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How Cs-137 dispersions due to atmospheric deposition to East Vietnam Sea: a hypothetical level 7 incident from the Fangchenggang Nuclear Power Plant (China)

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ABSTRACT

Only about 50 km from the Quang Ninh coastal area in Vietnam, the Fangchenggang Nuclear Power Plant (China) operation causes excellent concerns for the environment, especially the marine environment, if an incident occurs. Based on topographic and hydrometeorological data and assumptions about radiation release conditions when an incident occurs, the Delft3D-Part modeling system was set up to assess/forecast the effect of Cs-137 radioactive activity on the source of air deposition in the water environment of Vietnam. The results showed that the sources of the drop from the air significantly affected and caused a faster impact than direct radioactive sources after the incident. Under the influence of marine circulation, wind radioactive material after falling into the sea will quickly disperse and may affect the entire East Vietnam Sea after 3–6 months. The area with high radioactivity is concentrated mainly in the Tonkin Gulf and along the coast of Vietnam. Especially in the Gulf of Tonkin, the radioactivity can reach 300–1,200 Bq/m^3 after the 5-day incident. The amount of radiation then gradually decreases to almost less than 100 Bq/m^3 after one year and below 20 Bq/m^3 after two years. According to depth, the amount of radioactive Cs-137 tends to shift between layers from the surface to the bottom: higher at first in the upper layers, then gradually decreasing and increasing in the lower layers. Radioactivity significantly reduced after two years of the incident but still exceeded QCVN 10: 2008/BTNMT.

Keywords: Delft3D, Fangchenggang, nuclear power plant, Cs-137, East Vietnam Sea, Tonkin Gulf.

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INTRODUCTION

Nuclear incidents often devastate the ecological environment, human health, and life [1, 2]. Therefore, assessing and forecasting the spread and release of nuclear radiation are critical in providing response plans if a nuclear incident occurs to minimize the impacts on the environment, biological resources, and humans [3]. Up to now, there have been many studies related to this issue worldwide. These studies showed that the dispersion of radionuclides on the sea strongly depends on realistic marine conditions such as current, salinity, and sea surface height. In marine ecosystems, radionuclides will disperse with currents, accumulate in biota, and be adsorbed by particles and sediment depending on local conditions and radionuclide properties. The major processes are water transport, dispersion due to diffusion and mixing, the interaction of dissolved radionuclides with suspended matter and sediments, and transfer from the abiotic components to biota and between different components within biota [4, 5]. Due to the complications of the dispersion of radionuclides, models constitute prominent tools to link observations, understand different processes, and predict future radionuclide distributions and concentrations [6]. Depending on their scope, models can focus on radionuclide transport with currents and exchange with sediments, such as settling or re-suspension [7, 8]. With much more advances, model tools have been used widely to simulate and forecast radioactive release [1, 9–14].

In recent years, in the face of a high demand for energy sources to serve the rapid development of the economy, the Chinese government has made a policy of prioritizing the development of nuclear power sources. Among the many Chinese nuclear power plants under construction are several nuclear power plants located very close to Vietnamese territories, such as Fangchenggang and Changjiang. The Changjiang Nuclear Power Plant (NPP) was built in Tangxing Village, Haiwei Township, southwest of Hainan Island, about 100 km southeast of Bach Long Vi Island. In particular, Fangchenggang NPP is only about 50 km from the coastal waters of Quang Ninh Province and about 500 km from Hanoi City. As recommended by the International Atomic Energy Agency (IAEA), the extended planning distance (EPD) is less than 100 km, and the food and goods planning distance (ICPD) is less than 300 km. Thus, Quang Ninh Province and some Northern provinces of Vietnam are also in the EPD and ICPD areas in correlation with Fangchenggang and Changjiang NPP, and it is necessary to prepare contingency response plans. When a nuclear incident occurs, radiation leaks from the NPP will directly release the North water region of the Tonkin Gulf and radionuclides in air deposition.

According to recent research results, after a nuclear accident in Fukushima NPP (Japan), the radiation activity released in the air environment ranges from over 3,000 km. In the seawater environment, the nuclear radiation leak caused by the Fukushima nuclear accident can reach over 2,600 km [15–17]. Although there are many concerns about the effects of radiation incidents from China's NPPs on our country's waters, scientific studies of these effects have been minimal, especially quantitative studies of the scope and extent of the impact of accidents [18]. It is worth noting that recent research simulated nuclear radiation propagation in the event of a breakdown with different dynamic conditions [19]. These studies were based on the assumption that most radiation leaks from the plant to the sea. In addition to the amount of radiation directly entering the aquatic environment, a significant amount of nuclear radiation is settling from the air to the marine environment. Therefore, the simulation of radioactive propagation from the atmosphere falling down the sea surface is necessary and has practical implications. This study was conducted based on the hypothesis that the incident from the Fangchenggang NPP with a level 7 incident (equivalent to the Fukushima NPP incident) and the radioactive source was entirely caused by falling from the atmosphere to the sea surface.

The release and transport of the Cs-137 when it falls into the sea is simulated based on the Delft3D-Part module. This model simulates the path/dispersal of matter in water based on the movement of dissolved matter (or particles) of particles in the aquatic

environment under the influence of flow and diffusion components (vertical/horizontal). The movement of pollutants (or particles) consists of 2 periods. The initial stage is the stage of moving the lower stratosphere due to the stress of the flow (in the lower layers). The second step moves randomly under the influence of stratospheric and vertical diffusers. The study results will provide more insights into the extent and scope of the incident under the impact of meteorological conditions and the motivation for the propagation and dispersion of radiation when the incident occurs.

MATERIAL AND METHODS

Material

Digitized coastal bathymetry in the study area was from topography maps of 1:50,000 and 1:25,000 by the Vietnamese People's Navy (2017). Offshore bathymetry was from the GEBCO-1/8 database (General Bathymetric Chart of the Ocean of British Oceanographic Data Centre) [20, 21]. This paper uses sea level data at Hon Dau, Bach Long Vi, and Hon Ngu stations and project VT-UD-02/17–20 flow data in August and December at Thanh Hoa and Thua Thien-Hue coastal stations for model calibration and validation. The harmonic constants at sea boundaries were extracted from FES2014 of LEGOS (Laboratoired' Etudeen Géophysique et Océanographie Spatiales, Toulouse) and CLS (Collecte Localisation Satellites) [22]. The meteorological data such as wind, atmospheric pressure, air temperature, solar radiation, and cloud volume from 2018 to 2019 were collected from NCEP [23]. In addition, salinity and water temperature for the sea boundaries were extracted from the WOA13 (World Ocean Atlas) database [24] for the East Vietnam Sea. Besides, the monthly average discharge of rivers along Vietnam's coastal area is used as the river boundaries of the model.

