

# **SUMMARY REPORT (2013 – 2017)**

## **Cooperation between the International Atomic Energy Agency and Fukushima Prefecture And Activities undertaken By Fukushima Prefecture**

**Radiation Monitoring and Remediation Following the  
Fukushima Daiichi Nuclear Power Plant Accident**

**30 May 2018**

**Vienna/Fukushima 2018**



# Contents

|   |    |
|---|----|
| 1. Introduction .....   | 1  |
| 1.1. Background .....   | 1  |
| 1.2. Objectives and scope of the cooperation .....  | 1  |
| 1.3. Topics of cooperation .....  | 1  |
| 1.4. Provision of assistance and structure of this report .....   | 2  |
| 2. Use of Environmental Mapping Technology for Data Gathered by Unmanned Aerial Vehicles and Walking Surveys..... | 2  |
| 3. Long Term Monitoring of Radioactive Material in Forests and Associated Countermeasures .....                   | 3  |
| 3.1. Background and objectives .....  | 3  |
| 3.2. Monitoring programmes.....   | 4  |
| 3.2.1. Air dose rate .....  | 4  |
| 3.2.2. Radiocaesium in forest trees.....  | 6  |
| 3.3. Distribution of radiocaesium in forests .....  | 6  |
| 3.4. Effectiveness of forest countermeasures .....  | 8  |
| 3.5. Satoyama Rehabilitation Model Project.....   | 9  |
| 3.6. Managing the timber industry .....   | 9  |
| 3.7. Protection of forest workers against radiation.....  | 10 |
| 3.8. Forest fires.....  | 10 |
| 3.9. Radiocaesium transfer to forest mushrooms and bamboo shoots.....   | 12 |
| 3.10. Section Summary .....   | 12 |
| 4. Use of Radiation Monitoring Data to Develop Maps to be Made Available to the Public .....                      | 13 |
| 4.1. Background and objectives .....  | 13 |
| 4.2. Development of revised website .....   | 15 |
| 4.3. Final website design .....   | 17 |
| 4.4. Section Summary .....  | 19 |
| 5. Off-Site Decontamination and Environmental Monitoring.....   | 19 |
| 5.1. Background and objectives .....  | 19 |
| 5.2. Behaviour of radiocaesium in the natural environment.....  | 21 |
| 5.3. Results of monitoring programmes .....   | 22 |
| 5.4. Application of simulation models .....   | 27 |
| 5.5. Experience with remediation and decontamination in river and lakes.....                                      | 28 |
| 5.6. Experience with remediation and decontamination in residential areas.....                                    | 31 |
| 5.7. Section Summary .....  | 33 |

|  |    |
|--|----|
| 6. Management of Waste from Remediation Activities .....   | 34 |
| 6.1. Background and objectives .....   | 34 |
| 6.2. Temporary storage sites.....  | 35 |
| 6.3. Development of technical guidelines for temporary storage sites.....  | 37 |
| 6.4. Development of a safety assessment for temporary storage sites .....  | 38 |
| 6.4.1. Safety Assessment Framework software tool.....  | 39 |
| 6.4.2. Building capacities of the Prefecture for performing safety assessment of temporary storage sites.....              | 40 |
| 6.4.3. Safety assessment for a “model” temporary storage site.....   | 40 |
| 6.4.4. Trial safety assessment of temporary storage site in Fukushima Prefecture .....                                     | 43 |
| 6.4.5. Safety assessment for nine representative temporary storage sites .....   | 43 |
| 6.5. Retrieval strategies for waste stored in temporary storage sites and decommissioning of temporary storage sites ..... | 44 |
| 6.6. Section Summary .....   | 44 |
| 7. Report Summary .....  | 46 |

# 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 Fukushima 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. The Practical Arrangements were signed on December 2012 and are valid for a period of five years after signature, and can be extended by the mutual consent of both sides.

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

## 1.2. Objectives and scope of the cooperation

Practical Arrangements and Modification No. 1 to the Practical Arrangements were signed by representatives of the Prefecture and the IAEA in December 2012 and April/May 2016, 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.

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 those living in the Fukushima 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 IAEA Safety Standards and good international practices. During several missions to the Prefecture, site visits were made to various locations such as temporary storage sites, 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 5 Year Summary Report summarizes the current status and progress made in the cooperation conducted under the Practical Arrangements and activities undertaken by Fukushima Prefecture from 2013 through 2017. The body of this report is organized in 5 main sections that correspond to the main points of Section 2 of the Practical Arrangements.

## **2. Use of Environmental Mapping Technology for Data Gathered by Unmanned Aerial Vehicles and Walking Surveys**

The Prefecture identified a need to conduct radiation monitoring in areas that are not accessible by other survey methods, such as car-borne surveys. Consequently, the Prefecture developed a methodology for a walking survey and for the use of Unmanned Aerial Vehicles (UAVs) in areas that or not accessible on foot, or where high radiation levels might exist. Significant assistance was provided to the Prefecture in both these projects. This included the provision of a UAV capable of making radiation measurements under another IAEA cooperative project “Rapid Environmental Mapping with UAV”, which is administered by the IAEA Department of Nuclear Applications.

While the use of monitoring data collected from walking surveys and the use of UAVs formed a part of discussions under this project, the design and development aspects of walking surveys and of a UAV capability falls outside the scope of the project and is not addressed further in this report.

### 3. Long Term Monitoring of Radioactive Material in Forests and Associated Countermeasures

#### 3.1. Background and objectives

Forests cover approximately 70% of the surface area of the Prefecture. 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. In contrast to the situation in Europe, many 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 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 signed in 2012, the Prefecture assessed that the most significant radiological hazard to people was that from external radiation emitted by  $^{137}\text{Cs}$  and  $^{134}\text{Cs}$  (collectively referred to herein as radiocaesium), which was present in both the terrestrial and aquatic ecosystems. The half-life of  $^{134}\text{Cs}$  is approximately two years;  $^{137}\text{Cs}$  decays more slowly with a half-life of approximately 30 years. Both  $^{137}\text{Cs}$  and  $^{134}\text{Cs}$  were released to the environment in approximately equal amounts following the Fukushima Daiichi accident.  $^{137}\text{Cs}$  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  $^{137}\text{Cs}$  having a much longer half-life than  $^{134}\text{Cs}$ , in December 2017 the ratio of  $^{137}\text{Cs}/^{134}\text{Cs}$  was about 8:1. The Prefecture concluded that radiocaesium levels in the environment, and associated doses to people would 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.

In this area of cooperation, the Practical Arrangements focused on 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 and the IAEA’s assistance in the use of radiation monitoring data to develop maps to be made available to the public.

As part of the cooperation, the IAEA also provided advice to the Prefecture on the long term monitoring of radiocaesium in forests and associated countermeasures performed by the Prefecture in relation to characterizing the distribution of radiocaesium, establishing radiation monitoring programmes, reviewing the effectiveness of countermeasures, providing advice on the *Satoyama* Rehabilitation Model Project, addressing countermeasures for reducing radiation exposures of forest workers, assessing the radiological effects of forest fires, and assessing the implications of radiocaesium transfer to forest mushrooms and bamboo shoots.



FIG 3.1: Coniferous forest in Tokiwa district (Image credit: Fukushima Prefecture)

### 3.2. Monitoring programmes

A long term monitoring programme in forests has been established by the Prefecture 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.

#### 3.2.1. Air dose rate

The number of monitoring locations in forests for air dose rate has been extended each year by the Prefecture since the accident and at the end of 2017 totalled 1,300 (See Table 3.1.). The monitoring locations are within forests in Fukushima Prefecture including prefectural forest and private owned forest.

TABLE 3.1. Forest monitoring sites established in the Prefecture (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                            |

Based on measurements made by the Prefecture, the air dose rate averaged over all survey points for the reference date of 1 March 2017 was 0.42  $\mu\text{Sv/h}$ ; the maximum air dose rate from an individual monitoring site was 4.59  $\mu\text{Sv/h}$  and the minimum was 0.03  $\mu\text{Sv/h}$ . Compared with August 2011, the air dose rate overall has decreased by about 70%. When only the original 362 monitoring locations that were established in 2011 are considered, between August 2011 and March 2017, the number of survey points with measured air dose rates of less than 0.23  $\mu\text{Sv/h}$  increased from 42 to 309; also, the number



of survey points with measured air dose rates of greater than 1  $\mu\text{Sv/h}$  decreased from 127 to 61. These results are broadly in line with the reduction of air dose rate due to radioactive decay of radiocaesium. See Fig. 3.2, which shows measured air dose rates, estimated air dose rates based on the radioactive decay of radiocaesium, and estimated air dose rates in the future at 362 monitoring points in forests within the Prefecture. There are indications that the measured air dose rate is decreasing faster than would be predicted due to radioactive decay.

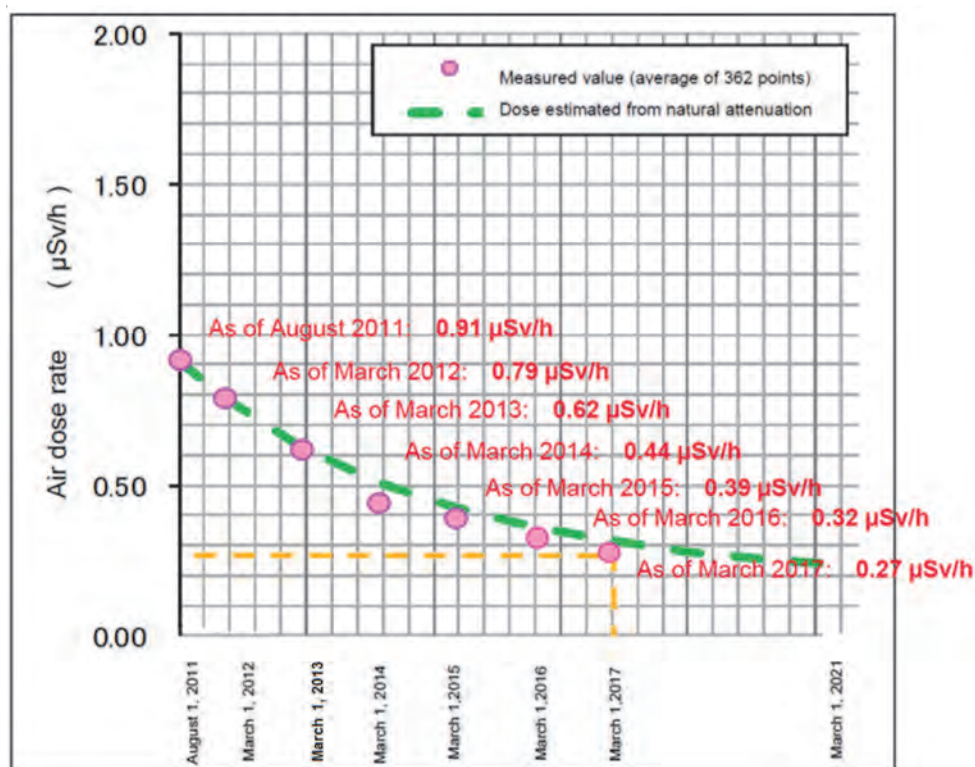


FIG 3.2: Measured air dose rates, estimated air dose rates based on radioactive decay of radiocaesium, and estimated air dose rates in the future at 362 monitoring points in forests within the Prefecture (Fukushima Prefecture)

These data can be used to predict air dose rates in the future. Assuming air dose rates continue to fall in line with the radioactive decay of radiocaesium and no remediation work is undertaken, for the majority of monitoring sites outside the evacuation zone will be below 0.23  $\mu\text{Sv/h}$ <sup>1</sup> by March 2031, i.e. 20 years after the Fukushima Daiichi accident.

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 one or two 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

<sup>1</sup>An air dose rate of 0.23  $\mu\text{Sv/h}$  corresponds to an additional annual effective dose of 1 mSv above the natural background dose

still being monitored and continue to provide new and important information. The frequency of monitoring could be reduced with time, but data should continue to be collected for many more years.

### 3.2.2. Radiocaesium in forest trees

The sampling programme for radiocaesium in timber conducted by the Prefecture includes separate measurements of bark, sapwood, heartwood, old leaves and new leaves. At a number of sites, soil is also collected by the Prefecture and measured for radiocaesium. In Japanese cedar trees, the concentration of radiocaesium is higher in the heartwood than in the periphery. Over time, the data collected by the Prefecture indicated that 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.<sup>2</sup> The value that resulted from this process, measured at a height of 1 m, was 1.33  $\mu\text{Sv/h}$ . 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 3.6 ‘Managing the timber industry’.



*FIG 3.3: Collecting samples of wood for analysis (Image credit: Fukushima Prefecture)*

The radiocaesium content of saplings planted in 2013 has been evaluated by the Prefecture. 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 5.2 of this report for further information about the behaviour of radiocaesium in the environment.)

