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Modelling the dispersion of the caesium-137 in the coastal waters of Fukushima using Telemac-3D

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Abstract—The objective of this work is to present the implementation, verification and validation of a three-dimensional model capable to reproduce the propagation of the caesium-137 radionuclide in coastal waters and its interaction with suspended sediments, in the framework of the open-source TELEMAC-MASCARET modelling system. The mathematical model is based on the non-conservative transport of radionuclides, where the interaction with the particulate matter is considered. The resulting numerical model is verified by comparisons between numerical and analytical solutions of selected test cases. Finally, the model is validated with the Fukushima Dai-ichi case by comparing numerical results with field measurements of radionuclides concentration in the Japan Sea.

I. INTRODUCTION

On March 11, 2011, a devastating earthquake of magnitude 9.0 and a tsunami struck the Tohoku area, Japan, causing major damage to the cooling systems of reactors in the Fukushima Dai-ichi Nuclear Power Plant (NPP), operated by Tokyo Electric Power Company (TEPCO). In order to cool the reactor cores and the spent fuel in storage pools, large amounts of seawater and freshwater were used. A significant part of this radioactivity-contaminated water was discharged into the Pacific Ocean close to the power plant. In addition, between March 12 and 15 2011, several hydrogen explosions resulted in the release of significant radioactivity into the atmosphere, some of which was deposited onto the sea surface over a wide area of the Pacific Ocean. Consequently, high concentrations of iodine (^{131}I), strontium (^{90}Sr) and caesium-137 (^{137}Cs) were found in seawater and seabed sediments along the coastline of Fukushima Prefecture [25]. Moreover, radionuclides were detected in marine debris caught near Fukushima Prefecture [7]. The human and non-human populations of the nearby regions were exposed temporarily or permanently to the substances, either by external irradiation or by ingesting plants growing in the local area.

A significant number of modelling studies on the dispersion of radionuclides released from Fukushima into the Pacific Ocean have been recently published in the scientific literature. Recently, in the framework of the MODARIA project, supported by the International Atomic Energy Agency (IAEA), different models were applied to the accidental releases and discharges from Fukushima Dai-ichi NPP accident. A brief description of these models is given below. The reader is referred Periáñez et al. [19] for a detailed description of these models.

The model developed by IMMSP/KIOST (Institute of

Mathematical Machine and System Problems, Ukraine, with the Korea Institute of Ocean Science and Technology, Republic of Korea) for radionuclide transport proposes two approaches: Eulerian and Lagrangian, and water circulation and sediment transport are obtained from the hydrodynamic SELFE model [22], [29]. The oceanic dispersion model named LORAS (Lagrangian Oceanic Radiological Assessment System) has been developed by Korea Atomic Energy Research Institute (KAERI) to evaluate the transport characteristics of the radionuclides released into the sea for a nuclear accident [13]. A particle random-walk model (SEA-GEARN) has been used by the Japan Atomic Energy Agency (JAEA) to simulate radionuclide transport in the Pacific Ocean. This model is based on the three-dimensional advection/diffusion dispersion equations. The SisBAHIA model [1] was developed by the Instituto de Engenharia Nuclear in Brazil and solves the transport of contaminants with the Eulerian and Lagrangian approaches. Finally, the USEV model, developed by the University of Sevilla (Spain), is based on the three-dimensional advection/diffusion dispersion equations. For these models, water circulation has been obtained from JCOPE2 hydrodynamic model [17], [18].

The numerical experiments of the MODARIA project were carried-out for a perfectly conservative radionuclide (Exercises 1 and 2) and for ^{137}Cs , including water/sediment interactions (Exercises 2, 3 4a and 4b), using different hydrodynamic forcings and numerical and physical parameters (Exercises 1 and 4b). The model outputs were also compared with TEPCO measurements of radioactivity in water and sediments [25]. As a conclusion, it was found that the main reason of discrepancies between the model results was due to the differences between the numerical schemes and parameterizations used among these models.

The common point of all these models is the size of the computational domain (35°N–38.5°N, 140.5°E–144°E, covering approximately 670 km long and 620 km wide) and the need of employing a realistic reproduction of oceanic conditions such as ocean current, temperature, salinity, and sea surface height (SSH) for performing accurate numerical simulations on the oceanic dispersion of radionuclides. In general, these models use the hydrodynamics obtained with general circulation models based on data assimilation techniques (NCOM, JCOPE2) or variational method, as for the JAEA model which uses the three-dimensional variational (3D-VAR) data assimilation system [28], Meteorological Research Institute (MRI) Multivariate Ocean Variational Estimation (MOVE)

with the eddy-resolving ocean general circulation model, MRI Community Ocean Model (www.mri.com; [27]) at the Japan Meteorological Agency (JMA), which makes it possible to adjust the numerical results with field observations.

It can be considered that these models should be useful and powerful tools in post-emergency situations, when the estimation of future contamination of water, sediments and biota rely on data from analogous periods of previous years [21], or for the assessment of the long-term consequences of the accident, including transfers of radionuclides to sediments and biota, as well as evaluating the potential role of sediments as a source of contamination once radionuclide concentrations in seawater have decreased [15]. However, a model should be capable of providing quick-responses to emergency situations [21]. Rapid responses can be achieved using meteorological data or tide conditions from operational numerical models in order to accurately predict the radioactivity transport. In this case, the accuracy of the model could be improved by a refined spatial discretization and the model extension could be limited to the coastal area in the vicinity of the NPP.

