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2015 Environ. Res. Lett. 10 014013

(http://iopscience.iop.org/1748-9326/10/1/014013)

Environmental Research Letters

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OPEN ACCESS

RECEIVED
13 August 2014

ACCEPTED FOR PUBLICATION
5 January 2015

PUBLISHED
21 January 2015

LETTER

Sediment and ^{137}Cs transport and accumulation in the Ogaki Dam of eastern Fukushima

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Keywords: Fukushima Daiichi Nuclear Power Plant, sediment, dams, cesium, contamination

Abstract

The Ogaki Dam Reservoir is one of the principal irrigation dam reservoirs in the Fukushima Prefecture and its upstream river basin was heavily contaminated by radioactivity from the Fukushima Daiichi Nuclear Power Plant accident. For the purpose of environmental assessment, it is important to determine the present condition of the water in the reservoir and to understand the behavior of sediment-sorbed radioactive cesium under different modes of operation of the dam, as these factors affect further contamination of arable farmlands downstream of the reservoir through sediment migration. This paper addresses this issue with numerical simulations of fluvial processes in the reservoir using the two-dimensional Nays2D code. We distinguish three grades of sediment (clay, silt, and sand), as cesium adherence depends on sediment grain size and surface area. Boundary conditions for the simulations were informed by monitoring data of the upstream catchment and by the results from a separate watershed simulation for sediment transport into the reservoir. The performance of the simulation method was checked by comparing the results for a typhoon flood in September 2013 against field monitoring data. We present results for sediment deposition on the reservoir bed and the discharge via the dam under typical yearly flood conditions, for which the bulk of annual sediment migration from the reservoir occurs. The simulations show that almost all the sand and silt that enter into the reservoir deposit onto the reservoir bed. However, the locations where they tend to deposit differ, with sand tending to deposit close to the entrance of the reservoir, whereas silt deposits throughout the reservoir. Both sand and silt settle within a few hours of entering the reservoir. In contrast, clay remains suspended in the reservoir water for a period as long as several days, thus increasing the amount that is discharged downstream from the reservoir. Under the current operating mode of the dam, about three-quarters of clay that enters the reservoir during the flood is discharged downstream during and in the days following the flood. By raising the height of the dam exit, the amount of clay exiting the reservoir can be reduced by a factor of three. The results indicate that the dam can be operated to buffer radioactive cesium and limit the contamination spreading into lowland areas of the Ukedo River basin. These results should be a factor in considerations for the future operation of the Ogaki Dam, and will be of interest for other operators of dam reservoirs in areas contaminated by radioactive fallout.

1. Introduction

The magnitude 9.0 earthquake and subsequent tsunami on 11 March 2011 resulted in the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident and the release of significant quantities of radionuclides into the atmosphere. The eventual deposition of these radionuclides contaminated wide areas of northeast Japan. Now it is a priority to predict the distribution and fate of the radionuclides in the environment to comprehend external and internal radiation hazards, and the environmental impact to agriculture, forests, rivers, and oceans in the region. A number of intensive surveys have been performed, and Chartin *et al* (2013), Evrard *et al* (2013), and Hashimoto *et al* (2013) are but a few of the recent examples.

The most significant radioactive contaminants that remain in the environment are radioactive cesium isotopes. It is estimated that about 6.4 PBq of both ^{134}Cs and ^{137}Cs were deposited on the land surface in Japan (Stohl *et al* 2012) and predominantly in Fukushima Prefecture, where the nuclear plant is located. Cesium is an alkali metal and is strongly sorbed by soil particles, especially clay-rich soils. Its primary transport mechanism is in the form of soil erosion on the land surface and transport of sediment-sorbed contaminants in aquatic systems, such as rivers and lakes. Floods and typhoons cause the re-suspension of sediments in rivers, thereby increasing water radio-cesium concentrations, and are responsible for the bulk of the annual sediment transport (Nagao *et al* 2013, Ueda *et al* 2013).

Agriculture is a significant component of the economy in Fukushima Prefecture; in particular, rice and crop farming, and dam reservoirs play an important role in supporting agricultural activities. In many areas, there are restrictions on these activities due to radio-cesium contamination, rendering crops unfit for consumption. Contamination migration presents a further risk to farming in the region. There are over a thousand reservoirs and more than ten dams for agricultural and surface water management purposes in Fukushima Prefecture. The Ogaki Dam Reservoir is one of the main irrigation reservoirs in the prefecture and the upstream river basin of this dam was heavily affected by the FDNPP fallout. Significant endeavors are being paid to resuming agricultural and farming activities in Fukushima Prefecture by reutilization of this dam reservoir.

Before this can occur, it is necessary to know the present condition of the water in the reservoir and to predict the radioactive cesium concentrations in the long term. Excessive migration of radioactive cesium-bearing sediment from the Ogaki Dam could lead to increased contamination of farmlands between Minamisoma and Namie along the eastern coast of the prefecture. These are areas displaying relatively little contamination, in comparison, and the farming economy is at risk if excessive migration of contaminated sediment occurs.

The purpose of this study is to quantify the behavior of sediment and water radio-cesium concentrations in the Ogaki Dam Reservoir. To evaluate countermeasure options against contamination migration downstream, predictions are required for sediment and radio-cesium migration from the reservoir under typical flood conditions that account for the bulk of annual sediment migration. One option is to operate the Ogaki Dam in a way to buffer contamination in the reservoir. Such reservoir management was previously attempted at the Kiev Reservoir on the Dnieper River after the Chernobyl accident (Voitsekhovitch *et al* 1997). Here, we report numerical simulations of sand, silt, and clay transport in the Ogaki Dam Reservoir to achieve this goal.

