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Construction of Loss Assessment Method of Eco-service Value in Sea Area Polluted by Chemical Leakage Accidents Based on Ecological Impact Prediction Model

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Construction of Loss Assessment Method of Eco-service Value in Sea Area Polluted by Chemical Leakage Accidents Based on Ecological Impact Prediction Model

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Abstract. There is no unified and standardized method for assessing the loss of eco-service value in sea area polluted by chemical leakage accidents. In this study, an index system and a set of assessment procedures for the loss of eco-service value in chemically polluted sea areas are established, and an assessment method based on the ecological impact prediction model is constructed. The validity of this method is demonstrated by taking the northern coast of Hangzhou Bay, that is, the southern sea area of Jinshan District in Shanghai as an example. The conclusion of this study is that once the leakage accident of 2000 tons soluble toxic chemicals occurs in the sea area, 1860 ha sea areas may be affected, resulting in 1.68 billion economic losses; once the leakage accident of 5000 tons oil-insoluble toxic chemicals occurs, 34000 ha sea areas may be affected, resulting in 2.61 billion economic losses.

1. INTRODUCTION

Frequent chemical leakage accidents in the world not only cause serious damage to the ocean, but also cause huge economic and ecological losses to human beings [1-4]. The international assessment of the loss of eco-service value in sea area mainly focuses on that of oil spill pollution. However, there is no unified and standardized method for assessing the the loss of eco-service value in sea area polluted by bulk chemicals at home and abroad, because chemicals have various types, different characteristics, and complex forms of movement in water. [5-7] HNS Convention is the only comprehensive convention in the world on compensation for damage caused by toxic and harmful substances, but it lacks technical provisions on the extent and scope of environmental damage. In China, due to the lack of effective and quantitative assessment techniques for ecological damage and loss of eco-service value caused by chemical leakage, the damage caused by chemical leakage is often not fully and reasonably compensated [8-10].

In this study, an index system and a set of assessment procedures for the loss of eco-service value in chemically polluted sea areas are established, and an assessment method based on the ecological impact prediction model is constructed. The validity of this method is demonstrated by taking Hangzhou Bay as an example. This study can provide a basis for marine environmental damage compensation, and provide relevant technical support for environmental impact assessment as well as chemical environmental risk assessment.

2. OVERVIEW OF THE RESEARCH AREA

In this study, the northern coast of Hangzhou Bay, i.e. the southern sea area of Jinshan District in Shanghai, is taken as an example to assess the eco-service value of the sea area polluted by chemical leakage accidents. This study cited the data from the survey of marine ecological status which is made by Donghai Institute of Fisheries of Chinese Academy of Fishery Sciences in August 2007 and July 2012. There are five survey stations, as shown in figure 1.

3. METHODOLOGY

3.1 Construction of Assessment Index System for the Loss of Eco-service Value in the Sea Area Contaminated by Chemical Leakage

Referring to the international authoritative classification system of the United Nations *The Millennium Ecosystem Assessment*[11], this study divides ecosystem services into four categories: provisioning services, regulating services, cultural services and supporting services. Each category also contains a number of sub-services. Based on this framework, considering the characteristics of China's marine ecosystem, this study establishes an assessment index system of eco-service value in chemically polluted sea areas in offshore China, as shown in Table 1.

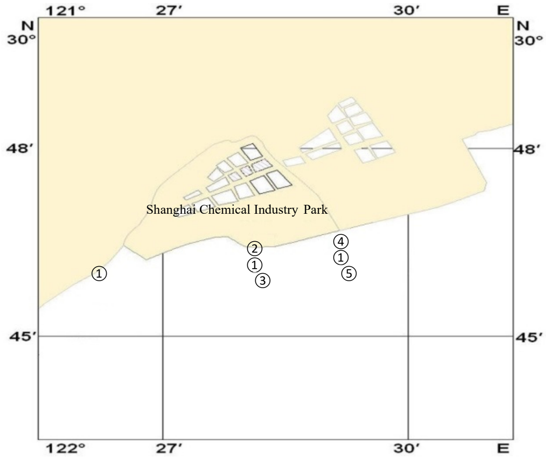

Figure 1. Location Map of Monitoring and Investigation Station in the Northern Sea Area of Hangzh Bay ou

Table1. The assessment index system of eco-service value in chemically polluted sea areas in offshore China

