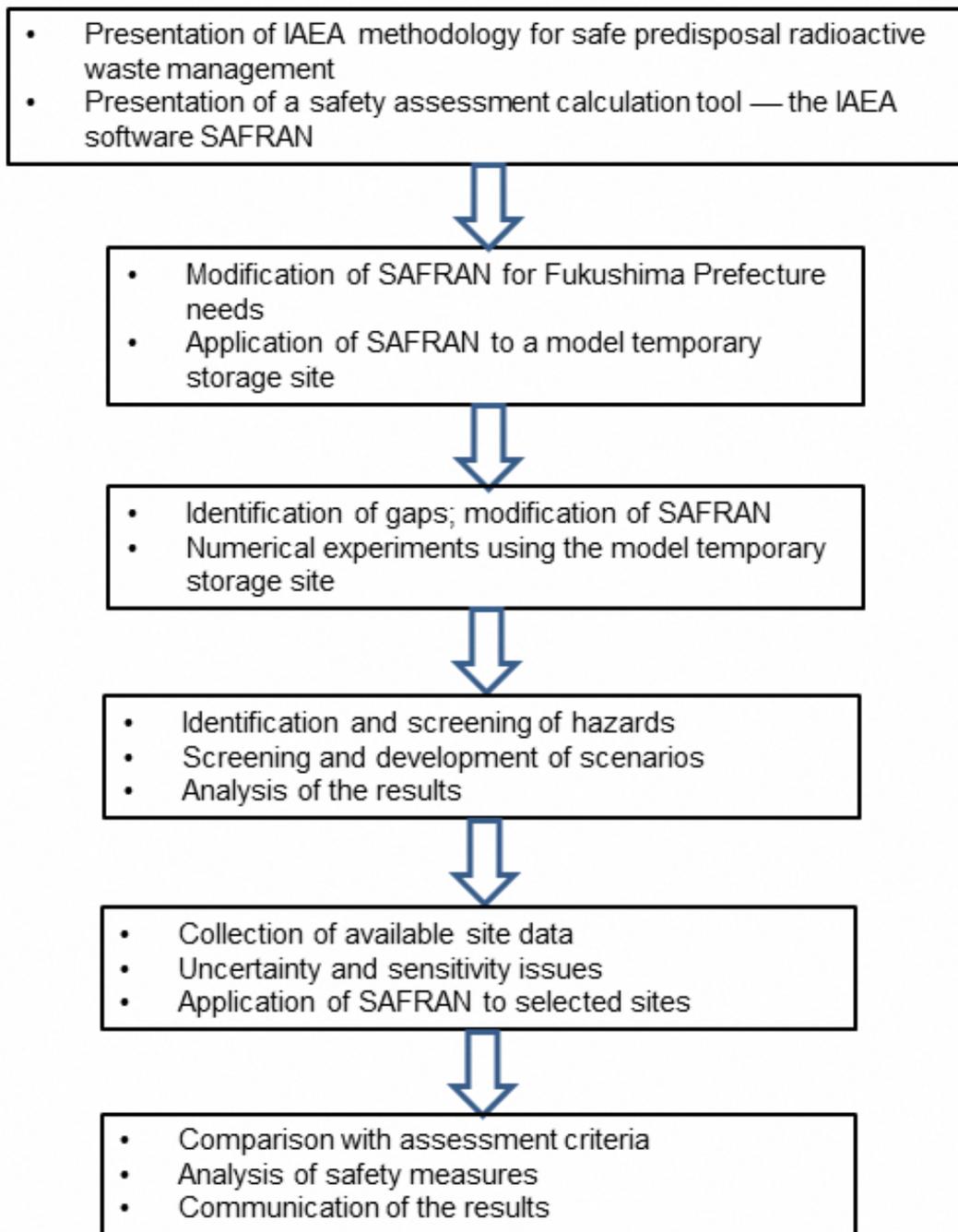


FIG. 4.3: Activity flow of the development of a safety assessment for TSS in the Prefecture.

The demonstration of the safety of the TSS developed under the Practical Arrangements was supported by the use of SAFRAN. In some cases, this involved adapting SAFRAN so that it could be better applied to the specific situations in the Prefecture.

4.4.2. Building capacities of the Prefecture for performing safety assessment of temporary storage sites

In 2014, an IAEA team conducted a training session for the Prefecture experts that addressed the demonstration of safety (including safety assessment) and specifically the use of SAFRAN for TSS. Information about the IAEA methodology for the evaluation of the safety of predisposal management of radioactive waste as established in the IAEA Safety Standards was provided. The IAEA team and Prefecture experts identified the purpose, scope, approach and endpoints of activities concerned with safety assessment of TSS. Key elements of the regulatory framework relevant to the safety assessment which were identified are dose limits for occupationally exposed individuals and dose limits for the public in accordance with the IAEA Safety Standards, both for normal operating conditions and accident scenarios; these values were then entered into SAFRAN.

SAFRAN was adapted by the IAEA to consider the structure of an ‘open type’ TSS with several layers of bags containing radioactive waste from remediation activities, liners on the top and bottom of the stacked waste bags, and various types of cover and radiation shielding.

During the subsequent period, from 2014 up to and including 2022, further advice has been given to the Prefecture experts on safety assessment (e.g. on regulatory criteria, on scenarios, on safety assessment tools, on the possibilities for verification of safety assessment results using measurements), and relevant experiences in countries outside Japan (e.g. in Brazil, Sweden, UK, Ukraine, US) have been presented and discussed.

To address specific questions that are becoming more relevant as time passes since the Fukushima Daiichi Accident, including the potential migration of radiocaesium into groundwater at TSS and the suggestion from the IAEA team that some materials might not need to be managed as radioactive waste because they contain extremely low levels of radioactive contamination, training has been provided on further safety assessment tools, including ECOLEGO and Normalysa¹.

The process of development of a safety assessment for TSS should also include the sharing and explanation of the results of the assessment the interested stakeholders, such as members of the public. As such, assistance was provided to the Prefecture experts on the explanation and dissemination of the results of the safety assessments made for each stage of facility development.

4.4.3. Safety assessment for a ‘model’ temporary storage site

As an educational tool for the Prefecture experts and to assure the applicability of the safety assessment methodology including the use of SAFRAN, the IAEA methodology was initially applied to a ‘model’ TSS having generic but conservatively estimated site, facility and waste characteristics. A schematic depiction showing the distance from stored waste to a location where radiation doses would be evaluated is shown in Figure 4.4. Three general activities concerning waste bags and the model TSS were addressed by SAFRAN: waste emplacement, waste storage, and waste retrieval. Safety assessments for the sites of former TSS from which the waste has been removed to the ISF are discussed in Section 4.6.

¹ <http://project.facilia.se/normalysa/software.html>

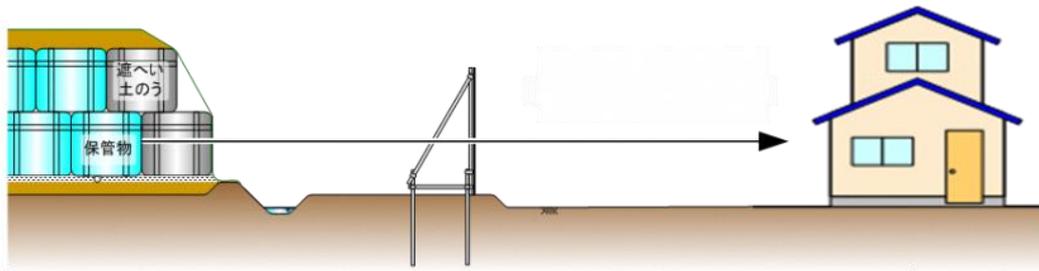


FIG. 4.4: Typical layout for a TSS. Radiation doses are calculated with respect to the distance from stored materials (Image: Fukushima Prefecture).

The safety of the TSS, depends on the characteristics (e.g. activity level) of the waste, robust design and appropriate construction and operation of the facility. The most important design features are those that provide necessary assurances that the radioactive waste can be handled, stored, retrieved, etc. without undue risk to workers, the public or the environment. Understanding of detailed facility design and fundamental assumptions upon which the design is based is necessary in order to assess the safety of the facility currently and in the future. Even though a TSS is not a complicated civil engineering structure, it still has several important safety features which have to be properly quantified and understood. Therefore, the work started with definition of parameters used in assessment models and which describe the range of conditions under which the facility may operate.

Discussions were held concerning the data to be entered into SAFRAN. When available, actual data were used. For parameters that could not be established with a high degree of accuracy, a process for conservatively estimating such information was implemented by the Prefecture experts. This approach was used throughout the development of the safety assessment.

Information about the radioactive waste to be stored was gathered, including a set of physical, chemical, biological, radiological and other data, and information about the waste packages, i.e. characteristics of the waste bags in which the waste is stored. Waste streams, inventories, throughput rates, and activity concentrations, etc. were estimated as required for quantitative assessments in SAFRAN. Other parameters important for the safety assessment, such as the vicinity of the nearby houses, data about the site, the engineering features, etc. were collected and/or estimated by the Prefecture experts.

A hazard analysis was performed based on an in depth analysis of waste management activities at the model TSS, which addressed the hazards under normal operation conditions and which could result from accidents. An initial screening of the hazards was performed and hazards which were not relevant for the model TSS were excluded. A final screening of specific scenarios was performed based on qualitative assessments of the likelihood of identified events and the significance of possible impacts.

After defining the parameters needed for safety assessment, it became necessary to slightly adjust SAFRAN in order to represent the design aspects of the existing and planned TSS in the Prefecture. One specific change was made to SAFRAN so that it could analyze releases of radioactive material to air and to groundwater.

Joint discussion and analysis of data emphasized that results of the safety assessment should be used to facilitate exchange between interested parties on issues relating to the safety of TSS. Through the step by step approach, the Prefecture could engage with the public concerning any specific decision points.

Normal operating conditions

The assessment of the impacts of normal operations at a model temporary storage site included calculation of annual radiation doses to both occupationally exposed persons and residents living in the vicinity of the facility. An occupationally exposed worker may receive a radiation dose under varying conditions, e.g. during the emplacement of the waste packages, or during their removal. Nearby residents could be exposed due to direct exposure during the emplacement/replacement operations. However, under normal operating conditions these exposures are very small. Under normal operating conditions the assessed exposures during the storage period were shown to be a small fraction of the radiation dose limits.