2. Materials and methods

2.1. Study area

The Ogaki Dam Reservoir (figure 1) supplied water to paddy fields in the lower Ukedo River Basin in eastern Fukushima Prefecture before the nuclear accident. The Ogaki Dam is located 22 km upstream from the Ukedo River mouth. The catchment area of the Ogaki Dam is 111 km^2, which is about one-quarter of the total Ukedo River Basin (420 km^2). The reservoir water level was lowered from 170 to 140 m above sea level after the accident to protect the dam structure against subsequent earthquakes and to ensure against collapse. As the upper part of the Ukedo River Basin is substantially more contaminated than the arable land on the coast, movement of radioactive cesium from the reservoir is a major concern in the considerations to reutilize the dam to support arable farming in the downriver basin.

Recently, Iwasaki *et al* (2015) simulated sediment-sorbed ^{137}Cs in the Abukuma River and they estimated that 3.3 TBq of ^{137}Cs was discharged to the ocean during a flood in September 2011. This value is comparable to the annual ^{137}Cs discharge from the Abukuma River of 3.0 TBq calculated by our previously developed soil and cesium transport (SACT) model (Yamaguchi *et al* 2013, Yamaguchi *et al* 2014). Thus, typhoons are the most significant influence on sediment migration for river basins in the region. We simulate sediment movement in the Ogaki Dam Reservoir during two typhoon floods: i) for a flood that occurred between 15–17 September 2013 and ii) for a hypothetical 'average' yearly flood based on ten-year averaged data for floods in this river basin (Yamaguchi *et al* 2014, Kitamura *et al* 2014).

2.2. Simulation method

For the present study, we use the combined river flow and riverbed deformation solver Nays2D of the iRIC (International River Interface Cooperative) package. Nays2D was developed to predict the distribution of sediments and radioactive materials in dam reservoirs in a two-dimensional (2D) configuration (Shimizu 2003, Wongsa and Shimizu 2004). It is a simulation code for calculating unsteady 2D plane flow and riverbed deformation using boundary-fitted coordinates within general curvilinear coordinates (Shimizu *et al* 2012).

The absorption of cesium by sediments is strongly affected by particle size, surface area, mineral composition (Jackson and Inch 1983, Tanaka and

