MID TERM SUMMARY REPORT
(2013 – 2020)

Cooperation between the International Atomic Energy Agency and Fukushima Prefecture

Radiation Monitoring and Remediation

Vienna/Fukushima December 2020

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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 was valid for a period of five years after signature and has been extended and modified by the mutual consent of both sides in April 2016 and December 2017 and will continue 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 on-going 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 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 Mid Term Summary Report summarizes the current status and progress made in the activities conducted under the Practical Arrangements from 2013 through Spring 2020. The Mid Term Summary Report updates and replaces "SUMMARY REPORT (2013-2017); Cooperation between the International atomic Agency and Fukushima Prefecture and activities undertaken by Fukushinma Prefecture" (hereinafter referred to as "previous report") 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.

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, 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 air-borne 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}Cs/^{134}Cs was about 8:1 and by December 2019 this had increased 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 1,300 (See Table 2.1.). Air dose rate is measured at all monitoring points and, at 81 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.

Table 2.1. Forest monitoring sites established by Fukushima Prefecture

Year	Number of Monitoring Sites Added	Total Number of Monitoring Sites
2011		362
2012	563	925
2013	81	1,006
2014	187	1,193
2015	37	1,230
2016	20	1,250
2017	50	1,300
2018	-	1,300
2019	-	1,300

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 μSv/h in August 2011 to 0.20 μSv/h at the end of 2019 i.e. a reduction of 78%, entirely by natural processes (see Figure 2.2).

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.

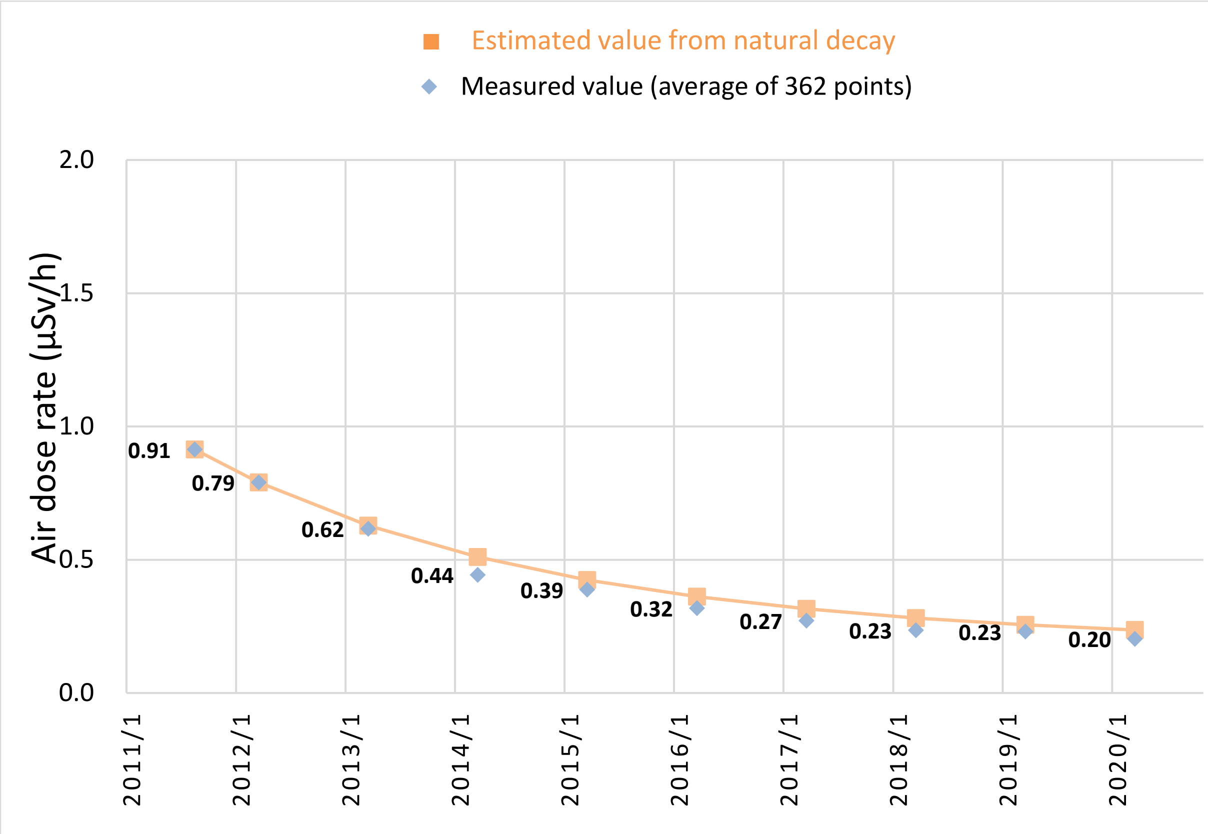

FIG 2.2: Measured air dose rates at 362 monitoring points in forests within the Prefecture and estimated air dose rates based on radioactive decay of radiocaesium, (Image: based on data from Fukushima Prefecture)

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, with the remaining approximately 3% distributed among the trees (see Figure 2.3). This observation still applies at the end of 2019. 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.

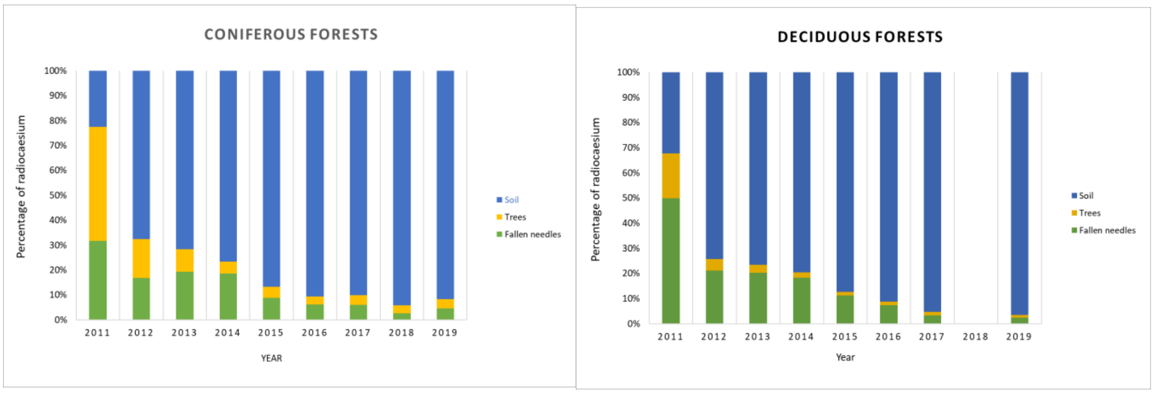

FIG 2.3: Change in distribution of radiocaesium in the Prefecture's coniferous forests and deciduous forests from 2011 to 2019 (Adapted from cooperation with the Ministry of Agriculture, Forestry and Fisheries, and the Fukushima Prefectural Forestry Research Centre)

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.

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 8,000 Bq/kg was estimated for various species of trees.[1] The value that resulted from this process, measured at a height of 1 m, was 1.57 μSv/h. It should be noted that, while such estimated values have significant uncertainties associated with them, they provide a useful and rapid means for making decisions on whether or not trees can be felled and harvested. This is discussed further in Section 2.3.5 'Managing the timber industry'.

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.)

2.3. Specific Studies

2.3.1. Radiocaesium transfer to mushrooms

The Prefecture is the principal producer of *Shiitake and Nameko* mushrooms in Japan. These mushrooms are grown on rotting wood and therefore tend to contain lower radiocaesium concentrations than those that grow in forest soil.

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[1] Japanese National legislation requires any material that exceeds an activity concentration of 8,000 Bq/kg of radiocaesium to be managed as radioactive waste, and such waste is considered 'designated waste'. Details on the selection of the threshold of 8,000 Bq/kg for designated waste and the reasons for targeting radiocaesium are described in Guidelines for Processing Waste Contaminated by Nuclear Accident-Derived Radioactive Materials, Ministry of the Environment (2013).

Shiitake mushrooms

There are presently restrictions in place in the Prefecture on the distribution of *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 national limit of 50 Bq/kg for radiocaesium in oak logs destined for mushroom production therefore appears to be conservative.

Forest 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 forest mushrooms while in the others collection and personal consumption is allowed but sharing the mushrooms with friends and family is forbidden.

The restrictions in place apply to all species of mushrooms. To lift a restriction on one species in any given municipality, 60 samples must be collected within the municipality at the start of the season and all of them must be below the 100 Bq/kg distribution limit. Depending on the species, a sample may be one or several individual mushrooms. Once a species is de-restricted, at the start of the next season and all subsequent seasons, three samples must be collected, 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 over very small areas. The samples analysed 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.

Over the past three years, no reductions have been observed in the concentrations of ^{137}Cs in forest mushrooms. The IAEA team commented that in the first eight years after the Chernobyl accident, concentrations in forest mushrooms in some European countries were reasonably constant, but subsequently fell will 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.

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.

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. Most restrictions have been lifted or are expected to be lifted in the near future. At the end of 2018 (when this topic was last discussed during the project), restrictions were still in place in eight different areas for seven species – carp, crucian carp, mitten crab, eel, char, dace and land-locked salmon.

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 Abukuma 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 Prefecture 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 1,240 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 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 several years, or even decades. 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 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. 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 to 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 to 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.

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

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 run-off, particularly when the slope of the terrain is 30 degrees or greater. Any radiocaesium lost through sedimentation is likely to be associated 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.

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.

2.3.5. Managing the timber industry

National legislation requires any material that exceeds an activity concentration of 8,000 Bq/kg of radiocaesium to be managed as radioactive 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 1.57 µSv/h roughly corresponds to a radiocaesium concentration of 8,000 Bq/kg in bark, but a range of values from 1.47 to 3.30 µSv/h was observed. The Prefecture had adopted the criteria whereby, in areas where the air dose rate is below 0.5 µSv/h, the trees can be felled and processed without restriction. If the air dose rate exceeds this value, a sample of the bark must be analysed to determine the actual activity concentration of radiocaesium. This is a conservative approach, but it seems to work well.

An additional criterion is to restrict the activity concentration of radiocaesium in firewood to 40 Bq/kg, which would ensure that the radionuclide concentration of the ash does not exceed 8,000 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 5,500 Bq/kg. Using the methodology outlined in IAEA TECDOC-1376, *Assessing radiation doses to the public from radionuclides in timber and wood products*, if such wood were used for house construction, the annual dose to occupants is estimated to be 0.132 mSv. Scaling up, at 8,000 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.

2.3.6. 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 μSv/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%.

2.3.7. Forest fires

IAEA-TECDOC-1240, *Present and future environmental impact of the Chernobyl accident*, states "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 re-suspension 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 national authorities and 14 of the 17 municipalities in the Hamadori and Nakadori Regions are participating.

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

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;
- Maintenance of the (mainly broadleaf and bamboo) forest areas;
- Installation of biomass boilers at central locations;
- Other initiatives on a case-by-case basis

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 μSv/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.

In Kawauchi village, an area where the dose rate was 0.24 μSv/h (just above the ‘target’ value of 0.23 μSv/h), 9 cm of litter and topsoil was removed, resulting in a reduction in the dose rate to 0.19 μSv/h. The experts commented that in a few months the dose rate would have reduced in any case to 0.23 μSv/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.

