

The Impact of Oil Spills on Marine Ecosystems and Long-Term Recovery Strategies

^{1*} Hiroshi Nakamura, Japan Institute for Advanced Digital Futures, Tokyo, Japan.

² Yuki Tanaka, Japan Institute for Advanced Digital Futures, Tokyo, Japan.

Abstract: One of the most pervasive and substantial human impacts on the marine environment is that from oil spills, which have caused devastating and long-term impacts on the marine environment for decades. This review compares the impacts of three major oil spills, namely Exxon Valdez (1989), Deepwater Horizon (2010), and Prestige (2002), on marine ecosystem; including its biodiversity, water and sediment quality, and food web; by taking the systematic review of the documented ecological monitoring results, satellite imagery and visual observation and identification of biota at the coast from these spills. Both the immediate and long-term impacts on marine species were compared, as well as different rates of recovery across the taxonomic groups (phytoplankton, benthos, fish, marine mammals, and seabirds). Also, the efficiency of different mitigating measures, including mechanical recovery, chemical dispersion, bioremediation, and natural attenuation, was discussed. While the response community appears to achieve a partial recovery within 5-15 years, it was demonstrated that certain key species, such as Pacific herring and sea otter, and the deep-sea benthic community showed suppressed status lasting for over 25 years. In the end, the integrated long-term framework, including active restoration measures combined with adaptive monitoring, was proposed, which emphasizes the importance of science-based interventions, efficient international co-operation in responding to spills, and long-term monitoring efforts to contribute to ecosystem sustainability and conservation policy formation.

Keywords: Oil Spill Ecology; Marine Ecosystem Recovery; Hydrocarbon Toxicity; Bioremediation; Deepwater Horizon; Exxon Valdez; Long-Term Ecological Monitoring.

(Submitted: September 23, 2025; Revised: October 27, 2025; Accepted: December 05, 2025; Published: December 31, 2025)

I. Introduction

Accidental discharge of petroleum hydrocarbons into the marine environment is one of the most destructive anthropogenic disturbances impacting coast and marine ecosystems worldwide (Kingston, 2002). The oil spills cause acute and chronic ecosystem damage due to effects on structure and chemistry, and direct toxicology on organisms from microscopic plankton to top predators (Barron et al., 2020). The effect of a spill is seldom restricted to the local spill vicinity, as the oceanic transport (e.g., surface currents, wind transport, and vertical transport) can extend petroleum contamination over huge geographical areas. As a result, it is more difficult to carry out and interpret monitoring data and manage/remediate the spill site (Yusup, 2024). Even though improved containment technology and regulatory frameworks such as MARPOL have been developed, massive spills continue to be one of the global severe environmental threats; thus, further scientific research on response and recovery patterns in an ecosystem is needed (Peterson et al., 2003). Also, oil is a complex mixture (thousands of different hydrocarbon compounds in variable proportions ranging from volatile to heavy hydrocarbons) where the toxicological behavior of a chemical constituent in the marine environment depends on its varying persistence profiles (Zhang et al., 2019).

Three main contributions of this paper to current oil spill ecology: (1) The comparative study based on three key landmark oil spills (Exxon Valdez, Deepwater Horizon, Prestige spills) shows how they differed and how they were similar from ecological perspectives in varying geographical, meteorological, and oceanographic environments. (2) Based on long-term ecological data from monitoring, the taxonomically dependent recovery time scale shows fast-recovering organisms versus chronically impacted species. (3) An integrated framework that coordinates active restoration with natural attenuation is presented, with evidence of a monitoring program that adapts species-specific ecological recovery time. Through integrating both ecological and chemical impacts with management strategy, this work expands the current knowledge base for post-spill recovery and conservation in the marine environment, and links oil spill

ecology with issues of sustainability in marine environments such as collapsing fisheries or other aquatic pollution concerns (Bosco, 2025).

This paper continues as follows. The related study on past and current literature of oil spill ecology and chemistry is briefly reviewed in Section 2. In Section 3, the selection of the study site and analytical methodology used is detailed. In Section 4, key results are presented as a tabular comparison and temporal recovery pathways. Section 5 integrates and discusses the ecology and management implications of this paper, and Section 6 concludes with a summary of the main findings, relevant policy implications, and future research opportunities.