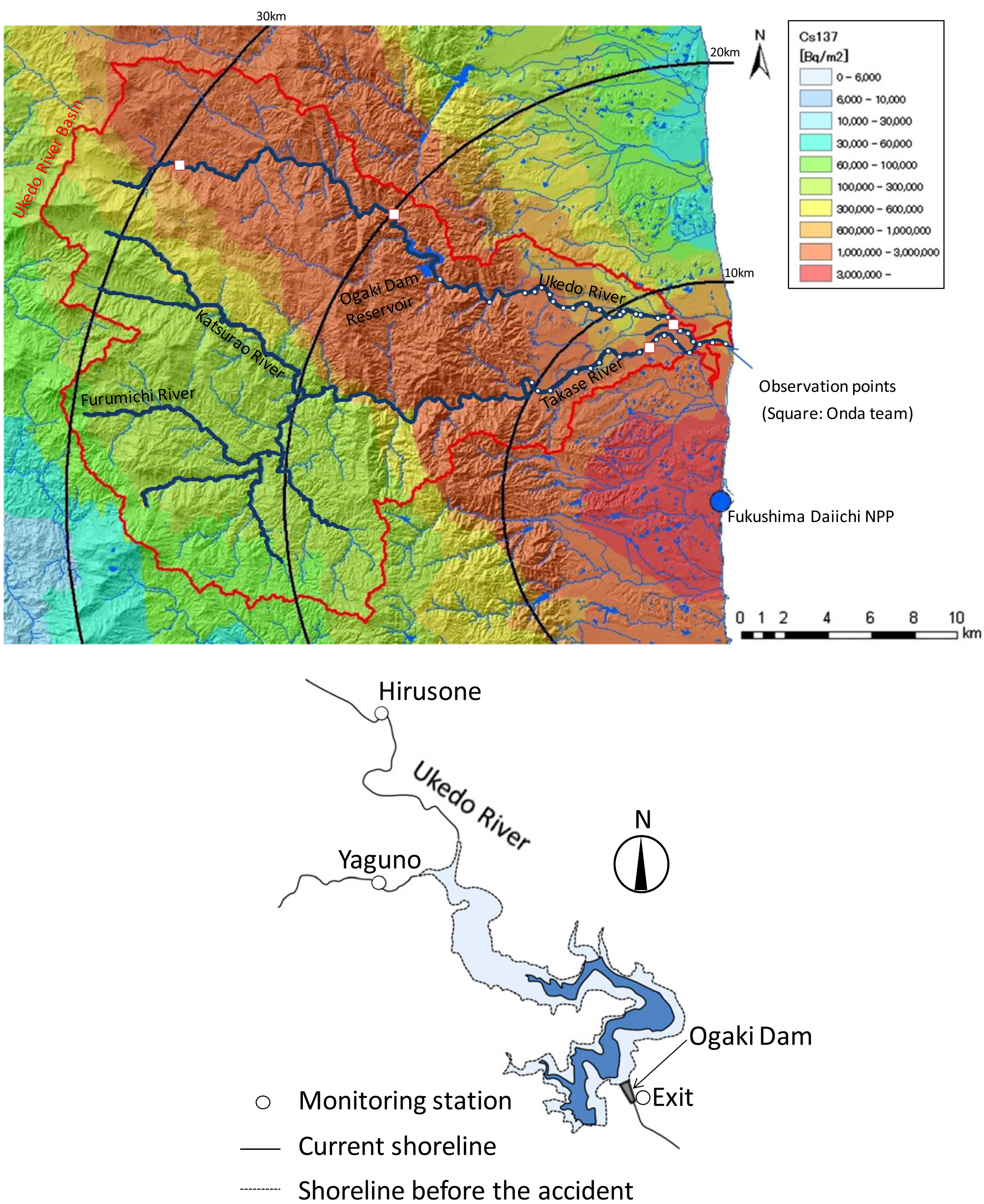

Figure 1. The contamination map around FDNPP and the Ukedo River basin (top), and the Ogaki Dam Reservoir and connecting rivers with the Hirusone and Yaguno monitoring stations (bottom). The current shoreline (June 2014) corresponds to a reservoir water height of 140 m above sea level. Prior to March 2011, the average water height was 170 m above sea level.

Yamamoto 1988), and organic matter content. We considered three types of sediment, namely clay, silt, and sand, and modeled particles with representative diameters of 0.001, 0.01, and 0.1 mm for each sediment grade, respectively. The surface area proportionality of cesium absorption in these sediment types was accounted for by the method outlined by Yamaguchi *et al* (2014). In summary, we assumed that the total volume of ^{137}Cs fallout was instantly absorbed into surface soil, and assumed that the ^{137}Cs inventory in each fraction is given by $C_n = 22.1 \cdot S_{sp}^{0.60}$, where C_n is the ^{137}Cs concentration (mBq g^{-1}) and S_{sp} is a specific surface area (m^2 g^{-1}) (He and Walling 1996).

For this study, we required calculations for sediment and cesium transport over a relatively large area of the reservoir and over a long period of time. We therefore parallelized the Nays2D code to run the Japan Atomic Energy Agency (JAEA) supercomputers and simulated 201 × 201 grids covering a 2 km × 2 km area. Each cell size was 10 m × 10 m and the time step of simulation was 0.2 s.

This study utilizes previously published results from two other watershed simulation models. Results from the SACT model (Yamaguchi *et al* 2013, Yamaguchi *et al* 2014) were used to inform boundary conditions to initiate the Nays2D simulation of the average annual flood (see section 2.3). Results for sediment discharged from the reservoir over the course of a flood from the time-dependent one-dimensional degradation and migration model (TODAM) (Kurikami *et al* 2014) were used to check the Nays2D simulations against an independent simulation method.

Neither SACT nor TODAM were able to determine accurately the locations where contaminated sediment tends to accumulate in the reservoir. As pointed out by Yamaguchi *et al* (2014), SACT cannot properly treat sediment deposition on reservoir and riverbeds, and TODAM is a one-dimensional (1D) code, hence it cannot determine locations of sediment deposition across the width of the reservoir. The key advantage of Nay2D is that it can model these processes; this is why using Nays2D was necessary for this study on using Ogaki Dam Reservoir management as a countermeasure for environmental protection.

2.3. Input data

The administrator of the Ogaki Dam, the Tohoku Regional Agricultural Administration Office (TRAAO), has been monitoring the waters entering the reservoir from two tributaries (at the Hirusone and the Yaguno monitoring stations, figure 1) and the water discharged at the reservoir exit since September 2012. The river discharge rate, the sediment concentration, and the radioactive cesium concentration in the water are being archived to understand their behavior through the Ogaki Dam Reservoir (Tohoku Regional Agricultural Administration Office (TRAAO) (2014)). The river discharge rate is monitored by pressure sensors and the sediment concentration and radioactive cesium concentration are analyzed by taking water samples.

Between September 2012, when TRAAO commenced their monitoring program, and July 2014, there have been two heavy rainfall events caused by typhoons, in September 2013 and October 2013 respectively (Kurikami *et al* 2014). During these events, higher concentrations of suspended sediment and radioactive cesium were detected at all three monitoring posts. The September 2013 typhoon was the stronger typhoon and the resulting concentrations of suspended sediment and radioactive cesium in the water were highest in this case. Our modeling approach in this study was to begin by simulating the sediment migration behavior during and after this rainfall event. The input data to the Nays2D simulation of the September 2013 flood were TRAAO time series of water and sediment inflow into the reservoir. Concentrations of sediment inflow at the Hirusone and the Yaguno monitoring stations during this flood are shown in figure 2. The performance of the simulation method was checked by comparing temporal results for the sediment concentration exiting the reservoir with field monitoring data.

We compliment the simulation for this large flood (September 2013) with simulations for a hypothetical flood representative of the average yearly flood that occurs in the basin. These simulations are based on ten-year averaged data for the water inflow rate to the reservoir during flooding periods (Ministry of Land, Infrastructure and Transport (MLIT) (2013), Yamaguchi *et al* 2014, Kitamura *et al* 2014). SACT model results were used as boundary conditions for sediment inflow rates to the reservoir. The simulation conditions were a flood occurring over 40 h with an average reservoir inflow rate of 35 $m^3 s^{-1}$. After 40 h, the average inflow rate decreased to 2 $m^3 s^{-1}$, representing ambient river conditions. For the average yearly flood, we simulated two reservoir water levels (140 and 170 m above sea level).