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

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; people need to be encouraged to use this service also for wild foods. In the case of forest products such as wild boar, the IAEA team suggested to develop the 'in vivo' technology used widely after the Chernobyl 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 agreed that restrictions are likely to be necessary for certain wild foods in some parts of the Prefecture for many years or even decades. Monitoring programmes will need to be maintained and public information for hunters and others who source food in the forest will be essential to help people understand the long-term nature of the situation and that there are no proven and cost-effective measures that can be taken to reduce the concentrations of radiocaesium. The IAEA team also noted that there are differences in the approach to initiating and lifting restrictions for freshwater fish and forest mushrooms and other forest products. Additionally, the criteria for lifting restrictions are very difficult to meet and restrictions can be re-imposed very easily.

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.

5. All components of the forest ecosystem are inter-dependent: 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 2019 FY. It is intended to publish the results obtained and make them widely available to the general public. This information is particular 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 inter-dependent, the data for forest 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 well exceed the limit of 100 Bq/kg for general foods sold commercially that was established in April 2012.

14. For all these reasons, ongoing attention needs to be given to providing more and better information to those who collect wild foods for their own personal consumption so that they 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. 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 biomagnification of radiocaesium resulting in an approximately 3- to 4-fold increase in the activity concentration between each trophic level. 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.

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 global experience, 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.

Studies by research institutions (e.g. Fukushima University) have indicated that limited amounts of ^{90}Sr were released during the Fukushima Daiichi accident, and that, except in the immediate vicinity of the Fukushima Daiichi Nuclear Power Plant, ^{90}Sr activity concentrations in farmland and crops were nearly equal to those resulting from fallout of atmospheric nuclear weapons testing in the 1960s. These studies estimated that internal doses from ^{90}Sr due to ingestion of agricultural products in Fukushima City and Date City, are on the order of a few tens of µSv/yr, which does not result in significant changes in estimated doses to people.

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 wash-off 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;
- 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 run-off, 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.

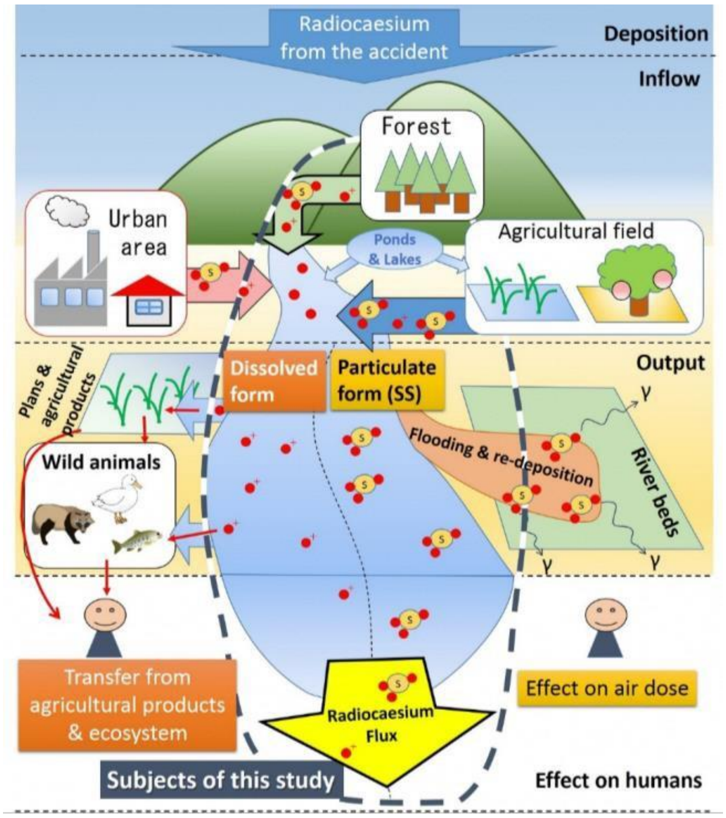

FIG 3.1. Illustration of radiocaesium transport through a catchment area and interactions with terrestrial elements (Image: Fukushima Prefecture)

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 established a comprehensive programme to monitor radiocaesium in fresh surface waters, which is performed by the Fukushima Prefectural Centre for Environmental Creation (see Figure 3.2 and Table 3.1).

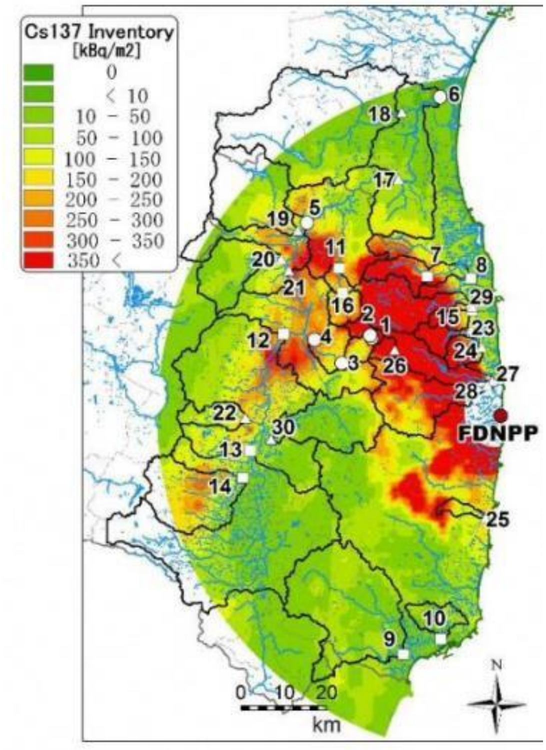

FIG 3.2. Distribution of ^{137}Cs-deposition in the Prefecture as determined during the Third Airborne Monitoring Survey (MEXT, 2 July 2011)

Table 3.1: Catchment area and average ^{137}Cs inventory in the wide-area river survey (data from https://www.pref.fukushima.lg.jp/uploaded/attachment/191954.pdf).

Site No.	Point Name	River 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 the detection limit of 0.05 Bq/L for the measurement technique used (a level that is well below the water quality objective for safe drinking water of 10 Bq/L).

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, suspended radiocaesium concentrations decreased due to a dilution effect caused by large amounts of sandy particles with low adsorption capacities in the sediment transport load in the river waters.

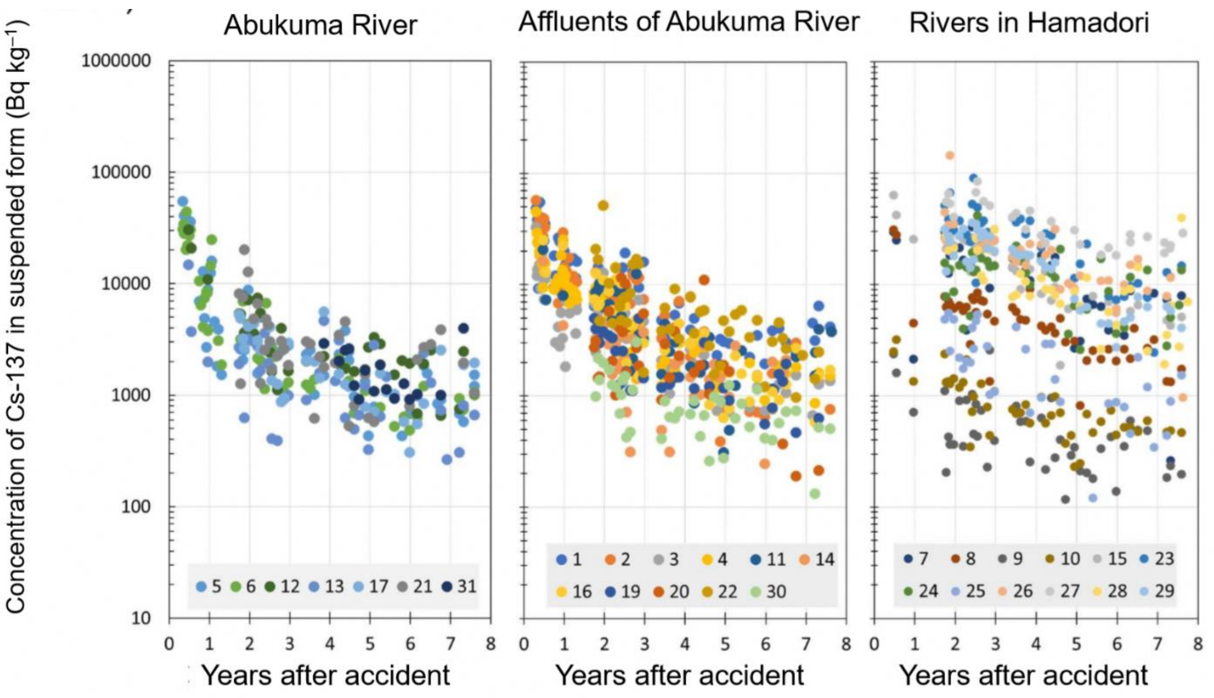

FIG. 3.3. Decline of ^{137}Cs in suspended matter of rivers in the Prefecture from 2011 – 2019 (Image credit: Fukushima Prefecture)

Since most of the radiocaesium in water bodies is associated with suspended sediments in river water, the measurements of radiocaesium, in combination with the data on water flow and sediment transport, allowed the estimation of the total flux of radiocaesium from the catchment area to the Pacific Ocean for the period of 2011 to 2016 (as reported in the 'previous report'). The decrement 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 3.4 (Panels A and D).

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 inter-comparison between aquatic systems, which allows the results to be compared with international literature.

3.3.2. Effective half-life of ^{137}Cs in Prefecture rivers

Data generated through monitoring suspended and dissolved ^{137}Cs over time has been used to estimate the effective half-life (T_{eff}) of ^{137}Cs in each of these forms. Effective half-lives of ^{137}Cs in rivers within the Prefecture ranged from 2.4 to 4.4 years for dissolved radiocaesium and from 2.6 to 2.9 years for suspended sediments, based on data collected between 2012 and 2018. The effective half-lives that have been determined for rivers in the Prefecture are consistent with those reported in rivers in Europe following the accident at Chernobyl.

It is important to note, however, that the effective half-life of a radionuclide (in this case, for ^{137}Cs) can change over time to reflect 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, ^{137}Cs concentration in suspended sediments rapidly declined, with a corresponding decrease in the effective half-life.

