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EDITED BY

Ruijie Zhang,
Guangxi University, China

REVIEWED BY

Neven Cukrov,
Ruđer Bošković Institute, Croatia
Wu Men,
Nanjing University of Information Science and
Technology, China

*CORRESPONDENCE

Wuhui Lin

✉ linwuhui8@163.com

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Deciphering decadal observation of Fukushima-derived radiocesium in the most polluted port near the Fukushima Daiichi Nuclear Power Plant: from seawater to marine fish

Wuhui Lin^{1,2*}, Yibang Zhang³, Jinqiu Du³, Jiliang Xuan²
and Fei Tuo⁴

¹Polar and Marine Research Institute, College of Harbour and Coastal Engineering, Jimei University, Xiamen, China, ²State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, Ministry of Natural Resources (MNR), Hangzhou, China, ³National Marine Environmental Monitoring Center, Dalian, China, ⁴National Institute for Radiological Protection, Chinese Center for Disease Control and Prevention, Beijing, China

The biological concentration effect of radionuclides in marine fish has exacerbated public anxiety about seafood security in the context of Fukushima nuclear-contaminated water discharged into the ocean. However, the most polluted port near the Fukushima Daiichi Nuclear Power Plant (FDNPP) has seldom been investigated, especially for radioactivity in marine fish. In this study, decadal observations of radiocesium in marine fish and seawater from the most polluted port were simultaneously established after the Fukushima Nuclear Accident. We found a generally decreasing trend of historical ¹³⁷Cs activity in seawater, with seasonal variations modulated by precipitation. Seasonal variations were elucidated with finer detail and divided into exponential decline in the dry season and steady variation in the wet season. A novel method was proposed to estimate the continuing source term of ¹³⁷Cs derived from the FDNPP, which was 3.9 PBq in 2011 and 19.3 TBq between 2012 and 2022 on the basis of historical ¹³⁷Cs. The biological concentration effect of marine fish is quantitatively emphasized according to the higher ratio of over-standards for radiocesium in marine fish relative to that in seawater. Long-term observation and analysis of radiocesium in marine fish and seawater from the most polluted port would provide insights into the scientific evaluation of the effectiveness of the decommissioning of the FDNPP in the past and share lessons on the fate of Fukushima-derived radionuclides in the future.

KEYWORDS

marine fish, ¹³⁷Cs, Fukushima, contaminated water, nuclear pollution

1 Introduction

Large amounts of artificial radionuclides have been released into the atmosphere (e.g., ~160 PBq of ^{131}I , 15 PBq of ^{137}Cs , and 14,000 PBq of ^{133}Xe) and the marine environment (e.g., 11 PBq of ^{131}I and 4 PBq of ^{137}Cs) since the Fukushima Nuclear Accident (FNA) on 11 March 2011 (Lin et al., 2016; Povinec et al., 2021). It has been estimated that 74% of Fukushima-derived artificial radionuclides released into the atmosphere were deposited in the North Pacific Ocean (Povinec et al., 2021), probably contributing to the FNA being the most serious nuclear accident that directly pollutes the marine environment with radioactive material (Lin et al., 2016). Artificial radionuclides are continuously discharged from the most polluted port (Figure 1) near the Fukushima Daiichi Nuclear Power Plant (FDNPP) (Machida et al., 2023). Subsequently, Fukushima-derived radionuclides have been widely elevated from the coastal sea to the open ocean (Povinec et al., 2021).

The most polluted port near the FDNPP serves as windows to reflect the progress and effectiveness of decommissioning of the FDNPP, which is inaccessible to the public and to many other countries around the world. Recently, extremely high $^{134}\text{Cs} + ^{137}\text{Cs}$ activity of 1.8×10^4 Bq/kg in marine fish from the most polluted port was reported to be 180 times higher than the Japanese regulatory limit (100 Bq/kg-wet) on 18 May 2023 (Tokyo-Electric-Power-Company, 2023a). Despite the continuous discharge of artificial radionuclides and frequent reports of abnormally high levels of radiocesium in marine fish, the most polluted port with the highest radioactivity near the FDNPP has seldom been investigated (Kanda, 2013; Machida et al., 2020, 2023), especially with regard to radioactivity in marine fish.

The biological concentration effect of radionuclides in marine fish has exacerbated public anxiety in the context of nuclear-contaminated water with 64 radionuclides discharged into the ocean (Buessler, 2020; Lin et al., 2021; Liu et al., 2022). In this study, we primarily focus on the long-term observation of radiocesium in marine fish because seafood consumption is the dominant pathway of ionizing radiation to humans and is a primary concern of the public and countries around the Pacific Ocean after the FNA. Additionally, historical levels of radiocesium in seawater are simultaneously discussed to reveal its effect on marine fish. We also attempted to determine the mechanisms of seasonal fluctuation

of ^{137}Cs in seawater in order to identify potential leak events, estimate the continuing source terms of ^{137}Cs discharged from the port, and verify the effectiveness of multiple countermeasures in the most polluted port near the FDNPP.

2 Materials and methods

2.1 ^{134}Cs and ^{137}Cs in seawater from the port

The most polluted port (Figure 1) near the FDNPP is inaccessible to the public and many other countries around the world. The availability and transparency of historical radioactivity in the most polluted port near the FDNPP played a key role in verifying the progress after the decommissioning of the FDNPP. We downloaded 1,196 daily reports of radiocesium in seawater provided by the Tokyo Electric Power Company (TEPCO) from 2 April 2011 to 30 June 2014 and 114 monthly reports of radiocesium in seawater released by the Ministry of Economy, Trade and Industry (METI) from July 2013 to April 2023 (Tokyo-Electric-Power-Company, 2011; Ministry-of-Economy-Trade-and-Industry, 2023b, 2018). The TEPCO's daily reports from 2 April 2011 to 30 June 2014 included 3–14 monitoring stations in the port, while the METI's monthly reports from July 2013 to April 2023 encompassed 9–14 monitoring stations in the port. In order to conservatively evaluate the radioactive level in seawater from the port, we chose and compiled the highest values of ^{134}Cs and ^{137}Cs activities among 3–14 stations in the port from the above-mentioned daily/monthly reports. If the data in the daily/monthly reports were lower than the minimum detection activity (MDA), the MDA was utilized for discussion. The highest value of ^{134}Cs and ^{137}Cs activity in a typical report is selected and shown in Figure 2.

