Modeling Migration of Cs-137 in Sewer System of Fukushima City Using Model for Radionuclide Migration in Urban Environment and Drainage System (MUD)

M. A. Pratama, M. Yoneda, Y. Yamashiki, Y. Shimada, and Y. Matsui

***Abstract*—Following Fukushima Daiichi Nuclear Power Plant accident, Cs-137 has entered sewer system of Fukushima City which was confirmed by detection of the radionuclide in dewatered sludge of waste water treatment plant (WWTP). Consequently, the sludge could not be transported to landfill facility due to radioactive content. Conducting simulation on migration of Cs-137 from urban area into WWTP becomes the objective of this study. MUD, a compartment model consisted of urban and WWTP sub model was used in this study. Migration process is simulated based on natural process and decontamination activities. Value of the parameters used in this study is combination between default general value and site specific value. The result of the model showed an agreement with observed data with 85% of the data in range of 10-90 percentiles of observed data. Value of R^2 between modeled and observed data about 0.84 shows the model could explain the seasonal variation occurred in real condition.**

***Index Terms*—Migration of Cs-137, sewer system, urban.**

I. Introduction

An earthquake with 9.0 Richter scale occurred in Japan on March 2011 which was followed by 5 to 8 meters tsunami wave hitting east coast of Tohoku including Fukushima Nuclear Power Plant. The disaster caused reactor meltdown which led to explosion and emission of radioactive substances to environment. Right after the accident, radionuclide were detected in air outside of restricted zone (Radius > 20 km) for 14-25.3 μSv/h, inside of restricted zone (Radius < 20 Km), radionuclide were detected in air for 0.5-110 μSv/h and in soil for 6.8-106 Bq/m3 (I-131), 1.8-3.7 ×105 Bq/m3 (Cs-134), and 3.3-380,000 Bq/m3 (Cs-137)[1], [2].

Fukushima City which is located 70 Km from Fukushima Dai-Ichi Nuclear Power Plant, received a high amount of radionuclides deposition. Based on survey conducted by Ministry of Education, Culture, Sport, Science and Technology Japan [1], 94,700 Bq/m^2 of radiocesium was deposited on the capital city of Fukushima Prefecture. Furthermore, the deposited radiocesium in urban area was transported mostly by rain-run off mechanism into other location such as sewer system. 6,158 Bq/Kg of Cs-137 was detected from sludge of waste water treatment plant (WWTP) on September 2011. In current time, the produced sludge still contains Cs-137 at 100-600 Bq/Kg. Such a problem that makes the operating company have to store the sludge since it is prohibited to be transported to landfill facility due to high radioactive content.

Previous studies had been explained and investigated behavior of radionuclide in urban environment [3], [4]. Study conducted by Carlsson [5], the initial fraction of radionuclide, *mobile form*, which deposited in surface ground would be instantaneously migrated into water body. The remaining part would be fixated at rate depending on the material where radionuclide is deposited and would be accumulated in the storage compartment available for delayed migration.

There are two mechanisms which could explain the process which are rapid wash off and long term wash off. Rapid wash off is occurred at small time scales (day, month, season), involving mobile form of radionuclide, which the rate is increased after heavy rainfall, flood and snowmelt [6].The occurrence of rapid wash off is intense during the few weeks after deposition [7]. Thereafter, the rate of wash off will be decreased but still active within years or decades referred as “long term” wash off. IAEA [8] refers this process as “peak and tail”, where “peak” represents the rapid wash off and “tail” represents the long term wash off.

Gallego [9] investigated migration of radionuclide in urban area based on Chernobyl accident data by developing model for Radionuclide Migration in Urban Environment and Drainage System (MUD). The model is divided into two sub-models which are urban sub-model and sewer system sub-model. The study showed a good result in case of Lund and Galve, Sweden. Therefore this study tried to find out the possibility of MUD application in case of Fukushima City. The aim of this paper is to simulate and investigate the migration of Cs-137 from urban area of Fukushima City into WWTP of the city. The key parameter in this study is activity concentration of Cs-137 in sludge of WWTP. The result of the model will be compared to observed data of activity concentration.