The relevant documents on the physical properties of nuclear radiation are referenced to establish the radiation propagation model [11, 20, 25]. The nuclear radiation data in the model are the results of calculating the amount of radiation Cs-137 settling from the atmosphere if a nuclear incident occurs from the FangChenggang NPP. The initial amount of radiation released was $1.0E^{16}$ Bq (equivalent to a level 7 nuclear incident). The propagation model disperses radiation in the air with a grid resolution of about 0.1 degrees. This data is the project's research result, "Research and assessment of the ability to spread and affect radiation from nuclear power plants of Fangchenggang and Changjiang ports to Vietnam" code KC.05.07/16–20 conducted by the Vietnam Atomic Energy Institute from 2017 to 2020.

Methods

The Delft3D model system that integrated hydrodynamics-sediment transportation and geochemical processes simulates hydrodynamics-water quality. It has been used in Vietnam to study hydrodynamic-sediment transportation processes and deposition and erosion in Hai Phong-Ha Long coastal areas, the Red River Delta, some Central lagoon areas, and the Mekong Delta [12, 13,26–30]. Moreover, this model also simulated water quality, spread pollutants, spread oil [31–33], and extended radioactive emission under several scenarios with incident levels 5, 6, and 7 when the Fangchenggang NPP incident occurred [18].

This study uses the Delft3D-Part (particle tracking) module to simulate radiation release when a nuclear radiation release occurs. Traces of pollutants are determined 3-dimension over time-based on variations in the contaminant's distribution over a grid cell. The Delft3D-Part model allows the simulation of fluctuations in material content over space and time under the influence of different dynamic conditions in estuaries, coastal, and marine areas [32]. The basic physical processes of the model include 1) Sources of emissions (continuous or instantaneous) from the air; 2) Definite material sources (concentration, mass, physical and chemical properties); 3) Temporal variation of the wind field and the effect of surface wind on transport; 4) Deposition (sinking) and re-suspending (erosion from the bottom) of matter; 5) decay rate. At any location, the

matter will be affected by three main processes: transport due to the movement of water masses (advection), diffusion/dispersion, and deposition (including deposition and re-suspending).

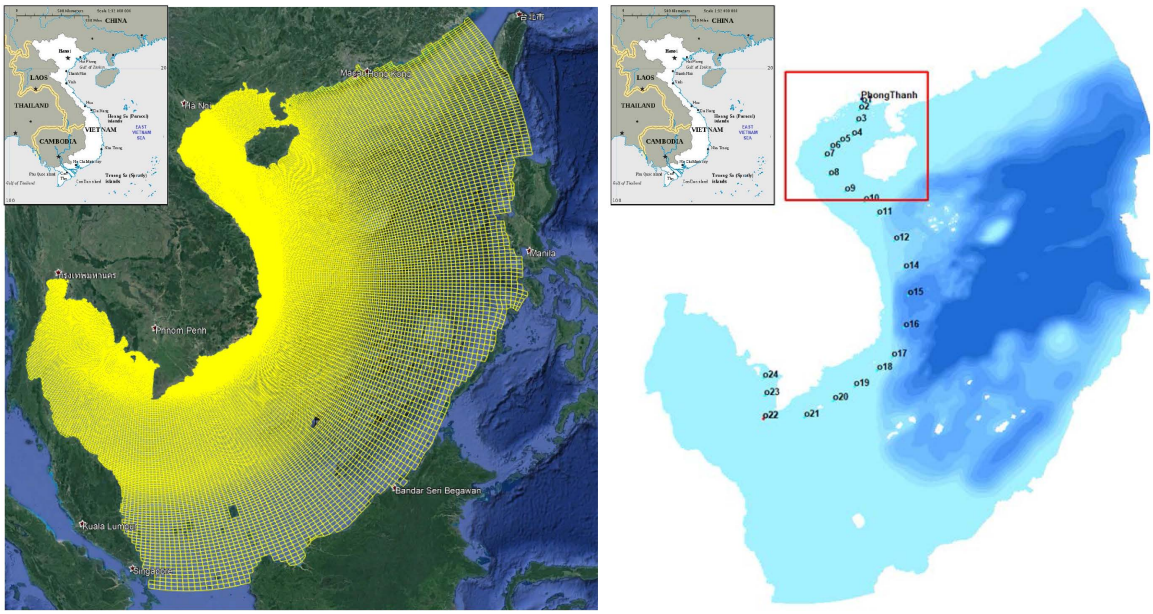

Figure 1. Model grid (left) and monitoring points (right)

Because the spread of radiation can extend to the entire East Sea, the model's domain covers the whole area. The grid used for the model is the orthogonal curvilinear grid, detailed in coastal regions and islands and sparse offshore where the topography is less variable. The domain measures about 2,800 km North-South and 2,550 km east-west, divided into 404 × 938 points with grid cell size from 47.5 m to 21,197 m (Fig. 1). Along the vertical grid, it was sigma coordinates with eight layers (12.5% of the depth for each layer). Time simulation: 2019–2020, time step: 60 seconds.

The initial condition of the hydrodynamics model: taking advantage of Delft3D software, the initial conditions of the present scenario employed model calculated results from the previous run. In the research area, due to the large domain, there is a significant difference in salinity, temperature, and water level, so the initial condition of the hydrodynamic model is the results calculated in the period before the 3-month radiation emission simulation.

Boundary conditions of hydrodynamics model: river boundaries took average seasonal values of discharge, salinity, and temperature of the principal rivers of the Red - Thai Binh River system, the Mekong River, and the rivers in the Central region. Marine thermal–salt boundary conditions using data from the WOA13 with a resolution of 0.25 degrees for the East Vietnam Sea [24].

The open seaward boundaries of the model include the Kalimantan Straits (Indonesia), Sulu Strait, Mindanao, Luzon (Philippines), and Bashi Strait (Taiwan). The data for these open boundaries are the tidal harmonic constants of the 13 main tidal components, which are M_2, S_2, K_2, N_2, O_1, K_1, P_1, Q_1, MF, MM, M_4, MS_4, MN_4. These tidal harmonic constants were collected and processed from the LEGOS FES2014 database [22].

Meteorological condition: considering the effects of surface wind stress and the temperature exchange across the water surface boundary. Therefore, wind field, air temperature, sky clouds, solar radiation, and atmospheric pressure (3 h, 2.5 deg., NCEP) were used in the simulation [23].

