Risk Assessment and Emergency Response Strategy of Oil Spills in Waters around Taiwan

Laurence Zsu-Hsin Chuang [1] Chi-Min Chiu [2*] Dong-Jiing Doong [3]
Chiung-Chu Huang [1] Li-Chung Wu [2] Yang-Ming Fan [2] Ching-Jer Huang [4]
Yinglong-Joseph Zhang [5]

[1] *Institute of Ocean Technology and Marine Affairs, National Cheng Kung University*
[2] *Coastal Ocean Monitoring Center, National Cheng Kung University*
[3] *Department of Hydraulics and Ocean Engineering, National Cheng Kung University, Coastal Ocean Monitoring Center, National Cheng Kung University*
[4] *Department of Hydraulics and Ocean Engineering, National Cheng Kung University*
[5] *Center for Coastal Resource Management, Virginia Institute of Marine Science*

ABSTRACT

There are frequent oil spill incidents in the waters of Taiwan. In addition to accidents such as ship grounding and oil pipeline leakage that may cause oil spills, pollution incidents with unknown sources of oil spill often occur, which will have varying degrees of impact on the environment and ecology of the sea. Wind and ocean currents are the main factors that dominate the drift trajectory and spread of oil spills in the open sea. These factors can be supplied through the ocean current fields simulated by the marine fluid dynamic numerical model (such as SCHISM), numerical wind fields provided by the Central Meteorological Bureau, and on-site observations (such as offshore data buoys, X-band radar, or TOROS HF radar) data for prediction or hindcast of oil spill numerical models (such as GNOME). The simulation results of oil spills can be loaded into the environmental sensitivity map established on the cross-platform Google Earth, and then the oil spill risk maps and risk-level assessment tables with different time delays can be produced in a rolling manner. The emergency response operation and communication platform built on this basis not only facilitates users inquiring into the latest oil spill risk information through computers or mobile devices of different operating systems, but also measuring and planning the quantity of materials and space arrangements required for emergency response.

Keywords: Oil spill, numerical simulation, risk map, level of risk, emergency response

* Corresponding author, E mail: chimin64@gmail.com

Received 20 October 2021, Accepted 9 December 2021.

1 INTRODUCTION

Taiwan's waters have experienced multiple oil-spill incidents since the implementation of the Marine Pollution Prevention Law in 1989. The Environmental Protection Agency and various agencies have improved the relevant response and treatment mechanisms for oil spills, and implementation is gradually being completed. There have also been many adjustments and revisions in the legal system. For instance, the "Major Marine Oil Pollution Emergency Contingency Plan" was revised on January 3, 2017, which mentioned that marine pollution occurs due to shipwrecks. The Ministry of Transport will set up a shipwreck disaster contingency center to coordinate contingency and implement oil-spill contingency. If marine pollution is not caused by a maritime accident, the Environmental Protection Administration of the Executive Yuan (hereinafter referred to as the EPA) will implement the contingency in accordance with the content of the contingency plan. Therefore, the Ocean Conservation Administration (hereinafter referred to as the OCA) was established on April 28, 2018, and the marine pollution prevention and control jurisdiction was changed from the EPA to the OCA on June 29, 2020.

In response to the oil-spill incidents, the integration and dispatch of antipollution materials are very important. Recently, with the efforts of the EPA and OCA, the facilities and plans required for oil-spill contingency have been integrated and established in all counties and cities. As a result, dispatch and response can be conducted in due time after an oil-spill incident. However, the situation and diffusion ranges of oil-spill incidents will vary with time. Therefore, allocating and arranging the location and quantity of limited response materials are complicated processes. Furthermore, it is necessary to consider many factors such as ocean currents, tides, wind speed and direction in the sea near the source of spilled oil, environmental sensitivity level, and the risk assessment of the oil spill with different time delays. Therefore, currently, the best countermeasure is to aggregate the above factors on a network information platform and integrate the results of oil-spill simulations to create a risk map for marine oil pollution, which can not only provide the latest information of various response units and personnel at any time, but also act as a reference for contingency planning.

The risk assessment of the areas that might be affected by oil-spill depends on the effective prediction of diffusion and drift trajectory of spilled oil. If the real-time observation data of marine and meteorology are collected and the numerical simulation is started immediately in the early stages of the oil-spill event, then the range of impact of spilled oil with different time delays can be grasped through the oil-spill model. Nowadays, the development of numerical models is very mature. According to the occurrence of oil spill, simulation or measured information from different sources can be selected for combination to improve the prediction accuracy of drift trajectory and the diffusion range of spilled oil (Chuang et al., 2017; Chiu et al., 2018b). Therefore, this paper selects four different types of domestic oil-spill incidents, discusses the feasible schemes of oil-spill risk assessment in the waters, and makes recommendations for integrating information in emergency contingency strategies.