First level index	Second level index	Third level index	Explanation
Loss of eco-service value in chemically polluted sea areas	Provisioning services	Food provision	The direct pollution damage to marine living resources which can be used as seafood results in the decrease of quantity and quality of edible biological resources (mainly marine resources, including phytoplankton, zooplankton and benthic organisms).
		Material provision	The direct pollution damage to marine biological resources has led to the reduction of the number of biological resources (mainly algae and swimming organisms, such as crustaceans, cephalopods, reptiles, mammals and fish) that can be used as industrial raw materials, drugs, feed and additives, which has a negative impact on the production of related industries.
		Gene resources	Impacts on the genetic diversity of marine wildlife (very rare)
	Regulating services	Gas regulation	Pollution causes damage to photosynthetic marine plants (phytoplankton, benthic plants, such as algae, marsh grass, mangrove, etc.), which results in the weakening of photosynthesis by these marine plants, resulting in the weakening of the ability of marine ecosystems to provide oxygen to the atmosphere and the decline of air quality.

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		Climate regulation	Pollution causes damage to marine organisms (phytoplankton, benthic plants, such as algae, marsh grass, mangrove, etc.) that can carry out photosynthesis, calcification and biological pumping. It leads to the weakening of photosynthesis, calcification and biological pumping in marine ecosystems, the weakening of the ability of ecosystems to absorb CO in the atmosphere, and the increase of global greenhouse gas content.
		Waste treatment	①Discharging a large amount of pollutants causes impacts on water quality and sediment environment; ②Pollution causes damage to marine microorganisms; ③Pollution causes damage to marine plants.
		Biological regulation	①It hinders the photosynthesis of phytoplankton in the ocean; ②The decrease of the number of zooplankton will promote the explosive growth of the number of some phytoplankton to a certain extent, which will lead to red tide disasters; ③The decrease of the number of swimming animals and benthic animals will weaken the control and regulation function of zooplankton; ④Toxic substances circulate, accumulate and concentrate in the food chain, and eventually enter the human body from fish and shellfish.
		Disturbance regulation	The damage of special ecological environment formed by benthic plants, such as algae forest, salt marsh community and mangrove bottom will lead to a decline in the attenuation and buffering of marine natural disasters.
	cultural services	Leisure service	①Pollution causes damage to reptiles (such as turtles), mammals (such as seals) and marine fish (such as tropical fish and coral fish) in swimming organisms, resulting in a decrease in the number of ornamental marine organisms; ②The decrease of fish resources will weaken the ability of people to engage in recreational activities such as fishing; ③Decrease in ornamental Coral Reef Resources; ④Reduction of aesthetic landscape and tourism and entertainment places
		Cultural uses	It reduces the places and inspirations provided by the ocean for the creation of human aesthetics, literature, film and television.

3.2 Assessment Procedures of Eco-service Value in the Sea Area Contaminated by Chemical Leakage

The procedure for assessing the eco-service value in chemicals-contaminated sea areas is shown in Figure 2.

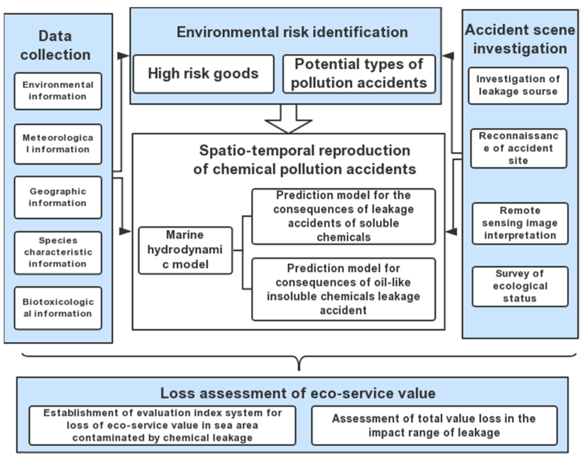

Figure2. Procedure map for assessing the value of eco-services in chemicals leakage polluted sea areas

