JAEA Modeling of Cs transport within Fukushima aquatic systems

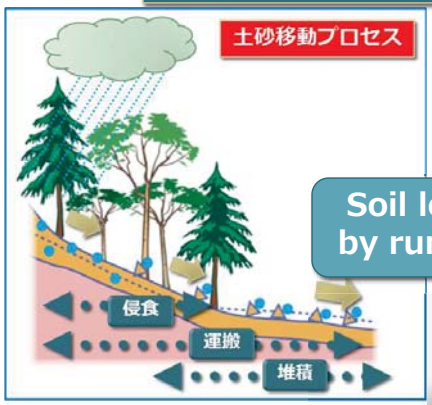
Hiroshi Kurikami
Fukushima Environmental Research Group
Fukushima Environmental Safety Center
Sector of Fukushima Research and Development
Japan Atomic Energy Agency (JAEA)

2nd Caesium Workshop: meeting challenges for Fukushima recovery (2014/10/7)

Objectives of the F-TRACE project

Develop mechanistic models to predict quantitatively transport of radioisotopes (especially radioactive Cs) along river systems

Transport passway

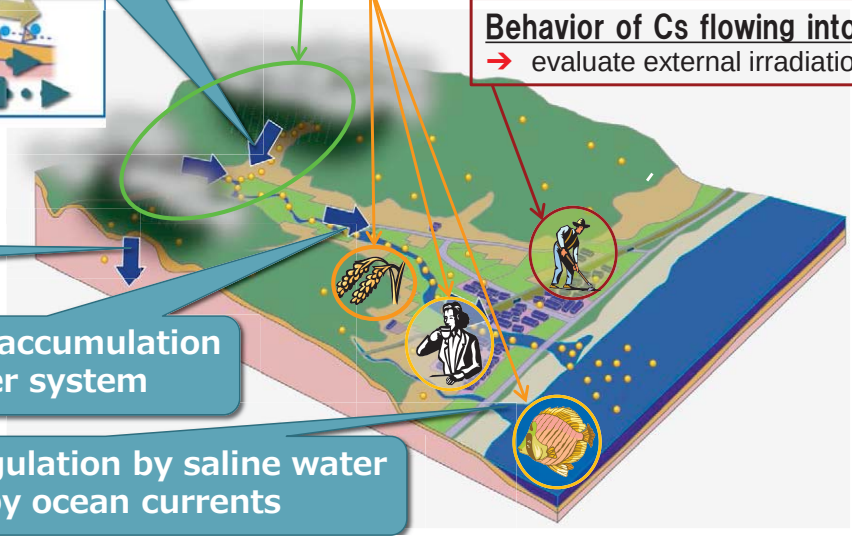


Transport behavior of Cs to be modeled

Behavior of each species of Cs in forests
- ➔ evaluate external irradiation of forestry workers in the forest
- ➔ apply to evaluate cycle of Cs in forest eco system

Behavior of each species of Cs in water system
- ➔ evaluate internal exposure by intake of water
- ➔ apply to evaluate Cs uptake by vegetation / fishes

Behavior of Cs flowing into biosphere
- ➔ evaluate external irradiation in the biosphere