2.2 ^{134}Cs and ^{137}Cs in marine fish from the port

Radiocesium levels in marine fish were compiled from 130 monthly reports provided by TEPCO from December 2012 to May 2023 (Tokyo-Electric-Power-Company, 2018, 2023b). There were seven fishing areas in the port (Figure 3) (Tokyo-Electric-Power-

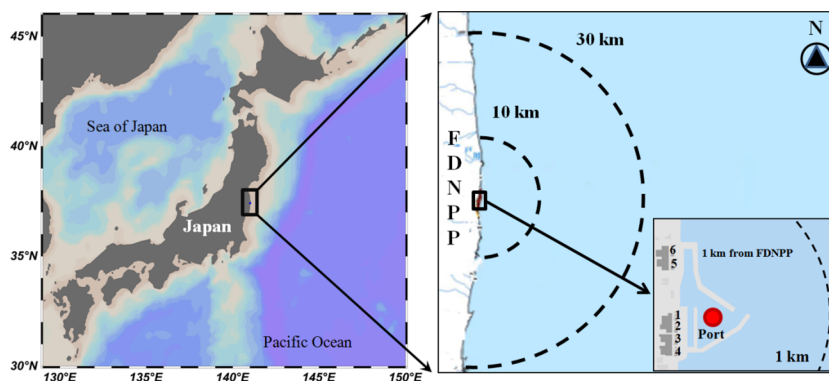


FIGURE 1
Map of the most polluted port near the FDNPP.

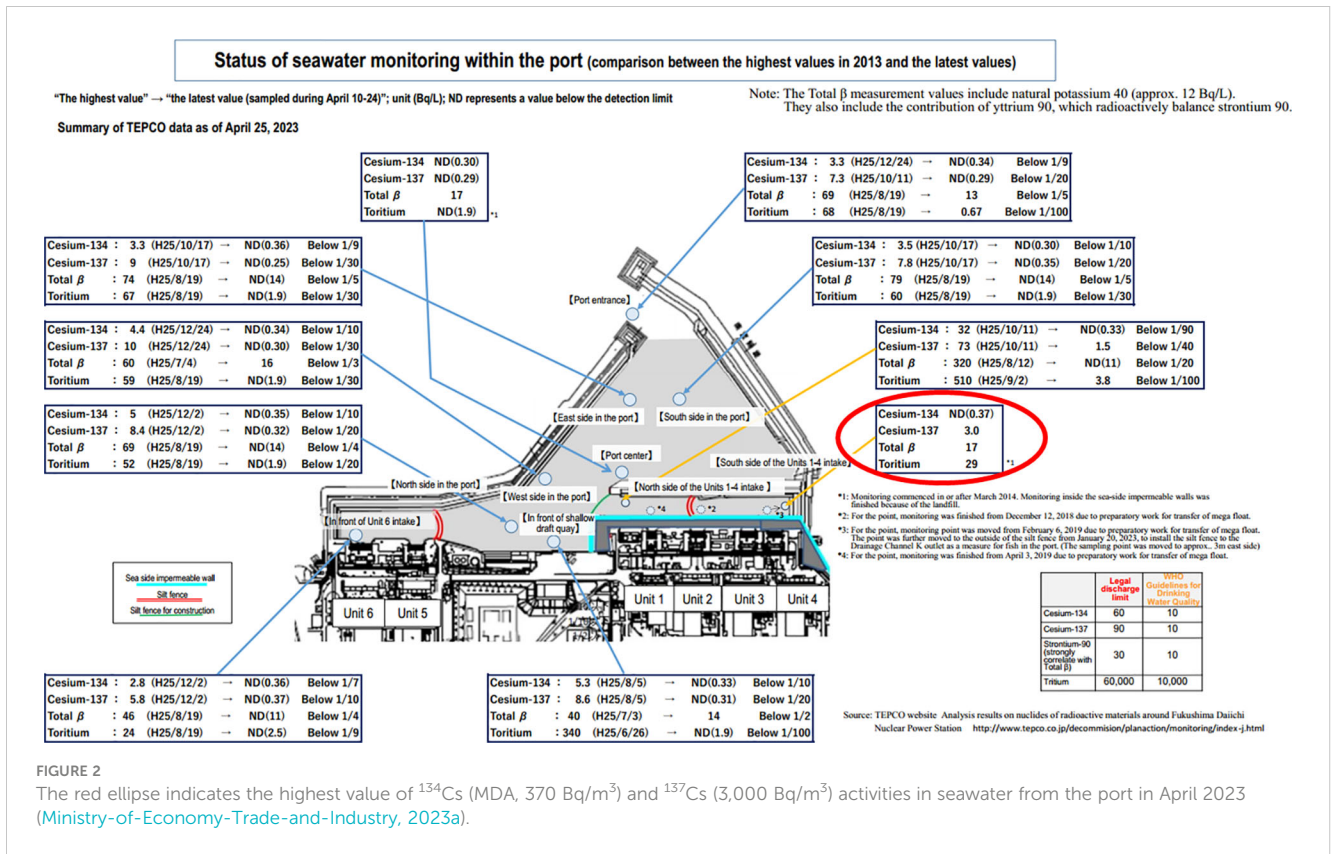
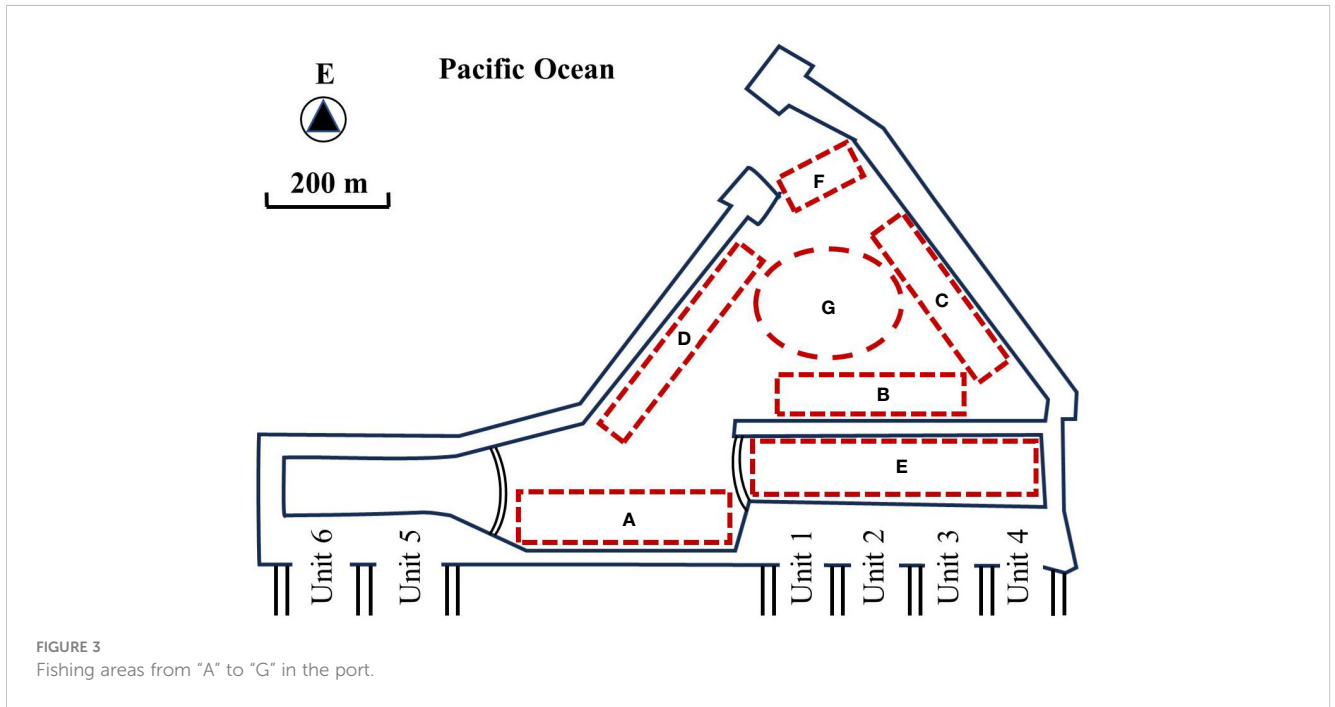


