One-dimensional Numerical Simulations of Oil Spill in a Coastal Bay with Delayed Removal Mechanisms

Teerat Kasamwan, Nopparat Pochai

***Abstract*—Oil spills in marine and coastal areas can result from various activities, such as oil drilling, transportation, shipping, tank cleaning, illegal disposal of oil-contaminated or used water, and accidents like ship collisions or sinking incidents. These events result in oil slicks or tar balls that form in the sea and eventually drift towards the coast. There are many methods for addressing oil spills, such as containment, employing skimmers, chemical dispersants, bioremediation, burning, beach cleanup, environmental restoration, and monitoring and assessing long-term impacts on the shoreline. A delay in oil spill response can have severe consequences for both the environment and local economies. When oil spills occur, rapid and effective action is essential to minimize damage. Unfortunately, delays in response can exacerbate the problem and lead to more extensive environmental harm. In this research, a one-dimensional mathematical model for an oil spill in a coastal bay with delayed removal mechanisms is considered. The governing equation for an oil spill in a coastal bay with delayed removal mechanisms is introduced. The initial and boundary conditions for an oil spill in a coastal bay are also presented. A mathematical model incorporating delayed removal mechanisms is proposed. The solution of the proposed model is approximated using a finite difference method, specifically the forward time-centered space (FTCS) method. In the simulations, two scenarios are illustrated, namely, the instant removal mechanism scenarios and the delayed removal mechanism scenarios. In the instant removal mechanism scenarios, various average removal rates and basic water flow behaviors are simulated. In the delayed removal mechanism scenarios, realistic oil spill situations are considered. Therefore, the spillage rate and removal mechanism rate throughout the simulation period are analyzed. The simulation results show that the concentration of the late-coming removal mechanism leads to a poorer recovery outcome than the faster-coming removal mechanism in all scenarios. This aligns with the reality that when oil spill removal is effectively managed, the concentration of oil in the sea should decrease. The findings of this study demonstrate that, under all circumstances, delayed oil removal has more detrimental effects on seawater recovery than speedy removal. Therefore, removing oil spills quickly and effectively will significantly reduce the amount of oil in the water.**

***Index Terms*—Oil Spill, Coastal bay, Finite difference method, FTCS**

I. Introduction

Manuscript received September 15, 2024; revised March 8, 2025.

This work was supported by King Mongkut's Institute of Technology Ladkrabang.

T. Kasamwan is a Ph.D. candidate of Mathematics Department, Faculty of Science, King Mongkut's Institute of Technology Ladkrabang, Bangkok, 10520, Thailand (e-mail: kasamwan.t@gmail.com).

N. Pochai is an Associate Professor of Department of Mathematics, Faculty of Science, King Mongkut's Institute of Technology Ladkrabang, Bangkok, 10520, Thailand (corresponding author to provide phone: 662-329-8400; fax: 662-329-8400; e-mail: nop_math@yahoo.com).

OIL spills in the sea are one of the major environmental issues that severely impact both marine ecosystems and human populations. Oil spills can occur for various reasons, such as accidents involving oil tankers, leaks from oil drilling platforms, or other maritime incidents.

Oil spills have multiple consequences, including ecological damage. When oil contaminates water, it forms a film that prevents oxygen from dissolving into the water and blocks sunlight, hindering aquatic plants and phytoplankton from photosynthesizing. As primary producers struggle to survive, the effects cascade through the food chain, impacting various marine organisms, including fish, turtles, and shrimp, which may also perish. This disruption of the marine ecosystem ultimately leads to negative consequences for humans.

Economic damage is another major consequence. Oil spills degrade the scenic beauty of coastal areas, reducing the attractiveness of tourist destinations and leading to a decline in tourism. This, in turn, diminishes the income of local vendors and service providers, including accommodations and hotels in affected areas. Additionally, oil spills impact the livelihoods of fishermen by hindering their ability to fish, thereby affecting their income and well-being.

Oil spills also pose significant health risks. Consuming seafood from contaminated waters can lead to the ingestion of toxins present in oil that have been absorbed by marine organisms. Long-term exposure to oil vapors can cause acute symptoms such as eye and skin irritation, while prolonged exposure may result in swelling, redness, and burns. Ingesting oil-contaminated food can cause diarrhea, nausea, vomiting, and dizziness. Chronic exposure can lead to severe respiratory diseases, an increased risk of miscarriage in pregnant women, and a higher likelihood of developing leukemia due to the presence of benzene in oil.

Several methods are used to manage oil spills, including chemical dispersants, physical techniques such as oil booms and skimmers, controlled burning, absorbent materials, and biological approaches that utilize microorganisms to break down oil. However, effectively addressing oil spills requires cooperation among all stakeholders, including governments, private sectors, environmental organizations, and the general public. Collaborative efforts in prevention and management will help safeguard the environment and preserve natural resources for future generations.

In 1989, A. H. Al-Rabeh et al. [1] simulated a surface oil spill in the Abu Ali region on the western side of the Arabian Gulf using a comprehensive model. They predicted the fate and transport of oil slicks with reasonable accuracy. In 2001, X. Chao et al. [2] presented a two- and three-dimensional oil trajectory and fate model for coastal waters. The two-dimensional model predicted the movement of oil slicks on the water surface, while the three-dimensional model, developed based on the mass transport equation, analyzed the concentration distribution of oil. They then compared the numerical results with observational data. In 2004, J. L. S. Pinho et al. [3] developed an information system as a management support tool for accidental oil spills in the Atlantic coastal waters of the Iberian Peninsula. They used a transport model for prediction. In 2007, T. O. Ojo et al. [4] presented a numerical method for evaluating diffusion coefficients in anisotropic flow using HF radar. They applied this model within the framework of constituent tracking in Corpus Christi Bay, located in the Texas Gulf of Mexico region. In 2009, W. J. Guo and Y. X. Wang [5] used an Eulerian-Lagrangian approach to simulate oil spills. They compared the numerical results with satellite images of oil slicks on the surface, demonstrating that the model achieved reasonable accuracy.