Soil loss by runoff

advection

Transport / accumulation in a river system

Desorption / coagulation by saline water
Transport by ocean currents

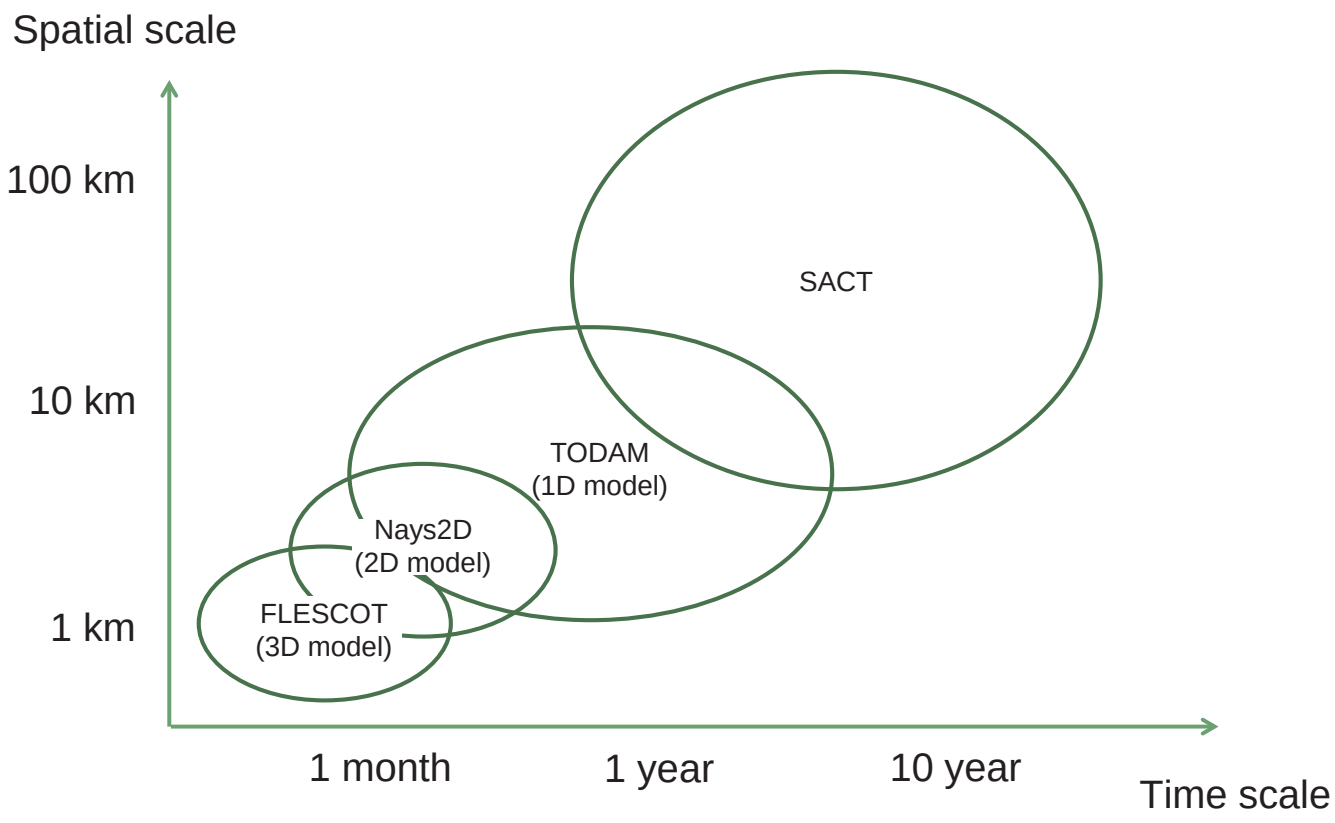
Models

- **River basin models**
  - **SACT model (originally developed by JAEA)**
    - Soil and radioactive cesium transport mainly on the land surface using USLE
  - **GETFLOWS (Developed by GETC)**
    - Alternative watershed model
- **River/reservoir models**
  - **TODAM model (developed by PNNL)**
  - **Nays2D (developed by Hokkaido Univ.)**
- **Reservoir/coast/ocean models**
  - **FLESCOT model (developed by PNNL)**
  - **ROMS (openly developed)**
- **Radiation transport model**
  - **PHITS (developed by JAEA)**

By combining/modifying these originally developed and various existing models in a flexible way, we can solve various issues.

SACT model: Soil And Cs Transport model
GETFLOWS: GEneral purpose Terrestrial fluid-FLOW Simulator
GETC: Geosphere Environmental Technology Corp.
TODAM model: Time-dependent, One-dimensional Degradation And Migration model
PNNL: Pacific Northwest National Laboratory
FLESCOT model: Flow, Energy, Salinity, Sediment Contaminant Transport model
ROMS: Regional Ocean Modeling System
PHITS: Particle and Heavy Ion Transport code System

Applicability of models

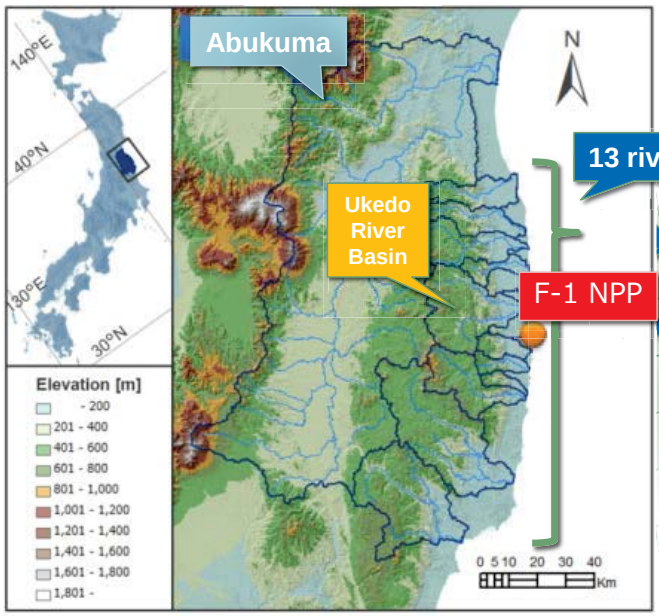


According to time and spatial scales of events, we select models to be applied.

SACT (Soil and Cs transport) model

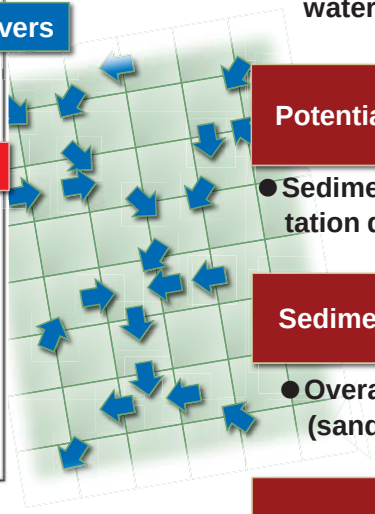
SACT model for predicting future distribution of Cs

Region



■ 14 river basins were selected

Procedure



Step 1
Potential soil loss per grid cell

- Soil erosion due to surface water（Sheet erosion and rills)