### 3.3. Distribution of radiocaesium in forests

The data collected by the Prefecture indicate that radiocaesium that is present in coniferous and deciduous forests is distributed mainly among soil and the litter layer and trees. Through ecological

---

<sup>2</sup>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).

cycling of materials within these forest types, 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 Fig. 3.4). 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 should be focused on 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.

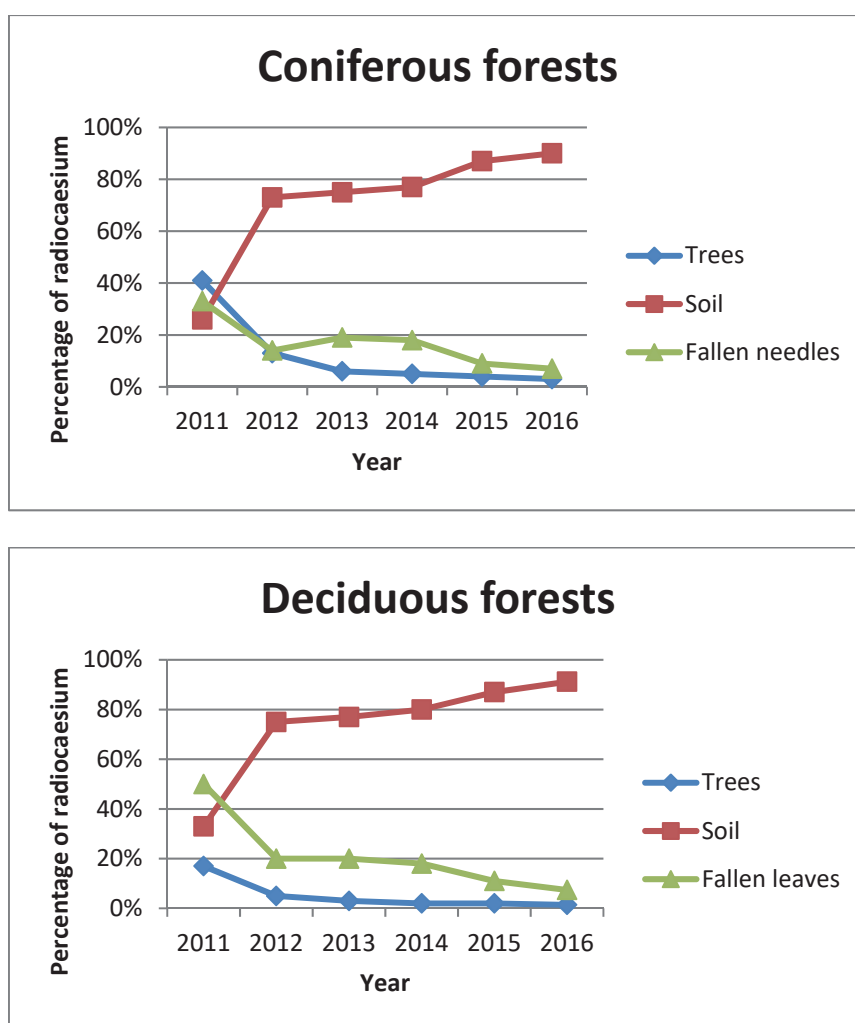


FIG 3.4: Change in distribution of radiocaesium in the Prefecture's coniferous forests and deciduous forests from 2011 to 2016 (Ministry of Agriculture, Forestry and Fisheries, and the Fukushima Prefectural Forestry Research Centre)

A soil survey undertaken in forests by 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 5.2, 5.3 and 5.4.) Research undertaken by the Prefecture 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 discharge and landslides.

### 3.4. Effectiveness of forest countermeasures

Various countermeasures concerning radioactive material in forests have been evaluated by the Prefecture 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 understory 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%.

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

Based on the findings by the Prefecture, 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.

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. While the addition of soil/wood chips has been shown to be an effective countermeasure, it is presently not in routine use. A priority is to install log fencing on higher ground to prevent soil erosion and subsequent recontamination of decontaminated areas.

### **3.5. 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. Ten communities within the evacuation zones and neighbouring municipalities were selected for participation in the project between September and December 2016. 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 IAEA team noted that the effectiveness of countermeasures in these areas may be limited and that consideration should be given to defining how the success of the project will be evaluated. As of 2017, the project was in the initial stages of implementation.

### **3.6. 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 fuel for biomass plants. It is important to ensure 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 by the Prefecture 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 1.33  $\mu\text{Sv/h}$  roughly corresponds to 8,000 Bq/kg in bark, but a range of values from 0.65 to 4.59  $\mu\text{Sv/h}$  was observed. The Prefecture had adopted the criteria whereby, in areas where the air dose rate is below 0.5  $\mu\text{Sv/h}$ , 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 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 by the Prefecture 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.

### **3.7. Protection of forest workers against radiation**

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

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

### **3.8. 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 report 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. Fukushima 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 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 conducted by the Prefecture 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.

### 3.9. Radiocaesium transfer to forest mushrooms and bamboo shoots

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.

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

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.

Issues to be considered in the future are the production and the use of raw wood from the Prefecture's forests, and the prediction of the transfer of radiocaesium from oak logs to shitake mushrooms, which are a valuable economic product of the Prefecture's forests.

### 3.10. Section Summary

An extensive work program has been undertaken by the Prefecture to better understand 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.

The key conclusions which the Prefecture derived from this programme to date are:

- 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.
- Forest maintenance procedures have helped to prevent erosion and soil-loss and are also very effective at retaining radiocaesium within forests.
- 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, based on measurements undertaken by the Prefecture, the activity concentrations of radiocaesium in plants and animals in the Prefecture's forests are considerably lower than those observed in European forests after the Chernobyl accident.
- Based on experience with radiation monitoring in areas affected by the Chernobyl accident, radiation monitoring in forests may be necessary for many more years and monitoring procedures for measuring air dose rates and the radioactive 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 higher.

- 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.
- Covering the forest floor with soil or wood chips that has no radiocaesium is an effective means of reducing air dose rates. However, such procedures are expensive and their long term effectiveness should continue to be evaluated. Regardless, it may be justified to apply them over limited areas with high air dose rates, especially if such areas are close to inhabited areas.
- Various issues should be addressed in the early stages of the *Satoyama* Rehabilitation Model Project such as the possible generation of radioactive waste, the effectiveness of countermeasures, and defining how the success of the project will be evaluated.
- To date there appears to be no need to restrict the production and use of the timber harvested from forests. However, monitoring of timber should continue, especially as work commences in areas with higher concentrations of radiocaesium.
- 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.
- Studies of forest fires conducted by 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.

It is important that monitoring programs are maintained by the Prefecture so that any unforeseen changes in the behaviour of radiocaesium in forests is quickly identified and addressed. If survey data indicates that air dose rates over time are relatively stable, it may be justified to reduce the number of samples collected and monitoring points maintained.

## **4. Use of Radiation Monitoring Data to Develop Maps to be Made Available to the Public**

### **4.1. Background and objectives**

In this area of cooperation, the Practical Arrangements focused on the IAEA's assistance in the use of radiation monitoring data to develop maps to be made available to the public.

As of the commencement of 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:

- Over 3,500 fixed monitoring locations (only 24 of these existed prior to the accident);
- Car-borne surveys;
- Radionuclide data for foodstuffs, drinking water and other environmental media.

As of 2014, the number of site visitors was approximately 20 to 50 thousand per month. The Prefecture gathered a number of recommendations from these users about how the website could be upgraded 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 simple, easy to understand information, compatibility with mobile technology, and an explanation of the health risks.

The IAEA team presented information about web maps that have been developed in a number of countries and provided various technical advice concerning the mapping of radiation monitoring data and presenting such information to the public.

## 4.2. Development of revised website

### *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 introduce apparent differences in the results of surveys such as a large variability in the air dose rates between seasons (e.g. because of 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 might 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 Fukushima 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, and terrestrial and marine foods.

### *Discussion on Website Development*

The IAEA team made available a review of web maps in Austria, Belarus, Canada, China, European Union, France, Germany, Russia, Turkey and Ukraine. Most national maps are based exclusively on data from fixed monitoring locations; while walking surveys might 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 work being undertaken by the Prefecture therefore seems to be unique.

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

- There are two development projects to be considered: an appropriate mapping tool is required and this is 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. The promotional role of the website as part of an overall communications strategy is also important.
- 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. In order to keep the website simple, the value of including air dose rate data from other prefectures on the map should be considered. Also, administrative boundaries in the Prefecture could be integrated into the map.
- For those who require more detailed information, such as on units of measurement, radiation risks, etc., this can be provided through a separate link, or through the use of explanatory graphics.
- The importance of large scale overview maps was discussed, as was the importance of maps showing localized/detailed information. One suggestion was to use “clickable” maps where

one could access progressively more detailed maps by clicking on an area of interest on a map. Scalability of grid sizes must be considered.

- It is important to emphasize and make readily available the most important information, which is usually the most recent information.
- Historical data is valuable in demonstrating how the radiation doses have decreased since March 2011. Where possible, this data should be retained and used. In particular, air dose rates prior to the Fukushima Daiichi accident should be made available.
- It would be helpful to include some data from “high natural background” areas in the world, for comparison with the current air dose rates in the Prefecture.
- The concept of having “key messages” on the website was considered useful and it was noted that these might need to be regularly updated.
- The Google Application Program Interface (API) currently used may not provide sufficient flexibility and other APIs (such as java script, Environmental Systems Research Institute (ESRI) or open layers) should be considered.
- All maps should be consistent in the use of data schema, colour codes, ranges, etc. Where possible, the lower end of the lowest range should be as close to natural background as possible.
- A time slider is a very useful way to show progressive reduction in air dose rates and incorporating such a feature should be considered.
- Greater public interaction can be encouraged through links to social media.
- It is important to consider the weighting to be assigned to each dataset in developing the overview maps.
- It might be desirable to provide automatic access to the GPS location from which access is made, i.e. people can see the exact radiation situation in the location where they are at the time.
- Adding a search parameter of ‘dose rate’ should be considered.
- 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. While no permanent fixed monitoring sites are located in the forests, the data from the network of measurement stations established by the forestry group might be used.
- There are a number of areas within the Prefecture with 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 standard 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.
- It is essential to provide sufficient background information to support interpretation and understanding of the available maps.
- The JAEA and the Prefecture datasets can be used separately (i.e. separate maps), they can be merged directly, or the raw data can be merged and new maps developed. As the scales and colour coding of the JAEA and the Prefecture maps are different, it was agreed that the option of merging the information and creating new maps is probably preferable.
- It is suggested that the Prefecture decides what information will be made available to the public on its new website, for example whether it will be possible only to download the existing maps or whether the raw data will 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. The IAEA team advised that, in their experience, data are seldom intentionally misused but accidental misuse and misinterpretation should be considered and factored into a final decision.