3.3 Environmental risk identification
On the North Bank of Hangzhou Bay, a chemical industrial park has been built in Jinshan District of Shanghai, involving a variety of oil products and chemical materials. There are many kinds and large quantities of toxic, harmful, flammable and explosive chemical raw materials in the storage and transportation process, so there is a certain potential risk of pollution accidents in the storage and transportation process. Once a potential accident occurs, it may cause great loss of life and property and environmental pollution damage. The main dangerous goods involved in the wharf of chemical industrial zone are oil and liquid chemical products. Oil products include fuel oil, gasoline and diesel oil. There are more than 20 kinds of liquid chemical products, which are classified according to their pollution characteristics as shown in the table2. The pollution of dangerous cargo species to marine organisms includes: (1) bioaccumulation and biodegradation; (2) toxicity of aquatic organisms; (3) hazards to human health (toxicity to mammals); (4) impacts on marine wildlife and marine ecological environment; (5) impacts on coastal recreational environment. Therefore, the potential environmental risks of dangerous goods are mainly water pollution accidents caused by chemical leakage. The pollution classification of some chemical products in this area according to *Annex II of MARPOL 73/78 Convention* is shown in Table 2.

Table 2. Pollution classification of some chemicals in the north coast of Hangzhou Bay according to Annex II of MARPOL 73/78 Convention[14]

Operation classification	**Pollution categories in Annex II**	**Types of cargoes**
Implementation of AnnexII	X-type	/
	Y-type	methanol, ethylene glycol, PX (p-xylene), toluene, TDI (toluene diisocyanate), Cumene (isopropyl benzene), propylene oxide, vinyl acetate, sulfuric acid, xylene, phenol, aniline, butadiene, styrene
	Z-type	acetone, acetic acid, hydrochloric acid, glycerol
	OS	/
Implementation of Annex I	Petroleum	180 # fuel oil, non-standard fuel oil, gasoline, diesel oil

3.4 Spatio-temporal reappearance of chemical leakage accident consequences and prediction method of ecological impact

3.4.1 Spatio-temporal reappearance method of chemical leakage accident consequences
(1) Prediction model for the consequences of leakage accidents of soluble chemicals

In this study, the total differential equation of soluble substances transport and diffusion is used to quantitatively explain the impact of typical chemical pollution accidents on water quality. The difference mesh scale is 200 m (long) 200 m (wide) 5 m (depth). The horizontal components of ocean currents in different depths are calculated by TIDE2D model.

$$\frac{\partial C_P}{\partial t} + u\frac{\partial C_P}{\partial x} + v\frac{\partial C_P}{\partial y} + w_p\frac{\partial C_P}{\partial z} = K_X\frac{\partial^2 C_P}{\partial x^2} + K_y\frac{\partial^2 C_P}{\partial y^2} + K_Z\frac{\partial^2 C_P}{\partial z^2} + \sum S_P \quad (1)$$

In the formula: C_P-pollutant concentration; x, y, z -Cartesian three-dimensional coordinates; t-time; u, v- average current velocity in the depth of X and Y direction; w_p-gravity settling rate of pollutant in Z-direction, taking 0.5m/d; S_P-discharge rate of pollutant concentration; K_X, K_y, K_Z-turbulence and friction diffusion coefficient in x, y, z direction, Okubo's "unified diffusion speckle map" is selected to determine the horizontal diffusion coefficient according to the grid scale, and the vertical diffusion parameters calculated by the empirical formula of similar field tests.

(2)Prediction model of consequences of oil-like insoluble chemicals leakage accident

The CWCM2.0 developed by the Institute of Water Transportation Science of the Ministry of Transportation is applied to simulate and predict the environmental impact of spillover accidents. The model assumes that marine spills (oil spills and chemical spills) consist of many smaller spill particles.

According to Lagrange's full dynamic trajectory model, the spatial distance of a particle moving under full dynamic action is calculated by the following formula.

$$\Delta x_p = (U_{tide} + U_{turbulent} + U_{wind} \times f + U_W)dt \quad (2)$$

$$x_p = \int_{t_1}^{t_2}(U_{tide} + U_{turbulent} + U_{wind} \times f + U_W)dt \quad (3)$$

In the formula, Δx_p-spatial moving distance of P particle in very short time interval(dt), m; x_p- the space moving distance of p-particle in T1-T2 time interval, m; U_{tide} -tidal current velocity, m/s; $U_{turbulent}$ -turbulent flow velocity, m/s; $U_{turbulent} = \left[(6D_x/\Delta tR_u)^{1/2}, \ (6D_y/\Delta tR_v)^{1/2}, \ (6D_z/\Delta tR_w)^{1/2}\right]$, m/s; D_x, D_y, D_z-diffusion coefficient in x, y and Z directions; R_u, R_v, R_w- rectangular probability distribution random variables, distribution range (-1,1); U_w -the velocity of gravity settlement, calculated according to Stokes formula. U_{wind}- wind current velocity,m/s;f- wind-driven current coefficient, generally 3-5%. U_{wind}- It indicates that the flow direction is deflected to the right by the wind, and the deflection value is usually 10-15°.

