Problem Chosen	2025 ShuWei Cup Summary Sheet	Team Control Number
D		SHUWEICUP2550146

Modeling and Optimization Research on the Impacts of Fukushima Nuclear Wastewater Discharge on the Marine Environment

Summary

This study simulates the ten-year diffusion process of radionuclides in the ocean, builds a risk assessment model for the possible impacts of six typical countries, and respectively, establishes three-dimensional assessment models. The impact of three known scenarios on the marine environment is quantified on a 30-year scale, which allows for the nuclear wastewater treatment scheme's evaluation and optimization.

For question one: The first question is to establish a diffusion model based on multi-source data from 2023 to 2025 to simulate the diffusion process of nuclides in the ocean within 0-10 years,in Figure3. The most important step is to clean and handle the collected data. Then, based on the three physical mechanisms, we established a three-dimensional convection-diffusion-decay coupling model to achieve the goal. The result is that the core wastewater will spread to the whole Pacific Ocean and the Indian Ocean in 10 years. The earliest time to reach Busan, Shanghai and Los Angeles is 12,29 and 42 months, respectively. The second question will continue to use the ocean diffusion model.

For question two: In this study, six representative countries were selected to construct a three-dimensional evaluation system of " marine ecology-fishery economy-food safety." Through the entropy weight-AHP combination method to quantify the index weight, combined with K-means clustering to achieve risk classification.The results show that Japan and South Korea are high-risk countries, the United States and Canada are medium-risk countries, and China and Australia are low-risk countries.

For question three: The first step is to construct a three-dimensional evaluation model for three nuclear wastewater treatment schemes. Firstly, nuclide evolution, environmental impact index and cost model are established respectively to quantify the several aspects of the three schemes on the 30-year scale. The second step is to use the multi-objective optimization method to sort the schemes and optimize them on the original basis. After comprehensive consideration, it is concluded that the second scheme is relatively better.

For question four: Based on the previous research, we propose policy and institutional improvements to the Japanese government and the International Atomic Energy Agency.

Key word: Radionuclide Migration, Entropy Weight-AHP method, Multi-objective Optimization Method

Content

1. Problem Restatement

1.1 Background

On August 24, 2023, the Japanese government launched the nuclear wastewater discharge plan for the Fukushima Daiichi Nuclear Power Plant without fully consulting the international community. Until April of this year, more than 200,000 tons of nuclear wastewater has been discharged. It is estimated that about 1.3 million tons of nuclear wastewater will be discharged in the next 30 years, sparking strong criticism and opposition worldwide.

The latest data from Tokyo Electric Power Company show that although the nuclear wastewater is purified by the 'multi-nuclide treatment system'(ALPS),the Fukushima Daiichi nuclear power plant still stores about 1.05 million tons of untreated nuclear wastewater, and new wastewater is produced every day for reactor cooling. Tests show that nuclear wastewater contains a variety of radionuclides with extremely long half-life, which are easy to accumulate in the marine food chain, causing irreversible long-term hazards to benthic organisms and sedimentary environments. In turn, it increases the potential risk of thyroid disease after human intake of seafood.

1.2 Our work

Task 1: Based on multi-source ocean observation data(including ocean current, temperature, salinity, tide and seabed topography around Fukushima)from 2023 to 2025, after cleaning and standardizing the data, a three-dimensional ocean diffusion model coupling ocean current, tide and seawater mixing effect is established. Using this model, the nuclide migration path and range of Fukushima nuclear wastewater within 0 to 10 years after discharge into the sea are simulated. Calculate and output the earliest arrival time of polluted seawater to Shanghai, Los Angeles and the adjacent waters of Busan, and the curve of pollutant concentration with time over a period of time.

Task 2: Based on the 0-10-year global diffusion results of nuclear wastewater in Task 1, focusing on six representative countries, from the three dimensions of marine ecology (nuclide accumulation, plankton death), fishery economy (decreased catches, export losses, and fishermen 's income), food safety (adult / child intake, excessive risk, decreased trust, and replacement cost), quantify the degree of impact and divide high / medium / low risk levels, and clarify the classification basis and core characteristics.

Task 3: Collect relevant data and quantitatively compare the three treatment schemes of Fukushima nuclear contaminated water (marine emission, enhanced treatment storage, zero emission). By constructing a three-dimensional evaluation model that integrates cost, environmental impact and safety time limit, simulate its 30-year total cost, marine ecological effect and nuclide decay process, and implement multi-objective optimization to find the optimal solution.

Task 4: Based on the above modeling and simulation experiments, we propose policy and institutional improvements for the Japanese government and the International Atomic Energy Agency.

2. Problem Analysis

2.1 Analysis of Question One

The first question is to establish an ocean diffusion model based on multi-source data from 2023 to 2025 to simulate the diffusion process of nuclear wastewater discharged into the sea within 0-10 years. Firstly, spatial interpolation is performed on Argo buoys, satellite remote sensing and ocean station data, and seabed topographic maps around Fukushima to extract features such as temperature, flow rate, and salinity. Then, a three-dimensional temperature field and salt field are formed. Then, a three-dimensional convection-diffusion-decay coupling model combined with data is used to simulate the diffusion process. The results show that the core wastewater will spread to the entire Pacific Ocean and Indian Ocean in 10 years. The second question is to use the ocean diffusion model and introduce the detection threshold to obtain the earliest arrival time of Busan, Shanghai and Los Angeles.

2.2 Analysis of Question Two

Based on the radionuclide concentration data of key sea areas in 0-10 years after nuclear wastewater discharge provided by task 1, the core task of this part is to select six geographically representative countries and construct a comprehensive evaluation model covering three dimensions. The severity of the impact is quantified by comprehensive scoring and cluster analysis, and the risk level is scientifically classified according to the results.

2.3 Analysis of Question Three

The third question is to construct a three-dimensional evaluation model for three disposal schemes of nuclear wastewater. Firstly, the cost, environmental impact and safety time limit of the three schemes on the 30-year scale are quantified by establishing nuclide evolution, environmental impact index and cost model respectively, and the results are obtained. Then, on the basis of the three schemes, the multi-objective optimization method is used to optimize and sort the schemes.

2.4 Analysis of Question Four

Based on the scientific conclusions of the above model, we write letters of recommendation to the Japanese government and the International Atomic Energy Agency respectively, aiming to urge more responsible action and strengthen international supervision and cooperation.

3. Model Assumptions

1.The stratification of ocean density maintains a steady state in the 0-10 year time scale, and the temperature and salinity anomalies are only reflected by the observation field without additional strong and intermittent interference.

2.The hypothesis of nuclide migration: radionuclides migrate only through decay and ocean diffusion, and do not need to consider biodegradation.

3.Data stability hypothesis: The average daily consumption of seafood and the bioconcentration factor (K value) of each country refer to the FAO 2024 database and remain stable within 30 years ; the correlation coefficient between seafood exports and catches is 0.8, and the correlation coefficient between fishermen 's income and catches is 0.9 (based on FAO 2023-2025 trade and economic data fitting).

4.Hypothesis of AHP method: The judgment matrix of five experts (environmental science, fishery economy and food safety) is consistent (consistency ratio CR < 0. 1).