### 4.3. Final website design

Following the revision of the website, a presentation on the completed work was made by the Fukushima 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. Fukushima 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 fully accessible from both PCs 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 Fig. 4.1). Air dose rates and the results of environmental samples are displayed on the same map. The variation of air dose rates with time can be accessed intuitively through the use of a “time ruler” (See Fig. 4.2). Also, the revised website has the capability to present the transition of doses over time through the generation of graphs (See Fig. 4.3). 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/>

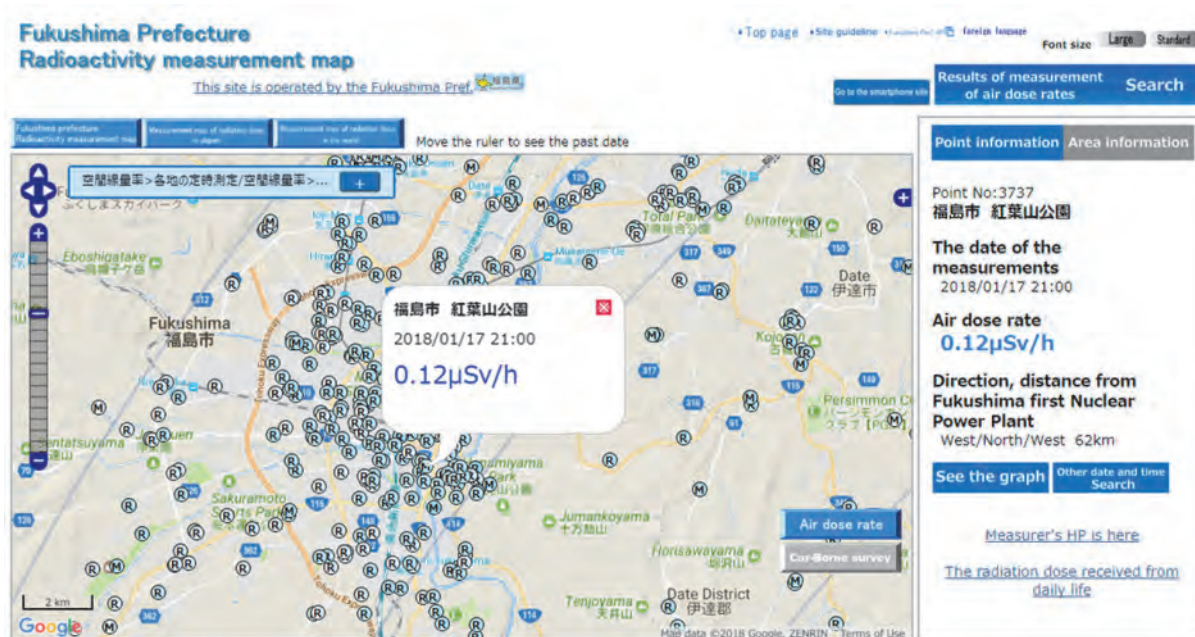


FIG. 4.1. Clickable Radiation Measurement Map (Fukushima Prefecture website)



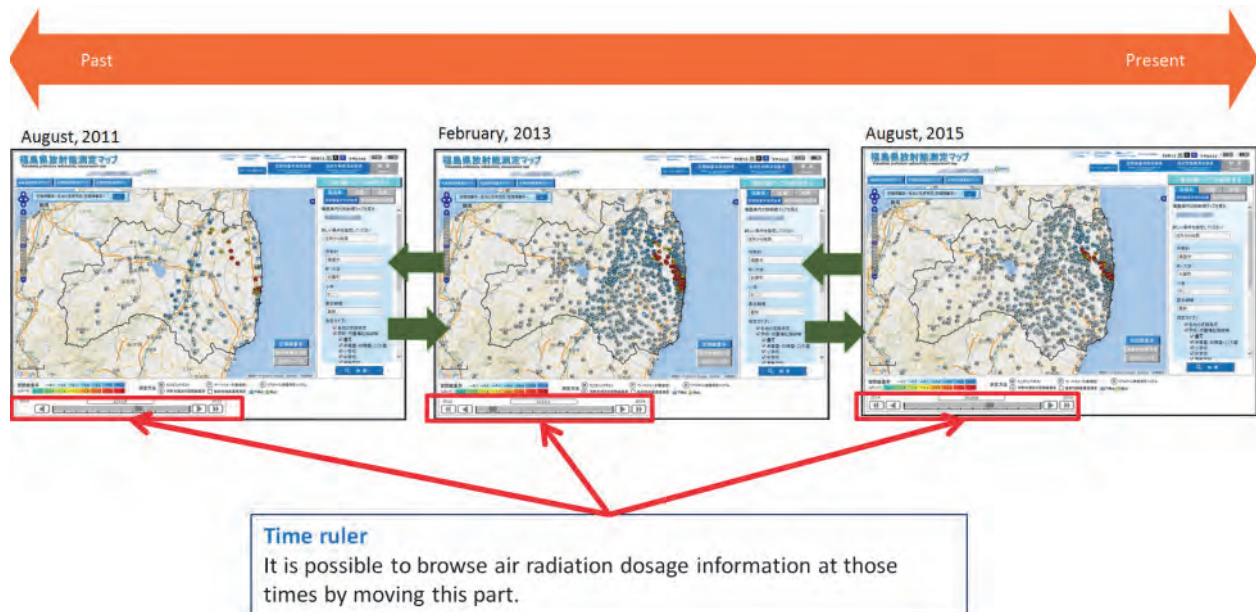


FIG. 4.2. Time ruler from Radiation Measurement Map (Fukushima Prefecture website)

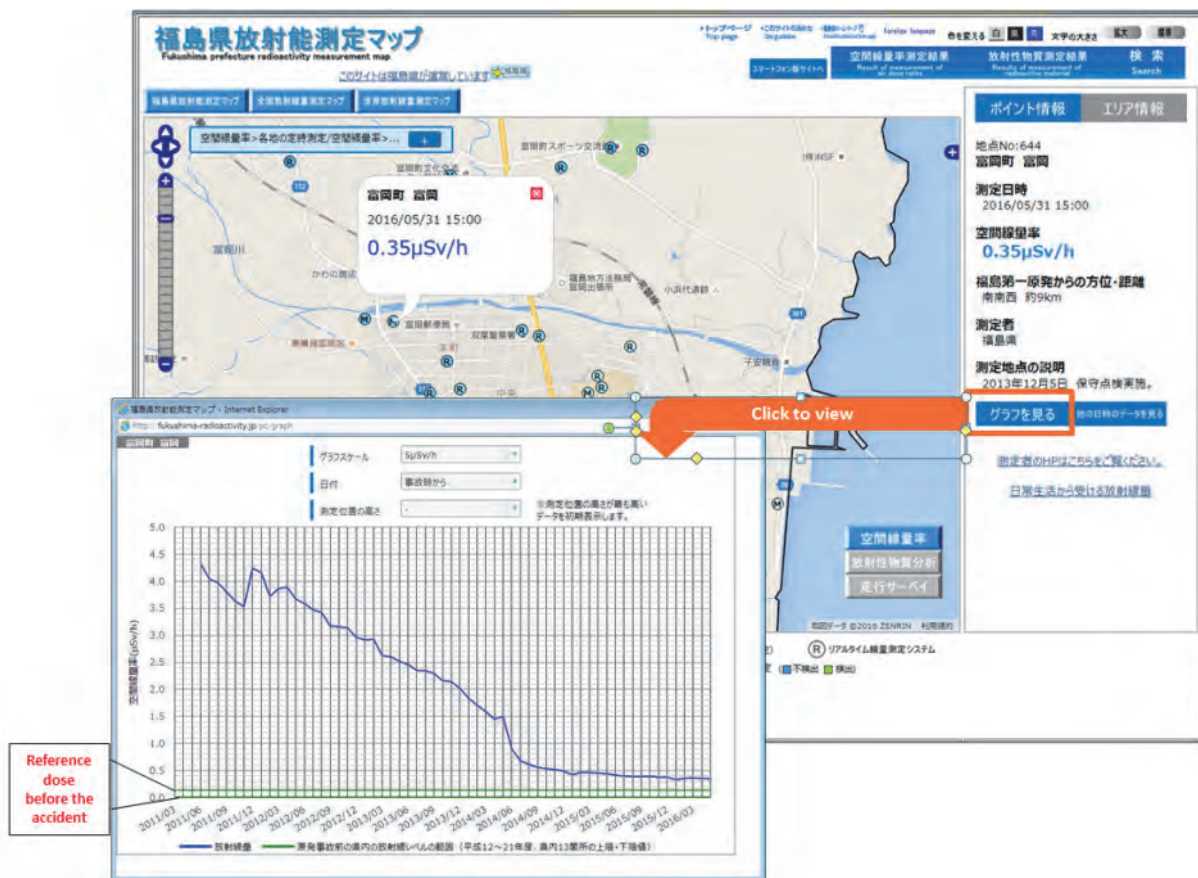


FIG. 4.3. Graph of measurement data from a specific measuring point over a specified timeframe from Radiation Measurement Map (Fukushima Prefecture website)

## 4.4. Section Summary

The Prefecture recognized that 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. Specifically, the Prefecture identified that while overview maps 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 Prefecture's 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).

The Prefecture recognized the challenges of presenting different datasets that were collected under varying conditions that could affect the results. For example, the air dose rate on a road is unlikely to be identical to that on a nearby footpath and snow cover in winter will reduce the air dose rate, which will increase when the snow melts. The height above ground at which the measurement is made and the speed of car travel compared with an individual undertaking a walking survey also needs to be taken into account.

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 Fukushima experts in IT, public information strategy and radiation measurement.

The IAEA team noted that the provision of information through a website is only one component of a communications strategy.

The Prefecture identified the growing demand for the Prefecture to provide information and advice to potential returning evacuees on the expected reduction in air dose rate with time and the associated health risk. The presentation of such information must take account of 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 Prefecture recognized that such information cannot easily be provided through a website and that further consideration will be necessary on how the Prefecture can best meet these requests.

## 5. Off-Site Decontamination and Environmental Monitoring

### 5.1. Background and objectives

According to data collected and an assessment conducted by the Prefecture, significant amounts of radioactive fallout were deposited in the Prefecture as a consequence of TEPCO's Fukushima Daiichi accident, especially in the area northwest of the Fukushima Daiichi Nuclear Power Plant. During the time period in which the Practical Arrangements were active, the Prefecture identified that the most significant radiological hazard to people was from external radiation emitted by radiocaesium. (See also section 3.1 for further information about radiocaesium in the environment). Based on data

collected, the Prefecture determined that radiocaesium levels in the aquatic and terrestrial ecosystems, and associated doses to people have declined because of decontamination activities, radioactive decay, and the removal of radiocaesium by weathering from surfaces and vertical migration down soil and sediment profiles. Figure 5.1 shows air dose rates in the Prefecture at a height of 1 meter on August 28, 2011 (5 months post-accident) and November 18, 2016 (5 years and 8 months post-accident). These dose rates were calculated by using data obtained from aircraft monitoring. The Prefecture concluded that the significant decrease in dose rates was due to decontamination activities, radioactive decay, and the removal and movement of radiocaesium caused by natural processes.

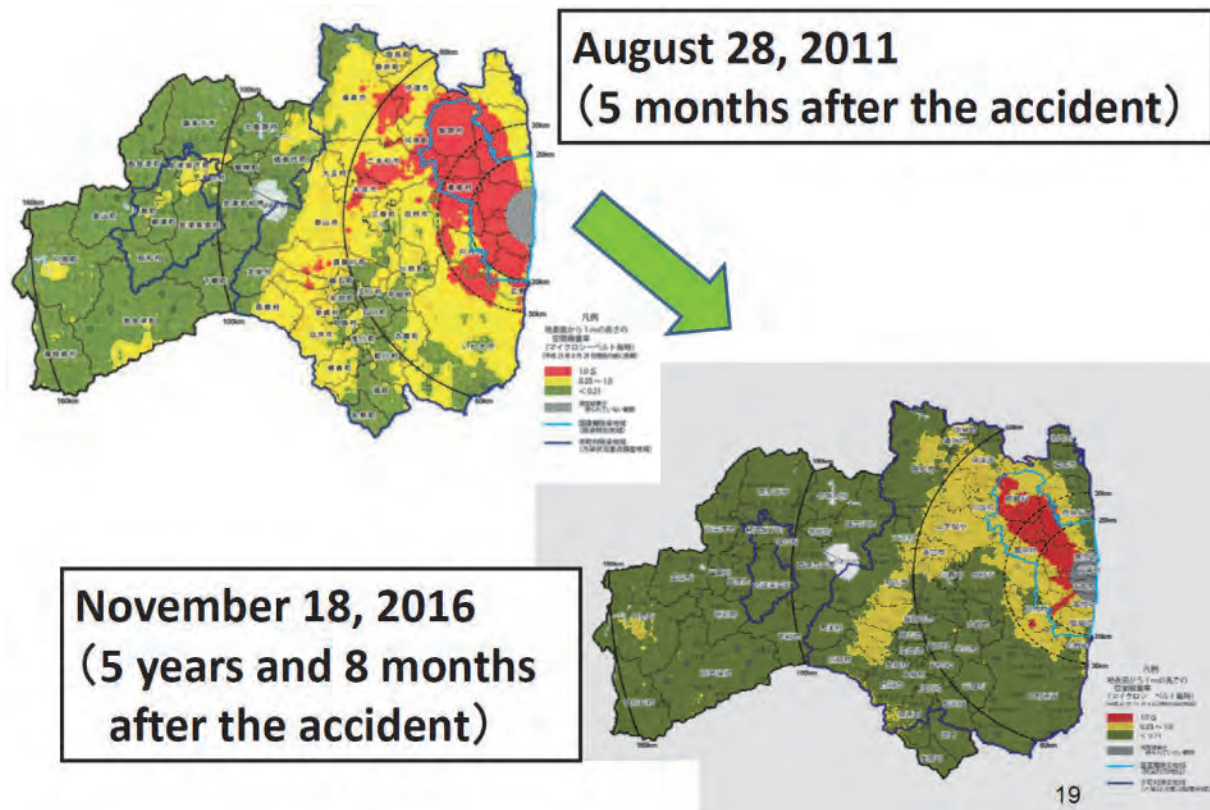


FIG. 5.1. Air dose rates in the Prefecture at a height of 1 m on August 28, 2011 and November 18, 2016 (Image credit: Fukushima Prefecture)

The Prefecture recognizes 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 future doses that would be reduced by remedial actions and those that would occur without intervention. It is therefore helpful to make predictions regarding changes over time in air dose rates and doses to people.