II. Literature Survey

Over the last four decades, scientific knowledge of oil spill effects on marine environments has evolved considerably, primarily as a result of studies undertaken following large spill incidents. Provides background for the concept of a split between acute mortality and sub-lethal effects on marine species (such as impairment to reproduction and immune function). There were studies performed post-Exxon Valdez in which the effects on the environment lasted for decades, and affected species such as the Pacific herring and sea otter remained absent from baselines for over 10 years and still showed no return to baselines in many other species (Peterson et al., 2003). More recently described sources, chemistry, and environmental impacts of petroleum pollution in the marine environment (Zhang et al., 2019). Their research discussed such an impact in coastal wetlands, as well as offshore and deep-sea habitats. One observation from each study has been that estimations of damage due to short-term measurements tend to underestimate actual harm, and there is an increasing necessity for long-term studies that incorporate delays in ecosystem response.

Comparative studies on the effects of multiple spill events have demonstrated the importance of geographic, environmental, and oceanic variables in predicting ecological response, but overall patterns are clearly emerging. Showed similar responses in the Exxon Valdez, Hebei Spirit, and Deepwater Horizon spill incidents across a trophic range, where phytoplankton production, benthic invertebrates, and predators were adversely affected by spills. Seabird communities were examined over more than 10 years following Prestige, and significant changes in prey availability and trophic relationships were identified, reinforcing the idea that seabirds can be used as good bioindicators for an ecosystem's response to spills (Venesjärvi et al., 2023). Studies also identified the fragmentation of the habitat and trophic cascades as longer-lasting ecological effects of petroleum pollution (Schwing et al., 2020). This reinforces the requirement that studies of ecosystem rather than species responses and of indirect toxicological effects must be conducted.

Although the area of remediation science has seen considerable advances, the effectiveness of any of these remediation treatments has been strongly dependent on the environmental setting. It has been reviewed that physical clean-up and chemical dispersants may effectively manage surface oil on a short-term basis in case of an oil spill, but do not have any significant effect on long-term deposition of sediments or subsurface hydrocarbons (Frasier, 2019). Critical coastal habitats such as mangroves, salt marshes, and rocky shores are vulnerable to contamination, necessitating location-specific approaches to spill response (Asif et al., 2022). Bioremediation remains the technology that offers long-term ecological success with reductions in hydrocarbons of up to 85% under the right conditions (Seara et al., 2022). Recently proposed adaptive responses would incorporate sensitivity mapping, remote sensing, and real-time data acquisition and analysis to enhance spill response (Yusup, 2024). It is likely that integrated, multi-technology approaches hold the most promise for ecological remediation (Al-Majed et al., 2012).

There are a number of factors that influence the rate and success of ecosystem recovery after a spill. These include: the organisms' capacity to recover (biological resilience), the environment (habitat and geology), severity of contamination, and the quality of remediation efforts. Some researchers have found that benthic communities may recover within 5-10 years given appropriate environmental conditions, but fish stocks and large vertebrates take much longer to recover to pre-spill conditions (decades) (Borja et al.,

2010). Deep-sea ecosystems have been found to continue showing both biological effects and contamination many years after large spills occurred, and research in marine mammals indicates that chronic health effects of long-term exposure are present (Bosco, 2025). The interaction of oil pollution with increasing other environmental problems, such as antimicrobial resistance, is raising new concerns regarding aquatic ecosystems (Moreno et al., 2013). Overall, the process of an ecosystem's recovery from a spill is complex, variable, and long-term, relying on sustained monitoring, adaptable management, and long-term institutional capacity.

III. Materials and Methods

Study Area

This work explores three significant regions of marine oil spills, which include Prince William Sound (Alaska) post-Exxon Valdez spill, the Gulf of Mexico post-Deepwater Horizon accident, and the Galician coast of Spain post-Prestige tanker accident. The sites chosen were representative of specialized marine habitats with relatively long-term monitoring programs and a well-documented history of oil spills. These habitats range from subarctic coastal to tropical deep-sea habitats to temperate Atlantic shore habitats, all habitats that are ecologically and commercially important to species and fisheries.