4. Data Preprocessing

In the data preprocessing stage of this study, the original ocean observation records are first subjected to outlier elimination and missing value completion. The abnormal values were screened by 3σ **rule**: if the flow velocity in the open sea exceeded 5 ms^{-1}, or the sea water temperature was lower than 0 ℃ or higher than 30 ℃, the records were regarded as abnormal and eliminated. The missing values are filled by **Kriging interpolation** in the coastal waters with strong spatial and temporal continuity (such as Japan Sea), and the interpolation error is controlled within 5%. In order to ensure the consistency of multi-source data, the Argo buoy is cross-compared with the flow velocity obtained by satellite remote sensing. The least square method is used to correct the system error. After calibration, the determination coefficient R2 > 0.9 is required to ensure the compatibility of the two sets of observations.

After the quality control is completed, all variables are unified into the space-time standardization process. The global sea area is divided into 360 × 180 horizontal units by using 11 latitude and longitude grids. In the vertical direction, a depth profile of 10 layers of 0-500 m was constructed with 50 m as the layer thickness. The time dimension selects a one-day step size, covering a 10-year (3 650 days) simulation period to match the sampling requirements of the tidal cycle. The unit is unified as flow velocity (ms^{-1}), concentration ($Bq\cdot L^{-1}$), temperature(oC)and salinity, and interpolation is completed on all grid points, so that the three-dimensional field at each time has complete physical properties.

The four-dimensional data(longitude-latitude-depth-time-concentration) output by the model are stored in the NetCDF format commonly used in the marine / meteorological field, retaining complete coordinate axis information for subsequent fast slicing and visualization. For example, the ,Global Concentration Distribution at 50 m Depth on Day 2 of 2025, can be directly queried to provide a plug-and-play data interface for subsequent analysis software. The whole preprocessing process lays a reliable foundation for the numerical solution of the subsequent three-dimensional convection-diffusion-decay coupling model under the premise of ensuring data integrity and consistency.

5. Models and Solutions

5.1 Model of Question One

5.1.1 Model

Table 1 Symbol Description Table

Symbol	Description	Explanation
$\frac{\partial C}{\partial t}$	The rate of change of concentration over time	Variables to be solved
u, v, w	Ocean current velocity in the x, y, z directions	Obtain from Argo
D_h	Horizontal diffusion coefficient	$500m^2/s$(sourced from IAEA 2024)
D_v	Vertical diffusion coefficients	$10^{-4}m^2/s$(sourced from IAEA 2024)
λC	Radioactive decay term	Obtain from the topic
S	Pollution source items	Obtain from the topic

In order to simulate the migration of radionuclides in the ocean, we consider the three physical mechanisms of ocean current advection, turbulent diffusion and radioactive decay, and establish a three-dimensional convection-diffusion-decay coupling model.

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} + w\frac{\partial C}{\partial z} = D_h(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2}) + D_v\frac{\partial^2 C}{\partial y^2} - \lambda C + S$$

On the left side is the time change term + ocean current advection transport term, and on the right side is the horizontal diffusion term + vertical diffusion term - nuclide decay term + source term.

Numerical solution: The finite volume method is used to divide the calculation area into three-dimensional grid elements, which can maintain the mass balance. Initial conditions(t = 0,August 24, 2023) Source term function:

$$S = Q_t \cdot \delta(x - x_0)\delta(y - y_0)\delta(z - z_0)$$

Emission point coordinates:

$$x_0 = 141.03E, y_0 = 37.42N, z_0(\text{Seasurf ace}) = 0, Q_t = 100t/d, C = 0$$

Boundary conditions:

1. The sea surface and the seabed are set to the flux-free boundary(Neumann)condition, that is, the sea surface(z = 0)and the sea foot(z = -H): $-D_v\frac{\partial C}{\partial z} = 0$, indicating that the nuclide cannot cross the sea surface into the atmosphere or cross the seabed into the sediment.

2. Open boundary (the edge of the model area), set the radiation boundary condition (Orlanski condition), allowing the free outflow of nuclides, but not reflecting the calculation area.

Earliest arrival time: The detection threshold $C_{threshold} = 0.1Bq/m^3$ is defined, and the arrival time is the time when the concentration exceeds the threshold for the first time.

It is necessary to speculate results over 10 years based on the data of this 1 year(2023.8.24-2024.8.24).

5.1.2 Experiment

The model is programmed in Python and other languages, and relies on some modules of the mature ocean numerical model library (such as FESOM, ROMS, etc.). The simulation time span is 10 years (2023-2033).

Dynamic Evolution:Figure2visually illustrates the spatial distribution of H3 concentration at four critical time points (16,72,238,512) to demonstrate the complete trajectory of a radionuclide plume originating from the Fukushima coast. Driven by the powerful Kuroshio Current, the plume rapidly diffused northeastward before being gradually carried eastward across the Pacific by the North Pacific Current. This visualization confirms the model's successful simulation of the ocean circulation's advection effects.

Long-term distribution:Figure1 shows the surface concentration distribution of Sr-90 in the 10 th year. It can be seen that the high concentration area (dark blue) has spread throughout the northwest Pacific Ocean and formed a clear pollution belt along the North Pacific Current extending to the eastern Pacific Ocean. Low-concentration water has even crossed the equator into the South Pacific, and through the Indonesian waters into the Indian Ocean, obtained 'within ten years spread to most of the Pacific and Indian Ocean' conclusion.

