Development of a radionuclide transport model applicable to coastal regimes with multi-fractional cohesive and non-cohesive sediments

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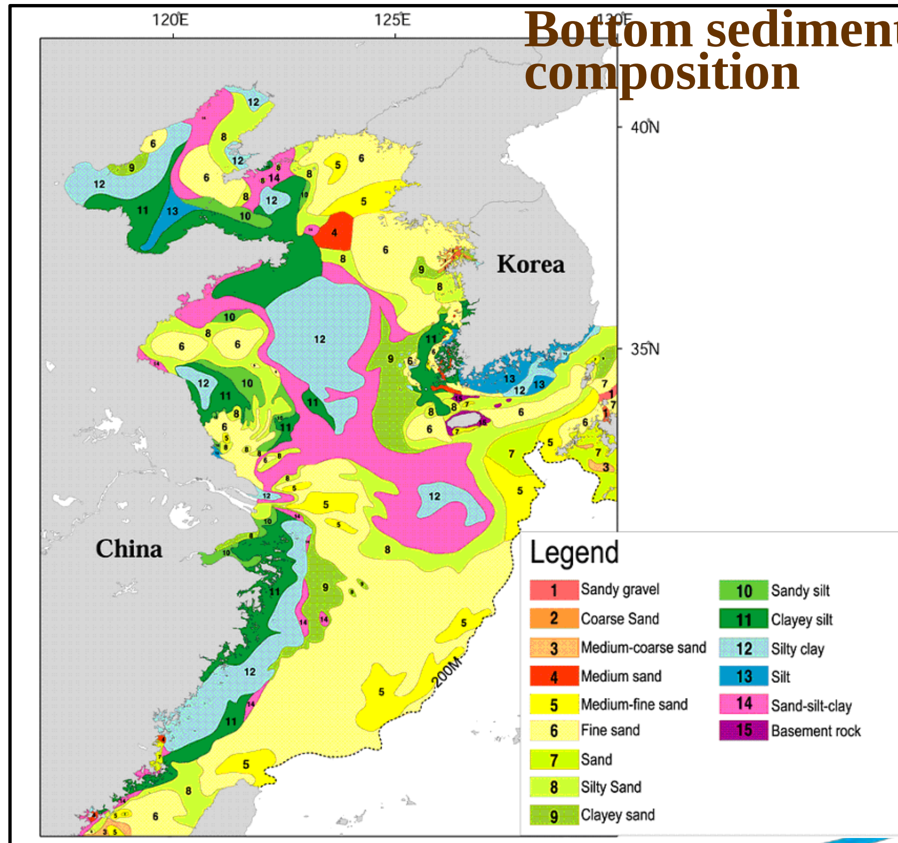
Features of Yellow and East China Seas

Multi-scale circulation with tidal, wind-driven & oceanic currents
High turbidity with cohesive & non-cohesive sediments