In 2010, J. Wang and Y. Shen [6] developed a three-dimensional integrated model for simulating the transport and fate of oil spills at sea. They employed a finite difference method to solve the problem and compared the analytical and numerical solutions. In 2013, Y. Li et al. [7] used a three-dimensional Lagrangian random walk oil spill model to study the influence of sea surface waves on the vertical turbulent movement of oil particles. They demonstrated that different vertical diffusion schemes could generate different horizontal trajectories and spatial distributions of oil spills on the sea surface. In 2014, A. Azevedo [8] applied a high-order Eulerian-Lagrangian method for computational efficiency, ensuring consistency with the distinct mathematical nature and time scales of the problem. The modeling system was applied to a spill scenario at the entrance of a port in a coastal lagoon. In 2020, R. Periáñez [10] developed an oil spill model for the Red Sea. The researcher used the HYCOM ocean model to forecast local winds and applied a Lagrangian approach that included advection/diffusion as well as specific oil-related processes. The model was compared with real-world observations. In 2021, K. Panagiota et al. [11] conducted a review of oil transport and weathering processes, critically examining eighteen state-of-the-art oil spill models in terms of their capabilities. In 2022, N. Kastrounis et al. [12] used Eulerian/Lagrangian equations to simulate oil spills. They performed a brief analysis of the model and compared the weathering model with a mathematical model to predict the spreading behavior of an oil spill. In 2022, D. Ülker et al. [13] employed HYDROTAM3D to simulate 36 oil spill scenarios and collect hydrodynamic data. Their study evaluated the weathering process of Basrah light, Iranian light, and Russian oil using ADIOS2. They compared weathering model data for each oil type to support oil spill contingency planning. In 2024, Y. Li et al. [14] developed a model based on one-dimensional nonlinear shallow water equations. The results were validated using experimental data on continuously related $n-$heptane spill fires.

A. Lemos et al. [15] investigated the circulation and chemical processes associated with the deposition of the largest oil spill that reached the northeast coast of Brazil during the second half of 2019 using the Oil Spill Contingency and Response (OSCAR) model. They suggest that prevention, monitoring, and international cooperation are essential for reducing the risks of future environmental accidents and protecting the affected environment. S. Mohammadium [16] developed a multi-agent decision support system to effectively coordinate mechanical containment and recovery (MCR) of spilled oil and oily wastewater management (OWM) operations. The multi-agent system was used to manage a hypothetical case study in Canada. The developed system facilitates decision-making in complex marine oil spill scenarios. T. H. H. Nguyen [17] developed a study on the Sanchi oil spill event. The research utilized the Advanced Research Weather Research and Forecasting (WRF-ARW) model as well as the Princeton Ocean Model (POM). The oil slicks observed in satellite images closely matched the numerical results.

Water contamination models are explained using numerical approaches in [18] – [21]. Mathematical models of shoreline evolution with groin structures are presented in [22] – [28], where the concept has been extended by incorporating the influence of wavelength on the structure within the system.

This research presents a one-dimensional numerical model of an oil spill in a coastal bay that incorporates a delayed removal method.

II. Governing Equation

There are several challenges in oil spill modeling, including the complexity of oil behavior, environmental variability, and data limitations. The complexity of oil behavior arises from the diverse properties of the oil mixture. Environmental variability refers to rapidly changing ocean conditions that affect the movement of oil. Data limitations involve insufficient accurate data on oil properties, environmental conditions, and spill characteristics.

In this research, a simple one-dimensional Eulerian oil spill model, which considers insufficient data on oil properties, environmental conditions, and spill characteristics, will be focused on.

A one-dimensional dispersion-advection equation with a removal mechanism is introduced in Eq. (1):

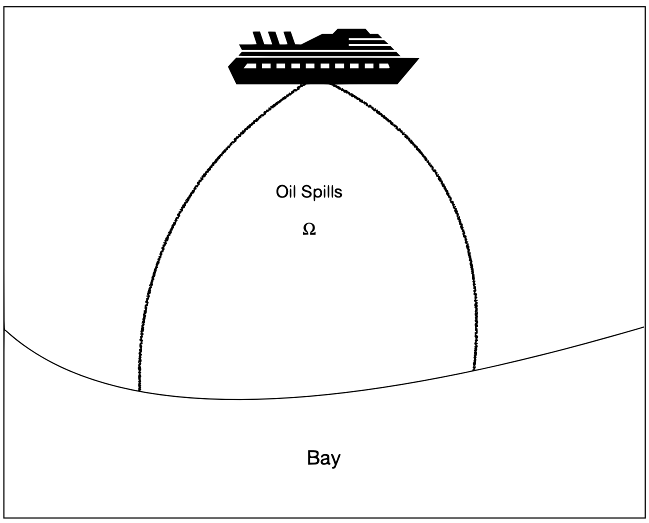

Fig. 1: Oil spilling into a coastal bay.

