



Simulating short-term dispersion of Cs-137 in the East Vietnam Sea: atmospheric fallout from a hypothetical nuclear accident as a source term

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Abstract

This study combines the FLEXPART atmospheric transport model with the DELFT-3D marine hydrodynamic model to simulate the short-term dispersion of Cs-137 in the East Vietnam Sea following a hypothetical nuclear accident at the Fangchenggang Nuclear Power Plant. Atmospheric deposition from FLEXPART serves as the source term input for marine dispersion in DELFT-3D, enabling a comprehensive assessment of radionuclide transport across air and sea. The findings reveal rapid dispersion patterns influenced by atmospheric fallout and ocean currents, with notable accumulation in coastal zones and near river mouths, and a gradual decline offshore. This work highlights the value of integrating atmospheric and marine modeling approaches to understand radionuclide behavior, offering insights that can enhance emergency response strategies and environmental monitoring frameworks. The approach builds on prior studies of nuclear accident simulations, refining its application to the East Vietnam Sea context.

Keywords Cesium-137 · Atmospheric fallout · Marine dispersion · FLEXPART · DELFT-3D

1 Introduction

The increasing reliance on nuclear power over recent decades has amplified the demand for precise modeling and forecasting of radioactive dispersion in marine environments, driven by the persistent risks of nuclear accidents (IAEA, 2019; Perri      et al. 2019a). Radioac-

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tive pollutants, such as cesium-137 (Cs-137), pose severe and enduring threats to human health, biodiversity, and critical socio-economic sectors like aquaculture and fisheries. These impacts often extend far beyond national borders, making radioactive contamination a pressing global issue, particularly for coastal nations dependent on marine resources for food security and economic development (AbuQamar et al. 2023; Alexeev and Galtsova 2012). Accurate prediction and response to radionuclide dispersion are thus vital for ensuring nuclear safety, preserving environmental integrity, and supporting sustainable development (Ashley et al. 2017). Beyond risk assessment, such predictive capabilities enable the calculation of the J-value—a metric for evaluating the cost-effectiveness of protective measures—facilitating informed decisions on evacuations, fishery suspensions, or other interventions based on radiation levels (Waddington et al. 2017).

Nuclear accidents frequently release radionuclides into the atmosphere, where they can travel vast distances before depositing onto land and marine environments as atmospheric fallout (Christoudias and Lelieveld 2013; Katata et al. 2015; Kaeriyama 2017). Although direct discharges into the sea can occur, these events are rare compared to the more common pathway of atmospheric dispersion and subsequent deposition onto ocean surfaces (Aoyama et al. 2013; Buesseler et al. 2012; Ito et al. 2020). Historical nuclear incidents, such as Chernobyl (1986) and Fukushima (2011), have illustrated how radionuclides, particularly Cs-137 with its 30-year half-life and tendency to bioaccumulate, can contaminate distant marine ecosystems via this route (Dietze and Kriest 2012; Saito et al. 2024). While many existing models emphasize direct oceanic discharges (Tsumune et al. 2012; Kawamura et al. 2017), research on atmospheric fallout and its short-term marine dispersion remains limited. This gap is significant, as the initial days to weeks following deposition—driven by surface currents, ocean mixing, and wind patterns—play a crucial role in determining the early spread of radionuclides, influencing timely emergency responses like evacuation planning and resource protection (Murat et al. 2024).

Traditionally, radionuclide dispersion models have relied on long-term ocean circulation frameworks that assume averaged yearly flow conditions (Nakano and Povinec 2012; Tsumune et al. 2012; Kawamura et al. 2017; Delaval et al. 2021). These models, while computationally efficient for projecting contamination over decades, often fail to capture the short-term dynamics critical during the early stages of a nuclear accident. The rapid dispersion processes immediately following atmospheric fallout—governed by dynamic interactions between currents, tides, and mixing—require detailed, time-sensitive simulations to inform decision-making in the critical first weeks (Murat et al. 2024). Such short-term forecasts not only mitigate immediate risks to human populations and marine ecosystems but also lay the groundwork for effective long-term mitigation and recovery strategies. The Fukushima disaster, for instance, underscored the need for models that integrate atmospheric fallout with marine dispersion to comprehensively track radionuclide pathways and assess their environmental consequences (Buesseler et al. 2012).

Efforts to combine atmospheric transport simulations with ocean dispersion models for assessing radioactive contamination have been well-documented in prior studies. Perriñez et al. (2015) applied this approach to the Fukushima Dai-ichi accident, linking atmospheric deposition data with marine dispersion models to simulate Cs-137 transport in the Pacific Ocean as part of the IAEA's MODARIA program. Likewise, Bezhenar and Kovalets (2023) employed the JRODOS system to couple atmospheric dispersion (via RIMPUFF) with marine transport (via POSEIDON-R), modeling contamination in the Black Sea from a

hypothetical severe accident at the Zaporizhzhia Nuclear Power Plant (ZNPP). These studies affirm the value and feasibility of integrated modeling. Building on this established foundation, our research refines this methodology by focusing on short-term dispersion in the East Vietnam Sea, a region with complex marine dynamics and heightened vulnerability to radiological fallout from nearby nuclear facilities, such as China's Fangchenggang Nuclear Power Plant (Hien and Long 2023).

In Southeast Asia, the East Vietnam Sea stands out as a critical area due to its ecological richness, economic importance, and proximity to nuclear installations (Behrens et al. 2012). A radiological release in this region could deposit significant amounts of Cs-137, threatening marine ecosystems and coastal communities reliant on seafood (Nakano and Povinec 2012). To address this, we employ the FLEXPART Lagrangian particle dispersion model to simulate atmospheric transport and deposition of Cs-137, leveraging its proven efficacy in tracking radioactive fallout under diverse meteorological conditions (Stohl et al. 2005, 2012; Brioude et al. 2013; Pisso et al. 2019). For marine dispersion, we use the DELFT-3D hydrodynamic model with particle tracking, which captures interactions between ocean currents, winds, tides, and mixing processes (Deltares 2024). Using a hypothetical accident scenario inspired by Silva et al. (2021), FLEXPART generates deposition data that serves as the source term for DELFT-3D to simulate Cs-137 dispersion in the East Vietnam Sea. While the concept of integrating atmospheric and marine models builds on prior work, this study represents their first combined application for short-term simulations in this region, enhancing prediction accuracy during the critical early phase of a nuclear incident. By bridging atmospheric fallout and marine circulation, our approach delivers detailed, actionable insights to strengthen emergency preparedness, minimize environmental risks, and bolster resilience against potential nuclear accidents in Southeast Asia.

2 Materials and methods

2.1 FLEXPART modelling framework

The simulation of atmospheric dispersion of radionuclides was conducted using the FLEXPART version 9.02, following the parameters described by Silva et al. (2021) in their benchmark study of transboundary atmospheric dispersion within the ASEAN Network on Nuclear Power Safety Research (NPSR) framework. FLEXPART, a Lagrangian particle dispersion model, was implemented on a CentOS Server 6.5 system, with meteorological input data from the National Centers for Environmental Prediction (NCEP) CFSv2 dataset at $0.10^\circ \times 0.10^\circ$ resolution.

The FLEXPART model generated comprehensive outputs that include maps of atmospheric Cs-137 concentrations, rates of dry and wet deposition, and total effective dose equivalents, providing a multifaceted understanding of the dispersion and deposition processes of radionuclides in the environment (Pisso et al. 2019). These outputs offer crucial insights into the behavior and distribution of Cs-137 following a simulated nuclear accident and form the basis for further marine dispersion modeling.