NOAA, Oct 1997



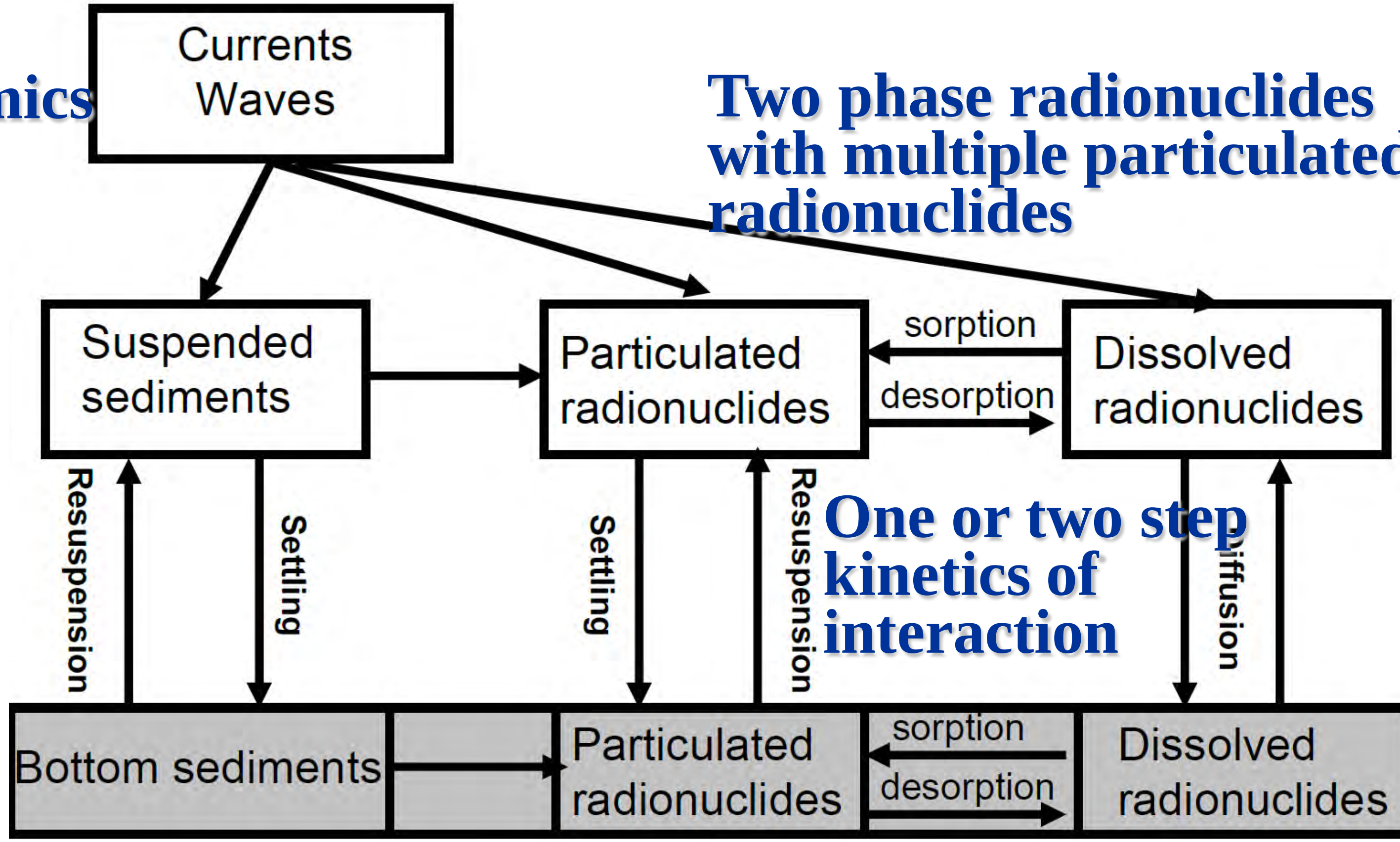
B.H.Choi et. al. 2003

Radionuclide transport processes considered

Multi-scale hydrodynamics

Two phase radionuclides with multiple particulated radionuclides

Multi-fractional ss



One or two step kinetics of interaction

Single or multiple bed layers

Eqs. for the dissolved and particulated radionuclides in the sea water

Adsorption/desorption-related flux

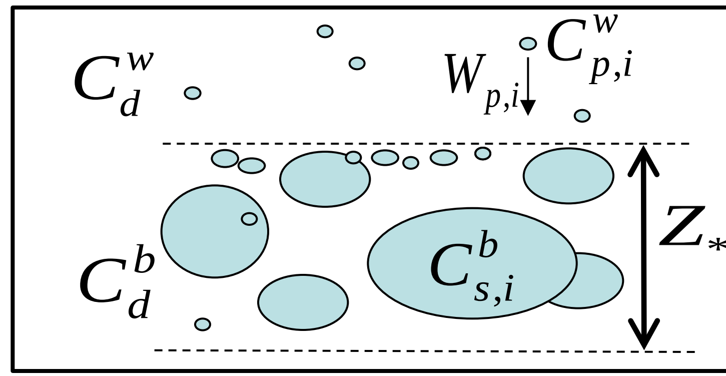
$$\frac{\partial C_d^w}{\partial t} + \vec{U}\nabla C_d^w = -a_{12}\left(C_d^w \sum_{i=1}^{n} S_{p,i} K_{d,i}^w - C_p^w\right) - \lambda C_d^w + DIFF(C_d^w)$$

$$i = 1, \cdots, n$$

$$\frac{\partial C_{p,i}^w}{\partial t} + \vec{U}\nabla C_{p,i}^w = W_{p,i}\frac{\partial C_{p,i}^w}{\partial z} + a_{12}\left(C_d^w S_{p,i} K_{d,i}^b - C_{p,i}^w\right) - \lambda C_{p,i}^w + DIFF(C_{p,i}^w)$$

Settling velocity

where $C_p^w = \sum_{i=1}^{n} C_{p,i}^w$



BCs at the sea surface and sea bottom

$$\nu_T \frac{\partial C_d^w}{\partial z} + W C_d^w = Q_d \qquad \nu_T \frac{\partial C_{p,i}^w}{\partial z} + (W - W_{p,i}) C_{p,i}^w = Q_{p,i} \quad \text{at } z = \eta$$

$$\nu_T \frac{\partial C_d^w}{\partial z} + W C_d^w = \varepsilon W_{pw}(C_d^w - C_d^b) \qquad \nu_T \frac{\partial C_{p,i}^w}{\partial z} + (W - W_{p,i}) C_{p,i}^w = \frac{C_{p,i}^w}{S_{p,i}} D_i - C_{s,i}^b E_i \quad \text{at } z = -H$$

Eqs. for the dissolved (pore water) and particulated radionuclides for a single bed layer

Water column-to-pore water flux Adsorption/desorption-related flux

$$\frac{\partial \varepsilon Z_* C_d^b}{\partial t} = \varepsilon W_{pw}(C_d^w(-H) - C_d^b) + a_{12}\theta Z_* \rho_s (1-\varepsilon)(C_d^b \sum_{i=1}^n K_{d,i}^b \phi_i - C_s^b) - \lambda \varepsilon Z_* C_d^b$$

$$\frac{\partial Z_* C_{s,i}^b}{\partial t} = a_{13}\theta Z_*(K_{d,i}^b C_d^w - C_{s,i}^b) + \frac{D_i C_{s,i}^w}{S_{p.i}(-H)\rho_s(1-\varepsilon)} - \frac{E_i C_{s,i}^b}{\rho_s(1-\varepsilon)\phi_i} - \lambda Z_* C_{s,i}^b \quad (i = 1, \cdots, n)$$

where $C_s^b = \sum_{i=1}^n \phi_i C_{s,i}^b$

With assumption of steady balance in pore water, we can get

$$\frac{\partial Z_* C_{s,i}^b}{\partial t} = a_{13}\theta Z_*(\sum_{i=1}^n K_{d,i}^b C_d^w(-H) - C_{s,i}^b) + a_{rs}\left(C_s^b K_{d,i}^b / \sum_{i=1}^n K_{d,i}^b - C_{s.i}^b\right) + \frac{D_i C_{s,i}^w}{S_{p.i}(-H)\rho_s(1-\varepsilon)} - \frac{E_i C_{s,i}^b}{\rho_s(1-\varepsilon)\phi_i} - \lambda Z_* C_{s,i}^b$$

where $a_{13} \cong \frac{\varepsilon W_{pw}}{Z_* \rho_s (1-\varepsilon)\sum_{i=1}^n K_{d,i}^b \phi_i}$; $a_{rs} = a_{12}\theta$

Desorption rate in the absence of transfer from water column to bottom sediment

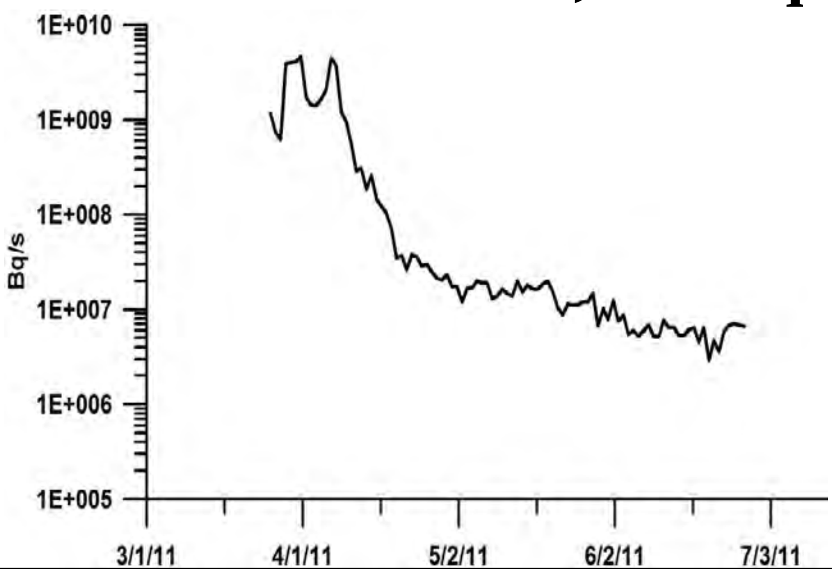
Application to FDNPP accident carried out as a part of IAEA MODARIA WG10 activities