Step 2
Potential sediment discharge per grid cell

- Sediment transport and sedimentation due to surface water

Step 3
Sediment transport between grid cells

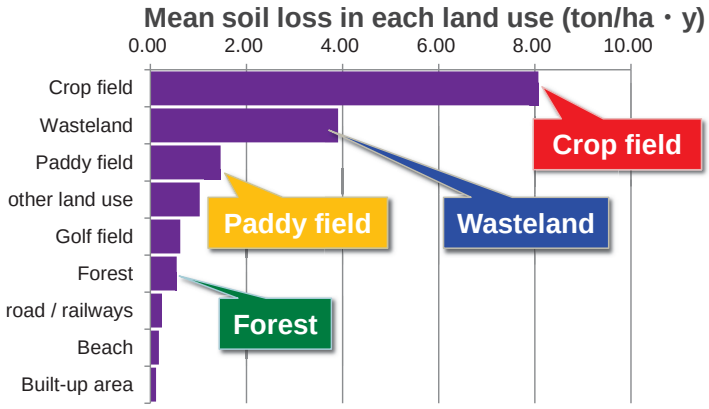
- Overall Sediment transport (sand, silt and clay)

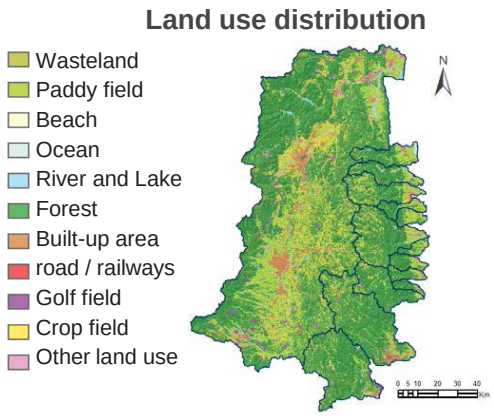
Step 4
Cesium-137 transport between grid cells

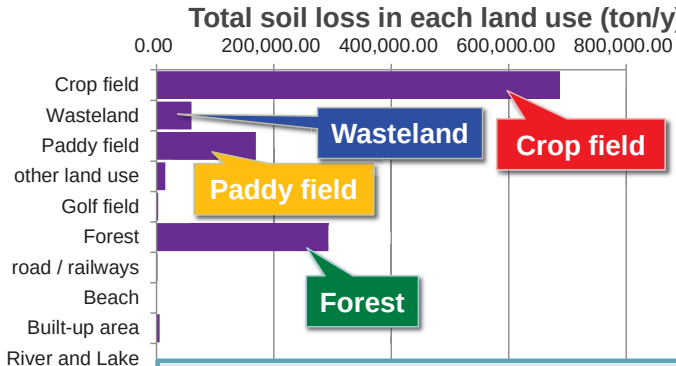
- Overall Cesium-137 transport

Yamaguchi et al., J Nucl Fuel Cycle Environ, 2013

Soil & Cs loss in each land use







Land use	Area (km^2)	Soil loss (t/y)	Initial Cs (Bq)	Cs loss (Bq/y)	Cs loss / Initial Cs
Forest	5329	292,773	9.2×10^{14}	3.0×10^{12}	0.3%
Total	8370	1,233,801	1.3×10^{15}	7.4×10^{12}	0.6%
%	64%	24%	69%	41%	

- Forest occupies 64% of land surface but only accounts for 24% of total soil loss.
- Portion of Cs loss from forest is only 0.3% (these are collected by water systems).
- If woods are removed for decontamination purpose, the area may become wasteland and ended up with increasing Cs runoff (Measures should be treated with cautions).

Kitamura et al., Anthropocene, 2014

Model validation

	Simulated results	Monitoring based results
Annual ^{137}Cs discharge rate from forest	0.3%	0.3%
Annual ^{137}Cs discharge rate from rivers		
Abukuma River	3.0×10^{12} Bq	3.4×10^{12} Bq [b)] 5.3×10^{12} Bq [c)]
Ukedo River	2.4×10^{12} Bq	2.3×10^{12} Bq [b)]
Niida River	1.1×10^{12} Bq	6.0×10^{11} Bq [b)]
Kuma River	2.8×10^{11} Bq	4.2×10^{11} Bq [b)]
Tomioka River	1.1×10^{11} Bq	2.3×10^{11} Bq [b)]
Ohta River	2.7×10^{11} Bq	2.0×10^{11} Bq [b)]
Mano River	2.0×10^{11} Bq	1.8×10^{11} Bq [b)]
Natsui River	1.1×10^{11} Bq	1.4×10^{11} Bq [b)] 5.2×10^{10} Bq [d)]
Kido River	1.4×10^{11} Bq	8.9×10^{10} Bq [b)]
Same River	8.9×10^{10} Bq	2.7×10^{11} Bq [d)]
Annual sediment discharge from river		
Abukuma River	3.0×10^{5} t	1.9×10^{5} t [e)]
^{137}Cs concentration in deposited sediments		
Ukedo River Basin	8.6×10^{4} Bq/kg	Order of 10^{5} Bq/kg [f)]
Odaka River Basin	5.3×10^{4} Bq/kg	Order of 10^{4} Bq/kg [f)]
Ohta River Basin	1.6×10^{5} Bq/kg	1.6×10^{5} Bq/kg [g)]

a) Field study on Mt Tsukuba in the Ibaraki prefecture by NIES (2012)
b) Based on provisional monitoring data from between April to September 2012 by Kanda (2012)
c) Monitoring data from 10 August 2011 to 10 May 2012 (274 days) by Yamashiki et al. (2014)
d) Nagao et al. (2013)
e) Based on the surveyed results performed from 1985 to 1995 by Sato et al. (1996)
f) Yui (2013)
g) Chartin et al. (2013)

Kitamura et al., Anthropocene, 2014

Sensitivity analyses

Table 1
Values selected for the ten cases studied; shaded numbers show values changed in each case.