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} = D\frac{\partial^2 C}{\partial x^2} + S(t) - Q(t), \tag{1}$$

where C is the oil concentration (mg/L), u is the water flow velocity (m/hr), D is the diffusive tensor (m^2/hr), $S(t)$ is the point source function representing the growth of oil spill concentration (m^3/d), and $Q(t)$ is the removal mechanism (m^3/d).

Initial condition: Since there is some oil concentration before it leaks throughout the entire domain, the initial condition is given by:

$$C(x, 0) = C_0, \tag{2}$$

where C_0 is the initial oil spill concentration before the leak.

Boundary conditions: Assuming that the shoreline absorbs the spilling oil, the absorption boundary is described by the following condition:

$$\frac{\partial C}{\partial x}(L, t) = C_s, \tag{3}$$

where C_s is the absorption rate of the shoreline over the simulation time. The oil spill point source concentration is represented by:

$$C(0, t) = f(t), \tag{4}$$

where $f(t)$ is an interpolation function of the oil spill concentration at the point source.

III. A DELAYED REMOVAL MECHANISM MODEL

Oil spills refer to the accidental release of petroleum or other oil products into the environment. These spills can occur on land, in freshwater bodies, or in the ocean. Oil spills can have devastating consequences for marine life, wildlife, and the environment. The oil spill caused widespread damage to the coastline.

There are several methods for addressing oil spills, such as containment, which uses booms or barriers to prevent the oil from spreading further. Second, skimmers can be employed to collect the oil from the water's surface. Third, chemical dispersants are applied to break up the oil into smaller droplets, making it easier for microorganisms to biodegrade. Fourth, bioremediation involves using microorganisms that can break down the oil. Fifth, burning the oil on the water's surface is another method, though this can create air pollution. Sixth, beach cleanup involves manually cleaning oil-soaked shorelines. Seventh, environmental restoration includes planting mangroves to restore damaged ecosystems. Finally, it is crucial to monitor and assess the long-term impacts on the shoreline.

A delay in oil spill response can have fatal consequences for both the environment and local economies. When oil spills occur, rapid and effective action is essential to minimize damage. Unfortunately, delays in response can exacerbate the problem and lead to more extensive environmental harm.

Several common causes of delays in oil spill response include a lack of preparedness, bureaucratic hurdles, insufficient resources, adverse weather conditions, and geographic challenges. The delay in oil spill response and the functioning of the removal mechanism can be represented by $Q(t)$ as:

$$Q(t) = \begin{cases} 0, & \text{for } 0 \le t \le D_t, \\ g(t), & \text{for } D_t < t \le T. \end{cases}$$

where D_t represents the delay in the oil spill response time period.

IV. NUMERICAL TECHNIQUES

In this section, we use the finite difference method to approximate the solution of the one-dimensional advection-diffusion equation. This problem depends on time, and we will perform the calculation over the time interval $0 < t < T$ on a uniform grid in space: $x_j = j\Delta x$ where $j = 1, 2, 3, \ldots, L$, and $t_k = k\Delta t$ where $k = 0, 1, 2, 3, \ldots, T$.

In this paper, we use an explicit forward-difference approximation for the time derivative (FT) and a central-difference approximation for the spatial derivative (CS). This is known as the forward-time central-space (FTCS) method. Using this method to derive the governing equation (1), we get:

$$\begin{aligned} &\frac{C_m^{n+1} - C_m^n}{\Delta t} + u\left(\frac{C_{m+1}^n - C_{m-1}^n}{2\Delta x}\right) = \\ &D\left(\frac{C_{m-1}^n - 2C_m^n + C_{m+1}^n}{\Delta x^2}\right) + S(t_n) - Q(t_n). \end{aligned} \tag{5}$$

Rearranging Eq. (5), we obtain:

$$\begin{aligned} C_m^{n+1} = C_m^n &+ \alpha\left(C_{m-1}^n - 2C_m^n + C_{m+1}^n\right) \\ &- \beta\left(C_{m+1}^n - C_{m-1}^n\right) + \Delta t\left(S^n - Q^n\right), \end{aligned} \tag{6}$$

where $\alpha = \frac{\Delta t D}{\Delta x^2}$, $\beta = \frac{\Delta t u}{2\Delta x}$, $\Delta t = 0.25$, and $\Delta x = 0.25$. At the right boundary of this domain, a fictitious point will appear, which we eliminate using the central space (CS) method. The result is:

$$\begin{aligned} C_m^{n+1} = C_m^n &+ \alpha\left(C_{m-1}^n - C_m^n\right) \\ &- \beta\left(C_m^n - C_{m-1}^n\right) + \Delta t(S^n - Q^n). \end{aligned} \tag{7}$$

V. NUMERICAL EXPERIMENTS

A. Simulation 1 : Instant removal mechanism

In this case, we assume that the oil spill can be quantified and the source of the spill is known. Therefore, we use a constant value for the removal mechanism and assume that the water flow velocity increases. Next, we will use Eq. (7) to calculate the numerical results, which will be presented in cases 1.1–1.4.