Calibration and validation of the hydrodynamic model:

The model reliability index E (Nash) [34, 35] was used in this study to evaluate the reliability and effectiveness of the model. This index evaluates the number of forecasts that guarantee the allowable reliability [35]:

$$E = 1 - \frac{\sum_{i=1}^{n}\left(O_i - P_i\right)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2} \quad (1)$$

When the value of E approaches 1, the forecasting results have the best performance, whereas when E comes to 0, the forecasts are unreliable. When E has a negative sign (-), the average features calculated from the observed series give better prediction results from the model [33]. Ịn this study, we used measured data at Marine Station (Hon Dau, Co To, Bach Long Vi, Hon Ngu, Con Co) and measured current data from the VT-UD-02/17-20 project. After calibrations, the E value fluctuated between 0.85 and 0.93 for water level and ranged from 0.65 to 0.83 for flow. These results show a good agreement between the calculated value and the model's results.

Radioactive dispersion model:

The radiation propagation model is established based on the hydrodynamic model results: domain extent, grid, topography, calculation results of water level fluctuations, flow fields, temperature, salinity, and bottom stress field. In this study, the select radioactivity was Cs-137, a radioactive isotope of cesium formed by the nuclear fission of uranium 235. Cs-137 has a specific density of about 1,800–1,900 kg/m^3 and a decomposition period of approximately 30.05 years.

The model's diffusion coefficient is based on Bent et al.'s formula [36]. After being adjusted and selected, the coefficients a and b are 1.5 and 0.7, respectively. The model can consider the processes of radioactive exchange through the sediment. However, in this study, we ignore the re-suspension of radioactivity from the deposit. The coefficient of the material element in the Delft3D -Part model is determined through the correction processes. After calibration, the non-periodic velocity component (A0) was selected with 0.0005 m/s, while the time variable cyclic velocity component was 0 m/s.

According to the International Atomic Energy Agency (IEAE) classification, nuclear incidents include seven different levels [37], of which level 7 is the highest accident level or major accident. Level 7 accidents have been documented in several nuclear incidents with widespread health and environmental effects (e.g. Chornobyl, Ukraine, 1986; Fukushima, Japan, 2011). For example, after the Fukushima accident, various studies were conducted to determine how much radiation this plant released into the sea. However, this is extremely difficult, so the claims about radiation are very different: 14.5×10^{15} Bq [38]; $16.2 \pm 1.6 \times 10^{15}$ Bq [39]; $11–16 \times 10^{15}$ Bq [40]. These values differ from those published by Japanese authors, with only about 3.5×10^{15} Bq [13, 15, 40].

The radionuclides source item in this study is the simulation results of the radioactive deposition from the atmosphere if an accident event from the FangChenggang NPP. These sources resulted from the project KC.05.07/16–20, with a simulated grid of 0.1 degrees in resolution. The initial radioactivity released was 10×10^{15} Bq (equal to level 7), equivalent to that used in related studies [13, 15, 40]. Studies related to the Fukushima NPP incident have shown that the amount of radiation released into the atmosphere only occurs in the first 4–5 days after the NPP incident. Then, due to the wind, circulation, and radioactive clouds being carried away, the amount of radiation from the air brought to the sea surface near the incident site concentrated mainly in the early days [21–23]. The amount of radioactive fall that settles during travel also decreases sharply with time and distance from the incident location. The incident time and radioactive fall from the atmosphere to the sea surface is within 24 h, from 0:00 on May 6 to 0:00 on May 7, 2019.

RESULTS AND DISCUSSION

Spatial variation of nuclear radioactivity after the accident

It is assumed that when the accident of FangChenggang NPP occurs, the radioactive material dispersed in the air will fall into the sea

according to the circulation, affecting the entire Gulf of Tonkin and along the coast of Vietnam.

For the surface layer, after one day, the entire coastal area from Quang Ninh to Thanh Hoa is contaminated with nuclear radioactivity, with high concentrations (300–9,350 Bq/m^3). The affected area of the radioactive material expands to 2/3 of the Tonkin Gulf after only 5 days, with radioactivity of 50–350 Bq/m^3. After 10–15 days, radioactive material is present in the Gulf of Tonkin. Highly radioactive material (250–1,050 Bq/m^3) is detected in most of the bay, except the mouth area, which is only about 50–350 Bq/m^3. In addition, radioactive substances are also found in the coastal province of Binh Dinh, with values less than 20 Bq/m^3. After the incident, for about 20–25 days, radioactive material spread to the Vung Tau coastal area. The entire Tonkin Gulf is still radioactive with 150–550 Bq/m^3, especially in coastal regions from Quang Ninh to Thua Thien-Hue; it can reach 250–500 Bq/m^3. Radioactivity in Southern Vietnam's coastal waters is almost less than 50 Bq/m^3.

The radioactive material continued to expand into Ca Mau waters after about one month. However, the radioactive concentration reduced significantly. The entire Tonkin Gulf and the coastal area from Quang Ninh to Thua Thien-Hue can reach 100–500 Bq/m^3. In the coastal area from Quang Nam to Ca Mau Cape, the activity of radioactive substances is smaller, ranging from 50–100 Bq/m^3. After two months, more radioactive material moved into the Southern sea, reducing radioactivity in the Tokin Gulf. The highly radioactive waters are concentrated mainly in the coastal areas of Quang Ninh to Thanh Hoa and from Binh Thuan to Ca Mau, with a value of 150–200 Bq/m^3. The value is almost less than 100 Bq/m^3 in other areas.

The scope of influence of radioactive substances extended to the maximum after three months, and the radioactivity decreased markedly. High levels of radioactive material are only found near the coast of Binh Thuan to Ca Mau Cape, with a value of about 150–320 Bq/m^3. In other areas, the radioactive activity is almost less than 50 Bq/m^3, especially in the Middle East Vietnam Sea, which is virtually unaffected by radioactive material. After 5–6 months, the range of effects and the radioactive substance is narrower. On the coast of Binh Thuan - Ca Mau, the radioactive activity is higher than in other areas, with a value of about 150 Bq/m^3. Different regions of Tonkin Gulf have radiation levels of less than 50 Bq/m^3. From the 7^{th} to the 14^{th} month, the range of waters affected by radioactive material continues to decrease. Radioactive material is concentrated mainly in the coastal waters of Vietnam, with a value of almost less than 50 Bq/m^3, except for Binh Thuan - Ca Mau waters, which can reach 80–100 Bq/m^3. Two years after the incident, in the entire Tonkin Gulf and the coastal area of Vietnam, the radioactivity was less than 20 Bq/m^3 (Fig. 2).