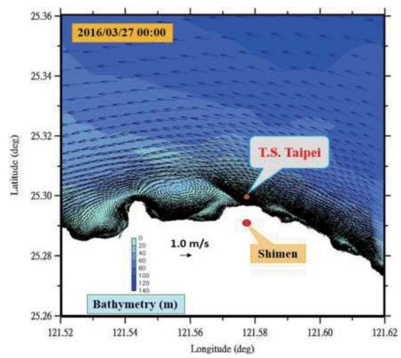
The four cases were the oil-spill of TS Taipei (Container Ship) in 2016, the scenario-simulated oil spill from the oil-unloading buoy off the coast of Kaohsiung, the oil spill incidents with unknown sources at Lyudao in 2017, and at the Port of Taichung in 2018. The first two cases are oil-spill incidents with known locations and times of pollution sources that are due to shipwrecks and accidents. If such incidents occur near the shore area (within 5 km from the coast), then the range of spilled oil on the sea surface can be detected by X-band radar and used as the initial condition for the oil-spill model to simulate the oil spill diffusion. Furthermore, combining it with physical conditions such as the ocean current and wind provided by the high-resolution ocean numerical model, the rolling prediction of the drift trajectory and the diffusion range of oil spill is implemented. The last two cases are oil-spill incidents with uncertain locations and times of pollution sources. Oil spills may occur due to unexplained reasons, such as undiscovered equipment failures, pipeline ruptures, or the secret discharge of waste oil during voyages. Although pollution sources can be identified through detection equipment or satellite image analysis, they may be unable to identify and search for pollution sources in time due to the tight response time or the influence of the weather. Hence, instead of using the simulation prediction method of the first two cases, hindcast simulations were adopted to trace the locations and times of oil spills. This study adopts the General NOAA Operational Modeling Environment (GNOME) (Beedgle-Krause, 2001) oil-spill diffusion numerical model combined with the synthetic ocean current (TUV) of the flow measurement system of the Taiwan Ocean Radar Observing System (TOROS) established by the Taiwan Ocean Science and Technology Research Center with high-frequency (HF) radar, or the flow field calculated by the SCHISM model, as well as the measured wind data nearby or the wind field numerical model provided by the Central Meteorological Bureau, so as to execute backward hindcasts in different scenarios to determine where and when the unknown sources of oil spill may be discharged.

In addition, after the occurrence of an oil-pollution incident, nearby natural landscapes, ecosystems, seawater quality, sensitive resources, and other marine environments will be affected. Therefore, it is necessary to evaluate the risk level of environmentally sensitive areas that oil pollution may affect with different time delays (Chiu et al., 2017b), and use this to determine the priority of emergency response. The environmental sensitivity map in this paper is constructed on the cross-platform Google Earth. Then, the results of the drift trajectory and the diffusion range of oil pollution simulated using the numerical model are loaded into the environmentally sensitive map in the KMZ data file format, which can be used to display and query the pollution risk maps of various sea areas and serve as an operation and communication platform for management- or command-level planning, as well as the dispatch of response materials and facilities.

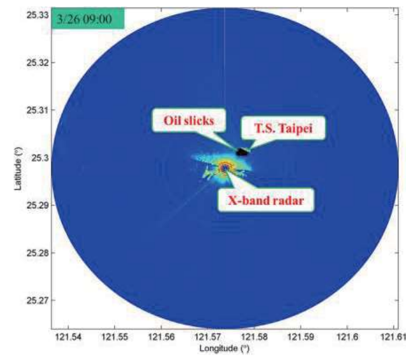
2 CASE STUDY OF TS TAIPEI OIL-SPILL

The coastal topography of Taiwan's coastal areas is curved and changeable, which leads to more complicated changes in the ocean currents of the coastal areas. The Semi-implicit Eulerian-Lagrangian finite-element model (SCHISM) uses unstructured grids to describe the curved and complicated coastal terrain and can simulate the high-resolution ocean current flow field in the coastal waters. Therefore, for the oil-spill incident caused by the TS Taipei stranded in the extremely shallow waters of Shimen District, New Taipei City, on March 10, 2016, this study used SCHISM to simulate the coastal flow field, and for the simulation of oil-spill trajectory, the study used Lagrangian particle-tracking in the SCHISM model to explore the applicability of SCHISM in the coastal waters of Taiwan.

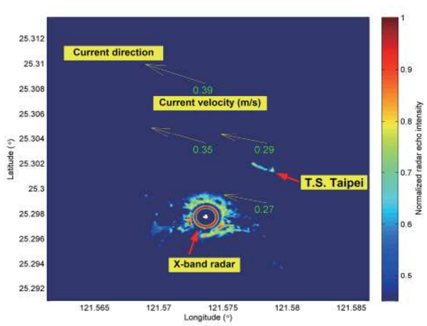
SCHISM was developed by Zhang and Baptista (2008), which considers air-sea exchange and combined with the WWM-III (Wind Wave Model-III) wave model to improve the prediction accuracy of nearshore and estuary fluid dynamic phenomena. In this case, the SCHISM wave-current coupling module and wind field data provided by the meteorological model WRF of the Central Meteorological Bureau are used for marine dynamic simulation and as the input conditions of the oil-spill model. Fig. 1a is the ocean current flow field simulated by SCHISM. It shows that the ocean current presents circulation characteristics (Chiu et al., 2018c) in the extremely nearshore area due to the effect of curved terrain. In contrast, the ocean current approximately 1.8 km away from the Shimen coast presents general tidal characteristics that flow back and forth in a direction parallel to the coastline. The Coastal Ocean Monitoring Center (COMC) of National Cheng Kung University (NCKU) and the Harbor and Marine Technology Center (HMTC) of the Institute of Transportation, MOTC, worked together and rushed to the scene to use the X-band radar to detect oil pollution, wave field, and coastal flow field on the sea surface after the oil spill occurred. The area marked in black in Fig. 1b is the range of oil spill on the sea surface detected via radar, and this result is used as the input condition for the initial range of oil pollution in the diffusion simulation. The current vector marked in Fig. 1c is the size and direction of the ocean current on the sea surface calculated using the X-band radar image. Fig. 1d shows the comparison between the ocean current detected by X-band radar and the ocean current predicted by SCHISM. The current velocity and direction of the two are consistent (Chuang et al., 2017; Chiu et al., 2017c). The SCHISM model simulates the sea conditions since 00:00 on March 26, 2016, and the range of influence of oil-spill pollution on the coast 34 days later. The simulation results (Fig. 1e) are consistent with the on-site investigation by the Environmental Protection Agency (the dark-red line marked on the coast in Fig. 1f) (Chiu et al., 2018c).