The total length of the simulations for the September 2013 and average yearly flood with 140 m reservoir water level was 10 days. For the average yearly flood with the higher reservoir water level (170 m), the length of the simulation was increased to 80 days to allow settlement of suspended sediments in the reservoir.

3. Results and discussion

3.1. September 2013 flood

There is reasonable agreement between the simulation predictions for the sediment concentration in the reservoir outflow and the observed values (upper panel of figure 3). The quantities of sediment discharge decrease over time because of the decreasing sediment inflow to the reservoir as the flooding abates. The simulation results over-predict the sediment concentration about the peak flow rate for the flood, and tend to under-predict the concentration as the flooding subsides. Also shown in figure 3 are the predictions for the ^{137}Cs loading of the water along with the observed values. The simulations reproduced the ^{137}Cs concentrations for the peak in the flooding well, but underestimated the values at later stages. The simulation results are therefore suitable for understanding the qualitative behavior of the bulk of contamination transport through the reservoir, which occurs during the peak of the flooding.

3.2. Results for average yearly flood

We next evaluated the average amount of sediment deposited onto the reservoir bed, the suspension in the reservoir waters, and the discharge from the reservoir for the typical yearly floods. Currently, the water level in Ogaki Dam Reservoir is set at a low level (figure 1) and we considered this case first. The simulation results show sand that enters the reservoir is deposited almost immediately onto the reservoir bed. The sand deposition thus occurs where river tributaries enter

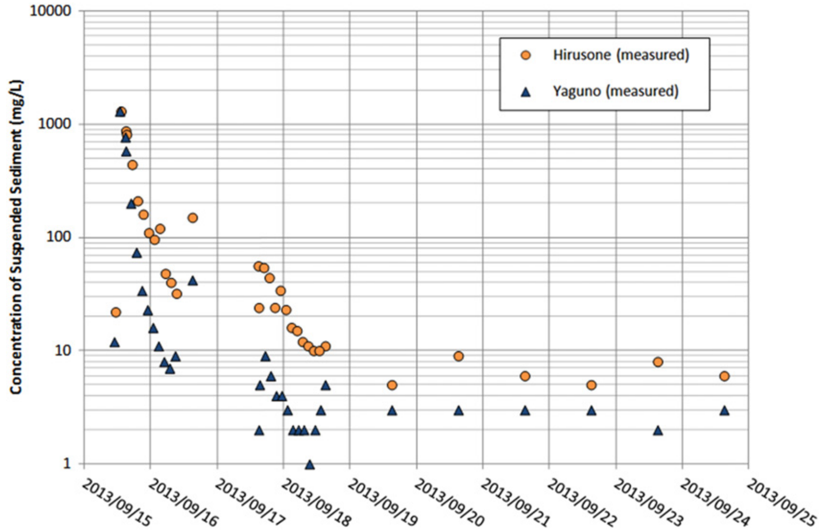

Figure 2. Suspended sediment concentrations observed at the Hirusone and the Yaguno monitoring stations during and after the flood event in September 2013.