II. Description of the Model

MUD is multi compartment model which analyzes migration of radionuclide from one compartment into another where the migration process is represented by transfer rate. Moreover, beside transfer between compartment, decay process is also counted for describing dynamic of radionuclide in one compartment. Gallego [9] constructed the governing equation for MUD which can be expressed as:

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$$\frac{dA_s}{dt} = \left(\sum_{r=1}^{n} R_{r\to s}\right)A_r - \left(\sum_{r=1}^{n} R_{s\to r}\right)A_s - \lambda_s A_s + I_s \quad (1)$$

where A_s and A_r are the activity present in compartment s and r respectively at time *t*. $R_{r\to s}$ and $R_{s\to r}$ represent transfer rate from compartment *r* to *s* and *s* to *r*. λ represents the specific decay rate of radionuclide, whereas I_s represents the initial input of radionuclide in the compartment. The calculation has been programmed by using Fortran®.

A. Urban Sub-Model

Sub-model urban divides urban area based on covering material of surface ground where radionuclide is deposited. Four types of surface ground are used in this model, namely tree, paved, wall and roof which are classified as built-up area. Each type of surface ground represents one compartment. Processes calculated in sub-model are:

- Deposition. Deposition of Cs-137 becomes an input of this model
- Fixation. As Cs-137 deposited on surface ground, the radionuclide is in mobile form. Then after it would be fixated into fixed form.
- Wash off process. Migration of radionuclide from surface ground into sewer system naturally occurs due to wash off process facilitated by surface run-off. About 10-70% of mobile form of radionuclide would be washed off by first heavy rain[10].
- Leaves fall. For tree compartment, besides washed off process, migration of radionuclide caused by leave fall is also considered in MUD.
- Decontamination activities. Local community conducted decontamination on roof and paved area on August 2011. This activity significantly change amount of radionuclide in surface ground.

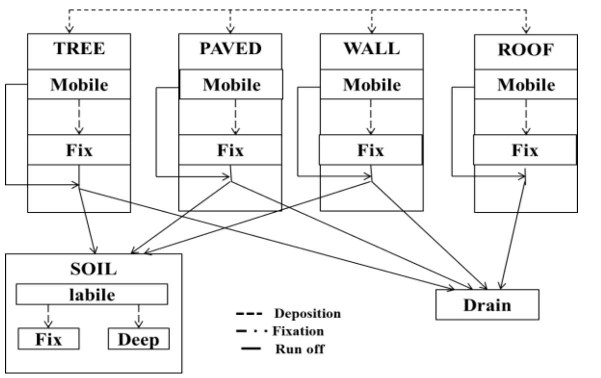

Fig. 1. Structure of urban sub-model.

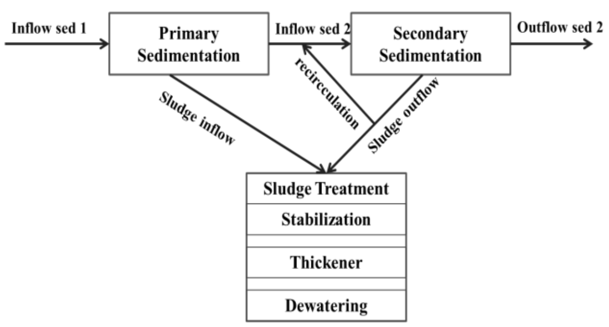

Fig. 2. Structure of WWTP Sub-model.

Run-off mostly plays as an important role for radionuclide migration from surface ground to sewer system. Some fraction of run-off flows into sewer system. It was estimated by curve fitting method, about 0.75% of surface run off infiltrate separate sewer system. The structure of urban sub-model which includes all of the considered process is shown in Fig. 1.

B. WWTP Sub-Model

After radionuclide enters sewer system, about 75-80% of it would be adsorbed by suspended solid which is contained in waste water [10]. Then after, radionuclide enters WWTP where treatment units would significantly affect amount of radionuclide in waste water. Since significant part of radionuclide is attached with suspended solid particle, sub-model WWTP only involves treatment unit that affects suspended solid content. Typically, those units are primary sedimentation, secondary clarifier and sludge treatment unit (Fig. 2).