For this simulation, a hypothetical accidental release was modeled from the Fangchenggang Nuclear Power Plant (FCG NPP), located in Guangxi province, China. This plant was selected due to its proximity to Southeast Asia, as it lies approximately 50 km from Mong

Cai city in Quang Ninh province, Vietnam, making it an ideal candidate for studying the potential cross-border atmospheric dispersion of radionuclides.

The scenario simulates a severe nuclear incident classified as a level 7 event on the International Nuclear and Radiological Event Scale (INES). This classification denotes a significant accident with widespread consequences. The accident is assumed to have occurred on May 6, 2019, with the release of Cs-137 into the atmosphere. The scenario assumes that the cause of the accident is a prolonged station blackout at the FCG NPP, resulting in the failure of all electrical systems, including critical cooling functions, leading to damage to the reactor core (Silva et al. 2021).

During the release, approximately 10 petabecquerels (PBq) of Cs-137 were emitted into the atmosphere over a 24-hour period. The release occurred continuously from a height of 10 m, with a heating content of 500 megawatts (MW). This significant amount of thermal energy can affect the dispersion dynamics of the radioactive plume, as it might elevate the particles higher into the atmosphere and contribute to a broader geographical spread. The release scenario was modeled to reflect the realistic atmospheric conditions and transport mechanisms that would influence both the immediate and long-term movement of the radionuclides in the atmosphere.

In addition to simulating the airborne dispersion of Cs-137, the study also focused on the deposition of the radionuclide on various surfaces. Both wet and dry deposition rates were tracked during the 12-hour period to identify areas that could experience the highest levels of contamination. Wet deposition occurs through precipitation, while dry deposition happens as particles settle directly onto surfaces. Understanding the deposition patterns is crucial for assessing which regions face the greatest environmental and health risks from Cs-137 contamination. The source term, release scenario and meteorological conditions used in this study are summarized in Table 1.

Following Table 1, the atmospheric model (FLEXPART) simulates the initial short-term dispersion of Cs-137, using a fine timestep of 0.5 h to capture rapid changes in airborne transport and deposition driven by dynamic weather conditions. The meteorological data for FLEXPART was sourced from the National Oceanic and Atmospheric Administration (NOAA), including wind speed, wind direction, rainfall, and atmospheric stability, with a high resolution of $0.1^\circ \times 0.1^\circ$, covering a domain from 6.5°N to 32.0°N latitude and 95.5°E to 122.5°E longitude to encompass affected areas over the 12-hour simulation period. In contrast, the ocean model (DELFT-3D) focuses on longer dispersion over many months and is less affected by rapid changes, using coarser meteorological data to simplify calculations.

Table 1 Source term and meteorological condition for trans-boundary atmospheric dispersion calculations

Source term

Isotope: Cs-137
Release amount [Bq]: 1.10^{16}
Release period [h]: 24 (constant rate)
Release height [m]: 10
Heat content [MW]: 500

Meteorological condition

Dry scenario: from May 6, 2019, 00:00 (UTC)
Wet scenario: from May 6, 2019, 00:00 (UTC)
Timeframe [h]: 0.5
Meteorological data used: Wind characteristics, rainfall, data to determine weather stability.
Calculation domain: 6.5°N – 32.0°N and 95.5°E – 122.5°E
Data resolution: $0.1^\circ \times 0.1^\circ$.

while still capturing seasonal oceanic trends. The FLEXPART simulation covers many days to ensure comprehensive tracking of the atmospheric plume.

2.2 DELFT-3D modelling framework

The hydrodynamic modeling of Cs-137 dispersion in the marine environment was carried out using the DELFT-3D 4.04.01 software suite, a comprehensive tool designed for simulating various physical and environmental processes in both two-dimensional and three-dimensional spaces. DELFT-3D incorporates several integral components to ensure accurate and detailed simulations.

The Grid and Bathymetry component allows for the creation of detailed grids and bathymetric maps, providing a precise representation of the marine topography. The Hydrodynamics (Flow) module simulates water flow dynamics and morphological changes, essential for understanding how radionuclides are transported in the aquatic environment. The Wave module focuses on the modeling of wave dynamics, which play a critical role in surface mixing and the dispersion of pollutants. The Particle Tracking (Part) module, which was employed in this study, is specifically designed to track the movement, dispersion, and deposition of particles such as Cs-137, enabling detailed simulations in both coastal and offshore waters. Visualization tools, including plotting, three-dimensional rendering, and animation, enhance the interpretation and presentation of the modeling outcomes. Together, these features make DELFT-3D a robust platform for analyzing the dispersion of Cs-137 in marine environments with high spatial and temporal resolution.

2.2.1 Study area and initial setup

The domain for this simulation covered the entire East Vietnam Sea, extending over an area of approximately 2,800 km north-south and 2,550 km east-west. This region, sensitive to both atmospheric fallout and marine contamination due to its proximity to nuclear power facilities like the Fangchenggang Nuclear Power Plant in China, was modeled using an orthogonal curvilinear grid system. This grid provided finer resolution near coastlines and islands, with cell sizes as small as 47.5 m, to account for complex hydrodynamic processes such as tides, waves, winds, nearshore currents, and river outflows. In contrast, cell sizes in offshore regions were coarser, reaching up to 21,197 m, simplifying calculations where such dynamics are less pronounced. This refined grid structure enabled the model to accurately simulate the dispersal of Cs-137, particularly in areas where interactions between water currents and topography significantly influence radionuclide movement.

Figure 1 illustrates the study area and seabed. The model employed sigma coordinates vertically, dividing the water column into four equal layers: 25% each for the top layer, upper middle layer, lower middle layer, and bottom layer. These layers, categorized by depth into top, middle, and bottom sections, effectively captured vertical gradients in pollutant distribution, such as surface accumulation, mid-layer dispersion, and seabed deposits. This setup provided a detailed representation of Cs-137 distribution across depths, reflecting interactions with surface currents, vertical mixing, and seabed sediment dynamics.

To enhance the assessment of Cs-137 dispersion in the marine environment, four modeling tracking points, designated O1 through O4, were strategically selected along the Viet-