In the middle layer, the range of radioactive waters is quite similar to the surface layer after one day. However, after about five days, the affected area expanded to 2/3 of the Tonkin Gulf, with a value of 50–8,500 Bq/m^3. After 10–15 days, the entire Tonkin Gulf is contaminated with highly radioactive material (250–1,000 Bq/m^3), except the mouth of the bay is only about 50–250 Bq/m^3. In addition, radioactive material can move out of the bay through Quynh Chau Strait and to the south, affecting Binh Dinh waters with values less than 20 Bq/m^3. After 20–25 days since the incident occurred, radioactive material spread as far as Vung Tau waters. The entire Tonkin Gulf still has radioactive material, with 250–550 Bq/m^3. Other seas are almost less than 50 Bq/m^3. The radioactive material continued to expand into Ca Mau waters after about one month. The area with high radioactivity is still located mainly in the Tonkin Gulf (250–500 Bq/m^3). After two months, radioactive material moved more into the Southern sea, reducing radioactivity in the Tonkin Gulf area. The high radioactive activity in the Gulf of Tonkin no longer exists; only the nearshore area can reach 200–300 Bq/m^3. In other regions, the radioactive substances are almost less than 100 Bq/m^3. The influence range of radioactive substances peaks after 3–6 months, and the activity decreases markedly. The high radioactive activity is west of Tonkin Gulf and close to the coast of Binh Thuan to Ca Mau, with values of 100–150 Bq/m^3.

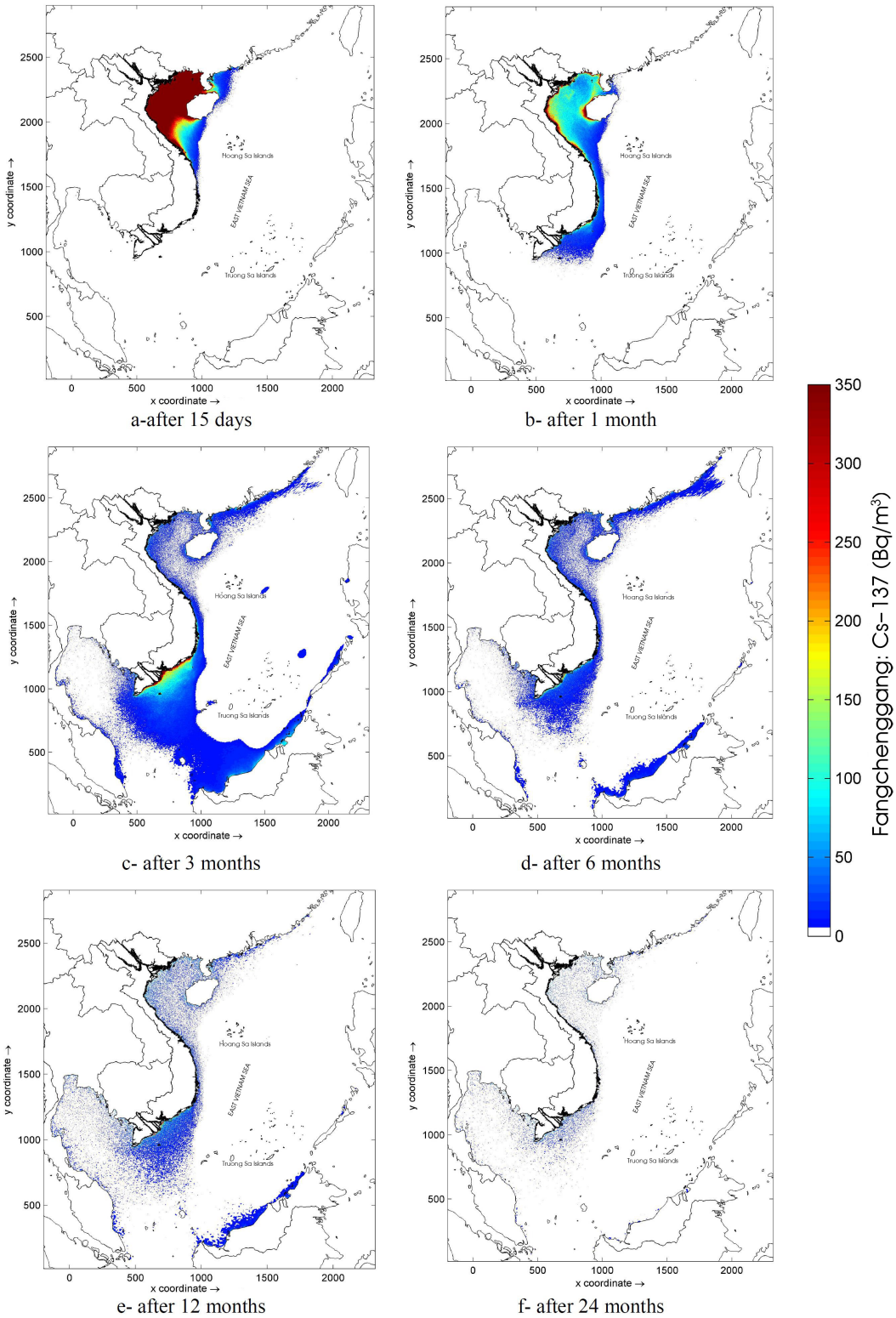

Figure 2. Distribution of Cs-137 concentration (Bq/m^3) in the surface layer during a level 7 incident from FangChenggang NPP with atmospheric sources