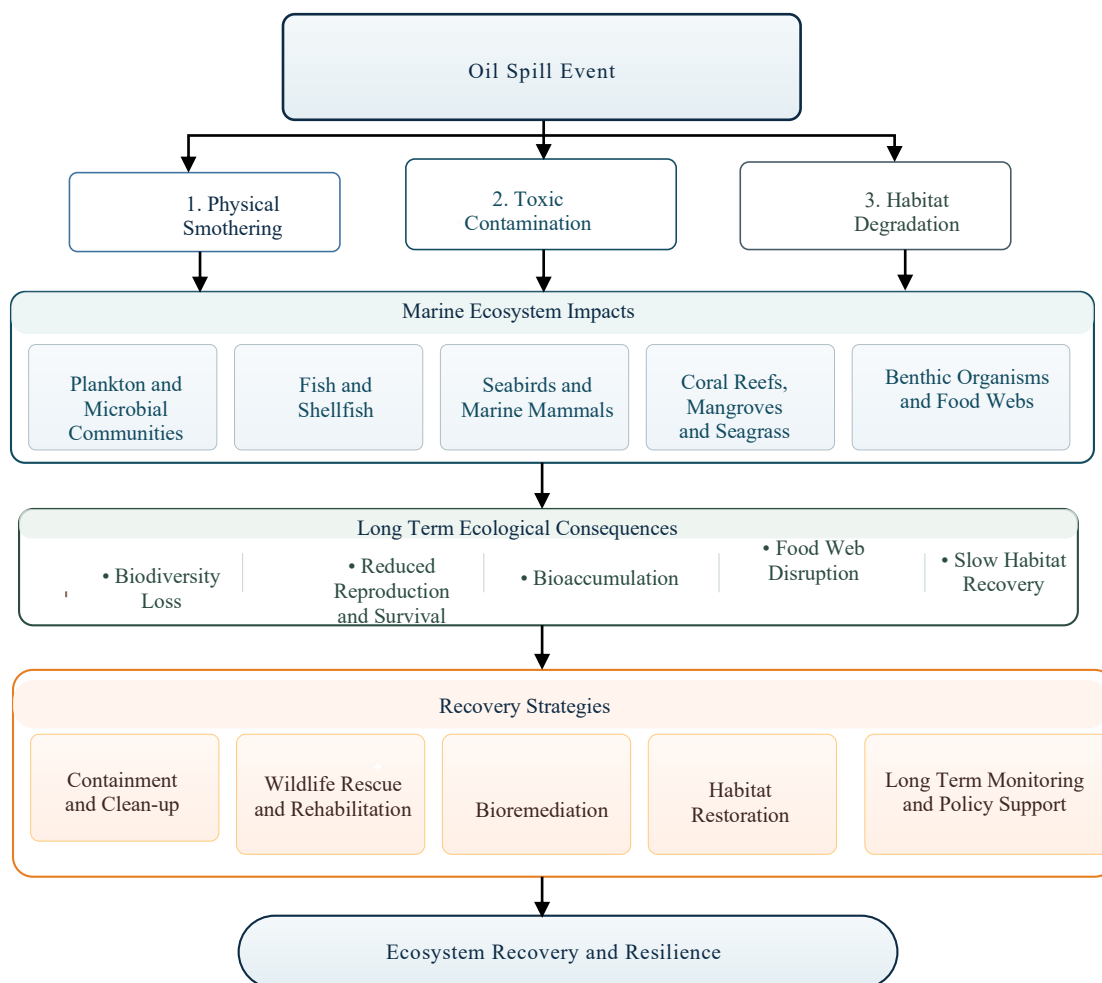


Figure 1: Conceptual Framework of Oil Spill Impacts and Recovery Strategies

Figure 1 is showing cascade effect of an oil spill on the marine system. Effect of initial processes such as smothering (physical), poisoning (chemical), and habitat destruction, are given; they are associated with

system-level consequences, such as diversity reduction, bio-accumulation, and food web disturbance. Recovery processes like oil containment, bioremediation, habitat restoration, long-term monitoring and finally system resilience.

Data Collection and Sources

The data for this review were synthesized from scientific peer-reviewed literature, government monitoring reports and public environmental databases covering important marine oil spills. The data on long-term environmental and biological surveys (tissue hydrocarbon data, bottom community data, seabird kill counts) are compiled from 1989 to the present from numerous sources. Sediment chemistry data (total petroleum hydrocarbon and polycyclic aromatic hydrocarbon data) have been generated for decades following major spills from a number of monitoring program locations. Oceanographic data, including salinity, temperature, dissolved oxygen and turbidity, were gathered. Satellite imagery from both Landsat and SAR sensors was collected, detailing spill size and habitat recovery following the spill events.

Analytical Framework and Recovery Assessment

The restoration of ecological processes was determined using an overall multi-indicator strategy combining four indices: the Species Population Recovery Index (PRI), Benthic Community Integrity Score (BCIS), Sediment Hydrocarbon Attenuation Rate (SHAR), and Trophic Network Completeness Index (TNCI). Species population recovery, condition of benthic communities, attenuation rates of sediment hydrocarbons, and restoration of food web structure were quantified by these indices. Data were obtained from population studies, analyses of benthic communities, sediment measurements, and assessment of trophic levels at sampling sites. Linear and non-linear regression models were employed to assess trends of recovery. Statistical comparison between pre-spill and post-spill values was analyzed for statistical differences, and the multivariate ecological structure was further analyzed by Principal Component Analysis.