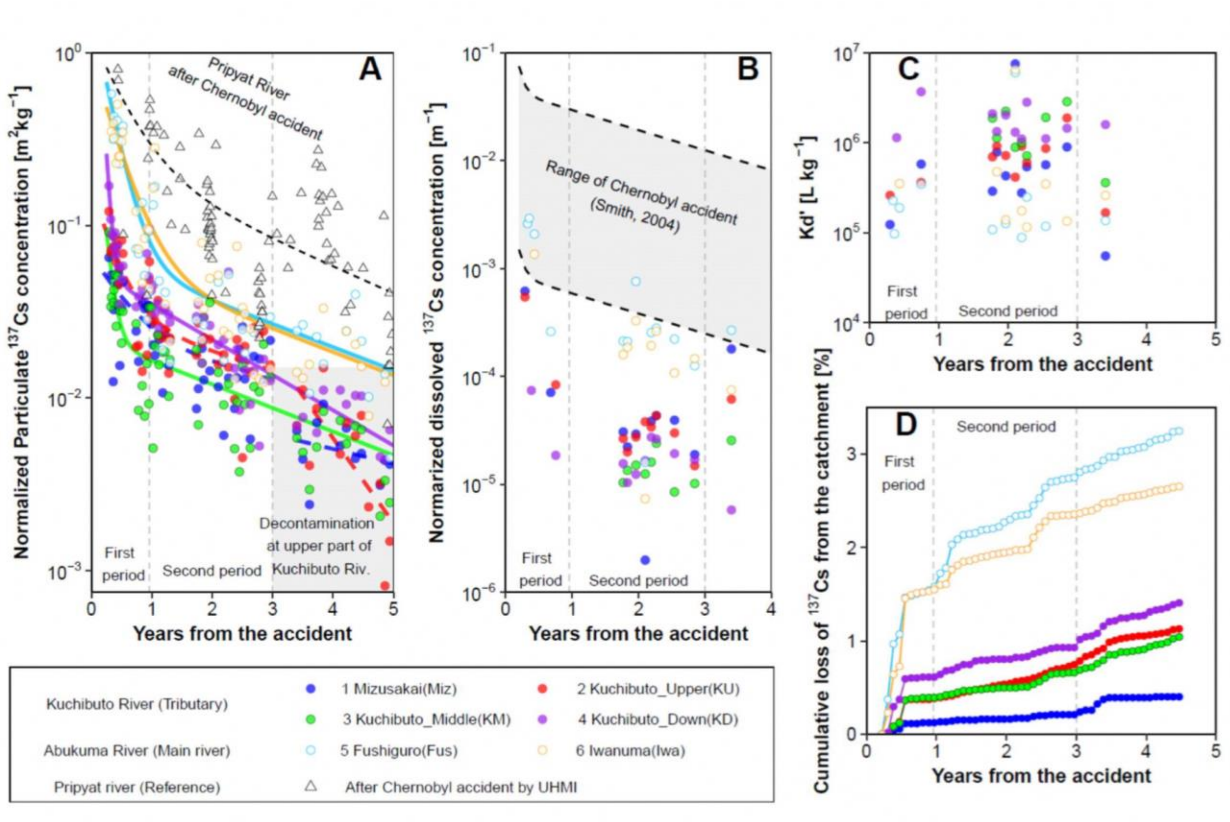

FIG 3.4. Temporal trends in ^{137}Cs in rivers of the Prefecture during periods before, during and after decontamination (2011 − 2016), depicting: 1) Declines in particulate and dissolved ^{137}Cs activity concentrations normalized for particle size (Panels A and B, respectively); 2) Sediment-to-water distribution coefficient (K_d) (Panel C); and 3) Cumulative loss of ^{137}Cs from the catchments of rivers in the Prefecture from June 2011 to 2016 (Panel D). In this figure, solid circles indicate monitoring points in Kuchibuto River (tributary of Abukuma River), and open circles indicate monitoring points in Abukuma River.

3.3.3. Radiocaesium in phytoplankton and zooplankton

Measurements of radiocaesium levels in phytoplankton and zooplankton (‘plankton’) populations from freshwater bodies in the Hamadori and Nakadori districts by research institutes in the Prefecture were described in the ’previous report’. The densities of plankton were very low and varied both temporally and spatially. In the Yokokawa Dam Reservoir, the density of phytoplankton in water was determined to be on the order of 0.1 mg/L; the densities of zooplankton were approximately a factor of 10 lower.The total radiocaesium activity concentrations for both phytoplankton and zooplankton comprised only a small fraction of a percent of the radiocaesium present in a given water body.

3.3.4. Characterization and occurrence of radiocaesium-bearing radioactive particles

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 (Cs)-bearing microparticles (CsMPs) may have been entrained into the sample. Through this assessment, a small number of CsMPs of two types were found; Type A particles were typically 1 to 2 µm in diameter and typically contained 1 to 2 Bq of ^{137}Cs. Type B particles were typically 5 to 250 µm in diameter and typically containing 5 to 100 Bq of ^{137}Cs.

International experience on radiocaesium-bearing radioactive particles, their occurrence and characterization was provided by the IAEA team. During discussions, although it was anticipated that that CsMPs are unlikely to contribute significantly to public exposure and corresponding dose, it was recognized that screening for such particles as part of existing monitoring programmes is important for due diligence. In addition, characterization of sources of CsMPs, their composition, size distribution, density, weathering rates and mobility, and evaluation of these factors in the context of risk assessment, were suggested by the IAEA team as possible areas for further study. The application of CsMPs as environmental tracers was also suggested by the IAEA Team and Prefecture experts.

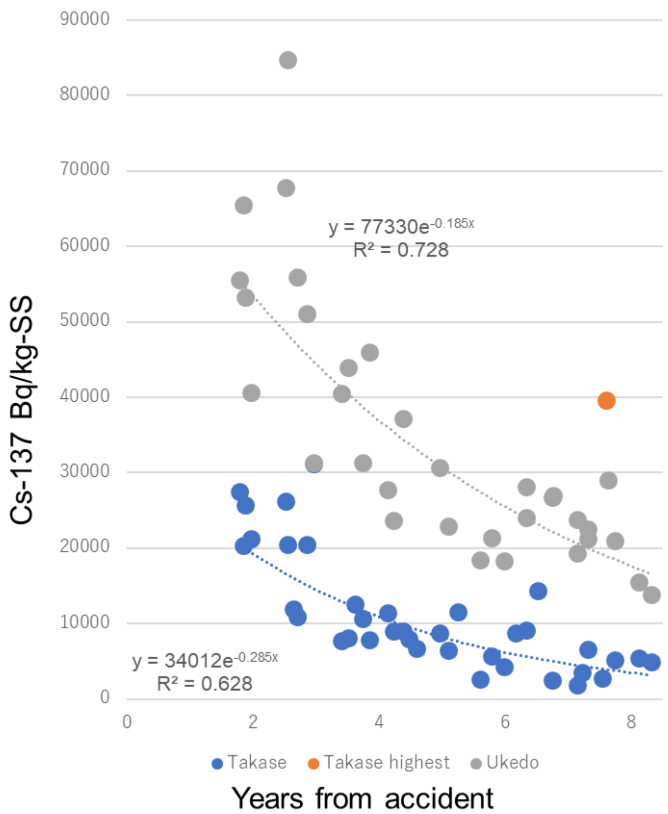

FIG. 3.5. Temporal changes in activity concentrations of ^{137}Cs in suspended sediment (SS) samples collected from a river in the Hamadori Region, Fukushima Prefecture) (Image credit: Fukushima Prefecture).

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).

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 ($\delta^{13}C$) are fairly distinctive in different environmental media, as well as for different types of plants. Therefore, characterization of $\delta^{13}C$ signatures, in addition to ^{137}Cs activity concentrations, can serve as tools to gain a better understanding of radiocaesium dynamics in catchments.

An analysis performed by the Prefecture indicated that between 2011 and 2016, the cumulative loss of ^{137}Cs activity from the catchments of the Abukuma and the Kuchibuto tributary was about 2.7% (ranging between 2.5% and 3.0%) and 1% (ranging between 0.5% and 1.5%) of the initial ^{137}Cs deposition, respectively (as reported in the ‘previous report’). 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 wash-off 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.

Assessment of the relative amounts of ^{137}Cs 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 (as reported in the ‘previous report’). The relationship between the activity concentration and flux of suspended ^{137}Cs and the land coverage ratio was evaluated for different land applications; it was concluded that the reduction rate for the 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 3.6). The areas with human activities contributed a total of 85% of the 12 TBq in ^{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[3].

Dissolved and suspended radiocaesium were measured in the Yokokawa dam reservoir in 2014 by research institutes in the Prefecture in 2014. 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 also lakes. In this way, reservoirs act as a kind of sediment trap.

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[3] TANIGUCHI, K., Y. ONDA, H.G. SMITH, W. BLAKE, K. YOSHIMURA, Y. YAMASHIKI, T. KURAMOTO, K. SAITO, 2019. TRANSPORT AND REDISTRIBUTION OF RADIOCESIUM IN FUKUSHIMA FALLOUT THROUGH RIVERS, *ENVIRON. SCI. TECHNOL.* 2019, 53, 21, 12339–12347 HTTPS://PUBS.ACS.ORG/DOI/10.1021/ACS.EST.9B02890

Since the sorption to suspended matter 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 river water, 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 particulates[4] (see Figure 3.4, Panel C). As expected, based on the international literature, K_d values increased with decreasing particle size. Similar to ^{137}Cs in the suspended sediments, the activity concentration of dissolved ^{137}Cs also declined over time. Dissolved activity concentrations for ^{137}Cs are at least one order of magnitude lower than the data measured after the Chernobyl accident (Figure 3.4, Panel B) and this is supported by the K_d values shown in Figure 3.4, Panel C [3].

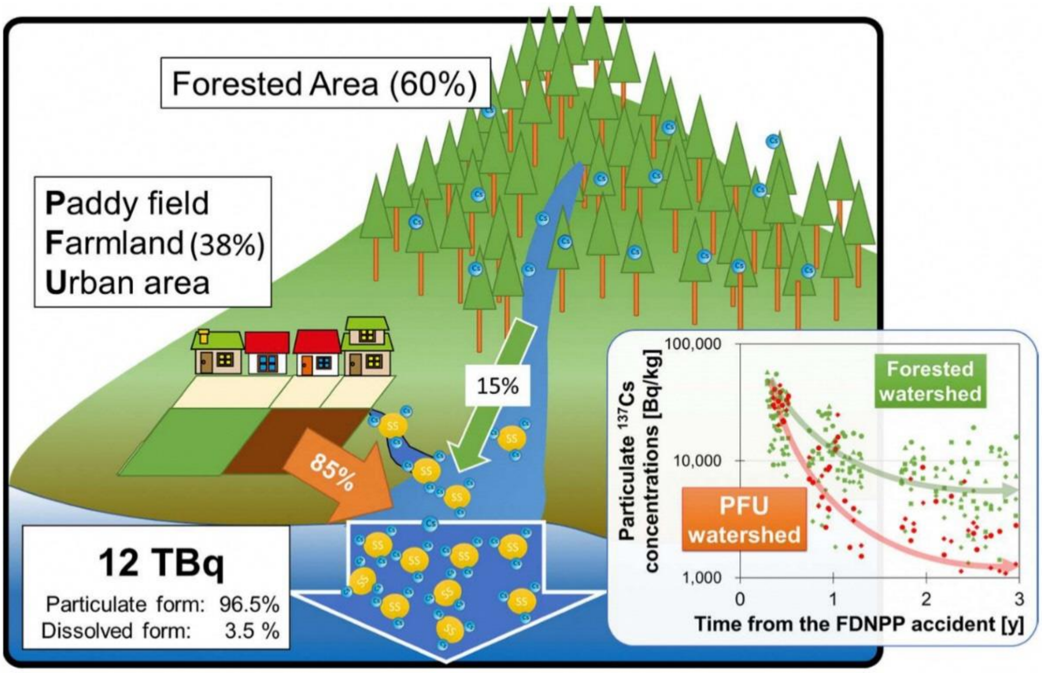

FIG. 3.6. Relative ^{137}Cs fluxes from forested areas relative areas of human activities (paddy fields, farmlands and urban areas) of the Abukuma River during the five-year period following the Fukushima Daiichi accident (see footnote 3).