3.4.2 Ecological impact prediction method

(1) Assessment method of environmental pollution degree affected by soluble chemicals

Refer to MARPOL73/78 Convention Annex II on the classification of chemical pollution categories to evaluate the impact of soluble chemicals. The assessment indexes are listed in Table 3.

Table 3. Assessment indexes of environmental pollution degree affected by soluble chemicals

Unit:mg/L

Environmentalpollution degree / Pollution category	Extreme pollution	Serious pollution	Moderate pollution	Slight pollution	General impact	Slight impact
Category X	>20	10~20	5~10	1~5	0.1~1	0.01~0.1
Category Y	>100	20~100	10~20	5~10	1~5	0.1~1
Category Z	>500	100~500	20~100	10~20	5~10	1~5
Category OS	>10000	2500~10000	500~2500	100~500	20~100	10~20

(2)Estimation method of ecological loss and economic value of biological resources loss

Based on the analysis of the mechanism of the impacts and the measured data, the assessment method of the impacts of construction projects on marine biological resources in the Technical Regulations for Impact Assessment of Construction Projects on Marine Biological Resources(SC/T9110-2007) is adopted to estimate the loss of marine biological resources. The calculation formulas are as follows:

$$W_i = D_i \times S_i \quad (4)$$

In the formula, Wi-- damage to type i biological resources, unit is kg; Di- density of type i biological resources in the assessment area, units are $/km^2$, $/km^3$, kg/km^2;Si-- area or volume of fishery waters occupied by species i, units are km^2 or km^3.

The formula for estimating the economic loss of marine living resources is shown as follows:

$$M = W \times E \quad (5)$$

M--amount of economic loss, unit is yuan (yuan); W-- loss of biological resources, unit is kilogram (kg); E-- prices of biological resources, unit is yuan per kilogram(yuan/kg).

4. RESULTS AND DISCUSSION

4.1 Prediction results of leakage accidents of soluble chemicals

In this study, ethylene glycol is selected as the representative cargo. And the total differential equation of soluble substances transport and diffusion is used to simulate the pollutant concentration field within

12 hours after the leakage of 100t and 2000t ethylene glycol chemicals in the inbound and outbound channel through differential numerical simulation method, in order to quantify the extent to which typical chemical pollution accidents affect water quality.

Ethylene glycol belongs to category Y. If it is more than 100mg/L, the environment is extremely polluted; if it is 20～100mg/L, the environment is seriously polluted; if it is 10～20mg/L, the environment is moderately polluted; if it is 5～10mg/L, the environment is slightly polluted; if it is 1～5 mg/L, it has general impact on the environment; and if it is 0.1~1 mg/L, it has slight impact on the environment.

The predicted results are shown in Figures 3. The spatial distribution of 12h pollutant diffusion is shown in Figures 4.

Based on the predicted results, the estimated range of impacts of soluble chemical spills is shown in Table 4 .

Table4. Range of impact of soluble chemicals Unit: ha

Leakage	**Maximum impact range**
100t	964
2000t	1860

4.2 Prediction results of oil-like insoluble chemicals leakage accident

This study compares and calculates the impact range of oil-like chemicals through the simulation of the impact range of oil spill. The CWCM2.0 developed by the Institute of Water Transportation Science of the Ministry of Transportation is used to simulate and predict the environmental impact of spillover accidents. The simulated tidal current field data are selected as the flow field calculation parameters. According to the characteristics of the annual wind field and the location of the sensitive target in the sea area, wind directions with the largest wind frequency and their perennial wind velocities are selected for wind field calculation parameters. For Tanhu Island, the environmentally sensitive target, NW wind direction is the most disadvantageous one. In this model, the selected leakage of fuel oil is 1,100 t and 5,000 t. According to the above simulation conditions, the trajectory simulation results, impact degree and range of impact are calculated when the wind fields on the sea surface are NW, ESE and NNW. The simulation figures are shown in figure 5 to figure 8 respectively.