Item 2 of the Practical Arrangements focuses on research and study of 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. The cooperation addressed the following topics for which the IAEA provided technical advice:

- Behaviour of radiocaesium in the terrestrial and aquatic ecosystems in the areas of the Prefecture affected by the Fukushima Daiichi accident;
- Effectiveness of remediation and decontamination measures for aquatic systems;
- Analysis of monitoring results in order to identify time trends of radiocaesium concentrations in environmental media (soil, water, sediments) and of the 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.

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

## **5.2. Behaviour of radiocaesium in the natural environment**

### *Global experience with radiocaesium in the natural environment*

Radiocaesium has been released to the natural environment by atmospheric nuclear weapon tests, operations of nuclear facilities, and as a consequence of accidental releases. In general, in the terrestrial ecosystem, radiocaesium is strongly bound by mineral soil components, which results in its slow movement in soil and a low uptake by plants from soil. 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 disintegrated with potassium leaching in acidic conditions and may no longer be present in significant quantities; therefore, the uptake by plants may be much higher.

In freshwater ecosystems, caesium binds strongly to suspended sediments, which causes a rapid decline in dissolved radiocaesium, and the ultimate deposition of caesium that is bonded to sediment on the bottom of bodies of water. The transport of radiocaesium in rivers and lakes is largely caused by the redistribution of sediments. Because radiocaesium in dissolved form is readily taken up by freshwater biota and readily absorbed by particles and suspended sediments, the amount in freshwater systems depends on radiocaesium sorption, sedimentation and uptake by biota.

### *Caesium 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 carried out by the Prefecture since 2011. These studies have addressed the long term behaviour of radiocaesium in soil including the uptake by crops and the downward migration in soil profiles. Due to the strong sorption of radiocaesium in soil, in agreement with global experience, both the downward migration of radiocaesium in soil and the uptake of radiocaesium through crops from soil are very low. Radiocaesium in soil is gradually bound with soil components, especially clay particles. This sorption may be reversible, which constitutes the fraction of exchangeable radiocaesium, or, largely irreversible, which constitutes the fixed fraction.

According to studies conducted by Fukushima University, the proportion of the exchangeable fraction of radiocaesium in soils continuously decreased over time, and the radiocaesium levels in crops 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 the transfer to crops.

The studies of research institutions (e.g. Fukushima University) indicated that very limited amounts of  $^{90}\text{Sr}$  were released during the Fukushima Daiichi accident, and that, except for the immediate vicinity of the Fukushima Daiichi Nuclear Power Plant,  $^{90}\text{Sr}$  concentrations in farmland and crops were nearly equal to those resulting from fallout of atmospheric nuclear weapons testing in the 1960s.

The study performed by the institutions, including Fukushima University, estimated internal doses due to ingestion of agricultural products in Fukushima City and Date City, are on the order of a few tens of  $\mu\text{Sv}$  per year, which does not modify the dose estimates for people significantly.

International experience with the behaviour of  $^{137}\text{Cs}$  in the environment and environmental remediation projects was provided by the IAEA team. Following the Chernobyl accident and the Fukushima Daiichi accident it was observed that natural attenuation processes contributed to the reduction of radiation levels and to the decline of radioactivity levels in the environment. However, the wash-off of radiocaesium was observed 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.

All these factors significantly affected  $^{137}\text{Cs}$  wash-off from the contaminated watersheds in the Fukushima Prefecture.

### 5.3. Results of monitoring programmes

#### *Transport processes*

The transport of radiocaesium from a catchment area via a river or a river system is illustrated schematically in Figure 5.2. Radiocaesium is deposited in forests, and 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. The figure also indicates the interaction between the terrestrial and the aquatic ecosystems as well as the possible transfer routes 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, river flooding and turbulent flow can affect previous deposits of radiocaesium bound to sediments.
- Some amounts of radiocaesium will be transported to the ocean.

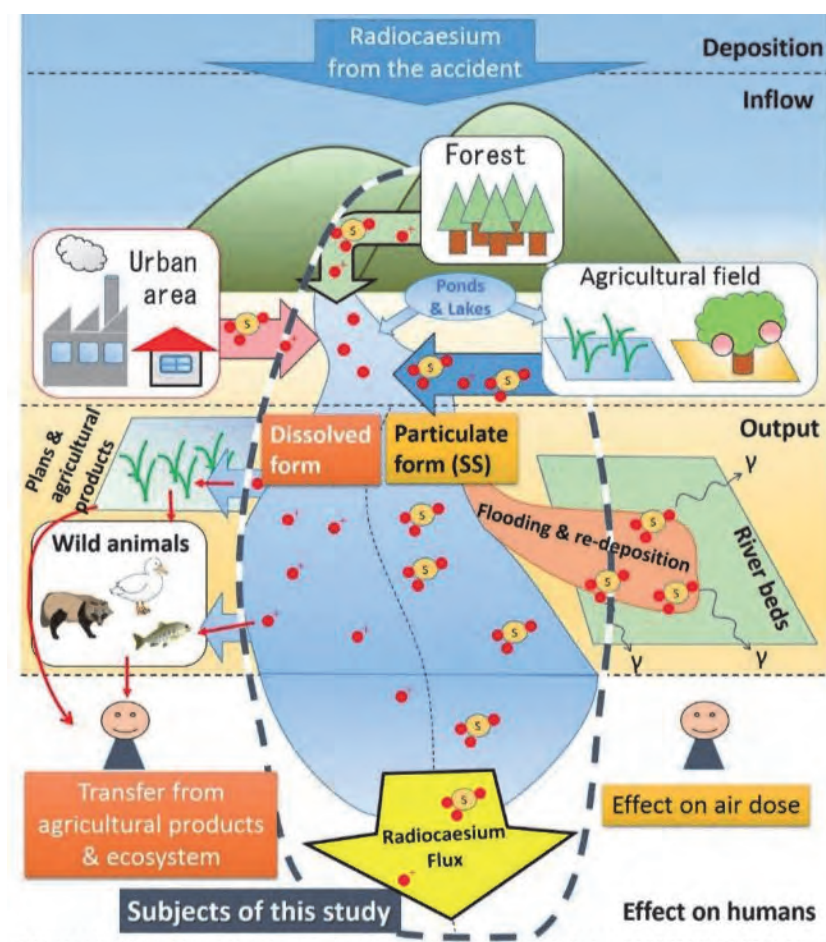


FIG 5.2. Illustration of radiocaesium transport through a catchment area and interactions with terrestrial elements (Image credit: Fukushima Prefecture)

### Caesium 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 freshwater bodies, which is performed by the Fukushima Prefectural Centre for Environmental Creation.

The programme of survey includes the measurement of radiocaesium dissolved in water as well as radiocaesium bound to suspended sediments in rivers and lakes. Due to the strong sorption of radiocaesium by suspended sediments and its deposition on the bottom of water bodies, radiocaesium levels in river water declined considerably with time and have reached a safety level which allows its use as drinking water.

Beyond the general surveillance of radiocaesium levels in water, the monitoring programme conducted by the Prefecture focuses on studying the long term behaviour of radiocaesium in the catchment areas of the Prefecture, and specifically on two aspects:

- *Levels and the behaviour of radiocaesium associated with suspended particles.* This includes the deposition or removal of radiocaesium bound by sediments and floodplain soils during floods including the effects on air dose rates.

- *Radiocaesium in its dissolved form*, i.e. transfer to agricultural products, wild animals and plants via the accessible ecosystem. Further studies will also be focused on better understanding of the dynamics of particulate and dissolved radiocaesium.

In addition to the radiocaesium levels in water and sediments, for characterizing the physico-chemical properties of the water, the concentrations of major ions (potassium, calcium, magnesium, and ammonium) are determined.

The measurements made by the Prefecture were focused on the catchment areas that were affected by the deposition of  $^{137}\text{Cs}$ , see Figure 5.3. Emphasis was given to the Hirose River basin, where eleven monitoring points were set up. The monitoring points were located along the river and its tributaries, including the Takane River, the Nuno River and the Oguni River, respectively. Beyond the parameters mentioned above, the measurements included determination of water flow rates, turbidity of water and the concentration of suspended sediments. As expected, rainfalls coincided – with some delay – with an increase of the flow rate and an increased concentration of suspended sediments. Although there are considerable fluctuations with time, the  $^{137}\text{Cs}$  levels have decreased continuously since 2011.

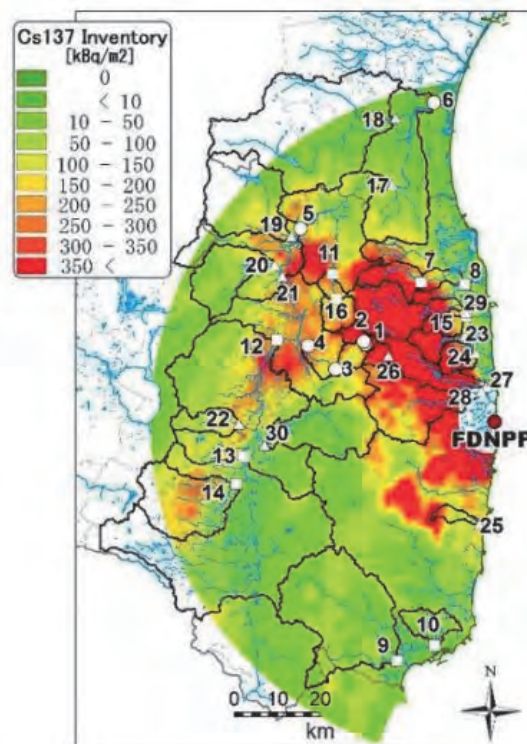


FIG 5.3. Distribution of  $^{137}\text{Cs}$ -deposition in the Prefecture as determined during the Third Airborne Monitoring Survey (MEXT, 3 July 2011)

Meanwhile — more than 6 years after the accident — measurements by the Prefecture indicate that dissolved radiocaesium levels in water are close to or below the detection limit. This can be explained by the strong sorption of radiocaesium by sediments, in which much higher radiocaesium levels are observed. There is also a clear decline of the concentration of radiocaesium in suspended sediments, especially when further erosion from contaminated catchment areas is limited. Radiocaesium concentrations in sediments tend to increase with decreasing particle size.

Measurements made by the Prefecture showed that radioactivity concentrations in water and suspended matter in the Abukuma River and its tributaries declined as well. The investigations of the transport of radiocaesium in rivers within the Prefecture included also the Hamadori and the Nakadori



districts. Measurements covered more than 30 points; the results for the suspended  $^{137}\text{Cs}$  concentrations since 2011 are shown in Figure 5.4. In this figure, solid circles indicate monitoring points in Kuchibuto River and its tributaries, and open circles indicate monitoring points in Abukuma River and its tributaries. The suspended radiocaesium levels have decreased continuously since 2011. During the heavy rainfall event in September 2015, the suspended radiocaesium concentrations decreased, which was a consequence of the dilution effect caused by the large amounts of sandy particles in the sediment transport load in the river waters with low adsorption capacities.