TABLE I: The paremeter is used in case 1.1

Case No.	D	u	Q
1.1.1	1.71×10^{-6}	$0.2556\lvert\sin(0.1t)\rvert$	0.0001
1.1.2	1.71×10^{-6}	$0.2556\lvert\sin(0.1t)\rvert$	10×0.0001
1.1.3	1.71×10^{-6}	$0.2556\lvert\sin(0.1t)\rvert$	20×0.0001
1.1.4	1.71×10^{-6}	$0.2556\lvert\sin(0.1t)\rvert$	40×0.0001

TABLE II: The paremeter is used in case 1.2

Case No.	D	u	Q
1.2.1	1.71×10^{-6}	$10 \times 0.2556\lvert\sin(0.1t)\rvert$	0.0001
1.2.2	1.71×10^{-6}	$10 \times 0.2556\lvert\sin(0.1t)\rvert$	10×0.0001
1.2.3	1.71×10^{-6}	$10 \times 0.2556\lvert\sin(0.1t)\rvert$	20×0.0001
1.2.4	1.71×10^{-6}	$10 \times 0.2556\lvert\sin(0.1t)\rvert$	40×0.0001

TABLE III: The paremeter is used in case 1.3

Case No.	D	u	Q
1.3.1	1.71×10^{-6}	$20 \times 0.2556\lvert\sin(0.1t)\rvert$	0.0001
1.3.2	1.71×10^{-6}	$20 \times 0.2556\lvert\sin(0.1t)\rvert$	10×0.0001
1.3.3	1.71×10^{-6}	$20 \times 0.2556\lvert\sin(0.1t)\rvert$	20×0.0001
1.3.4	1.71×10^{-6}	$20 \times 0.2556\lvert\sin(0.1t)\rvert$	40×0.0001

TABLE IV: The paremeter is used in case 1.4

Case No.	D	u	Q
1.4.1	1.71×10^{-6}	$40 \times 0.2556\lvert\sin(0.1t)\rvert$	0.0001
1.4.2	1.71×10^{-6}	$40 \times 0.2556\lvert\sin(0.1t)\rvert$	10×0.0001
1.4.3	1.71×10^{-6}	$40 \times 0.2556\lvert\sin(0.1t)\rvert$	20×0.0001
1.4.4	1.71×10^{-6}	$40 \times 0.2556\lvert\sin(0.1t)\rvert$	40×0.0001

The numerical results for the cases of instant removal mechanisms are shown in Figures 2 to 6.

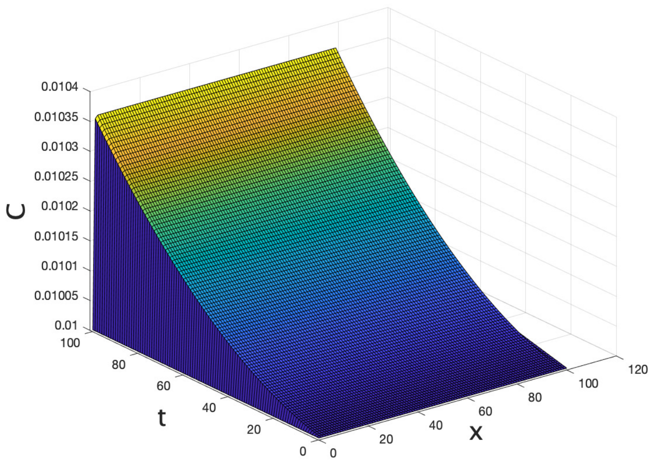

Fig. 2: Oil spill concentration of case 1.1 when instant removal mechanism; $Q = 0.0001$ and $u = 0.2556|\sin(0.1)t|$.

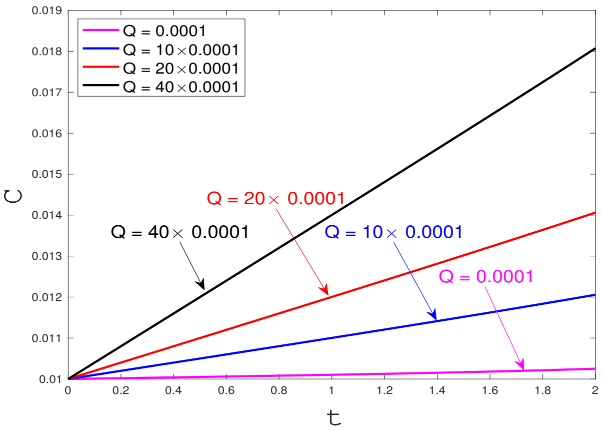

Fig. 3: Oil spill concentration of cases 1.1.1-1.1.4 with several instant removal mechanism rates.

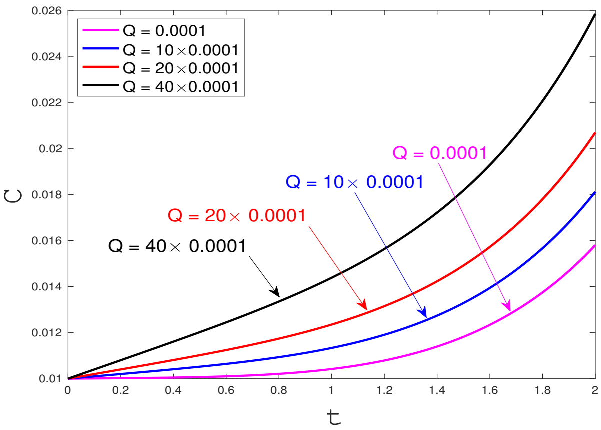

Fig. 4: Oil spill concentration of cases 1.2.1-1.2.4 with several instant removal mechanism rates.