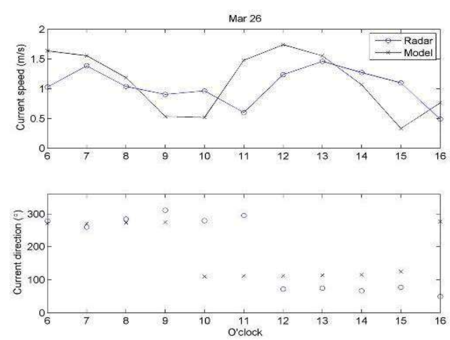
(a) The high resolution flow-fields were obtained from SCHISM. (Chiu et al., 2018c)



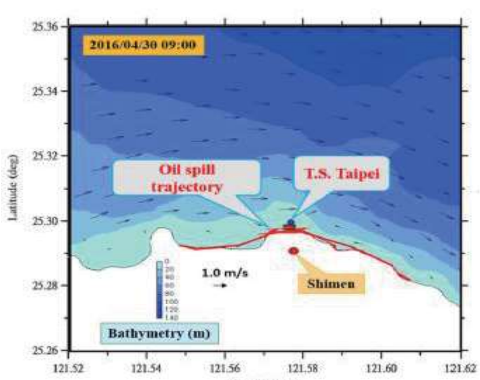
(b) Identification of the location and extent of oil slicks by the X-band radar. Oil slick area is marked black. (Chiu et al., 2018c)



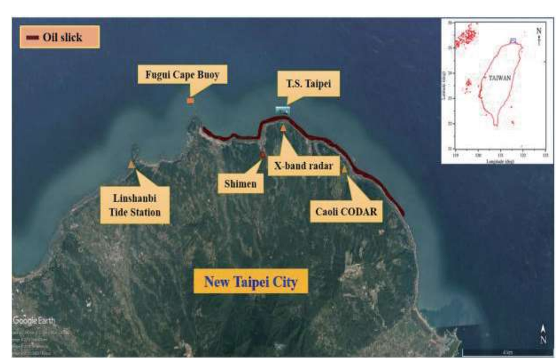
(c) Surface current distribution detected using an X-band radar on the Shimen coast.



(d) Comparison of the time series of surface current speed (top) and direction (bottom) detected using an X-band radar (circumference) with those predicted using the SCHISM (multiplied). (Chuang et al., 2017)



(e) SCHISM-simulated surface oil-slick trajectory after the oil spill occurred at the Shimen coast over 34 days. (Chiu et al., 2018c)



(f) Extent of oil slick (brown color) on the coastline obtained from EPA (Taiwan) during the period from March 26, 2016 to May 10, 2016. (Chiu et al., 2018c)

Figure 1. Validation of oil trajectory and fate modeling of the TS's Taipei oil-spill.

The TS Taipei incident is an extremely nearshore oil spill. The oil pollution in the extremely nearshore area is susceptible to the influence of coastal bending circulation (Fig. 1a) and remains for a long time; however, after the wind direction changes, oil pollution will be carried to the open sea and drift to the reciprocating flow area of tidal currents, which will expand the range of influence of oil pollution on the northeast coast. In view of this, the recommendations for contingency strategy in similar cases are: After the ship is stranded, the high-resolution ocean mode (e.g., SCHISM) will start to simulate the ocean current flow field, and the X-band radar will be used to detect the sea surface flow field in the coastal waters, so as to check the correctness of the simulated flow field. The predicted wind field and the location and area of the oil spill identified by the radar are taken as the initial input conditions for the numerical simulation of oil spill. The drift trajectory and range of influence of the oil-spill simulation can also be compared with the oil-spill images continuously monitored by the X-band radar (Chuang et al., 2017; Huang et al., 2016; Chiu et al., 2016, 2017c, 2018b), and the results are also discussed and verified in-depth in the published literature.

3 A CASE STUDY OF OIL SPILL OF UNKNOWN SOURCE AT LYUDAO

The waters around Taiwan are important international waterways. Fig. 2 shows that there are a large number of tankers (the red arrow marked on the sea surface in the picture) and cargo vessels (the green arrow marked in the picture). Oil spills of unknown source are often caused by the discharge of waste oil from large ships sailing at night, which will have a direct impact on the ecology of the sea. Through the effects of wind and currents, oil spills will often drift to the nearshore area, causing greater environmental impact; however, it is difficult to track oil spills of unknown source.