The radionuclide model was embedded to FEM-based SELFE

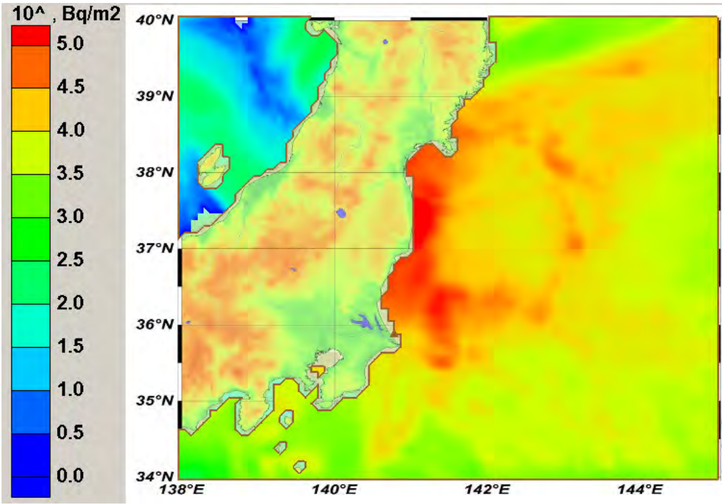
Cs-137 Source conditions

Direct release to the coastal sea | **Atmospheric deposition**

JAEA, 3.5PBq



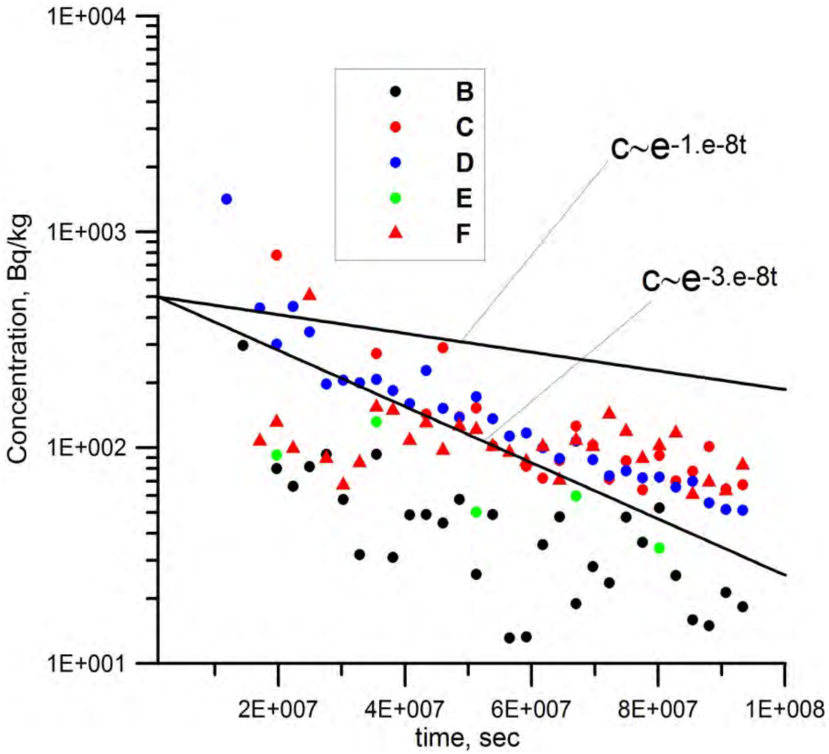
JAEA, KAERI 2.5 PBq



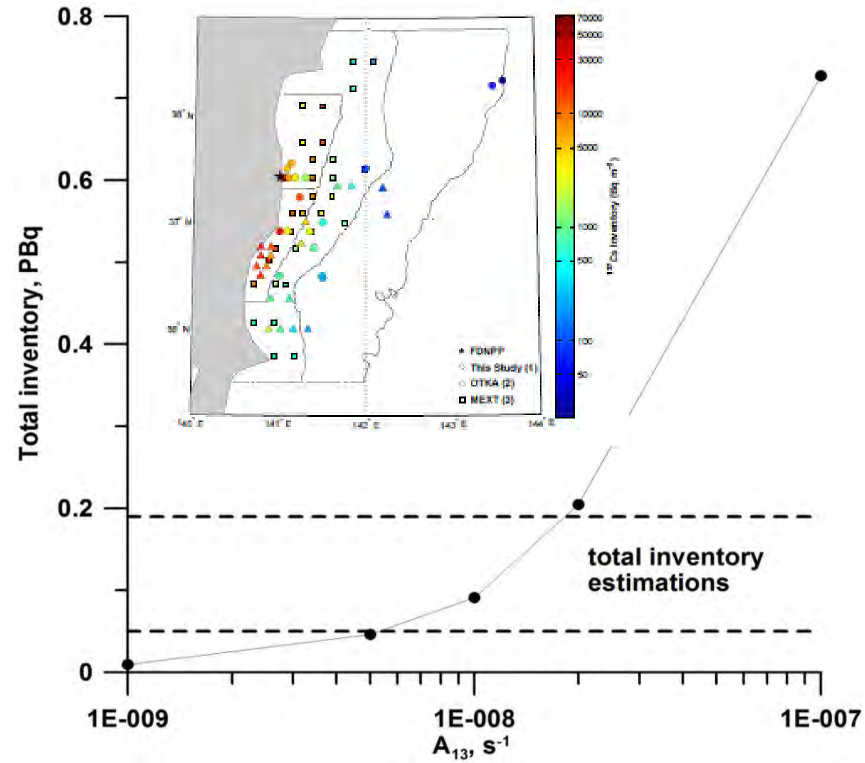
Bed layer thickness: 2 cm; Not taking into account SSC

Determination of a_{13}

Measured decay rates (Sohtome et. al. 2014)