The doses for normal situations were assessed for the case in which all operations were performed as planned, assuming the operators spend an average amount of time to perform tasks involving exposure to radiation, and assuming average air dose rates expected during these activities.

SAFRAN was used to evaluate TSS of three different sizes representing existing and planned TSS in the Prefecture. For these three model facilities, various shielding configurations were assessed, such as the use of sand bags and soil spread on the top of the facility.

Calculations were performed with SAFRAN in which the distance from the TSS to the nearest residential buildings was varied from 1 to 100 meters.

External exposures of people were calculated based on measured air dose rates, average residence times and taking account of shielding effects. Internal exposures were calculated on the basis of radionuclide dependent activity concentrations, dose conversion factors, and residence times. The total dose to members of the public was calculated by summing the external and internal exposures.

Accident scenarios

Deviations from planned operating conditions may cause unplanned exposures of workers and the public. The safety assessment of the model TSS, therefore, also included an assessment of hazards resulting from accidents throughout the life of the facility.

The Prefecture experts performed a comprehensive analysis of the possible impacts of accidents on the TSS following the IAEA methodology. The assessment of impacts from accidents required detailed consideration and analysis of possible initiating events. These events were analyzed and a list of resulting potential scenarios was created. As expected, the fact that the engineering structure of the model TSS is relatively simple, does not exclude scenarios which required further examination and the potential need for countermeasures.

The hazard screening process excluded irrelevant exposure pathways (including those with an extremely low probability of occurrence).

Regarding the choice of the accidental scenarios, and having in mind the layout and structure of a TSS, various scenarios were considered such as waste bags falling to the ground, damage to waste bags due to various causes such as high temperature, snow and high winds, and damage to the facility by various means such as earthquakes and fire.

Accidental releases into the atmosphere (e.g. as a result of fires at the facility) may cause exposures of the workers at the site and/or the public. Accidental releases into water pathways (e.g. rivers, groundwater) may be more relevant to exposures to the public than to workers.

Conclusions regarding application of SAFRAN to operations at a model temporary storage site

The use of SAFRAN to represent waste emplacement, waste storage and waste retrieval at the model TSS formed the basis for applying the safety assessment to several representative TSS.

The assessment for normal operational conditions clearly showed that shielding in the form of protective walls made of sand bags can significantly reduce the radiation doses to the nearby population. Adding soil on the top of the facility further reduces predicted radiation doses by an order of magnitude, to a level that is significantly less than 1mSv/year. Regarding operational radiation protection, assessed doses to workers for normal operating conditions were also below the occupation radiation dose limits, even using conservative assumptions.

Based on input data developed by the Prefecture experts and the use of SAFRAN involving many different numerical simulations, was concluded that for normal operational conditions, the model TSS has been designed properly, and would not cause any undue risk to workers at the sites or nearby residents.

Calculated potential doses to occupationally exposed workers resulting from accidents generally do not exceed 1mSv, including in assessed extreme cases.

When considering radiation doses to the public as a result of accidents, the analysis of most scenarios predicted doses to the public that would be a small fraction of applicable dose limits. However, certain scenarios that were analyzed indicated that the public could receive doses in excess of 0.5 mSv and, therefore, that further analysis of these scenarios should be performed and the possible need for the implementation of countermeasures should be considered under these circumstances.

Based on the analysis performed, the potential for radioactive material leaking from the TSS into groundwater and rivers is very limited, resulting in very low potential radiation doses from exposure to groundwater and from the consumption of fish.

4.4.4. Trial safety assessment of a real temporary storage site in the Prefecture

Following the successful application of SAFRAN to operations at a model temporary storage site, the Prefecture experts applied the IAEA safety assessment methodology to an existing temporary storage site in the Prefecture. The lessons learned and the experience gathered through this activity were designed to facilitate development of the safety assessments for other TSS. As with the safety assessment for the model facility, the trial safety assessment involved the use of SAFRAN to evaluate predicted potential radiation doses to workers and the public from TSS under normal operating conditions and as a result of accidents.

The results of the trial safety assessment carried out by the Prefecture experts were similar to the results of the model safety assessment, which clearly indicates that the process of developing the safety assessment was coherent, that the data used as input to the safety assessments were satisfactory and no major safety issues were identified under the conditions that were considered. The process of developing the safety assessment using more realistic data for the trial safety assessment contributed to the further building of confidence in the Prefecture experts.

4.4.5. Safety assessment for several representative temporary storage sites in the Prefecture

A decision was reached to apply the safety assessment methodology to nine selected TSS throughout the Prefecture. The selected sites were chosen so that their characteristics would be representative of the TSS within the Prefecture. Actual data were acquired for these sites and in situations where data could not be obtained, data were estimated conservatively as was the case for the model TSS.

During the further development of the safety assessment for the TSS, further initiating events that had not been previously included in the safety assessment were incorporated into the process, including the impact of, flooding, retrieval of waste bags from TSS, transport of waste bags, and aging of waste bags and facilities beyond three years (the storage period originally anticipated for the TSS).

The results of the safety assessment for the nine representative TSS in the Prefecture were similar to those obtained for the model temporary storage site, even with the consideration of additional initiating events. Safety was demonstrated for TSS under normal operating conditions but for large scale accidents (e.g. fire), countermeasures were shown to be necessary.

It was noted that where waste is stored in TSS for longer periods of time than originally assumed, it is necessary to take into account the effects of ageing on the waste bags and on the overall structure of the facilities. According to the manufacturers of the waste bags, the working lives for the waste bags could be guaranteed for approximately three years. As the storage time of the waste bags in the TSS will exceed the working life of the bags, it was deemed necessary that the safety assessment should address this issue.

Initial results from a detailed study conducted by the Prefecture experts on the durability of waste bags were presented and discussed with the IAEA at the mission held in Fukushima during 26 January to 2 February 2019. This study had examined the tensile strengths of the waste bags and the mechanisms of their degradation. The potential implications of bag degradation were discussed, including the potential effects on the ability to lift the bags (e.g. with cranes) during their retrieval from the TSS, and the potential effects of bag degradation on impacts from scenarios involving dropping of a waste bag.

Throughout the assistance, discussions have been held concerning the documentation and dissemination of the results of the safety assessments.

4.5. RETRIEVAL STRATEGIES FOR WASTE STORED IN TEMPORARY STORAGE SITES AND DECOMMISSIONING OF TEMPORARY STORAGE SITES

In the later stages of the cooperation under the Practical Arrangements, the IAEA team and the Prefecture experts discussed the strategy for a retrieval strategy of the for waste stored in TSS and the decommissioning and cleanup of the sites of the former TSS.

Because of the ageing of waste bags as discussed previously in Section 4.4.5, it was anticipated that the degradation of waste bags would lead to difficulty in retrieving these bags from the TSS. The IAEA team suggested that the study of the durability of waste bags should be continued, that the results of this review needed to be entered into a database, and that this information should be used in a very practical way to inform the development of a prioritization for the retrieval of waste bags. A significant issue that needed to be addressed was the transport of waste bags from TSS to other storage facilities (such as the ISF); procedures for managing transport accidents should be in place; the results of a safety assessment should specifically inform the development of a prioritization of the specific waste bags to be transported.

The IAEA team also noted that it might be possible, from a radiological safety perspective, to use municipal landfills for the disposal of remediation waste. Examples of the disposal of radioactive waste in landfills in countries outside Japan were presented and discussed during the missions held during 2018, to 2022. It was noted that based on an IAEA project on the derivation of specific clearance levels for landfill disposal of bulk amounts of waste, in terms of radiation protection principles, there should be no objections to disposing of waste in landfills containing concentrations of ^{137}Cs with maximum concentrations up to 8000 Bq/kg.

The IAEA team noted that decommissioning of TSS after all waste material has been removed would be a significant undertaking that should be approached in a systematic way in accordance with the IAEA Safety Standards. Various issues in this regard needed to be addressed such as techniques for site restoration including radiation survey procedures and the establishment and implementation of radiation protection objectives including radiation dose criteria.

According to the discussions held, the restoration of sites is progressing well, for example, by the end of 2022 there anywhere no operating TSS in the Prefecture and by 2024 all sites of former TSS in the Prefecture will have been restored. In addition, it is not expected that any further radioactive waste will be generated in the Prefecture.

4.6. LONG TERM SAFETY OF FORMER TEMPORARY STORAGE SITES

The operators of the TSS are working to ensure that after removal of the waste to the ISF and cleanup, as appropriate, any residual contamination is at levels that are not a safety concern. The approach is aligned to the Guidelines of the MOE and includes verifying the final state of the sites of former TSS principally using measurements of air dose rate, supported by further measurements of radionuclide concentrations in soil. The IAEA experts noted that this approach is appropriate, but that it is important that enough measurements are made.

Correspondingly, in the latter part of the project, the IAEA provided assistance to the Prefecture on the development of a generic safety assessment methodology that could be applied to specific sites of former TSS from which the waste had been removed.

This generic safety assessment method was designed so that it could be applied to specific sites with the aim of demonstrating that the sites are safe now and will be safe in future for a wide range of potential uses, and thus to be useful in building the confidence of landowners and the local population.

The assistance comprised discussions of issues, including:

- the range of potential future land uses at the sites and the scenarios considered in the safety assessments;
- details of the potential exposure pathways and durations;
- details of models and parameters values;
- the number of soil sampling points at the sites and the subdivision of larger sites into smaller areas for sampling;
- the calibration of the method for estimating caesium concentrations in soil from air dose measurements;
- the possibility of localized contamination ‘hot spots’ at the sites;
- the presentation and communication of the safety assessments and the results for interested parties.

The potential exposure pathways considered in the generic safety assessment methodology are illustrated in Figure 4.5.

The generic safety assessment methodology was applied by the Prefecture experts in some case study calculations to calculate the potential doses for three TSS sites based on measured caesium concentrations in soil. Further calculations were made using air dose measurements at TSS to estimate caesium concentrations in soil and to calculate the potential doses at those sites. For all scenarios considered, the doses calculated by the Prefecture experts were well below 1 mSv/year.