FIGURE 2
 The red ellipse indicates the highest value of ¹³⁴Cs (MDA, 370 Bq/m³) and ¹³⁷Cs (3,000 Bq/m³) activities in seawater from the port in April 2023 (Ministry-of-Economy-Trade-and-Industry, 2023a).

Company, 2013). The typical species of marine fish from the port included *Conger myriaster*, *Hexagrammos otakii*, *Microstomus achne*, *Paralichthys olivaceus*, *Pleuronectes yokohama*, and *Sebastes cheni* (Tokyo Electric Power Company, 2023b). Detailed information on the size, diet, and habitat of marine fish was not provided in the monthly reports, probably because of the large number of fish and the temporal variations of fish species in the port. We conservatively

selected and compiled the highest value of ¹³⁴Cs and ¹³⁷Cs activities in the muscle of marine fish caught from seven fishing areas in the port to conservatively evaluate the radiological impact. The value of MDA was utilized in the condition of the activity of radiocesium below the MDA. Only the maximum activity in marine fish was selected in order to discuss the relationship between radiocesium in seawater and marine fish; it was consistent with the highest value in seawater.



2.3 Data on precipitation in Fukushima Prefecture

In order to investigate the mechanism of seasonal variation of ^{137}Cs in the port, we downloaded 145 monthly precipitation reports in Naniue and Tomioka near the FDNPP released by the Japan Meteorological Agency (JMA) from May 2011 to May 2023 (Japan-Meteorological-Agency, 2023). We calculated and compiled the mean value of monthly precipitation in Naniue and Tomioka because the FDNPP is located between them (Figure 4). The average monthly precipitation (119.8 mm) from May 2011 to May 2023 was calculated to define the wet season and the dry season in Fukushima Prefecture.

3 Results and discussion

3.1 Historical observation of ^{137}Cs activity in seawater from the port

Historical ^{137}Cs activity in seawater (Figure 5) from the most polluted port was systematically compiled from April 2011 to April 2023 based on 1,310 documents that were officially released by TEPCO and METI. Although the historical ^{137}Cs activity in seawater generally decreased due to the continuing decommissioning work at the FDNPP, the most recent monthly ^{137}Cs activity in seawater ($3 \times 10^3 \text{ Bq/m}^3$ in April 2023) was still over 1,000 times higher than the background value ($1\text{--}2 \text{ Bq/m}^3$) of ^{137}Cs before the FNA (Povinec et al., 2021). In this study, the historical ^{137}Cs activity in seawater was divided into three periods: April 2011 to June 2011 (purple area in region I), July 2011 to January 2016 (brown area in region II), and February 2016 to April 2023 (green area in region III).

Region I from April 2011 to June 2011 was recognized as the initial stage of FNA and was characterized by the direct discharge of contaminated water into the coastal sea. Two peaks of ^{137}Cs — $1.9 \times 10^{12} \text{ Bq/m}^3$ on 2 April 2021 and $1.2 \times 10^9 \text{ Bq/m}^3$ on 12 May 2021—were clearly recorded, corresponding to two leak events

officially confirmed by TEPCO in 1–6 April and 10–11 May (Kanda, 2013). A sudden decline in ^{137}Cs activity was subsequently observed after TEPCO's operation to stop the leak in front of Unit 2 on 4 April 2016 (Kanda, 2013). The most significant phenomenon in region I was the appearance of an extremely high ^{137}Cs value, followed by a rapid exponential decline.