Cases	Rainfall and runoff factor	Critical shear stress (sand)		Critical shear stress for resuspension (silt and clay)		Critical shear stress for deposition (silt and clay)		Grain size distribution (sand:silt:clay)	Flow rate at lakes	Vertical distribution of ^{137}Cs
		River	Overland	River	Overland	River	Overland			
	R (MJ mm ha^{-1} h^{-1} y^{-1})	τ_c (N m^{-2})	τ_{cr} (N m^{-2})	τ_{cd} (N m^{-2})	R_d (%)	V_{lake} (m s^{-1})	α (cm^{-1})			
NORMAL	336.6	0.180	0.260	0.060	0.260	0.043	0.260	40:40:20	0.01	1.20
RAIN-1	421.65	0.180	0.260	0.060	0.260	0.043	0.260	40:40:20	0.01	1.20
RAIN-2	198.57	0.180	0.260	0.060	0.260	0.043	0.260	40:40:20	0.01	1.20
TAU_C-1	336.6	0.180	7.000	0.060	7.000	0.043	7.000	40:40:20	0.01	1.20
TAU_C-2	336.6	0.180	0.260	1.300	0.260	0.800	0.260	40:40:20	0.01	1.20
GRAIN	336.6	0.180	0.260	0.060	0.260	0.043	0.260	40:50:10	0.01	1.20
LAKE_V	336.6	0.180	0.260	0.060	0.260	0.043	0.260	40:40:20	0.20	1.20
CS_PROF	336.6	0.180	0.260	0.060	0.260	0.043	0.260	40:40:20	0.01	0.50
MAX	421.65	0.180	0.260	0.060	0.260	0.043	0.260	40:40:20	0.20	0.50
MIN	198.57	0.180	7.000	1.300	7.000	0.800	7.000	40:50:10	0.01	1.20

: Parameters focused in each case.

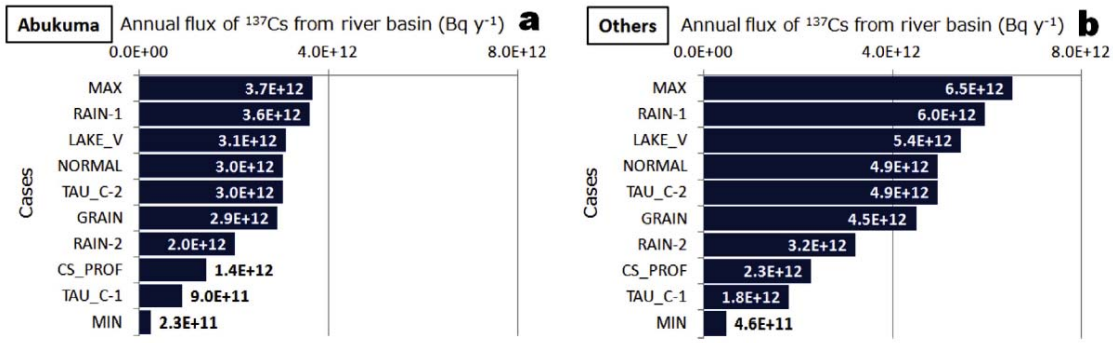


Fig. 6. Calculated annual ^{137}Cs outflow from the Abukuma (a) and the other river basins (b) during the first year.

-> Critical shear stresses and depth profiles of cesium have high sensitivities.

Yamaguchi et al., J Environ Radioact, 2014

1D / 2D river models: TODAM / Nays2D(iRIC)

Suspended sediment transport C_j (kg・m^{-3})

$$A\frac{dC_j}{dt}+UA\frac{dC_j}{dx}=\underbrace{\frac{d}{dx}\left(\varepsilon_X A\frac{dC_j}{dx}\right)}_{\text{Dispersion}}+\underbrace{Q_{Sj}-Q_l C_j}_{\text{Inflow/outflow}}+\underbrace{B(S_{Rj}-S_{Dj})}_{\text{Deposition/ resuspension}}$$

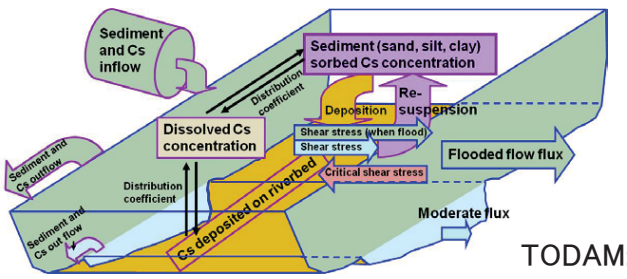
Dissolved cesium G_w (Bq・m^{-3})

$$A\frac{dG_w}{dt}+UA\frac{dG_w}{dx}=\underbrace{\frac{d}{dx}\left(\varepsilon_X A\frac{dG_w}{dx}\right)}_{\text{Dispersion}}\underbrace{-\lambda AG_w}_{\text{Decay}}\underbrace{-Q_l G_w+Q_w}_{\text{Inflow/ outflow}}\underbrace{-\sum_{j=1}^{Nf}AK_j(K_{dj}C_jG_w-G_j)}_{\text{Adsorption/desorption to suspended sediment}}\underbrace{-\sum_{j=1}^{Nf}B\gamma_j(1-n)d_jK_{bj}(K_{dj}G_w-G_{Bj})}_{\text{Adsorption/desorption to bed sediment}}$$