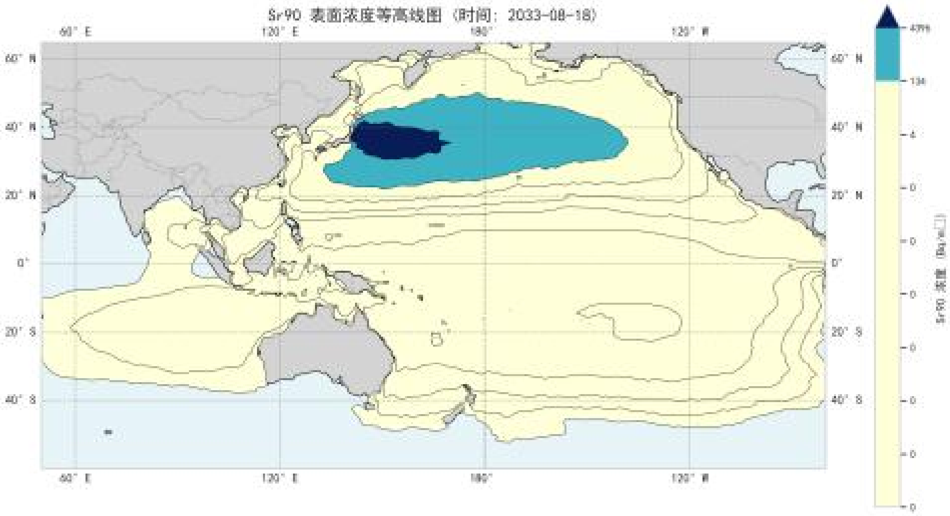

Figure 1 Surface concentration contour of Sr90

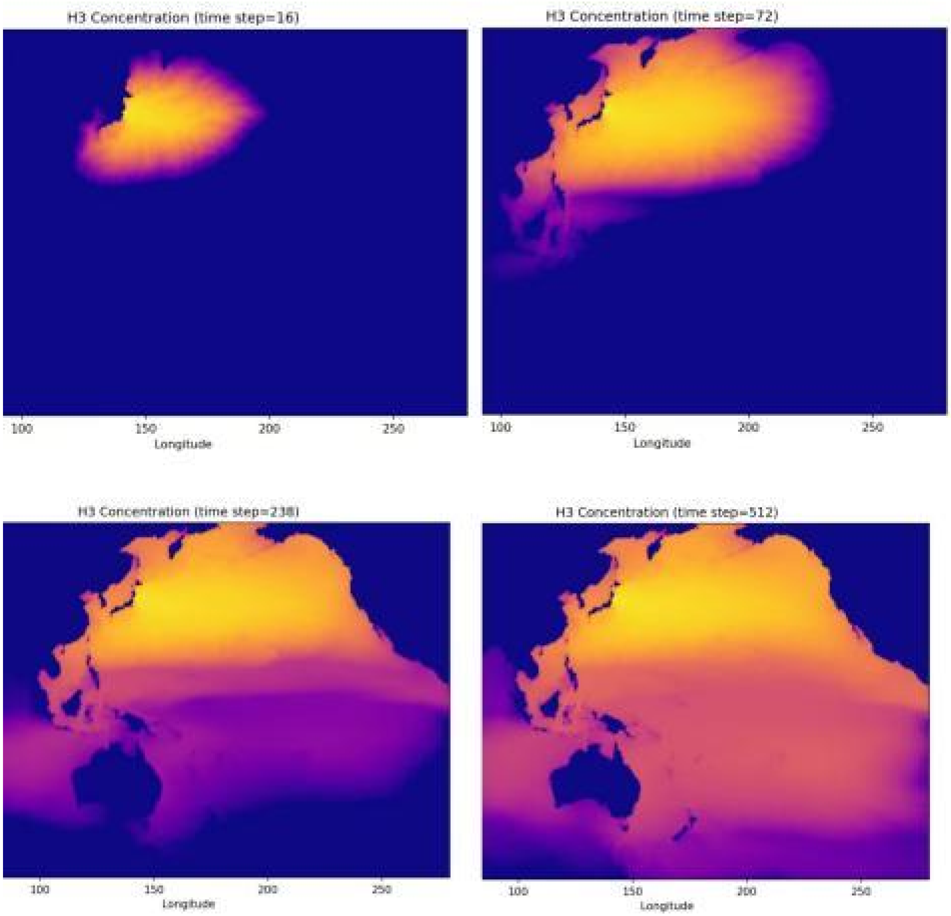

Figure 2 H3 Concentration

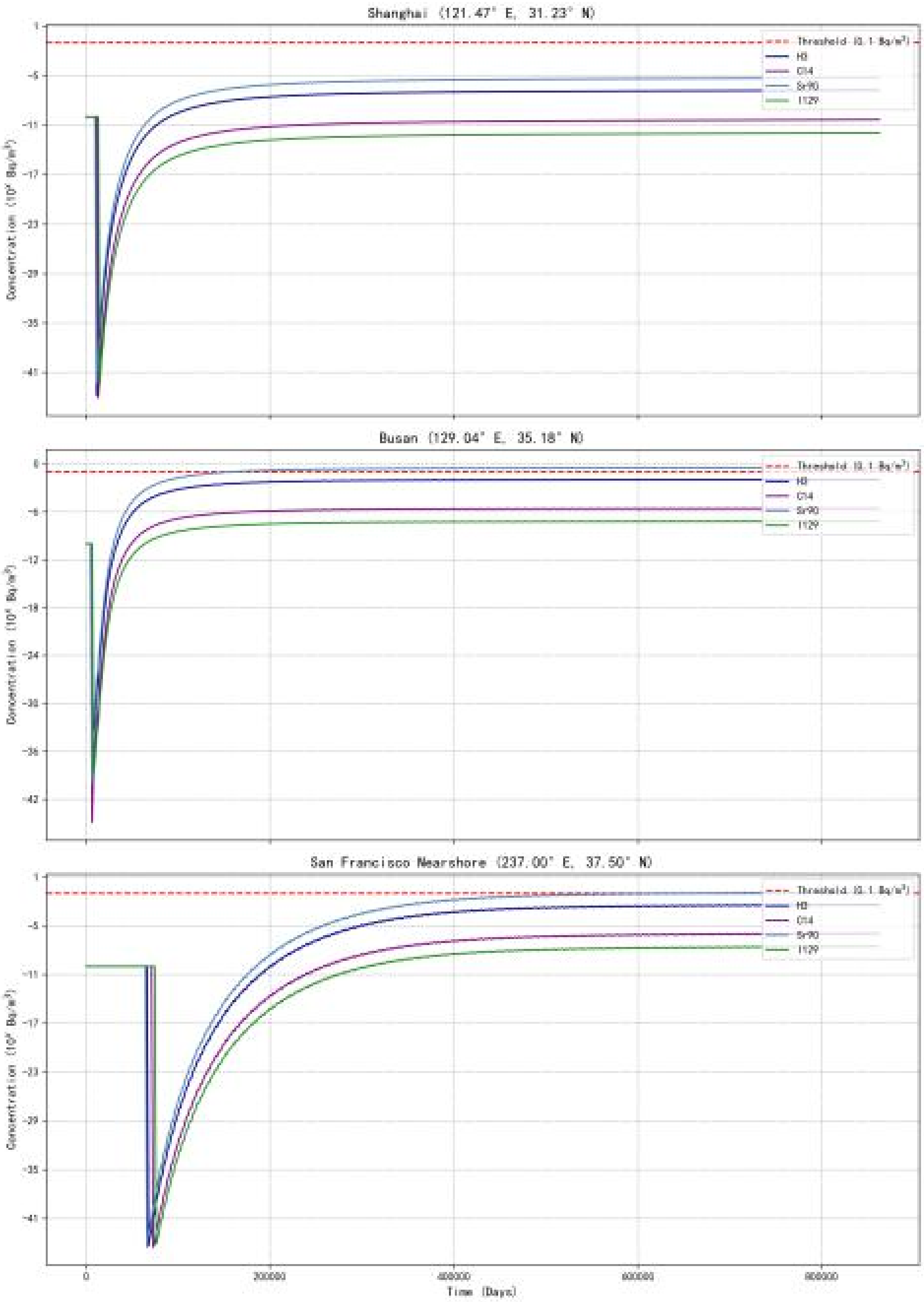

Figure 3 Ten-year variation curve of nuclide concentration at key monitoring points