In this context, the objective of this study is to develop a three-dimensional (3D) numerical tool able to reproduce the dispersion of radionuclides in coastal waters in an emergency situation such as the Fukushima Dai-ichi NPP accident. With this aim, the developed model has been forced only with data available immediately after (or during) the accident, as the weather conditions (wind, pressure, temperature) and/or the harmonic components of tides, and the model domain was limited to the coastal area near Fukushima and refined in the coastal area nearby the NPP.

The model was developed within the open source TELEMAC-MASCARET system, which is an integrated modelling tool for use in the field of free-surface flows. The various simulation modules use efficient algorithms based on the finite-element or finite volume methods. Space discretization is performed with unstructured triangular elements, which means that it can be locally refined in particular areas of interest. The mathematical model for radionuclides transport was built based on previous studies on non-conservative radionuclides [11], [16], where the interactions with the particulate matter has been considered. To account for these processes, a module that solves three-phase interaction has been implemented and described in the next section. This newly developed module was coupled with the 3D Reynolds-Averaged Navier-Stokes hydrodynamics module TELEMAC-3D of the TELEMAC-MASCARET system. Details on the 3D hydrodynamics model can be consulted in [5] and are not presented hereafter.

II. RADIONUCLIDES TRANSPORT MODEL

A. Conceptual Model

The radionuclides transport model is based on previous studies on non-conservative radionuclides propagation in sea waters, e.g. [11], [14], [16]. In particular, the model implemented in this work is a three phase's model with the following characteristics: (i) dissolved phase consists of radionuclides that are dissolved and adsorbed onto fine particles without settling velocity (diameter < 0.8 mm is preferred, according to Kobayashi et al. [9]), (ii) the large particle matter (LPM) phase consists of radionuclides that are adsorbed with the

LPM which has settling velocity, (iii) active bottom sediment phase consists of radionuclides that are adsorbed with the LPM which deposit on the seabed, and the particle re-suspends according to the bottom velocity. For sediments, it is assumed that the LPM is an aggregate which has a single radius and density and the movement of each particle is characterized by velocity, diffusivity and settling velocity of the particle itself. For these conditions, a conceptual scheme describing the interaction between phases and the ionic exchanges is showed in Figure 1, where radionuclides uptake/release processes between water and sediments are formulated in terms of kinetic transfer coefficients k_1 and k_2 . A detailed description of this formulation can be found in [16], [17].

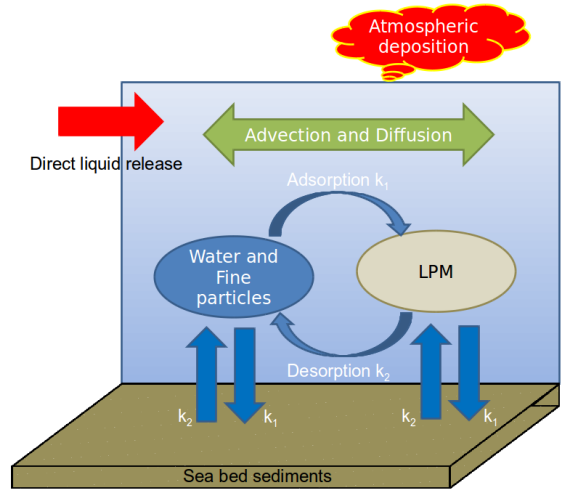


Fig. 1: Conceptual sketch describing the interaction between the three phases model and the ionic exchanges. The kinetic model considers that exchanges of radionuclides between water and sediments are governed by a first-order reversible reaction, being k_1 and k_2 the forward and backward rates, respectively.

B. Governing Equations

The radionuclide transport model describes the water-sediment sorption processes. It includes the advection-diffusion equations for dissolved C_s^w and adsorbed by suspended sediment C_p^w radioactivity in the water column, and the equations for concentration of the dissolved C_s^b and adsorbed C_p^b radioactivity in the bottom deposits, expressed in [Bq/l], [Bq/m³] or [kg/m³]. The transport of radionuclides dissolved (or adsorbed by sediments) in water can be written as a classic advection-diffusion equation, by considering as an additional source term the exchange between the solid and the dissolved phases:

$$\begin{aligned} \frac{\partial C_s^w}{\partial t} + \frac{\partial UC_s^w}{\partial x} + \frac{\partial VC_s^w}{\partial y} + \frac{\partial WC_s^w}{\partial z} = \\ \frac{\partial}{\partial x} \left(\nu_h \frac{\partial C_s^w}{\partial x} \right) + \frac{\partial}{\partial y} \left(\nu_h \frac{\partial C_s^w}{\partial y} \right) + \frac{\partial}{\partial z} \left(\nu_v \frac{\partial C_s^w}{\partial z} \right) - \\ \lambda C_s^w - a_{1,2}^w (C_d^w K_d^w C_s^w - C_p^w) + P_s^w \end{aligned} \quad (1)$$