Remediation Strategy Evaluation

An objective system was applied to evaluate the efficacy of remediation strategies. Four criteria were used in this system: hydrocarbon removal efficiency, side impacts to the ecosystem, cost-effectiveness, and the extent to which it facilitates long-term habitat restoration. Response data of mechanical recovery, chemical dispersants, in-situ burning, shoreline cleaning, and bioremediation were retrieved from incident reports and published studies. Every response was scored according to a 5-point scale, and then RES was calculated for each response method to allow easy comparison between different techniques. The overall trends of ecosystem recovery were evaluated by time series modeling of the concentration of hydrocarbons. This provides an objective and quantitative indication of the best method(s) for marine oil spill response and management in the future.

IV. Results

Comparative Overview of Oil Spill Incidents

A review of the five major marine oil spills, Exxon Valdez, Prestige, Deepwater Horizon, Hebei Spirit, and MV Wakashio, demonstrates that the spills differ greatly in their volume, geographic location, and ecological context. The Deepwater Horizon blowout is by far the largest marine oil spill in history, releasing an estimated 500,000+ tons of crude oil over a period of 87 days and inflicting significant impacts upon both shallow-shelf and deep-sea benthic communities. Table 1 provides the main features of the five major oil spills and the reported effects on the environment. It clearly shows that the five oil spills all have documented negative effects, including drops in local marine biodiversity, changes in local water quality, and economic impacts to commercial fish/shellfish stocks. The environmental damages of deep-water blowout events have significantly more ecological impact than tanker spills, which could likely be due to both the longer spill duration and the chemical dissolution of oil at deep sea depths.

Table 1: Comparative Summary of Major Marine Oil Spill Events and Ecological Impacts

Oil Spill Incident	Year	Volume (tons)	Region	Primary Impact
Exxon Valdez	1989	37,000	Prince William Sound, Alaska	Seabird & fish mortality
Prestige	2002	63,000	Galician Coast, Spain	Coastal wetland degradation
Deepwater Horizon	2010	500,000+	Gulf of Mexico, USA	Deep-sea benthic damage
Hebei Spirit	2007	10,900	Yellow Sea, South Korea	Shoreline contamination
MV Wakashio	2020	1,000	Mauritius, Indian Ocean	Reef & mangrove damage

Biological Recovery Trajectories

Analysis of long-term monitoring data from Prince William Sound demonstrated varied recovery responses across taxa. Long-term data indicate that intertidal invertebrate communities recovered substantially within 10 to 15 years due to natural recolonization from adjacent unimpacted source populations and high population turnover rates. Sea otter populations had only recovered to about 65% of their pre-spill numbers after 25 years. Pacific herring, an important forage species that subsidizes most food webs within Prince William Sound, experienced a severe 70% population collapse after the Exxon Valdez oil spill and has not recovered over 30 years after the spill. While seabird populations, especially common murre and pelagic cormorants, appeared to recover between 15 and 20 years post-spill, trophic monitoring revealed continuing changes in diet and foraging behavior due to prey reduction. See table 2 for pre- and post-spill density estimations and recovery status of Prince William Sound biological groups.

Table 2: Biological Recovery Status of Key Marine Species, Prince William Sound (Post-Exxon Valdez)

Species / Ecosystem	Pre-Spill Density	Post-Spill Density	Recovery Status (Years)
Sea Otters (<i>Enhydra lutris</i>)	High (>2,000 ind.)	Severely Depleted (~700)	Partial recovery: ~25 yrs
Pacific Herring (<i>Clupea alasii</i>)	Abundant	~70% decline	Not fully recovered (>30 yrs)
Seabirds (Murre, Cormorants)	High-density colonies	~300,000 birds killed	Recovering: 15–20 yrs
Intertidal Invertebrates	High diversity	Sharply reduced	Recovered: 10–15 yrs
Subtidal Kelp Forests	Dense canopy	Moderate disturbance	Substantially recovered: 8 yrs