Estimation of total inventory (0.15PBq, Black & Buesseler, 2014)

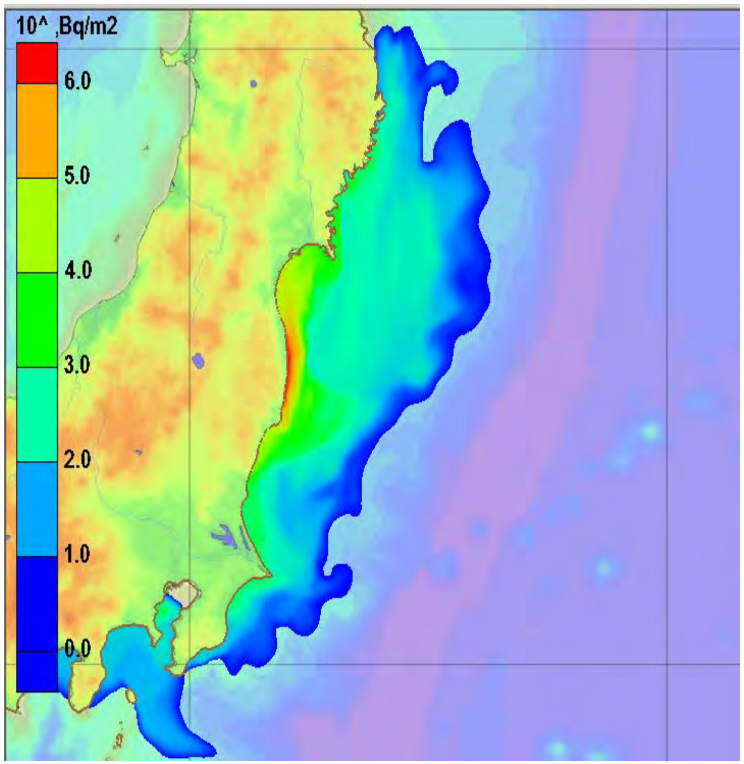


$a_{13} = 2\times10^{-8}$ **matches total inventory and decay estimations**

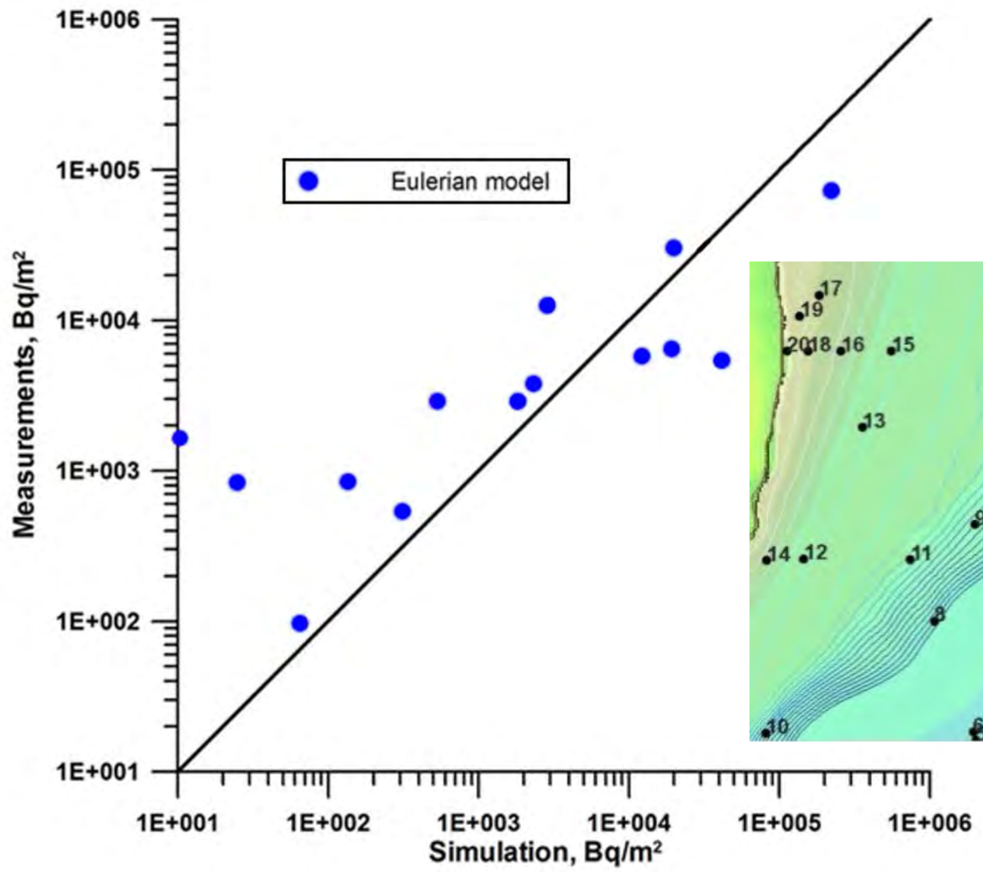
$(W_{pw} = 1.9\times10^{-6})$

Simulated vs. measured (Black & Buesseler, 2014)