Stable carbon isotope techniques have been applied and corresponding parameters have been measured in the Hirose river and its tributaries (including ^{137}Cs activity concentrations in suspended sediments, concentrations of total carbon (TC) and concentrations of suspended sediments) to compare sources of suspended sediments under base flow versus high water flow conditions and their influence on ^{137}Cs transport dynamics within the catchment. Results of ongoing research were presented by the Prefecture experts during the February 2020 mission. Seasonal sampling during typical base flow conditions relative to during periods of high flow indicate that, in most cases, the concentration of suspended sediments was higher during periods high flow. Although the suspended sediments consisted predominately of inorganic substances, as suspended sediments increased, the concentration of total carbon in river water also increased, indicating the introduction of organic material during high flow conditions, possibly from the surrounding catchment.

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[4] A distribution coefficient (Kd) of for example 1,000,000 L/kg means that the concentration in the sediment is 1,000,000 times higher than in water. This indicates a very strong caesium sorption and that the vast majority of the radiocaesium inventory is bound to sediments.

In addition, as the concentration of suspended sediments increased, the $\delta^{13}C$ signature tended to decrease and was lower than signatures measured in suspended sediments in the Hirose River and its tributaries during base flow conditions. By comparison, $\delta^{13}C$ signatures in suspended sediments during high flow conditions were consistent with those measured in soil in the surrounding catchment, indicating the possible introduction of soil with lower $\delta^{13}C$ signatures than riverbed sediments, into the Hirose River and its tributaries from the surrounding catchment.

Comparison of ^{137}Cs activity concentrations in suspended sediments between base and high flow conditions indicated that ^{137}Cs 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 ^{137}Cs in suspended sediments (described above).

The use of other possible environmental tracers and their application for this situation was discussed between the Prefecture experts and the IAEA Team and has been identified as an area for ongoing cooperation.

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)[5]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 re-contamination 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.

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 3.7). 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.

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[5] Onishi et al. (Development of a Multimedia Radionuclide Exposure Assessment Methodology for Low Level Waste Management, PNL-3370, Pacific Northwest National Laboratory, Richland, Washington, USA (1983)

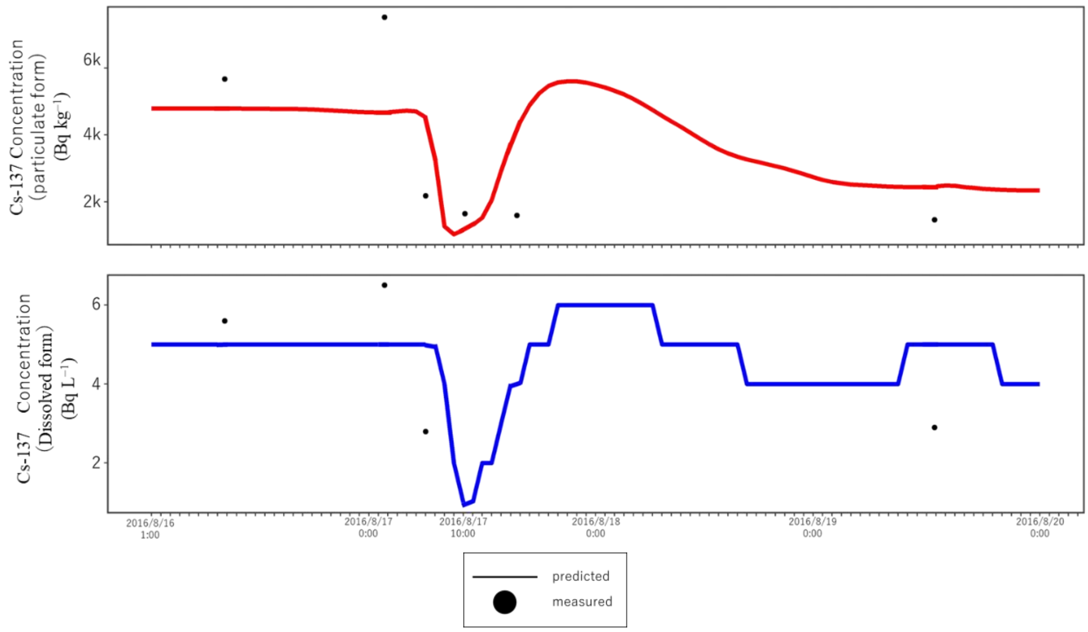

FIG. 3.7. Comparison of ^{137}Cs activity concentration measurements in dissolved and particulate forms over time relative to TODAM model predictions at the lowest downstream monitoring station in the Hirose River during conditions of high-water level [Image: Fukushima Prefecture].

3.5. Experience with remediation and decontamination in river and lakes

3.5.1. Global experience

In recent decades, a number of areas world-wide 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 characterised 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 designed zones in 2014 (as presented in the ‘previous report). 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 on-going.

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 3.8). 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. It was concluded that the ^{137}Cs flux did not decrease downstream due to the increased earth and sand flux per unit flow rate of the river.

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 3.9). Monitoring data collected before and after implementation of decontamination measures shows that the air dose rates were reduced by about 50% (see Figure 3.10).

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 3.10) did not indicate significant change in the air dose rate as a result of the flood.

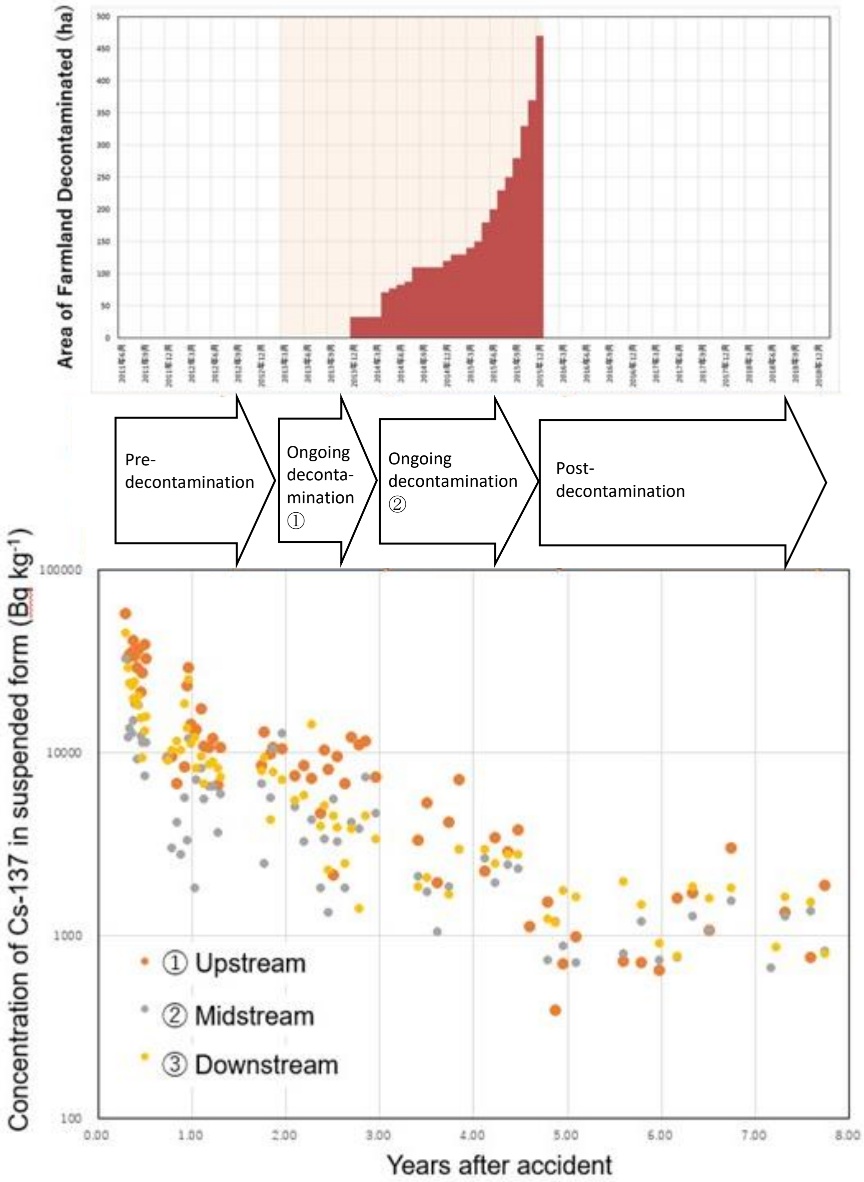

FIG. 3.8. Temporal changes in activity concentrations of ^{137}Cs in suspended sediments during pre-decontamination, ongoing decontamination 1, ongoing decontamination 2 and post-decontamination periods in the Kuchibuto river basin [Image: Fukushima Prefecture].

FIG 3.9. River bed before (left) and after (right) decontamination measures in the Kami-Oguni river (Image: Fukushima Prefecture – presented in 'previous report').

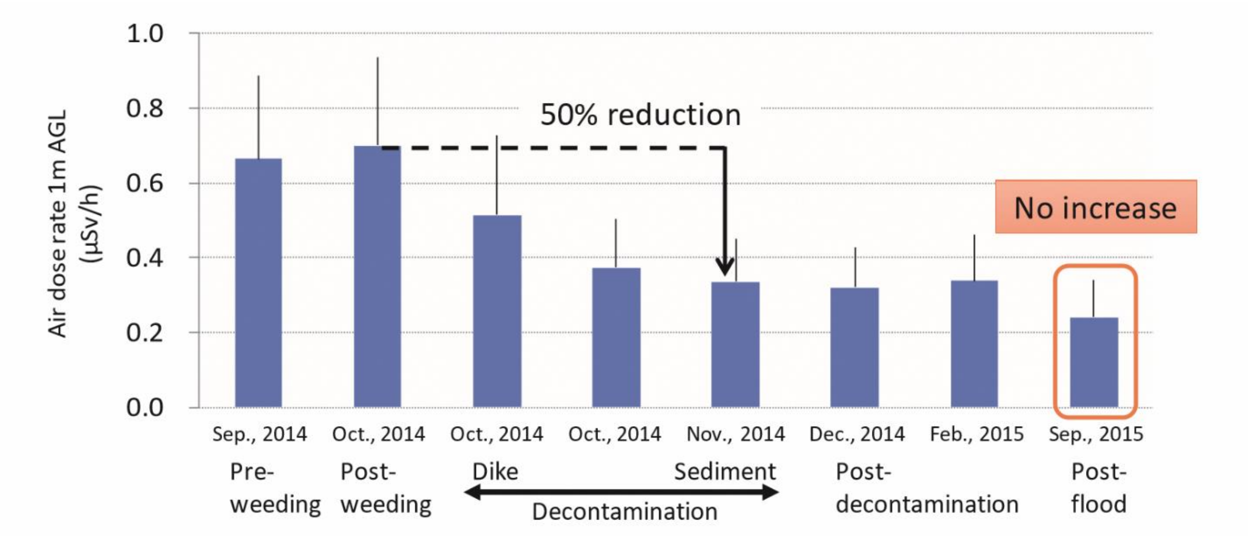

FIG 3.10. Air dose rate at 1 m height before, during and after the remediation and decontamination measures at a river in the Prefecture (presented in 'previous report') [Image: Fukushima Prefecture]

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 µSv/h (as reported in the 'previous report'). By comparison, air dose rates of 0.20 µSv/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 3.2). 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 µSv/yr. Results of projected individual doses related to the use of this part of the Niida River are given in Table 3.2. 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 3.2. Estimation of dose reduction at a demonstration site through decontamination (Fukushima Prefecture) (as reported in the 'previous report)

Item	Activity			
	Recreation	Walking	Cleaning/ beautification	Water activity
Dose rate after decontamination (μSv/h) (derived from air dose measurements over 15 minutes)	0.53	0.38	0.39	0.26
Occupancy (hours per year)	16 (4 h/d × 4 d/y)	111 (1 h/d × 111 d/y)	48 (1 h/d × 48 d/y)	9 (0.5 h/d × 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 year without decontamination	0.007	0.032	0.015	0.002

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 3.11).