$$\begin{aligned} \frac{\partial C_p^w}{\partial t} + \frac{\partial UC_p^w}{\partial x} + \frac{\partial VC_p^w}{\partial y} + \frac{\partial(W - w_s)C_p^w}{\partial z} = \\ \frac{\partial}{\partial x} \left(\nu_h \frac{\partial C_p^w}{\partial x} \right) + \frac{\partial}{\partial y} \left(\nu_h \frac{\partial C_p^w}{\partial y} \right) + \frac{\partial}{\partial z} \left(\nu_v \frac{\partial C_p^w}{\partial z} \right) - \\ \lambda C_p^w - a_{1,2}^w (S_d^w K_d^w C_s^w - C_p^w) + P_p^w \end{aligned} \quad (2)$$

where U, V, W [m/s] are the velocity field components along the x, y, z -directions, respectively, ν_h and ν_v [m²/s] are respectively the horizontal and vertical diffusion coefficient for radionuclides, λ [s⁻¹] is the radionuclide decay constant, P_s^w and P_p^w are the input of the dissolved radionuclides from the source point and the input of the radionuclides which adsorbed to the LPM from the source point [kg/m²s], respectively, S_d^w [kg/m³] or [g/l] is the sediment concentration and w_s [m/s] is the sediment settling velocity. Above, the distribution coefficients K_d^w and K_d^b [m³/kg] are defined under steady hydraulic conditions as:

$$S_d^w K_d^w = \lim_{t \rightarrow \infty} \left(\frac{C_p^w}{C_s^w} \right), \quad \frac{S_d^b}{\epsilon} K_d^b = \lim_{t \rightarrow \infty} \left(\frac{C_p^b}{C_s^b} \right) \quad (3)$$

with ϵ [-] the bed porosity.

In Equations (1–2), the radionuclides are treated as passive tracer, and the exchanges between the different phases are described by diffusion, sorption, and sedimentation-resuspension processes. The adsorption and desorption of radionuclides between liquid and solid phases are described by the radionuclide exchange rates $a_{1,2}^w$ [day⁻¹] and $a_{1,2}^b$ [year⁻¹], usually considered as constants for practical applications [11]. The variation of the dissolved ($m_s^b = C_s^b Z_b$) and adsorbed ($m_p^b = C_p^b Z_b$) mass of radioactivity in the bottom deposits can be written as follows:

$$\frac{\partial m_s^b}{\partial t} = \frac{F_{dif}}{Z_b} \left(C_s^w - \frac{C_s^b}{\epsilon} \right) - \lambda m_s^b - a_{1,2}^b \left(\frac{S_d^b}{\epsilon} K_d^b C_s^b - C_p^b \right) Z_b \quad (4)$$

$$\frac{\partial m_p^b}{\partial t} = \left(\frac{C_p^w D}{S_d^w} - \frac{C_s^b E}{S_d^b} \right) - \lambda m_p^b - a_{1,2}^b \left(\frac{S_d^b}{\epsilon} K_d^b C_s^b - C_p^b \right) Z_b \quad (5)$$

Above, F_{dif} [m²/s] is the diffusion coefficient describing the exchange between the bed and the water at the bottom and Z_b [m] is the thickness of the bottom layer.

C. Boundary conditions

The boundary condition for C_s^w and S_d^w at the free surface Z_s is a no-flux condition, expressed as:

$$\left(\nu_v \frac{\partial S_d^w}{\partial z} + w_s S_d^w \right)_{z=Z_s} = 0, \quad \left(\nu_v \frac{\partial C_s^w}{\partial z} + w_s C_s^w \right)_{z=Z_s} = 0 \quad (6)$$

where Z_s is the z -coordinate of the free surface. The boundary condition for C_s^w, C_p^w and S_d^w at the bed describes the exchange of radionuclides and of sediments with the bed. The fluxes into the bottom are induced by the diffusion of radioactivity (desorption) between the bed sediments and water, and the flux of radioactivity associated to the depositional and

erosional rates, as follows:

$$\begin{aligned} \nu_v \frac{\partial C_s^w}{\partial z} &= \frac{F_{dif}}{Z_b} \left(C_s^w - \frac{C_s^b}{\epsilon} \right), \\ \nu_v \frac{\partial C_p^w}{\partial z} + (W - w_s) C_p^w &= \frac{C_p^w}{S_d^w} D - \frac{C_p^b}{S_d^b} E, \\ \left(\nu_v \frac{\partial S_d^w}{\partial z} + w_s S_d^w \right)_{z=Z_s} &= D - E. \end{aligned} \quad (7)$$

For cohesive sediments, the deposition rate equation is described by the empirical Krone law [4]:

$$D = \begin{cases} w_s S_d^w (1 - \tau/\tau_{cd}) & \text{if } \tau < \tau_{cd} \\ 0 & \text{otherwise} \end{cases}$$

where τ_{cd} [N/m²] is the deposition critical bed shear stress, w_s [m/s] the mud settling velocity near the bed and τ [N/m²] is the bed shear stress. The erosion rate follows the empirical Partheniades law [4]:

$$E = \begin{cases} M(\tau/\tau_{ce} - 1) & \text{if } \tau > \tau_{ce} \\ 0 & \text{otherwise} \end{cases}$$

where τ_{ce} [N/m²] is the erosion critical shear stress of the mud layer and M the Partheniades coefficient (kg/sm²). For a single layer bed with a concentration S_d^b [kg/m³], the mass conservation equation for the bed evolution is given by:

$$S_d^b \frac{\partial Z_b}{\partial t} = D - E. \quad (8)$$

III. MODEL VERIFICATION

In this section, the capability of the model at reproducing the advection and dispersion of radionuclides and its interactions is assessed by comparisons between numerical and analytical solutions.