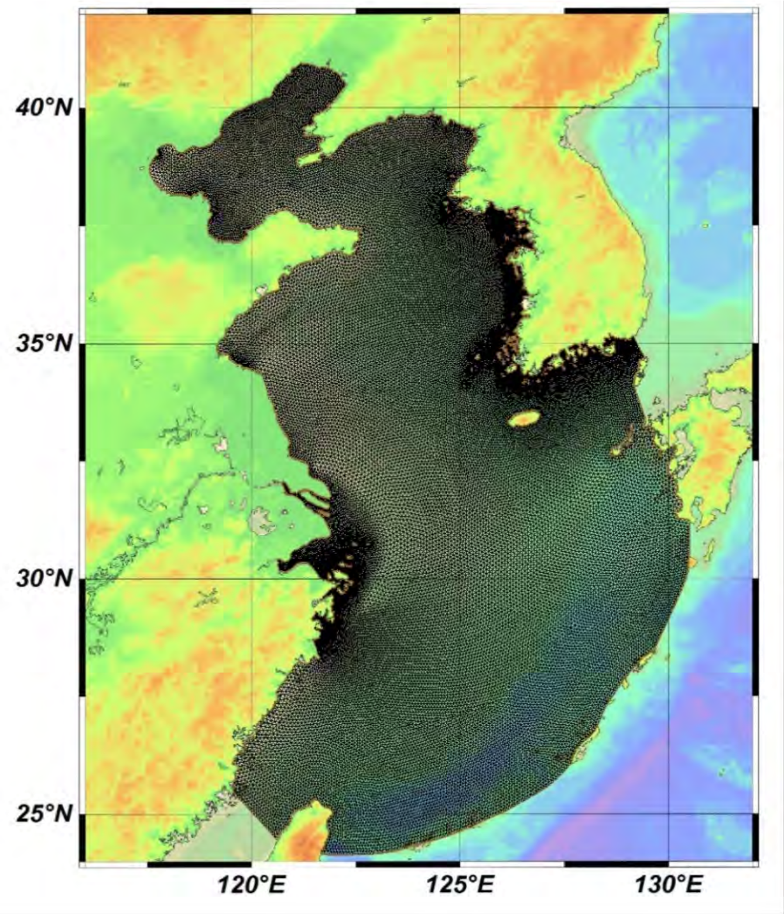
Model results



Comparison with measurements



Application to the YSECS – Model configuration



- OPB : HYCOM (UV,TS,El)
- Tides : NAO99 DB
- Meteo : Era-Interim
- Others : 8 river inputs
- Vertical grids: Mixed s-z coord., 11s-layers in upper 200m, 9z-layers below.
- Horizontal resolution: 400m to 8km
- Calculation period: from 2007 to 2011

SS transport model – deposition & erosion fluxes in non-cohesive & cohesive sediments

For sediment class, *j* , deposition & erosional fluxes are given by:

$$D_j = -W_{p,j} C_j F_D \quad \text{where } F_D = 1 \text{ for non-cohesive}$$

$$F_D = 1 - \tau_b / \tau_{cd} \quad \text{for cohesive}$$

$$E_j = E_{0,j}(d)(1-p)\ f_j \left(\frac{\tau_b}{\tau_{cr,j} F_E} - 1 \right)^n \quad for \quad \tau_b \geq \tau_{bcr,j} F_E$$

$$\text{where } F_E = 1 + f_0 \quad for\ \ non-cohesive$$

$$F_E = 1 \quad for\ \ cohesive$$

f_0 (*Mud content fraction*)

SS transport model – floc size model

Employing the approach given by Winterverp (1998-2012)

$$W_{p,0} = \frac{(\rho_f - \rho_w)g}{\rho_w 18\nu} D_f^2 \frac{1}{1.+0.15\,\mathrm{Re}^{0.687}}$$

("0" index for cohesive sediment class)

$$\frac{dD_f}{dt} = k_A C G D_f^{\,4-F} - k_B G^{3/2} D_f^{\,2}\left(D_f - D_p\right)^{3-F}$$