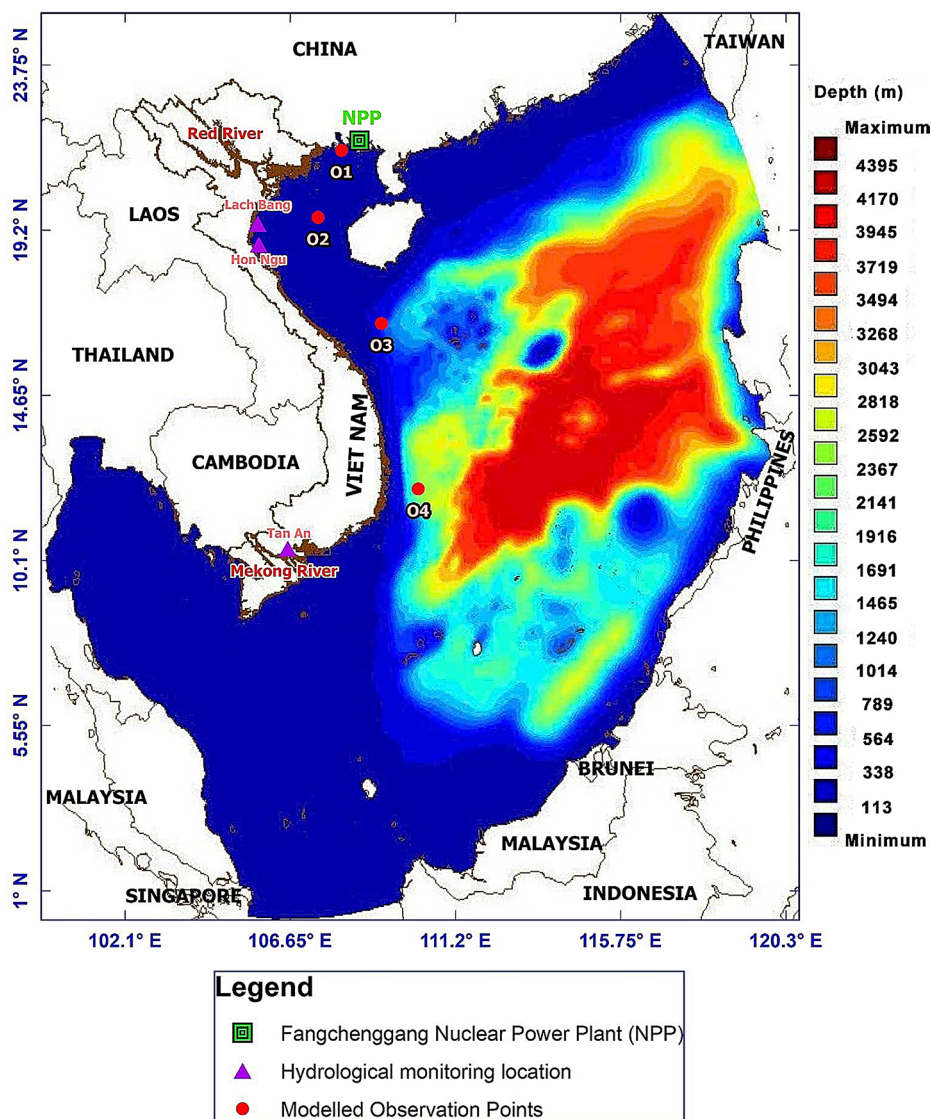


Fig. 1 Map of the study area and seafloor topography

namese coastline, extending from Quang Ninh to Nha Trang Province (Fig. 1). These points were chosen to capture both spatial and temporal variations in radionuclide dispersion, providing a comprehensive understanding of Cs-137 behavior in the marine environment. The aim is to identify potential contamination hotspots and to support effective emergency response and environmental monitoring strategies.

- Point O1: Located 50 km from the nuclear plant, 10 km from the coastline, and at a depth of 10 m, this point represents an area close to the source of dispersion and offers

insights into immediate near-shore contamination.

- Point O2: Located 250 km from the nuclear plant and 170 km from the coastline, with a depth of 47 m, this location captures intermediate dispersion processes in the mid-shelf region in the Continental Shelf.
- Point O3: Located 550 km from the nuclear plant, 170 km from the coastline, and at a depth of 68 m, this point represents radionuclide behavior in offshore waters at Continental Slope, farther from the release site.
- Point O4: Located 1050 km from the nuclear plant, 100 km from the coastline, and at a depth of 2232 m, this point provides insights into the deep-sea dispersion dynamics and long-distance transport of radionuclides.

The selection of these points allows for a detailed analysis of how Cs-137 disperses across different distances from the source and varying depths, contributing valuable information for managing nuclear contamination in marine environments.

2.2.2 Topographic data

Topographic data for the East Vietnam Sea region were collected from 1:50,000-scale topographic maps covering coastal areas for the entire Vietnam. These topographic maps were digitized, and the individual pieces were integrated into a larger dataset encompassing the entire study area. For offshore regions, topographic data were supplemented with information from the General Bathymetric Chart of the Oceans (GEBCO), with a resolution of 30 arc-seconds (~0.92 km), provided by the British Oceanographic Data Centre.

2.2.3 River hydrology data

The study area is influenced by the Red River-Thai Binh and Mekong River systems, both of which are monitored by national river discharge observation systems providing reliable data, particularly during the rainy season. Additional rivers, such as Chanh, Rut, Bach Dang, Cam, Van Uc, Thai Binh, Tra Ly, Ma, Chu, and Gianh, also benefit from similar national monitoring efforts, supplying monthly average discharge data for river boundaries. However, some locations, such as Van Uc and Cua Cam, lack consistent national observation data, so discharge information for these sites was obtained from research studies by Piton et al. (2020) and Vinh and Ouillon (2021).

2.2.4 Tidal and currents data

Water level fluctuation (WLF) data were collected at 1-hour intervals from coastal stations (Hon Ngu) in the East Vietnam Sea, measured by the Vietnam Meteorological and Hydrological Administration. Current data (speed and direction) were obtained at 3-hour intervals from Lach Bang and Thuan An (Tan An) National Monitoring Stations, with measurements taken at three depths corresponding to the surface (20%), middle (60%), and bottom (80%) layers during December 2018. These instantaneous values were used to calibrate and validate the DELFT-3D model, ensuring accurate representation of hydrodynamic processes in the study area.

Tidal WLF data were processed to develop a hydrodynamic model. Nearshore boundary data were processed using observational results from agencies such as the Marine Meteorological Center, the Institute of Geography, the Institute of Mechanics, and the Institute of Marine Resources and Environment. For the offshore boundaries of the model, harmonic tidal constants (34 tidal components in a same and unique archive: K1, M2, M4, N2, O1, P1, Q1, S1, S2, K2, 2N2, E2, J1, L2, La2, M3, M6, M8, Mf, MKS2, Mm, MN4, MS4, MSf, MSqm, Mtm, Mu2, N4, Nu2, R2, S4, Sa, Ssa, T2) were obtained from the FES2014 tidal database with the spatial resolution is $1/16^\circ$. This dataset was developed by the Laboratoire d'Étude en Géophysique et Océanographie Spatiales (LEGOS) and Collecte Localisation Satellites (CLS), under the French National Centre for Space Studies (CNES). FES2014 represents the version of the FES (Finite Element Solution) tide model, developed between 2014 and 2016. It is an enhanced version of the previous FES2012 model, developed, implemented, and validated through a collaborative effort by LEGOS, NOVELTIS, and CLS within a project funded by CNES.

2.2.5 Meteorological data

Long-term wind observations were gathered from National Marine Observation Stations, such as Hon Dau, Nam Dinh, and Dong Ha, to provide detailed local insights into wind patterns affecting nearshore dynamics in the East Vietnam Sea. Additionally, broader meteorological data, including wind, pressure, and air temperature, were obtained from the NCEP dataset, with a resolution of 0.2° and a 3-hour frequency, covering the entire region. These data were incorporated into the DELFT-3D model to drive marine dispersion scenarios (Fig. 2). Unlike the atmospheric dispersion calculations in FLEXPART, which use high-resolution NOAA data ($0.1^\circ \times 0.1^\circ$) to track rapid, short-term changes over days, the ocean model relies on coarser NCEP data and station observations to simulate dispersion over many months. This choice balances computational simplicity with the need to capture seasonal oceanic trends, reflecting the longer timescales and wider spatial scope of marine processes compared to the detailed, short-term focus of atmospheric modeling.

2.2.6 Initial and boundary conditions

The hydrodynamic model was initialized using temperature and salinity profiles from the World Ocean Atlas 2013 (WOA13), a global dataset providing critical background information on the ocean's physical state for accurate simulation of hydrodynamic behavior. Discharge data from major Vietnamese rivers were also included to account for freshwater inputs affecting pollutant movement in nearshore areas. Surface wind stress, derived from NCEP wind data, was integrated into the DELFT-3D model to capture its influence on the transport and dispersion of Cs-137 across the sea surface. To ensure robust simulation results, the model was run from May 1, 2018—one year before the hypothetical nuclear accident—to May 1, 2020—one year after the event. This two-year period captured both pre-accident baseline conditions and post-accident dispersion dynamics, offering a comprehensive view of hydrodynamic processes in the East Vietnam Sea.