“Region II from July 2011 to January 2016 was defined because of the completed construction of the seaside impermeable walls in February 2016 after carefully comparing the progress after the decommissioning in the monthly reports from METI in January and February 2016. The ^{137}Cs activity gradually decreased in region II due to the continuing decommissioning work, such as the relocation of the drainage channels from June 2014 to April 2015, the seabed covering of the port in April 2015, the removal of highly contaminated retained water in December 2015, the filling of tunnels and towers in December 2015, and the completed construction of seaside impermeable walls in February 2016 (Machida et al., 2020, 2023). Seasonal fluctuation of ^{137}Cs activity was also observed, in addition to a decreasing trend at a slower rate in region II relative to a rapidly decreasing rate in region I. It was obvious that the average ^{137}Cs activity ($7.0 \times 10^3 \text{ Bq/m}^3$) in region III from February 2016 to April 2023 was approximately 40 times lower than that ($2.7 \times 10^5 \text{ Bq/m}^3$) in region II after the completed construction of seaside impermeable walls. However, a seasonal variation of ^{137}Cs without a significant decreasing trend is shown in region III.

3.2 Estimation of continuing source terms of ^{137}Cs based on the wet–dry season model

Although the key feature of the seasonal variation of ^{137}Cs has been observed after the initial stage of FNA, the factors influencing the seasonal variation of ^{137}Cs have not been discussed in detail (Machida et al., 2020). To determine the seasonal variations of ^{137}Cs activity in seawater from July 2011 to April 2023 in detail, ^{137}Cs activity and monthly precipitation were simultaneously displayed to

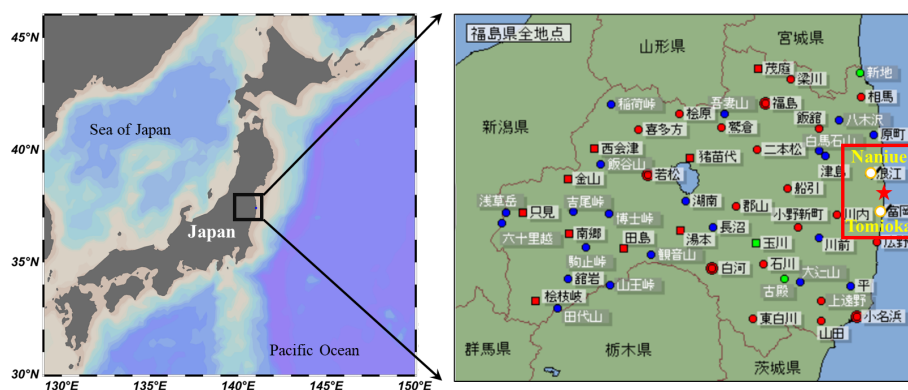


FIGURE 4

Map of Naniue and Tomioka. The star in the red rectangle represents the location of the FDNPP (Japan-Meteorological-Agency, 2023).

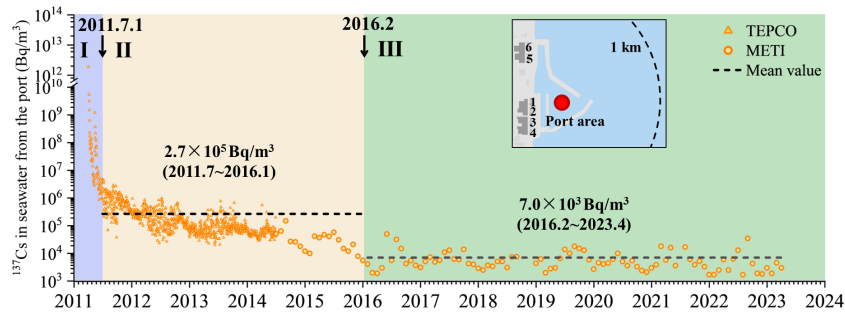


FIGURE 5
Historical ¹³⁷Cs activity in seawater from the most polluted port near the FDNPP from April 2011 to April 2023.

reveal the contrasting patterns of the exponential decrease of ¹³⁷Cs in the dry season (light blue in Figure 6) and the steady variation of ¹³⁷Cs in the wet season (yellow in Figure 6).

It was reasonable to expect the exponential decline in ¹³⁷Cs activity from the port, analogous to previous studies on the exponential decrease of ¹³⁷Cs activity in river water, seawater, sediment, and marine biotas because of the decommissioning work and stabilization at the FDNPP (Povinec et al., 2021). The exponential decline in ¹³⁷Cs activity in the dry season is well-fitted and quantitatively depicted with effective half-lives (EHLs) in different time intervals in Figure 6 and Table 1. Two groups of

EHLs have been quantified: 0.14 ± 0.03 a (seven time intervals fitted with red lines) and 0.41 ± 0.26 a (six time intervals fitted with green lines). The EHLs of ¹³⁷Cs in region II and region III were much longer than those in region I (1.58 d) at the initial stage of the FNA (Kanda, 2013), implying multiple continuing source terms of ¹³⁷Cs to lengthen EHLs and slow down the decreasing trend in the port after the initial stage of the FNA. The apparent decreasing rate (k_2) in the dry season is calculated in Table 1. Combined with the exchange rate ($k_1 = 0.44 \text{ d}^{-1}$) and seawater volume ($2.78 \times 10^5 \text{ m}^3$) in the port from Kanda (2013), the source terms of ¹³⁷Cs in the dry season could be quantified according to Equations 3, 4.