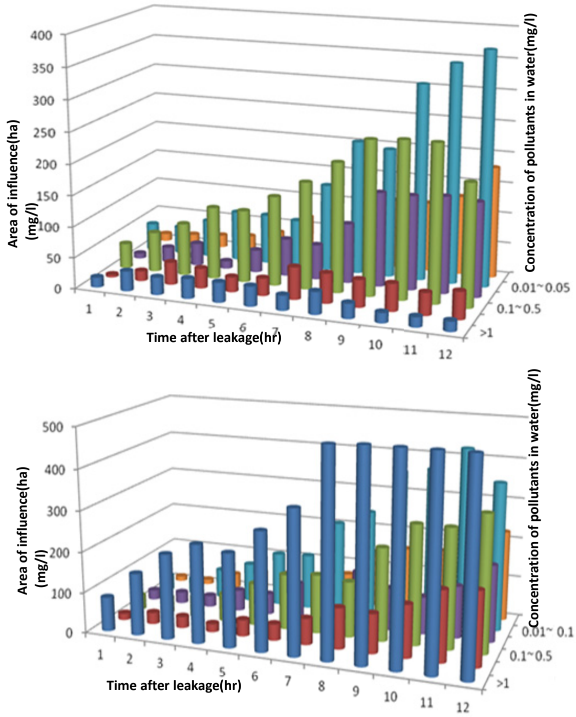

Figure3. Range of environmental pollution impacts of ethylene glycol spill accidents (spillage: above: 100t; below: 2000t)

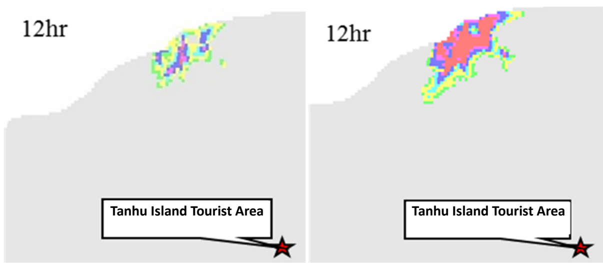

Figure4. Simulation results of spatial and temporal distribution of environmental pollution impact of ethylene glycol spill accidents (spillage: left: 100; right: 2000t)

Based on the predicted results, the impact range of oil-like insoluble chemicals leakage accidents is assessed as Table 5.

4.3 Analysis of loss assessment result of eco-service value

①Food production

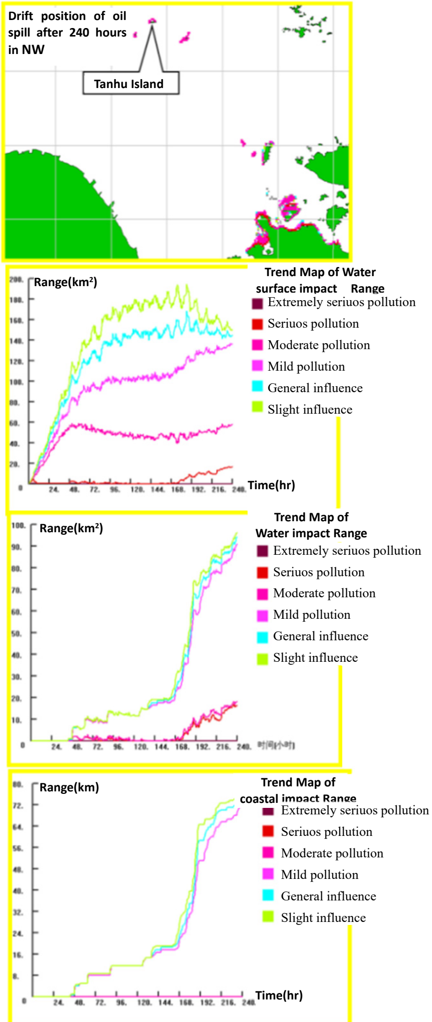

Figure5. Simulation results of drift trajectory of 1100t oil spill in NW wind direction and tendency of impact range of water surface, water and shoreline

Table 5 Impact range of oil-like insoluble chemicals unit:ha

Leakage	**Wind direction**	**Maximum impact range**
1100t	NW	20000
	ESE	11800
	NNW	18000
5000t	NW	34000

For a long time, Hangzhou Bay has provided people with a large number of aquatic products. Based on the analysis of the impact mechanism and the measured data, this study estimates the loss of marine organisms in the maximum impact area by analogizing the damage assessment methods of marine biological resources caused by engineering construction.