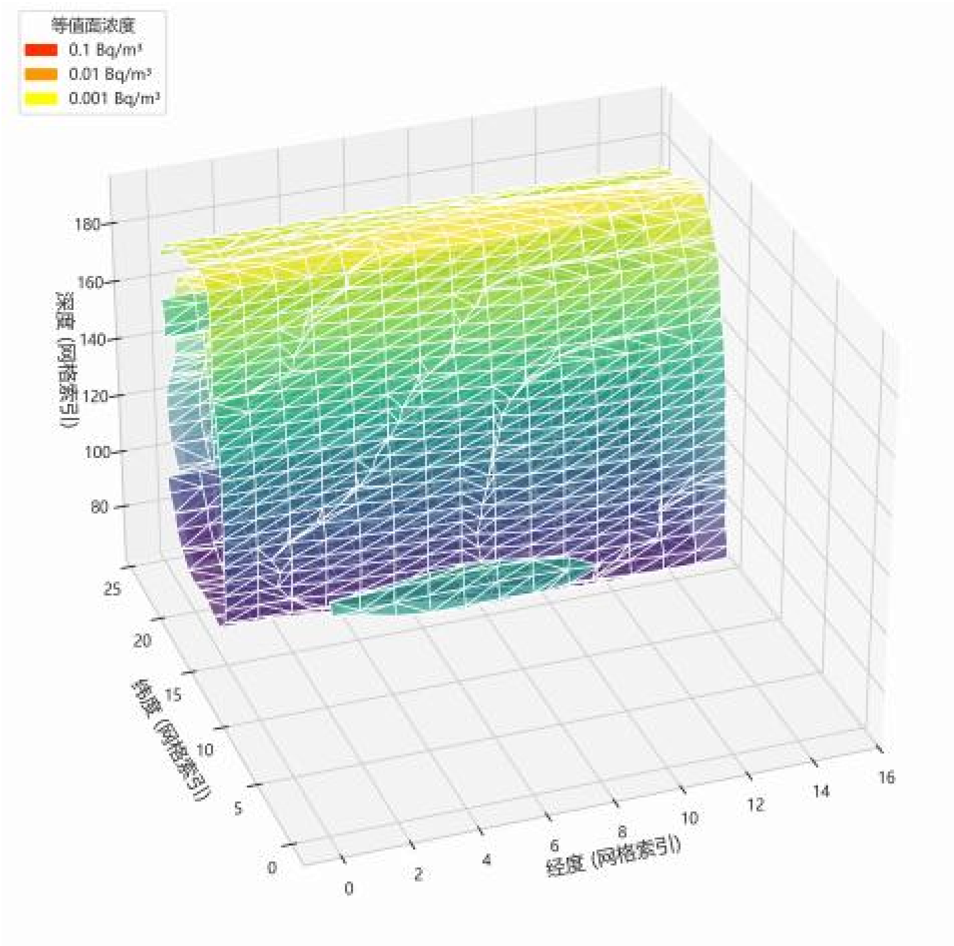

Figure 4 Three-dimensional isosurface of pollutant plume(the tenth year)

One of the models' most significant findings is the dominant role of ocean vertical stratification in radionuclide fate. Figure5, along with a similar diagram Figure6, unequivocally demonstrates that even 10 years after emission, the vast majority of radionuclides remain confined within the top 200 meters of the ocean.

The concentration decreases exponentially with the increase of depth. The surface concentration is highly variable, while the deep concentration is low and uniform.It is proved that the stable stratification effect is the key barrier to prevent the rapid entry of pollutants into the deep sea.

Based on the three-dimensional diffusion model, we define the detection threshold of specific nuclides.The simulation results show that due to differences in ocean current paths and distances, there is a significant gradient in the initial affected time of various cities, the results are shown in table2: radionuclides are first diffused to the northwest Pacific coast under the strong Kuroshio Current. Busan, South Korea, due to its geographical proximity and the influence of the Kuroshio Current branch, becomes the earliest affected coastal city. Subsequently, pollutants further diffuse southward and westward with coastal currents and seasonal circulation, allowing an estimated earliest arrival time for Shanghai, China. For the west coast of North America, radionuclides need to cross the entire Pacific Ocean, with the main transport path being the North Pacific Current. Although the transport distance is long, the current has a stable flow rate.

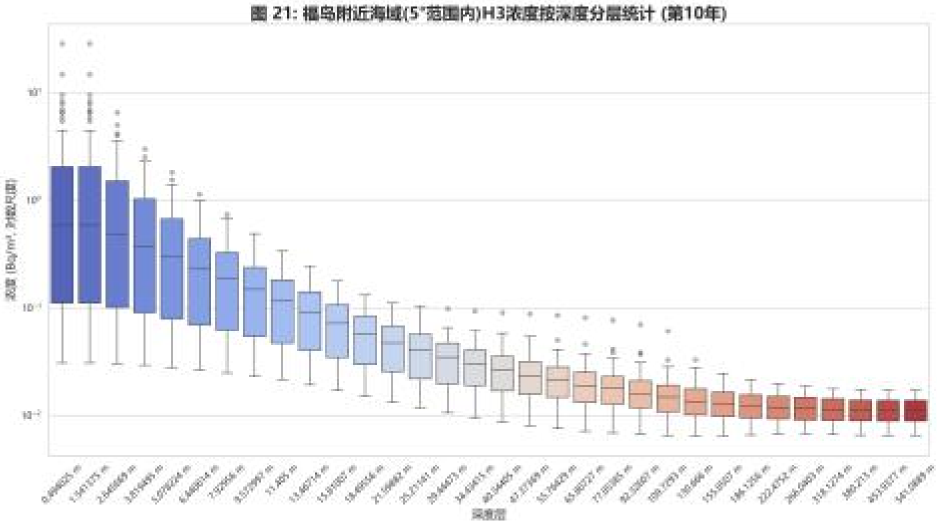

Figure 5 H3 concentration according to the depth statistics

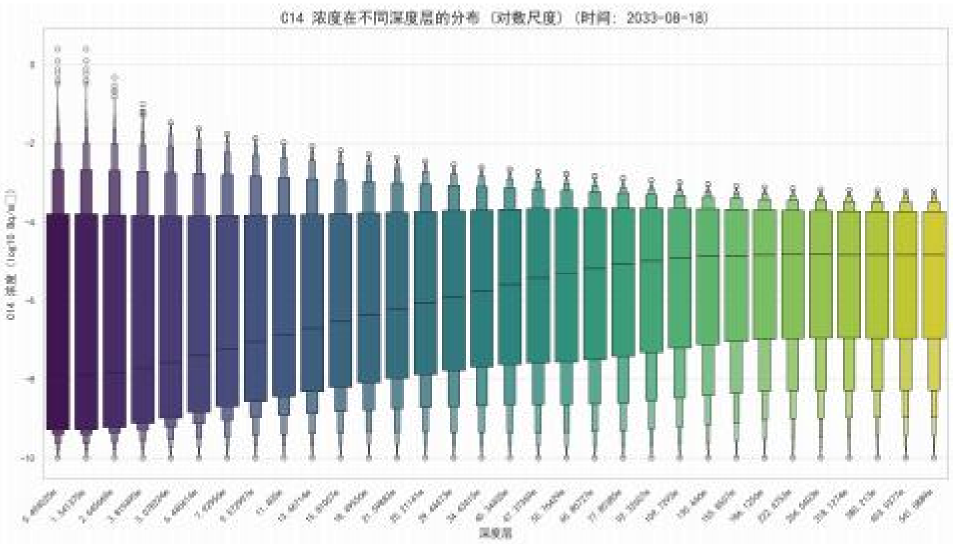

Figure 6 C14 concentration according to the depth statistics

Table 2 Time statistics of nuclear wastewater reaching each city

City	Earliest arrival date	Emission duration (months)
Busan	2024.09.05	12
Shanghai	2026.02.12	29
Los Angeles	2027.03.04	42

5.2 Model of Question Two

5.2.1 Model

To solve this problem, we designed a systematic modeling process, as shown in Figure7. The process starts from the construction of the evaluation system, carries out index quantification, data standardization, weight determination, and finally realizes risk classification through comprehensive scoring and cluster analysis to ensure that the process is rigorous and the results are credible.