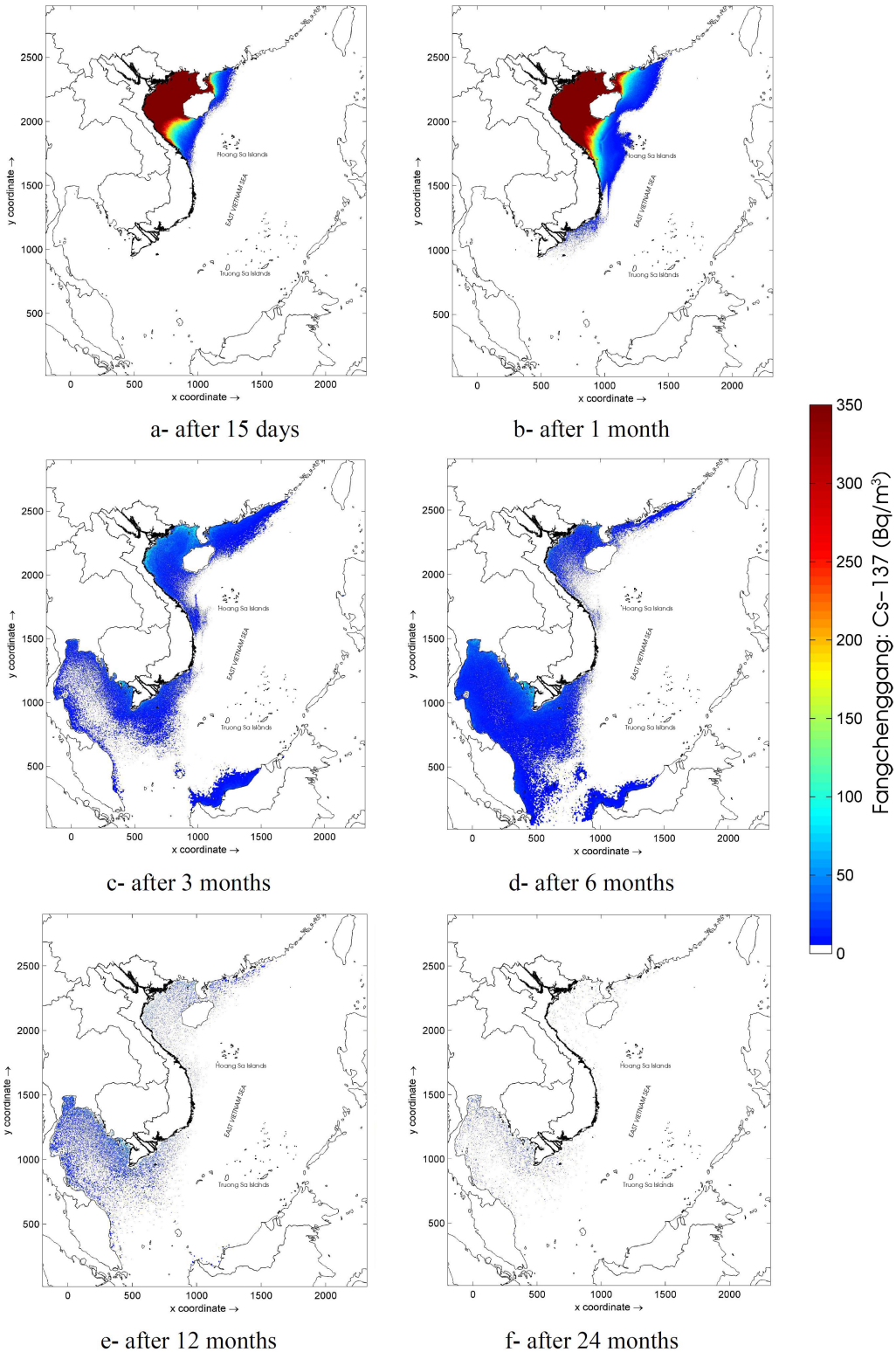

Figure 3. Distribution of Cs-137 concentration (Bq/m^3) in the middle layer during a level 7 incident from FangChenggang NPP with atmospheric sources

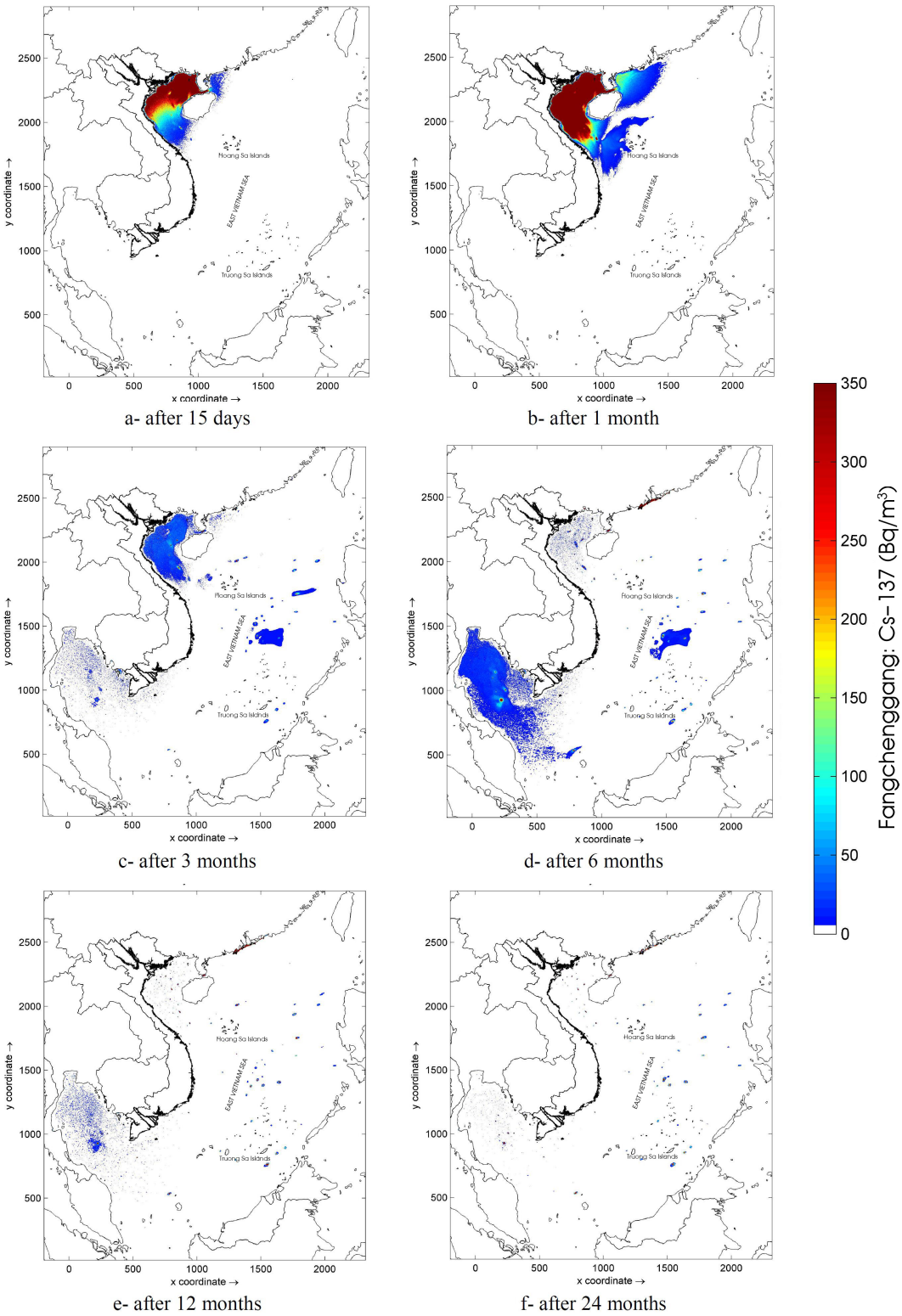

Figure 4. Distribution of Cs-137 concentration (Bq/m^3) in the bottom layer during a level 7 incident from FangChenggang NPP with atmospheric sources

From the 7th to the 15th month, the scope of influence and the level of radioactive substances is narrower. Areas with higher radioactivity are still located near the coast of Tonkin Gulf and Binh Thuan - Ca Mau coastal area, with values less than 80–100 Bq/m^3. Other regions have radioactivity of less than 50 Bq/m^3. The amount of radioactive material decreases from the 16th to the 24th month. In the entire Tonkin Gulf and the coastal area of Vietnam, the radioactive activity is less than 20 Bq/m^3 (Fig. 3).