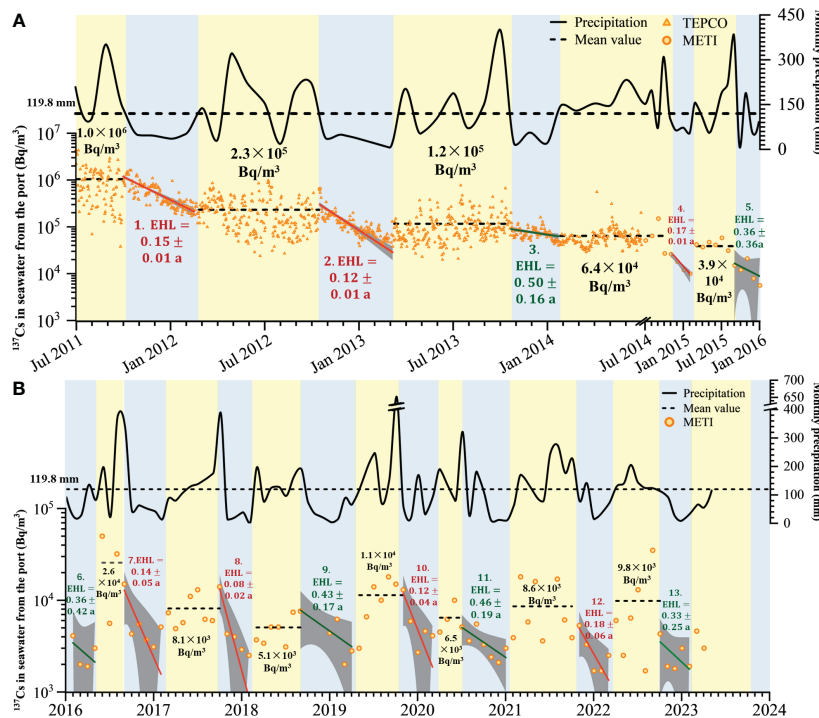


FIGURE 6
Seasonal variations of ¹³⁷Cs in seawater from the port and monthly precipitation in Fukushima Prefecture from July 2011 to January 2016 (A) and February 2016 to April 2023 (B). The average monthly precipitation is presented with a dotted line to distinguish the wet season (yellow) from the dry season (light blue). Effective half-lives (EHLs) and average ¹³⁷Cs activity are quantitatively displayed for the dry season and wet season, respectively.

TABLE 1 Exponential fitting, EHLs, and apparent decreasing rate (k_2) of time intervals in dry seasons.

Group	Time	Exponential fitting	r	p	EHL (a)	k_2 (a^{-1})	Mean value of EHL	Mean value of k_2
1	20111002–20120225	$A = 1.2 \times 10^6 \times e^{-4.6 \times (T-2011.10.2)}$	0.80	6.2×10^{-27}	0.15 ± 0.01	4.56 ± 0.34	0.14 ± 0.03 a	$4.95 \pm 1.06a^{-1}$
	20121016–20130307	$A = 3.1 \times 10^5 \times e^{-6.0 \times (T-2012.10.16)}$	0.75	5.9×10^{-23}	0.11 ± 0.01	6.08 ± 0.51		
	201411–201502	$A = 2.5 \times 10^4 \times e^{-4.2 \times (T-2014.11)}$	0.99	6.4×10^{-3}	0.17 ± 0.01	4.18 ± 0.34		
	201609–201702	$A = 1.2 \times 10^4 \times e^{-5.1 \times (T-2016.9)}$	0.80	0.06	0.14 ± 0.05	5.06 ± 1.99		
	201710–201802	$A = 1.3 \times 10^4 \times e^{-8.2 \times (T-2017.10)}$	0.94	0.04	0.08 ± 0.02	8.18 ± 2.25		
	201911–202003	$A = 1.1 \times 10^4 \times e^{-5.6 \times (T-2019.11)}$	0.87	0.06	0.12 ± 0.04	5.57 ± 1.95		
	202110–202203	$A = 5.0 \times 10^3 \times e^{-3.9 \times (T-2021.10)}$	0.86	0.06	0.18 ± 0.06	3.90 ± 1.36		
2	20131021–20140122	$A = 8.6 \times 10^4 \times e^{-1.4 \times (T-2013.10.17)}$	0.32	2.2×10^{-3}	0.50 ± 0.16	1.40 ± 0.44	0.41 ± 0.26 a	$1.69 \pm 1.07a^{-1}$
	201509–201601	$A = 1.7 \times 10^4 \times e^{-1.9 \times (T-2015.9)}$	0.55	0.38	0.36 ± 0.36	1.90 ± 1.87		
	201602–201605	$A = 3.4 \times 10^3 \times e^{-1.9 \times (T-2016.2)}$	0.49	0.47	0.36 ± 0.42	1.94 ± 2.21		
	201809–201904	$A = 7.6 \times 10^3 \times e^{-1.6 \times (T-2018.9)}$	0.82	0.09	0.43 ± 0.17	1.57 ± 0.63		
	202007–202012	$A = 5.2 \times 10^3 \times e^{-1.5 \times (T-2020.7)}$	0.75	0.06	0.46 ± 0.19	1.51 ± 0.62		
	202210–202302	$A = 3.5 \times 10^3 \times e^{-2.1 \times (T-2022.10)}$	0.59	0.28	0.33 ± 0.25	2.06 ± 1.60		
Kanda, 2013	20110406–20110419					1.58 d	$0.44 d^{-1}$	

$$V \frac{dA_{137Cs}}{dt} = S_{dry} - k_1 A_{137Cs} V = -k_2 A_{137Cs} V \tag{1}$$

$$S_{dry} = (k_1 - k_2) A_{137Cs} V \tag{2}$$

where A_{137Cs} refers to the ^{137}Cs activity in seawater. V and S_{dry} are the mean volume of seawater and the source terms of ^{137}Cs in the port during the dry season, respectively. k_1 and k_2 are the exchange rate of the port with outer seawater and the apparent decreasing rate of ^{137}Cs in the port, respectively (see values in Table 1).