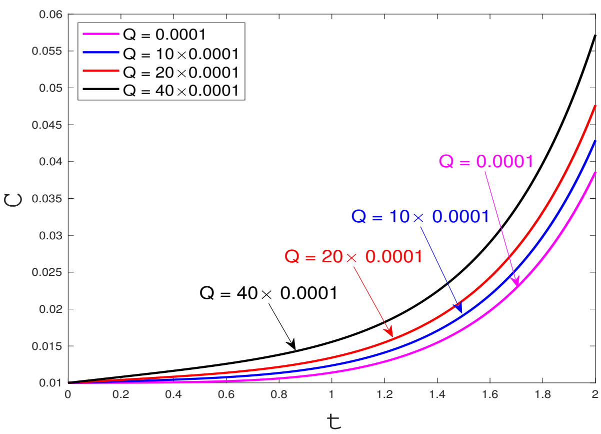

Fig. 5: Oil spill concentration of cases 1.3.1-1.3.4 with several instant removal mechanism rates.

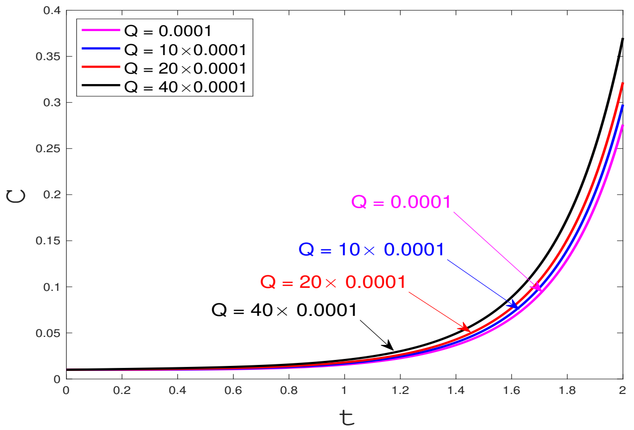

Fig. 6: Oil spill concentration of cases 1.4.1-1.4.4 with several instant removal mechanism rates.

B. *Simulation 2 : Delayed removal mechanism*

In this case, we will consider a more complex problem, as in real situations the oil spill rate is not constant over time. Therefore, we will use time-dependent functions for the source point and removal mechanism, which will be presented in cases 2.1 - 2.4. The rates of oil spill removal mechanisms are assumed by Eq.(10) and Eq.(11). The growing rates of oil spilled chemical reactions are assumed by Eq.(8) and Eq.(9). They are assumed as follows:

$$\begin{aligned} S_1(t) &= 0.0103t^{12} - 0.0019t^{11} - 0.1039t^{10} \\ &+ 0.0339t^9 + 0.402t^8 - 0.2055t^7 - 0.7064t^6 \\ &+ 0.554t^5 + 0.412t^4 - 0.6229t^3 + 0.3403t^2 \\ &- 0.1478t + 0.0375 \end{aligned} \tag{8}$$

$$\begin{aligned} S_2(t) &= -0.009t^{12} - 0.0226t^{11} + 0.1021t^{10} \\ &+ 0.1973t^9 - 0.4738t^8 - 0.6347t^7 + 1.1516t^6 \\ &+ 0.876t^5 - 1.5673t^4 - 0.3154t^3 1.1635t^2 \\ &- 0.5824t + 0.1128 \end{aligned} \tag{9}$$

$$\begin{aligned} Q_1(t) &= -0.009t^{12} + 0.0226t^{11} + 0.1021t^{10} \\ &- 0.1973t^9 - 0.4738t^8 + 0.6347t^7 + 1.1516t^6 \\ &- 0.876t^5 - 1.5673t^4 + 0.3154t^3 + 1.1635t^2 \\ &+ 0.5824t + 0.1128 \end{aligned} \tag{10}$$

$$\begin{aligned} Q_2(t) &= 0.0103t^{12} + 0.0019t^{11} - 0.1039t^{10} \\ &- 0.0339t^9 + 0.402t^8 + 0.2055t^7 - 0.7064t^6 \\ &- 0.554t^5 + 0.412t^4 + 0.6229t^3 + 0.3403t^2 \\ &+ 0.1478t + 0.0375 \end{aligned} \tag{11}$$

TABLE V: The paremeter is used in delayed removal mechanism

Case No.	D	u	$S(t)$	$Q(t)$
2.1.1	1.71×10^{-6}	$0.2556\|\sin(0.1t)\|$	$S_1(t)$	$Q_1(t)$
2.1.2	1.71×10^{-6}	$0.2556\|\sin(0.1t)\|$	$S_2(t)$	$Q_2(t)$
2.2.1	1.71×10^{-6}	$10 \times 0.2556\|\sin(0.1t)\|$	$S_1(t)$	$Q_1(t)$
2.2.2	1.71×10^{-6}	$10 \times 0.2556\|\sin(0.1t)\|$	$S_2(t)$	$Q_2(t)$
2.3.1	1.71×10^{-6}	$20 \times 0.2556\|\sin(0.1t)\|$	$S_1(t)$	$Q_1(t)$
2.3.2	1.71×10^{-6}	$20 \times 0.2556\|\sin(0.1t)\|$	$S_2(t)$	$Q_2(t)$
2.4.1	1.71×10^{-6}	$40 \times 0.2556\|\sin(0.1t)\|$	$S_1(t)$	$Q_1(t)$
2.4.2	1.71×10^{-6}	$40 \times 0.2556\|\sin(0.1t)\|$	$S_2(t)$	$Q_2(t)$

We using D_t in the case of poor performance is 60 hr and in high performance is 40 hr. The numerical result of delayed removal mechanism are show in the Figure 7–10