A. Kinematic exchange of radioactivity between water and suspended sediment in a basin

The objective of this test case is to assess the ability of the model to reproduce the kinematic exchange of radioactivity between suspended sediments and water. A square basin $\Omega = [5 \times 5]$ [m²] with constant water depth $h = 2$ [m] is considered, zero flow velocity $\vec{U} = (U, V, W) = (0, 0, 0)$ [ms⁻¹] and solid boundaries. The initial distribution of the dissolved $C_{s,0}^w = C_s^w(t = 0)$ and adsorbed by sediments $C_{p,0}^w = C_p^w(t = 0)$ radioactivity is uniform and equal to 10.0 [Bq/l] and the value of the diffusion coefficient of the tracers $K = 10$ [m²s⁻¹]. The decay constant $\lambda = 0.00001$ [s⁻¹] and the radionuclide exchange rate $a_{1,2} = 0.000001$ [day⁻¹]. For these conditions, Equations (1–2) simplify into:

$$\frac{\partial C_s^w}{\partial t} + \lambda C_s^w = a_{1,2}^w C_p^w, \quad \frac{\partial C_p^w}{\partial t} + \lambda C_p^w = -a_{1,2}^w C_p^w \quad (9)$$

Analytical solutions of Equations (9) are:

$$C_s^w(t) = (C_{s,0}^w + C_{p,0}^w) \exp^{-\lambda t} + C_p^w(t), \quad (10)$$

$$C_p^w(t) = C_{p,0}^w \exp^{-(\lambda + a_{1,2}^w)t} \quad (11)$$

For this test case we use an unstructured mesh and a time step of 10 [s]. Figure 2 shows the good agreement between the numerical and the analytical results for both the dissolved and adsorbed radioactivity.

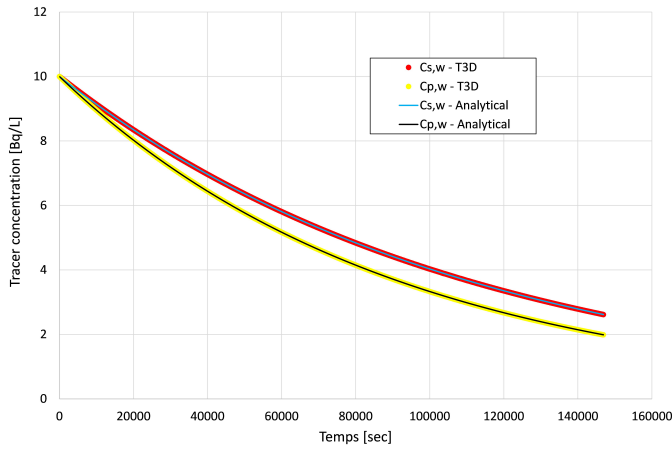


Fig. 2: Comparison between the numerical results and the analytical solution for the kinematic exchange of radioactivity between water and suspended sediment in a basin, see section III-A.

B. Tracer decay in a permanent flow field

The purpose of this test case is to assess the ability of the numerical model to reproduce the physical behavior of radionuclides dissolved in water, when transported by an uniform flow field in a rectangular domain $\Omega = [1 \times 500]$ [m²] with initial constant water depth $h = 1.0$ [m] and flow velocity $\vec{U} = (U, V, W) = (0, 0, 0)$ [ms⁻¹]. At boundaries $x = 0$ and $x = 500$ m, a constant water discharge $Q(0, t) = 1.0$ [m³s⁻¹] and water depth $h(500, t) = 1.0$ [m] were imposed, respectively. No friction is considered at the bottom of the channel. At $t = 0$ [s], an initial triangular distribution of the dissolved radioactivity is considered between $x = 95$ [m] and $x = 105$ [m], with a peak value equal to 1.0 Bq/l at $x = 100$ [m]. At the inflow and outflow boundaries, a constant zero radioactivity and a Neumann-like boundary condition are imposed, respectively. An unstructured mesh with typical element size equal to 0.5 [m] and time step of 0.5 [s] was used. The decay constant $\lambda = 0.0007$ [s⁻¹]. For a uniform and unidirectional flow field, the analytical solution of the tracer transport equation is reported in detail in [12]. In Figure 3, numerical results show that the temporal variation of the tracer concentration at the middle of the channel (orange line) is accentuated by the radioactivity decay, in comparison with a reference situation without decay (blue line). This result confirms that the simulated behavior of the dissolved radioactivity is physically based and in agreement with the analytical solution.