FIG. 3.11. Before and after pictures of 2019 excavation work (Sep 2019) and Typhoon No. 19 (12-13 Oct 2019) in the Kami-Oguni river. Photograph A was taken prior to excavation (27 Aug 2019) and Photograph B was taken after excavation (30 Sep 2019). Photograph C (30 Sep 2019) was taken after the excavation work and before Typhoon No. 19. Photographs D to G were taken after Typhoon No. 19 (18 Oct 2019). Photograph D was taken at approximately the same location as Photograph C (Image: Fukushima Prefecture).

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 from 12-13 October 2019 and caused collapse of the river bank, deposition of sediment, cobbles and rocks, and flooding (see Figure 3.11, 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 3.12). Air dose rates (1 m above ground surface) measured on the shoreline of the Kami-Oguni river prior to the typhoon (31 Jan 2018) were 0.34 µS/h, compared to 0.18 µSv/h after the typhoon (17 Oct 2019).

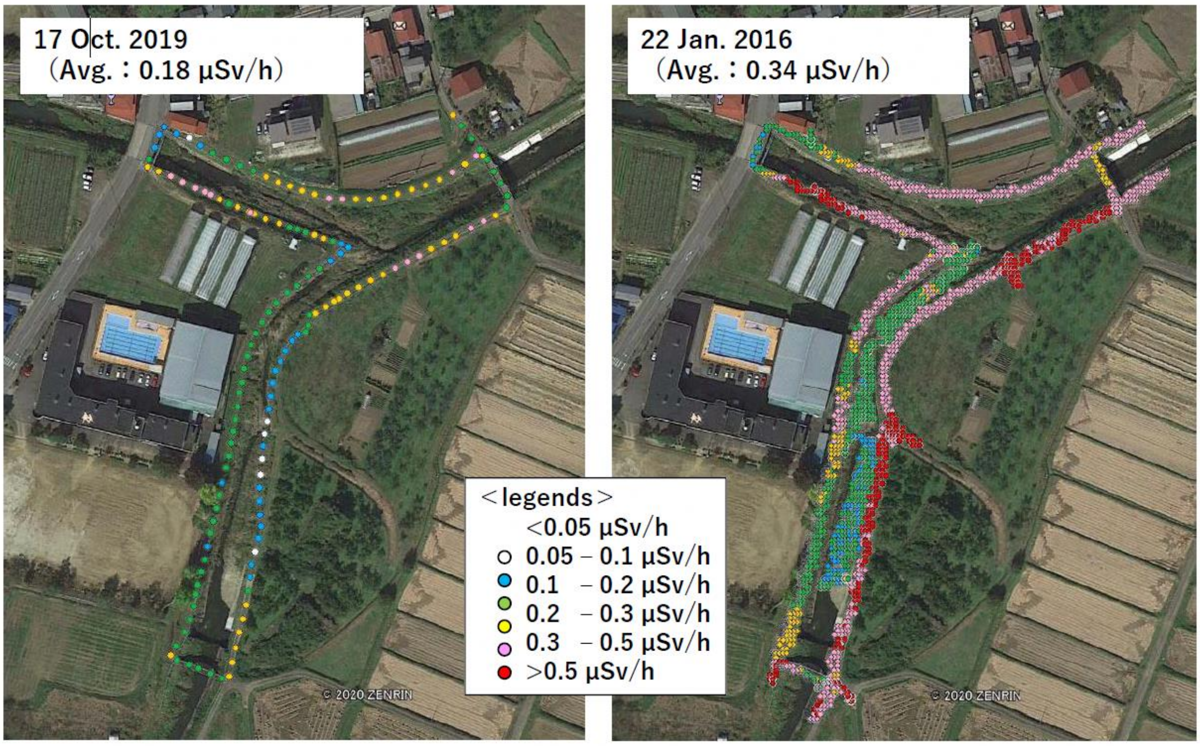

FIG. 3.12. Maps of air dose rates at 1 m height above the ground before and after Typhoon No. 19 (Image: Fukushima Prefecture).

Findings were similar in the areas of Niida River park (0.30 μSv/h before and 0.20 μSv/h after Typhoon No. 19) and the Mizunashi river (0.214 μSv/h before and 0.156 μSv/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 analyse ^{137}Cs in suspended sediments and river water downstream of areas impacted by the typhoon.

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 3.13.

FIG. 3.13. Main decontamination techniques (Image: Fukushima Prefecture)

In Table 3.3, the status of the effort to decontaminate different categories of buildings and areas is summarized. 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. As of March 2018, all of the area-wide decontamination workswere completed.

Table 3.3. Summary of decontamination completed in the municipalities (as presented in the 'previous report')

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)	4,307 (4,513)

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 3.4); such reduction factors are very similar to those achieved by remediation measures in areas affected by the Chernobyl accident. Table 3.4 is based on measurements performed before and after decontamination work that was performed from March 2012 to October 2013. Further details on countermeasures implemented in forests are given in Section 2.

Table 3.4. Reduction of the air doses rate due to decontamination work

Category	Number of measurements	Reduction of air dose rate (%)
Residences areas	82,757	36
Public facilities	32,311	45
Roads	33,451	31
Agricultural land	20,147	29
Forests	12,697	21

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.

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 inter-comparison 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 the detection limit of 0.05 Bq/L, a level that is well below the water quality objective for safe drinking water (10 Bq/L). This can be explained by the strong sorption of caesium by sediments in riverbeds, in which much higher radiocaesium levels are observed. There also continues to be a clear decline of the concentration of radiocaesium in suspended sediments.

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.

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 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.

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 ca. 20 – 50%, similar to results achieved by remediation in areas affected by the Chernobyl accident. Area-wide decontamination works 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 "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) have been established in municipalities and the Prefecture based on laws and government guidelines. 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.

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, because of delays in the development of the ISF, waste has been stored in TSS for more than three years. Consequently, the safety of the storage of waste in TSS for greater than three years is an issue that need evaluating to ensure the safety of these facilities and also 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 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 clean up of the former sites of 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.

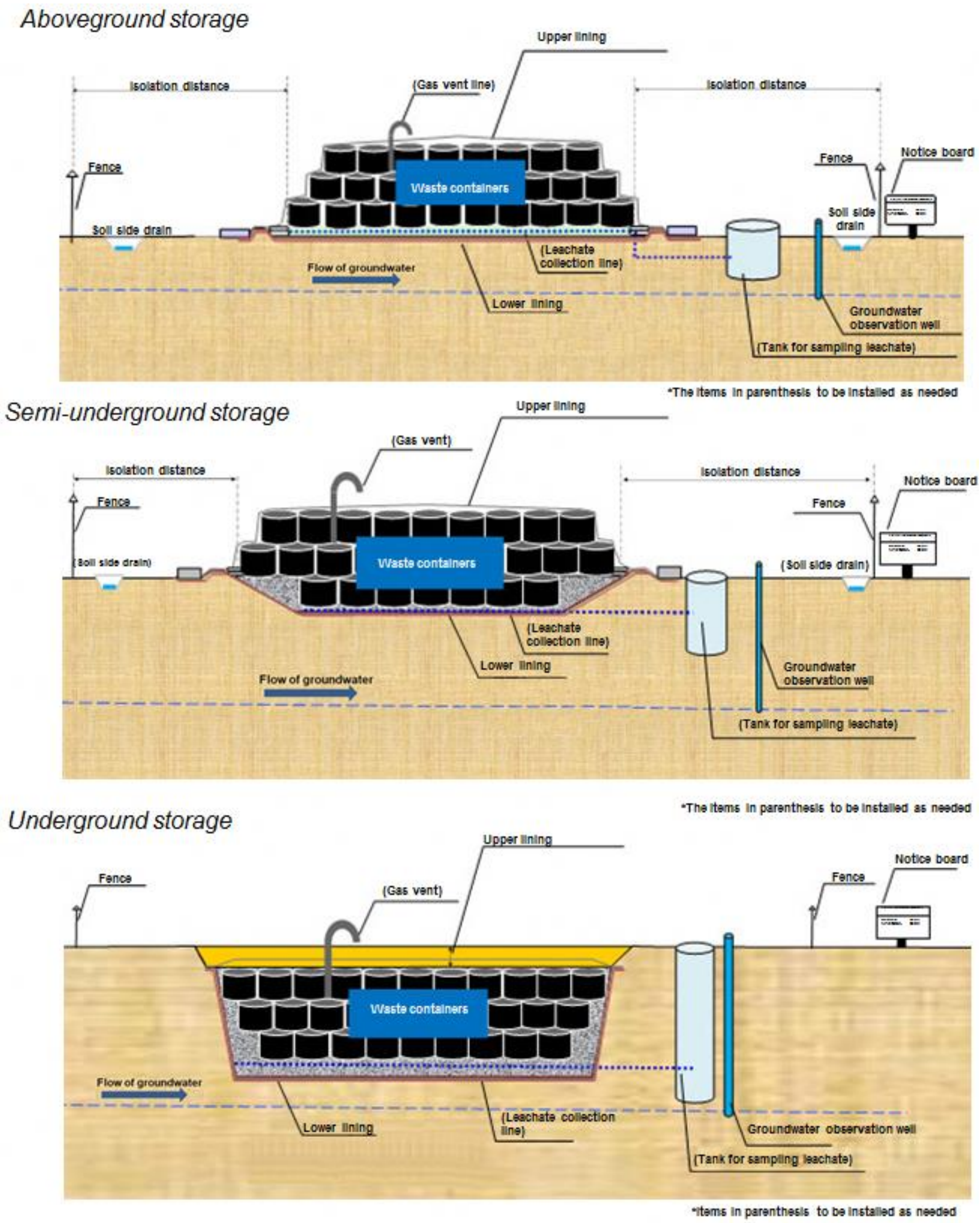

FIG. 4.1 Conceptual diagrams of three types of TSS (Image adapted from Technical Guidelines for Temporary Storage Sites, Fukushima Prefecture)

As of March 2020, 619 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 2016 and has since slowly decreased.