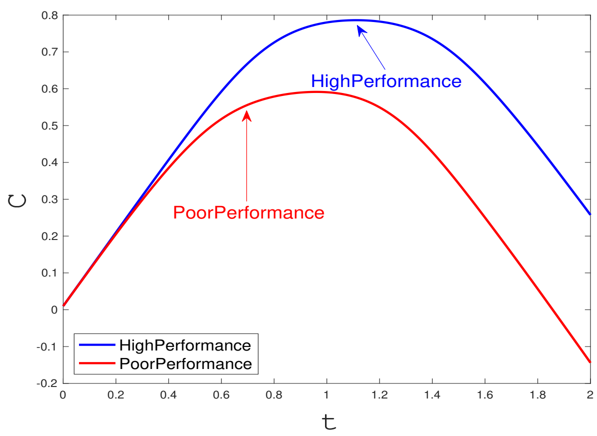

Fig. 7: Oil spill concentration of cases 2.1.1-2.1.2 with high and low performance of delay removal mechanism rates, $D_t = 40,\ 60\ hr$, respectively and $u = 0.2556|\sin(0.1t)|$.

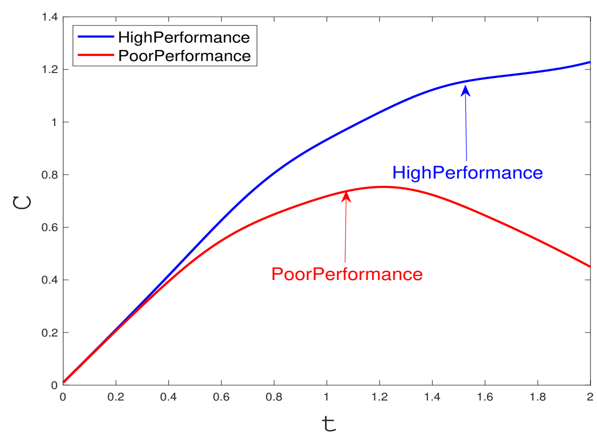

Fig. 8: Oil spill concentration of cases 2.2.1-2.2.2 with high and low performance of delay removal mechanism rates, $D_t = 40,\ 60\ hr$, respectively and $u = 10 \times 0.2556|\sin(0.1t)|$.

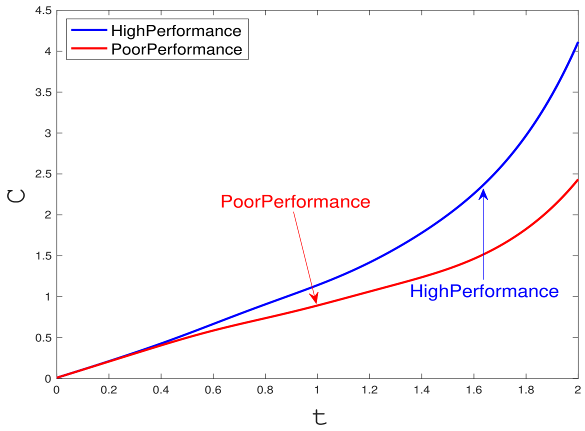

Fig. 9: Oil spill concentration of cases 2.3.1-2.3.2 with high and low performance of delay removal mechanism rates, $D_t = 40,\ 60\ hr$, respectively and $u = 20 \times 0.2556|\sin(0.1t)|$.

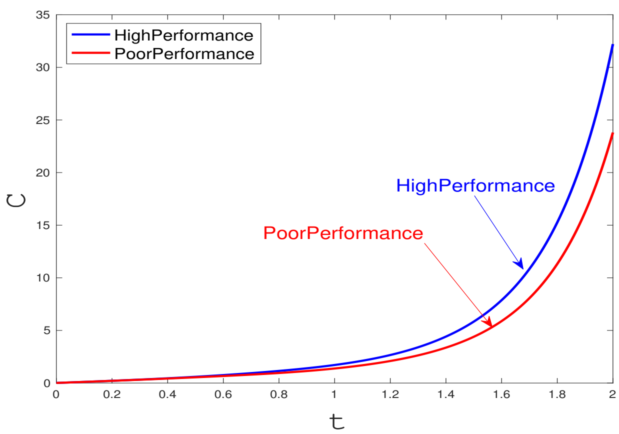

Fig. 10: Oil spill concentration of cases 2.4.1-2.4.2 with high and low performance of delay removal mechanism rates, $D_t = 40,\ 60\ hr$, respectively and $u = 40 \times 0.2556|\sin(0.1t)|$.

In Figure 11, the values of point oil spilling source $S(t)$ and removal mechanism $Q(t)$ used in the calculation for Case 2 are shown, illustrating both high performance and poor performance scenarios.

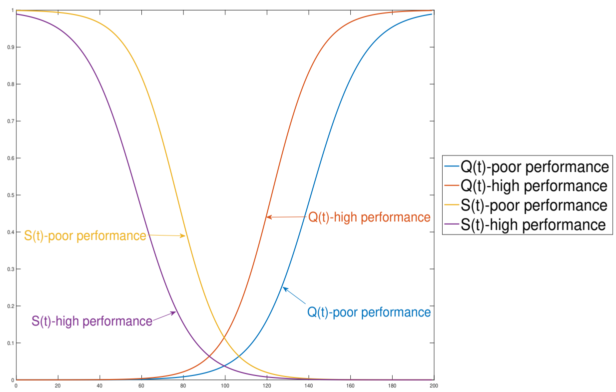

Fig. 11: A comparison of oil spill concentration of the case 2 with high and low performance of delay removal mechanism rates, $D_t = 40,\ 60\ hr$, respectively.