4.7. SECTION SUMMARY

Activities concerning the management of waste from remediation activities under the Practical Arrangements focused initially on assisting the Prefecture to develop technical guidelines for the establishment of temporary storage facilities and assess and demonstrate the safety of the temporary storage facilities.

When managing radioactive waste, the operator of relevant facilities and activities (e.g. temporary storage sites) is required to demonstrate that the facilities and activities are safe. Prior to the commencement of the activities under the Practical Arrangements, Prefecture experts had limited experience in the performance of safety assessments as required by the IAEA Safety Standards. Therefore, training and assistance was provided on the development of safety assessments for the TSS. This was done in a stepwise fashion, beginning with an educational phase and followed by subsequent phases in which the IAEA Safety Assessment Framework software tool (SAFRAN) was applied.

As time has passed, the provision of assistance has shifted gradually to focus more on the safety of the longer term operation of the TSS, on strategies for the retrieval of waste from the TSS, and on the long term safety of the sites of former TSS. A key aspect of the assistance provided has been the sharing of expertise and experiences of relevant radioactive waste management practices from outside Japan.

The use of the IAEA's SAFRAN tool enabled an iterative approach to safety assessment of TSS. The safety assessment was carried out by the Prefecture experts following the IAEA methodology for assessing the safety of predisposal radioactive waste management facilities and activities. It also provided a means to go through the key steps in developing a safety assessment several times and to refine assumptions, add elements, and optimize the balance between conservatism and realism.

The safety assessment carried out by the Prefecture using the IAEA methodology for assessing the safety for predisposal radioactive waste management facilities and activities demonstrated fully applicability of the methodology itself, including the applicability of the IAEA's SAFRAN software. During the implementation of the software, a part of the SAFRAN database was modified to better represent the specific conditions of the TSS in the Prefecture.

The development of a safety assessment for the TSS in the Prefecture, through the application of SAFRAN to a model temporary storage site, one in the Prefecture; and nine selected TSS, is an important step toward establishing a demonstrably safe and reliable way to store the large amount of radioactive waste accumulated from remediation activities after the Fukushima Daiichi accident.

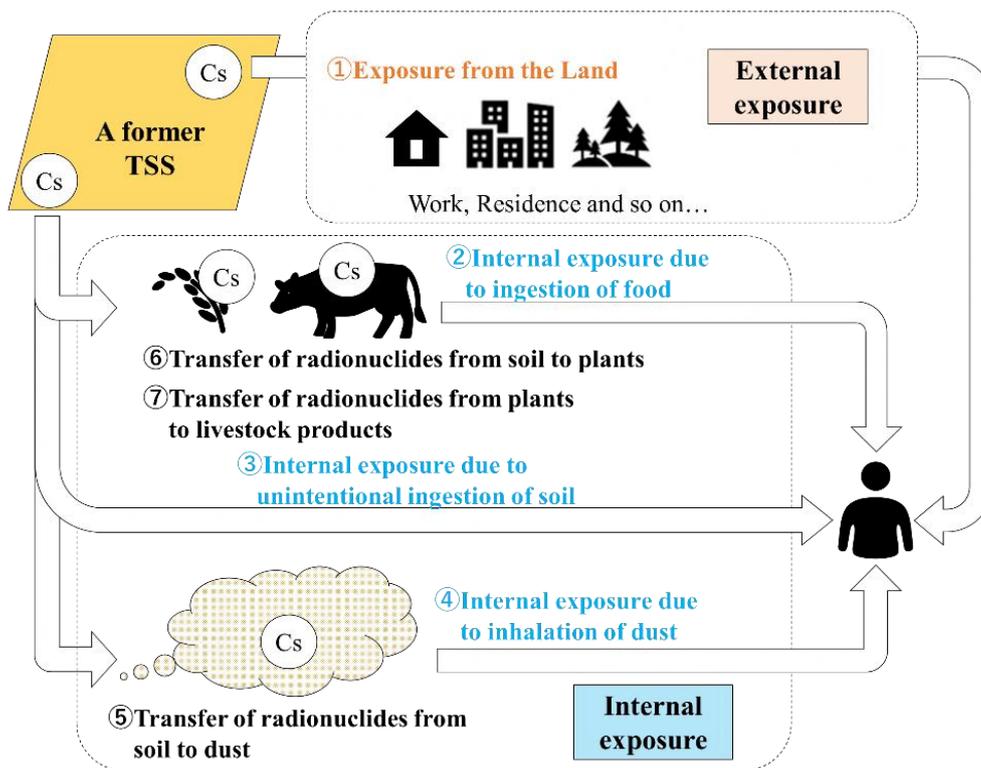


FIG. 4.5. Illustration of potential exposure pathways for sites of former TSS.

During the development of the safety assessment for TSS, several technical issues were identified whose impact on safety was evaluated (e.g. localized water accumulation in the temporary storage facilities, flooding, fires, degradation of waste bags, transport of waste bags, collapse of waste packages, etc.). On the basis of specific evaluations of the impact of these issues on safety, technical measures to remediate and prevent the problems were identified and their effectiveness estimated.

The systematic process followed using SAFRAN included assessment of all credible hazards and technical issues and provided arguments and confidence that no significant issues were omitted or disregarded. It also provided a framework for explaining why certain systems and processes are considered safe and why certain improvements of safety and countermeasures are necessary.

The results gained from the safety assessments for the TSS in the Prefecture clearly indicated that as long appropriate operating procedures were followed and appropriate measures are put in place, all radiation doses should be below the relevant dose limits. The systematic analysis of all relevant hazards also provided a sound justification for imposing control measures as necessary, to avoid or significantly reduce any possible unacceptable impacts on consequences to people and to the environment from events including accidents.

Discussions were held involving IAEA and Prefecture experts concerning waste retrieval strategies for waste stored in TSS, taking account of the ageing of waste bags.

The IAEA also provided assistance to the Prefecture on the development of a generic safety assessment methodology that could be applied to specific sites of former TSS from which the waste had been removed.

5. APPLICATION OF ENVIRONMENTAL MAPPING TECHNOLOGY USING UNMANNED AERIAL VEHICLES

5.1. BACKGROUND AND OBJECTIVES

The Prefecture identified a need to conduct radiation monitoring in areas that are not accessible by other characterization methods, such as car-borne surveys. Consequently, the Prefecture developed a methodology for the use of Unmanned Aerial Vehicles (UAVs) in areas that are inaccessible on foot or where high radiation levels might exist. Significant assistance was provided to the Prefecture in the two consecutive cooperative projects: ‘Rapid Environmental Mapping with UAV’ and Rapid Environmental Mapping with UAV Phase II: Operational Support’, both administered by the IAEA Department of Nuclear Sciences and Applications.

5.2. DEVELOPMENT AND DELIVERY OF UAV-BASED SYSTEM

Under the first project, ‘Rapid Environmental Mapping with UAV’ a complete UAV-based system was delivered to the Prefecture (see Figure 5.1). The device was specifically customized for airborne radiological measurements in Japan, i.e. comprised of a versatile detection system, remote control compliant with Japanese regulations, carbon rotor blades, laser altimeter, and some other additions.

The project also included training of the Prefecture staff in the use of UAV, its instrumentation and related software for data taking and analysis. This was achieved by performing numerous tests in laboratory as well as in situ flights under realistic conditions.

5.3. IN SITU CALIBRATION OF EQUIPMENT AND VALIDATION OF METHODOLOGY

The follow up project ‘Rapid Environmental Mapping with UAV Phase II: Operational Support’ included calibration of equipment and validation of measurement methodology before performing measurements in the areas not accessible otherwise or where high radiation levels might exist.

Five sites with different levels of gamma dose rates have been selected to perform calibration measurements. The respective dose equivalent rates varied from $0.1\mu\text{Sv/h}$ to $8\mu\text{Sv/h}$. The different altitude measurements were performed with the UAV-based system equipped with Geiger–Müller counter. The same area was also characterized by using backpacks, loaded with CsI spectrometers. Finally, reference measurements using NaI detectors also were carried out. As an example of one of such measurement campaigns is illustrated in Figure 5.2.

As a result of these measurements the following has been systematically confirmed:

- The altitude dependence of the measurements performed with the UAV-based system follows an exponential law, and therefore the gamma dose rates can confidently be extrapolated to ground level values (see Figure 5.3 on the left);
- Ground level values, obtained from the UAV-based system, are systematically higher than equivalent values reported by the NaI reference measurements; therefore, systematic correction factor can be applied when reference measurements are not possible (see Figure 5.3 on the right).



FIG. 5.1: UAV-based system and its instrumentation components delivered to the Prefecture. Image: IAEA.



FIG. 5.2: Example of in situ measurements (not corrected raw data) performed in the area accessible both for backpack and UAV techniques: data points obtained with the UAV system (Geiger-Müller counter) flying at 10m altitude (on the left); data points obtained with backpack system (CsI spectrometer) walking throughout the area with the detector located at 1m altitude (on the right). Image: Fukushima Prefecture.

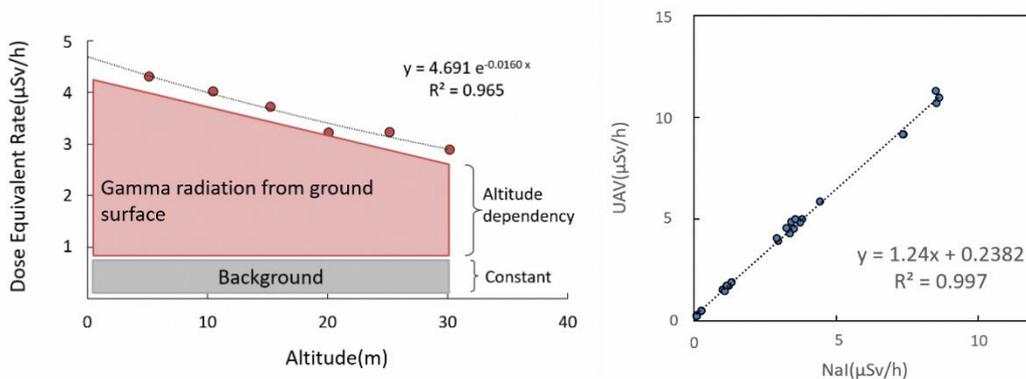


FIG. 5.3: On the left: illustration of exponential dependence of the dose equivalent rates measured by the UAV-based system and represented as a function of altitude. On the right: illustration of linear dependence of UAV data obtained with Geiger-Müller counter with respect to reference NaI data (both measurements were performed at 1 m altitude and for different dose equivalent rates). Image: Fukushima Prefecture.