(1) Estimation of benthic biomass loss

The average values of total benthic biomass and total habitat density were $0.80g/m^2$ and $16.00g/m^2$, ranging from $0.111.93g/m^2$ to $10.0030.00/m^2$, respectively. The estimated loss of benthic organisms in the affected area is shown in Table 6.

(2) Loss of fishery resources

According to the present situation monitoring, the density of fishery resources in the survey area is shown in the table 7. The estimated loss of adult fish in the affected area is shown in Table 8.

(3) Estimation of economic value of loss of biological resources

IOP Conf. Series: Earth and Environmental Science **310** (2019) 052065 doi:10.1088/1755-1315/310/5/052065

The loss of economic value is calculated as 15,000 yuan per ton of biological resources, and the total loss is shown in the table 9.

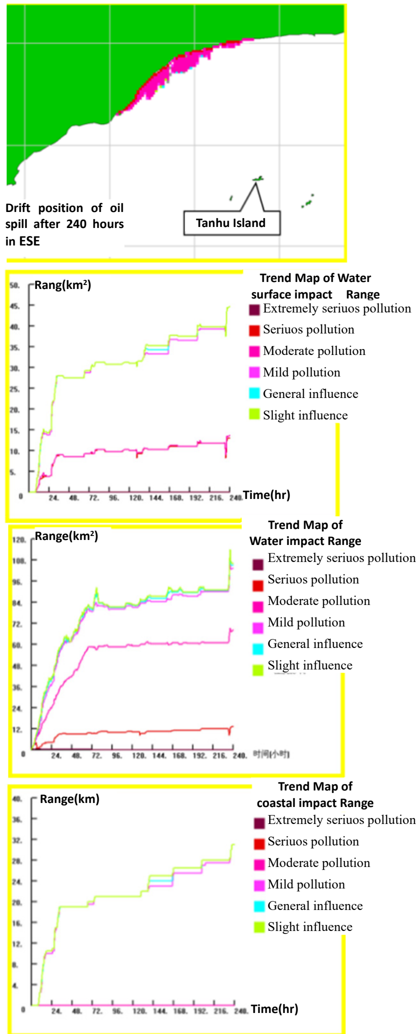

Figure6. Simulation results of drift trajectory of 1100t oil spill in ESE wind direction and tendency of impact range of water surface, water and shoreline

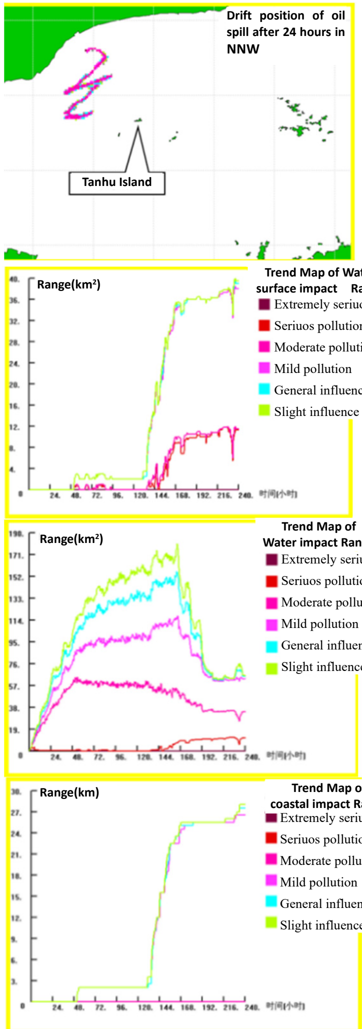

Figure7. Simulation results of drift trajectory of 1100t oil spill in NNW wind direction and tendency of impact range of water surface, water and shoreline