Sediment Hydrocarbon Attenuation and Water Quality

All three study sites exhibited a general bi-phasic pattern for sediment PAH concentrations, a first rapid loss due to photo-oxidation, volatilization, and microbial degradation over the first 1–3 years after the spill, and a second very slow loss where recalcitrant subsurface oil remained at toxicologically relevant levels for 10–25 years. Sediment PAH concentrations subsurface at Prince William Sound were still elevated to 55,000 g kg dry weight at a sheltered cobble beach in the study for at least 20 years following the Exxon Valdez spill, and represent a source of continuous re-exposure to hydrocarbons for organisms on the seabed. TPH concentrations in the water column dropped from 2,100 g L at Deepwater Horizon when the blowout was active to undetectable levels by 3 years after the wellhead was capped, although dissolved PAHs from the dispersant were detected in the water column at over 1200 m for 5 years after the blowout had ceased. Intertidal hydrocarbon concentrations in sediments on the Galician coast were reduced by roughly 80% over 8 years after intensive cleaning and remediation operations.

Ecological Recovery Index Graphical Representation

The averaged composite ecological recovery trajectories of surface-water community, intertidal benthic community, fish assemblage, and marine mammal populations at all three study sites from a 30-year period post-spill monitoring are depicted in figure 2 below. Recovery curves are presented as a percent of the pre-spill ecological state (0 = complete recovery loss and 100 = complete recovery). The distinct levels of recovery were observed among taxa: surface water phytoplankton communities return close to baseline level within 2–5 years, surface benthic community recover to 70–85% baseline within 15 years, and recovery rates of fish assemblage and marine mammal communities reach 60–75% by year 20, and marine mammal population recovery rates fluctuate between 45–70% at year 30 respectively. The overall result supports that

ecosystem recovery is not a linear process across decades, but an ongoing, nonlinear process with great variability among different groups of species; also, those keystone species like apex predators and long-lived fish species are particularly susceptible to long-term hydrocarbon exposure.

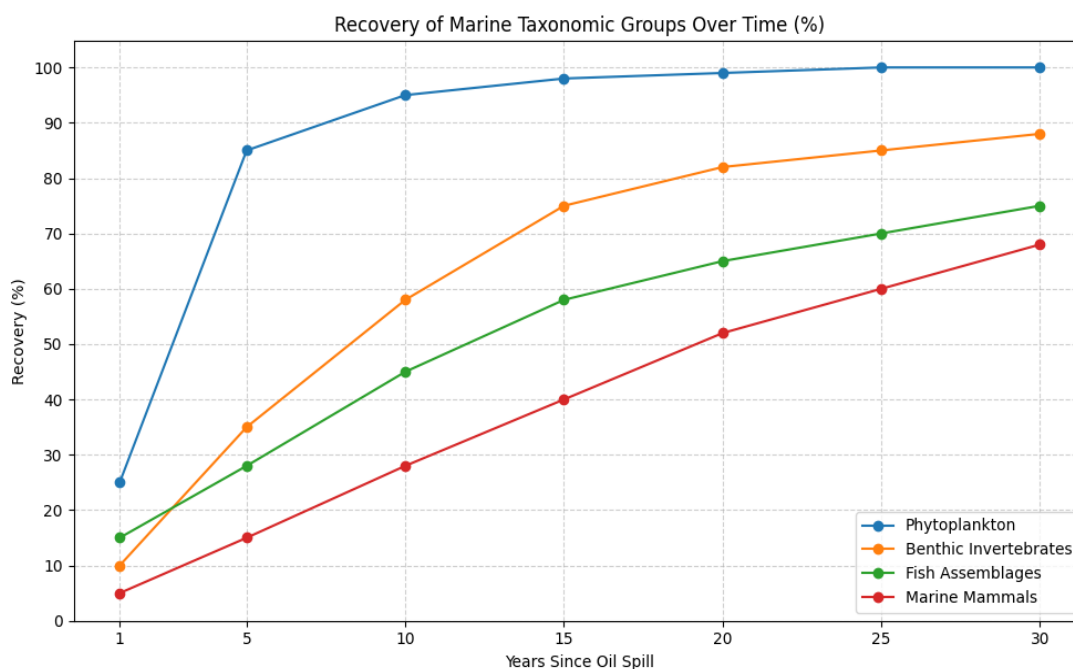


Figure 2: Comparative Ecological Recovery Trajectories (% of Pre-Spill Baseline) Over 30 Years Post-Spill

V. Discussion

Based on this study, it was found that the biological impacts of marine oil spills are long-term and highly variable in magnitude, but are dependent on the size of the spill, properties of the oil and the habitat, and quality of the response. In cases of high spill impact, they can lead to changes in ecosystem structure that last for decades and declines of particular species cause lasting food web impacts and decreases in ecosystem resilience. In turn, initial impacts and their extent are good predictors of the ultimate outcome, showing high correlations with recovery time. Therefore, short term studies of oil spill impacts may greatly under-estimate the true extent of the damage that occurred, since recovery can continue for decades. Accordingly, a long-term outlook is essential for environmental management after major spill events.