C is SSC $\quad G = \sqrt{\varepsilon / \nu}$

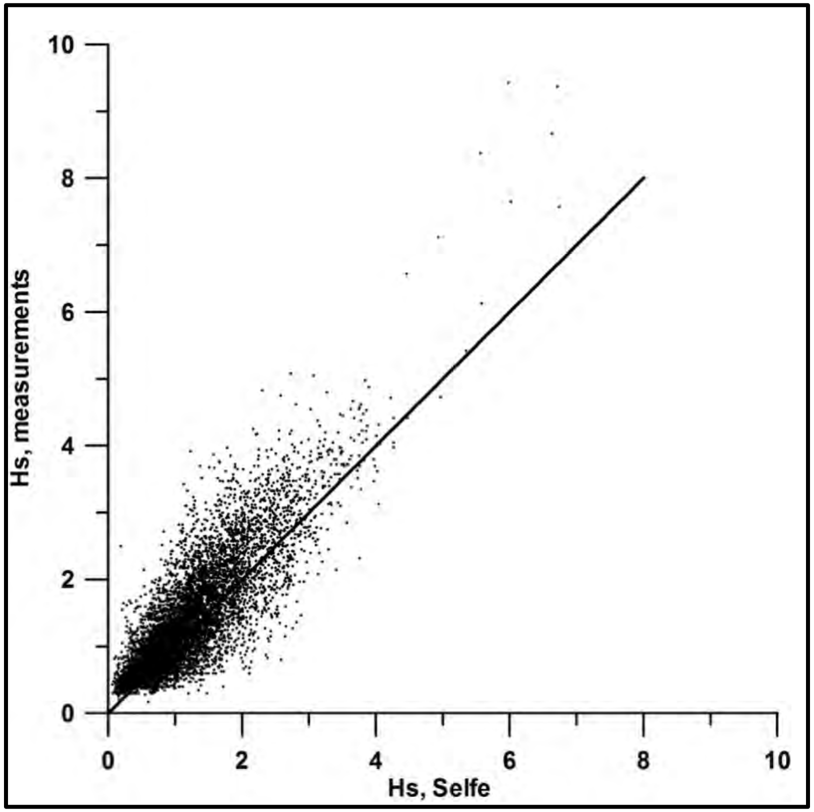
ε is dissipation rate

$$k_A = 14.6$$

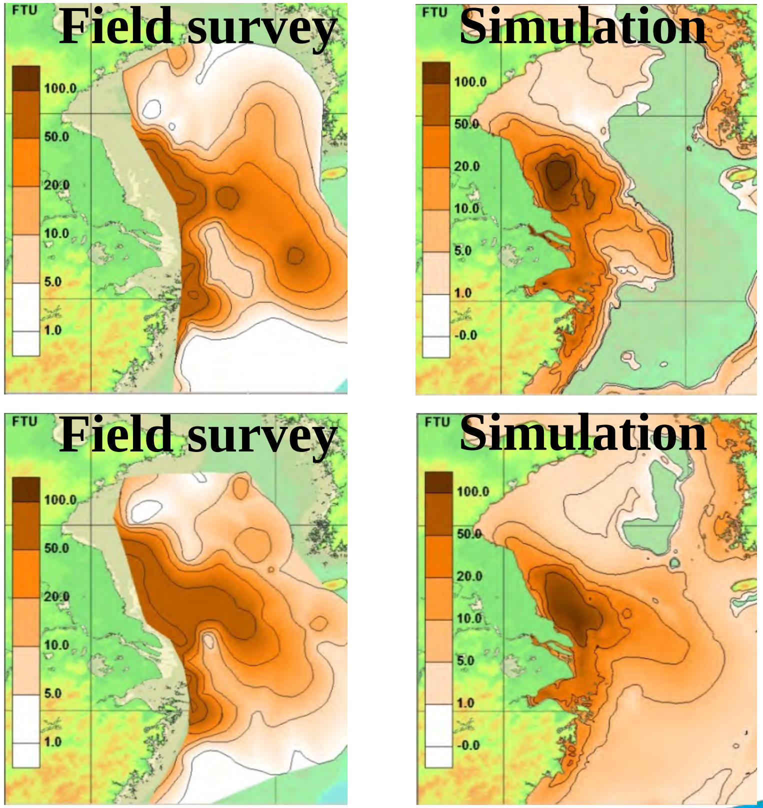
$$k_B = 14000.$$

Wave & SSC(FTU) validations

Observed and computed significant wave heights in ECS



Observed & computed turbidity in ECS converted using Guillen et al (2000) $SSC = 1.74FTU - 1.32$