FIG. 5.4: Combination of UAV (marked within red rectangle) and backpack based radiological mapping, carried out at one of the temporary storage sites of the Fukushima Prefecture. Image: Fukushima Prefecture.

The measurement methodology as well as altitude correction factors, including sensitivity analysis, were further confirmed using advanced Monte Carlo modelling. The dependence on different geometry considerations, homogeneous versus heterogeneous source distribution, different gamma energy emission, soil type, contamination depth profile, and some other variables were systematically investigated. Finally, statistical data analysis and interpolation–extrapolation treatment were developed and tested using R-code, what allows detailed 2-D radiological mapping based on UAV measurements.

5.4. TRIAL MEASUREMENTS AT TEMPORARY STORAGE SITES

After the measurement methodology was validated, trial measurements were started. Figure 5.4 illustrates clear advantages of performing measurements using the UAV based system. In this case the radiological mapping was done at one of the temporary storage sites located in the Fukushima Prefecture, where a combination of backpack (loaded with CsI spectrometer) and UAV based measurements were performed. The latter was carried out by flying over the above ground storage site at 10m altitude. Indeed, walking with backpack on the top of piled waste containers is neither practical nor desirable.

Other similar temporary storage sites have been identified and more trial measurements are planned, both before and after removal of contaminated soil. One notes separately that the UAV based measurements might have certain advantages when compared to backpacks in the case of eventual spill of the soil during manipulation or transportation: quick UAV based survey would allow remote determination of radiation levels in such situations.

5.5. SECTION SUMMARY

The Prefecture developed a methodology for the use of instrumented UAVs in areas that are not accessible on foot or where high radiation levels might exist. Significant assistance was provided by the IAEA Department of Nuclear Sciences and Applications through two consecutive cooperative projects. This included the provision of a complete UAV based

instrumentation system capable of making radiation measurements together with the post-measurement analysis and interpretation methodology. These projects also included training of the Prefecture staff in the use of UAV, its instrumentation and related software for data taking and analysis.

The first part (validation) of the project consisted of in situ calibration of equipment and validation of measurement procedures. Both experimental data from reference NaI surveys, combined with Monte Carlo modelling, were used to establish altitude dependence of the UAV based measurements, define correction factors between UAV and NaI results and perform extensive sensitivity analysis. In most of the cases UAV based data were also compared to equivalent backpack surveys, obtained using CsI spectrometers.

In the second part (application), trial measurements were carried out in areas that are not accessible on foot or where high radiation levels might exist. The established methodology has a great potential to be expanded and applied in radiological mapping relevant to contaminated sites as a result of nuclear accidents, mining activities as well as part of decommissioning and remediation projects.

6. INFORMATION DISSEMINATION FOR THE PUBLIC IN FUKUSHIMA PREFECTURE

6.1. BACKGROUND AND OBJECTIVES

Radiation monitoring undertaken by the Prefecture authorities confirmed that radiation levels in publicly accessed areas of the Prefecture are within the in Japan. The Prefecture government sought support, via cooperation under the Practical Arrangements, in disseminating and explaining these results and achievements to the public in a timely and understandable manner, based on global experience in dealing with similar situations worldwide.

To strengthen efforts in information dissemination, the IAEA and the Prefecture organized several activities under the scope of each topic under the Practical Arrangements.

Prior to the start of the activities under the Practical Arrangements in 2013, the Prefecture's main activity in information dissemination related to radiation was a website that made radiation monitoring data available to the public. The website provided detailed information on air dose rate measurements and measurements of radioactivity concentrations in material from several different sources, including:

- (1) About 3500 fixed monitoring locations (only 24 of these existed prior to the accident);
- (2) Car-borne surveys;
- (3) Radionuclide data for foodstuffs, drinking water and other environmental media.

Since shortly after the accident, the Prefecture government disseminated information about radiation monitoring results, radiocaesium levels in the environment, decontamination, remediation and waste related activities in the area, provided explanations of the concepts of radiation doses to the public. For this purpose, the Prefecture used a dedicated website and newsletter as its main distribution channels.

As of 2014, the number of site visitors to the website was between 20 000 and 50 000 per month. Some of these users made a number of recommendations about how the website could be improved to better meet their information needs. The Prefecture also consulted with the public through a survey about ways in which the website could be improved. There was a clear wish for information in easy to understand language, compatibility with mobile technology, and an explanation of the radiation doses.

6.2. DEVELOPMENT OF REVISED WEBSITE, 2013–2016

In the period 2013–2016, the IAEA team supported the Prefecture in the development of a revised website. The IAEA team presented information about web maps that developed in a number of countries and provided technical advice concerning the mapping of radiation monitoring data and presenting such information to the public.

6.2.1. General mapping considerations

In many instances, data collected from separate surveys and using different instrumentation are available for the same location; however, as a result of differences in monitoring procedures, multiple measurements made at the same location may vary and it is important to account for these differences in information presented to the public. If the available datasets are merged, the need to apply correction factors to data from different survey types is an important consideration. Also, other factors may also introduce apparent differences in the results of

surveys such as a large variability in the air dose rates between seasons (due to, for instance, snow cover) and between on-road and off-road measurements made at the same location. As such, the differences in air dose rate between these survey types are likely to be within the experimental error of each measurement. It was considered that infographics could be useful for explaining these differences. It was also noted that a decision should be made on the frequency with which these datasets are to be updated on the website.

In December 2015, the Japan Atomic Energy Agency (JAEA) presented their mapping project at a joint meeting of the IAEA team and Prefecture experts. An environmental monitoring database had been developed by standardizing and integrating data from several different organizations. As of 2015, the database included over 400 million data points covering air dose rate, soil (activity concentration and deposition), dust, water as well as terrestrial and marine foods.

6.2.2. Discussion on website development

The IAEA team made available a review of web maps from Austria, Belarus, Canada, the European Union, France, Germany, the Hong Kong SAR of China, Russia, Turkey and Ukraine. Most of these maps were based exclusively on data from fixed monitoring locations; where walking surveys could be undertaken, they were typically only used for detailed monitoring of small areas. These maps are normally not published on publicly accessible websites or merged with other datasets. The approach of the Prefecture therefore seemed to be unique.

As part of detailed discussions, the following main points were covered:

- An appropriate mapping tool is required to be used within a redeveloped website. It is important to identify both components of the project individually as they require different skills sets.
- The website should be considered as both a source of information and a tool to promote the work that is being carried out.
- In considering the changes to be made, the Prefecture is paying particular attention to making the website more user friendly and to providing information through maps and infographics.
- It is preferable to keep the website and maps simple and intuitive. Most of the target audience is not familiar with radiation protection terminology and concepts, and for them the conclusion is more important than the numbers. It is therefore essential to provide sufficient background information to support interpretation and understanding of the information.
- For those who require more detailed information, such as units of measurement, radiation doses, etc., this can be provided through a separate link, or through the use of explanatory graphics.
- The importance of displaying the most recent information first and the large scale overview maps was discussed, as was the importance of maps showing localized/detailed information.
- Historical data is also valuable, especially for demonstrating how radiation doses decreased since March 2011. Where possible, this data should be retained and used.
- In the future it could be desirable to map the air dose rates in the forests, which represent 70% of the surface area of the Prefecture. The data from the network of measurement stations established by the forestry group could be used.

- There are a number of areas within the Prefecture where there were relatively high thorium concentrations in the soil. As a result, the background air dose rate may be highly variable across the Prefecture and the use of one generic background value for all air dose rate charts may not provide the correct picture. Data on the potassium, uranium and thorium concentrations in soils are available on the website of the Japan Geological Society — this may allow calculation of the actual air dose rate at various locations.
- As the scales and colour coding of the JAEA and the Prefecture maps are different, merging the raw data and using it to create new maps is the recommended approach.
- The Prefecture needs to decide what information to be made available to the public on its new website, i.e. will it be possible only to download the existing maps or will the raw data be made available to allow individuals to prepare their own maps? In deciding this issue, a balance must be achieved between the benefits of transparency versus the risk of misuse of the data.

6.2.3. Final website design

Following the revision of the website, a presentation on the completed work was made by the Prefecture experts at the joint meeting held with the IAEA team in June/July 2016. Much of the advice received from the IAEA team was applied to the development of the design and functionality of the new website. Prefecture experts confirmed that the monitoring data collected as part of the car-borne surveys had been normalized to 1 m above ground in outdoor air. The new website was more user friendly and faster than the previous version, and optimized to both computer screens and smartphones. With the revised website, it became possible to easily browse data associated with specific locations and to specify dates of interest. Clickable maps allowed users to access data from specific points on a map (see Figure 6.1). Air dose levels and the results of environmental samples were displayed on the same map. The changes in air dose rates over time could be accessed intuitively through the use of a ‘time ruler’ (see Figure 6.2). Also, the revised website had the capability to present the transition of doses over time through the generation of graphs (see Figure 6.3). In addition to the Japanese, the website was also made available in English¹, Chinese and Korean.

6.3. FUKUSHIMA REVITALIZATION STATION WEBSITE

Since 2015, the Prefecture has operated the Fukushima Revitalization Station website as a main resource of information for people in Japan and abroad. The website integrates information about the reconstruction work in the Prefecture for visitors and citizens, and information about air dose rate measurements and measurements of radioactivity concentrations in material. The website also hosts the radiation monitoring measurement map displaying monitoring data accessible to the public.

To assist the Prefecture with maintaining and strengthening the website, the IAEA team held lectures and practical sessions on international examples and best practices in online communication of radiation related information.