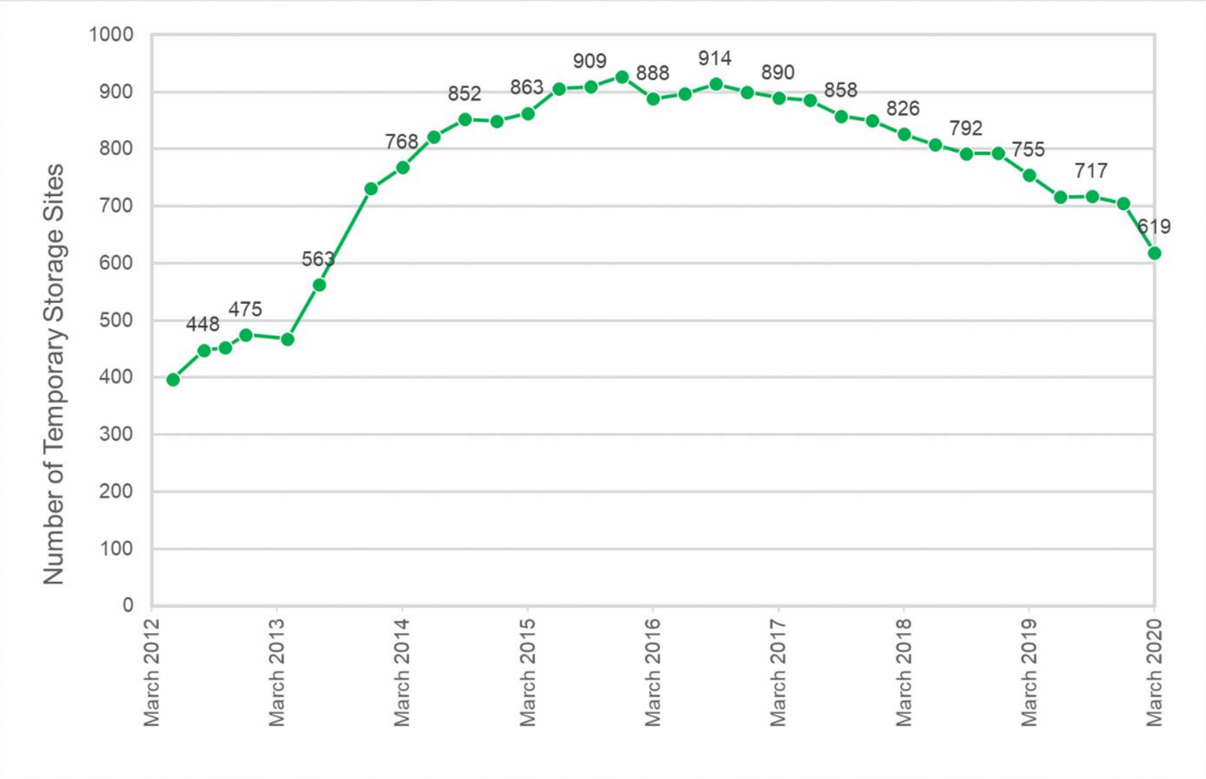

FIG.4.2. *Number of TSS in Municipalities from March 2012 to March 2020 (Image: Fukushima Prefecture)*

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

— Limitations on the number of waste bags that can 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. Such an approach should 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 clean up 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), and 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 clean-up 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.

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 presenting 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 operated safely and people and the environment 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 a quantitative evaluation of the radiological impact (safety assessment) of the facility or activity, under normal operating conditions and accident scenarios.

Confidence in the safety of TSS would be increased by showing evidence that the TSS would have minimal radiological impact. 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 parameter values to quantitatively assess the impact of the temporary storage of the waste under normal operating conditions and accident scenarios.

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) 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.

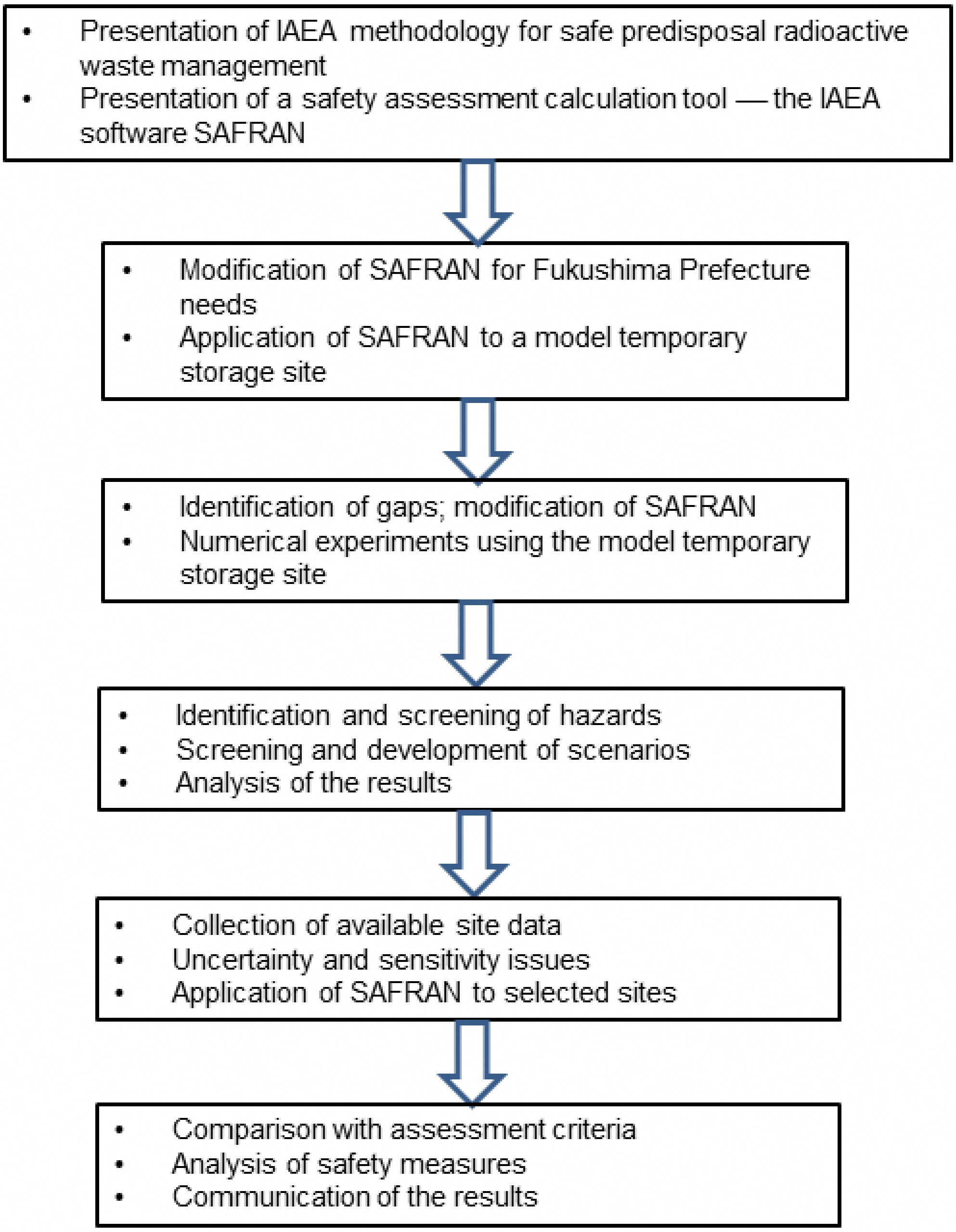

FIG. 4.3 Activity flow of the development of a safety assessment for TSS in the Prefecture

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 Safety Guide GSG–3, The Safety Case and Safety Assessment for the Predisposal Management of Radioactive Waste. GSG-3, which provides recommendations on meeting the safety requirements in GSR Part 5, Predisposal Management of Radioactive Waste. 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 could be 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.

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 adjustments were made to the software by the IAEA so that it could be 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 (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 2020, 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 Normalysa.

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 assessment.

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 IAEA 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: emplacement, storage, and retrieval. Normal operating conditions and accident scenarios were evaluated. Each of these activities requires separate analyses, with specific conditions under normal operating conditions and accident scenarios taken into account.

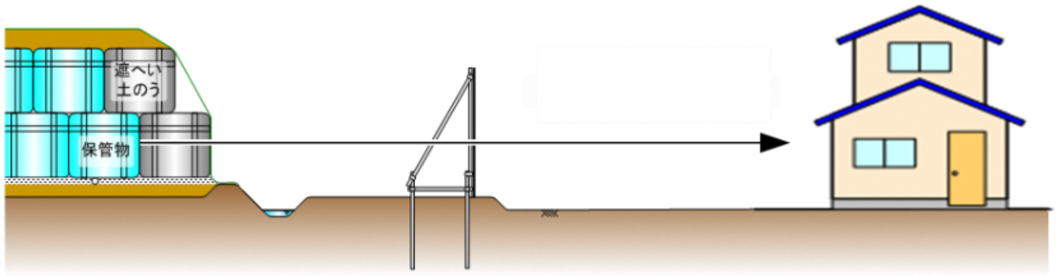

FIG 4.4. Typical layout for a TSS. Radiation doses are calculated with respect to the distance from stored materials (Image: Fukushima Prefecture).

The safety of the model TSS, as for other engineered facilities, depends on robust and proven design and construction. 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 are 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 that must 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 must be gathered, which includes 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 were estimated including inventories, throughput rates, activity concentrations, etc. that are 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 associated with the model TSS, which addressed the hazards which arise 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. Through this process an extensive set of hazards during emplacement, storage and retrieval of waste was analyzed under normal operating conditions and in accident scenarios.

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

Joint discussion and analysis of data reveals again 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 should engage consultation 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 are a small fraction of the radiation dose limits.

The doses for normal situations were assessed for the case in which all operations are 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 analysed 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 a model temporary storage site

The use of SAFRAN to represent the relevant waste management activities and facilities 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, one could conclude 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.

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 analysed 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 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 should 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 are were similar to the results of the model safety assessment, which clearly indicates that the process of developing the safety assessment is coherent, that the data used as input to the safety assessments are satisfactory and there that 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 in the safety assessment process.

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

A decision was reached to apply the IAEA 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 was acquired for these sites and in situations where data could not be obtained, data was 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 may be necessary.

It was noted that if waste is stored in TSS for longer periods of time than originally assumed, it will be necessary to revise the safety assessment 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 ongoing 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. According to the Prefecture, the results have been compiled as a document, describing the development process for the safety assessment and its conclusions, and this was disseminated on the Prefecture’s website in Japanese in March 2020. The completed documentation has not been discussed with the IAEA experts.

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 clean up of the sites of the former TSS.

Because of the ageing of waste bags as discussed in Section 4.4.5, it can be anticipated that the degradation of waste bags will lead to difficulty in retrieving these bags from the TSS. The IAEA team suggested that the ongoing review study of the durability of waste bags should be continued, that the results of this review should 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 should be addressed through the safety assessment process is 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. As new information arises from as a result of the ongoing work on concerning the ageing of waste bags and the consideration of transport issues, the safety assessment and strategy should be revised to take this information into account.

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 in 2018, 2019 and 2020. 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 8,000 Bq/kg.

The IAEA team noted that decommissioning of TSS after all waste material has been removed will be a significant undertaking that should be approached in a systematic way in accordance with the IAEA Safety Standards. Various issues in this regard must 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.

It is expected that a substantial proportion of the TSS in the municipalities will be restored during the period 2019 to 2021.

According to the discussions held in February 2020, the restoration of sites is progressing well and, for example, by 2022 there will not be any 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.

The operators of former TSS (relevant municipalities) are planning to decommission the sites so that after clean up they have contamination levels below those which existed immediately before the TSS was established. The approach summarized by the Prefecture experts, which is aligned by the Guidelines made by the MOE for 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, seems appropriate, but it will be important that sufficient numbers of measurements are made. Safety assessment for the restoration of the sites is in progress and should demonstrate that the sites of former TSS will be safe now and for future use.