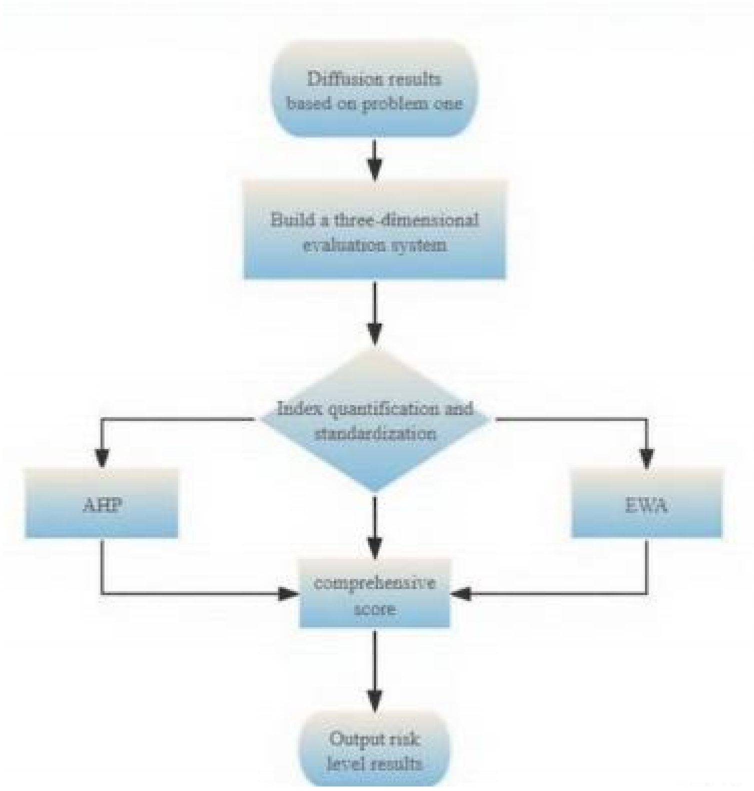

Figure 7 Flow chart of task 2

Based on the migration path affected by nuclear wastewater(marine environment → fishery production → social consumption), we constructed an evaluation system consisting of 3 first-level indicators (marine ecology, fishery economy, food safety) and 10 second-level indicators. The system comprehensively covers the complete chain from ecological impact to socio-economic impact:

Table 3 Comprehensive impact assessment index system of nuclear wastewater discharge

First index	Second index	Data sources
Marine ecology	Accumulation of nuclides (A1)	Task 1 Model output
	Phytoplankton mortality rate (A2)	preference[3]
Fishery economy	Rate of decline in catches (B1)	FAO Fishery Database
	Loss of export volume (B2)	FAO trade database
	Fishermen 's income reduction rate (B3)	National Bureau of Statistics data
Food safety	adult intake (C1)	FAO food consumption index
	Children's annual intake (C2)	FAO food consumption index
	Exceeded Risk Rate (C3)	IAEA2024 Guide Chapter 7.3
	Food trust decline (C4)	Global Consumer Confidence Survey
	Food Substitution Cost (C5)	National Food Price Database

The calculation method of the secondary indicators in the table is as follows:
A1 = CXk(K is the FAO bioconcentration factor);
Logistic model: $A_2 = \frac{1}{1+e^{-\frac{(C-0.5)}{0.1}}}$
Linear regression: B1 = 0.02C(Cunit : Bq/L)

$$B2 = B1X0.8$$

$$B3 = B1X0.9$$

$$C1 = DXCX365$$

$$C2 = 0.5XC1$$

$$C3 = 1(\text{if } C1 > 100\text{Bq/year}), \text{otherwise}0$$

$$C4 = 0.03C$$

C5 = 0.01C

according to the basic data of nuclide concentration in the sea area of each country in the 10 th year provided by task 1 (the following table), the original values of 10 secondary indexes of each country are calculated one by one by applying the index calculation formula.

Due to the huge difference in the dimension and order of magnitude of each index, in order to eliminate the influence of dimension and make a comprehensive comparison, the Min-Max standardization method is used to scale the original data to the [0,1] interval. The standardized formula is :

$$X_{ij} = \frac{X_{ij} - \min(X_j)}{\max(X_j) - \min(X_j)}$$

where min (Xj), max (Xj) is the 6 th minimum and maximum value of the j th index.

In order to take into account the objective law of index data and the subjective judgment of expert experience, this study adopts a combination weighting method combining EWA (objective) and AHP (subjective).

The entropy weight method determines the objective weight (Wo) : EWA determines the weight according to the amount of information provided by each index data. The greater the degree of dispersion (the smaller the information entropy), the greater the impact of the index on the comprehensive evaluation.

Calculate the index probability:

$$P_{ij} = \frac{X'_{ij}}{\sum_{i=1}^{6} X'_{ij}}$$

Calculate information entropy:

$$E_j = -\frac{1}{\ln 6}\sum_{i=1}^{6} P_{ij} \ln P_{ij} (\ln 6 \approx 1.792)$$

Calculate the objective weight:

$$W_{o,j} = \frac{1 - E_j}{\sum_{j=1}^{10}(1 - E_j)}$$

Hierarchical structure:

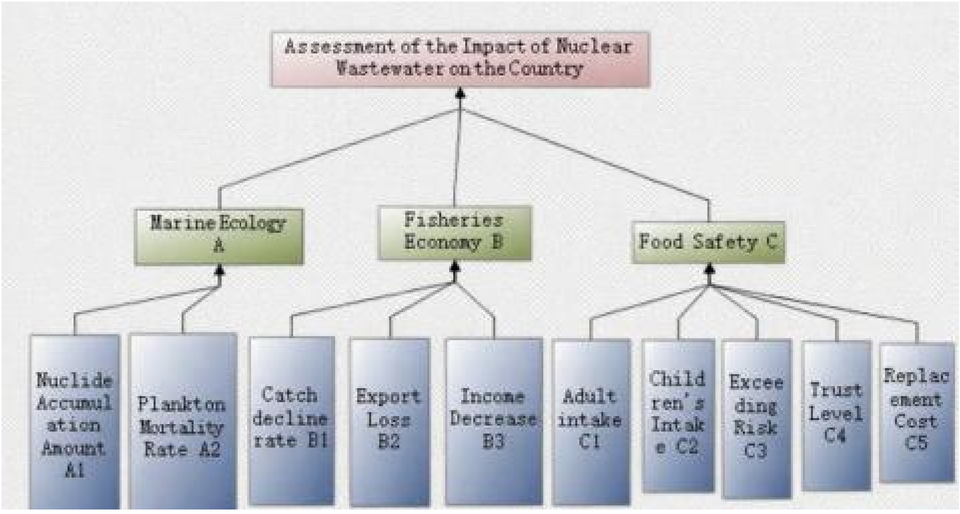

Figure 8 Hierarchical structure

AHP determines the subjective weight (Ws) AHP quantifies the judgment of experts on the relative importance of indicators by constructing a judgment matrix.

Construction of judgment matrix : According to the connotation of each index in table 1, we construct the judgment matrix of pairwise comparison for the criterion layer (A, B, C) and the index layer (A1-A2, B1-B3, C1-C5).

Table 4 First-level index weight matrix

Criterion layer	Marine ecology(A)	Fishery economy(B)	Food safety(C)
Marine ecology(A)	1	3	1/2
Fishery economy(B)	1/3	1	1/5
Food safety(C)	2	5	1

Table 5 a

A-II	A1	A2
A1	1	3
A2	1/3	1

Table 6 b

B-II	**B1**	**B2**	**B3**
B1	1	5	4
B2	1/5	1	1/2
B3	1/4	2	1

Table 7 C

C-II	**C1**	**C2**	**C3**	**C4**	**C5**
C1	1	3	5	7	7
C2	1/3	1	1/2	3	5
C3	1/5	2	1	4	6
C4	1/7	1/3	1/4	1	3
C5	1/7	1/5	1/6	1/3	1

Calculate the global weight : multiply the weight of the criterion layer by the local weight of the index layer to obtain the global subjective weight Ws of each secondary index relative to the total target.