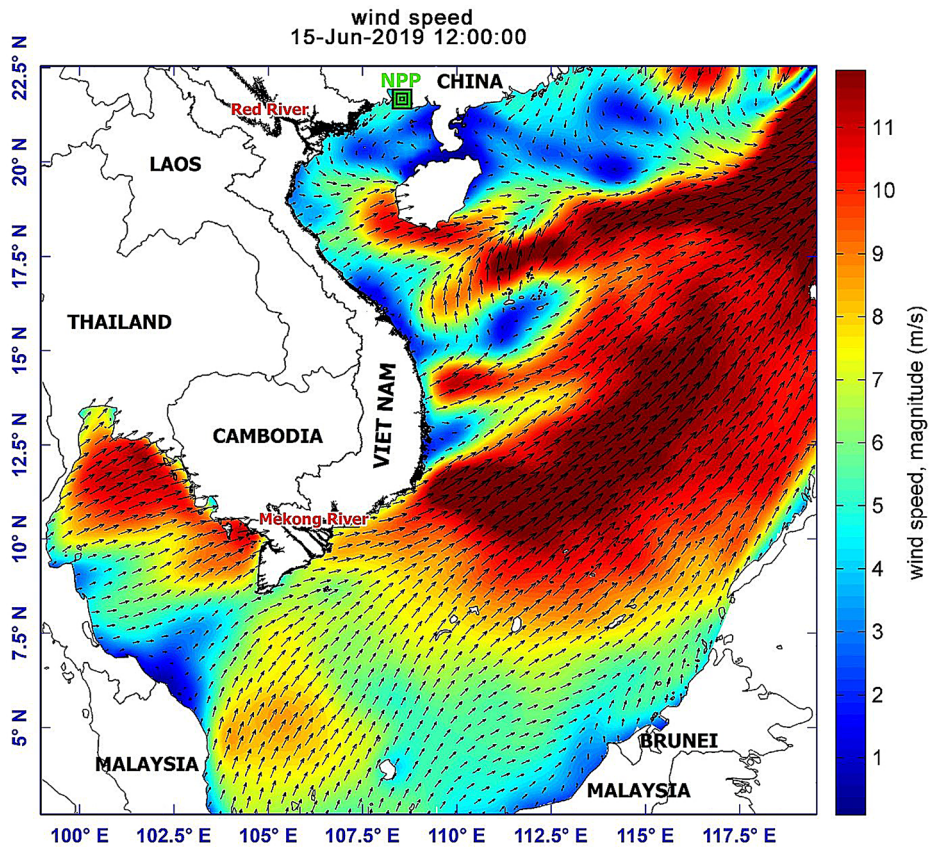


Fig. 2 Wind direction and velocity vectors on the sea surface

2.2.7 Hydrodynamic modelling

The hydrodynamic modeling of the East Vietnam Sea was conducted using the DELFT-3D FLOW module to simulate water movement across the region on a daily scale. The experiment began with the preparation of a computational grid based on topographic data, which was configured to cover the entire study area with varying cell sizes to ensure accurate resolution of nearshore and open-sea dynamics. Input datasets, including river discharge from major Vietnamese rivers, tidal forces from the FES2014 database, and meteorological conditions from NCEP, were integrated into the model to drive the simulation. These data were processed and formatted into time-dependent boundary conditions, enabling the model to account for daily fluctuations in oceanographic processes.

The simulation was set up to capture the interplay of multiple physical factors influencing water movement, such as tidal oscillations derived from harmonic constants, wind-induced currents, and vertical mixing parameterized through sigma coordinates dividing the water column into four equal layers (25% each). To reflect realistic conditions, the experiment spanned from May 1, 2018, to May 1, 2020, covering a two-year period around the hypothetical nuclear accident. This extended timeframe allowed the model to establish baseline

hydrodynamic behavior before introducing Cs-137 dispersion. The daily timestep was chosen to resolve short-term variations, with calculations performed iteratively to update water velocities and levels across surface and subsurface layers. Calibration was conducted by adjusting model parameters, using observed current and water level data from coastal stations like Lach Bang, Tan An and Hon Ngu, ensuring the simulation aligned with real-world measurements.

2.3 Intergration of models

To integrate FLEXPART and DELFT-3D, atmospheric deposition data of Cs-137 from FLEXPART (in Bq/m²) were used as a time-dependent source term for the DELFT-3D Particle Tracking module, simulating marine dispersion in the East Vietnam Sea. The continuous release functionality in DELFT-3D enabled input of time-varying deposition rates, with parameters such as release coordinates, layer, particle count, radius, and duration customized for precision. The horizontal diffusion coefficient of Cs-137 was set to 10 m²/s and the vertical diffusion coefficient to 10⁻⁴ m²/s, following Periañez et al. (2019b). Based on Fukushima-related studies (Periañez et al. 2015), we assumed that 99% of Cs-137 remains dissolved in seawater as a soluble cation (Cs⁺), with only 1% adsorbed onto suspended matter due to its low affinity for particulate matter under typical oceanic conditions with minimal suspended sediment loads. The adsorbed fraction undergoes settling, modeled with a settling velocity of approximately 0.1 mm/s (8.64 m/day) for fine particles, as adopted from Periañez et al. (2015). This velocity is incorporated into the DELFT-3D model to simulate the downward movement of particles in the water column, ensuring accurate representation of Cs-137 dispersion and sedimentation processes.

3 Results and discussion

3.1 FLEXPART deposition result

The total Cs-137 deposition in the East Vietnam Sea, including both dry and wet deposition processes, amounts to 2.015 PBq, equivalent to approximately 0.627 kg. Figure 3 illustrates the dry deposition of Cs-137 within the first 24 h after the incident. Driven by atmospheric conditions such as wind speed and direction, dry deposition occurs across a wide area, affecting both terrestrial and marine environments. The patterns reveal widespread fallout extending far from the source, with wind dynamics causing significant dispersion over land and the East Vietnam Sea. This extensive reach underscores the far-ranging impact of airborne radionuclide transport compared to a hypothetical direct discharge into seawater, which would result in more localized dispersion confined to nearshore areas.

Figure 4 depicts the wet deposition of Cs-137 within the same 24-hour period post-incident, where radioactive particles are scavenged from the atmosphere by precipitation and primarily deposited on the sea surface. The dominance of wet deposition over the marine environment is driven by high precipitation levels in the East Vietnam Sea, which enhance scavenging efficiency over water. Additionally, the proximity of the accident source to the coastline, combined with prevailing offshore wind patterns, directs radioactive material