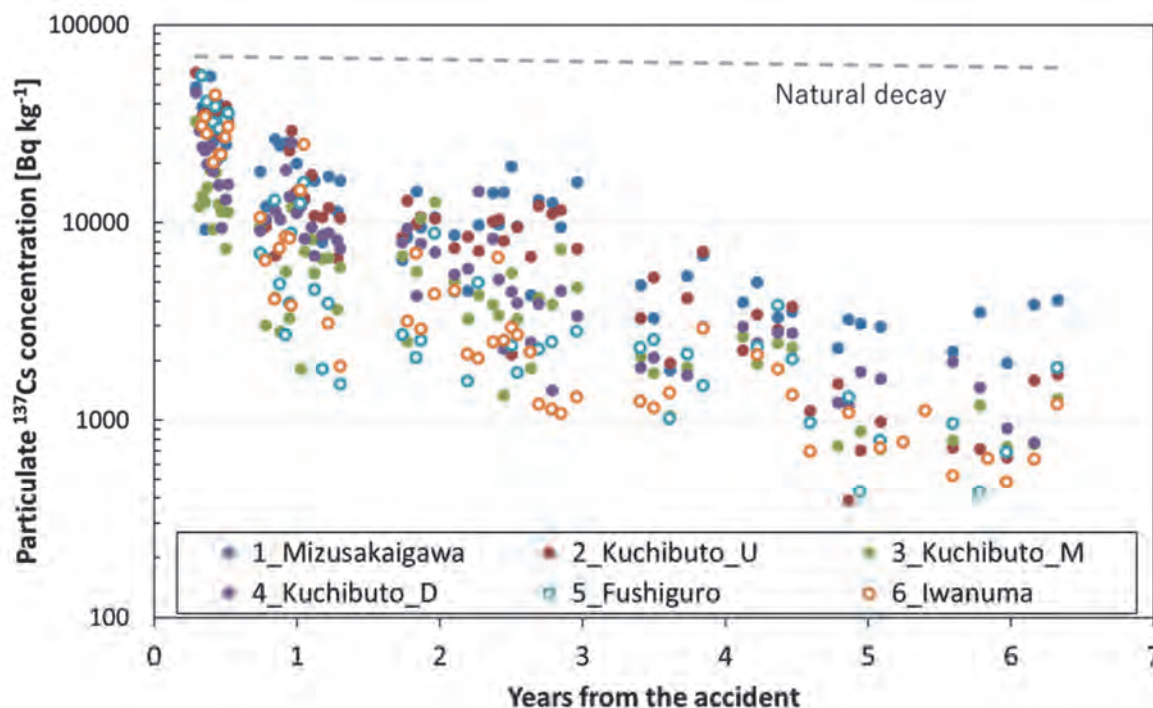


FIG5.4. Decline of  $^{137}\text{Cs}$  in suspended matter of rivers in the Prefecture from 2011 – 2017 (Fukushima Prefecture)

Since most of the radiocaesium in water bodies is associated with suspended materials in the river waters, the measurements allowed — in combination with the data on water flow and sediment transport — the estimation of the total flux of radiocaesium from the catchment area to the Pacific Ocean for the period of 2011 – 2015. The increase of 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, and can be observed as a lessening of the slope of the lines presented in Figure 5.5. In this figure, solid circles indicate monitoring points in Kuchibuto River and its tributaries, and open circles indicate monitoring points in Abukuma River and its tributaries.

An analysis performed by the Prefecture indicated that since 2011, the cumulative loss of  $^{137}\text{Cs}$  activity from the catchments of the Abukuma and the Kuchibuto tributary was about 2.7% (2.5% – 3.0%) and 1% (0.5% – 1.5%), respectively. These small percentages indicate that the reduction of the radiocaesium levels in the natural environment is mainly caused by the radioactive decay of radiocaesium, and that the run-off of radiocaesium provides only a minor contribution to the reduction of the overall inventory in the catchment (due to wash-off and erosion process affect only the very top surface layer of the contaminated soils at the water catchments). These results also indicate that the exchange of radiocaesium between different elements of the landscape is limited.

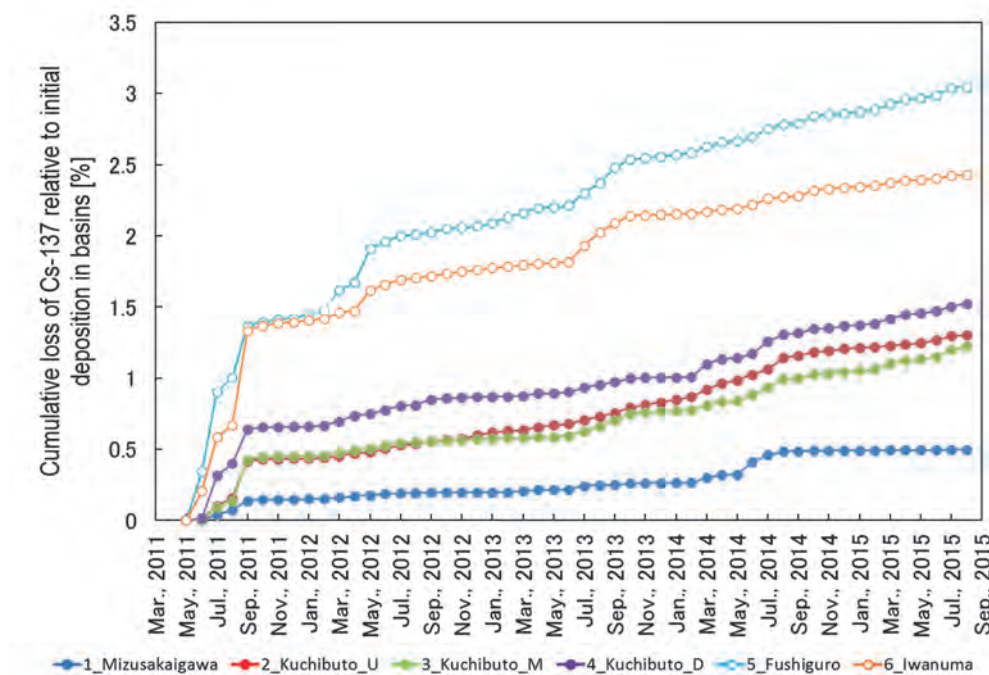


FIG5.5. Cumulative loss of  $^{137}\text{Cs}$  from the catchments of rivers in the Prefecture from June 2011 to August 2015 (Fukushima Prefecture)

The measurement campaign by research institutes in Fukushima Prefecture included measurements in reservoirs and the investigation of the  $^{137}\text{Cs}$  balance of reservoirs. Measurements performed in 2014 for the Yokokawa dam reservoir included the radiocaesium dissolved in water as well as radiocaesium in suspended matter. It was observed that the total activity of radiocaesium dissolved in water in the inflow and in the outflow of a reservoir was very similar. However, the amount of particulate radiocaesium in the outflow is 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 in a reservoir. This example shows that reservoirs act as a kind of sediment trap. This observation is, in principle, also applicable to lakes.

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 usually characterized by the distribution coefficient ( $K_d$ ), which is derived from measurements of radiocaesium in the dissolved and particulate phase. For the investigated lake water,  $K_d$ -values in the range of  $10^5$  to  $10^6$  L/kg were measured, reflecting the strong sorption of caesium to particulates<sup>3</sup>. The  $K_d$ -values increased with decreasing particle size. It was concluded that, in comparison to the observations of the caesium sorption made after the Chernobyl accident in Ukraine and the Russian Federation, in general, higher  $K_d$ -values for caesium were observed in the Prefecture.

#### *Radiocaesium in phytoplankton and zooplankton*

The measurements by research institutes in Fukushima Prefecture of radiocaesium in freshwater bodies of the Hamadori and Nakadori districts included measurements of phyto- and zooplankton and

<sup>3</sup> A distribution coefficient ( $K_d$ ) of, e.g. 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.

their radiocaesium levels. The expected amounts of phyto- and zooplankton were very low. There were temporal and spatial variations in the amounts of plankton in the water. In the Yokokawa Dam Reservoir, the concentration of phytoplankton in water was determined to be only on the order of 0.1 mg/L; the concentrations of zooplankton were approximately a factor of 10 less, although the radiocaesium activities for both phyto- and zoo plankton range from tens to tens of thousands of Bq/kg (dry weight). This means that the total radiocaesium activity, which is incorporated into phyto- and zooplankton, did not exceed a small fraction of a percent of the radiocaesium present in the body of water.

### *Caesium in irrigation ponds*

The Prefecture determined radiocaesium concentrations in water and sediments for about 3 thousand irrigation ponds inside and outside the evacuation order zone in 2014.

Since radiocaesium bounds strongly to clay particles, the concentrations of dissolved radiocaesium in the water of these ponds are orders of magnitude lower than the radiocaesium concentrations in sediments. This finding agrees very well with the observations made by the Prefecture in rivers and lakes. In 1% of the water samples collected in the irrigation ponds, the concentrations of radiocaesium in the dissolved phase were above 1 Bq/L, and these ponds are mainly found inside the evacuation order zone. The number of ponds with dissolved radiocaesium of above 1 Bq/L decreased from 2013 to 2014.

The Fukushima Prefecture government tested technologies to reduce the concentrations of dissolved radiocaesium in pond water. The technologies were selected through open recruitment in fiscal 2014 and 2015. The methods 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 caesium activity concentrations in sand and gravel particles are much lower than in clay materials. 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.
- Removing water from the pond and fixing 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 against radioactive material are implemented in accordance with this manual.

## **5.4. Application of simulation models**

To facilitate the interpretation of monitoring results, models were applied by the Prefecture 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) developed by Onishi, Y., 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)) was applied to simulate the  $^{137}\text{Cs}$  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 all around the world. All previous applications involved assessments, analysis and evaluation of the transport of radionuclides following releases to the environment

following the Chernobyl accident, and from nuclear facilities in Mayak (Russian Federation), Hanford and Savannah River (USA).

The TODAM model can estimate the transport of  $^{137}\text{Cs}$  with sediments and water in the rivers. This model produces results that take account of the possible influence of water flow, topography and land use. The model provides valuable information on:

- The possibility of using the water for domestic and agricultural purposes.
- The effectiveness of remediation measures to be applied to rivers can be assessed, which may support decision making.
- The effect of re-contamination of rivers, which is important for evaluating the permanence of remediation measures.
- The  $^{137}\text{Cs}$  flux from the catchment area to the ocean can be estimated.

The TODAM model was applied by the Prefecture to simulate the movement of  $^{137}\text{Cs}$  in the Ogaki Dam Reservoir and to investigate the role of the dam for the dispersion of radiocaesium. It was found 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 favours the sedimentation of suspended sediments.

During several workshops involving the IAEA and Fukushima Prefecture experts from different Japanese and other international institutions discussed their experience in the use of different types of models for radiocaesium prediction in aquatic ecosystems.

## 5.5. Experience with remediation and decontamination in river and lakes

### *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 are 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).

All of these events were unique; they varied in terms of areas affected, level of contamination, relevance of the exposure pathways, the levels of doses to people, the relevance of the aquatic pathways with regard to exposure of people living in those areas, and the measures taken in the aquatic system to mitigate radiological and social consequences. Following these contamination events, two different types of countermeasures were applied:

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

One lesson derived from the analysis of past events is that technical measures have only a limited potential to control the dispersion of radionuclides in water bodies. Freshwater systems are



characterised by a pronounced time-dependence of water flow rates and water levels, which is associated with enormous variation in flow velocities and water levels. Transport of radionuclides occurs predominantly during temporary periods of high water volume flow, usually associated with re-suspension, displacement and re-deposition 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 restriction of access and the implementation of recommendations is less complicated. Such measures with regard to the use of freshwater bodies are easy to implement and have been proven effective in reducing radiation exposure through aquatic pathways. However, clear instructions and recommendations are necessary for successful implementation. Experience shows that 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 (1) to determine time-trends of activity levels in water, sediments and biota, (2) to identify new contamination patterns which may be created through displacement of material and sediment during high waters and floods, and, (3) to verify the success of countermeasures should they have been applied.

#### *Demonstration of test decontamination measures in Fukushima Prefecture*

In this project, the Prefecture tested decontamination measures at riverside areas in the Prefecture to reduce air dose rates. These works continue and are described below.

##### *Demonstration at the Kami-Oguni River*

Part of one side of the 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 concentrations in bottom sediments. Decontamination measures such as weeding, removal of sediments in the low-water bed, and removal of vegetation and soil from the river dykes were implemented in autumn 2014 (See Figure 5.6). The results of the air dose rate measurements before and after the decontamination campaign are shown in Figure 5.7. According to the monitoring measurements carried out before and after the decontamination measures, the air dose rates were reduced by about 50 %.



*FIG5.6. River bed before (left) and after (right) the implementation of decontamination measures (Fukushima Prefecture)*

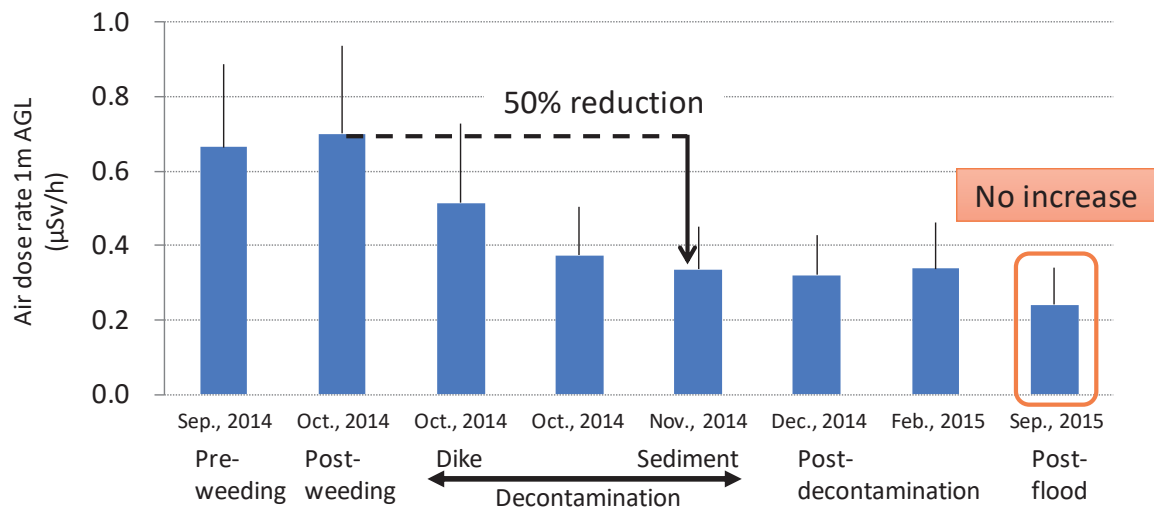


FIG5.7. Air dose rate at 1 m height before, during and after the remediation and decontamination measures at a river in the Prefecture

The area was affected by a severe flood in September 2015, which caused intensive re-suspension, displacement and sedimentation of radiocaesium associated with suspended particles. Sediments and vegetation in the river were removed and new material containing mainly coarse material and stones was deposited at this place. The measurements of the air dose rate carried out after the flood by the Prefecture (See Figure 5.7.) did not indicate significant modification of the air dose rate as a result of the flood.