VI. Discussion

In this section, we will explain the various graphs shown in the previous section. We will divide them into two main cases: Case 1, where the removal mechanism $Q(t)$ is constant, and Case 2, where the point source $S(t)$ and the removal mechanism $Q(t)$ are functions of t. For the numerical results in Case 1, we use the values $D = 1.71 \times 10^{-6}$ and $Q(t) = 0.0001, 10 \times 0.0001, 20 \times 0.0001$ and 40×0.0001, respectively. In this case, we will use different values for the water flow velocity u, specifically $u = 0.2556|\sin(0.1t)|, 10 \times 0.2556|\sin(0.1t)|, 20 \times 0.2556|\sin(0.1t)|$ and $40 \times 0.2556|\sin(0.1t)|$ as shown in Figures 2–6. It can be observed that as the value of u increases, the concentration of oil C also increases. Additionally, from Figures 3–6, it can be seen that as the removal mechanism $Q(t)$ increases, the concentration of oil converges as the value of u increases. In Case 2, we will determine the concentration of oil using the point source $S(t)$ and the removal mechanism $Q(t)$ as functions dependent on time t. We will use the value $D = 1.71 \times 10^{-6}$. The values of $S(t)$ and $Q(t)$ will be determined using a $12th-$order polynomial approximation, with the coefficients of this polynomial approximation shown in Eq.(8)–Eq.(11). We will use the values $u = 0.2556|\sin(0.1t)|, 10 \times 0.2556|\sin(0.1t)|, 20 \times 0.2556|\sin(0.1t)|$ and $40 \times 0.2556|\sin(0.1t)|$, respectively. The high-performance and poor-performance values will be shown in Figures 7–10. It can be observed that the concentration of oil in the case of poor performance is lower than that in the high-performance case, which aligns with the initial hypothesis.

Therefore, the concentration of oil in the ocean will be significantly reduced if oil spill removal is done quickly and efficiently.

VII. Conclusion

In this research, a one-dimensional mathematical model of an oil spill in a coastal bay with delayed removal mechanisms is considered. The governing equation for an oil spill in a coastal bay with delayed removal mechanisms is introduced, along with the initial and boundary conditions that arise from the oil spill in the coastal bay setting. A mathematical model of the delayed removal mechanism assumptions is proposed, and the solution to the proposed model is approximated using a finite difference method, specifically the Forward Time-Centered Space (FTCS) method. The right boundary of the equation is approximated using the centered space method. In the simulations, two scenarios are illustrated: the instant removal mechanism scenario and the delayed removal mechanism scenario. In the instant removal mechanism scenario, several simple average removal rates and water flow behaviors are simulated. In the delayed removal mechanism scenario, more realistic oil spill scenarios are considered. Therefore, the concentration of oil is modeled as a function of the source rate and the removal mechanism rate over the simulation period. The $12th-$degree polynomial curve fitting method is employed to represent these rates. The simulations show that the concentration of oil is higher in the delayed removal mechanism scenario, resulting in a poorer recovery outcome compared to the instant removal mechanism scenario. This aligns with the reality that when oil spill removal is effectively managed, the concentration of oil in the sea decreases.

The experiments demonstrate that, in all cases, seawater recovery rates are lower when oil removal proceeds slowly compared to when it proceeds quickly. Therefore, clearing oil spills quickly and effectively significantly reduces the amount of oil in the water.

This study not only contributes to the understanding of the dynamics of oil spill concentration over time but also highlights the critical importance of timely intervention in mitigating environmental damage. By providing a more accurate prediction of the effects of delayed removal mechanisms, this research aids in decision-making for disaster response teams and policymakers. The findings can be used to improve oil spill management strategies, potentially guiding the development of more effective response protocols, resource allocation, and public awareness initiatives. Ultimately, the study provides a valuable framework for enhancing environmental protection efforts, reducing the long-term impact of oil spills, and ensuring the sustainability of coastal ecosystems.

ACKNOWLEDGMENT

Teerat Kasamwan gratefully acknowledges the invaluable support received throughout this study, especially from Assoc. Prof. Dr. Nopparat Pochai and all individuals whose guidance and encouragement contributed significantly to the research.

REFERENCES

[1] A. H. Al-Rabeh, H. M. Cekirge, and N. Gunay, "A stochastic simulation model of oil spill fate and transport," *Applied Mathematical Modelling*, vol. 13, no. 6, pp. 322–329, 1989.

[2] X. Chao, N. Jothi. Shankar, and H. F. Cheong, "Two- and three-dimensional oil spill model for coastal waters," *Ocean Engineering*, vol. 28, no. 12, pp. 1557–1573, 2001.

[3] J. L. S. Pinho, J. S. Antunes, and J. M. P. Vieira, "Mathematical Modelling Of Oil Spills In TheAtlantic Iberian Coastal Waters," *WIT Transactions on Ecology and the Environment*, vol. 68, 2004.

[4] T. O. Ojo, J. S. Bonner, and C. A. Page, "Simulation of constituent transport using a reduced 3D constituent transport model (CTM) driven by HF Radar: Model application and error analysis," *Environmental Modelling & Software*, vol. 22, no. 4, pp. 488–501, 2007.

[5] W. J. Guo and Y. X. Wang, "A numerical oil spill model based on a hybrid method," *Marine Pollution Bulletin*, vol. 58, no. 5, pp. 726–734, 2009.

[6] J. Wang and Y. Shen, "Modeling oil spills transportation in seas based on unstructured grid, finite-volume, wave-ocean model," *Ocean Modelling*, vol. 35, no. 4, pp. 332–344, 2010.