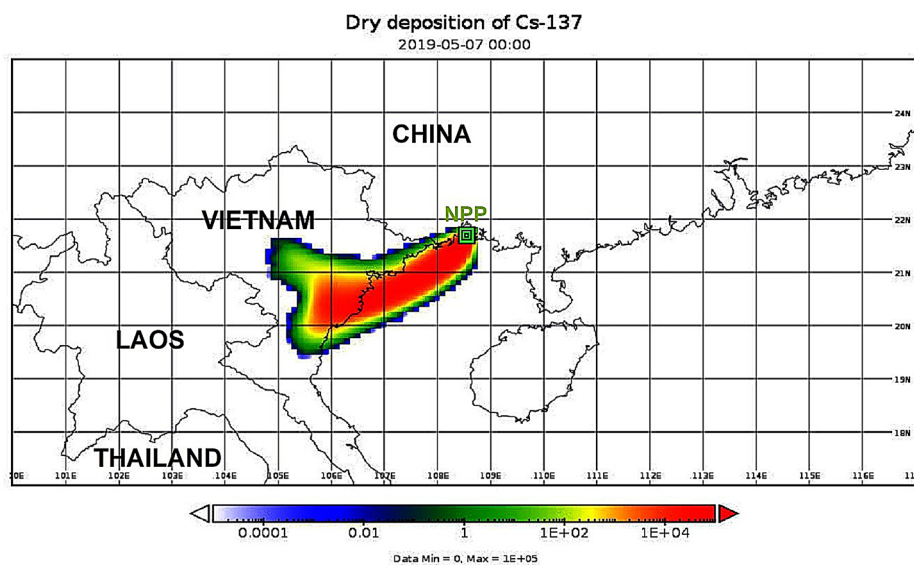


Fig. 3 Dry Deposition of Cs-137 within 24 h from a Hypothetical Accident at the Fangchenggang Nuclear Power Plant Simulated by FLEXPART

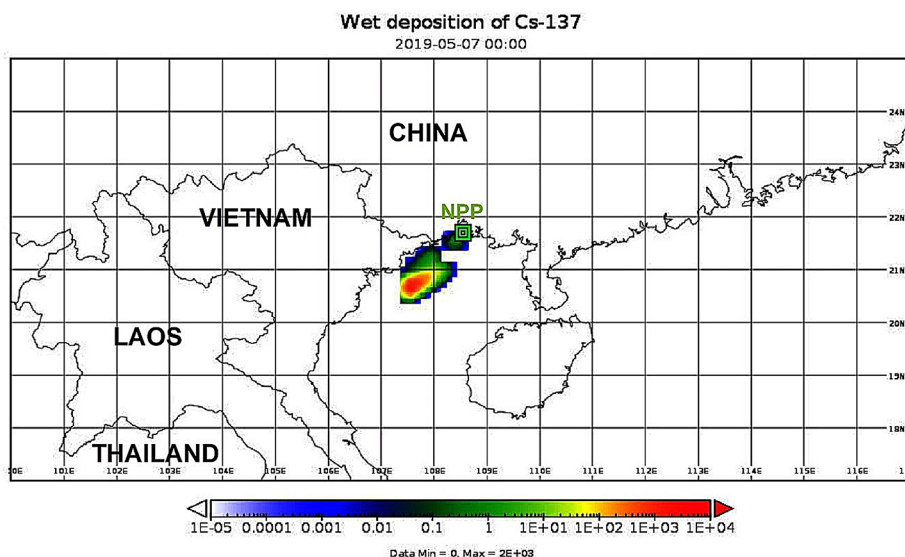


Fig. 4 Wet Deposition of Cs-137 within 24 h from a Hypothetical Accident at the Fangchenggang Nuclear Power Plant Simulated by FLEXPART

toward the sea, where rainfall events deposit most of the fallout. This results in higher wet deposition concentrations over the marine environment compared to terrestrial areas.

The deposition data from FLEXPART, encompassing both dry and wet processes, are essential for simulating Cs-137 dispersion in the East Vietnam Sea using DELFT-3D. By

integrating spatially resolved deposition data, the model accurately captures the interplay between atmospheric fallout and marine transport processes, including interactions with currents, tides, and mixing. This approach ensures a realistic representation of radionuclide dispersion patterns across the region, providing a foundation for environmental risk assessments.

Figures 3 and 4 highlight the potential environmental impacts of nuclear fallout, particularly in regions near nuclear facilities. Dry deposition patterns indicate extensive dispersion zones that could affect terrestrial ecosystems and coastal areas, while wet deposition emphasizes the significant accumulation of Cs-137 in marine environments, driven by regional precipitation and wind patterns. These findings are vital for informing emergency response strategies, such as prioritizing monitoring in high-deposition zones and developing mitigation measures for both terrestrial and marine ecosystems.

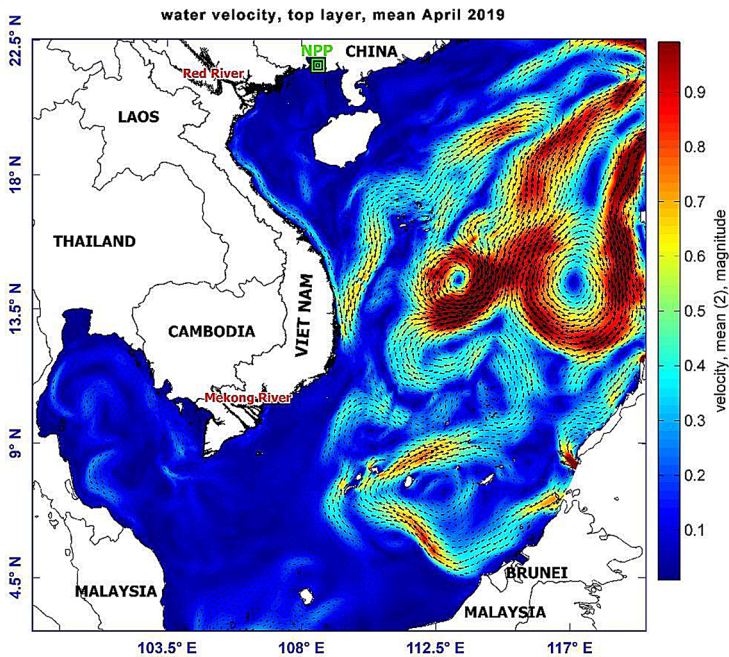
3.2 Hydrodynamic model results and evaluation

The simulation outputs, as illustrated in Fig. 5, reveal intricate flow structures shaped by the interaction of local bathymetry, atmospheric conditions, and tidal dynamics. A clear distinction emerged between surface and bottom currents, with surface currents exhibiting significantly higher velocities. This disparity can be attributed to the direct influence of wind stress on the ocean's surface layers, while bottom currents are dampened by frictional interactions with the seabed, as well as reduced energy transfer from the upper layers.

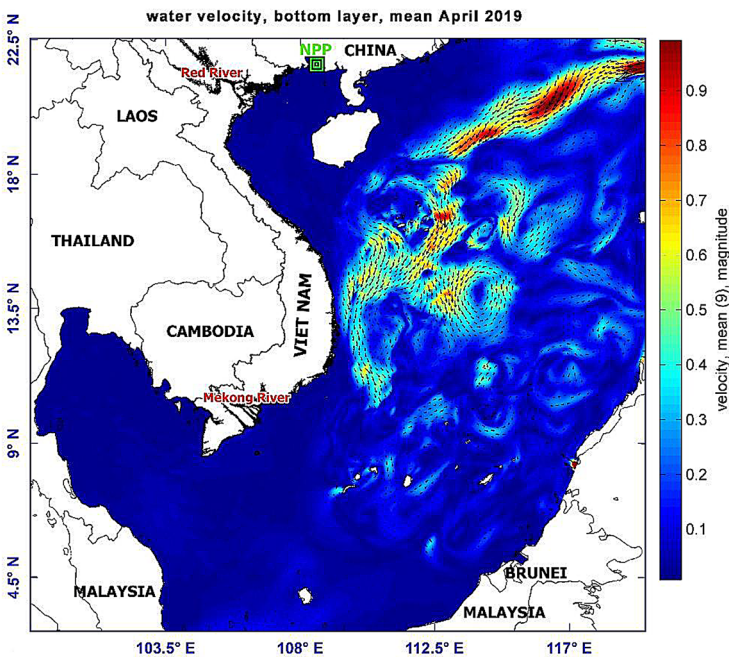
The simulations highlight the marked temporal variability of surface currents, driven by seasonal wind patterns and tidal forces. These currents play a pivotal role in the transport and dispersion of sediments, pollutants, and other materials across the marine environment. In contrast, bottom currents, though weaker, are vital for processes like sediment resuspension and deposition. These dynamics underscore the necessity of modeling both surface and subsurface flows to fully understand radionuclide transport and other marine dispersal processes.