Particulate cesium G_j (Bq・m^{-3})

$$A\frac{dG_j}{dt}+UA\frac{dG_j}{dx}=\frac{d}{dx}\left(\varepsilon_X A\frac{dG_j}{dx}\right)-\lambda AG_j-Q_lG_j+Q_{Pj}+AK_j(K_{dj}C_jG_w-G_j)+B\left(G_{Bj}S_{Rj}-\frac{S_{Dj}G_j}{C_j}\right)$$

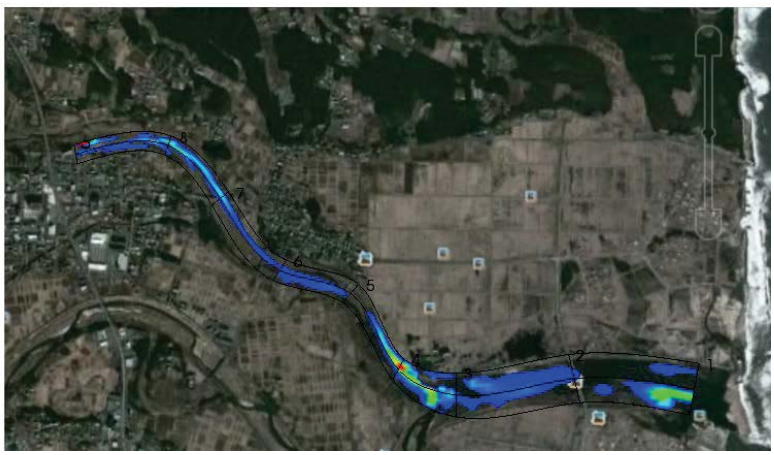
Model treats dispersion equations of sediment concentration (sand, silt, clay) and cesium concentration (dissolved, sediment-sorbed)



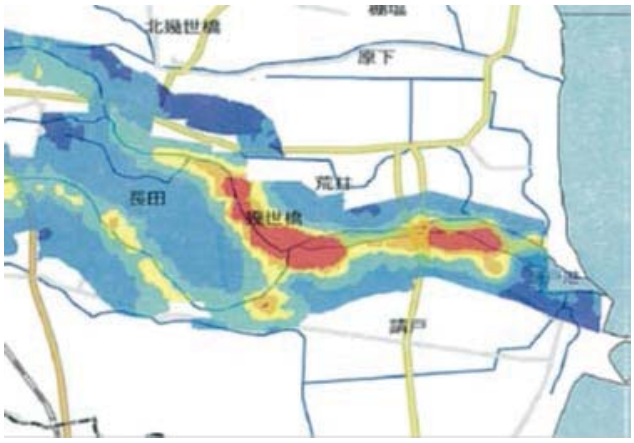
TODAM: developed by Pacific Northwest National Laboratory
Nays2D: developed by Hokkaido University

Example: deposition of sediment in a river (Nays2D)

Elevation change due to deposition of sediment (simulated)



Air dose rate distribution measured by air born survey

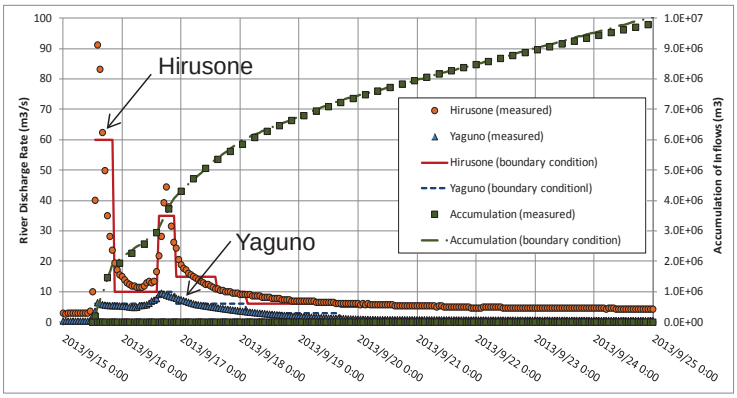


Example: application to the Ogaki Dam Reservoir (TODAM)

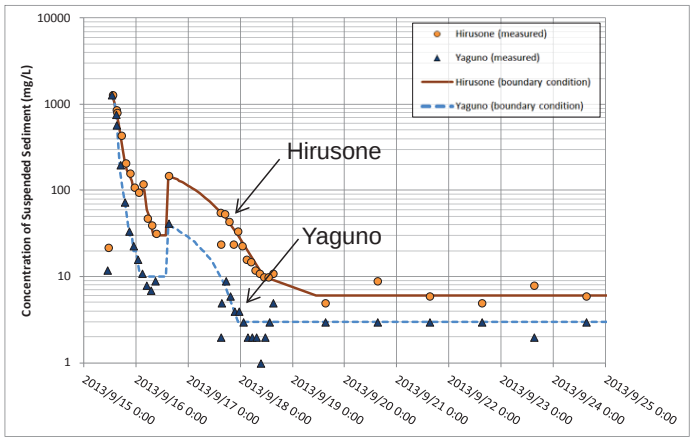
(BC:Discharge Rates, Sediment Concentrations, ^{137}Cs Concentrations at Monitoring Stations)