At the bottom layer, it takes two days for radioactive material to appear in the coastal area of Hai Phong, with a value of about 30–700 Bq/m^3. After five days, the radioactive material was detected mainly in the western part of the Gulf of Tonkin. Areas with high radioactive activity (200–600 Bq/m^3) are smaller than other layers and concentrate primarily in the Hai Phong coastal area. The range of radioactive waters expanded to 2/3 of the Tonkin Gulf after ten days. The area with a radioactive of 250–500 Bq/m^3 is located mainly northwest of Tonkin Gulf and the coastal region from Quang Ninh to Thanh Hoa. The radioactive material then gradually decreases towards the mouth of the bay (less than 50 Bq/m^3). After 15–20 days, the radioactive material expands to the whole Tonkin Gulf. About 2/3 of the Bay area has a value of 300–500 Bq/m^3. The range of areas with high radioactivity (300–550 Bq/m^3) peaks after 25–30 days. Almost the entire Tonkin Gulf is radioactively contaminated with high value, except for areas near the mouth of the bay (less than 200 Bq/m^3). After 2–3 months, the range of radioactive waters is expanded to the middle of the East Vietnam Sea, and the area of high radioactive activity decreases significantly. If after two months, highly active radioactive material is still present in most of Tonkin Gulf, after three months, it is only small areas scattered in the Tonkin Gulf. The radioactive material is expanded to the middle of the Tonkin Gulf and released into the Thailand Gulf, especially after three months. Radioactive material moved to the south more, increasing the activity in the Thailand Gulf and decreasing in the Tonkin Gulf from the fourth to the sixth month. However, the high activity of radioactive substances is only about 150–200 Bq/m^3, which are small areas scattered in Tonkin Gulf, the Thailand Gulf, and the middle of the East Vietnam Sea. From the seventh month onwards, the range of influence and the activity of the radioactive substance reduces significantly. Radioactive material is concentrated mainly in the Gulf of Thailand, with activity ranging from 50 Bq/m^3 to 100 Bq/m^3, mostly still found in small scattered areas with values reaching 150–200 Bq/m^3 in the East Vietnam Sea. Then, the radioactivity decreased significantly and appeared scattered throughout the East Vietnam Sea. About two years after the incident, the radioactivity across the region was less than 20 Bq/m^3 (Fig. 4).

Temporal variation of the radioactive after the accident

The report calculated the average radioactivity for two years in some coastal locations to assess the distribution of radioactive material (Fig. 1). In the surface, 2nd and 3rd layers, the highest levels of radioactive material are found near the incident site (O1–O2), with 100–800 Bq/m^3. The radioactive material gradually decreases to the south and reaches the lowest in Quang Ngai - Phu Yen sea (O12–O15), with a value of only about 0.5–1 Bq/m^3. Radioactivity increases again in the southern region (O17–O23), with 5–30 Bq/m^3. The radioactive material at the surface layer is usually lower than the 2nd and 3rd layers, except for the area of O16–O19 (Fig. 5).

The bottom layer tends to be different from the other layers. The radioactive substance activity is initially smaller than other layers (O1) because moving to the bottom takes a specific time. Then, radioactive substances in this layer tend to be higher than different layers from the middle of Tonkin Gulf to the mouth (O3–O12), with values ranging from 50 Bq/m^3 to 80 Bq/m^3. After that, the radioactive material tends to decrease, with values of almost less than 1 Bq/m^3 (except for the O22 point). At this layer, the average radioactive activity is minimal in Khanh Hoa - Binh Thuan (O16–O17), with activity less than 0.01 Bq/m^3 (Fig. 5).