The hydrodynamic simulations, conducted over a comprehensive timeframe from May 1, 2018, to May 1, 2020, were designed to capture both short-term fluctuations and long-term trends in hydrodynamic behavior within the East Vietnam Sea. To ensure the model's accuracy, calibration and validation were systematically performed using observational data collected from multiple stations, including Lach Bang, Tan An, and Hon Ngu, which provided detailed measurements of water currents. Additional validation was conducted against current flow data from monitoring stations in Thanh Hoa and Thua Thien-Hue. These comparisons utilized key metrics such as water levels and current velocities, demonstrating a high degree of agreement between observed and simulated values. The rigorous calibration and validation process confirmed the model's reliability in accurately representing the hydrodynamic conditions of the study area, providing a solid foundation for subsequent analyses.

The calibration of the hydrodynamic model was essential to ensure accurate simulation of water levels and flow velocities in the East Vietnam Sea. Model performance was evaluated by comparing observed and simulated data at Hon Ngu, Lach Bang, and Tan An stations. Observed instantaneous flow velocities (3-hour intervals) were measured at depths of 20%, 60%, and 80% of the water column, corresponding to surface, middle, and bottom layers, respectively. Simulated velocities were computed as mean values over sigma



a) Top layer: Represents the top 25% of the water column in sigma coordinates.



b) Bottom layer: Represents the bottom 25% of the water column in sigma coordinates.

Fig. 5 Map of surface and bottom currents in the East Vietnam Sea in April

coordinate layers (25% of depth for surface, 50% for middle, 25% for bottom). Correlation coefficients, a robust measure of agreement (Krause et al. 2005), were used to quantitatively assess the model's accuracy.

The comparison of observed and simulated water levels at Hon Ngu for August and December 2018 yielded correlation coefficients exceeding 0.98 in both cases, demonstrating the model's exceptional accuracy in capturing tidal dynamics and water level fluctuations (Fig. 6a and b). These results highlight the model's capability to represent seasonal variations effectively, as the East Vietnam Sea is subject to distinct hydrodynamic conditions influenced by monsoonal shifts.

The calibration of flow velocity was carried out for December 2018, using data collected at Lach Bang and Tan An (Fig. 6c and d). Correlation coefficients for velocity predictions ranged between 0.6 and 0.99. Notably, mid-layer and surface flow velocities achieved the highest correlation values, suggesting that the model accurately represents the primary hydrodynamic forces driving water movement in these layers.

In contrast, the correlation values for bottom-layer flow velocities were lower, approximately 0.6. This discrepancy may stem from the increased complexity of near-bottom dynamics, where factors such as seabed topography, sediment transport, and turbulence play a more significant role. These processes are inherently more variable and challenging

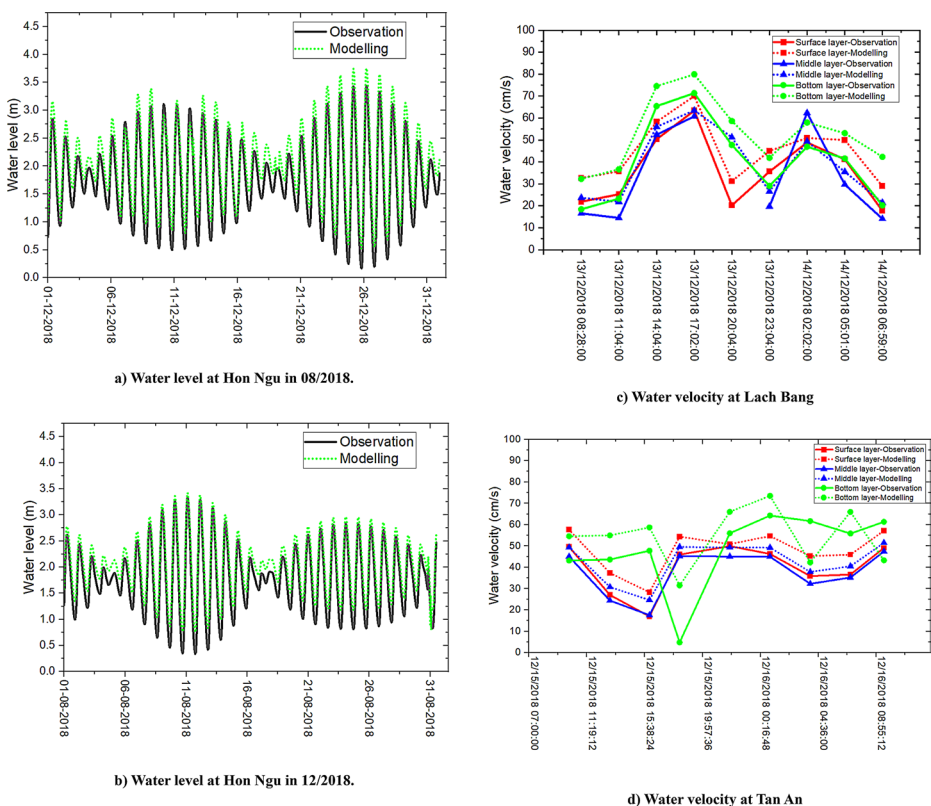


Fig. 6 Comparison water level and velocity between observation and DELFT-3D modelling

to model with precision, as they involve interactions between physical processes that introduce additional uncertainty.

The results of the hydrodynamic calibration underscore the robustness of the DELFT-3D model in simulating key hydrodynamic parameters across different layers of the water column. The strong agreement between observed and simulated water levels reflects the model's capability to reproduce tidal forcing and surface dynamics accurately. The moderate correlation for bottom-layer flow, while indicative of some limitations, provides valuable insights into the complexity of seabed interactions that can inform future improvements to the model.

The overall performance of the model suggests it is well-suited for simulating the transport and dispersion of radionuclides, as accurate representation of hydrodynamic conditions is crucial for modeling the spread of Cs-137 and other substances in the marine environment.

3.3 General distribution of Cs-137 in the study area

The dispersion of Cs-137 following a nuclear accident exhibits notable temporal and spatial variations. In the first 7 days after the accident, the radioactive plume expanded to cover the entire Gulf of Tonkin. During these early stages, high concentrations of Cs-137 (ranging from 1000 to 10,000 Bq/m³) were observed near the nuclear power plant. As the radioactive material dispersed and diluted, concentration decreased with increasing distance from the source. This dispersion pattern is clearly illustrated in Fig. 7, which shows the distribution of Cs-137 across the surface layer of the East Vietnam Sea.

By day 14 the accident event, the distribution of Cs-137 extended to about one-fifth of the Vietnamese East Sea. By the 30th day, approximately 60% of the East Sea was affected, and by the 45th day, 90% of the East Sea was contaminated with varying levels of radiation. Higher concentrations were observed near coastal areas and river mouths, with Cs-137 levels ranging between 100 and 1000 Bq/m³. In Red river mouth regions, levels ranged between 1000 and 10,000 Bq/m³. Conversely, radiation levels in the central East Sea were significantly lower, below 1 Bq/m³, with a few areas ranging between 1 and 10 Bq/m³ or occasionally 10–100 Bq/m³.