[7] Y. Li, J. Zhu, and H. Wang, "The impact of different vertical diffusion schemes in a three-dimensional oil spill model in the Bohai Sea," *Advances in Atmospheric Sciences*, vol. 30, no. 6, pp. 1569–1586, 2013.

[8] A. Azevedo, A. Oliveira, A. B. Fortunato, J. Zhang, and A. M. Baptista, "A cross-scale numerical modeling system for management support of oil spill accidents," *Marine Pollution Bulletin*, vol. 80, no. 1, pp. 132–147, 2014.

[9] M. L. Spaulding, "State of the art review and future directions in oil spill modeling," *Marine Pollution Bulletin*, vol. 115, no. 1–2, pp. 7–19, 2017.

[10] R. Periáñez, "A Lagrangian oil spill transport model for the Red Sea," *Ocean Engineering*, vol. 217, pp. 107953, 2020.

[11] P. Keramea, K. Spanoudaki, G. Zodiatis, G. Gikas, and G. Sylaios, "Oil Spill Modeling: A Critical Review on Current Trends, Perspectives, and Challenges," *Journal of Marine Science and Engineering*, vol. 9, no. 2, pp. 181, 2021.

[12] N. Kastrounis, G. Manias, M. Filippakis, and D. Kyriazis, "Mathematical Modeling and Forecasting the Spread of an Oil Spill using Python," *WSEAS TRANSACTIONS ON FLUID MECHANICS*, vol. 17, pp. 163–172, 2022.

[13] D. Ülker, S. Burak, L. Balas, and N. Çağlar, "Mathematical modelling of oil spill weathering processes for contingency planning in Izmit Bay," *Regional Studies in Marine Science*, vol. 50, pp. 102155, 2022.

[14] Y. Li, Y. Meng, X. Song, L. Zhang, and J. Shuai, "Modelling study of the spread of liquid fuel spill fires using shallow water equations," *Journal of Loss Prevention in the Process Industries*, vol. 87, pp. 105227, 2023.

[15] A. Lemos et al., "Ship Route Oil Spill Modeling: A Case Study of the Northeast Brazil Event, 2019," *Applied Sciences*, vol. 14, no. 2, pp. 865–865, 2024.

[16] S. Mohammadiun et al., "Integrated optimization of marine oil spill response and liquid oily waste management using mathematical programming and evolutionary metaheuristic techniques," *Journal of Hazardous Materials*, vol. 463, pp. 132838, 2023.

[17] T.-H.-H. Nguyen, T.-H. Hou, H.-A. Pham, and C. Tsai, "Hindcast of oil spill pollution in the East China Sea in January 2018," Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, vol. 238, no. 1, pp. 90-101, 2023.

[18] B. Vanishkorn and N. Pochai, "A One-dimensional Salinity Measurement Model in the Chao Phraya River with the Chao Phraya Barrage Dam Using a Shooting Method," IAENG International Journal of Computer Science, vol. 50, no. 1, pp219–224, 2023.

[19] W. Kraychang, S. Meechowna, W. Welamas, and N. Pochai, "A Simple Mathematical Model of Water Quality Control for Recirculating Pond on a Shrimp Farm," Engineering Letters, vol. 29, no. 4, pp1470–1477, 2021.

[20] N. Pongnu and N. Pochai, "Mathematical Modelling of Groundwater Quality Measurement around a Landfill for Residential Water Usage," Engineering Letters, vol. 30, no. 3, pp1006–1016, 2022.

[21] P. Klankaew and N. Pochai, "A Numerical Groundwater Quality Assessment Model Using the Cubic Spline Method," IAENG International Journal of Applied Mathematics, vol. 54, no. 1, pp111–116, 2024.

[22] S. Manilam and N. Pochai, "A Non-Dimensional Mathematical Model of Shoreline Evolution with a Groin Structure Using an Unconditionally Stable Explicit Finite Difference Technique," IAENG International Journal of Applied Mathematics, vol. 52, no. 2, pp473–481, 2022.

[23] P. Unyapoti and N. Pochai, "A Shoreline Evolution Model with a Twin Groins Structure using Unconditionally Stable Explicit Finite Difference Techniques," Engineering Letters, vol. 29, no. 1, pp288–296, 2021.

[24] P. Unyapoti and N. Pochai, "A Shoreline Evolution Model with a Groin Structure under Non-Uniform Breaking Wave Crest Impact," Computation, vol. 9, no. 4, p. 42, 2021.

[25] P. Unyapoti and N. Pochai, "A Shoreline Evolution Model With the Wavelength Effect of Breaking Waves on Groin Structures," IAENG International Journal of Computer Science, vol. 49, no. 3, pp683–694, 2022.

[26] P. Unyapoti and N. Pochai, "A Combination of A Shoreline Evolution Model and A Wave Crest Model on T-Head Groin Structures With the Breaking Wave Effect," IAENG International Journal of Computer Science, vol. 50, no. 2, pp347–358, 2023.

[27] P. Unyapoti and N. Pochai, "A Shoreline Evolution Model with Wave Crest Model on I-Head and T-Head Groin Structures with Different Types of Breaking Wave," Engineering Letters, vol. 32, no. 6, pp1146–1162, 2024.
[28] S. Manilam and N. Pochai, "An Unconditionally Stable Explicit Finite Difference Method for a Non-Dimensional Mathematical Model of Shoreline Evolution with a Twin Groins Structure," Engineering Letters, vol. 32, no. 2, pp296–304, 2024.