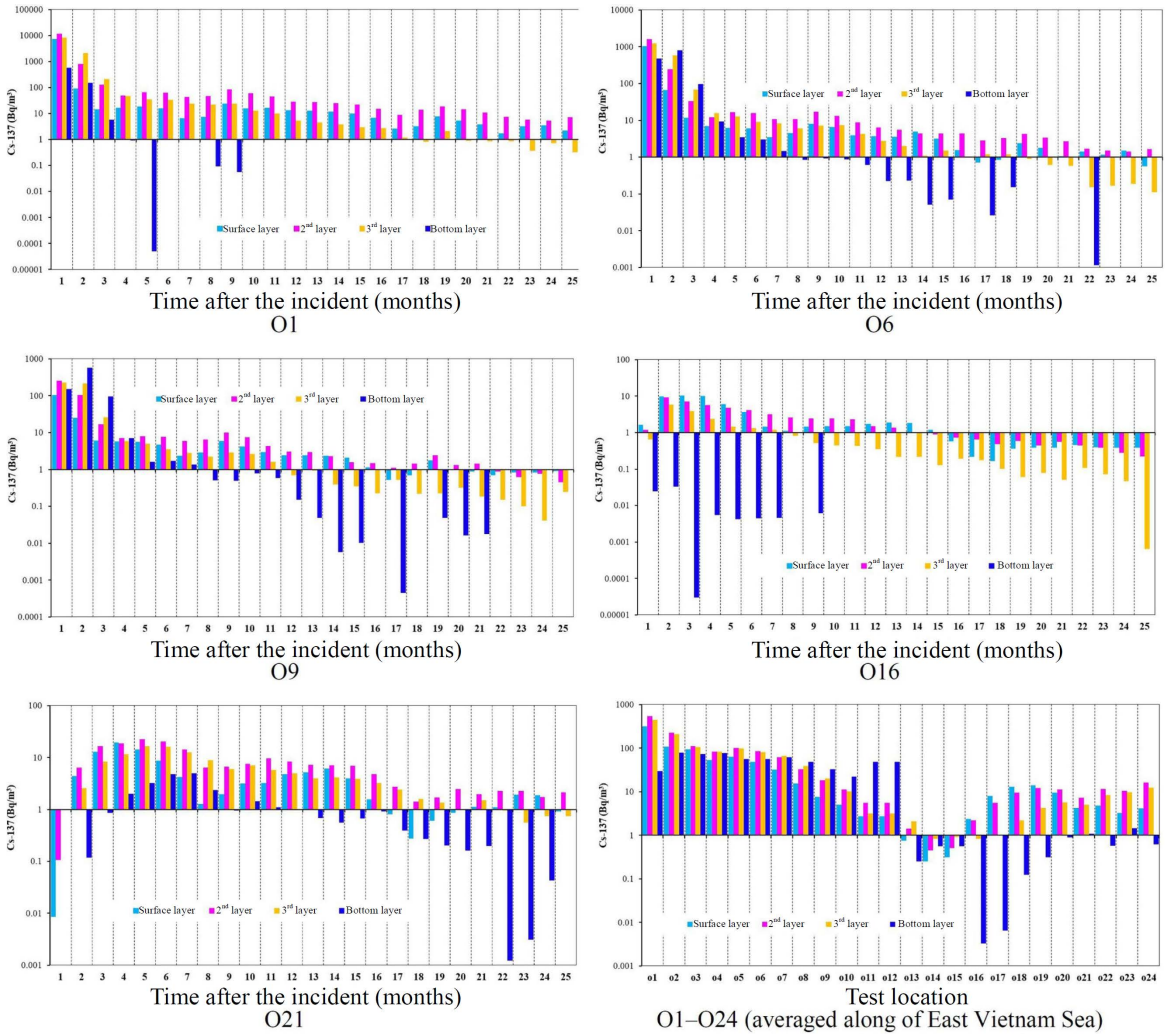

Figure 5. Variation of radioactivity Cs-137 over time at some points

Radioactive substance tends to decrease over time. At point O1, about one month after the incident, the radioactive level is more significant than 900 Bq/m^3, especially in the surface layer. In the 2nd and 3rd layers, they can reach 10,000 Bq/m^3. If the difference of radioactive material in the 3 upper layers is negligible in the first month, this difference is more pronounced from the 2nd month onwards. The greatest level of radioactive material is usually in the 2nd layer, except for the 2nd to 4th month, which falls into the 3rd layer. After 24 months, the radioactive level is still around 3 Bq/m^3 and 10 Bq/m^3 in the surface and 2nd layers. It is less than 1 Bq/m^3 in the 3rd layer from the 18th month onwards. The radioactive substance at the bottom layer is less than that of other layers and lasts the shortest time. It only appears until the 9th month, especially in the 5th month, when the concentration is less than 0.0001 Bq/m^3 (Fig. 4).

In point O2 (south of point O1, Fig. 1b), the simulation results also show a significant difference in radioactive levels between layers. It tends to be higher in the middle layer with a maximum of 9,000 Bq/m^3, as opposed to the bottom layer, which is only about 1,000 Bq/m^3. The general trend is that the radioactive material decreases gradually from January to the following months after the incident. Cs-137 level in the 2nd layer is almost more considerable than in the other layers (except

for February, March, and April). The surface layer has the most significant radioactive level, about 4 Bq/m^3, after 24 months. The 2nd layer is about 3 Bq/m^3, less than 1 Bq/m^3 in the 3rd layer. Particularly in the bottom layer, it is greater than 1 Bq/m^3 to 8 months, then decreases below 1 Bq/m^3 to 11 months and almost no longer from December onwards.

For points O3 and O4, in the first month, there is no significant difference between the three upper layers, with values ranging from 4,000 Bq/m^3 to 10,000 Bq/m^3. Most of the layers' radioactive substances tend to decrease in the following months. While the radioactive level in the bottom layer is smaller than in other layers in the first month, it is higher than others in the 2nd and 3rd months. The difference between the layers is quite significant, especially between the surface and bottom layers. The radioactive activity in the 2nd layer is higher in the following months than in the other layers (except the 4th month). After two years of the incident, the radioactive substances are less than 3 Bq/m^3 in the surface and 2nd layers and less than 1 Bq/m^3 for the 3rd layer. In the bottom layer, 8–9 months, radioactive material sharply reduced to only about 3 Bq/m^3. From the 10th to the 21st month, the radioactive substance is less than 1 Bq/m^3, especially after 22 months, and the bottom layer is not affected by the radioactive substance.

At O5–O6 points, the Cs-137 concentration is almost less than 1,000 Bq/m^3, except for the first and second months can reach 1,200 Bq/m^3. In the first month, the radioactive substance in the upper three layers (surface, 2nd, and 3rd layers) does not differ much, and it is the largest in the 2nd layer. Then, in the 2nd and 3rd months, they have an increasing trend in the lower layers, which makes the 3rd and bottom layers higher in concentration than the upper two layers. In the following months, radioactive substances are highest in the 2nd and 3rd layers and the lowest in the bottom layer. However, there is a common decreasing trend in all layers over time. After two years, the radioactive concentration is almost less than 1 Bq/m^3, especially in the bottom layer, which is practically negligible from November onwards (Fig. 5).

At the O7 point, Cs-137 concentration is almost less than 1,000 Bq/m^3. In the first month, it is the largest in the 2nd layer. After 2–3 months, the amount of radioactive material increases in the lower layer, giving the bottom layer a more excellent value than the above. In the following months, it is almost the highest in the 2nd layer and lowest in the bottom layer. In all layers, there is a common downward trend over time. From the 21st month onwards, Cs-137 concentration is almost less than 2 Bq/m^3 at the surface and second layers. On the 3rd layer, from the 20th month, it is less than 1 Bq/m^3, especially less than 0.0001 Bq/m^3 after two years. From the 9th month onwards, the radioactivity is less than 1 Bq/m^3 for the bottom layer. In the 22nd month, the radioactivity is only about 0.1×10^{-5} Bq/m^3.

From point O8 onwards, Cs-137 concentrations are less than 1,000 Bq/m^3. In the first month, they do not differ much between the layers, and the 2nd layer has the most considerable value. However, after 2–3 months, the difference in concentration is noticeable, and the bottom layer has the most significant value. From the 4th month onwards, the 2nd layer has more significant concentration than the other layers. They tend to decrease over time at all layers. If at O8, the radioactive substance in the surface and 2nd layers is still more significant than 1Bq/m^3 after two years, they are more than 1 Bq/m^3 only until the 21st month at points O9–O10. Cs-137 concentration at the 3rd layer is less than 1 Bq/m^3 and 0.01 Bq/m^3 after ten and 21 months, respectively. For the bottom layer, it is less than 1 Bq/m^3 at the 9th, 10th, and 11th months for points O8, O9, and O10, respectively. In particular, it is less than 0.001 Bq/m^3 at O9 in the 17th month and 0.0001 Bq/m^3 at O10 in the 20th month.