Processes calculated in WWTP sub-model are:

- Sedimentation process conducted by primary and secondary sedimentation
- Sludge treatment conducted by sludge thickener and dewatering unit
- Recirculation of sludge that is produced by secondary sedimentation.

The amount of radionuclide which is attached into solid particle at final form of sludge would be the end point of this model. The detail of calculation used in MUD is explained in Gallego [9].

III. Study Location

A. Catchment Area of the Sewer System

WWTP of Fukushima City is located at the south part of Fukushima City. Providing service for 269,100 inhabitants and covering 76,200 Ha, the plant receives 36,000-42,000 m^3/day. Fig 3 shows location of WWTP in Fukushima City. Four districts are served by this WWTP which are Fukushima City, Date City, Koori Town, Kunimi Town (Fig. 3). The sewer system flow municipal waste water by 56.2 km of pipe, separated with drainage system and distributed within service area with range of diameter from 400-1,650 mm.

TABLE I: Coverage Area of WWTP, Land Cover and Average Deposition of CS-137 in Fukushima City [11]-[12].

District	Area Ha	Percentage of Roof (%)	Average Deposition of Cs-137 (Bq/m^2)
Fukushima City	101,706	70	101,705.90
Date City	210,412	48	210,412
Koori Town	171,476	46	171,476.10
Kunimi Town	157,022	43	157,021.90

70% of land cover of the catchment area is built up where the density of building in Fukushima City is higher than the other districts (Table I). About 70% of built up area in Fukushima City is occupied by roof. In the other hand, roof only covers 43% of built up area in Kunimi Town. Deposition of radionuclide data were also collected from each district (Table I). Deposition of Cs-137 in Date City is the highest among other areas whereas Fukushima City received the lowest deposition of Cs-137.