By contrast, the steady variation of ^{137}Cs without the decreasing trend in the wet season is illustrated in Figure 6. We found that the average ^{137}Cs activities in wet seasons from July 2011 to January 2016 also gradually decreased from 1.0×10^6 Bq/m³ to 3.9×10^4 Bq/m³ in Figure 6A. The average ^{137}Cs activities in wet seasons from February 2016 to April 2023 varied from 5.1×10^3 Bq/m³ to 2.6×10^4 Bq/m³ without a decreasing trend in Figure 6B. Previous studies have pointed out that the ^{137}Cs activity in the river and coastal sea has been significantly elevated during the flood season, especially

with the additional influences of typhoons and storms (Tanaka et al., 2022; Uchiyama et al., 2022). The positive relationship between ^{137}Cs activity and monthly precipitation ($r = 0.44$, $p < 0.0001$) from February 2016 to April 2023 is also shown in Figure 7. Precipitation probably contributed to the additional input of ^{137}Cs into the port via leaching and erosion of ^{137}Cs from a terrestrial environment in the wet season, resulting in the steady variation of ^{137}Cs activity in the wet season in contrast to a decreasing trend of ^{137}Cs in the dry season. The source terms of ^{137}Cs in the wet season could be quantified according to Equation 3, Equation 4.

$$V \frac{dA_{137Cs}}{dt} = S_{wet} - k_1 A_{137Cs} V = 0 \tag{3}$$

$$S_{wet} = k_1 A_{137Cs} V \tag{4}$$

where S_{wet} refers to the source terms of ^{137}Cs in the wet season. Other parameters are the same as in Equations 1, 2.

Therefore, historical ^{137}Cs activity and its associated mechanisms are suggested to be delicately classified into the wet

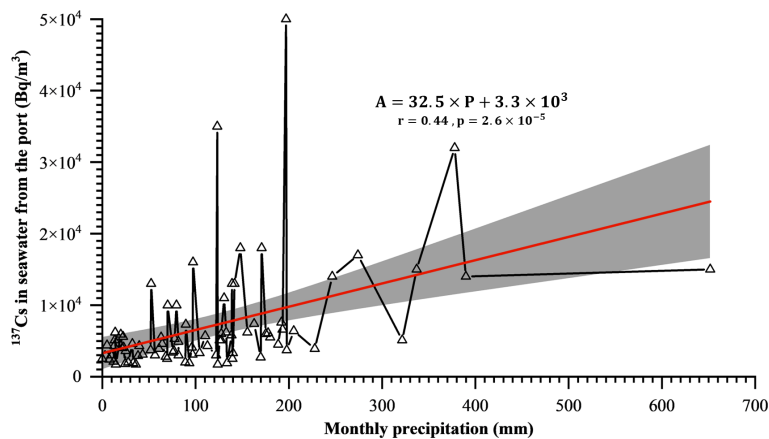


FIGURE 7 Positive relationship between ¹³⁷Cs activity from the port and monthly precipitation from February 2016 to April 2023.

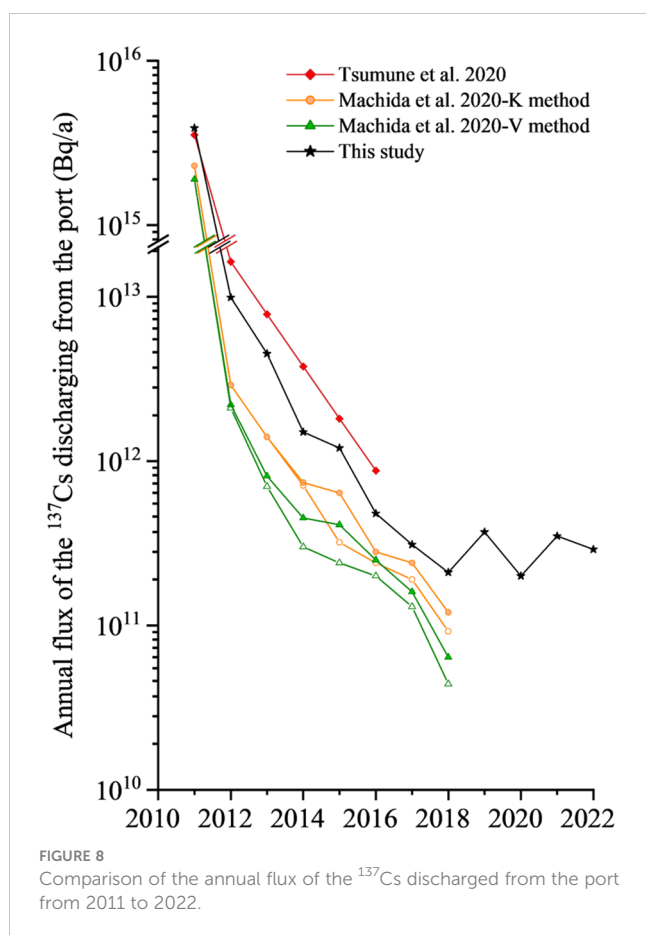
season and the dry season for quantitative discussion. Our study also implied that the source terms of radionuclides derived from the FDNPP to the Pacific Ocean should be different between the wet season (Equation 2) and the dry season (Equation 4) rather than a simple assumption of steady state in previous studies (Kanda, 2013; Machida et al., 2020, 2023). The annual flux of ¹³⁷Cs discharged from the port to outer seawater was 3.9 PBq in 2011 and 19.3 TBq from 2012 to 2022, which is generally consistent with previous studies, as shown in Table 2 and Figure 8 (Machida et al., 2020).