Calculation of combined weights (Wj) Linear weighting method is used to synthesize subjective and objective weights, and the subjective preference coefficient is set to be 0.4, and the objective preference coefficient is 0.6, so as to slightly focus on the objectivity of the data.

The calculation formula is :

$$wj = 0.6wo + 0.4ws$$

The following comprehensive risk score calculation formula is used to calculate the comprehensive risk score of 6 countries :

$$S_i = \sum_{j=1}^{10} W_j \cdot X_{ij}$$

Based on the score results, the elbow rule is used to calculate the WCSS under different K values, and the optimal cluster number K of K-means clustering is finally determined.

In order to objectively divide the national risk level, this study uses K-means clustering algorithm to classify the comprehensive risk scores of 6 countries without supervision. Firstly, the initial clustering center is randomly selected. Then, the algorithm enters the core two-layer iterative optimization stage (the distance function used in this study is Euclidean distance) The formula of Euclidean distance is :

$$d = |x - \mu_k|$$

The process continues until the position of the clustering center no longer changes, indicating that the algorithm has converged to a stable solution. Finally, the level is defined according to the comprehensive score of the cluster.

5.2.2 Experiment

According to the calculation method of each secondary index above, we can get the original value of the corresponding index of each country, and standardize the value according to min-max method. The results are shown in the following table8and figure9.

Table 8 Indicator Weights

Indicator	Entropy Weight (w_o)	AHP Weight (w_s)	Combined Weight (w_j)
A1	0.097	0.232	0.151
A2	0.033	0.077	0.051
B1	0.097	0.075	0.088
B2	0.097	0.013	0.063
B3	0.097	0.022	0.067
C1	0.130	0.247	0.177
C2	0.130	0.103	0.119
C3	0.126	0.159	0.139
C4	0.097	0.049	0.078
C5	0.097	0.024	0.068

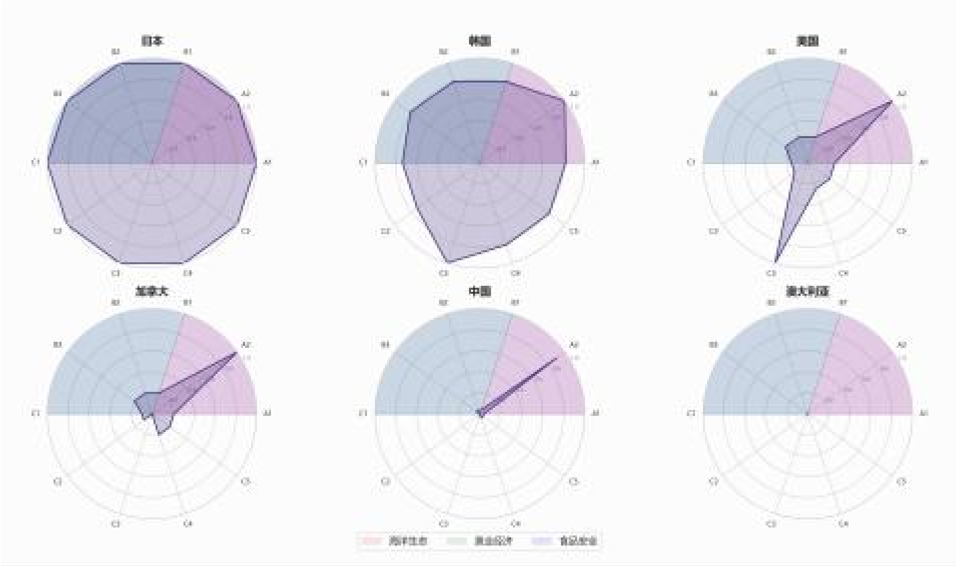

Figure 9 Six countries risk assessment index standardized radar chart

The score of each country is calculated by using the comprehensive risk score formula to further evaluate the risk level. The results are shown in Figure11.

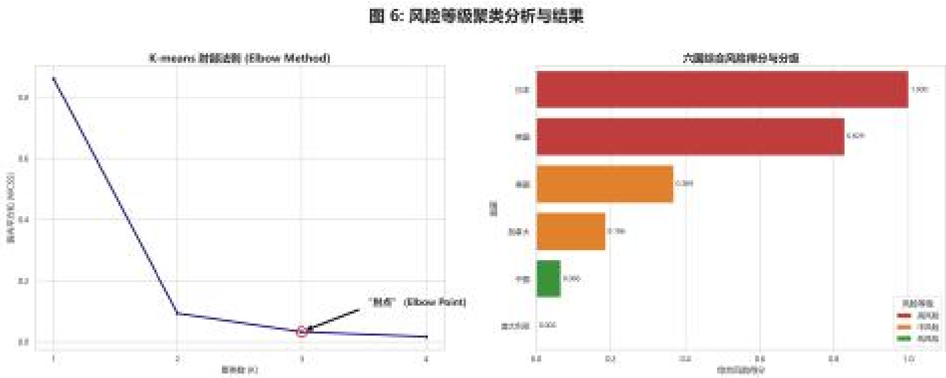

Figure 10 K-means Clustering

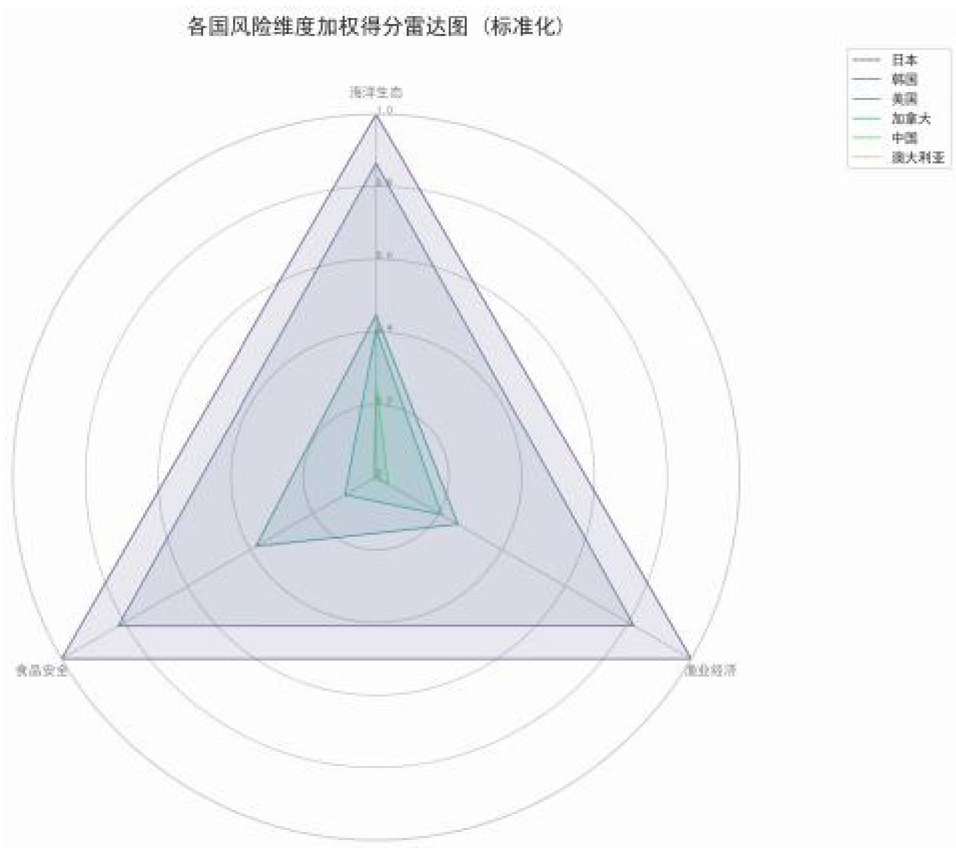

Figure 11 Risk-weighted score radar chart of each country (standardized)