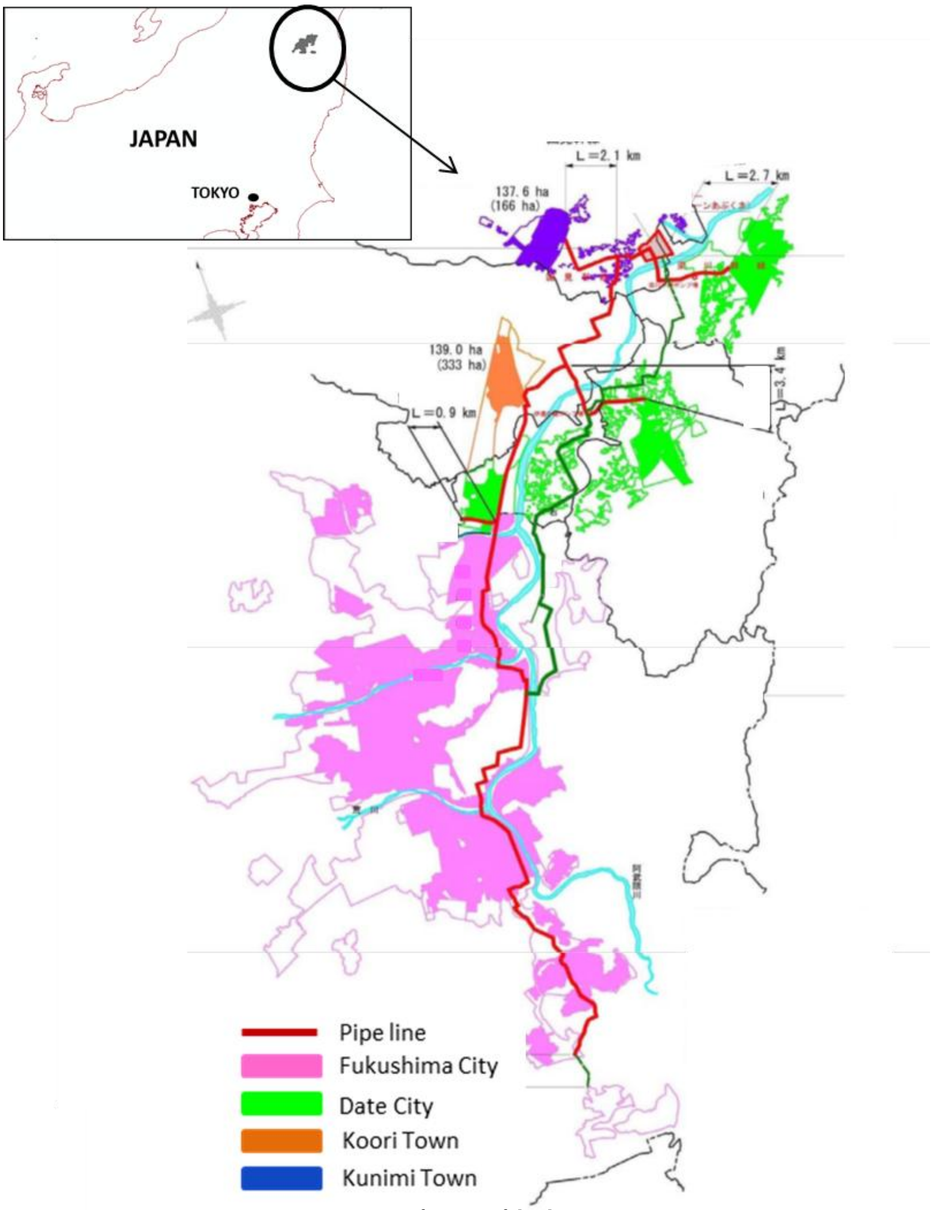

Fig. 3. Map of WWTP fukushima city coverage service[11].

B. WWTP of Fukushima City

WWTP Fukushima City uses physical-biological and chemical treatment for removing contaminant from waste water. The configuration of treatment plant is started by screening for relatively bigger size contaminant. Primary sedimentation is used to remove suspended solid. Then after, activated sludge and secondary clarifier would remove organic contaminant and the remaining suspended solid. Chlorination is used to remove microorganism content in the wastewater before it is discharge into receiving water body. Utilization of primary sedimentation and secondary clarifier would consequently produce sludge. Sludge treatment unit used in this plant consist of sludge stabilization and dewatering to reduce its water content before transported into landfill facilities for final disposal.

Seasonal trend of inflow rate was observed based on data of 2009-2013 periods (Table II). Inflow rate is relatively higher during high frequency of rainfall (September/October). Although the sewer uses separate system, surface runoff which is resulted from rainfall might enter the pipe line through gap in manhole, crack within the pipe system, old joint, etc. Despite the seasonal variation of inflow rate, suspended solid loading into the WWTP tends to be consistent. Based on data from 2009-2013 periods, average inflow of suspended solid into WWTP was in range of 122-145 mg/l.

Related to sludge production, performance of primary sedimentation and secondary clarifier were monitored based on data from 2009-2013. The average of suspended solid removal of primary sedimentation is 66% whereas the removal rate of secondary clarifier is 94% (Fig. 4).

Comparing both values to default value used in MUD (60% and 85% respectively) indicates both units have a good performance.

TABLE II: AVERAGE DAILY INFLOW RATE OF WASTEWATER AND SUSPENDED SOLID IN WWTP FUKUSHIMA CITY [11]

Month	Average inflow rate (m^3/day)	Average SS inflow (mg/l)
Jan	39,647	135
Feb	42,805	129
Mar	38,115	122
Apr	36,640	130
May	35,712	139
Jun	38,861	145
Jul	38,538	134
Aug	39,858	127
Sep	42,734	131
Oct	40,876	129
Nov	41,355	133
Dec	39,186	127

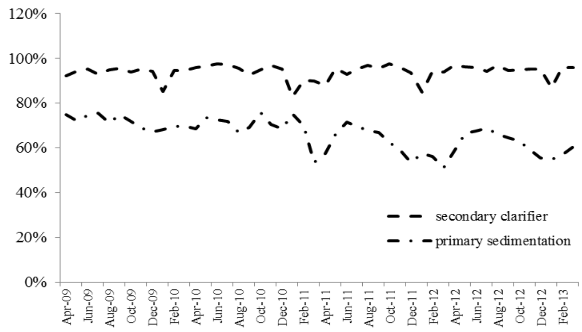

Fig. 4. Monthly average of suspended solid removal of primary sedimentation and secondary clarifier in WWTP Fukushima city [11]