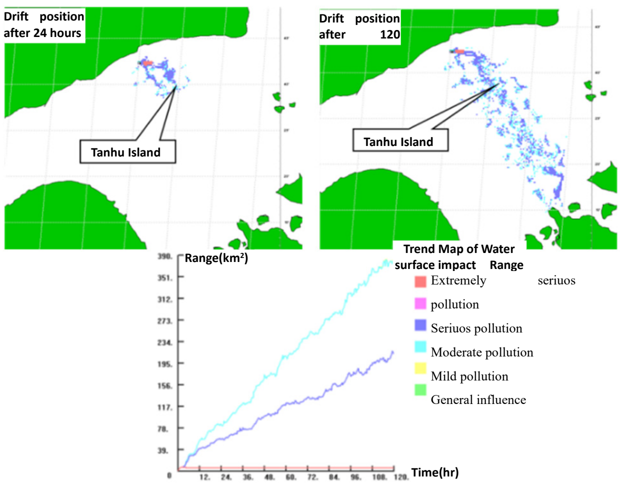

Figure8. Simulation results of drift trajectory of 5000 t oil spill in NW wind direction and dynamic trend of oil spill diffusion on water surface

Table6. Calculations results of benthic biomass loss in the impact range

Categories of chemicals	**Leakage**	**Wind direction**	**Amount of loss(t)**
Soluble chemicals	100t	/	563.94
	2000t	/	1088.1
Oil-like insoluble chemicals	1100t	NW	11700
		ESE	6903
		NNW	10530
	5000t	NW	19890

Table7. Density of fishery resources

Affected objects	**Density of biological resources**	**Notes**
Adult fish	71.53kg/km^2	/
Fish eggs	1.97eggs/m^2	Fish eggs up to 100g/ind product specificationsby 1%
Larvae	6.7156larvae/m^2	Larvae up to 100g/ind product specifications by 5%

Table8. Calculation results of loss of adult fish in the impacted area

Categories of chemicals	**Leakage**	**Wind direction**	**Loss of adult fish(t)**	**Loss of fish eggs(t)**	**Loss of larvae(t)**
Soluble chemicals	100t	/	0.7	19.0	323.7
	2000t	/	1.3	36.6	624.6
Oil-like insoluble chemicals	1100t	NW	14.3	394.0	6715.6
		ESE	8.4	232.5	3962.2
		NNW	12.9	354.6	6044.0
	5000t	NW	24.3	669.8	11416.5

Table9. Total loss of fishery resources and its economic value in the impact range

Categories of chemicals	**Leakage**	**Wind direction**	**Total loss(t)**	**Economic value(ten thousand yuan)**
Soluble chemicals	100t	/	907.3	1361.01
	2000t	/	1750.6	2625.9
Oil-like insoluble chemicals	1100t	NW	18823.9	28235.85
		ESE	11106.1	16659.15
		NNW	16941.5	25412.25
	5000t	NW	32000. 6	48000.9

②Gas regulation

Hangzhou Bay has a vast water area, which plays an important role in the regional gas and climate regulation. For the value of gas regulation services in Hangzhou Bay, the role of phytoplankton in releasing oxygen through photosynthesis is mainly considered. Based on the primary productivity of Hangzhou Bay ecosystem, this study calculated the amount of oxygen released according to the photosynthesis equation, and then estimated the economic value of oxygen released by industrial oxygen production price.

The mean value of primary productivity of Hangzhou Bay ecosystem is estimated by chlorophyll method.

$$Ps(mg/m^3 \cdot d)=1000Ca \cdot Q$$

In the formula, Ca is the content of surface chlorophyll a (mg/m^3), Q is the assimilation coefficient (mgC/mgChla·d), and the assimilation coefficient of surface water is 3.7.

The primary productivity is estimated to be 4810 mg/m^3·d. The amount of oxygen released by phytoplankton through photosynthesis is estimated to be $1.65*10^6$ tons/(m^3·year). The value of gas regulation in Hangzhou Bay is estimated as 660 million yuan per ton (m^3·year) based on the current price of 400 yuan per ton for industrial oxygen production.

③Climate regulation

For the value of climate regulation services in Hangzhou Bay, the role of phytoplankton in absorbing CO_2 through photosynthesis is mainly considered. Based on the primary productivity data of Hangzhou Bay ecosystem, the amount of fixed C is calculated according to the photosynthesis equation.