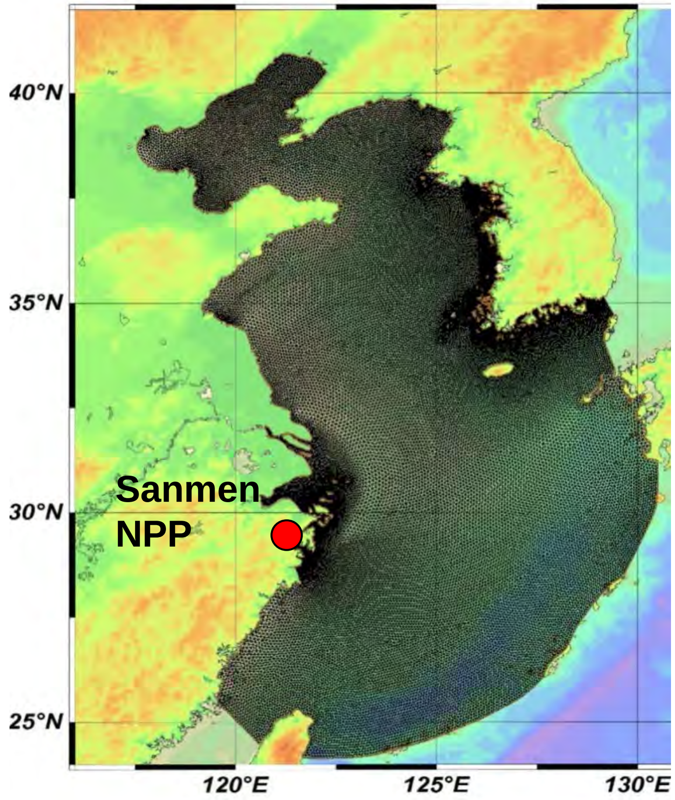
Summer 5 – 25 Jul 2011

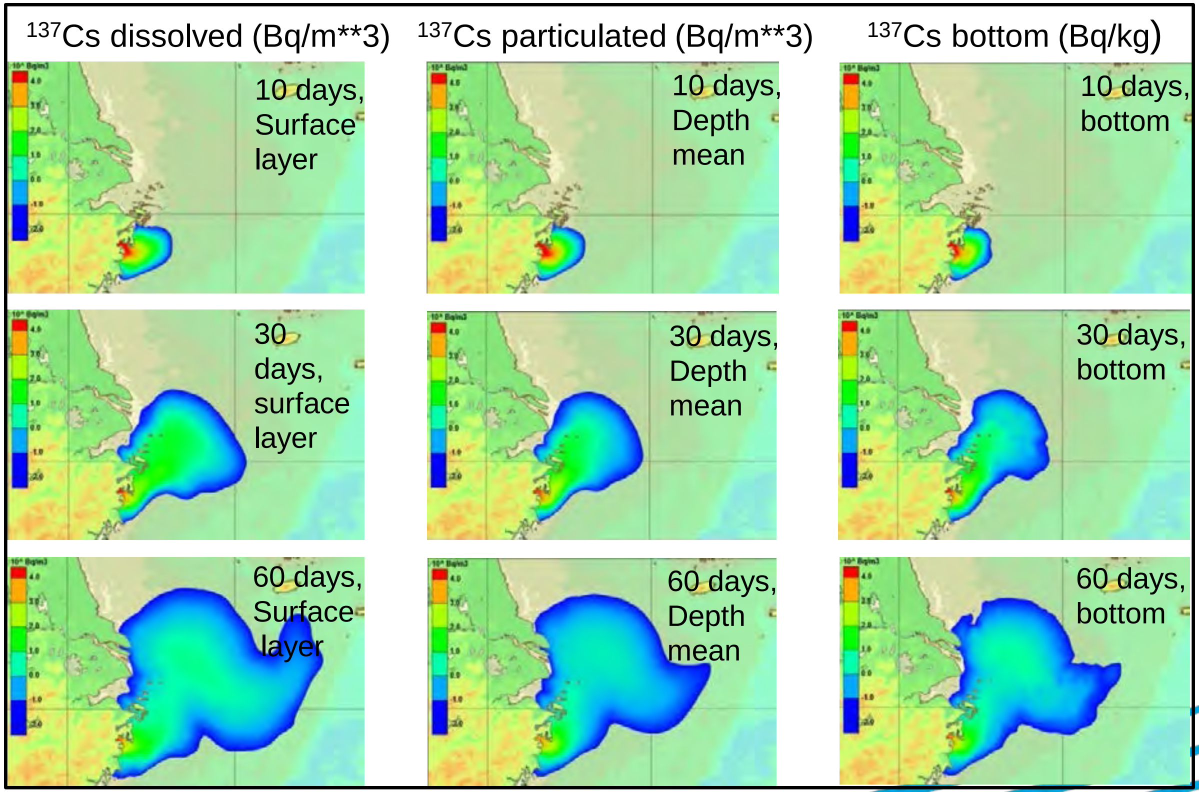
Winter 17-31 Dec 2011

Model application to Sanmen NPP – horizontal distribution maps

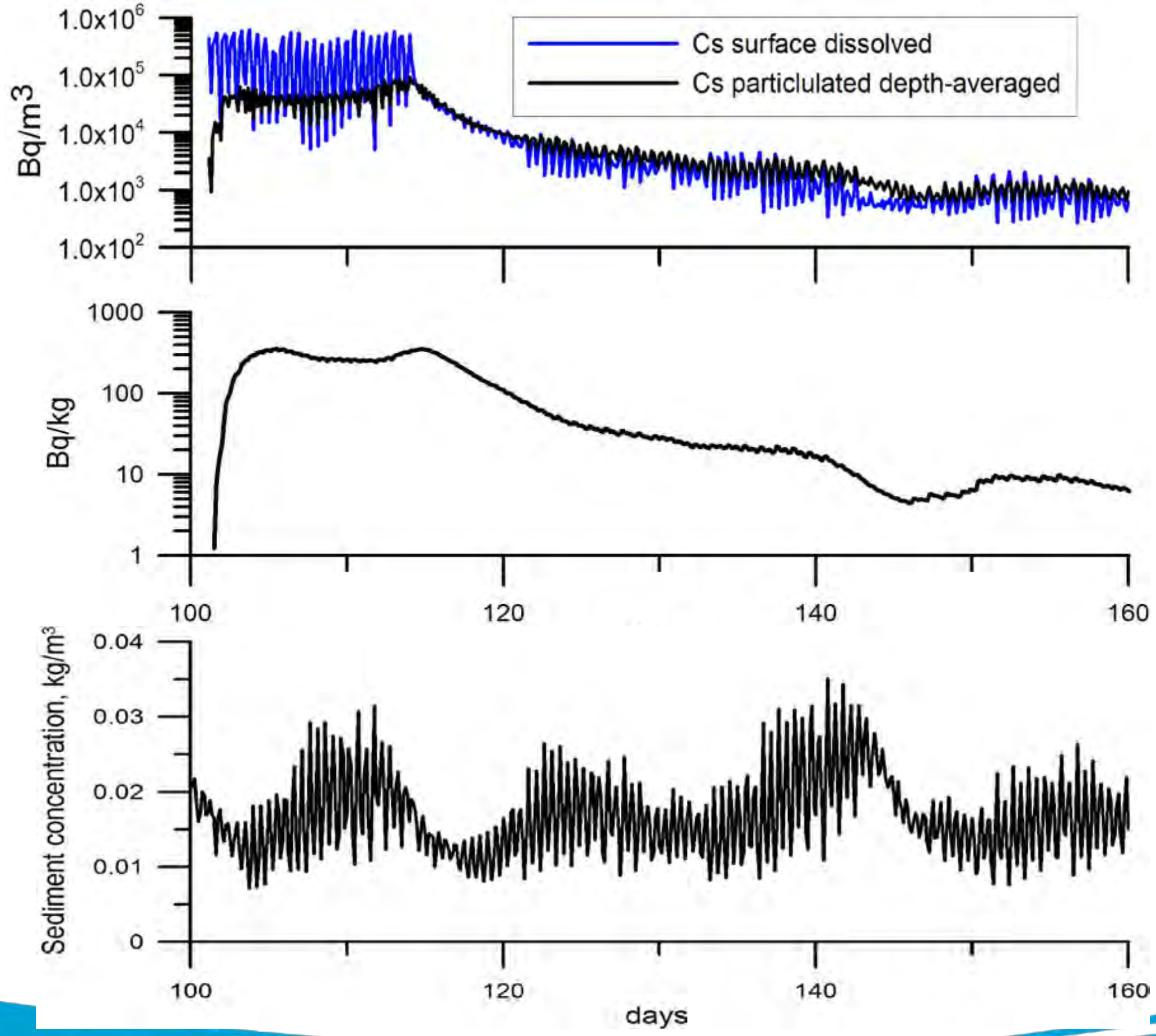
Amount of direct coastal release: 1 PBq

Duration of release: 14 days





Model application to Sanmen NPP – time-varying behavior near the NPP outlet



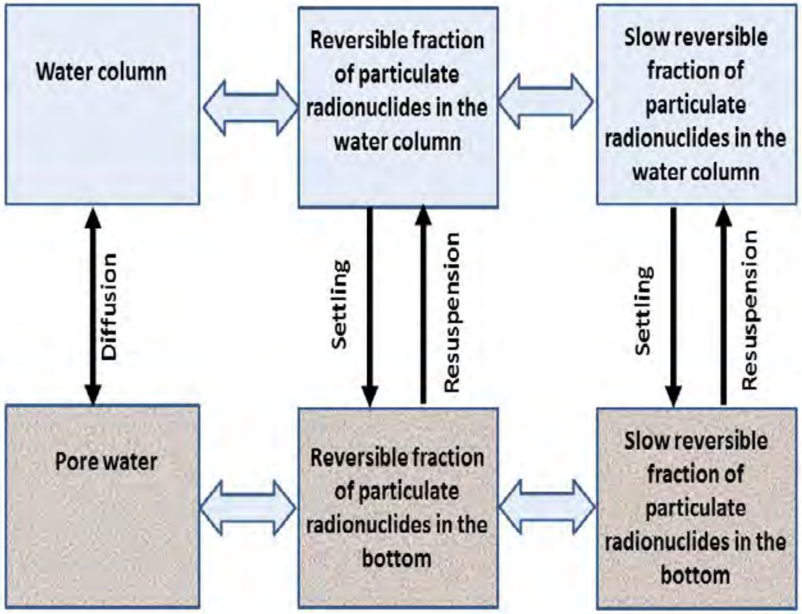
Dissolved and Depth-total particulated of Cs137 near the outlet

Bottom contamination near NPP outlet

Depth-mean SSC concentration near NPP outlet

On-going extension of the model

Two-step kinetics including fast & slow transfer processes



New sets of eqs associated with two-step kinetics & multiple bed layers

$$\frac{\partial \tilde{C}^{w}_{p,i}}{\partial t} + \vec{U}\,\nabla \tilde{C}^{w}_{p,i} = W_{p,i}\,\frac{\partial \tilde{C}^{w}_{p,i}}{\partial z} + a_{fs} C^{w}_{p,i} - a_{sf}\tilde{C}^{w}_{p,i} - \lambda\,\tilde{C}^{w}_{p,i,1} + DIFF(\tilde{C}^{w}_{p,i})$$