¹ The English language portal for the revised website can be found at this web address:
<http://fukushima-radioactivity.jp/>

Fukushima Prefecture Radioactivity measurement map

• Top page • Site guideline • Fukushima Pref. 伊達県
Font size **Large** Standard

This site is operated by the Fukushima Pref. 伊達県

Go to the smartphone site

Results of measurement of air dose rates **Search**

Fukushima prefecture Radioactivity measurement map
Measurement map of radiation dose in Japan
Measurement map of radiation dose in the world

Move the ruler to see the past date



Point information Area information

Point No:3737
福島市 紅葉山公園

The date of the measurements
2018/01/17 21:00

Air dose rate
0.12µSv/h

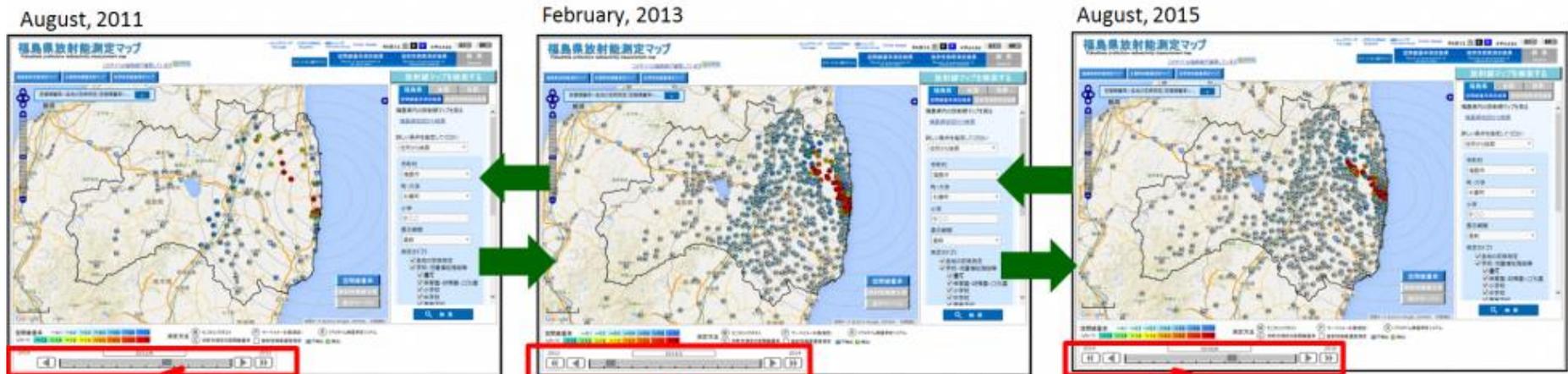
Direction, distance from Fukushima first Nuclear Power Plant
West/North/West 62km

See the graph Other date and time Search

[Measurer's HP is here](#)

[The radiation dose received from daily life](#)

FIG. 6.1: Clickable Radiation Measurement Map (Fukushima Prefecture website).



Time ruler
It is possible to browse air radiation dosage information at those times by moving this part.

FIG. 6.2: Time ruler from Radiation Measurement Map (Fukushima Prefecture website).

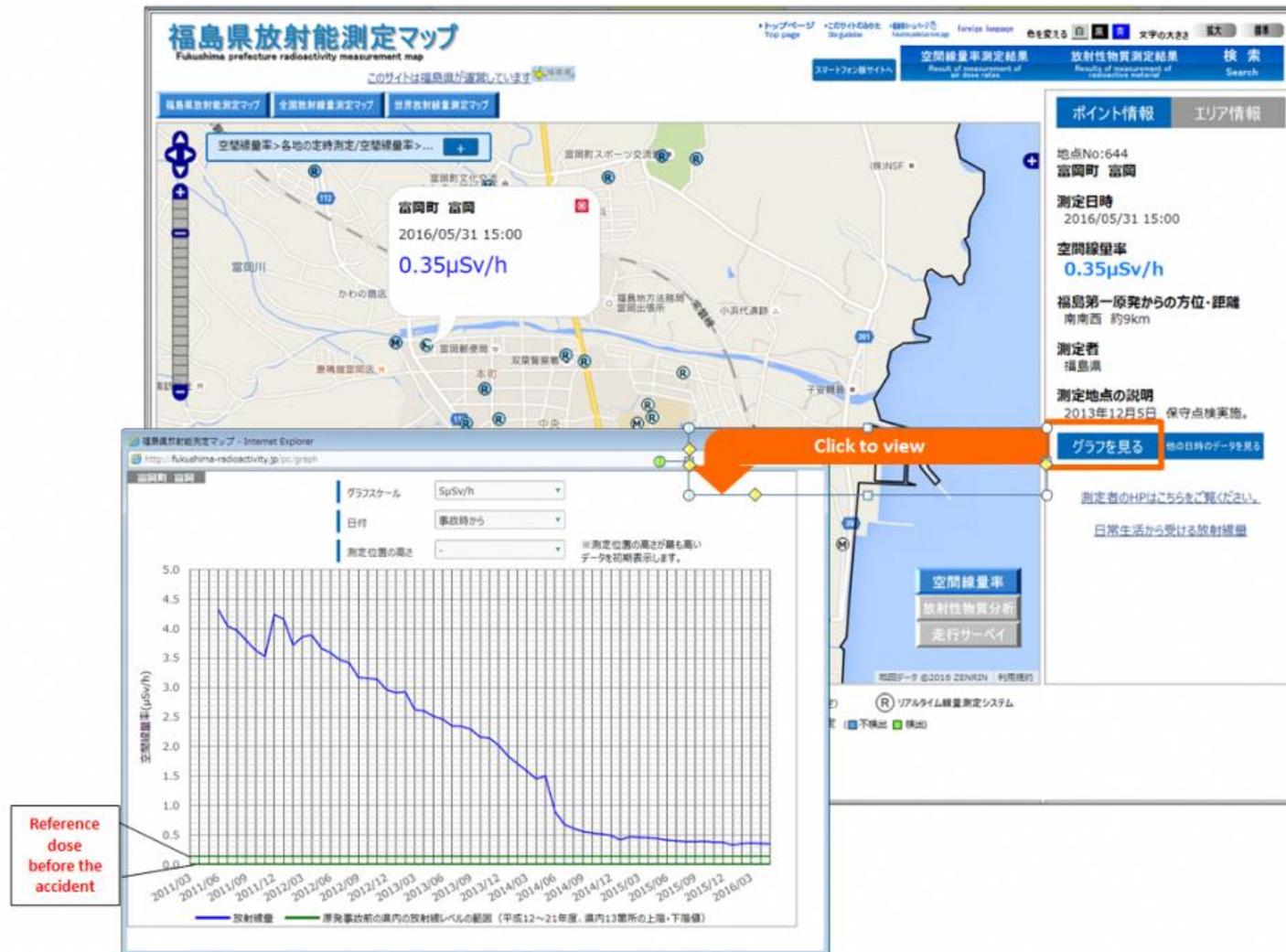


FIG. 6.3: Graph of measurement data from a specific measuring point over a specified timeframe from Radiation Measurement Map (Fukushima Prefecture website).

The IAEA team and the Prefecture concluded that simple and well-structured web content is important. The home page should include main points and recent updates, while the more detailed content should be provided on supporting pages. ‘Push’ information via social media or newsletters reaching people not actively looking for this information is another engaging way of targeting the public.

The Prefecture and the IAEA team further discussed the recent communication trends in displaying monitoring data through visualization tools such as maps, animations and infographics. As international examples showed, these proved to be effective in conveying data in an understandable manner to the public in other situations with radiological concerns.

The Fukushima Revitalization Station is available in ten languages (Japanese, English, Chinese (simplified and traditional), Korean, Thai, German, French, Italian, Spanish, and Portuguese).

Analytical tools such as Google Analytics support the understanding of website visibility and functionality. Results from April 2019 show that the visits to foreign language webpages account for 4.8 per cent out of the total number of visits. English pages attract half of the foreign visitors and the most visited webpage is ‘Radiation levels in the prefecture’.

To further assist the Prefecture, the IAEA team provided written recommendations on how to optimize information dissemination via the Fukushima Revitalization Station site. This paper provided recommendations and information to the following:

- Tailor website content and layout to audience needs;
- Launch a poll on the website on surveying audience needs;
- Concentrate on the most visited languages: English, Chinese and Korean;
- Translate videos on monitoring available on the Japanese website;
- Use the results of Google Analytics for further optimizing website;
- Ensure all pages of the website are secure;
- Work on search engine optimization for better search engine ranking;
- Improve web publishing workflow, so that technical divisions can update their content more regularly according to a plan.

In 2021, the Forestry Promotion Division in the Prefecture successfully published information on monitoring and restrictions on wild mushrooms on their website, provided information to the media as well as broadcast information on radio. The Division created maps of distribution restrictions that were to be updated when restrictions are lifted. The map is colour coded. The IAEA team advised that, as well as colour coded maps, the data could be presented in a database format that could be filtered by the user. A visitor to the website could, for example, select 1) the municipality and/or 2) the species of interest; the website would display the corresponding restrictions.

6.4. INFORMATION DISSEMINATION

The Prefecture government disseminates information about radiation monitoring results, radiocaesium levels in the environment, decontamination, remediation and waste related activities in the area, and explains the effects of radiation to the public and other relevant stakeholders. For this purpose, the Prefecture uses dedicated websites (see Sections 6.2 and 6.3) and a newsletter.

The Fukushima Prefecture public relation magazine on ‘Environmental radiation monitoring’ published in March 2022¹⁰.

A 2017 public opinion poll targeting Tokyo residents, presented by the Prefecture, showed that residents still did not have a correct understanding of the current situation in the Prefecture — on average a third would not recommend family members, children, friends, foreign tourists to visit the Prefecture. This poll and other information presented by the Prefecture indicated that communicating radiation and associated risks and shifting perceptions from perceived risks to actual risk remains a challenge.

To strengthen efforts in information dissemination, organized activities for the topics under the scope of the Practical Arrangements were carried out between 2018 and 2022. These were based on international examples of best practices in informing the public about the effects of radiation.