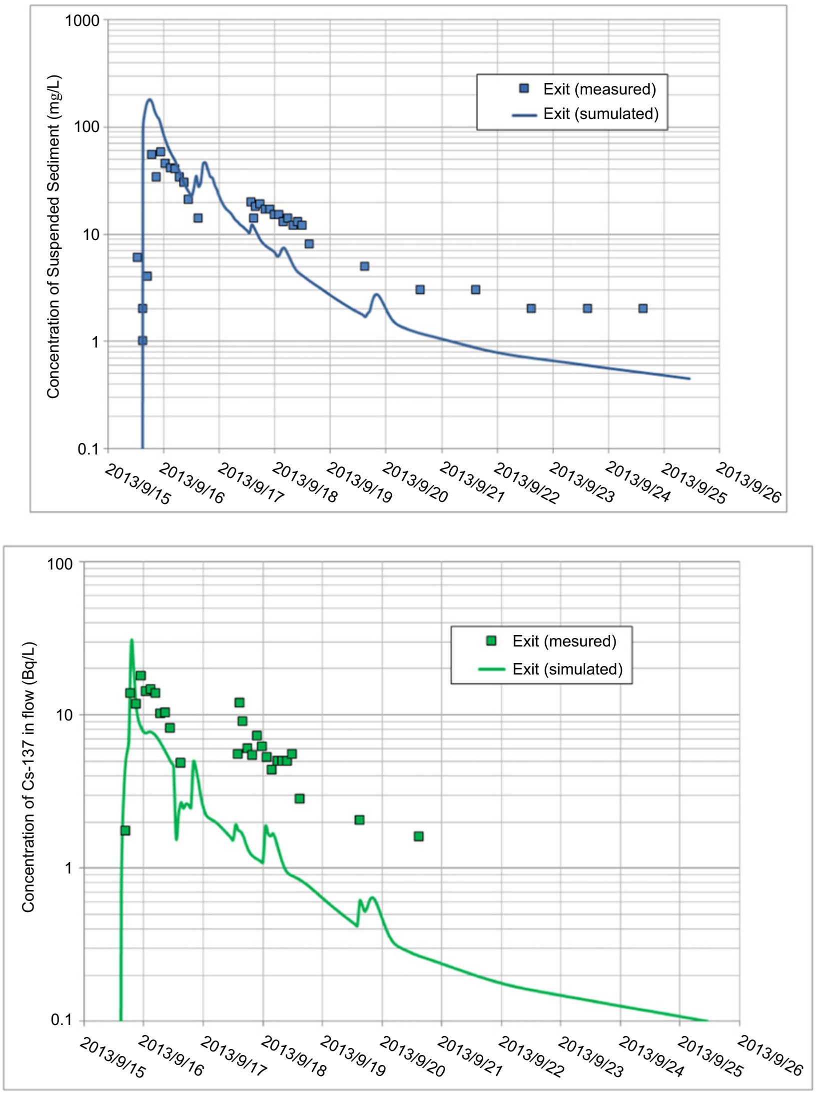

Figure 3. Comparison between monitored and simulated results of suspended sediment (upper panel) and ^{137}Cs concentrations (lower panel) at the exit of the Ogaki Dam Reservoir during and after the flood in September 2013.

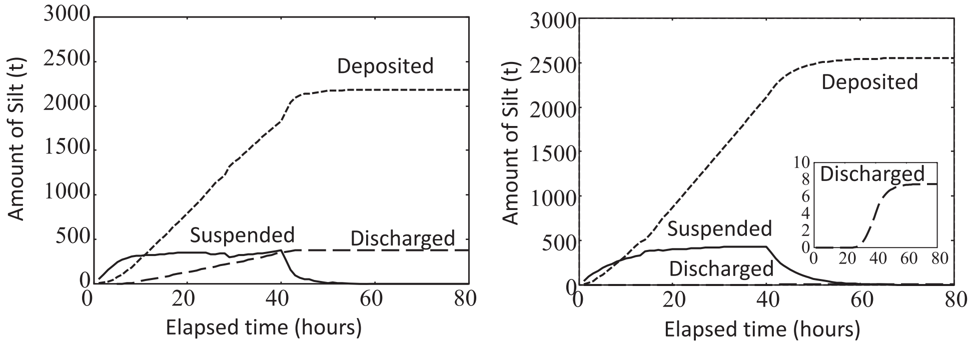

Figure 4. Amounts of silt deposited within, suspended within, and discharged from the Ogaki Dam Reservoir for the representative annual flood when the exit is (a) 140 m and (b) 170 m.

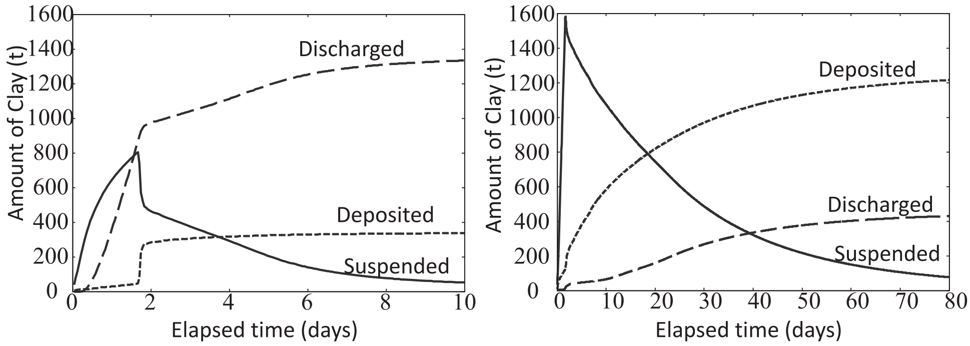

Figure 5. Amounts of clay deposited within, suspended within, and discharged from the Ogaki Dam Reservoir for the representative annual flood when the exit is at (a) 140 m and (b) 170 m.

the reservoir. The amount of sand that remains suspended in the reservoir water or that has the opportunity to be discharged downstream is negligible.

In terms of silt, most of this sediment type deposits on the reservoir bed over the course of the flood. Silt deposition occurs across the entire length and width of the reservoir bed after a lag period of a few hours, in which it is suspended in the reservoir water (figure 4(a)). Due to this lag period, the suspended silt has the opportunity to migrate across the length and width of the reservoir, and a small percentage (15%) is discharged downstream.

In the case of clay transport, the results are substantially different. The primary tendency is for clay to remain suspended in the reservoir water and ultimately to be discharged downstream (figure 5(a)). In contrast to sand and silt, only about 30% of the clay entering the reservoir deposits onto the reservoir bed. The residence time for the suspension of clay in the reservoir water is thus substantially longer. In comparison to the characteristic suspension time for silt of a few hours, clay remains suspended in the reservoir water for over 200 h after the 40 h flood event had subsided.

Based on these results, we estimate an annual quantity of sediment deposition on the Ogaki Dam Reservoir bed between 7.0×10^3 to 8.0×10^3 t. JAEA has a field survey group that is undertaking measurements to calculate the annual sediment deposition in the dam so these simulated values can be checked more completely in the future. However, their provisional results agree with the simulation result presented here within one order of magnitude.

3.3. Comparison between september 2013 and average yearly floods

The average yearly flood is two times larger in terms of the water inflow rate to the reservoir, and this results in a six times larger inflow of sediment to the reservoir over the course of the flood (table 1). The ^{137}Cs inflow is only four times larger for the average yearly flood than the September 2013 flood because, relatively, the larger flood transports more sand and radio-cesium has a lower affinity for binding to larger-grained sediments.