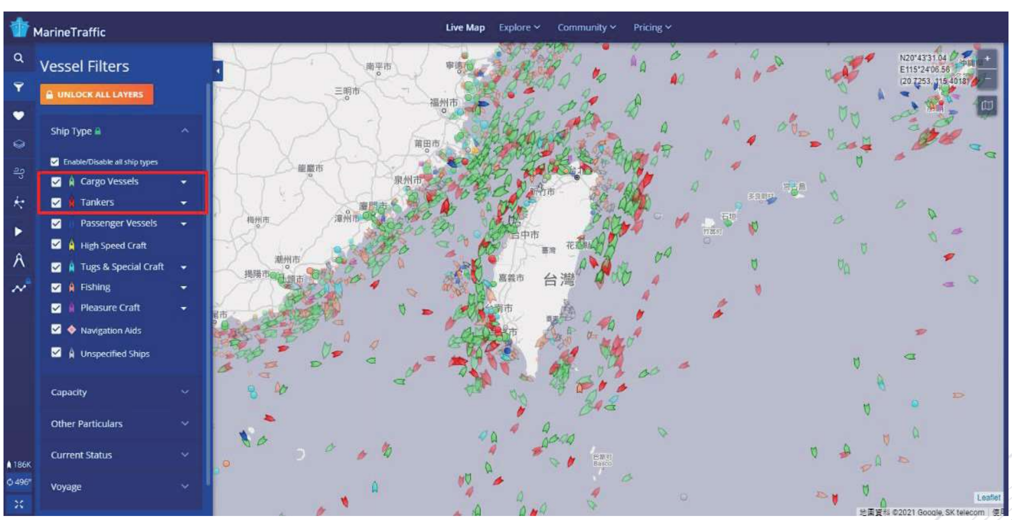
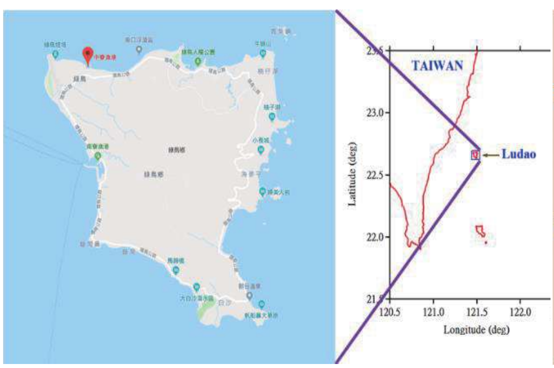


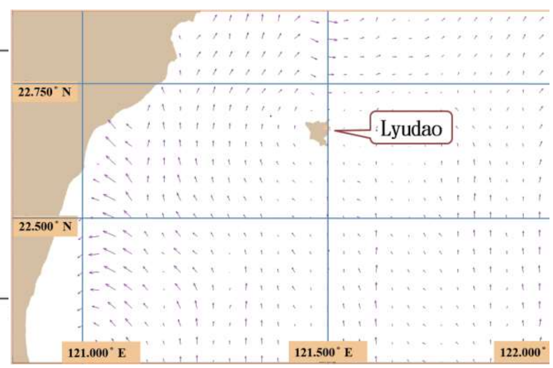
Figure 2. Distribution of ship positions in the waters around Taiwan. (https://www.marinetraffic.com/)

An oil spill was discovered at the Zhongliao Fishing Port on the northern shore of Lyudao, Taitung, on March 10, 2017 (Fig. 3a). The EPA speculates that it may have been caused by the discharge of heavy oil from ships passing through the waters near Lyudao. Although two suspicious ships were found through the Automatic Identification System (AIS) to pass through the waters near Lyudao at around 10 a.m. on March 9, there is no clear evidence to determine which ship secretly discharged the oil. The oil-spill numerical model GNOME developed by the NOAA of USA has a backward calculation function, which can be used to estimate the source of oil spills of unknown source. As the diffusion trajectory of oil pollution is only estimated for regional seas, in this case it uses the measured ocean current and wind data as the input conditions for the GNOME simulation. The ocean current input conditions adopt the 1/15-degree spatially resolved synthetic ocean current (TUV, as shown in Fig. 3b detected by the surface flow field measurement system of TOROS in the waters near Lyudao. Wind input conditions adopt the measured wind data from the Lyudao Weather Station of the Central Meteorological Bureau near the northern coast of Lyudao that is not affected by the alpine terrain.

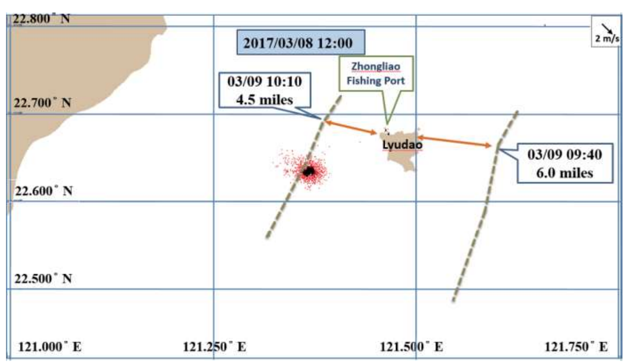
Fig. 3c is the possible source location and time of the oil spill through backward calculation of GNOME. The two-dashed lines on the east and west sides of Lyudao in the figure are the track coordinates of the two suspicious ships estimated by the Environmental Protection Agency (provided by the Hong Kong Research



(a) Oil spill found along the coast from the Zhongliao Fishing Port of Lyudao.



(b) Synthetic ocean current measured by TOROS in the waters near Lyudao.



(c) The model retrospectively calculates the possible location of oil spill source 55 hours previously until 12:00 on March 08.