IV. APPLICATION TO THE FUKUSHIMA DAI-ICHI ACCIDENT

A. Model construction

This study covers the oceanic coastal area nearby the Fukushima Dai-ichi NPP: 36.5°N–38.5°N, 140.6°E–143.4°E (covering an extension of c. 300 km to 300 km), see Figure 4). The computational domain was discretized with 62,451 triangular elements, followed by extruding each triangle along the vertical direction into linear prismatic columns spanning the water column from the bottom to the free-surface. Each column is composed of a fixed number

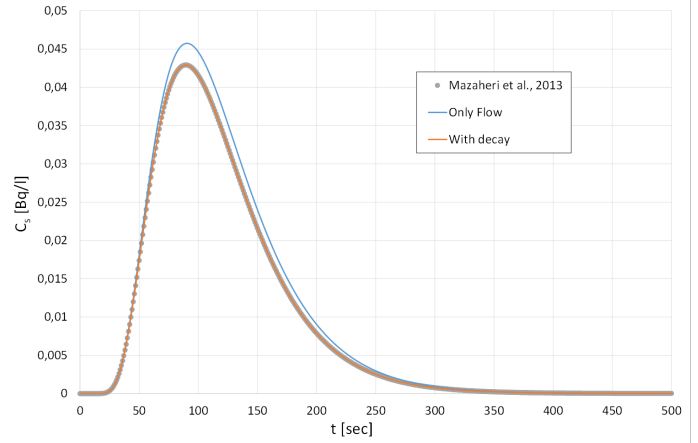


Fig. 3: Time evolution of the tracer decay in a permanent flow field test, see section III-B.

of prismatic elements, that number being chosen during the simulation set-up. The horizontal mesh size varied from 200 [m], near to the Fukushima Dai-ichi NPP to 10 [km] off-shore, depending on the resolution of the bathymetrical data (derived from the Japan Oceanographic Data Center) and the water depth. The vertical resolution of the layered mesh is 5 layers, resulting in elements with a height of the order of 50 [m] in the coastal area of the NPP and the computational time step was equal to 10 [s]. The simulations were performed for a total time of 90 days (from the March 1st 2011 to May 30th 2011). The model was initialised and forced at the oceanic boundary with tides (surface elevation and the currents). The tides are provided as complex amplitudes of earth-relative sea-surface elevation for eight primary ($M2, S2, N2, K2, K1, O1, P1, Q1$), two long period (Mf, Mm) and three non-linear harmonic constituents ($M4, MS4, MN4$), computed with the methodology reported in [2], [3]. The tidal constituents were extracted from the Oregon State University Tidal Prediction Software (OTPS/TPXO). These data are available on line (<http://volkov.oce.orst.edu/tides/OhS.html>). Current velocity and water surface elevation values were used to initialise the model the March 1st 2011. At initial time, the dissolved radionuclides concentration was set to zero. On the free surface, the model was also forced by wind and atmospheric parameters computed from the European Centre for Medium-Range Weather Forecasts (ECMWF) model.

B. Source terms

The amount of ^{137}Cs released directly into the ocean was given by [19]. According to Kobayashi et al. [10], this quantities correspond to the data of ^{137}Cs released directly into the ocean from the Fukushima Dai-ichi NPP. Four releases points were defined in the mesh along the coast between the northern discharge channel and the southern discharge channel of the Fukushima Dai-ichi NPP and it was assumed that the direct release into the ocean started on March 26th, see Figure 5. Discharges were assumed to continue until June 30. The blue line in Figure 5 shows the temporal variation of the released amount of ^{137}Cs used in the numerical simulations. These data were estimated based on the concentrations of radionuclides at the northern and southern discharge channels

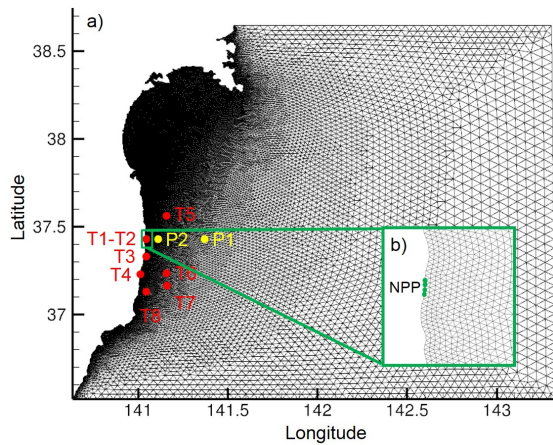


Fig. 4: a) Computational grid and sampling points where calculated $^{137}\text{C}_s$ concentrations in surface water have been compared with measurements. Points P1 and P2 are issued from the MODARIA project Exercise 1; b) grid points employed for reproducing the NPP (in green).

of the Fukushima Dai-ichi NPP, which were monitored almost twice a day. This source term estimation led to a total $^{137}\text{C}_s$ release of 3.5 PBq from March 26th to June 30.

In [19], the authors used the ensemble average values of wet deposition of $^{137}\text{C}_s$ on the free surface issued from two atmospheric dispersion models. These models were developed by KAERI [23], [24] and JAEA [26]. Both are particle tracking dispersion models and permit to model the dispersion of radionuclides released to the atmosphere and evaluate the subsequent deposition on the sea surface. In this work, this dataset was projected onto the computational domain. An example of wet deposition in the proximity of the NPP is reported in 5.

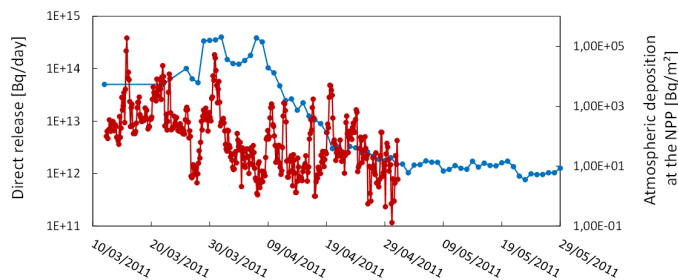


Fig. 5: Source term of caesium $^{137}\text{C}_s$ used in the numerical simulations, see section IV-B.