These distribution patterns highlight the impact of coastal dynamics, where Cs-137 concentrations are higher nearshore due to limited dilution and retention at river mouths. In contrast, the deep and dynamic waters of the central East Sea facilitate greater dilution and dispersion, resulting in lower Cs-137 levels.

3.4 Distribution of Cs-137 at modelling tracking points

Figure 8 illustrates the levels of Cs-137 concentrations at the designated modelling tracking points (O1 to O4) across the East Vietnam Sea over time and at different layers. Each panel (Fig. 8a, b and c, and d) represents the concentration distributions for the top, middle, and bottom layers at these specific points.

Point O1, located close to the nuclear power plant, exhibited the highest initial concentrations of Cs-137. One day after the accident, Cs-137 concentrations in the top layer reached 44,220 Bq/m³, while the middle and bottom layers recorded 36,460 Bq/m³ and 785 Bq/m³, respectively. Seven days after the accident, Cs-137 levels in the top layer dropped significantly to approximately 8,778 Bq/m³, while levels in the middle layer increased to

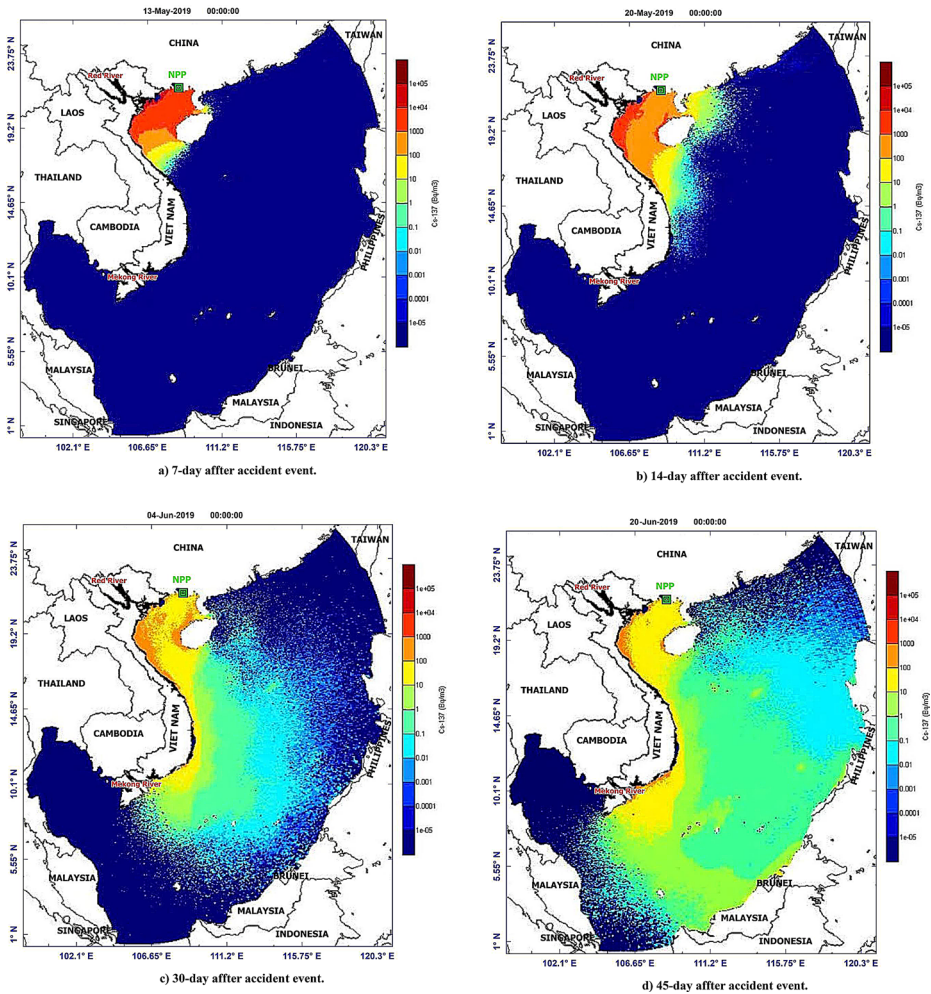


Fig. 7 Distribution of Cs-137 Dispersion in East Vietnam Sea (Surface layer)

19,820 Bq/m³. Bottom-layer concentrations decreased to 180 Bq/m³. These findings indicate strong mixing and flow dynamics in the top layer, facilitating rapid dilution. By the 14th day after the accident, Cs-137 levels in the top and bottom layers declined further, ranging between 1,022 Bq/m³ and 318 Bq/m³, respectively, whereas the middle layer retained the highest levels at 12,240 Bq/m³. By the 30th day, top-layer Cs-137 levels had reduced to 160 Bq/m³, while the middle and bottom layers registered 2,658 Bq/m³ and 173 Bq/m³, respectively. By the 90th day, top-layer levels dropped further to 17 Bq/m³, middle-layer concentrations were 114 Bq/m³, and bottom-layer levels were 17 Bq/m³. These variations indicate that the middle layer consistently exhibited higher levels over time, while the surface and bottom layers showed lower levels. This pattern can be attributed to the fact that nearshore surface and bottom layers are more dynamic, being strongly influenced by wind-driven flows and coastal wave interactions.

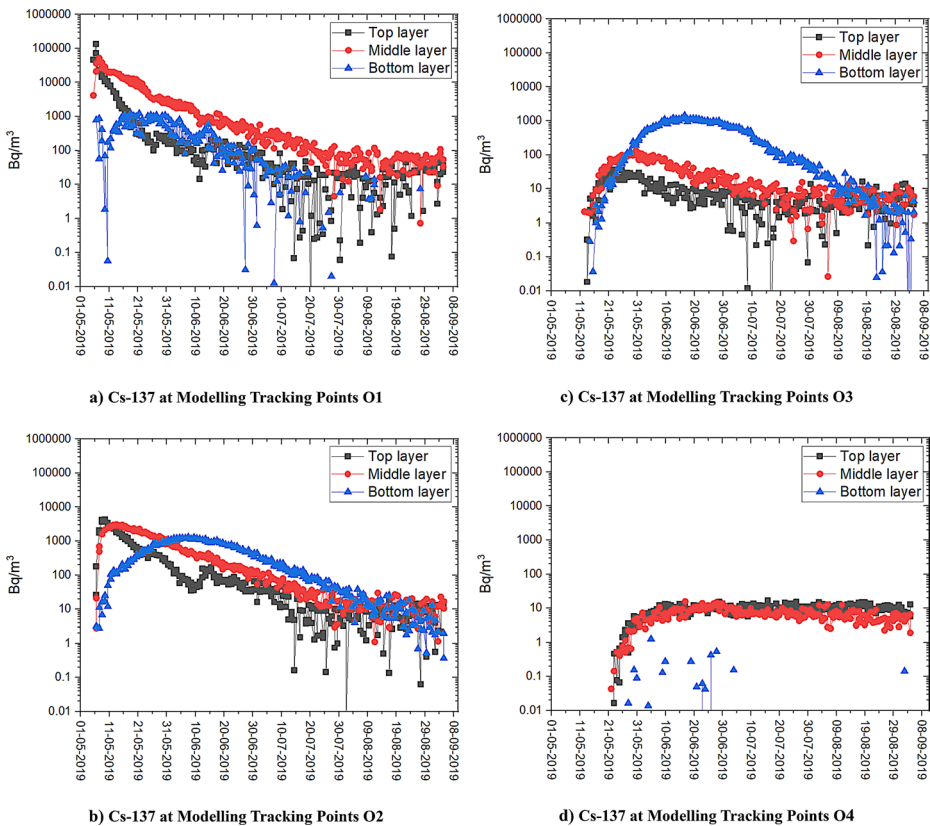


Fig. 8 Cs-137 Levels at Designated Modelling Tracking Points in the East Vietnam Sea (O1–O4)