As part of the ‘Long term Monitoring’ Working Group, in 2021, the IAEA team presented experiences of using informed decision making by the members of public in territories contaminated by deposited radioactive material from the Chernobyl accident (Ukraine, Belarus). A system of village radiologists was established in 1989–1990 who were educated and trained by central government. The candidates to become village radiologists were nominated from the trusted groups of population (teachers, doctors, agriculture specialists) and were local and so were trusted and were part of the community. During 1987–2000 over 12 700 specialists were trained for the agriculture and processing industry in Ukraine. In Belarus centers for practical radiological culture were established and equipped with modern instrumentation for measuring radiation in foodstuffs and other environmental samples, as well as for measuring ambient dose rates. This initiative allowed for developing a better attitude of people to the radiation risk associated with living in conditions of long term radioactive contamination (i.e. understanding and knowledge of the current situation, maintaining reasonable vigilance regarding the radiation risks, without exaggerating the danger) and creating conditions for managing possible risks.

6.4.1. Outreach materials

To support three main topic areas, radiation monitoring, off-site decontamination and remediation and the management of radioactive waste, the IAEA team and the Prefecture produced outreach materials targeting the general public.

Outreach materials were created in a form of flyers explaining:

- The current radiological trends and overall dose rates;
- Steps undertaken by the Prefecture in radiation monitoring and mapping, remediation, decontamination and management of radioactive waste;
- Radiation effects to the public and comparison to other situations;
- Results of the IAEA–Fukushima Prefecture cooperation from 2013 until 2017.

¹⁰ Available in English at:
https://www.iaea.org/sites/default/files/22/06/fuku-moni_march_2022revised_.pdf

The flyers included text, images and whenever possible, infographics and engaging graphs and charts to underline the monitoring data. These data visualizations help the public and other stakeholders understand the complex information in a plain language.

The flyers were developed under the each of three topics covered in Sections, 2, 3 and 4. They were presented and discussed at the workshop for officials from the Prefecture government organized from 6 to 8 February 2018 in Japan and later distributed to the municipalities in the Prefecture. English versions are also available online¹¹.

An illustration of the front page of one of the leaflets and a page with infographics is illustrated in Figure 6.4.

In February 2020, the IAEA team and the Prefecture discussed creating further outreach materials on an ongoing basis during the remainder of the duration of the Practical Arrangement. Topics that were raised were:

- Develop information on the prevalence and potential health effects of high Cs microparticles found in river sediments;
- To translate the results of decontamination and monitoring activities into English, Chinese and Korean for web site;
- To develop messages and have a communication plan to use in case of natural disasters like the recent typhoon;
- To strongly emphasize the message that radiation levels in most of the prefecture are now within the range of background radiation globally;
- Following safety assessments undertaken for the former TSS's, communicate that the sites are safe to use, including those on agricultural land (both for both farmers and consumers of the produce).

6.4.2. Brochure for local hunters and wild mushrooms

The IAEA provided assistance to the Prefecture by designing a brochure for local hunters containing information and advice on the consumption of meat of wild animals including wild boar captured in the Prefecture¹² (see Figure 6.5).

In 2021, the Local Branches in the Prefecture successfully published information on restrictions for wild mushrooms in their public relations magazine, created and distributed paper version material and disseminated material in shops. They created brochures and leaflets with visualization of the restrictions in chart form, as well as specific items concerning the peak season of mushroom distribution.

The IAEA team advised that the information dissemination products (such as the leaflets and brochures) contained too much information, which made them hard to understand and advised that the information and tables were reduced and simplified, focusing on what is most relevant.

¹¹ [https://www.fukushima-kankyoso.jp/lancelot/common_files/images/public/9_Leaflet\(English\).pdf](https://www.fukushima-kankyoso.jp/lancelot/common_files/images/public/9_Leaflet(English).pdf)

¹² https://www.iaea.org/sites/default/files/21/07/fp_brochure_for_hunters.pdf

Municipalities also published information on their websites as well as printed the information in their magazines. Their websites have been updated with restrictions on wild mushrooms and information has been distributed via magazines and local websites.

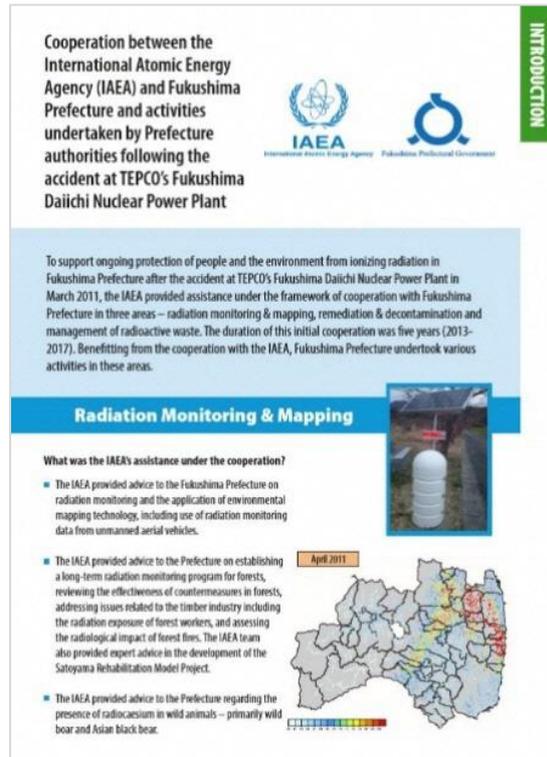
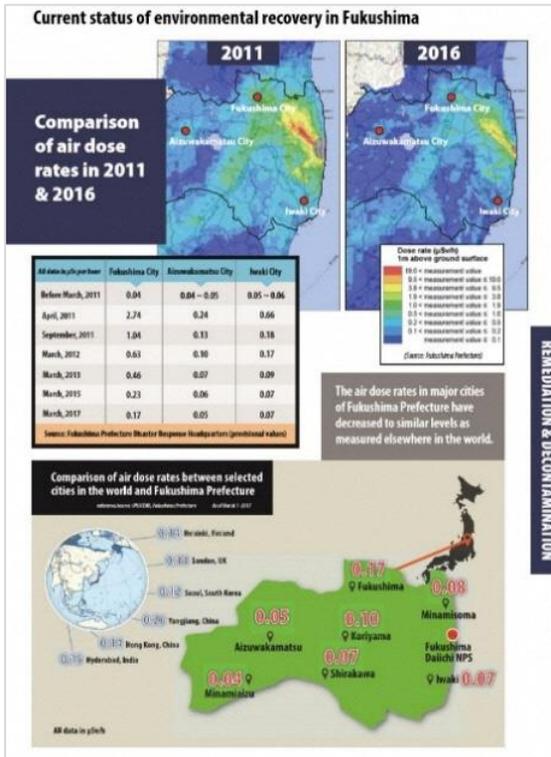


FIG. 6.4: An illustration of the front page of one of the leaflets and a page with infographics in English (Image: Fukushima Prefecture).

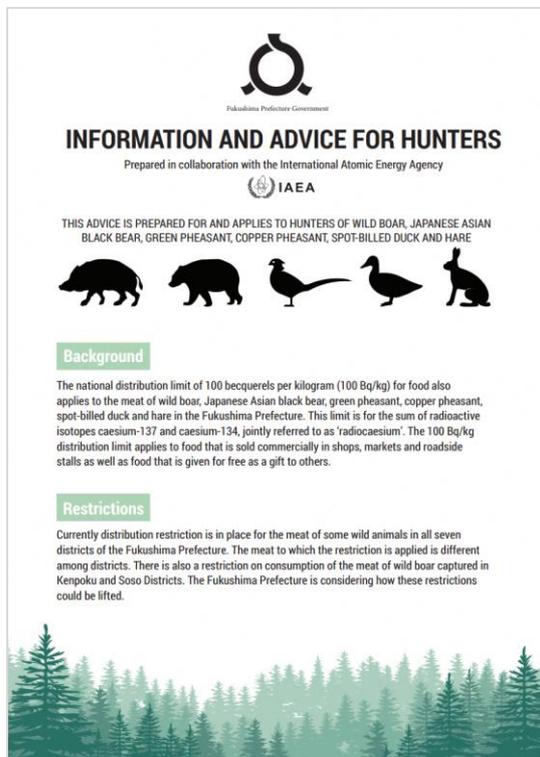


FIG. 6.5: An illustration of the front page of the informational brochures on advice and information for hunter and pickers and distributors of wild mushrooms 'in English' (Image: Fukushima Prefecture).

The IAEA team proposed to create a more generic information brochure, similar to the brochure created for hunters, with reference made to the website for details on actual restrictions and more up to date information. The proposal was that on a specific web page, individuals could select their preferred municipality and get more information tailored to their needs. This would allow users and readers to have a general idea of the information from the brochure but would also allow ones that need of more specific information to find it easily and readily. The IAEA team also suggested having interactive maps, which could help to increase the time span people stay on the website, as well as make information more understandable and visually appealing.

The IAEA team subsequently provided assistance to the Prefecture by designing a generic brochure on wild mushrooms, similar to the one prepared for hunters. The target audience of the brochure was the general public who gather wild mushrooms, as well as distributors to stores and farmers' markets. The key objective of the brochure is to inform the target audience about the restrictions on consumption and distribution, commercial and non-commercial, of different species of wild mushrooms. An online version of the brochure was issued in April 2022 and a printed version was issued in September 2022 (Figure 6.5 – English version). The Prefecture highlighted that the update of the brochure will take place once a year, in September before the picking season starts. The English version mentions that the updated information is only available in Japanese¹³.

6.4.3. Information Dissemination Seminar

In July 2019, a seminar was held in Japan which focused on dissemination of information related to radiation monitoring results, decontamination, remediation and waste related activities implemented by the Prefecture. The target audience was Prefecture officials with responsibilities for outreach and engagement with the public in various divisions.

The aim was to exchange knowledge and experience with international experts on effective communication strategies and best practice communication methods and techniques. The 2.5 day seminar was composed of a plenary style session and interactive sessions. During the Seminar, Prefecture representatives presented how they dealt with information dissemination to date and what challenges they were facing.

The IAEA team had experience in risk communication and showed case studies and advised on the specific situation of the Prefecture. The interactive sessions were led by communication experts facilitating the discussions in separate working groups.