Table 9 Risk Scores and Classifications of Representative Countries

Country	Comprehensive Risk Score	Risk Level
Japan, South Korea	1.000, 0.829	High Risk
United States, Canada	0.369, 0.186	Medium Risk
China, Australia	0.066, 0.002	Low Risk

The elbow rule was used to analyze the relationship between the sum of squares in the cluster (WCSS) and the number of clusters: when K = 3, WCSS plummeted from 0.0930 to 0.0332, and the subsequent decline was<0.1, so K = 3 (high, medium and low risk) was selected. Clustering center and threshold

High risk : cluster center = 0.9148, threshold $s_i > 0.5$; moderate risk: cluster center = 0.2778, threshold $0.15 < s_i < 0.5$;low risk : cluster center = 0.0338, threshold $s_i < 0.15$

The results9 show that Japan and South Korea are high-risk countries, the United States and Canada are medium-risk countries, and China and Australia are low-risk countries.

5.3 Model of Question Three

5.3.1 Model

This chapter aims to construct a comprehensive evaluation model to solve the multi-objective optimization problem of nuclear wastewater treatment schemes. The core of the model is to quantify the comprehensive performance of different schemes on the time scale of long-term environmental effect, economic cost and safety.

(1) The nuclide evolution model

The nuclide decay formulaFor each nuclide i, the initial activity $A_{0,i}$ and the half-life $T_{\frac{1}{2},i}$ are given respectively, and then the residual activity at time t is :

$$A_i(t) = A_{0,i}\, e^{-\lambda_i t}$$

2.Program processing efficiency couplingSuppose that the removal rate of nuclide i by scheme j is $\eta_{j,i}$ (different processing difficulties, matching nuclides), the activity of nuclide i treated by scheme j is :

$$A_{j,i}(t) = (1 - \eta_{j,i}) \cdot A_i(t)$$

(2) Environmental Impact Index Model

Combined with the output of the three-dimensional diffusion model, the environmental impact is converted into a grid weighted sum :

$$E_j(t) = \sum_{\text{grid}} C_{j,i}(x, y, z, t) \cdot W(x, y, z) \cdot V_{\text{grid}}$$

where V grid is the grid volume. Weight function W(x, y, z): Fishing ground/coral reef: W = 5 ;Inshore urban water intake: W = 3 ; High seas : W = 1

30 years cumulative total impact:

$$E_j^{30} = \sum_{t=0}^{30} E_j(t)\, \Delta t, \quad \Delta t = 1 \text{ year}$$

(3) Cost model

The total cost is composed of construction cost, operation and maintenance cost and intensive treatment cost :

$$C_j = C_{j,\text{build}} + \int_0^{30} C_{j,\text{op}}(t)\, \mathrm{d}t$$

Special scheme zero emission :

$$C_3 = C_{3,\text{facility}} + C_{3,\text{storage}}$$

operation and maintenance unit price(reference value):

$$c_j^{op} = 5.5 \text{ hundred million/year}$$

(4) Decay time model

Set the nuclide threshold

$$c_{thr,i}$$

Time to reach the standard: for each nuclide, meet

$$A_{j,i}(t_i') \le c_{thr,i}$$

Get

$$t_i' = \frac{1}{\lambda_i} \ln\left(\frac{A_{0,i}\,(1-\eta_{j,i})}{C_{thr,i}}\right)$$

2.Establish a multi-objective optimization problem

$$\min F_j = (E_j^{30}, c_j, t_j')$$

Constraint condition

$$E_j^30 \ge 0, \quad c_j \ge 0, \quad t_j' > 0$$

NSGA-II is used to solve the Pareto front solution. Code implementation : Python + pymoo library algorithm package (code implementation)

5.3.2 Experiment

For the nuclide evolution model, we put it into the computer environment to simulate the results as shown in Figure12.

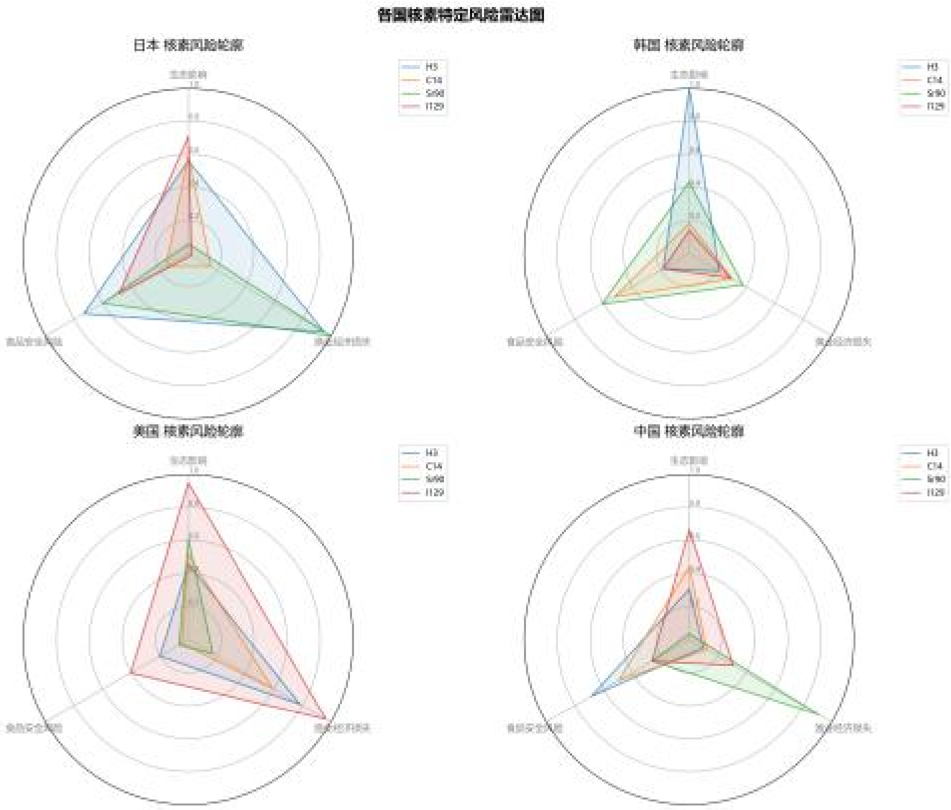

Figure 12 Radionuclide specific radar maps of various countries

Considering the nuclide evolution model, environmental impact index model and cost model, we draw the Figure13.