At points O11 and O12, Cs-137 concentration is most significant for the surface and 2nd layers in the first two months, with about 800 Bq/m^3. Then, it gradually decreases to about 1.5–2 Bq/m^3 in the 15th month and less than 1 Bq/m^3 from the 16th month onwards. In the 3rd layer, only from the 7th month onward, the radioactive substance is less than 1Bq/m^3, especially after two years less than 0.1×10^{-6} Bq/m^3. At the bottom layer,

in the first four months, Cs-137 concentration is higher than in other layers and can reach nearly 1,000 Bq/m^3 in the 2nd month after the incident. After that, it decreases gradually and less than 1 Bq/m^3 from the 5th month.

From the O13 to O16 point, Cs-137 concentration is almost less than 10 Bq/m^3. Radioactive substance in the 2nd and 3rd layers is more remarkable than in the others. In O13 and O16 point, it is more significant than 1 Bq/m^3, lasting until the 13th (O13) and the 15th (O16). In the area around point O13, the highest radioactive concentration is found on the 3rd layer in the 2nd month, with about 10 Bq/m^3. In contrast, at the O16 point, it is approximately 10 Bq/m^3 in the 2nd–4th month, falling on the surface or 2nd layer. They are almost less than 1Bq/m^3 in the bottom layer at O13 and O16. It is less than 0.1 × 10^{-6} Bq/m^3 in the 22nd month at O13 and only appears about the first nine months with a minimum value of 0.0001 Bq/m^3 at point O16. For points O14 and O15, in the first month, the radioactive material is less than 1 Bq/m^3 at all layers, then increases to the largest in the second month with 6 Bq/m^3. Radioactive levels greater than 1 Bq/m^3 persist until the 8th–9th month in some layers, then fall below 1 Bq/m^3 in all layers. After 2 years, the radioactive material is only about 0.08 Bq/m^3.

Radioactive substance tends to increase from point O17–O20, with a value of 80–90 Bq/m^3. It is minimal in the first month, then rises and peaks in the 3rd and 4th months. Radioactive concentration from the first to the 5th month, the 12th to 15th month, and the 22nd to 23rd in the surface layer is higher than in other layers. It is the lowest bottom layer at all times, almost less than 1 Bq/m^3. From point O21 to O24, a radioactive substance is almost greater than 1 Bq/m^3. The maximum concentration is about 30 Bq/m^3 in the 3rd to 6th month. In the bottom layer, they are higher than 1 Bq/m^3 in the 3rd to 7th month and less than 1 Bq/m^3 in the remaining months.

Discussion

The range of propagation and release of radiation depends on the leaking radioactivity mass. The range of propagation and release of radiation depends on the leaking radioactivity mass [36]. When a level 7 nuclear accident occurs, in addition to the most affected Tonkin Gulf, the entire East Sea will be contaminated with radiation, in which the concentration of Cs-137 will be higher in the coastal areas and the Red River and the Mekong estuaries, with 50–1,500 Bq/m^3. According to QCVN 10:2008/BTNMT, the permissible limits of a total radioactive substance a and b are 0.1 and 1 Bq/m^3, respectively. If a nuclear incident occurs at FangChenggang NPP, the impacts on the water environment will be enormous, affecting on marine resources and the environment in the East Vietnam Sea. The simulation results in this study show that the radioactivity is relatively high and persists for a long time in the aquatic environment (2–10 Bq/m^3 after two years of the incident) compared to the case of the Fukushima incident [1, 12–14]. This incident can be mainly explained by the topographical conditions in the water area of Japan as open seas, water exchange, and material dispersal into the surrounding seas are very strong under the influence of regional ocean currents, especially Kuroshio currents. Radioactive substances from the Fukushima incident (about 4,300 km from the Tonkin Gulf) have spread to the Gulf of Tonkin, with a Cs-137 level of about 0.67 Bq/m^3 [40, 41]. Meanwhile, the East Vietnam Sea is relatively closed [42, 43]. There is only water exchange through the Taiwan Strait (with the East China Sea), Luzon Strait (with the Pacific Ocean), Karimata Strait (with Java Sea), and a few small straits (with the Sulu Sea), so when a nuclear incident occurs, radioactive activity spreads to nearby seas that are less likely to be retained mainly in coastal and side waters of the East Vietnam Sea with high radioactivity, slow decline, will cause significant consequences on the environment and ecology of the region.

In the early stage of the accident, temporal and spatial variations of FangChenggang NPP-derived radionuclides in air, deposition, and dispersal depend greatly on hydrodynamic conditions, wind fields [14], and source term [44]. The role of hydrodynamic conditions and surface wind field was only evident in the first

three months after the incident when radioactivity was concentrated mainly in the surface layer in the form of radioactive clouds [45, 46]. In this study, compared to sources released directly into the sea [19] with atmospheric sources, it is clear that the effects of nuclear radiation from atmospheric sources in the beginning stage will be slower, depending on meteorological conditions (rainfall and wind). However, this difference only takes place in the early stages after the incident (within one month). After that, the radiation spread rapidly into the waters beyond the Gulf of Tonkin (one month) and covered the entire Vietnam Sea after six months. This result shows that assuming an incident occurs from FangChenggang NPP with a major accident (level 7), the extent of the impact does not depend much on the duration of the incident as well as the manner of dispersal, and can greatly affect the Vietnam Sea in the 6-months after the incident.

CONCLUSION

To predict the impact of radioactive sources from the atmospheric deposition when the FangChenggang NPP accident to the Vietnam Sea, a 3-D hydrodynamic-propagation model system radioactivity has been established. The results show that under the influence of circulation, winds in the area affected by the radioactive material might be the entire East Vietnam Sea. High radioactivity is concentrated mainly in the Tonkin Gulf and along the coast of Vietnam. Especially in the Gulf of Tonkin, the radioactivity can reach 300–1,200 Bq/m^3 after the 5-day incident. After the accident, the radiation spread rapidly into the waters beyond the Gulf of Tonkin (one month) and covered the entire Vietnam Sea after 6 months.

In the water column, the amount of radiation Cs-137 tends to shift gradually between the layers from the surface to the bottom layer: at first higher in the upper layers, then decreasing progressively and increasing in the lower layers. After about two years, the radioactivity incident decreased significantly but still exceeded QCVN 10:2008/BTNMT standards. This incident shows the extreme impact of the nuclear accident at FangChenggang NPP on the East Vietnam Sea area in general and the coastal area of Vietnam in particular.

The study's results only simulated the effect of radioactive sources falling from the air without considering the radiation source directly entering the aquatic environment, the radioactive source re-suspended from the sediment. Therefore, the effect of radiation on the marine environment will be much more significant if the total amount of radiation entering the marine environment is calculated.

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