Following Fukushima Dai-Ichi Nuclear Power Plant accident, the WWTP has to deal with the high amount of radiocesium content in its sludge. Table 3 shows empirical data of monthly average of activity concentration for Cs-137 and Cs-134 in dewatered sludge. It is shown that activity concentration of Cs-137 and Cs-134 was relatively high during June to September period compared to other months. It is expected that seasonal variation factor plays as the important factor on fluctuation of Cs-137 and Cs-134 activity concentration since the trend has high correlation with rainfall depth data.

TABLE III: MONTHLY AVERAGE OF CS-137 AND CS134 ACTIVITY CONCENTRATION OF DEWATERED SLUDGE OF WWTP FUKUSHIMA CITY [13]

Time	Cs-137 (Bq/kg)	Cs-134 (Bq/kg)	Rainfall depth (mm)
Jun-11	797.10	758.03	6.68
Jul-11	1104.77	1011.63	6.17
Aug-11	984.74	880.81	6.17
Sep-11	543.93	479.37	6.17
Oct-11	275.29	226.13	6.08
Nov-11	197.57	159.53	5.96
Dec-11	192.35	155.30	5.96
Jan-12	212.97	168.71	5.96
Feb-12	225.38	180.52	6.70
Mar-12	352.23	261.39	6.70
Apr-12	200.07	140.57	6.73
May-12	242.55	191.74	6.73

Parameter values for calculating the migration of cesium in urban area and WWTP are available in appendix.

IV. MODEL TEST

In the following calculation, it is assumed that fall out is a single event after the accident. Although many reports mentions fall out of radionuclides occurred continuously in some period, the amount of radionuclides after first event was not significant compared to first fall out where 2-3 orders of difference were observed. Therefore, single event of fall out was used and the following fall out could be neglected. However, fall out data was recorded at 26 May of 2011 which is more than one month after the accident. Thus, the real amount of Cs-137 which was deposited right after the accident was unknown. This problem will lead into uncertainty in the result of the model.

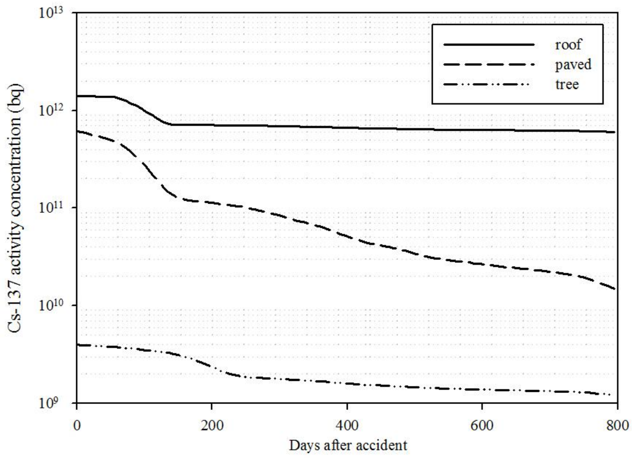

Fig. 4. Model result for dynamic of Cs-137 in tree (a). paved (b). roof and wall (c). compartment

Based on Fig. 4a, Fig. 4b, and Fig. 4c, one can note that:

- Due to the value of removal rate of fixed component by rainfall, the activity of Cs-137 in roof compartment is more persistent than other compartments. The figure shows after first heavy rain which is happened in 8^{th} day after deposition, the activity of Cs-137 is relatively stable over time. The value of removal rate which is only 0.0001 mm^{-1} could explain the persistency of Cs-137 activity in roof compartment.
- Two events of rapid decreasing of Cs-137 activity in tree compartment were occurred which are: heavy rain at 8^{th} day after deposition which washed of 40% of mobile form and Leaves fall during autumn season. Radionuclides which is attached on the surface of leaves and fixated on it migrated into surface ground and reduce the activity of Cs-137 in tree compartment. It is estimated that 60% of radionuclide attached on the leaves migrated into surface ground under leaves fall process.
- In paved compartment, increasing of activity was occurred during first autumn after the accident since the compartment received Cs-137 which was transported by leaves fall process. This Cs-137 was in mobile form at first, then it was fixated into pave material under fixation

rate of 0.23 day^{-1}. The following migration process is undergone under wash-off process by run-off.