The ecological value of fixed C is estimated by carbon tax rate method. Sweden's carbon tax rate is 150$/t·C. In this paper, Swedish carbon tax rate of 150$/t·C is used to evaluate the fixed C value of Hangzhou Bay. The results show that the amount of fixed C of phytoplankton in Hangzhou Bay is 6.2×10^5 tons per year. Its value is $3.6*10^4$ tons, or 104,000 yuan per (hectare·year). Estimation of climate regulation value in the impact range is shown in the table 10.

Table10. Estimation of climate regulation value in the impact range

Categories of chemicals	Leakage	Wind direction	Economic value(ten thousand yuan)
Soluble chemicals	100t	/	1002.56
	2000t	/	1934.4
Oil-like insoluble chemicals	1100t	NW	20800
		ESE	12272
		NNW	18720
	5000t	NW	35360

④Waste treatment

For the estimation of the value of waste treatment service in Hangzhou Bay, the absorption and degradation of N and P by phytoplankton are mainly considered.

When photosynthesis is used for photosynthesis, C, N and P are absorbed in a certain ratio (Redfield ratio), and the ratio of Redfleld is C:N:P=206:26:l. Based on the primary productivity and Redfield ratio of Hangzhou Bay, the number of N and P absorbed by phytoplankton can be determined. It can be calculated that the amount of N and P absorbed in Hangzhou Bay is $9.36*10^4$ tons/year and 5.89×10^3 tons/year respectively. The absorption value of N and P is the cost of domestic sewage treatment, N is 1.5 yuan / kg, P is 2.5 yuan / kg. It can be calculated that the value of Hangzhou Bay waste treatment service is l.55*104,000 yuan/year.

⑤Biological regulation

The water quality in Hangzhou Bay is highly eutrophic and the occurrence frequency of red tide is relatively high. The species of red tide algae is mainly diatom, which is non-toxic, but can cause hypoxia in water, causing organisms to die due to lack of oxygen. Regarding the value of the Hangzhou Bay marine ecosystem in regulating and controlling the number of diatoms and in reducing the probability of occurrence of red tide disasters, there is no final conclusion, so this paper does not evaluate this value.

⑥Disturbance regulation

At present, Hangzhou Bay protects marine natural disasters such as typhoons, big waves and storm surges mainly through artificial buildings such as dams. The role of marine ecosystems in resisting and reducing external fluctuations on Hangzhou Bay is not obvious. Therefore, this service is not considered.

⑦Leisure service

The value of leisure and entertainment services in Hangzhou Bay is mainly assessed by the value of tourism. In 2014, the comprehensive tourism revenue of Jinshan District in Shanghai is 3.8 billion yuan. Its tourism value is estimated to be 3.8 billion yuan / year. The loss after the accident is estimated at 20%, which is 760 million yuan.

⑧Cultural uses

The value of cultural services per unit area of Hangzhou Bay is 673.5 $/(hectare/year), i.e. 0.46 million yuan/(hectare/year), which is average for developed and developing regions. Estimation of cultural use value in the impact range of soluble chemicals is shown in the table 11.

Table11. Estimation of cultural use value in the impact range of soluble chemicals

Categories of chemicals	Leakage	Wind direction	Economic value(ten thousand yuan)
Soluble chemicals	100t	/	443.44
	2000t	/	855.6
Oil-like insoluble chemicals	1100t	NW	9200
		ESE	5428
		NNW	8280
	5000t	NW	15640

⑨Knowledge expansion

Based on the research results of Zheng Wei and others, the approximate estimation of the value of knowledge extension service in Hangzhou Bay is made by the corresponding research funds invested in the research papers of Hangzhou Bay. Since 2015 to 2017, the average annual output of papers of Hangzhou Bay is about 539, and the corresponding average scientific research expenditure for each paper in the marine field in China is 450,000 yuan. It is estimated that the value of knowledge expansion services in Hangzhou Bay is about 24.25 million yuan per year. The loss is estimated to be 48.51 million yuan by 20%.

In summary, the estimated values of total ecological damage under different environmental conditions for different levels of chemical spills is shown in the table 12.

Table12. Estimation of total value loss in the impact range of soluble chemicals

Categories of chemicals	Leakage	Wind direction	Economic value(ten thousand yuan)
Soluble chemicals	100t	/	165158
	2000t	/	167766.9
Oil-like insoluble chemicals	1100t	NW	220586.9
		ESE	196710.2
		NNW	214763.3
	5000t	NW	261351.9

Acknowledgment

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