Figure 3. Scenario Simulation of oil spill of unknown source at Lyudao. (Chiu et al., 2018c)

Center). The ship on the west side passes between the main island of Taiwan and Lyudao, and the track is approximately 4.5 miles away from Lyudao. The track of the ship on the east side is approximately 6.0 miles away from Lyudao. Considering the uncertainties of the wind and ocean currents, there are two types of simulation results for oil-pollution diffusion range (Zelenke et al., 2012), as shown by the red and black particles in Fig. 3c. The distribution positions of the red particles indicate that the simulated oil diffusion range has a 90% reliability, and the black particles are the best simulation results of oil diffusion. Based on the discovery location and the time of oil spill of unknown source, it is estimated back to 12:00 on March 8 (approximately 55 h). It meets the route of the ship on the west side of Lyudao in Fig. 3c. The oil-spill range of the red particle is diffused approximately 7.2 km in the horizontal direction, and the closest distance to the Lyudao Lighthouse is approximately 7.8 km. In comparison, the oil-spill range of the black particles is diffused approximately 1.6 km in the horizontal direction, and the closest distance to the Lyudao Lighthouse is approximately 9.3 km (Chiu et al., 2018a). The time when the oil spill may have been discharged here estimated by the above scenario simulation is compared with the time shown by the AIS trajectory of the ship on the west side. The interval between the two is approximately 22 h, which can rule out the possibility of the discharge of oil spill by the unknown ship.

The above method used the measured wind and ocean currents as the dynamic conditions of the oil-spill numerical model. GNOME can consider the uncertainty of wind and ocean currents and then simulate the possible time and location of the oil pollution discharged by ship, which can be further compared with the closest ship track in the AIS record. The actual ship track during the period is used as the source of oil spill to re-simulate the possible situation of oil-pollution drifting and diffusing to the Zhongliao Fishing Port at Lyudao. In this instance, the back-and-forth inspection method of traceability and calculation is scientifically based. In case the ship deliberately shuts down AIS after discharging oil to avoid tracking, the research team can also select the raw spectrum data of radar at a specific time from the TOROS radar station near the suspected pollution source to identify and locate the radar echo signal of the ship passing there and track its trajectory (Chuang, 2017). After trial and discussion similar to the above scenario simulation, it can be inferred that the unknown oil-spill incident at Lyudao may have been caused due to the discharge of a ship passing through the west side of Lyudao. The verification and recommendations of the contingency strategy, in this case, should be used as a reference for tracing the source of the unknown oil pollution at sea in the future.

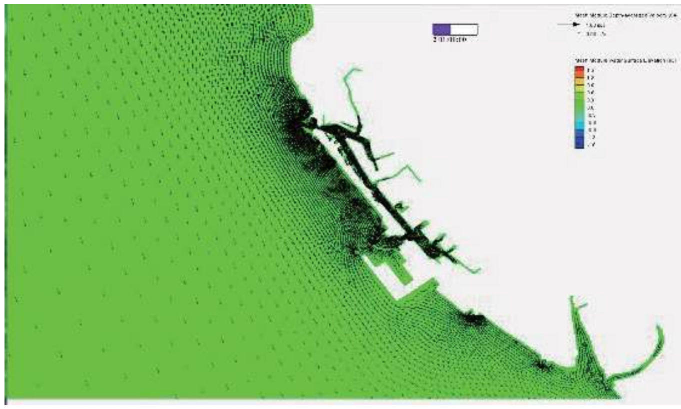
4 SCENARIO SIMULATION OF OIL SPILLS AT THE OFFSHORE OF KAOHSIUNG AND THE PORT OF TAICHUNG

We used SCHISM and GNOME respectively to simulate the drift trajectory and diffusion range of oil spill in the aforementioned events of TS Taipei and Lyudao, and have published papers (Chiu, et al., 2017a; Chiu, et al., 2018a) to verify the effectiveness of the simulation results of the two models. Next, we will combine these two numerical models, use the high-resolution ocean current simulated by SCHISM as the input conditions of the GNOME model to simulate the drifting and diffusion of oil spill, and use two cases with very different external conditions to proceed separately with scenario simulations and analysis discussions. Case one is the oil spill of the oil unloading buoy of CPC Corporation (Taiwan) off the coast of Kaohsiung, and case two is an incidence of oil spill of unknown source that occurred at the Port of Taichung on October 19, 2018.

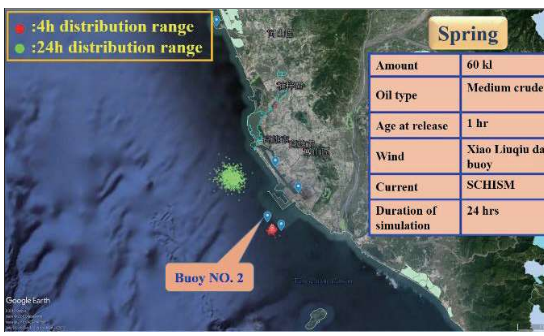
To import crude oil, CPC has installed offshore mooring buoys for unloading large oil tankers at Dalinpu in Kaohsiung. Oil spill incidents can be caused by careless operations when unloading oil. Accordingly, pre-simulation of oil spill can reduce the impact of the coastal and marine environment. In addition, simulation results are also used to develop an emergency operations plan. In this study, simulation scenarios that amount to 60-kilolitres of oil spilled from the No. 2 or No. 3 buoy in each season of 2016, spring (April), summer (August), autumn (October), and winter (January) respectively. SCHISM is used to simulate the high-resolution ocean current in the Kaohsiung waters in different seasons (Fig. 4a). Meanwhile, wind data was collected from the Xiaoliuqiu buoy. Simulation of ocean current and observation of wind data can provide GNOME the input conditions to simulate trajectory and diffusion of spilled oil for 24 hours in each scenario. The simulation results were mapped on the environmentally sensitive map to produce a coastal environmental risk map of the Dalinpu oil spill in Kaohsiung waters (Figs. 4b–e) (Chiu et al., 2019). The environmentally sensitive map is integrated with environmentally sensitive data published by various central authorities and drawn on Google Earth. Then, the simulation results of oil-spill diffusion are outputted as a KMZ data file and loaded into the environmentally sensitive map, which is convenient for users who use Google Earth on different operating system of computers or mobile devices to display and query risk maps of contaminated sea areas. Moreover, it can be used as a reference for emergency response of relevant agencies and units.