3.3 Delayed increase of ¹³⁴ + ¹³⁷Cs in marine fish following the ¹³⁴ + ¹³⁷Cs peak in seawater from the port

The long-term monthly ¹³⁴ + ¹³⁷Cs activity in marine fish and the corresponding value in seawater from the most polluted port are simultaneously shown in Figure 9 from December 2012 to May 2023. A clear decline in ¹³⁴ + ¹³⁷Cs activity in marine fish was observed before February 2016, consistent with the decreasing trend

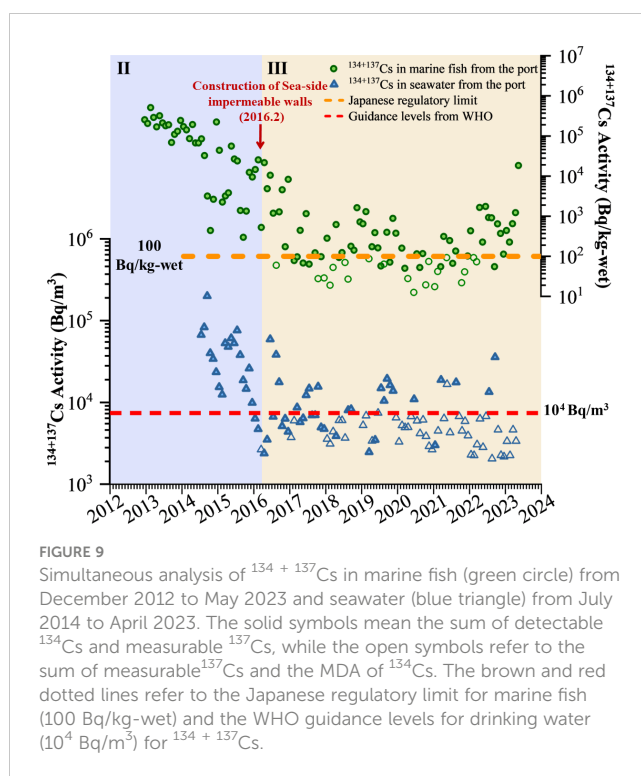
TABLE 2 Comparison of the annual flux of the ¹³⁷Cs discharged from the port.

Year	Annual flux of ¹³⁷ Cs (Bq/a)					This study
	Tsumune et al (Tsumune et al., 2020)	Machida-V method (Machida et al., 2020)		Machida-K method (Machida et al., 2020)		
		Min	Max	Min	Max	
2011	3.55×10 ¹⁵	1.9×10 ¹⁵	1.9×10 ¹⁵	2.3×10 ¹⁵	2.3×10 ¹⁵	3.9×10 ¹⁵
2012	1.63×10 ¹³	2.1×10 ¹²	2.2×10 ¹²	2.9×10 ¹²	2.9×10 ¹²	9.9×10 ¹²
2013	7.81×10 ¹²	7.0×10 ¹¹	8.1×10 ¹¹	1.4×10 ¹²	1.4×10 ¹²	4.5×10 ¹²
2014	3.76×10 ¹²	3.0×10 ¹¹	4.5×10 ¹¹	7.1×10 ¹¹	7.4×10 ¹¹	1.5×10 ¹²
2015	1.81×10 ¹²	2.4×10 ¹¹	4.1×10 ¹¹	3.2×10 ¹¹	6.4×10 ¹¹	1.2×10 ¹²
2016	8.75×10 ¹¹	2.0×10 ¹¹	2.5×10 ¹¹	2.4×10 ¹¹	2.8×10 ¹¹	4.8×10 ¹¹
2017		1.3×10 ¹¹	1.6×10 ¹¹	1.9×10 ¹¹	2.4×10 ¹¹	3.1×10 ¹¹
2018		4.4×10 ¹⁰	6.4×10 ¹⁰	9.2×10 ¹⁰	1.2×10 ¹¹	2.1×10 ¹¹
2019						3.7×10 ¹¹
2020						2.0×10 ¹¹
2021						3.5×10 ¹¹
2022						2.9×10 ¹¹



of $^{134} + ^{137}\text{Cs}$ activity in seawater (Figures 9, 10A). In contrast, periodic increases in $^{134} + ^{137}\text{Cs}$ activity without a decreasing trend in marine fish and seawater were observed after February 2016 (Figure 10B). The Japanese regulatory limit for marine fish (100 Bq/kg-wet) and the WHO guidance levels for drinking water (10,000 Bq/m³) for $^{134} + ^{137}\text{Cs}$ were adopted to evaluate the radioactive level. We found that the ratio of over-standard for $^{134} + ^{137}\text{Cs}$ in marine fish (>100 Bq/kg-wet) was 100% from December 2012 to January 2016 and 59% from February 2016 to May 2023. Meanwhile, the ratio of over-standard for $^{134} + ^{137}\text{Cs}$ in seawater (>10,000 Bq/m³) was 89.5% from July 2014 to January 2016 and 20.5% from February 2016 to April 2023. Obviously, the ratio of over-standard for $^{134} + ^{137}\text{Cs}$ in marine fish was higher than that in seawater, probably attributed to the biological concentration effect of marine fish.

Additionally, the delayed increase in $^{134} + ^{137}\text{Cs}$ activity in marine fish following the $^{134} + ^{137}\text{Cs}$ peak in seawater is also depicted by the orange shadow in Figures 10A, B. The positive relationship of peak $^{134} + ^{137}\text{Cs}$ activity between marine fish and seawater is well-fitted in Figure 11 ($r = 0.99$, $p < 0.0001$) on the basis of the corresponding peaks of $^{134} + ^{137}\text{Cs}$ activity in marine fish and seawater. The concentration factors of $^{134} + ^{137}\text{Cs}$ in marine fish ranged from 29 L/kg to 514 L/kg, with an average value of 136 L/kg from February 2016 to May 2023. The average value of 136 L/kg in marine fish was consistent with the recommended value of 100 L/kg



provided by the IAEA (2004), confirming the corresponding relationship of $^{134} + ^{137}\text{Cs}$ peaks between marine fish and seawater.