#### Waterside park at the Niida River

This park is close to a river which is used for leisure and recreational purposes. Air dose rates measured in 2015 by the Prefecture averaged approximately 0.6  $\mu\text{Sv/h}$ .

Model simulations performed for this area by the Prefecture indicated that decontamination measures may reduce the air dose rate in the considered area by about 35% (Table 5.1). Without any decontamination measures, the air dose rate would decline after one year by about 13% 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/beautification, and playing in or near the water.

Calculations performed by the Prefecture showed that decontamination measures may reduce the annual effective dose to an individual by 1–15  $\mu\text{Sv/yr}$ . Results of projected individual doses related to the use of this part of the Niida River are given in Table 5.1. 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 river bed. Parts of the river banks were removed, and at higher levels 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 river bed, measurements made by the Prefecture after these flooding events indicated that the effects of the remedial actions had not been affected significantly. Even considering this information, due to the likelihood of flooding in the coming years, monitoring of the effects of decontamination efforts should continue.

TABLE 5.1. Estimation of dose reduction at a demonstration site through decontamination (Fukushima Prefecture)

| Item  | Activity                     |                                    |                                  |                                  |
|---|------------------------------|------------------------------------|----------------------------------|----------------------------------|
|   | Recreation                   | Walking                            | Cleaning/<br>beautification      | Water activity                   |
| Dose rate ( $\mu\text{Sv/h}$ )<br>(derived from air dose<br>measurements over 15 minutes) | 0.53                         | 0.38                               | 0.39                             | 0.26                             |
| Occupancy (hours per year)  | 16<br>(4 h/d $\times$ 4 d/y) | 111<br>(1 h/d $\times$ 111<br>d/y) | 48<br>(1 h/d $\times$ 48<br>d/y) | 9<br>(0.5 h/d $\times$ 9<br>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<br>decontamination   | 0.007                        | 0.032                              | 0.015                            | 0.002                            |

## 5.6. Experience with remediation and decontamination in residential areas

In Fukushima 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 employed in the Prefecture are shown in Figure 5.8.



FIG. 5.8. Main decontamination techniques (Photo credit: Fukushima Prefecture)

In Table 5.2, the status of the effort by the Prefecture to decontaminate different categories of facilities and areas are summarized. For residences (houses), decontamination is the most advanced; as of the end of October 2017, 99.9 % of the planned activities were completed.

TABLE 5.2. Progress of municipality decontamination (as of end of October 2017)

| Category                       | Planned | Completed | Percentage completed |
|--------------------------------|---------|-----------|----------------------|
| Residences (houses)            | 418,582 | 418,579   | 99.9                 |
| Public facilities              | 11,653  | 11,627    | 99.8                 |
| Roads (km)                     | 18,785  | 17,701    | 94.2                 |
| Agricultural land (ha)         | 31,252  | 31,196    | 99.8                 |
| Forests (in living areas) (ha) | 4,398   | 4,307     | 97.9                 |

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

Specific sets of remediation 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 5.3); such reduction factors are very similar to those achieved by remediation measures in areas affected by the Chernobyl accident.

TABLE 5.3 is based on measurements performed before and after decontamination work that was performed from March 2012 to October 2013. (Japanese Government)

TABLE 5.3. 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                             |

## 5.7. 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 bodies of water and which causes a rapid decline of dissolved radiocaesium in water.

In the freshwater bodies of the Prefecture — more than 6 years after the accident — 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 caesium by sediments in riverbeds, in which much higher radiocaesium levels are observed. There is also 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 of radiocaesium, whereas the run-off of radiocaesium provides a further contribution to the reduction. The cumulative loss of  $^{137}\text{Cs}$  activity since 2011 until September 2015 from the catchments of the Abukuma and the Kuchibuto tributary was about 3 % (2.5% – 3.5%) and 1% (0.7% – 1.5%) respectively.

Measurements of radiocaesium in the in- and outflow of reservoirs show that the amount of suspended radiocaesium in the outflow is much less than in the inflow. This shows that reservoirs act as a kind of sediment trap.

Sorption of caesium to suspended matter plays a key role for its behaviour in the environment. Measurements by the Prefecture of the sorption of radiocaesium in soils and sediments show that it is in general stronger under the conditions of the Prefecture in comparison to the observations made after the Chernobyl accident in Ukraine and the Russian Federation.

Measurements performed by the Prefecture indicated that the amount of radiocaesium incorporated into zoo- and phytoplankton was very low. The radiocaesium activities for both phyto- and zooplankton range from tens to tens of thousands of Bq/kg (dry weight). This means that the total radiocaesium activity incorporated into phyto- and zooplankton did not exceed a small fraction of a percent of the radiocaesium present in the body of water.



To facilitate the interpretation of monitoring results, models were applied by the Prefecture to simulate the transport of radiocaesium from the catchment area through the river system to the Pacific Ocean. The Prefecture recognized that models were also very useful in assessing the effectiveness of remediation measures to be applied for rivers. In addition, simulation models allowed the assessment of the effect of re-contamination of rivers. The Prefecture recognized that if decontamination measures are necessary, the use of models may help to identify the most appropriate locations within the freshwater ecosystem to apply such measures.

Since the Fukushima Daiichi accident, the focus of remediation and decontamination activities of the Prefecture were on public areas including routes traversed by children going to and from kindergarten and schools, and on recreational areas. In addition, the Prefecture has initiated a number of projects concerning freshwater bodies to demonstrate the effectiveness of such countermeasures. Such measures reduce air dose rates.

The IAEA team described worldwide experience with freshwater remediation activities which indicates that technical measures have not, for the most part, been able to control the dispersion of radionuclides in freshwater bodies. The IAEA team indicated that for reducing exposure to the public from radionuclides deposited in freshwater bodies, recommendations and restrictions with regard to the use of these freshwater bodies are relatively easy to implement and more effective in reducing exposure than technical measures.

Since 2011, intensive decontamination work has been carried out by the Prefecture in private homes, public facilities, roads, agricultural land, and forests. For residences (houses), decontamination is the most advanced; as of the end of October 2017, 99.9 % of the planned activities were completed.

The Prefecture applied specific sets of remediation actions to residential areas, public facilities, roads, agricultural land, and forests. Depending on the type of area, the Prefecture observed that air dose rates were reduced by approximately 20% – 50%; such a reduction in dose rates are very similar to those achieved by remediation measures in areas affected by the Chernobyl accident.

## 6. Management of Waste from Remediation Activities

### 6.1. Background and objectives

As stated in Technical Volume 5, *Post-accident Recovery*, of the IAEA's *The Fukushima Daiichi Accident*, "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 sites. Afterwards, the material will be placed in the ISF (Interim Storage Facility). After interim storage for up to 30 years, final disposal will be take place outside Fukushima 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.

Representatives of the Prefecture stated that when activities under the Practical Arrangements commenced in 2013, the Prefecture was faced with an urgent shortage of TSSs in which to store waste from remediation activities. Furthermore, the Prefecture noted concerns that were raised by the public about the safety of existing TSSs, and prospective TSSs that were to be established to accommodate

radioactive waste generated by ongoing remediation activities. Also, it became necessary to store waste in TSSs for greater time periods than was originally intended. TSSs 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 is now being stored in TSSs for more than three years. Consequently, the safety of the storage of waste in TSSs for more than three years is an issue that should be evaluated to ensure the safety of these facilities and also to address public concerns.

Item 3 of the Practical Arrangements refers to 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.

The activities concerning the management of waste from remediation activities under the Practical Arrangements consequently focused on providing technical advice to the Prefecture related to:

- finalizing technical guidelines for the establishment of temporary storage sites;
- demonstrating the safety of temporary storage sites in different situations for the different phases of their development; and
- retrieval strategies for waste stored in TSSs.

## **6.2. Temporary storage sites**

Three main types of TSSs 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. However, the preferred option in the Prefecture for storing contaminated materials is the above-ground storage design. FIG 6.1 provides conceptual diagrams of three types of TSS designs.

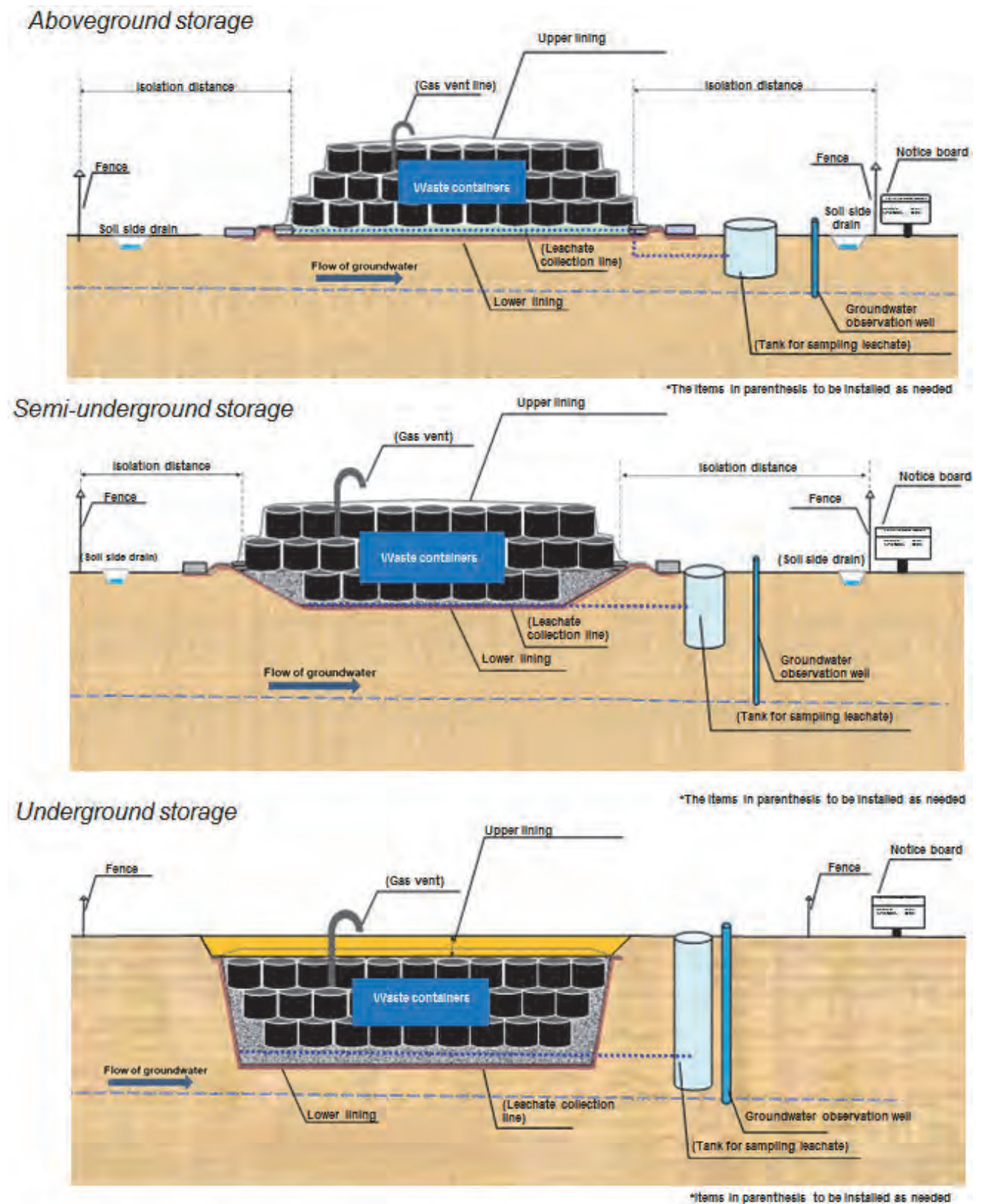


FIG. 6.1 Conceptual diagrams of three types of TSSs (Image adapted from Technical Guidelines for Temporary Storage Sites, Fukushima Prefecture)

As of September 2017, 843 TSSs have been established or are planned in municipalities within the Intensive Contamination Survey Area. As indicated by FIG 6.2, the number of TSSs increased dramatically from 2013 to 2014 and has increased moderately from 2014 to March 2017.