For consistency with IAEA Safety Standards, the safety assessment work done for operation of the TSS, for the removal of waste from the TSS, for transport of waste to the ISF, and for the restoration of the sites of former TSS should be fully documented and subject to appropriate review. The choices made in assessing the safety of the TSS (e.g. regarding scenarios, contamination pathways, parameters…) should be fully justified. Further discussion could be beneficial to help with the successful communication of the work done to relevant audiences. IAEA is available to continue providing assistance on these topics as requested.

4.6. 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 decommissioning and clean up 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. Since the safety assessment is updated automatically during each of these steps, the risk that such iterations lead to confusion, contradictions and the lack of consideration of important aspects is substantially reduced.

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. During the implementation of the software, a part of the SAFRAN database was changed to fit to 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 safe and reliable way to store the large amount of radioactive waste accumulated from remediation activities after the Fukushima Daiichi accident.

During the development of the safety assessment for TSS, several technical issues have been identified whose impact on safety has been evaluated (e.g. water accumulation in different places of the temporary storage facilities, flooding, fires, degradation retrieval of waste bags from TSS, transport of waste bags, collapse of waste packages, etc.). On the basis on these dedicated evaluations of the impact on safety, technical measures to remediate and prevent the problems can be established and their effectiveness can be estimated.

Several of the conclusions reached through the safety assessment process could have been identified through a less systematic approach (e.g. solely by expert judgment based on arguments of experience and good practice). However, such an approach would not necessarily have resulted in the same conclusions because a less systematic process may not have identified some relevant issues. The systematic process carried out using SAFRAN included assessment of all credible hazards and technical issues and provided arguments and confidence that no significant issues were 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 through the use of SAFRAN in for the development of a safety assessments for the TSS in the Prefecture clearly indicated that as long appropriate operating procedures are followed and appropriate measures are put in place, all radiation doses should be (calculated using conservative values) are in most of the cases well below the prescribed the relevant dose limits. A systematic analysis of the all relevant hazards also provided a sound justification for imposing the measures where, if necessary, to avoid or significantly reduce any possible unacceptable type of undue impacts on consequences 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. It was noted that the safety assessment for TSS should be revised to account for new information that arises as a result of the ongoing work on the ageing of waste bags.

Decommissioning of TSS after all waste material has been removed will be a significant undertaking that should be approached in a systematic way and the IAEA team advised that the applicable IAEA Safety Standards are used.

For consistency with IAEA Safety Standards, the safety assessment work done for operation of the TSS, for the removal of waste from the TSS, for transport of waste to the ISF, and for the restoration of the sites of former TSS should be fully documented and should be subject to appropriate review. The choices made in assessing the safety of the TSS (e.g. regarding scenarios, contamination pathways, parameter) should be fully justified. Further discussion could be beneficial to help with the successful communication of work done to the relevant audiences. IAEA is available to continue providing assistance on these topics as requested.

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 customised 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.

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

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 0.1μSv/h to 8μSv/h. The different altitude measurements were performed with the UAV-based system equipped with Geiger-Müller counter. The same area was also characterised 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.

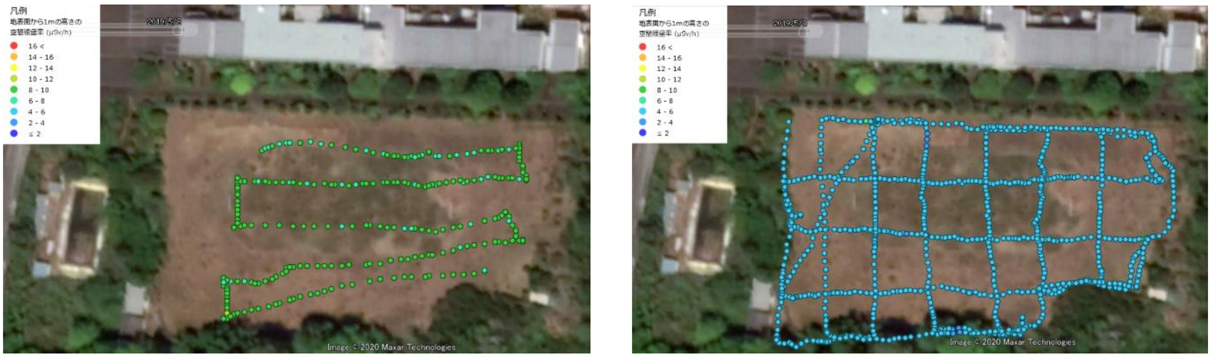

Fig. 5.2. Example of in-situ measurements (not-corrected raw data) performed in the area accessible both for backpack and UAV techniques: data points obtained with the UAV system (Geiger-Müller counter) flying at 10m altitude (on the left); data points obtained with backpack system (CsI spectrometer)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

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).

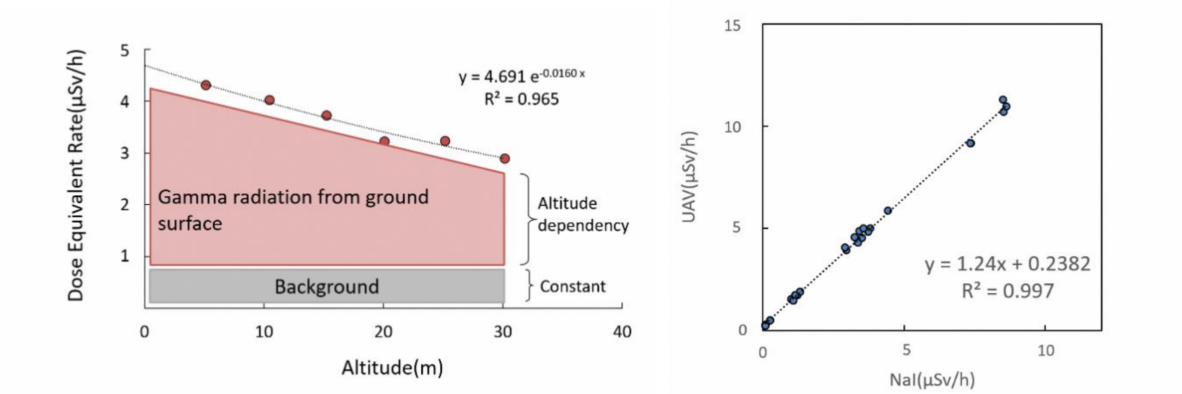

Fig. 5.3. On the left: illustration of exponential dependence of the dose equivalent rates measured by the UAV-based system and represented as a function of altitude. On the right: illustration of linear dependence of UAV data obtained with Geiger-Müller counter with respect to reference NaI data (both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

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 heterogenous 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 2D 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.

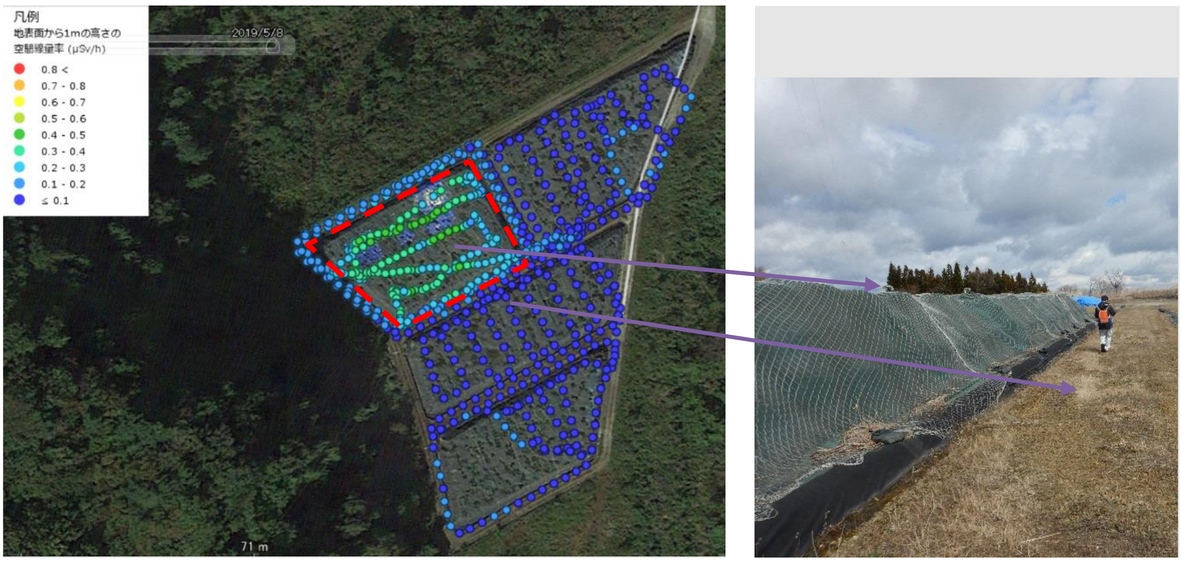

Fig. 5.4. Combination of UAV (marked within red rectangle) and backpack based radiological mapping, carried out at one of the temporary storage sites of the Fukushima Prefecture. Image: Fukushima Prefecture.

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 has confirmed that radiation levels in publicly accessed areas of the Prefecture are within the range of background levels of radiation in Japan. The Prefecture government has 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 have 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 maintained 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 3,500 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 has disseminated information about radiation monitoring results, radiocesium levels in the environment, decontamination, remediation and waste-related activities in the area, and has explained the concepts of radiation doses to the public and other relevant stakeholders. For this purpose, the Prefecture has 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 changed 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 have been 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 has 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 are based exclusively on data from fixed monitoring locations; while walking surveys could be undertaken, they are 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 seems 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. Many people are not familiar with radiation protection terminology and concepts, and for them the message 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 on 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 have decreased since March 2011. Where possible, this data should be retained and used.
- In the future it might 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 are 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 be misleading. 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 must decide what information will 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 has been 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 has been normalized to 1 m above ground in outdoor air. The new website is more user-friendly and faster than the previous version, and it is optimized to both computer screens and smartphones. With the revised website, it is now possible to easily browse data associated with specific locations and to specify dates of interest. Clickable maps allow users to access data from specific points on a map (See Figure 6.1). Air dose levels and the results of environmental samples are displayed on the same map. The changes in air dose rates with time can be accessed intuitively through the use of a "time ruler" (See Figure 6.2). Also, the revised website has 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 is also available in English, Chinese and Korean. The English language portal for the revised website can be found at this web address: http://fukushima-radioactivity.jp/