C. Numerical results

In this section, numerical simulations were performed from March 1st to June 1st 2011. Time series of calculated $^{137}\text{C}_s$ concentrations obtained with TELEMAC-3D were first compared to the measured concentrations obtained by TEPCO (T1 to T8, red points in Figure 4). These measurements were reported in regular press releases [25]. As showed in Figure 6, TELEMAC-3D reproduces well the concentration values at the measurements points. Particularly, nearby the NPP (points T1 to T4), good agreement between numerical results and observations is found from March 28th, two days after the

beginning of the direct release into the ocean. As observed in Figure 6, numerical results match well the measurements captured in the offshore zone, both in the south zone (points T6 to T8) and in the north zone (point T5) of the Fukushima Dai-ichi NPP. For these points, there is no evidence that the numerical results are improved starting from March 26. Conversely, the model is able to correctly reproduce the order of magnitude of the measured concentration of $^{137}\text{C}_s$ during the simulation period. The model is therefore able to reproduce the propagation and diffusion of the released $^{137}\text{C}_s$ in the vicinity of the NPP.

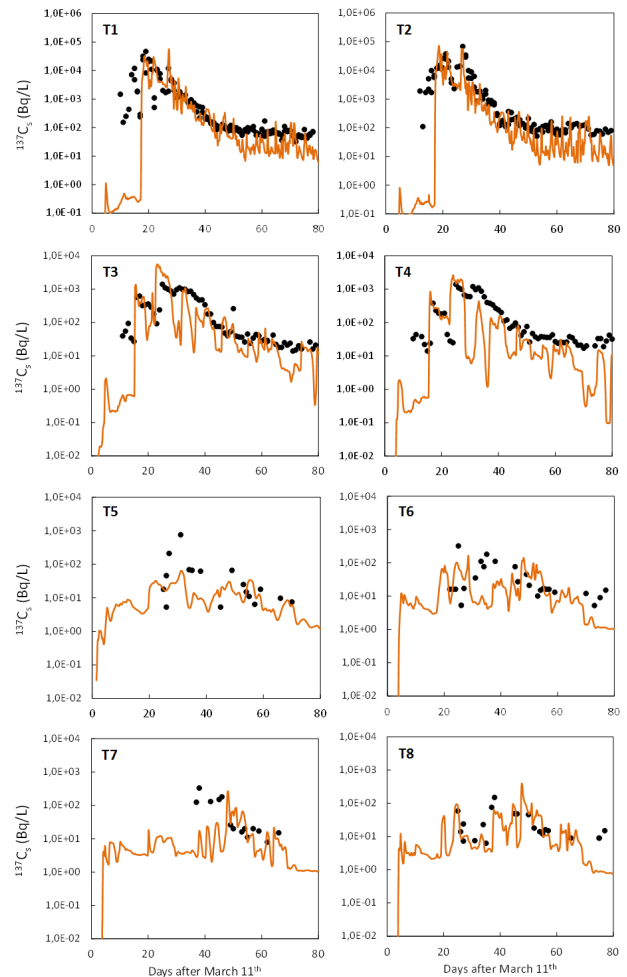


Fig. 6: Comparison between computed and measured $^{137}\text{C}_s$ concentration on the water surface, collected by TEPCO [25].

Maps of calculated $^{137}\text{C}_s$ distributions in surface water are presented in Figure 7. Corresponding maps obtained from interpolation of measurements are shown in Inomata et al. [6]. The calculated distributions, corresponding to the concentrations of the dissolved fraction of $^{137}\text{C}_s$ reflect the water circulation performed by the model. We observe that our model tend to produce an elongated patch in the North-South direction (Figures 7a-c) and, later, leading to offshore transport of radionuclides (Figures 7d-f). An accumulation of radionuclides is also observed along-shore and especially in the coastal zone of the numerical model, indicating that the main current direction is from South to North and, in a second time,

toward the North/East direction.

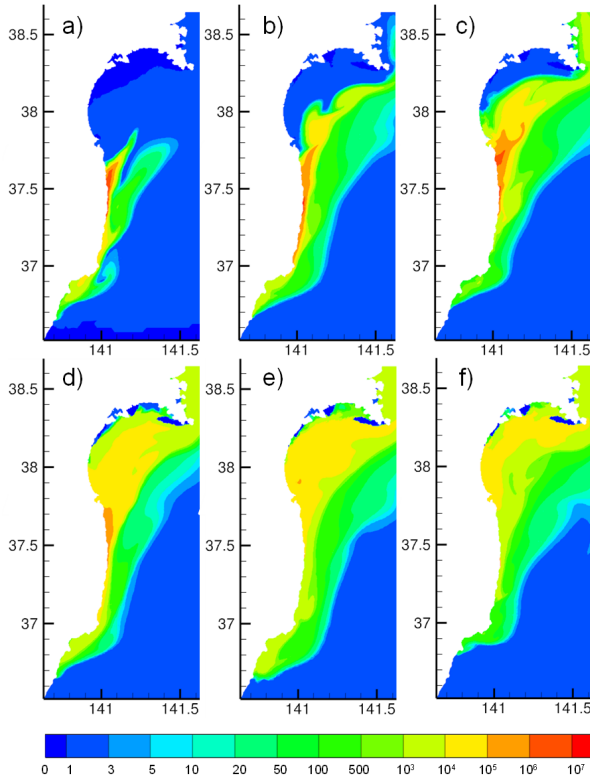


Fig. 7: Numerical results of the ^{137}Cs distribution on the water surface: a) April 1, b) April 6, c) April 11, d) April 21, e) May 1 and f) May 11, 2011.