It was noted that radiocesium in sediment also contributed to the elevated activity of radiocesium in marine fish (Wang et al., 2018; Song et al., 2020). Unfortunately, radiocesium in the sediment from the most polluted port was not available from TEPCO and METI, limiting our discussion of the pathway of sediment ingestion by marine fish. However, the continuing source of radiocesium derived from the FDNPP should increase radiocesium levels in seawater followed by those in sediment and marine fish. The corresponding peaks of radiocesium between seawater and marine fish should be logically correlated. Even so, radiocesium in the sediment from the most polluted port should be measured for a better understanding of frequent reports of extremely high radiocesium levels in marine fish from the port in the future.

4 Conclusion

Overall, we revealed the distinct seasonal patterns of an exponential decline in the dry season and steady variation in the wet season in detail based on the historical ^{137}Cs activity in seawater and proposed a novel method to quantify the continuing source terms of ^{137}Cs derived from the FDNPP (3.9 PBq in 2011 and 19.3 TBq from 2012 to 2022). Moreover, the biological concentration effect of marine fish was quantitatively emphasized on the basis of the higher ratio of excess $^{134} + ^{137}\text{Cs}$ in marine fish compared to seawater. Long-term observation and analysis of radiocesium in marine fish and seawater from the most polluted port would benefit

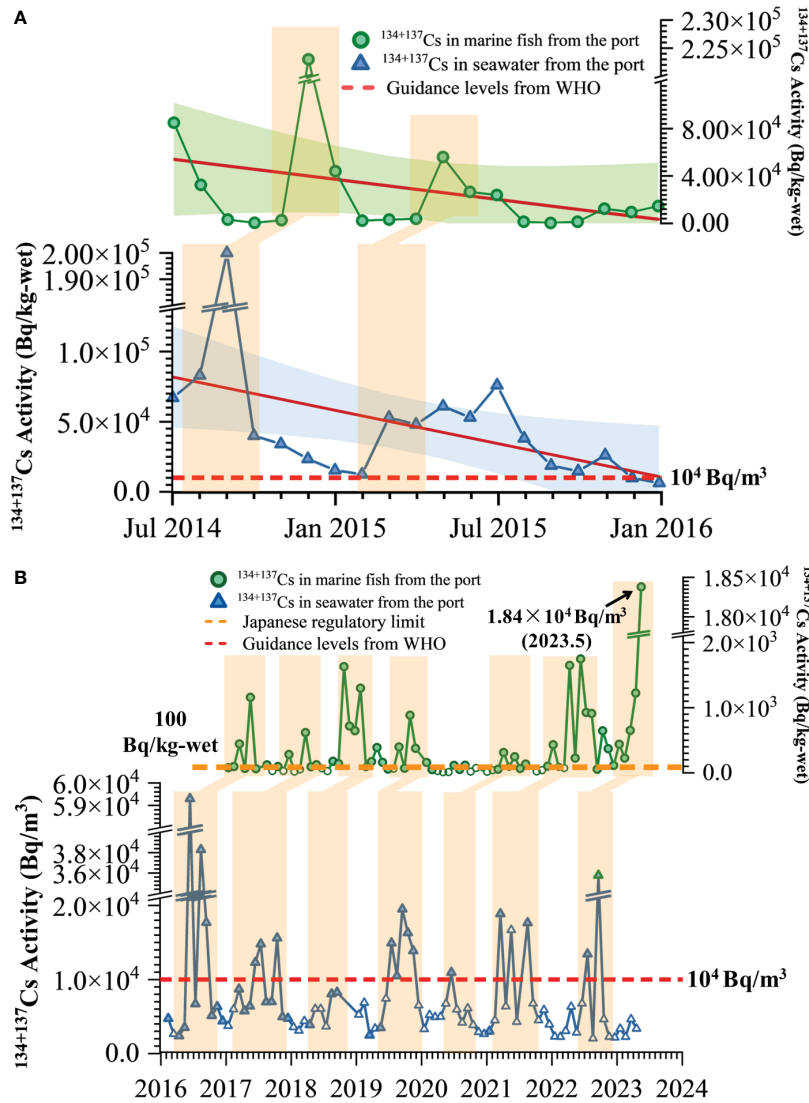


FIGURE 10 Delayed increase of $^{134} + ^{137}\text{Cs}$ in marine fish following the $^{134} + ^{137}\text{Cs}$ peak in seawater from July 2014 to January 2016 (A) and February 2016 to May 2023 (B). The orange rectangles indicate the corresponding $^{134} + ^{137}\text{Cs}$ peak in marine fish and seawater.

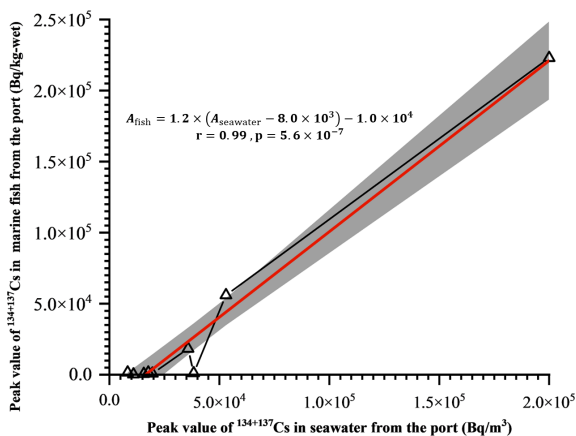


FIGURE 11 Positive relationship between the corresponding peak of $^{134} + ^{137}\text{Cs}$ activity in marine fish and seawater.

the scientific evaluation of the decommissioning of the FDNPP, and share lessons on the fate of Fukushima-derived radionuclides in the marine environment for the prediction and assessment of nuclear-contaminated water discharged into the ocean.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

WL: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project

administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft. YZ: Methodology, Software, Visualization, Writing – original draft. JD: Data curation, Formal analysis, Resources, Visualization, Writing – original draft. JX: Funding acquisition, Methodology, Resources, Software, Writing – original draft. FT: Methodology, Resources, Visualization, Writing – original draft.

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