In both cases, sand deposits quickly on entering the reservoir, and sediment outflow from the reservoir is dominated by clay and silt. The sediment outflow in the case of the average yearly flood is six times greater than the September 2013 flood, whereas the ^{137}Cs outflow is five times greater. As the deposited sediments contain a higher fraction of sand, in the case of the average yearly flood, ^{137}Cs deposition is only three times larger than the September 2013 flood.

Table 1. Comparison between September 2013 flood and average yearly flood (140 m water level) on sediment and ^{137}Cs inflow to the reservoir, discharge from the dam, and deposition on the reservoir bed at the end of the simulations.

Flooding event		Inflow	Outflow	Deposition	Suspension
2013.9	Sediment ($\times 10^3$ ton)	1.5	0.35	1.1	<0.01
	^{137}Cs (GBq)	230	68	161	<1
Average yearly	Sediment ($\times 10^3$ ton)	8.5	2.0	6.5	<0.01
	^{137}Cs (GBq)	900	350	550	<1
Ratio average yearly/2013	Sediment	5.8	5.6	6.1	—
	^{137}Cs	3.9	5.2	3.4	—

Table 2. Ratio of sediment removal from the Ogaki Dam Reservoir (=sediment outflow from the reservoir to downriver/sediment inflow from the upstream basin during the flood).

Exit Height			Nays 2D	TODAM
Low (140 m)	Silt	240 h later	10%	4.5%
	Clay	240 h later	77%	53%
High (170 m)	Silt	2400 h later	0.5%	1.6%
	Clay	2400 h later	25%	44%

3.4. Effect of reservoir water level

We next considered the effect of the reservoir water level on sediment transport. In a second set of simulations for average yearly flood conditions, the height of the water level exiting the dam was increased from 140 to 170 m above sea level. While the transport behavior for sand was basically unchanged, different results were obtained for both silt and clay transport. The bulk of silt deposits onto the reservoir bed (figure 4(b)), and only a very small portion discharges downstream from the reservoir, inset of figure 4(b).

For clay, the tendency to deposit onto the reservoir bed was much higher than in the case of the lower reservoir water level. The simulations showed a substantial settling period that lasted over 50 days after the two-day flood event subsided. On completion of the simulated period (about three months), 70% of the clay that entered the reservoir during the flood period had deposited onto the bed of the reservoir, figure 5(b). The remainder of the clay sediments passed downstream from the reservoir and a smaller portion remained suspended in the reservoir waters.

When figures 5(a) and (b) are compared, we observe that the residence time of clays suspended in the reservoir water increases by a factor of about 10 when the reservoir water level is increased by 30 meters. Such a large increase was not found for silt (see figures 4(a) and (b)), as it deposits quickly onto the reservoir bed for both reservoir water heights. A large reduction in the mass of silt and clay discharged from the reservoir was seen in both cases. Similar results were found using the 1-D TODAM code (Kurikami *et al* 2014), and qualitative agreement between the two sets of results can be observed in table 2.

We finally calculated the ^{137}Cs discharge from the dam and deposition onto the reservoir bed. Table 3 displays the values for both high and low reservoir water levels. When the reservoir water height is 140 m, the ^{137}Cs outflow from the reservoir was found to be four times larger than when the water level is 170 m. The corresponding ^{137}Cs deposition within the reservoir was found to be one-third lower for the 140 m reservoir water level than for the 170 m level. Because the clay and silt portions of the sediment play a dominant role in radioactive cesium transport (Yamaguchi *et al* 2013, Yamaguchi *et al* 2014, Kitamura *et al* 2014), and because our simulations indicate that by raising the height of the reservoir water level the clay outflow from the reservoir is substantially reduced, these results suggest that reservoir management can provide a countermeasure against radio-cesium migration downriver.

3.5. Locations of sediment accumulation

We next determined the locations where sediment tends to accumulate on the bed of the Ogaki Dam Reservoir. Figure 6 shows the temporal behavior of deposited sand, silt, and clay in the reservoir in the simulations for the low reservoir water level (140 m). Sand deposits on the bed close to where it enters the reservoir, whereas silt deposits across the length and width of the reservoir. For clay, the amount of deposition is minor during the initial stage of flooding due to its tendency to remain in suspension. However, deposition gradually increases in the hours after the flood, and occurs across the length of the reservoir and primarily toward the dam. Observations by TRAAO identified relatively high concentrations of radiocesium on the bed in the lower downstream portion of the reservoir (Tohoku Regional Agricultural Administration Office (TRAAO) (2014)), which is in agreement with our simulated results.

4. Conclusions

We have simulated sediment transport and deposition in the Ogaki Dam Reservoir during and after a historic flood event and for a hypothetical event representative of annual flooding in the basin using Nays2D. The simulations elucidated both the spatial and temporal deposition and transport of sediment during and after the floods. By simulating different sediment grades, we