Numerical results at coastal scale obtained with TELEMAC-3D are slightly different from the general path of an isotropic dispersion of radionuclides around the Fukushima Dai-ichi NPP reported by Inomata et al. [6]. Many reasons can explain these discrepancies. Firstly, the measured path has to be attributed to the small number of measurements and different sampling times used to produce these maps by an optimal interpolation method. Secondly, large scale models have showed the presence of a large anticyclonic eddy south of Fukushima, which plays a central role in the transport of radionuclides and which can affect the hydrodynamics near the coastal area around Fukushima, see [8]. Given the intensity and variability of currents in this area, as well as the presence of unsteady eddies due to current convergence here, small differences in the hydrodynamics can produce different dispersion patterns [19], [21].

V. CONCLUSIONS

The main objectives of this work were (i) to present the implementation, verification and validation of a three-dimensional model able reproducing the propagation of ^{137}Cs radionuclide in coastal waters and its interaction with suspended sediments, in the framework of the open-source TELEMAC-MASCARET modelling system and (ii) to evaluate the performances of the validated mode in an emergency situation as the Fukushima Dai-ichi NPP accident.

The mathematical model was based on the non-conservative transport of radionuclides, where the interaction

with the particulate matter is considered, see e.g. [11], [14], [16]. This process was accounted for by solving a three-phase interaction problem, where the transfer of radionuclides from the liquid (water) to the solid phase (sediments) is governed by kinetic transfer coefficients. The resulting numerical model was first verified by comparisons between numerical and analytical solutions of selected test cases. We observed that the agreement between the analytical and numerical solution was satisfying for the performed tests, showing that the spatial and temporal distribution of the tracer concentration was well reproduced by the model. Moreover, both the kinematic exchanges of radionuclides between water and sediments and the radioactive decay were well reproduced.

The validation of the model with the Fukushima Dai-ichi case was realized by comparing numerical results with field measurements of radionuclides concentration in the Japan Sea (TEPCO measurements performed after the accident of 2011). The numerical results show that the model is able to reproduce the propagation and diffusion of the released ^{137}Cs in the vicinity of the NPP. Therefore, numerical results obtained with a small scale model with a simple forcing are consistent, at a coastal-scale, with models which employed general circulation model based on data assimilation techniques or variation method for hydrodynamics, see e.g. [20]. As a consequence, this kind of model could be employed in an emergency situation, when the dissolved radioactivity is considered.

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REFERENCES

- [1] Cunha, C.L.N., Rosman, P.C.C., 2005. *A semi-implicit finite element model for natural water bodies*. Water Res. 39, 2034e2047.
- [2] Egbert, G. D., Bennet, A., F., Foreman, M. G. G., 1994. *TOPEX/POSEIDON tides estimated using a global inverse model*. Journal of Geophysical Research. Vol. 99, Issue C12.
- [3] Egbert, G. D., Erofeeva, S. Y., 2002. *Efficient Inverse Modeling of Barotropic Ocean Tides*. Journal of Atmospheric and Ocean Technology. Vol. 19. pp. 183-204.
- [4] García, M. (2008) *Sediment Transport and Morphodynamics*. Chapter 2 of *Sedimentation Engineering: Processes, Measurements, Modeling, and Practice* pp. 21-163. doi: 10.1061/9780784408148.ch02
- [5] Hervouet, J.-M., 2007. *Hydrodynamics of Free Surface Flows: Modelling with the Finite Element Method*. ISBN: 978-0-470-03558-0, 360 pp.
- [6] Inomata, Y., Aoyama, M., Tsubono, T., Tsumune, D., Hirose, K., 2016. *Spatial and temporal distributions of ^{134}Cs and ^{137}Cs derived from the TEPCO Fukushima Daiichi Nuclear Power Plant accident in the North Pacific Ocean by using optimal interpolation analysis*. Environ. Sci. Process. Impacts 18, 126136.
- [7] Kawamura, H., Kobayashi, T. and Furuno, A., In, T., Ishikawa, Y., Nakayama, T., Shima, S. and Awaji, T. 2011. *Preliminary numerical experiments on oceanic dispersion of ^{131}I and ^{137}Cs discharged into the ocean because of the Fukushima Daiichi nuclear power plant disaster*. J. Nucl. Sci. Technol., 48: 13491356.