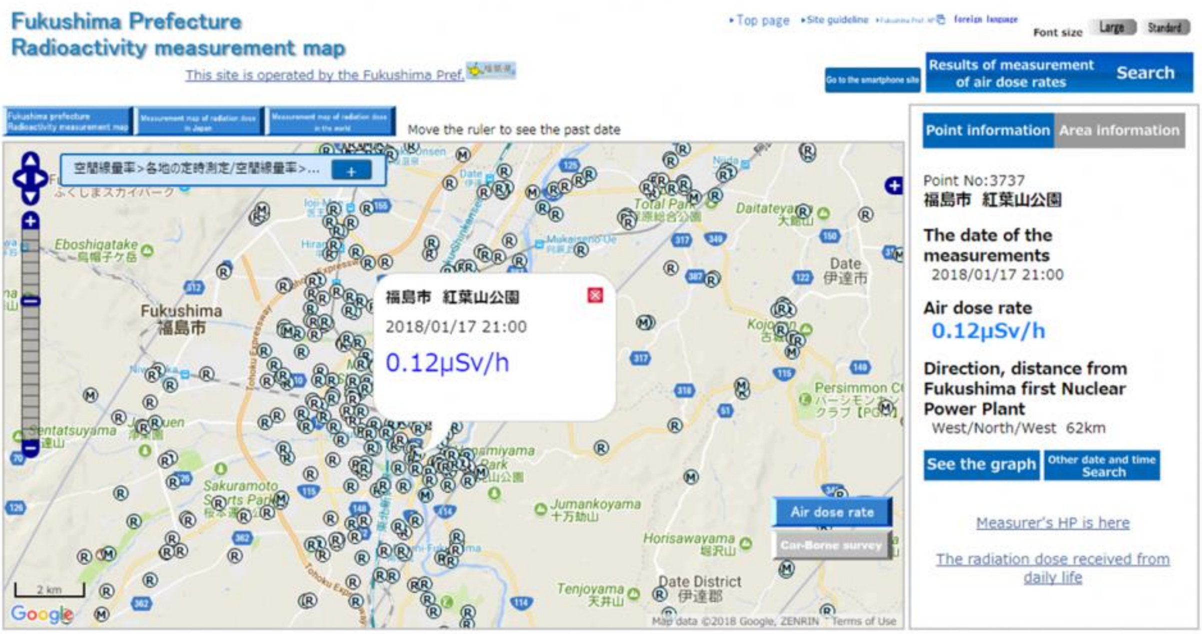

FIG. 6.1. Clickable Radiation Measurement Map (Fukushima Prefecture website)

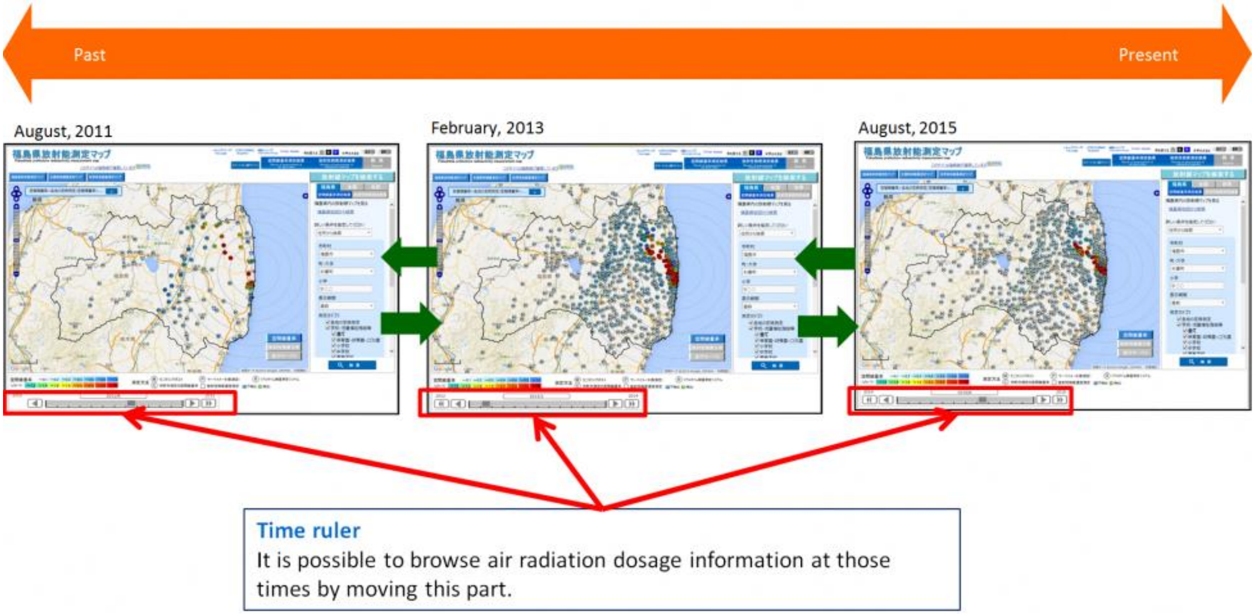

FIG. 6.2. Time ruler from Radiation Measurement Map (Fukushima Prefecture website)

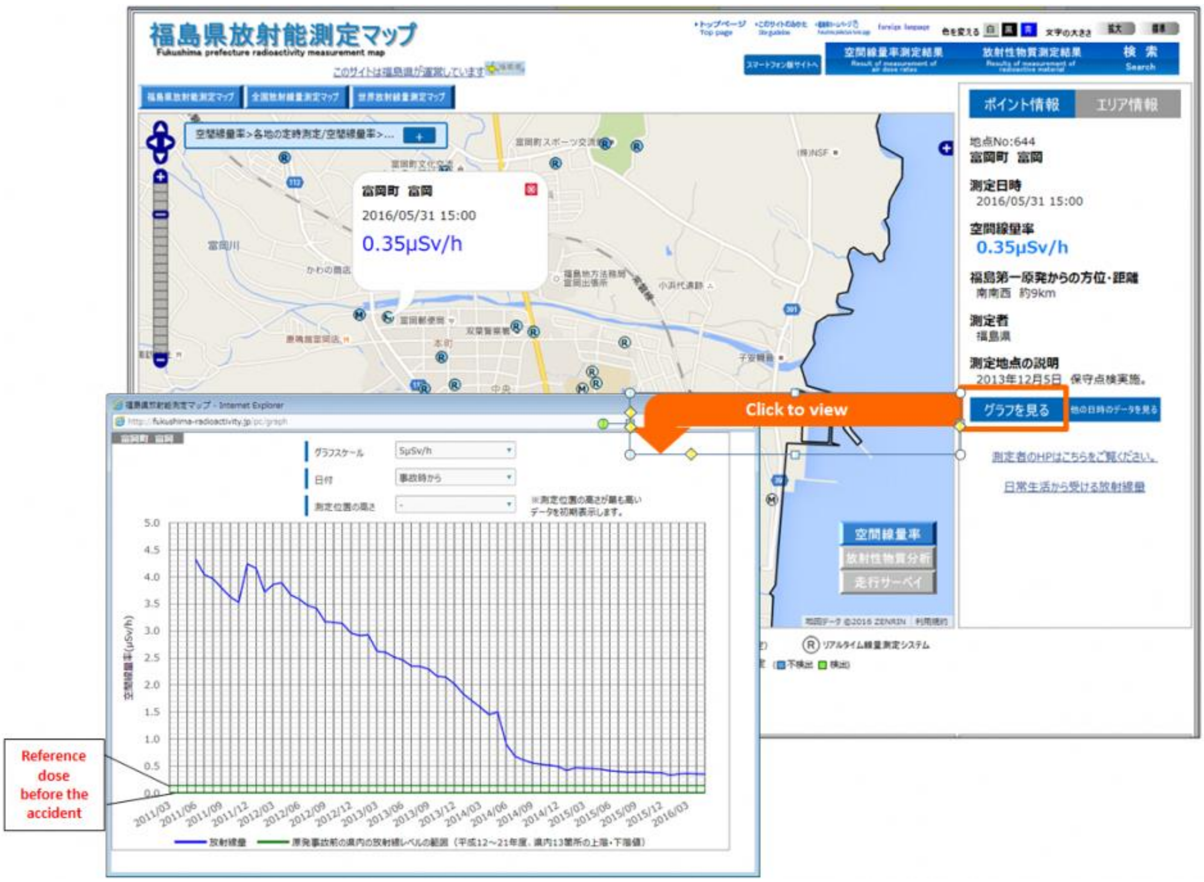

FIG. 6.3. Graph of measurement data from a specific measuring point over a specified timeframe from Radiation Measurement Map (Fukushima Prefecture website)

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.

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 currently 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 produced a paper on how to optimize information dissemination via the Fukushima Revitalization Station. This paper provided information on how to:

- 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.

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.

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 have been carried out between 2018 and 2020. These were based on international examples of best practices in informing the public about the effects of radiation.

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.

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 online on this link[1]

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

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1 https://www.fukushima-kankyosozo.jp//lancelot/common_files/images/public/9_Leaflet(English).pdf

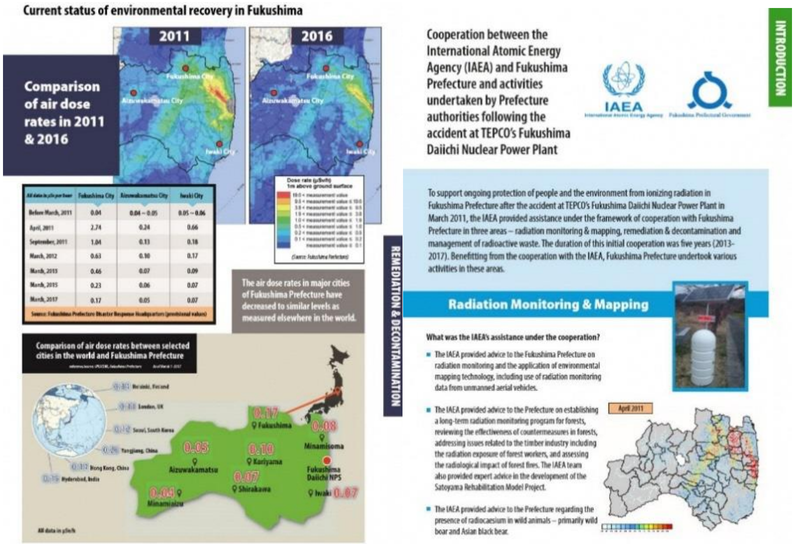

FIG 6.4. An illustration of the front page of one of the leaflets and a page with infographics in English *(Image: Fukushima Prefecture)*

The IAEA team and the Prefecture have agreed on creating further outreach materials on an ongoing basis during the remainder of the duration of the Practical Arrangements.

6.4.2. 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.

— 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 maplarge scale maps, available on the Prefecture website[1] give a general view of how air dose rates are reducing with 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 have been collected in a number of different ways, each of which uses different measurement methodologies. Over 3,000 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.

The provision of information through a website is only one component of a communications strategy. It has been recognised 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 take-aways arising from the cooperation with IAEA are:

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[1] " (http://fukushima-radioactivity.jp/pc/),

- 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 have highlighted the importance of sharing international examples and benefits of worldwide assistance.

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 Mid Term Summary Report covers the work undertaken under the Practical Arrangements from 2013 – 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 contained in the trees themselves. The relatively low concentrations measured in harvested wood to date support the continued unlimited 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 should 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 clean up 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 the clean up 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 safety assessment work done for operation of the TSS, for the removal of waste from the TSS, for waste transport to the ISF, and for the clean up of the sites of former TSS should be documented. Further discussion could be beneficial to help with the successful communication of work done to the relevant audiences. IAEA is available to continue providing assistance on these topics as requested.

7.4. Information dissemination for the public in Fukushima Prefecture

Since shortly after the accident, the Prefecture government has disseminated information about radiation monitoring results, radiocesium levels in the environment, decontamination, remediation and waste-related activities in the area to the public and other relevant stakeholders. 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. Work is ongoing on the implementation of these and on further analysis of web traffic figures and trends.