The red dots and green dots in the simulation results of each season (Figs. 4b–e) indicate the oil-spill diffusion range and trajectory after 4 hours and 24 hours of the oil spill, respectively. The spring simulation results showed that although the spilled oil drifted northward off the coast of Kaohsiung, the oil pollution did not affect the coast of Kaohsiung; however, the summer simulation results showed that spilled oil drifting northward off the coast of Kaohsiung was affected by the southwest monsoon in summer, and the oil spills drifted and close to the coast between Kaohsiung's second port and the first port; the autumn simulation results showed that the spilled oil drifted southward off the coast of Kaohsiung, but the oil pollution did not affect the coast of Kaohsiung; winter simulation results showed that spilled oil also drifted southward off the coast of Kaohsiung. Although the oil spill in the second season of autumn and winter did not affect the coast of Kaohsiung, if it continues to be affected by the northeast monsoon, it still has the possibility of impacting the southern coast of Kaohsiung Port.

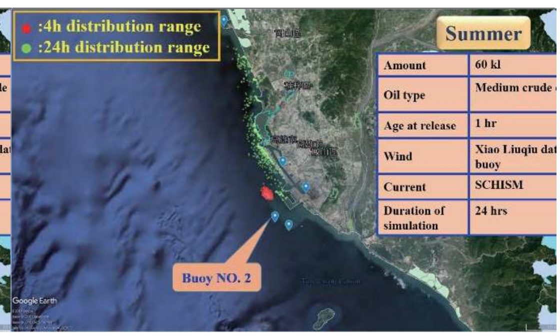
According to the possible impacts of oil-spill diffusion through scenario simulations and the characteristics of environmentally sensitive areas, the protection priority of environmentally sensitive areas can be divided into different levels. For example, in Table 1, the protection levels of environmentally sensitive areas and resource utilization sensitive areas are classified as "High" and "Moderate," and other areas with special characteristics are classified as "Low," respectively. Moreover, based on the simulation results, the possibility of an oil spill spreading to environmentally sensitive areas after different delays can be judged and different risk levels can be set respectively. Risk code 0 implies that it will not happen, 1 indicates that it might happen under changing marine meteorological conditions, and 2 represents that there will be an impact. For instance, Table 1 shows that 24 hours after the oil-spill on the No. 2 buoy, the Shoushan National Natural Park in Kaohsiung City, which is classified as an emergency protection grade, is at a greater risk of oil spill in summer, followed by spring, and remains unaffected in other seasons.



(a) Simulated sea surface current field along the Kaohsiung coast obtained by using SCHISM on August 25, 2016.



(b) Risk map 24 hours after the medium crude oil spill at the No. 2 buoy in the spring of 2016.



(c) Risk map 24 hours after the medium crude oil spill at the No. 2 buoy in the summer of 2016.

(d) Risk map 24 hours after the medium crude oil spill at the No. 2 buoy in the autumn of 2016.

(e) Risk map 24 hours after the medium crude oil spill at the No. 3 buoy in the winter of 2016.

Figure 4. Scenario simulation of the oil spill incident off Kaohsiung coast. (Chiu, 2019)

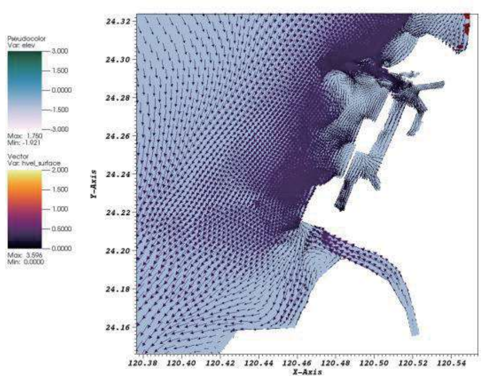
Table 1. Effects and risk evaluation of Dalinpuo oil spills in adjacent seas nearby Kaohsiung.

Affected area	Environmentally sensitive areas	Spring 24hr	Summer 24hr	Autumn 24hr	Winter 24hr
Tainan city	**Taijiang National Park**	0	0	0	0
	Zengwun Estuary Important Wetland	0	0	0	0
	Sihcao Important Wetland	0	0	0	0
	Yanshuei Estuary Important Wetland	0	0	0	0
Kaohusing city	Aquaculture Fishery Production Area: Xingang District	0	0	0	0
	Aquaculture Fishery Production Area: Mituto District	0	2	0	0
	Shoushan National Natural Park	1	2	0	0
Pingtung county	Aquaculture Fishery Production Area: Wunfong District	0	0	2	0
	Aquaculture Fishery Production Area: Siaputou District	0	0	1	0
	Aquaculture Fishery Production Area: Dajhuang District	0	0	1	0
	Aquaculture Fishery Production Area: Donghai District	0	0	1	0
	Aquaculture Fishery Production Area: Fanzihlun District	0	0	1	0

Risk codes: 0-Rarely; 1- May occur under changing sea and weather conditions; 2- It will have an impact.
Protection level of environmentally sensitive areas: "**High**", "Moderate", and "Low"