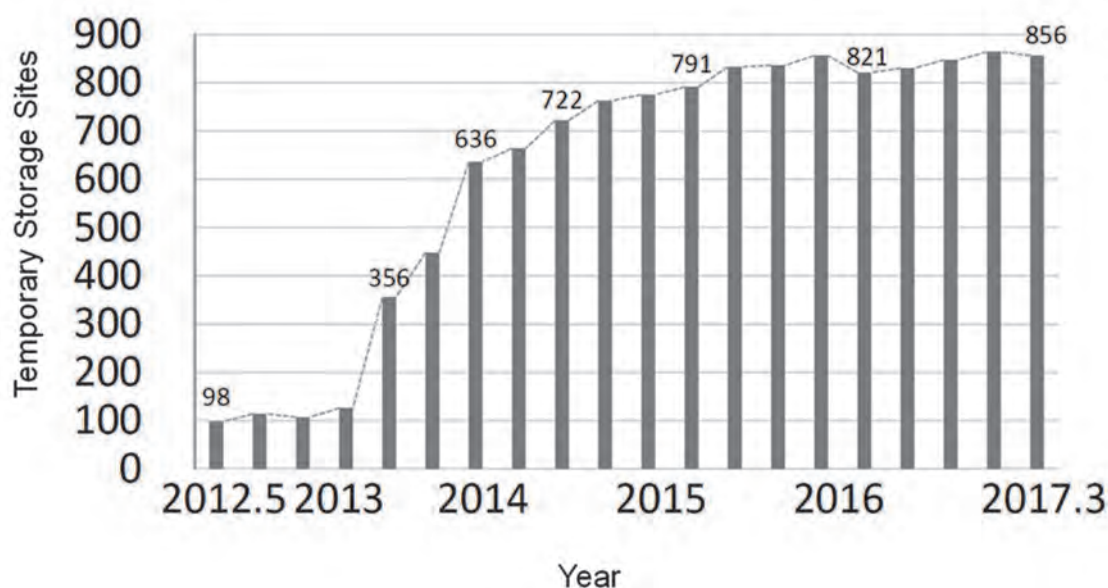


FIG.6.2. *Number of TSSs in Municipalities from May 2012 to March 2017*

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

- Limitation on the number of 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 of the long term stability of facilities established on sloping land;
- Potential leaching phenomena;
- Degradation of the organic matter in 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.

### 6.3. 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 TSSs were being established to store the resulting waste. In 2013, the Prefecture had been developing a guidance document on the establishment and operation of TSSs. 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 TSSs. Consequently, an analysis was conducted by the Prefecture of the activities carried out so far regarding the development of TSSs in the different municipalities. This analysis aimed at identifying the main issues affecting TSSs, identifying good practices implemented, and comparing the different strategies for developing TSSs in the different municipalities. Such an approach should serve as a basis for the development of an overall harmonized strategy for the development of TSSs in the Prefecture and identify potential improvements or corrective actions that could be applied to the existing temporary storage sites.

The IAEA team provided technical advice and feedback to the Fukushima experts concerning the development of the guidance document on TSSs including reviewing the draft text and providing

comments on its content. Version 1 of Technical Guidelines for Temporary Storage Sites was published by the Prefecture 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). The major issues to be addressed in Version 5 are extension of the storage period, export of stored waste, and remediation and restoration of TSSs. The following main topics were addressed in Version 2 (the latest version of the document available in English as of August 2017) of the document:

- Site selection, including: information to be gathered about site characteristics, criteria for site selection and relevant laws and ordinances concerning the establishment of TSSs;
- Structure and design, including: advantages and disadvantages of the three main types of TSSs (i.e. aboveground storage, semi-underground storage and underground storage); facility location, arrangement of waste bags, and use of shielding in order to reduce air dose rates; various aspects of waste bags; arrangement of waste bags so that integrity of the grouping of bags is maintained; storage of waste bags containing material that is subject to organic decay; specifications and information about various components of TSSs such as: liners, rainfall collection system, leachate collection system, water collecting tanks, gas venting mechanisms, monitoring equipment for contamination of ground water, ancillary facilities, fences and other enclosures, notice boards, and access roads;
- Installation, maintenance and management, including: radiation measurement procedures; prevention of penetration by rainwater; recordkeeping; regular reviews of the condition of TSSs.

The technical guidelines also provided information about the initial storage of waste material at locations where remediation activities are being performed.

#### **6.4. Development of a safety assessment for temporary storage sites**

When managing waste defined as radioactive waste, a demonstration of the safety of relevant facilities and activities should be developed by the so-called operator(s) either for authorization/approval by a regulatory authority, or to build its own confidence or the confidence of any other interested party in the safety of such facilities and activities. The demonstration of safety, in particular, aims at presenting the various aspects of the site and its design that would allow a regulatory authority to verify and ensure that the facility or activity may be operated safely and that people and the environment are protected from harmful effects of radiation now and for the life of the facilities. 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 TSSs would also be increased by showing evidence that existing and prospective TSSs would have minimal radiological impact. The development of a safety assessment would involve identifying all relevant parameters that could affect safety such as site characteristics, designed safety features of the site, characteristics of the waste and its containers to quantitatively assess the impact of the temporary storage for different periods of time, and different scenarios, in particular, normal operating conditions and accident scenarios. Such an assessment could be established for a generic or model storage facility, i.e. generic enough so that its parameters would be representative of all existing and potential storage facilities in the Prefecture.

Prior to the commencement of the activities under the Practical Arrangements, Fukushima experts had no experience with the performance of safety assessments as called for by the IAEA Safety Standards. As such, the development of a safety assessment for the TSSs proceeded in a stepwise fashion beginning with an educational phase and subsequent phases in which Safety Assessment Framework software tool (SAFRAN) (See Section 6.4.1) was applied first to a “model” TSS, then on a trial basis

to the TSS in Fukushima prefecture, and finally to 12 selected TSSs in the Prefecture. The safety assessment development process is presented schematically in FIG 6.3.

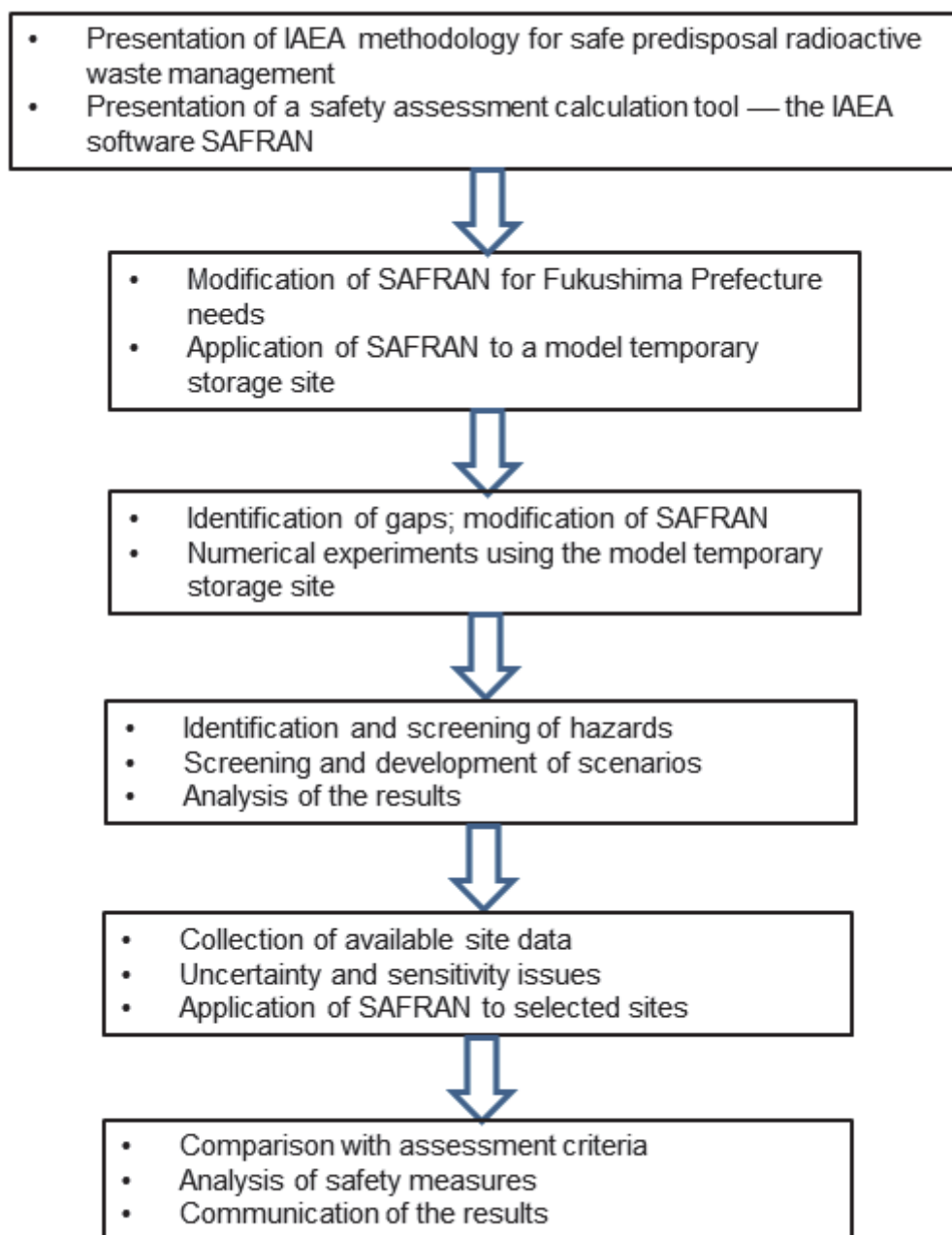


FIG. 6.3 Activity flow of the development of a safety assessment for TSSs in the Prefecture

#### 6.4.1. Safety Assessment Framework software tool

The IAEA methodology for safe 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 (IAEA, 2009), which provides recommendations on meeting the safety requirements in GSR Part 5, Predisposal Management of Radioactive Waste (IAEA, 2013). In order to facilitate the application of this methodology, the IAEA developed SAFRAN to guide the user in performing a systematic and structured safety assessment of facilities and activities related to

predisposal radioactive waste management and decommissioning. As such, SAFRAN could be used in developing a safety assessment for TSSs 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 according to user needs. The demonstration of safety of TSSs under the Practical Arrangements was supported by the use of SAFRAN. In some cases, adjustments were made to the software by the IAEA so that it could be applied to the specific situations in the Prefecture.

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

In 2014, an IAEA team conducted a training session for Fukushima experts that addressed the demonstration of safety (safety assessment) and specifically the use of SAFRAN for TSSs. 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 Fukushima experts identified the purpose, scope, approach and endpoints of activities concerned with safety assessment of TSSs. 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.

The process of development of a safety assessment for TSSs 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 Fukushima experts on the explanation and dissemination of the results of the safety assessment.

#### 6.4.3. Safety assessment for a “model” temporary storage site

As an educational tool for the Fukushima 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 FIG 6.4. 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.

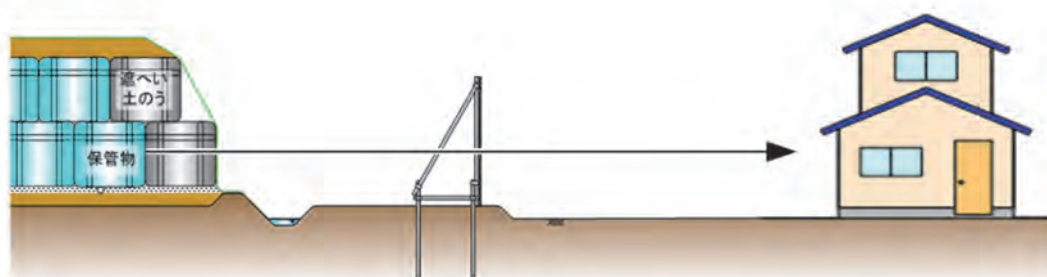


FIG 6.4. Typical layout for a TSS. Radiation doses are calculated with respect to the distance from stored materials.

The safety of the model TSS, as with 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. Regardless of the fact that a TSS does not represent a complicated civil engineering structure, it still has several important safety features which have to be properly quantified and understood. Therefore, the work of the Prefecture 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 by the Prefecture. For parameters that could not be established with a high degree of accuracy, a process for conservatively estimating such information was implemented by the Fukushima 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 Fukushima experts.