The Seminar was structured in two parts:

- (1) Lectures — these included:
 - Presentations on the Prefecture experience, results of their communication strategy and challenges encountered so far.
 - International case studies related to communicating incidents and radiation risks.
 - Possible solutions to the points raised by the Prefecture and feedback provided by IAEA and international experts.
- (2) Interactive sessions — these included:
 - Discussions based on information provided during the lectures.

¹³ The brochure in English can be found at:
<https://www.iaea.org/topics/radiation-protection/cooperation-fukushima-prefecture>

- Practical exercise and skill building through group dialogues and roles plays split into three parallel groups (web, face to face, events).

One conclusion of the Seminar was that it is important to communicate doses and dose rates in simple terms and putting them into perspective by providing context to show that the dose levels in most parts of the Prefecture are comparable to those in other parts of the world.

The IAEA team stressed that when communicating the beauty and diversity of the Prefecture to potential tourists, it is crucial to communicate that the dose rates are within the normal range and do not pose risks to tourists. When reaching out to foreign audiences, it is important to clarify that the term 'Fukushima' refers not to the Fukushima Daiichi nuclear power plant but to the entire prefecture.

The most efficient way of getting messages across to stakeholders is to move away from one way information disseminations to engagement. It was suggested to involve citizens in dose rate monitoring ('citizen science'). By identifying community ambassadors (people that are respected and closer to the community), information on decontamination, risks and waste storage could be provided directly to their peers. Early engagement of stakeholders is also a key for building trust as well as connecting with stakeholders at a personal level.

The Prefecture website was also a topic of the Seminar. More information is provided in Section 6.3.

6.5. SECTION SUMMARY

The availability of accurate and up to date information on the radiation situation in the Prefecture is important both for the local population and for visitors. While Fukushima Prefecture radioactivity measurement map large scale maps, available on the Prefecture website¹⁴ give a general view of how air dose rates are reducing over time, people also want more localized information regarding the location where they live, work or are visiting. The revised website that was finalized in 2016 made this information available in a form that is easy to understand and prioritized the most recent data while also ensuring that historic data is also available for those who wish to review it.

Radiation data were collected in a number of different ways, each of which uses different measurement methodologies. Over 3000 monitoring stations provide continuous data from fixed locations across the Prefecture, and these are augmented by data collected by car-borne surveys (where radiation monitors are affixed to vehicles that are driven around the streets of the Prefecture).

Several steps were necessary so that the public could access radiation monitoring information from the Prefecture website in a more organized and understandable way: standardization of the large volume of available data; development of maps to accurately represent the radiation situation at different levels of detail; and upgrading the website to allow access to these and other data. All of these issues were discussed in detail between the IAEA team and Prefecture experts in IT, public information strategy and radiation measurement.

¹⁴ <http://fukushima-radioactivity.jp/pc/>

The provision of information through a website is only one component of a communications strategy. It has been recognized that the Prefecture needs to provide information and advice to residents of the Prefecture as well as tourists from Japan and abroad on the expected reduction in air dose rates with time. This has to take into account natural reductions due to the physical half-life of radiocaesium and also the effectiveness of any applied countermeasures. Such calculations are site specific and the uncertainties in the estimates of the future situation must also be provided. The key takeaways arising from the cooperation with IAEA are:

- The most efficient way of getting messages across is to move away from one way information dissemination to engagement.
- An important task to increase trust of the general public in the Prefecture itself, in Japan and abroad, enabling them to form informed opinions. This can be done through active public engagement and easily understandable communication products.
- When reaching out to outside of Japan it is important to clarify that the term ‘Fukushima’ does not refer to the Fukushima Daiichi nuclear power plant but to an entire Prefecture.
- Channels such as well structured website are keys in reaching out to the target audience in a timely manner.
- Given the importance of traditional media in Japan, and even more so in the prefecture, communicating through mass media is important.

The results of the activities highlighted the importance of sharing international examples and benefits of worldwide assistance.

The IAEA team assisted the Prefecture in developing a brochure for local hunters and another one for the general public who gather wild mushrooms, as well as distributors to stores and farmers’ markets. The key objective of the brochures is to inform the target audience about the restrictions on consumption and distribution, commercial and non-commercial, of wild game and different species of wild mushrooms.

7. REPORT SUMMARY

From the time when Practical Arrangements was established in 2012, the most important exposure pathway for people is external radiation emitted by radiocaesium, which is present in both the terrestrial and aquatic ecosystems. Radiocaesium levels in the environment, and associated doses to people will decline without intervention as a result of the radioactive decay of radiocaesium, and the removal of radiocaesium by weathering from surfaces and vertical migration down soil and sediment profiles. Furthermore, the Prefecture has determined that radiocaesium levels in the terrestrial aquatic ecosystems and associated doses to people have declined due to remediation activities. Since the Fukushima Daiichi accident, the Prefecture has performed a significant amount of work concerning remediation activities and the management of the resulting radioactive waste. This report covers the work undertaken under the Practical Arrangements from 2013 to early 2020.

7.1. LONG TERM MONITORING OF RADIOACTIVE MATERIAL IN FORESTS AND ASSOCIATED COUNTERMEASURES

The importance of forests in the economy of the Prefecture and in the life of its inhabitants underlines the need to understand the mechanisms of movement and accumulation of radiocaesium within this ecosystem. While extensive research on forest ecosystems was carried out in the years following the Chernobyl accident in 1986, forests in Europe differ from those in Japan and the results of previous studies may not be directly applicable. For this reason, an extensive monitoring and research programme has been established by the Prefecture.

There are clear indications that clay minerals present in the forest soils in the Prefecture are immobilizing radiocaesium in a manner that reduces its uptake to understory vegetation and to trees. As a result, only approximately 0.2% of the radiocaesium in forests is now contained in the trees themselves. The relatively low concentrations measured in harvested wood to date support the continued use of timber from the forests in the Prefecture. It is important, however, to assess whether this trend continues, as well as any differences in uptake by newly planted saplings. With time, the reduction in air dose rates due to natural decay will allow access to areas of forest not currently being managed; this in turn may bring new challenges in terms of continued use of the timber as well as managing radiation exposure of forest workers.

An important observation is that the overwhelming majority of the radiocaesium initially deposited in the forests of the Prefecture has now been transferred to the soil and litter layer, where it continues to contribute to the air dose rate. Most of the radiocaesium initially deposited is retained within the forest and the amount of radiocaesium lost from the system to date seems to be low. This suggests that the likelihood of ongoing contamination of nearby agricultural land is low (unless through some unforeseen catastrophic event).

Forests are also an important source of foods such as mushrooms, sansei and the meat of wild boar. Additionally, freshwater fish are caught in rivers and streams, some of which partly transverse forests. While these can be considered as minority foods — compared to agricultural foods — they tend to concentrate radiocaesium; there are many outlier values and a very slow reduction in levels is observed to date. The activity concentrations in many of these wild foods well exceed the limit for radiocaesium of 100 Bq/kg for general foods sold commercially. For all these reasons, ongoing attention needs to be given to providing more and better information, including measurement data, to those who collect wild foods for their own personal consumption.

Looking to the future, the reduction in air dose rate within the forest will be dominated by the half-life of 30 years of ^{137}Cs . While monitoring programmes will need to be maintained for many years, those that have been established in earlier years need to be reviewed regularly to determine if, from a technical point of view, the frequency of monitoring can be reduced without the loss of necessary information.

The knowledge gained will allow the forests to be managed in an effective manner for the benefit of the people of the Prefecture. This knowledge should be disseminated widely so that the public has a clear understanding of the levels of radiation to which they are exposed.

7.2. MONITORING OF RADIOACTIVE MATERIAL AND ASSOCIATED REMEDIATION AND DECONTAMINATION IN TERRESTRIAL AND AQUATIC ENVIRONMENTS

In the freshwater bodies of the Prefecture, dissolved radiocaesium levels in water are close to or below the detection limit (of 0.05 Bq/L). This can be explained by the strong sorption of radiocaesium by sediments in riverbeds, in which much higher radiocaesium levels are observed. There is also a clear decline in the concentration of radiocaesium in suspended sediments.

The reduction of radiocaesium levels in the environment is mainly caused by the radioactive decay, whereas runoff and washoff provide further reduction. Suspended radiocaesium is subject to sedimentation in reservoirs, which act as a kind of sediment trap.

Simulation models have been used to assess the transport of radiocaesium from catchment areas through the river system to the Pacific Ocean. The results facilitate the interpretation of monitoring measurements and support decisions that can lead to reducing exposure to the public. Additionally, models provide valuable input when identifying appropriate countermeasures (including those related to decontamination and remediation) and evaluating their effectiveness. For example, several demonstration projects have been initiated to test the effectiveness of measures for reducing air dose rates in recreational areas near rivers.

Worldwide experience with freshwater remediation activities indicates that technical measures have only a limited potential to control the dispersion of radionuclides in freshwater bodies. Instead, administrative measures, such as restrictions on the use of freshwaters, are relatively easy to implement and more effective in reducing exposure to the public from radionuclides deposited in freshwater bodies.

Since 2011, intensive decontamination work has been carried out in private homes, public areas, agricultural land and parts of the forests close to inhabited areas. For residences (houses), decontamination is the most advanced the planned activities were completed by March 2018. Following decontamination, air dose rates were reduced by 20–50%, similar to those achieved by remediation in areas affected by the Chernobyl accident.

Monitoring of dissolved and suspended radiocaesium in rivers of the Prefecture continues, along with complementary studies applying tracer techniques, to gain a better understanding of transport processes and dynamics in river catchments, and the influence natural and anthropogenic activities on exposure. Such data can be used to respond to questions raised by local communities and publishing results of studies in peer-reviewed journals serves as independent verification of findings. The work being done provides an important body of literature for local residents and the international community.

7.3. MANAGEMENT OF WASTE FROM REMEDIATION ACTIVITIES

Activities concerning the management of waste from remediation activities under the Practical Arrangements focused initially on assisting the Prefecture to develop technical guidelines for the establishment of temporary storage facilities and on assisting the Prefecture to assess and demonstrate the safety of the temporary storage facilities.