In addition, the Port of Taichung is not only an international commercial port but a government-planned offshore wind power industrial park and operation base. This shows that Port of Taichung will play a decisive role in the future. Frequent ship transportation and loading as well as the unloading of oil supply may entail risk of oil spills. In particular, the Gaomei Wetland Reserve is adjacent to the north of Port of Taichung. If an oil spill occurs, it may impact the ecology of the Gaomei Wetland. This study used the unknown oil-spill incident at the North Terminal 2 at Port of Taichung at approximately 9:30 a.m. on October 19, 2018. It explored the impact of oil-pollution diffusion on the Port of Taichung and its surrounding areas (Chiu et al., 2020). Fig. 5a shows the changing trend of the ocean current in the sea area of Port of Taichung during the low tide period predicted by SCHISM. The color scale in the upper left corner of the figure shows the change of sea-level rises and falls, the color scale in the lower left corner shows the size of the velocity of ocean current, and the arrow direction in the figure shows the direction of the ocean current. The simulation results show that during the low tide of the sea area at Port of Taichung, the direction of the ocean current is from northeast to southwest. The ocean current approximately 6-km offshore from the port flows in the direction parallel to the coastline; the ocean currents near the coast of Port of Taichung are affected by the topography of Port of Taichung, which will produce a circulation effect.

The scenario assumes that 30 km of fuel oil is spilled, and the results of the oil-pollution diffusion after 12 hours (2018/10/19 20:30) are simulated, as shown in Fig. 5b. The oil spill was affected by the strong northeast wind, which caused it to drift and diffuse toward the southwest of Port of Taichung; then it held close to the West Wharf at the Port of Taichung and the Port Industrial Development Zone. Nevertheless, the oil spill did not drift or diffuse outside of the port. This result was consistent with the content reported in the electronic media. The simulation results of oil-pollution diffusion have been integrated into the environmental sensitive map to produce the risk map of the Port of Taichung. Then the response materials (such as the number of oil barriers) in the adjacent sensitive areas of Port of Taichung can be measured and planned on the Google Earth platform (Fig. 5c). For example, code E is the water intake of the Taichung LNG plant. According to the risk map, it is recommended to configure a 100-m-long oil boom to prevent equipment damage due to sucking in oil at the water intake.



(a) Simulated sea surface current field along the Taichung coast obtained by using SCHISM in Oct. 2018.

(c) Emergency resource allocation plan for unknown oil spill incident in Port of Taichung.

(b) GNOME-simulated drifting trajectory and diffusion range of the fuel oil after 24 hours since the oil spill occurred in the Port of Taichung.

Figure 5. Scenario simulation of the spilled oil diffusion of the unknown oil-spill incident in the Port of Taichung on October 19, 2018. (Chiu et al., 2020)

5 DISCUSSION AND CONCLUSIONS

The water depth and topography of the waters around Taiwan are complicated. In the event of an oil spill, the marine meteorological conditions in different waters will significantly vary in different seasons, which will cause the effects of the trajectory and the diffusion of oil spill to show different results. Based on the various conditions of oil-spill events in different sea areas, this study used different combinations of SCHISM and GNOME and input predicted or measured sea weather conditions to simulate the spread of spilled oil. For instance, the oil-spill diffusion range detected using the X-band radar can provide GNOME as the input condition for the location and quantity of initial oil-spill. Ocean currents can be obtained by combining SCHISM to predict the flow field, or the flow field can be detected by using (X-band/HF) radar. In addition, the predicted wind data provided by the Central Meteorological Bureau or the measured wind data by the adjacent offshore buoy stations are combined to perform simulations of the drift trajectory and the diffusion range of oil pollution, as well as the back calculation of the possible source location and the time of the unknown oil pollution in the open sea.

After an oil spill event, both predictions of the trajectory and diffusion of the oil spill are important to the emergency contingency plan. It must be updated in a rolling manner according to the changes in the marine meteorological conditions. As a result, the range of influence of the simulation results may continue to expand. To highlight the possible impact of oil pollution on the marine environment at different stages and consider the convenience of information users, this study integrates environmentally sensitive data published by various central authorities and produces environmentally sensitive maps on Google Earth. Then, the simulation results of the oil spill diffusion are output in the KMZ data file format, loaded into the environmentally sensitive map, and made into a risk map of the affected sea area. Based on this, the risk level of each environmentally sensitive area can be established and combined with the priority of the protection level of the environmentally sensitive area to determine the allocation of limited response resources and energy. With that, an optimal emergency contingency plan is able to be established in the shortest time to reduce the impact of oil pollution on the marine environment. This dynamic oil-pollution risk map can be operated in Google Earth on different operating systems on computers or mobile devices, and be used to display and query the risk information of polluted sea areas in order to measure and plan the contingency materials and configurations required in each risky sea area.

ACKNOWLEDGMENTS

Courtesy of the Harbor and Marine Technology Center (HMTC) funding research project "Development on the Technology of Oil Spill Monitoring and Simulation (3/3)" (2016), and the provision of the ship's track marked by the AIS. The authors would like to thank the Taiwan Ocean Research Institute for providing current data from the CODAR for verifying the accuracy of the simulated surface currents. Some simulations presented in this paper were conducted using the Sciclone cluster at the College of William and Mary, which was established under the auspices of the National Science Foundation, the Virginia Port Authority, Virginia's Commonwealth Technology Research Fund, and the Office of Naval Research. In addition, we also sincerely thank the OR&R (Office of Response and Restoration) of the NOAA (National Oceanic and Atmospheric Administration) for assistance in the application of GNOME model. The authors are also grateful to the anonymous reviewers for their helpful comments and suggestions.