- During August of 2011, decontamination activity was carried out by the local community. Paved and roof were decontaminated by using high pressure water hosing. It was estimated that the activity was removed 50% of Cs-137 contained in paved and roof compartment. Rapid decrement of Cs 137 activity during August 2011 is showed in fig.4 for roof and paved compartment.

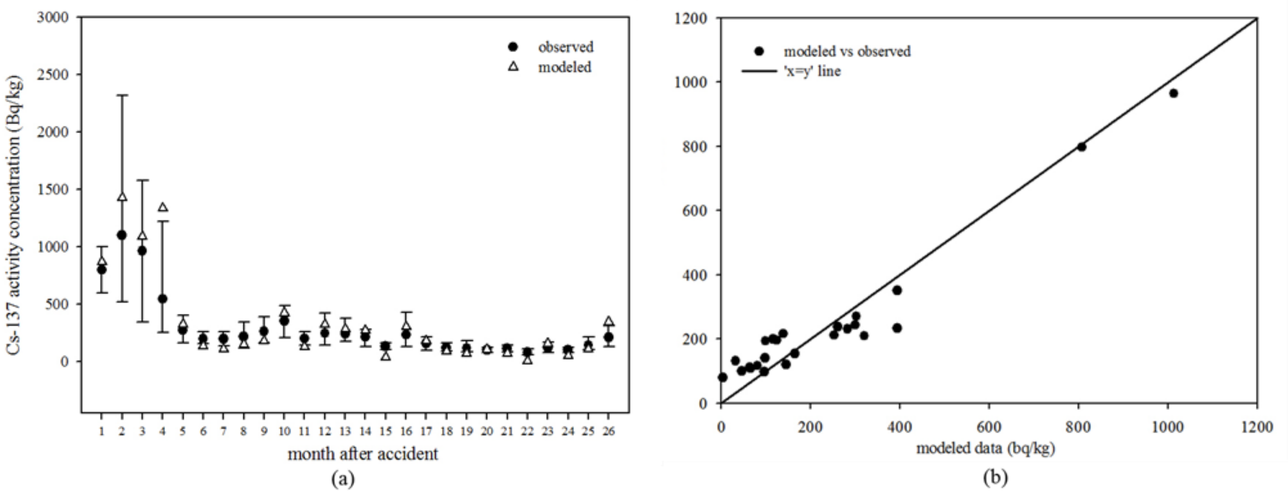

Fig. 5. Comparison between result of the model and empirical data (a) and scattered plot of modeled data And empirical data compared to *x*=*y* line (b).

Based on Fig. 5a and Fig. 5b, one can note:

- The result of the model showed that 85% of the modeled data are in the range of 10-90 percentiles of observed data. Both of the data are in the same order except in September of 2011 where the calculation result was one order higher than the empirical datum. High error was also observed on months with low rainfall rate where the result of the model is 1.5-2 times lower than the empirical data. The gap between result of model and empirical data roughly corresponds to the uncertainty in the empirical values.
- Fig. 5b shows almost all of the plot result of empirical data and modeled data are around the x=y line. With R^2 value of 0.84, it could be noted that the model could explain seasonal variability of observed data.
- September in Japan is characterized by high rainfall rate and high storm event. Operation performance of sedimentation unit is affected during storm event. This is caused by overload of suspended solid entering WWTP. During storm, removal rate of suspended solid by sedimentation decreases by 30-50%. This problem is not considered in this study since the storm data is unavailable, thus the removal rate of suspended solid used during storm event is removal rate in normal condition (66% for primary sedimentation and 94% for secondary clarifier). Overestimation of removal of suspended solid would lead to overestimation of sludge production and removal of radioactivity attached to suspended solid. Finally, overestimation of radioactivity in sludge of WWTP would be occurred. Storm event is one of the uncertainties in this study.
- It has to be noted that with the persistency of fixed form Cs-137 in wall and roof, the flux of radionuclide into WWTP would be continuously occured. However, the amount of flux would gradually decrease due to decay, washed off and decontamination process.