A flood due to the typhoon in September, 2013

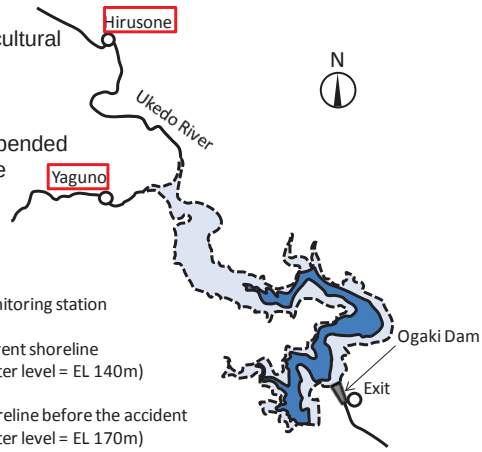
Discharge rates (m^3/s)



Concentrations of suspended sediment (mg/L)

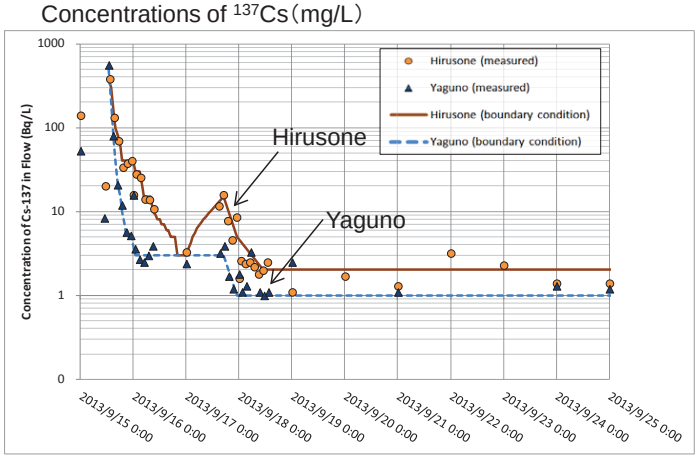


Monitored items
(Tohoku Regional Agricultural Administration Office*)
- Precipitation intensity
- Water level
- Concentrations of suspended sediment (including size distribution)
- ^{137}Cs concentrations

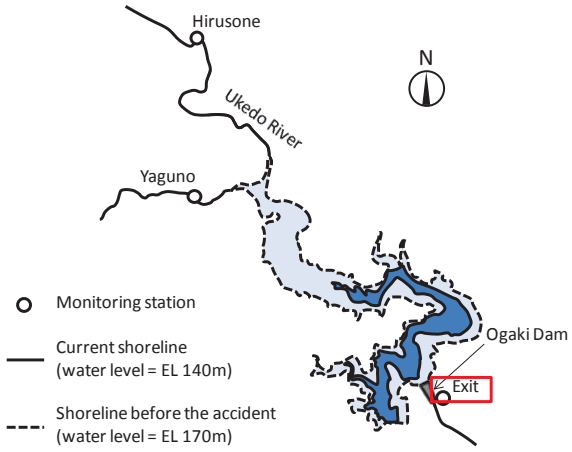


* http://www.maff.go.jp/tohoku/osirase/higai_taisaku/hukkou/140918_torimatome.html

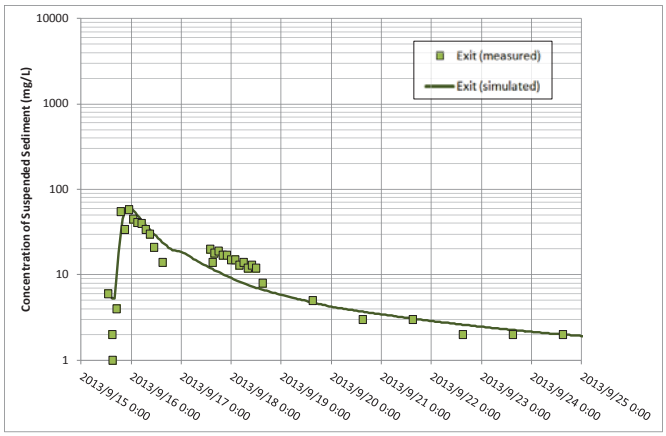
Concentrations of ^{137}Cs (mg/L)



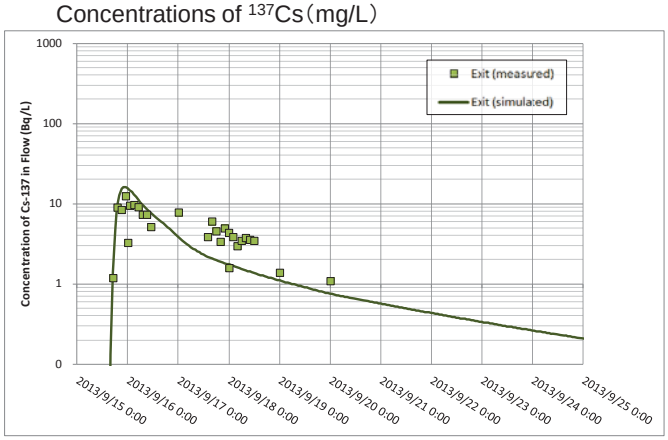
Results (Suspended Sediment at Exit)



Concentrations of suspended sediment (mg/L)