A hazard analysis was performed by the Prefecture 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. An extensive set of hazards during emplacement, storage and retrieval were analyzed under normal operating conditions and in accident scenarios through this process.

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 TSSs in Fukushima 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 TSSs. 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 impact of normal operations by the Prefecture at a model TSS was based on assessment of annual radiation doses for both, occupationally exposed persons and a resident living in the vicinity of the facility. An occupationally exposed worker may be exposed under varying conditions, e.g. during the emplacement of the waste packages, or during their removal, i.e. retrieval processes. Nearby residents could be exposed due to direct exposure during the emplacement/replacement operations. However, under normal operating conditions these exposures are very small. Predicted exposures during the storage period are a small fraction of allowable radiation dose limits under normal operating conditions.



The doses for normal situations are assessed by the Prefecture for the case when all operations are performed as planned, assuming an average time needed for specific activities, and assuming average air dose rates expected during these activities.

The potential exposure depends on the number of waste storage bags and their storage area; therefore, SAFRAN was used to evaluate TSSs of three different sizes, which would characterize the existing and planned TSSs in the Prefecture. For these three model facilities, various shielding configurations such as the use of sand bags and soil spread on the top of the facility were also evaluated using SAFRAN.

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 by the Prefecture based on air dose rates, residence time and shielding effects. The internal doses were calculated on the basis of the radionuclide dependent activity concentrations, dose conversion factors, and residence time. The total dose accumulated by members of the public was calculated by summing the predicted 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 by the Prefecture therefore also included an assessment of hazards resulting from accidents throughout the life of the facility.

The Prefecture performed a comprehensive analysis of different safety aspects and possible impacts on the TSS using the IAEA methodology. The assessment of impact from accidents required detailed analysis of the initiating events. These events were analysed by the Prefecture 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 require further examination and involvement of countermeasures.

The hazard screening process conducted by the Prefecture excluded irrelevant exposure pathways (or those with an extremely low probability of occurrence). Accidental releases into the atmosphere (e.g. fires at the facility) may cause exposures of the workers at the site and/or the public. Accidental discharges through the water pathways may be relevant only for the public.

The radiation doses due to the atmospheric releases were calculated as a sum of contributions from various exposure pathways such as inhalation, ingestion and external exposures from a passing plume.

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

### **Conclusions regarding application of SAFRAN to a model temporary storage site**

The Prefecture performed a complete representation of all relevant waste management activities and facilities within the scope of the model TSS using SAFRAN. A complete representation of the facilities, activities, waste streams and hazards were analyzed through the application of SAFRAN. This formed the basis for finalizing the safety assessment for application to 12 representative TSSs.

The preliminary analysis performed by the Prefecture 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, predicted radiation doses to workers (within the borders of the facility) for normal operating conditions as assessed by SAFRAN were also below the occupation radiation dose limits, even using conservative assumptions.

Based on input data developed by the Prefecture and the use of SAFRAN involving many different numerical simulations, one could conclude that based for normal operational conditions, the model TSS has been designed properly, without any undue risk to workers at the sites and for nearby residents.

Predicted doses to occupationally exposed workers resulting from accidents generally do not exceed 1 mSv including extreme cases such as the crushing of twenty waste containers by a falling tree.

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 by the Prefecture indicated that the public could receive doses in excess of 0.5 mSv and therefore further analysis of these scenarios should be performed and the implementation of countermeasures should be considered under these circumstances.

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

Finally, the analysis performed under the Practical Arrangements by the Prefecture demonstrates that the IAEA methodology including the application of SAFRAN for predisposal safety assessment is fully applicable to TSSs throughout their lifecycle for the all exposure pathways to workers and the public for both, normal operating conditions and accident scenarios.

#### **6.4.4. Trial safety assessment of temporary storage site in Fukushima Prefecture**

Following on the success of the application of SAFRAN to a model TSS, the Fukushima experts applied the IAEA safety assessment methodology to an existing TSS in Fukushima Prefecture. The lessons learned and the experience gathered through this activity should facilitate development of the safety assessments for other TSSs. As with the safety assessment for the model facility, the trial safety assessment used SAFRAN to evaluate predicted radiation doses to workers and the public from TSSs under normal operating conditions and as a result of accidents.

The results of the trial safety assessment carried out by the Fukushima experts are 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 building of confidence in the Fukushima experts in the safety assessment process.

#### **6.4.5. Safety assessment for nine representative temporary storage sites**

In order to complete the safety assessment of TSSs, a decision was reached to apply the IAEA safety assessment methodology to nine selected TSSs throughout the Prefecture. The selected sites were chosen so that their characteristics would be representative of the existing and prospective TSSs 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 by the Prefecture for the TSSs, further initiating events that had not been previously included in the safety assessment were incorporated into the ongoing safety assessment development process including the impact of, flooding, retrieval of

waste bags from TSSs, transport of waste bags, and aging of waste bags and facilities beyond three years (the storage period originally anticipated for the TSSs). If waste is stored in TSSs for long periods of time beyond what is currently expected, 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. The manufacturers of the waste bags specified working lives of the bags of several years and it appears that the storage time of the bags in the TSSs will exceed the working life of the bags and therefore it was deemed necessary that the safety assessment should address this issue.

The results of the safety assessment for the nine representative TSSs in the Prefecture were similar to those obtained for the model TSS, even with the consideration of additional initiating events. Also, safety was demonstrated for TSSs under normal operating conditions; however, for large scale accidents, e.g. fire, countermeasures may be necessary to protect against radiation doses.

Discussions were also held concerning the documentation and dissemination of the results of the safety assessment. Accordingly, as of September 2017, the Fukushima experts had prepared a draft document describing the development process for the safety assessment and its conclusions.

## **6.5. Retrieval strategies for waste stored in temporary storage sites and decommissioning of temporary storage sites**

In the later stage of the cooperation under the Practical Arrangements, the IAEA team and Fukushima experts discussed a retrieval strategy for waste stored in TSSs. Because of the ageing of waste bags as discussed in section 6.4.5, it can be anticipated that the degradation of waste bags will lead to difficulty in retrieving these bags from TSSs. The IAEA team suggested that the ongoing review 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 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 TSSs to other storage facilities (such as the ISF); 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 as a result of the ongoing work concerning the ageing of waste bags and the consideration of transport issues, the safety assessment should be revised to take this information into account. The IAEA team also noted that a substantial increase in radioactive waste options could be achieved, if municipal landfills could be used for the disposal of remediation waste. 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  $^{137}\text{Cs}$  with maximum concentrations up to 8,000 Bq/kg.

The IAEA team noted that decommissioning of TSSs 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.

## **6.6. Section Summary**

The use of the IAEA's SAFRAN provided the Prefecture with the ability to use an iterative approach in performing a safety assessment of TSSs. It also provided a means for the Prefecture to go through the key steps in developing a safety assessment several times 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, Fukushima experts noted, the risk that such iterations lead to confusion, contradictions and the lack of consideration of important aspects is substantially reduced.

During the implementation of the software, a part of the SAFRAN database was changed to fit to the specific conditions of the TSSs in the Prefecture.

Fukushima experts noted that the development of a safety assessment for the TSSs in the Prefecture through the application of SAFRAN to, a model TSS, a TSS in Fukushima Prefecture, and nine selected TSSs, 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 TSSs, several technical issues have been identified whose impact on safety has been evaluated by the Prefecture (e.g. water accumulation in different places of the temporary storage, flooding, retrieval of waste bags from TSSs, transport of waste bags, collapse of waste packages, and blockages of exhaust piping). On the basis of these dedicated evaluations of the impact on safety, the Prefecture could establish technical measures to remediate and prevent the problems and could assess their effectiveness.

Fukushima experts concluded that the systematic process carried out using SAFRAN 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 and the analysis conducted by the Prefecture in the development of a safety assessment for the TSSs in the Prefecture clearly indicated that all radiation doses (calculated using conservative values) are in most of the cases well below the prescribed dose limits.

Following discussions with the IAEA team concerning retrieval strategies for waste stored in TSSs that took account of the ageing of waste bags, Fukushima experts noted that the safety assessment for TSSs should be revised to account for new information that arises as a result of the ongoing work on the ageing of waste bags.

Fukushima experts also noted that decommissioning of TSSs after all waste material has been removed will be a significant undertaking that should be approached in a systematic way.

## 7. Report Summary

### *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 of radiocaesium within this ecosystem. While extensive research on forest ecosystems had been 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 program has been established in the Prefecture.

Data gathered by the Prefecture indicate 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 by the Prefecture 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.

Another 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). At the same time, the reduction in air dose rate within the forest is likely to be dominated by the half-life of 30 years of  $^{137}\text{Cs}$ . Some countermeasures are currently being evaluated in terms of long term effectiveness but their high cost is likely to limit their widespread applicability.

The life cycle of trees from planting to harvesting is normally a number of decades. At the time of the Fukushima Daiichi accident, the forests that received radioactive fallout were at various stages of development, from newly-planted saplings to fully mature trees ready for harvesting. The distribution and movement of radiocaesium between the forest floor and vegetation will therefore need to be monitored to ensure that long term cycling mechanisms are fully understood. The knowledge gained will allow the forests to be managed in an effective manner for the benefit of the people of the Prefecture.

### *Radiation Monitoring Data for Developing Maps to be Made Available to the Public*

The website of Fukushima Prefecture is extensively used by the local population as an authoritative source of information. The views of those who use the website have been sought to identify the type of information they require and how the website can be improved to better meet their needs. The need for the Prefecture to supplement the information available through the website with a broader outreach to the public was highlighted. In this regard, the information needs of returning evacuees are particularly important.

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. The variation of air dose rates with time can be accessed graphically and through the use of a “time ruler”. In addition to Japanese, the website is also available in English, Chinese and Korean.

### ***Off-site Decontamination and Environmental Monitoring***

In the freshwater bodies of the Prefecture—more than 6 years after the accident—measurements by the Prefecture indicate that 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 of radiocaesium, whereas the physical removal of radiocaesium through run-off provides a further contribution to the reduction. The suspended radiocaesium is subject to sedimentation in reservoirs; such waters act as a kind of sediment trap.

Simulation models have been used by the Prefecture to simulate the transport of radiocaesium from catchment areas through the river system to the Pacific Ocean. The results facilitate the interpretation of monitoring measurements. Additionally, models provide valuable input, when planning the possible effects of countermeasures. A number of demonstration projects were initiated by the Prefecture to test the effectiveness of measures for reducing air dose rates in recreation 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. For reducing exposure to the public from radionuclides deposited in freshwater bodies, recommendations and restrictions with regard to the use of these freshwater bodies are relatively easy to implement and more effective in urgently reducing exposure than technical measures.

Since 2011, intensive decontamination work has been carried out by the Prefecture in private homes, public areas, agricultural land and forests. For residences (houses), decontamination is the most advanced; the Prefecture indicated that as of the end of October 2017, 99.9% of the planned activities were completed. The Prefecture also indicated that depending on the type of area treated, air dose rates were reduced by approximately 20% – 50%: such reduction rates are very similar to those achieved by remediation measures in areas affected by the Chernobyl accident.

### ***Management of Waste from Remediation Activities***

The development of a safety assessment for the TSSs by the Prefecture through the application of the IAEA’s SAFRAN to, a model TSS, a TSS in Fukushima Prefecture, and nine selected TSSs, was an important step toward establishing a safe and reliable way to store the large amount of radioactive waste accumulated from remediation activities in the Prefecture. 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 the applicability of the methodology. The implementation process was supported by using SAFRAN, developed by the IAEA, which enabled an iterative approach to safety assessment of TSSs. It also enabled Fukushima experts to go through the

key steps relevant for safety several times to refine assumptions, add elements, optimize balance between conservatism and realism, etc.

During the application of the software, a part of the SAFRAN database was changed by the IAEA team to fit the specific conditions of the TSSs in the Prefecture.

An equally important benefit from the systematic assessment process is to provide a justification for imposing additional safety measures, if necessary. The results of applying SAFRAN to TSSs by the Prefecture indicated that all predicted radiation doses (calculated using conservative values) are in most of the cases well below prescribed dose limits. A systematic analysis of all relevant hazards provided a sound justification for imposing the measures, if necessary, to avoid or significantly reduce any type of undue consequences to people and to the environment.

The development of the safety assessment for the TSSs by the Prefecture is important, but represents only the first step in finding a safe and reliable solution for storage of large amount of radioactive waste accumulated from remediation activities. Discussions were held involving the IAEA team and Fukushima experts concerning retrieval strategies for waste stored in TSSs that take account of the ageing of waste bags. It was noted that the safety assessment for TSSs 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 TSSs after all waste material has been removed will be a significant undertaking that should be approached in a systematic way in accordance with IAEA Safety Standards.