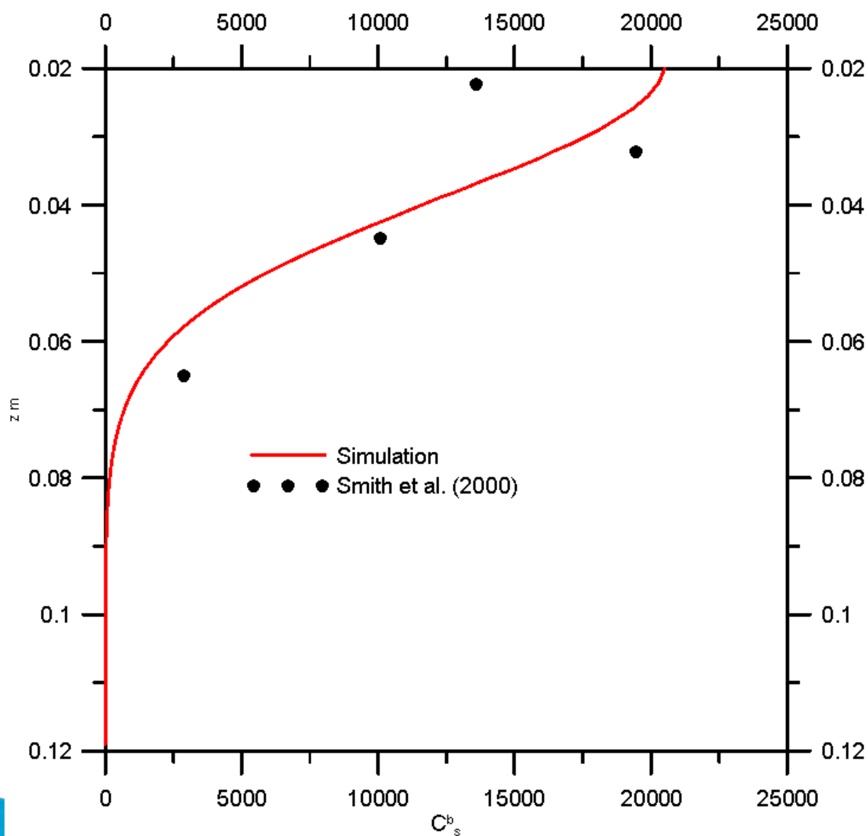
$$\frac{\partial Z_1 \tilde{C}^{b}_{s,i,1}}{\partial t} = -W_{bt}^{(1,2)}(\tilde{C}^{b}_{s,i,1} - \tilde{C}^{b}_{s,i,2}) + a_{fs} Z_1 C^{b}_{s,i,1} - a_{sf} Z_1 \tilde{C}^{b}_{s,i,1} + \frac{D_i\,\tilde{C}^{w}_{s,i}}{\rho_s(1-\varepsilon_1)} - \frac{E_i\,\tilde{C}^{b}_{s,i,1}}{\rho_s(1-\varepsilon_1)} - \lambda\,Z_j\,\tilde{C}^{b}_{s,i,1}$$

$$\frac{\partial Z_j \tilde{C}^{b}_{s,i,j}}{\partial t} = W_{bt}^{(j-1,j)}(\tilde{C}^{b}_{s,i,j-1} - \tilde{C}^{b}_{s,i,j}) - W_{bt}^{(j,j+1)}(\tilde{C}^{b}_{s,i,j} - \tilde{C}^{b}_{s,i,j+1}) + a_{fs} Z_j C^{b}_{s,i,1} - a_{sf} Z_j \tilde{C}^{b}_{s,i,1} - \lambda\,Z_j\,\tilde{C}^{b}_{s,i,1} \qquad i,\cdots,n$$

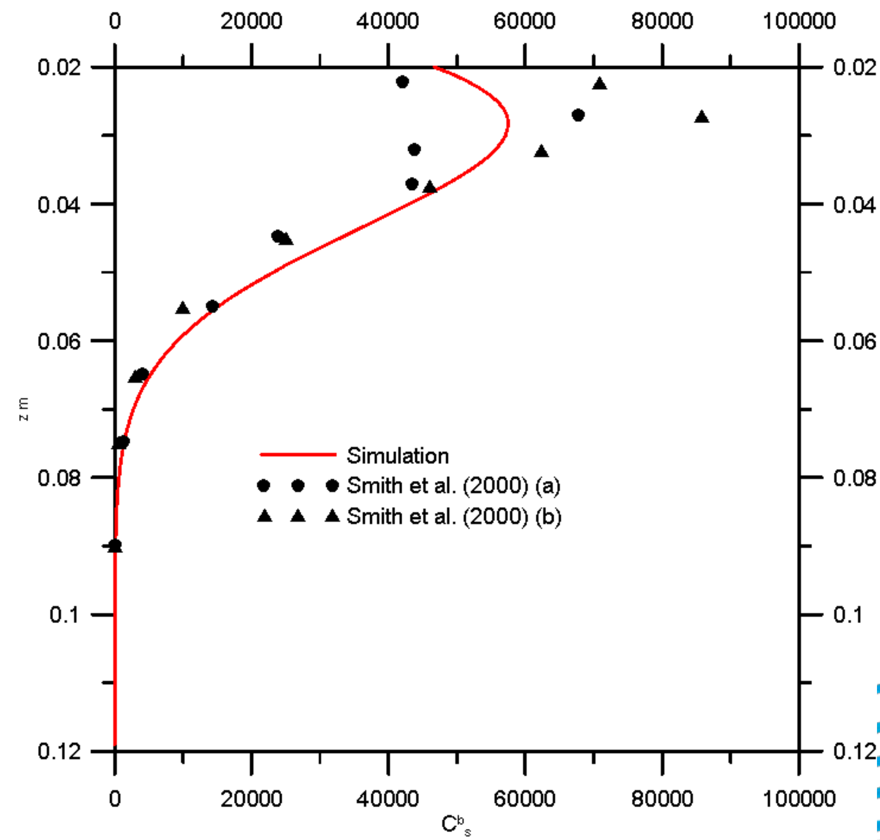
Extension with multiple bed layers & two-step kinetics – comp. with experiment by Smith et al (2000)

1DV calc. with initial conc. for the upper 2cm water (0 for the rest)

Conc. profile of Cs-134 in bed layer pore water (1 yr later)



Conc. profile of total Cs-134 in sediments (1 yr later)



Thanks for your attention!