When managing radioactive waste, the operator of relevant facilities and activities (e.g. temporary storage sites) is required to demonstrate that the facilities and activities are safe. Prior to the commencement of the activities under the Practical Arrangements, Prefecture experts had limited experience in the performance of safety assessments as required by the IAEA Safety Standards. Therefore, training and assistance was provided on the development of safety assessments for the TSS. This was done in a stepwise fashion, beginning with an educational phase and followed by subsequent phases in which the IAEA Safety Assessment Framework software tool (SAFRAN) was applied.

As time has passed, the provision of assistance has shifted gradually to focus more on the safety of the longer term operation of the TSS, on strategies for the retrieval of waste from the TSS, and on the decommissioning and cleanup of the former TSS sites. A key aspect of the assistance provided has been the sharing of expertise and experiences of relevant radioactive waste management practices from outside Japan.

The development of a safety assessment for the TSS in the Prefecture is an important step toward establishing a safe and reliable way to store the large amount of radioactive waste accumulated from remediation activities after the Fukushima Daiichi accident.

The results gained through the use of SAFRAN for the development of safety assessments for the TSS in the Prefecture indicate that as long appropriate operating procedures are followed and appropriate measures are put in place, radiation doses should be well below the relevant dose limits. A systematic analysis of the relevant hazards provided a sound justification for imposing measures where necessary to avoid or significantly reduce any possible unacceptable impacts to people and to the environment.

Discussions were held involving the IAEA team and Prefecture experts concerning retrieval strategies for waste stored in TSS that takes account of the ageing of waste bags. Decommissioning of TSS and any remediation of the sites after all the waste has been removed will be a significant undertaking and this should be approached in a systematic way and the IAEA team advised that the applicable IAEA Safety Standards are used.

The IAEA team provided assistance to the Prefecture on the development of a generic safety assessment methodology that could be applied to specific sites of former TSS from which the waste had been removed.

7.4. INFORMATION DISSEMINATION FOR THE PUBLIC IN FUKUSHIMA PREFECTURE

Since shortly after the accident, the Prefecture government has disseminated information¹⁵ about radiation monitoring results, radiocaesium levels in the environment, decontamination, remediation and waste related activities in the area to the public and other relevant stakeholders.

¹⁵ <http://www.pref.fukushima.lg.jp/site/portal/>

For this purpose, the Prefecture has used dedicated websites and a newsletter as its main distribution channels.

International experience in providing radiation data to the public was reviewed by radiation protection, public information and IT experts. A wide range of options regarding data presentation, including the use of interactive maps, were considered. Technical issues such as how to present representative data, how to indicate long term trends in air dose rate and how to merge data from fixed monitoring stations and different types of measurement surveys are not straightforward and different approaches and practical solutions were discussed.

The revised website, the development of which was informed by the advice provided by the IAEA team was completed in 2016; it is more user friendly and faster than the previous version, and it is fully accessible from both PCs and smartphones. With the revised website, it is now possible to easily browse data associated with specific locations and dates.

Advice, based on international advice and best practices, was also provided for information dissemination via face to face meetings and events, as well as on the new Fukushima Revitalization Website. The importance of engagement and the involvement of citizens in dose measurements was underlined. Several concrete suggestions on making the Revitalization website more targeted to the different audiences, including from abroad, were provided.

The IAEA team assisted the Prefecture in developing a set of flyers for the general public as well as specific brochures for local hunters and those who gather wild mushrooms in the forest, as well as distributors to stores and farmers' markets. The key objective of the flyers was to inform about the results of the cooperation and the decrease in radiation levels, while the brochure informed the specific target audiences about the restrictions on consumption and distribution, commercial and non-commercial, of wild game and different species of wild mushrooms.

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ANNEX:
**OUTCOMES FROM WORK UNDERTAKEN UNDER THE FUKUSHIMA
COOPERATIVE PROJECTS**

The key outcomes as a result of the 10 years cooperation under the Fukushima Cooperative Projects were summarized at the end of the Summary Workshop held between 31 January and 3 February 2023.

The outcomes were presented by the IAEA Technical Leader of the IAEA–Fukushima Project are given below.

**Monitoring of Radioactive Material in the Environment Associated Countermeasures
Monitoring: forests**

Radiocaesium in forests

- Radionuclides deposited in the forests of the Prefecture are effectively retained within the forest ecosystem and the likelihood of transfers of radiocaesium to agricultural land appears to be low.
- Forest maintenance procedures are very effective at retaining radiocaesium within forests.
- The presence of clay minerals in the underlying forest soils has chemically bind the radiocaesium and limit its transfer to vegetation.
- Measures have been implemented to restrict the radiation exposure of forest workers.

Monitoring in forests

- Radiation monitoring in forest may be necessary for many more years.
- Optimization of forest monitoring is needed moving forward due to available resources.

Monitoring of wild foods

- Activity concentrations in wild foods are variable but there are high concentrations still being measured in 2022 that are >100 Bq/kg.
- Decline in Cs concentrations in wild mushrooms and other wild foods is slow and restrictions may be required for many years for some species and in some areas. Therefore, monitoring will need to continue in the long term to provide surveillance and reassurance and to remain vigilant to changes in forest systems.
- A non-destructive analysis method has been tested for matsutake mushrooms to avoid destroying expensive mushroom species.
- Although significant progress has been made over the past decade in lifting distribution restriction for inland fish, there are still restrictions on some fish species in some areas, where recreational fishing is not allowed to resume.

Monitoring of Radioactive Material in the Environment Associated Countermeasures Monitoring: terrestrial and aquatic environments

Behaviour of caesium in aquatic systems

- Environmental and climatic conditions in the Fukushima and Chernobyl regions are quite different but the behaviour of radiocaesium in the environment is similar. In particular, strong sorption of caesium to solids is observed and, in fresh waters, most of the ^{137}Cs is found in suspended or bottom sediments.
- Survey data indicate a continuous decline in radiocaesium concentrations in rivers since 2011. Decline observed in the Prefecture and in other parts of the world agree reasonably well.
- Predictions using a simulation model for dynamics in rivers (TODAM) show agreement with measurements under base- and high-river flow conditions.
- In the Prefecture, loss of ^{137}Cs due to runoff depends on the land use. The loss is low — about 1% in the year of deposition and well below 1% per year thereafter. This is in general agreement with the experience in other countries.
- A small number of caesium microparticles (CsMPs) have been found with low levels of radiocaesium bound to them. Caesium bioavailability is likely to be low and no significant impacts are likely.

Remediation of the terrestrial environment

- Countermeasures that control release of ^{137}Cs into surface waters (e.g. decontamination of upstream environments) can be an effective approach to prevent accumulation in sediments in aquatic systems.
- Gamma dose rates in forests, on agricultural lands and residential areas after decontamination are reduced by about 20–50%, both after the Chernobyl and Fukushima accidents.
- For reducing ^{137}Cs levels in crops, a similar range of techniques was applied after the Chernobyl and Fukushima accidents. Where comparable, reduction factors are similar.

Control of dispersion in dynamic aquatic systems: engineering measures

- Aquatic systems are complex and very site specific.
- Large scale engineering measures are costly and often difficult to implement.
- Natural sediment traps have been demonstrated to work well e.g. at the Yokokawa dam and at the Kiev reservoir in Ukraine due to calm waters with low water flows leading to high sedimentation.
- Removal of bottom sediments is an effective and globally applied measure for remediation of water bodies (including demonstration test in the Fukushima Prefecture).
- Removal of riverside sediments and vegetation (demonstration test in Kam-Oguni River) reduced gamma dose rates by a factor of about 2: this reduction persisted and was not affected by typhoons and flooding.

Management of Waste from Remediation Activities

- After the 2011 Fukushima Daiichi accident, enormous amounts of materials were managed as radioactive waste.
- A cumulative total of over 1000 Temporary Storage Sites (TSS) were established in the Prefecture based on “Technical Guidelines”.
- The waste was later moved to Interim Storage Facilities
- IAEA assisted the Prefecture by:
 - Explaining IAEA Safety Standards;
 - Reviewing the Technical Guidelines;
 - Sharing expertise and experiences from outside Japan;
 - Training the Prefecture on assessing the safety of TSS;
 - Advising on the presentation and communication of information.
- The Prefectures’ capabilities on radioactive waste management were significantly enhanced over the period of the project.
- The Prefecture has Technical Guidelines for procedures for safe waste management. IAEA provided comments to the Prefecture on all the versions of the Technical Guidelines.
- Support was provided by the IAEA to the Prefecture for the safety assessment of Temporary Storage Sites (TSS) for normal and accidental situations and for all phases of their development.
- Assessed doses during operation of TSS and after waste removal are well below relevant dose limits and long term goals.

Information Dissemination to the Public

- IAEA’ s assistance on information dissemination interlinks with all the areas and activities of cooperation.
- IAEA’s assistance was provided on effective ways to communicate information to the public in a timely and understandable manner.
- Methodologies and expertise provided by IAEA were based on global experience in dealing with accidental releases.
- The most efficient way of getting messages across to the public and other interested parties is to move away from one way information dissemination to engagement with them.
- Concrete communication products were developed in order to better inform audiences about radiation levels, risks and the radiation levels in the Prefecture.
- The Prefecture websites was revised in line with IAEA recommendations, to provide a better user experience, higher search engine optimization and therefore a higher impact.
- The Google Analytics tool was used to obtain quantitative data on visitor rate, retention, revisiting rates, drill down and bounce rates.

- An important task is to increase trust of the general public in the Prefecture itself, in Japan and abroad, enabling them to make informed opinions. This requires the definition of target audiences, appropriate communication goals and tools and messages.
- It is essential to communicate accurate messages to the target audience without using too specific scientific concepts.
- To make outreach products easily understandable, it was recommended to simplify language and to use infographics, graphs, animations, videos, etc.
- Lesson learned were: to simplify information presented on the page of the website, to build information architecture/taxonomy, include more actionable items on main page (surveys, videos...), to focus on fresh news on regular basis.
- Radiation Safety Navigator was introduced as the new IAEA's online tool for effective communication about radiation safety. This tool can be utilized by the Prefecture, for example, in conveying messages about radiation doses.