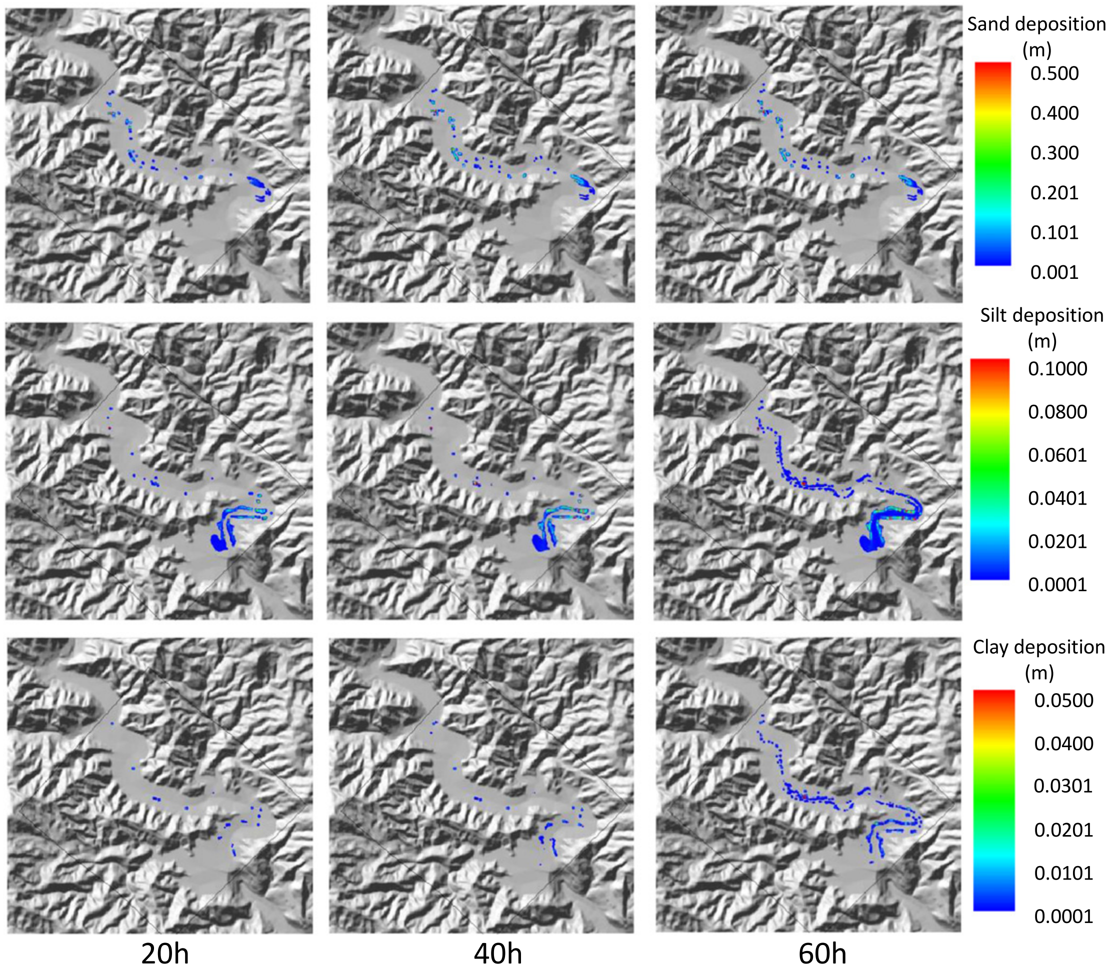

Figure 6. The deposition of sand, silt, and clay in the Ogaki Dam Reservoir for the representative annual flood (map drawn using Digital Elevation Model data provided by the Geophysical Survey Institute). Simulations are for 140 m reservoir water level.

Table 3. Comparison between ^{137}Cs discharge from the dam and deposition onto the reservoir bed at the end of the simulations for two different reservoir water levels.

Water level		Inflow	Outflow	Deposition	Suspension
Low (140 m)	GBq	900	350	550	<1
High (170 m)	GBq	900	88	800	12
Ratio Low/High	—	1.0	4.0	0.69	—

could convert sediment transport data into quantities of radioactive cesium transport.

For the current reservoir water level, almost all the sand and silt entering the reservoir during the flood deposits onto the reservoir bed. Only a small fraction of the silt input and essentially none of the sand is discharged downstream. However, because of the size difference between sand and silt, the location of deposition areas and characteristic sediment suspension times differ. While the sand deposits close to entrance points of the reservoir, silt deposition occurs in all areas of the reservoir. The suspension time in the reservoir water is limited to a few hours in both cases. In contrast, clay remains suspended in the reservoir water for a longer period and eventually most of the clay is discharged downriver.

The results are markedly different for a higher reservoir water level when the dam exit height is 30 meters higher. In this scenario, the amount of sediment discharge downstream is significantly lower for both silt and clay. Compared to the lower reservoir water level, discharge of silt downstream was essentially suppressed altogether, and discharge of clay was reduced by a factor of three. Deposition of silt in the reservoir completes immediately after the end of the flood period, whereas clay suspended in the reservoir water settles over a much longer period (months). The behavior for sand was essentially unchanged.

The contamination outflow from the reservoir is substantially lower for the higher reservoir water level, as clay and silt are responsible for the majority of radio-cesium transport. Tuning the height of the reservoir water level could therefore be used to mitigate against contamination migration downstream and to protect farmland in the lower Ukedo River Basin, which has a high economic value to the region. However, regrettably in this situation, no mode of operation of the Ogaki Dam would be without drawbacks, and limiting radio-cesium migration downstream will consequently result in higher radio-cesium deposition within the reservoir. Similar conclusions on reservoir management may apply for the operation of other dam reservoirs in the contaminated areas of Japan, if they are also characterized by high levels of fallout in the upper part of a river catchment.