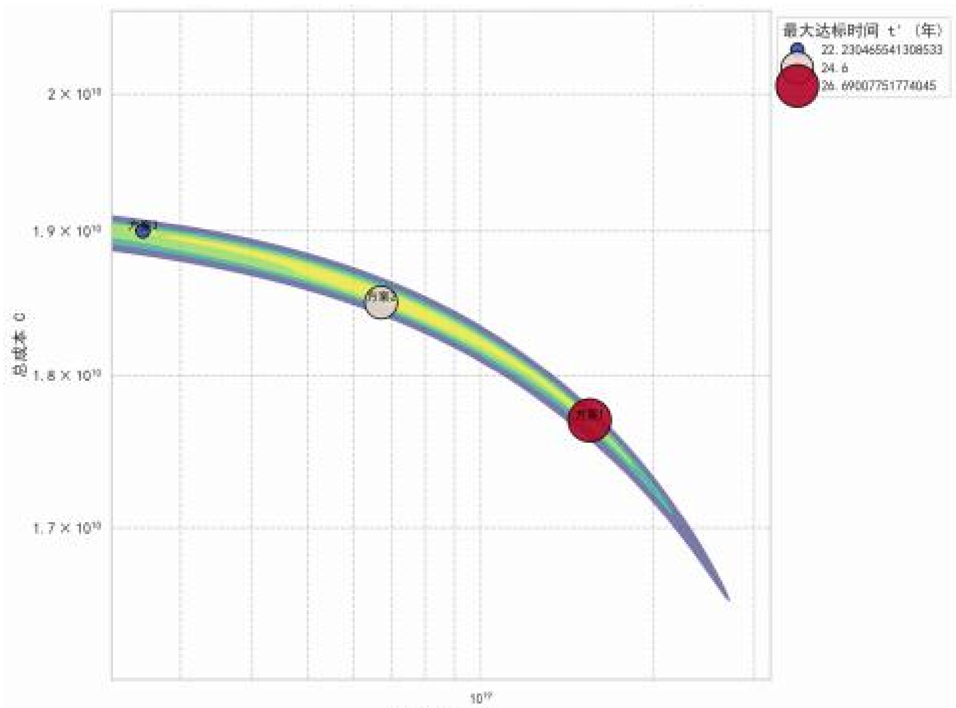

Figure 13 Handling scheme objective trade-off KDE diagram

Table 10 Comprehensive Indicators and Costs of Three Schemes

Scheme	Environmental Impact	Cost (Billion JPY)	Compliance Time (Year)
I	15.5	177	26
II	6.71	185	24
III	2.58	190	22

Where I is current marine emissions, II is enhanced treatment & long-term storage, and III is zero emissions.

Scheme 1 can achieve the fastest emission standard and the lowest economic cost, but its cost is the greatest negative impact on the marine environment ; on the contrary, Scheme 3 minimizes the potential impact on marine ecology by investing the highest cost, but the processing time is also the longest. The second scheme is between the two in all indicators, which represents a more compromised intermediate path in cost, environmental tolerance and time efficiency.

5.4 Recommendation letter

5.4.1 To the Government of Japan

According to the simulation results of problem one to question three, Japan will also receive the impact of nuclide return, and the international community is highly sensitive and concerned about the emission problem. The recommendations are as follows :

Reducing the discharge of nuclear wastewater and phased treatment: between the Figure 13 , the current discharge has a huge impact on the ecological environment, and is not recommended as a long-term plan. It is recommended to gradually transfer the nuclear wastewater treatment plan to enhanced treatment + long-term storage in 2028, and then adopt zero discharge.

Actively cooperate with coastal countries in nuclear waste water monitoring : Referring to Figure 2, the Japanese government should actively cooperate with potentially affected countries to share monitoring data and demonstrate national responsibility and international trust.

Establishment of fishery economic compensation and medical assistance : establish a fishery economic compensation fund for medium-and high-risk countries, and establish medical assistance for possible health problems caused by nuclear waste water, focusing on human health and safety.

5.4.2 To the International Atomic Energy Agency :

The IAEA should exert its international influence to help and coordinate the world 's response to nuclear emergencies and governance. Recommendations are as follows :

Develop and publish risk level warning : refer to the Figure 11, formulate high, medium and low risk level standards, and require member states to strictly abide by and report regularly.

Improve and increase global nuclear monitoring : Based on Argo buoys and global satellite remote sensing monitoring, according to Figures 2, the monitoring points of key risk areas in the Pacific Rim are increased to achieve more accurate and timely monitoring and control.

6. Sensitivity Analysis

The analysis determines the sensitivity of nuclear wastewater diffusion simulation, risk assessment classification and optimization decision model. The horizontal diffusion coefficient and the horizontal velocity of the ocean current in the diffusion model dominate the horizontal migration of nuclides, and the 5-10 layers in the vertical stratification can balance the accuracy and efficiency ; the risk assessment model is robust to changes in weights and clustering parameters, and the risk level classification is stable. The processing efficiency and cost parameters in the optimization decision model affect the details of the scheme, but the direction of the core technology is unchanged, and the decision preference is reflected for the multi-objective weight. The core conclusions of the three models are stable for reasonable changes in parameters.

7. Strengths and Weakness

7.1 Strengths

For task one: We consider the three core physical processes of advection, turbulent diffusion and radioactive decay, and completely covers the key mechanism of nuclide migration in the ocean. The model contains the three-dimensional space dimension, which is closer to reality and more accurate than the two-dimensional model. The model used in this paper is an extension of the classical convection-diffusion-reaction three-dimensional model, which is mature in the field of fluid mechanics.

For task two:The evaluation system is very comprehensive and close to the actual impact path. The three-dimensional evaluation system (marine ecology-fishery economy-food safety) constructed by the model accurately covers the core impact chain of nuclear wastewater on coastal countries. The selection of secondary indicators is 'scientific and targeted' ; the combination of 'entropy weight method-AHP method' is used to avoid the shortcomings of a single method, which is consistent with the mainstream optimization direction in the field of environmental assessment. The model realizes the whole process steps of 'index quantification → standardization → weight calculation → comprehensive score → clustering'.

For task three: The nuclide evolution model couples the nuclide decay with the processing efficiency, and the half-life of different nuclides is 12. Different from the difficulty of processing, the model takes into account the modeling of nuclides, avoids the error of the same processing efficiency of all nuclides, and the coupling of decay and processing efficiency is more in line with engineering logic. Considering the differences of different ecological regions, the environmental impact model is coupled with the spatial concentration output by the three-dimensional diffusion model, which realizes the combination of ' physical diffusion-ecological sensitive area ' and avoids the limitations of the traditional model. The cost model covers construction, operation and maintenance, and strengthening treatment, and considers the facilities and storage costs of the ' zero emission plan ' separately, which is in line with the full cycle perspective of engineering economy. The optimization model covers the three-dimensional decision-making dimensions of environment, economy and time. Using the optimization library of NSGA-II or Python, it can adapt to the Pareto frontier solution of multi-objective optimization, give the ' non-dominated solution set ', and provide a variety of trade-off schemes for decision makers.

7.2 Weakness

For task one: The uncertainty of parameter is high, and the value of core parameters (such as horizontal diffusion coefficient and vertical diffusion coefficient) depends on the state of ocean current, while ocean current has spatial and temporal heterogeneity. The process of chemical and biological reactions is ignored, and the model only considers the physical and decay processes. The boundary conditions and initial conditions are idealized, and the actual boundary conditions and initial conditions are over-simplified.

For task two: The correlation of indicators is too simplified, ignoring the differences between countries. The design of K-means model is simple, but there are limitations. The initial center is random, and the dependence of single dimension. The standardized method is sensitive to outliers, and the entropy weight method has data dependence.

For task three: The model involves multi-module coupling of'nuclide evolution-environmental impact-cost-optimization'. The assumptions and parameters of each module interact with each other, so it has certain computational complexity and brings difficulties. The environmental impact model is simplified in space and time. It is difficult to verify the model. It is necessary to verify the accuracy of nuclide decay, processing efficiency, spatial diffusion and cost estimation at the same time. The error of any module will affect the final optimization result.

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