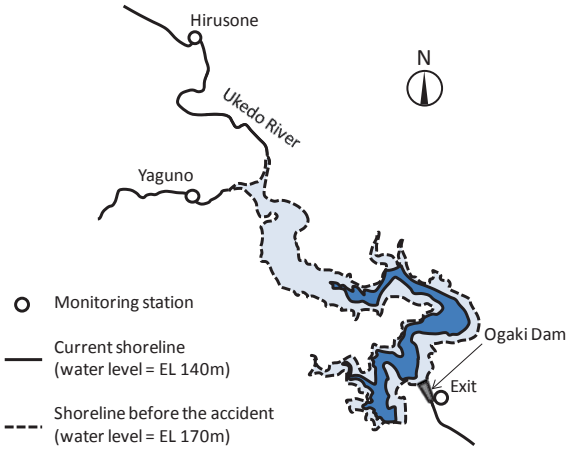
Concentrations of ^{137}Cs (mg/L)



✓ The simulation reproduced the measured values well.

Effect of water level on discharge of sediments/^{137}Cs

	Low water level (Real situation)	High water level (Normal situation)
Ratio of sand outflow	0.0%	0.0%
Ratio of silt outflow	4.5%	1.6%
Ratio of clay outflow	54%	34%
Ratio of ^{137}Cs outflow	9.0%	3.5%
Ratio of silt-sorbed ^{137}Cs	40%	18%
Ratio of clay-sorbed ^{137}Cs	60%	82%

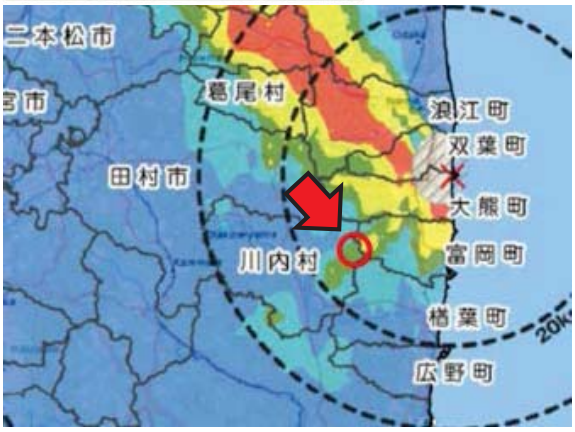


- ✓ The reservoir plays a major role to delay and buffer the movement of radioactive cesium in heavy rainfall events.
- ✓ The buffer feature of the reservoir depends on particle sizes of suspended sediment and the water level.
- ✓ Support decision making for the operation

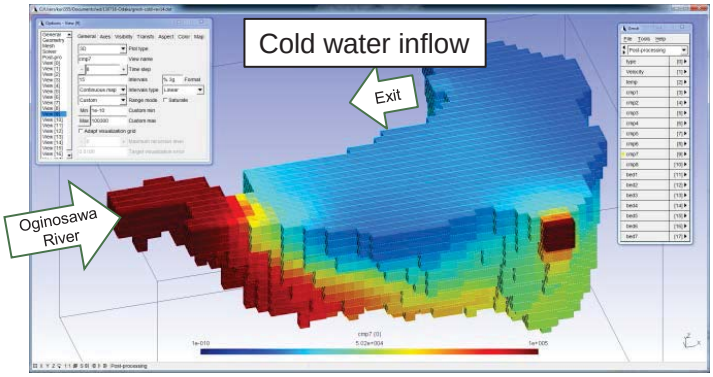
Kurikami et al., J Environ Radioact, 2014

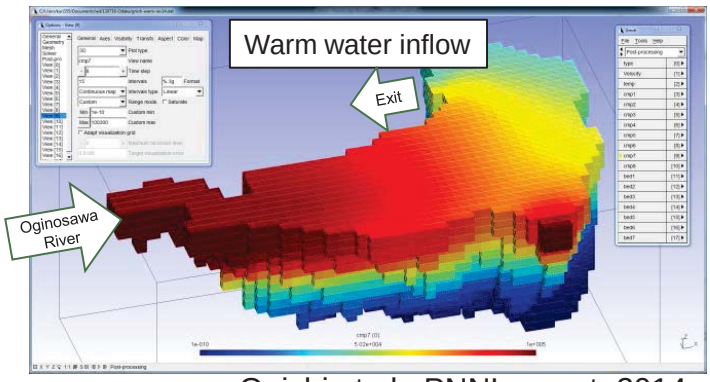
3D reservoir/coastal models: FLESCOT

Preliminary analysis of the Ogi Dam Reservoir



Distribution of clay-sorbed cesium



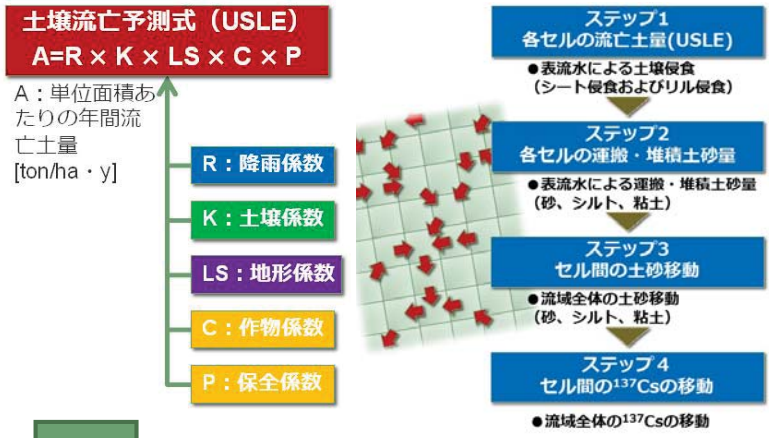


Onishi et al., PNNL report, 2014

Air dose evaluation tool (PHITS)