V. Conclusion and Comments

This paper has applied MUD which was developed based on Chernobyl accident data in Fukushima City case. MUD estimates discharge of radionuclide from urban area by natural (washed off by run off) and forced (washing, brushing, etc.) decontamination process into natural receiving water body such as river and artificial receiving water body such as drainage and sewer system. The estimation is calculated by using multi-compartment model and programmed by fortran®.

MUD consists of urban sub model and WWTP sub-model. Urban Sub-model divides urban area into four types which are paved, tree, rood and wall. Output of the model is discharge of radionuclide into sewer system. Sub-model WWTP considered primary sediment, secondary clarifier and sludge treatment as factor affecting amount of radionuclide in waste water. Output of WWTP sub-model is concentration of radionuclide in sludge.

In this study, all of obligatory parameter value in Urban Sub-Model was not changed whereas in WWTP sub-model, since the operational data of WWTP Fukushima City is available, the value of some operational parameter had been calibrated. Despite using value of parameter developed based on Chernobyl accident, the model gives a fair result and could be relied for rough prediction. Several uncertainties have to be dealt in this model such as storm effect and initial deposition data.

Improvement of the model could be done by measuring fraction of run-off that enters sewer system by analyzing inflow rate of WWTP during dry and wet weather. Moreover, since poor result occurred during low rainfall season, another source of Cs-137 has to be identified for improving the result of the model.

APPENDIX

Parameter value used in MUD:

SPECIFIC PARAMETER VALUE FOR FUKUSHIMA CITY

Definition	Unit	Value
Total area drained by the sewage	m2	76,200,000.00
Population (number of inhabitants)	inhab	269,100.00
Built-up fraction: fraction of drainage area	-	0.7
Fraction of built-up area occupied by roofs	-	0.75
fraction of runoff from wall to drainage	-	0.625
fraction of runoff from wall to sewerage	-	0.0075
fraction of runoff from wall to soil	-	0.3
fraction of runoff from tree to drainage	-	0.375
fraction of runoff from tree to sewerage	-	0.075
Fraction of runoff from tree to soil	-	0.55
Fraction of runoff from paved to drain	-	0.725
Fraction of runoff from paved to sewerage	-	0.075
Fraction of runoff from paved to soil	-	0.2
Removal rate of suspended solid on primary sedimentation	%	66
Removal rate of suspended solid on secondary sedimentation	%	94

GENERIC PARAMETER VALUE [9]

Definition	Unit	Value
Fixation rate of mobile component in paved areas	/d	0.23
Fixation rate of mobile component in roofs	/d	0.23
Fixation rate of mobile component in walls	/d	0.23
Fixation rate of mobile component in trees	/d	0.23
Radioactivity fraction from trees fixed on leaves	-	0.85
Radioactivity fraction from leaf fall to soil	-	0.6
Migration rate from surface soil to labile	-	0.000665
Migration rate from labile to fixed form in soil	-	0.0019
Migration rate from fixed to labile form in soil	-	0.00021
Migration rate from labile form in soil to depth	-	0.0000385
Removal rate of fixed component in paved area	/mm	0.00125
Removal rate of fixed component in roof area	/mm	0.0001
Removal rate of fixed component in walls area	/mm	0.000001
Removal rate of fixed component in trees area	/mm	0.00069
Fraction mobile component of paved removed by first heavy rain	-	0.6
Fraction mobile component of roof removed by first heavy rain	-	0.6
Fraction mobile component of walls removed by first heavy rain	-	0.4
Fraction mobile component of tree removed by first heavy rain	-	0.4
Fraction of roof component removed by decontamination activity		0.5
Fraction of paved component removed by decontamination activity		0.5
partition coefficient	l/kg	3000
radioactivity attached to suspended solid removed in primary	-	0.5
primary sludge concentration	%	4
secondary sludge concentration	%	0.8
radioactivity attached to suspended solid removed in secondary	-	0.75
dry solid after stabilitation	-	0.65
dry solid after thickening	-	0.8
dry solid after dewatering	-	0.9

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