- [8] Kawamura, H., Kobayashi, T., Furuno, A., Usui, N., Kamachi, M., 2014. *Numerical simulation on the long-term variation of radioactive cesium concentration in the North Pacific due to the Fukushima disaster*. J. Environ. Radioact. 136, 64-75.
- [9] Kobayashi, T., Otosaka, S., Togawa, O., and Hayashi, K.: *Development of a non-conservative radionuclides dispersion model in the ocean and its application to surface cesium-137 dispersion in the Irish Sea*, J. Nucl. Sci. Technol., 44, 238247, 2007.
- [10] Kobayashi, T., Nagai, H., Chino, M., and Kawamura, H.: *Source term estimation of atmospheric release due to the Fukushima Daiichi Nuclear Power Plant accident by atmospheric and oceanic dispersion simulations*, J. Nucl. Sci. Technol., 50, 255-264, 2013.
- [11] Margvelashvili, N., Maderich, V., Yuschenko, S., Zheleznyak, M., 2000. *3-D numerical modelling of mud and radionuclide transport in the Chernobyl Cooling Pond and Dnieper-Boog Estuary*. Fine Sediments Dynamics in the Marine Environment Proceedings of INTERCOH-2000. Ed. J.C. Winterwerp and C. Kranenburg, Elsevier, p. 595-610.
- [12] Mazaheri, M., Samani, J.M., Samani, M.V., 2013. *Analytical Solution to One-dimensional Advection-diffusion Equation with Several Point Sources through Arbitrary Time-dependent Emission Rate Patterns*. J. Agr. Sci. Tech., 15: 1231-1245.
- [13] Min, B.I., Periañez, R., In-Gyu, Kim, Kyung-Suk, Suh, 2013. *Marine dispersion assessment of 137Cs released from the Fukushima nuclear accident*. Mar. Pollut. Bull. 72, 22e33.
- [14] Periañez, R., 1998. *A three dimensional r-coordinate model to simulate the dispersion of radionuclides in the marine environment*. Ecological Modelling 114, 5970.
- [15] Periañez, R., 2003. *Redissolution and long-term transport of radionuclides released from a contaminated sediment: a numerical modelling study*. Estuar. Coast. Shelf Sci. 56, 514.
- [16] Periañez, R. 2005. *Modelling the dispersion of radio nuclides in the marine environment: An introduction*. Springer, Berlin, ISBN: 3-540-24875-7.
- [17] Periañez, R., Suh, K.S. and Min, B.I. 2012. *Local scale marine modelling of Fukushima releases. Assessment of water and sediment contamination and sensitivity to water circulation description*. Mar. Pollut. Bull., 64(11): 23332339.
- [18] Periañez, R., Suh, Kyung-Suk, Min, Byung-II, 2013. *Should we measure plutonium concentrations in marine sediments near Fukushima?* J. Radioanal. Nucl. Chem. 298, 635e638.
- [19] Periañez, R., Brovchenko, I., Duffa, C., Jung, K-T., Kobayashi, T., Lamego, F., Maderich, V., Min, B-I., Nies, H., Osvath, I., Psaltaki, M., Suh, K.S., 2015. *A new comparison of marine dispersion model performances for Fukushima Dai-ichi releases in the frame of IAEA MODARIA program*. J. Environ. Radioactivity, 150: 247-269.
- [20] Periañez, R., Suh, K.S. and Min, B.I. 2015. *Numerical Modeling as a Tool for Managing Nuclear Accidents: The Fukushima Daiichi Case*. Energy Vol. 4: Nuclear Science.
- [21] Periañez, R., Bezhenar, R., Brovchenko, I., Duffa, C., Iosjpe, M., Jung, K-T., Kobayashi, T., Lamego, F., Maderich, V., Min, B-I., Nies, H., Osvath, I., Outola, I., Suh, K.S., de With, G. 2016. *Modelling of marine radionuclide dispersion in IAEA MODARIA program: Lessons learnt from the Baltic Sea and Fukushima scenarios*. Science of the Total Environment, In press.
- [22] Roland, A., Zhang, Y.J., Wang, H.V., Meng, Y., Teng, Y.C., Maderich, V., Brovchenko, I., Dutour-Sikiric, M., Zanke, U., 2012. *A fully coupled 3D wave-current interaction model on unstructured grids*. J. Geophys. Res. 117, 1e18.
- [23] Suh, K.S., Jeong, H.J., Kim, E.H., Hwang, W.T., Han, M.H., 2006. *Verification of the Lagrangian particle model using the ETEX experiment*. Ann. Nucl. Energy 33, 1159e1163.
- [24] Suh, K.S., Han, M.H., Jung, S.H., Lee, C.W., 2009. *Numerical simulation for a dispersion of a pollutant using Chernobyl data*. Math. Comput. Model. 49, 337e343.
- [25] TEPCO (Tokyo Electricity Power Corporation). 2011. Available at: <http://www.tepco.co.jp/en/>.
- [26] Terada, H., Katata, G., Chino, M., Nagai, H., 2012. *Atmospheric discharge and dispersion of radionuclides during the Fukushima Daiichi Nuclear Power Plant accident. Part II: verification of the source term and analysis of regional-scale atmospheric dispersion*. J. Environ. Radioact. 112, 141e154.
- [27] Tsujino, H., Motoi, T., Ishikawa, I., Hirabata, M., Nakano, H., Yamanaoka, G., Yasuda, T., Ishizaki, H., 2010. Reference Manual for the Meteorological Research Institute Community Ocean Model (MRI.COM) Version 3. Technical Reports of the MRI. 59. Meteorological Research Institute, Tsukuba, Japan.
- [28] Usui, N., Ishizaki, S., Fujii, Y., Tsujino, H., Yasuda, T., Kamachi, M., 2006. *Meteorological Research Institute multivariate ocean variational estimation (MOVE) system: some early results*. Adv. Space Res. 37, 806e822.
- [29] Zhang, Y., Battista, A.M., 2008. *SELFE: a semi-implicit Eulerian-Lagrangian finite-element model for cross-scale ocean circulation*. Ocean. Model. 21 (3e4), 71e96.