Soil and cesium transport SACT

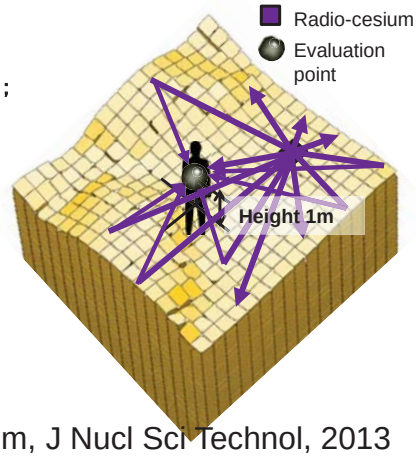
Simulate sediment-sorbed cesium migration using USLE and simple hydraulic equations



Air dose rate evaluation PHITS

Simulate air dose rate by PHITS from results of cesium distribution obtained by SACT

- Calculate radiation transport from radio-cesium on surface to measurement points（**Monte-Carlo；250,000×50,000**）
- Interaction between air and soil by gamma rays（200m、12.5m mesh、17×17）
  ①Radio-cesium conc. distribution
  ②Surface topography
  ③Radio-cesium conc. distribution profile in z-direction
  $C = C_0 \cdot \exp(-1.2) \cdot z$

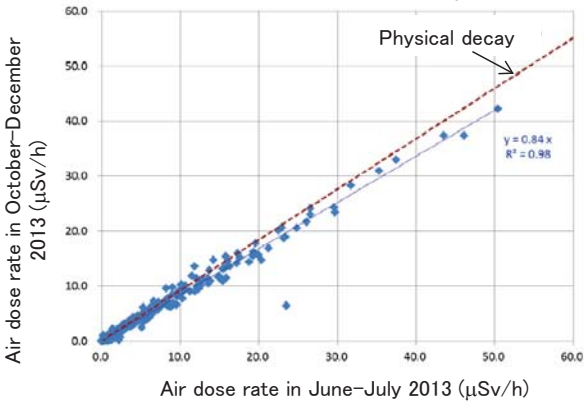


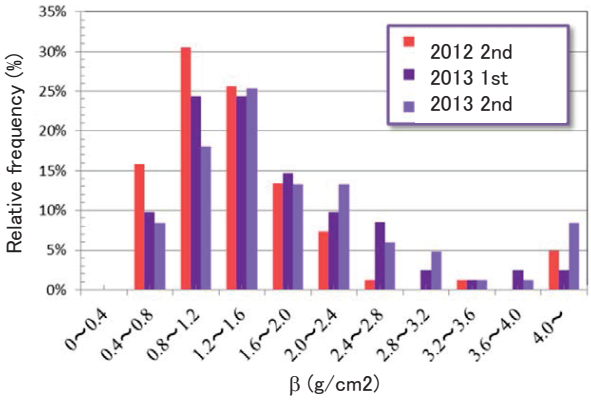
PHITS: Particle and Heavy Ion Transport code System, J Nucl Sci Technol, 2013

Air dose rate vs Cs intrusion into soil

Air dose rate tends to decrease more than physical decay. One of the reason is considered to be radioactive cesium intrusion into soil.

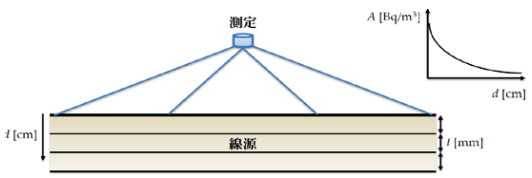
$$A(d) = A_0\exp(-d\alpha) = A_0\exp[-d\rho/\beta]$$

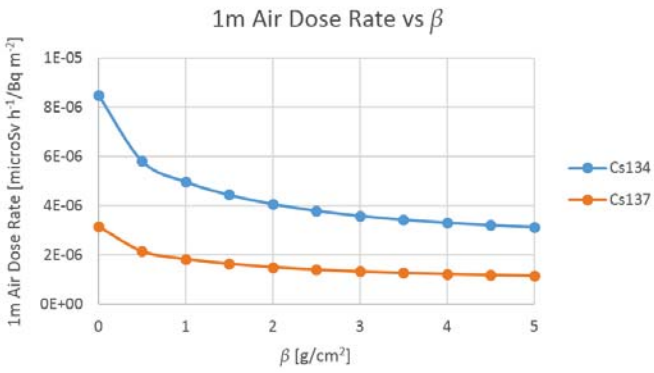




原子力規制庁委託事業「平成25年度東京電力（株）福島第一原子力発電所事故に伴う放射性物質の長期的影響把握手法の確立」事業　成果報告書

A tool to calculate arbitrary depth distribution of radioactive cesium in soil has been developed.





Summary

- Predictions of future radioactive cesium distribution and movements have been simulated by using various models.
- Comparing simulated results with available field-measurement based estimates showed that they were within the same order of magnitude.
- Currently, intensive field investigations have been continued with a goal to feed back the results from these efforts to modify or refine our simulation model as necessary.
- Our simulation results are being provided as guiding information for countermeasure considerations to ministries and agencies, as well as local government.