At Point O2, radiation from the atmospheric fallout took 36 h to reach due to its distance from the source. At this time, Cs-137 concentrations in the top layer were 180 Bq/m³, while the middle and bottom layers recorded 21 Bq/m³ and 3 Bq/m³, respectively. The delayed arrival and initial dominance in the top layer highlight the role of surface currents in transporting Cs-137 from the fallout region. Five days after the accident, Cs-137 concentrations increased, with the top layer at 3,100 Bq/m³, the middle layer at 2,450 Bq/m³, and the bottom layer at 49 Bq/m³. Over the following 14 days, the middle layer exhibited the highest concentrations (1,700 Bq/m³), followed by the bottom layer (340 Bq/m³) and the top layer (410 Bq/m³). From day 30 onward, a redistribution of Cs-137 was observed, with the bottom layer becoming the dominant layer for Cs-137 retention. By the 90th day, concentrations in the top, middle, and bottom layers were 12 Bq/m³, 21 Bq/m³, and 23 Bq/m³, respectively. This shift reflects the gradual sinking of Cs-137 particles and the influence of oceanic mixing processes, where bottom-layer retention becomes significant over time.

Radiation reached Point O3 nine days after the accident due to its greater distance from the fallout region. Initial Cs-137 concentrations at this location were lower than those at O1 and O2, measuring 2.4 Bq/m³ for the surface layer, 2.3 Bq/m³ for the middle layer, and 0.49 Bq/m³ for the bottom layer. By the 14th day, top-layer concentrations exceeded those of the middle and bottom layers, consistent with surface transport processes, with values of

28 Bq/m³, 38 Bq/m³, and 27 Bq/m³ for the surface, middle, and bottom layers, respectively. From day 30 to day 90, a redistribution trend like that observed at O2 emerged, with Cs-137 concentrations becoming highest in the bottom layer and lowest in the top layer. Specifically, at day 30, concentrations were 16 Bq/m³, 57 Bq/m³, and 50 Bq/m³ for the surface, middle, and bottom layers, respectively. By day 90, these values had decreased to 2.4 Bq/m³, 9.6 Bq/m³, and 4.7 Bq/m³ for the surface, middle, and bottom layers, respectively. The delayed and diluted arrival of Cs-137 at O3 highlights the significant influence of distance and ocean currents on the dispersion of radioactive materials.

Point O4, the farthest location from the nuclear plant, recorded the arrival of Cs-137 approximately 20 days after the incident. The concentrations were significantly lower compared to other points. Between days 30 and 90, Cs-137 concentrations ranged from 5.5 to 16.5 Bq/m³ in the top layer and 3.6 to 15.7 Bq/m³ in the middle layer, while the bottom layer exhibited levels between 0 and 1.3 Bq/m³. The minimal differences in Cs-137 concentrations between the layers highlight the reduced impact of vertical mixing and the limited extent of radioactive fallout at this location.

3.5 Factors influencing Cs-137 dispersion and accumulation patterns

Coastal and nearshore areas, particularly river mouths, exhibit significantly higher Cs-137 concentrations than offshore and deeper regions of the East Vietnam Sea. This pattern results from limited dilution, slower water exchange, and the trapping of radioactive particles in sediments, especially at river mouths where tidal dynamics can transport Cs-137 deeper into river systems. These processes increase long-term ecological risks due to the persistence of radioactive materials in sediments. In contrast, the central East Vietnam Sea and other offshore areas show lower Cs-137 concentrations due to strong hydrodynamic forces, such as currents and mixing, which enhance dilution and reduce accumulation. These findings emphasize the critical role of nearshore zones and river mouths in Cs-137 retention, guiding environmental risk assessments and prioritizing monitoring efforts in these high-risk areas.

3.6 Limitations and future research

This study provides valuable insights into Cs-137 dispersion but is subject to several limitations that highlight directions for future research. The DELFT-3D model does not account for water-sediment interactions, which are critical for accurately simulating Cs-137 accumulation, particularly in the bottom layer where particles settle over time. Modern models incorporate these interactions to better represent long-term radionuclide behavior, and future work should integrate such processes to improve accuracy. Additionally, DELFT-3D's high computational demands pose challenges for simulating large-scale regions like the entire East Vietnam Sea, especially with constrained resources. Developing optimized algorithms or leveraging high-performance computing could address this issue.

Another limitation arises from the differing grid systems of FLEXPART (regular grid) and DELFT-3D (spherical coordinates), which introduce inconsistencies during data integration. Similarly, the use of non-uniform meteorological data sources—finer NOAA data (0.1°) for FLEXPART and coarser NCEP data (0.2°, 3-hour) for DELFT-3D—further complicates model compatibility due to their distinct spatial and temporal resolutions. Future efforts should prioritize harmonizing grid structures, standardizing meteorological data inputs, and

improving interpolation techniques to enhance compatibility. Additionally, the manual integration of FLEXPART deposition data into DELFT-3D is time-consuming and error-prone. Automating this process through dedicated source codes or tools would improve efficiency and reliability. Addressing these challenges—incorporating water-sediment interactions, optimizing computational resources, harmonizing grids, standardizing meteorological data, and automating data integration—will significantly enhance the accuracy, scalability, and practical utility of radionuclide dispersion modeling in marine environments.

In a real-world nuclear accident, the lack of robust interdisciplinary coordination presents a critical barrier to operationalizing coupled atmospheric and marine dispersion models like FLEXPART and DELFT-3D. Seamless collaboration among modelers, nuclear physicists, meteorologists, and oceanographers is vital to integrate real-time data, validate model outputs, and inform emergency response. However, this demands pre-established data-sharing protocols and standardized operational frameworks to enable rapid and accurate Cs-137 dispersion predictions. Future research should prioritize developing training programs and simulation exercises to enhance interdisciplinary capacity and operational readiness.

4 Conclusion

This study successfully integrated the FLEXPART atmospheric transport model and the DELFT-3D marine hydrodynamic model to simulate the short-term dispersion of Cs-137 radionuclides in marine environments. Unlike traditional methods relying on direct discharge scenarios, this approach focused on atmospheric deposition as the primary source term, providing a more realistic and comprehensive framework for radionuclide transport simulations. The successful integration highlights the potential to capture both atmospheric and marine processes, improving the accuracy and applicability of such models.

Applied to the East Vietnam Sea, the model revealed rapid dispersion of Cs-137 driven by surface currents and wind, with approximately 60% of the region affected within 30 days. Vertical distribution patterns demonstrated that the middle layer retained the highest concentrations due to its stability, while the surface layer underwent significant dilution from turbulent mixing, and moderate concentrations were observed near the seabed in coastal areas. These findings emphasize the critical influence of hydrodynamic conditions, distance from the source, and geographic features on radionuclide transport.

The research provides valuable insights into the dynamics of Cs-137 dispersion in the East Vietnam Sea, a region uniquely vulnerable due to its proximity to nuclear facilities. These results are essential for improving emergency preparedness, environmental monitoring, and risk management strategies, particularly for coastal communities dependent on marine resources.

Future research should address computational limitations in large-scale modeling, automate data integration between atmospheric and marine systems, and explore long-term radionuclide interactions with sediments and biological systems. Solving these challenges will enhance the predictive capabilities and practical applications of radionuclide transport models, offering global benefits for coastal and marine safety.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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