REFERENCES

Beegle-Krause, J. (2001). General NOAA oil modeling environment (GNOME): A new spill trajectory model. International Oil Spill Conference, 2001(2): 865-871. https://doi.org/10.7901/2169-3358-2001-2-865

Chiu, C. M. (2019). *Forecasting of fate and transport of oil spills in Taiwan's coastal waters using SCHISM and GNOME* [Doctoral thesis]. National Cheng Kung University, Taiwan, R.O.C.

Chiu, C. M., Chuang, L. Z. H., Huang, C. J., Fan, Y. M., Wu, L. C., Su, C. H., and Lee, C. Y. (2017a). A simulation oil spill of "T.S. Line" incident using SCHISM model. Harbor and Marine Bulletin, 107: 69-77. (In Chinese)

Chiu, C.-M., Chuang, L. Z. H., Huang, C.-J., Huang, C.-C., and Kao, C.-C. (2017b). Oil spill simulation and risk assessment of the offshore oil-unloading buoy in Taoyuan using GNOME. Proceedings of the 39th Ocean Engineering Conference, Taichung, Taiwan, 395-400. (In Chinese)

Chiu, C.-M., Chuang, L. Z. H., Huang, C.-J., Huang, C.-C., Yang C.-T., Wang, S.-P., and Chang, K.-C. (2019). Scenario simulations of oil spill in Kaohsiung-Offshore using SCHISM and GNOME. Proceedings of the 41th Ocean Engineering Conference, Tainan, Taiwan, 602-607. (In Chinese)

Chiu, C.-M., Chuang, L. Z. H., and Huang, C.-J. (2020). Oil spill impact on green port development - an unidentified oil spill in 2018 at Port of Taichung. Proceedings of the 42th Ocean Engineering Conference, Keelung, Taiwan, 244-249. (In Chinese)

Chiu, C.-M., Chuang, L. Z. H., Lai, J.-W., Huang, C.-J., and Chen, Y. J. (2018a). Oil Spill Trajectory Hindcast Based on the GNOME Model and TOROS HF Radar Currents: the Case of Taiwan Green Island Seashore Dampened by Illegal Oil Dump. Journal of Ocean and Underwater Technology, 28(1): 45-51. (In Chinese)

Chiu, C.-M., Huang, C.-J., Chuang, L. Z. H., Fan, Y.-M., and Wu, L.-C. (2018b). Forecasting of oil spills in Taiwan's coastal waters using SCHISM and GNOME. Journal of Coastal and Ocean Engineering, 18(2): 85-119. https://doi.org/10.6266/ JCOE (In Chinese)

Chiu, C.-M., Huang, C.-J., Fan, Y.-M., Chuang, L. Z. H., Chien, C.-C., and Lee, C. Y. (2016). Application of numerical models to evaluate oil spills in harbor. Harbor and Marine Bulletin, 103: 25-41. (In Chinese)

Chiu, C.-M., Huang, C.-J., Wu, L.-C., Zhang, Y. J., Chuang, L. Z. H., Fan, Y.-M., and Yu, H.-C. (2018c). Forecasting of oil-spill trajectories by using SCHISM and X-band radar. Marine Pollution Bulletin, 137: 566-581. https://doi.org/10.1016/j.marpolbul.2018.10.060

Chiu, C. M., Huang, C. J., Wu, L. C., Zhang, Y. J., and Yu, H. C. (2017c). Oil spill forecasting system. The 27th International Ocean and Polar Engineering Conference. International Society of Offshore and Polar Engineers, San Francisco, USA, 667-672.

Chuang, L. Z. H. (2017). *Detection and Tracking of Surface Vessels by High-Frequency Oceanographic Radar System (III), Final Report* (Report No. MOST 105-2221-E-006-137-). Ministry of Science and Technology, Taiwan.

Chuang, L. Z. H., Wu, L.-C., Fan, Y.-M., Chiu, C.-M., Su, C. H., Lee, C.-Y., and Huang, C.-C. (2017). *Development on the Technology of Oil Spill Monitoring and Simulation (3/3), Final Report* (Report No. MOTC-IOT-105-H3DB002b). Harbor and Marine Technology Center, Institute of Transportation, Ministry of Transportation and Communications, Taiwan.

Huang, C. J., Chiu, C. M., Chuang, L. Z. H., Fan, Y. M., Wu, L. C., Chiu, Y. F., Su, C. H., and Lee, C. Y. (2016). Application of SCHISM model to simulate oil spill trajectories - A case study for the T.S. Taipei's oil spill, Proceedings of the 38th Ocean Engineering Conference, Taipei, Taiwan, 375-380. (In Chinese)

Zhang, Y., and Baptista, A. M. (2008). SELFE: A semi-implicit Eulerian–Lagrangian finite-element model for cross-scale ocean circulation. Ocean Modelling, 21(3-4): 71-96. https://doi.org/10.1016/j.ocemod.2007.11.005

Zelenke, B., Connor, O'Connor, C., Barker, C., Beegle-Krause, C. J., and Eclipse, L. (Eds.) (2012). *General NOAA Operational Modeling Environment (GNOME) Technical Documentation.* US Dept. of Commerce, NOAA Technical Memorandum NOS OR&R 40. Seattle. http://response.restoration.noaa.gov/gnome_manu