The limitation of this work is that further simulations are required at a variety of reservoir water heights to properly inform the most effective water level for environmental protection. As this study used a simple model for radio-cesium loading in different sediment types, a more complete analysis should consider the mineralogy of the sediment grains and the organic matter content to more accurately estimate quantities of radio-cesium transport.

Acknowledgments

We are grateful to members of the Center for Computational Science & e-Systems and the Fukushima Environmental Safety Center for their contribution to the project. We thank the Tohoku Regional Agricultural Administration Office for providing monitoring data. We also acknowledge anonymous reviewers for their constructive comments.

References

Chartin C, Evrard O, Onda Y, Patin J, Lefevre I, Ottle C, Ayrault S, Lepage H and Bonte P 2013 Tracking the early dispersion of contaminated sediment along rivers draining the Fukushima radioactive pollution plume *Anthropocene* **1** 23–34

Evrard O, Chartin C, Onda Y, Patin J, Lepage H, Lefevre I, Ayrault S, Ottle C and Bonte P 2013 Evolution of radioactive dose rates in fresh sediment deposits along coastal rivers draining Fukushima contamination plume *Sci. Rep.* **3** 3079

Hashimoto S, Matsuura T, Nanko K, Linkov I, Shaw G and Kaneko S 2013 Predicted spatio-temporal dynamics of radioactive cesium deposited onto forests following the Fukushima nuclear accident *Sci. Rep.* **3** 2564

He Q and Walling D 1996 Interpreting particle size effects in the adsorption of ^{137}Cs and unsupported ^{210}Pb by mineral soils and sediments *J. Environ. Radioactiv.* **30** 117–37

Iwasaki T, Nabi M, Shimizu Y and Kimura I 2015 Computational modeling of ^{137}Cs contaminant transfer associated with sediment transport in Abukuma river *J. Environ. Radioactiv.* **139** 416–26

Jackson R and Inch K 1983 Partitioning of strontium-90 among aqueous and mineral species in a contaminated aquifer *Enivorn. Sci. Technol.* **17** 231–7

Kitamura A, Yamaguchi M, Kurikami H, Yui M and Onishi Y 2014 Predicting sediment and cesium-137 discharge from catchments in eastern Fukushima *Anthropocene* **5** 22–31

Kurikami H, Kitamura A, Yokuda S T and Onishi Y 2014 Sediment and ^{137}Cs behaviors in the Ogaki Dam Reservoir during a heavy rainfall event *J. Environ. Radioactiv.* **137** 10–7

Ministry of Land, Infrastructure and Transport (MLIT) 2013 Water information system (http://www1.river.go.jp/) in Japanese

Nagao S, Kanamori M, Ochiai S, Tomiara S, Fukushi K and Yamamoto M 2013 Export of ^{134}Cs and ^{137}Cs in the Fukushima river systems at heavy rains by typhoon roke in september 2011 *Biogeosciences* **10** 6215–23

Shimizu Y 2003 Mutual relation between riverbed and bank variation characteristics in river channel landform formation *Proc. Hydraul. Eng.* **47** 643–8

Shimizu Y, Inoue T, Hamaki M and Iwasaki T (ed) 2012 *iRIC Software Nays2D Solver Manual* iRIC Project http://people.eri.ucsb.edu/~lharrison/MeanderModelLit/NAYS/Nays2D_SolverManual.pdf

Stohl A, Seibert P, Wotawa G, Arnold D, Burkhart J F, Eckhardt S, Tapia C, Vargas A and Yasunari T J 2012 Xenon-133 and caesium-137 releases into the atmosphere from the Fukushima Dai-ichi nuclear power plant: determination of the source term, atmospheric dispersion, and deposition *Atmos. Chem. Phys.* **12** 2313–43

Tanaka T and Yamamoto T 1988 Effect of soil characteristics on soil particle size dependence of distribution coefficient *J At. Energy Sci. Jpn.* **30** 933–41 in Japanese with English abstract

Tohoku Regional Agricultural Administration Office (TRAAO) 2014 (www.maff.go.jp/tohoku/osirase/higai_taisaku/hukkou/140918_torimatome.html) in Japanese

Ueda S, Hasegawa H, Kakiuchi H, Akata N, Ohtsuka Y and Hisamatsu S 2013 Fluvial discharges of radiocesium from watersheds contaminated by the Fukushima Dai-ichi Nuclear Power Plant accident, Japan *J. Environ. Radioactiv.* **118** 96–104

Voitsekhovitch O, Nasvit O, Los'y I and Berkovsky V 1997 Present thoughts on the aquatic countermeasures applied to regions of the Dnieper river catchment contaminated by the 1986 Chernobyl accident *Stud. Environ. Sci.* **68** 75–85

Wongsa S and Shimizu Y 2004 Modeling artificial channel and land-use changes and their impact on floods and sediment yield to the Ishikari basin *Hydrol. Process.* **18** 1837–52

Yamaguchi M, Kitamura A, Oda Y and Onishi Y 2014 Predicting the long-term ^{137}Cs distribution in Fukushima after the Fukushima Dai-ichi Nuclear Power Plant accident: a parameter sensitivity analysis *J. Environ. Radioactiv.* **135** 135–46

Yamaguchi M, Maekawa K, Takeuchi S, Kitamura A and Onishi Y 2013 Development of a model to predict a radionuclide distribution based on soil migration after Fukushima Dai-ichi Nuclear Power Plant accident *J. Nucl. Fuel Cycle Environ.* **20** 53–70 (in Japanese with English Abstract)