Comparative analysis of the treatment methods confirmed that bioremediation was ecologically superior by removing hydrocarbons, but adding negligible new stress to the ecosystem. However, conventional treatments like mechanical removal are often insufficient in preventing impacts on sediment and sensitive coastal ecosystems, and chemical treatments are effective at reducing surface cleanup, but introduce new stress into the environment. These results advocate the use of an adaptive, integrated approach combining multiple response methods for use in different habitats with varying sensitivity and ecological stress. The necessity for long-term monitoring programs extending beyond the initial immediate response is also evident, particularly in relation to keystone species and deep-sea species and ecosystems. These developments in the form of modeling, artificial intelligence and ecosystem simulation should be further incorporated in predictions and recovery planning in future impact assessments and restoration efforts. Future research should investigate the interactive effects of oil contamination and climate stressors such as increasing water temperature, acidification and deoxygenation to promote greater ecosystem resilience and effective management of fisheries and coastal resources.

VI. Conclusion

The findings of this study are a comprehensive multi-site compilation and synthesis of ecological consequences of major marine oil spills and post spill interventions. It is observed that large marine oil spills cause extreme, taxonomically different effects on ecosystems, with phytoplankton at the surface returning to pre spill levels in 5 years and intertidal benthics taking 10-15 years and fish 20+. In many cases like sea otters and pacific herring populations more than 30 years is likely needed for near baseline recovery of these populations. These ecological changes have considerable statistical weight, with 70% of long-term decline seen in Pacific herring and 55,000 g kg dry weight sediments persisting two decades post-spill being an issue not a margin for many parameters that causes widespread cascading effects on food webs, marine resources and marine biodiversity. This report has shown that, in terms of ecological compatibility and long-term recovery, bioremediation is the most effective treatment method, although mechanical and chemical processes are useful during the immediate response phase. An integrated post-spill recovery plan, presented in this report (combining active bioremediation and a long-term adaptive monitoring program with biologically-driven management of trophic interactions), will improve ecosystem health post-spill by incorporating the results and analyses herein. The work of many researchers into this area should continue with advances in recovery prediction including the interaction between the ecosystem and climate change, development and testing of eDNA technology to be used in initial impact assessments, and development of comparable international monitoring procedures.

Declaration Statement

Conflict of Interest: The authors declare no conflict of interest in the conduct or reporting of this research.

Funding: This research received no specific funding from any public, commercial, or not-for-profit funding agency.

Dataset Description: All ecological and geochemical data used in this study were derived from publicly available published literature, government environmental monitoring archives, and open-access scientific databases; no new primary datasets were generated.

References

- [1] Kingston, P. F. (2002). Long-term environmental impact of oil spills. *Spill Science & Technology Bulletin*, 7(1-2), 53-61. [https://doi.org/10.1016/S1353-2561\(02\)00051-8](https://doi.org/10.1016/S1353-2561(02)00051-8)
- [2] Barron, M. G., Vivian, D. N., Heintz, R. A., & Yim, U. H. (2020). Long-term ecological impacts from oil spills: comparison of Exxon Valdez, Hebei Spirit, and Deepwater Horizon. *Environmental science & technology*, 54(11), 6456-6467. <https://doi.org/10.1021/acs.est.9b05020>
- [3] Yusup, M. F. B. (2024). Mitigating the impact of oil spills in the sea with responsive strategies and ecosystem recovery. *Maritime Park: Journal of Maritime Technology and Society*, 86-91. <https://doi.org/10.62012/mp.v3i2.35387>
- [4] Peterson, C. H., Rice, S. D., Short, J. W., Esler, D., Bodkin, J. L., Ballachey, B. E., & Irons, D. B. (2003). Long-term ecosystem response to the Exxon Valdez oil spill. *Science*, 302(5653), 2082-2086. <https://doi.org/10.1126/science.1084282>
- [5] Zhang, B., Matchinski, E. J., Chen, B., Ye, X., Jing, L., & Lee, K. (2019). Marine oil spills—oil pollution, sources and effects. In *World seas: an environmental evaluation* (pp. 391-406). Academic Press. <https://doi.org/10.1016/B978-0-12-805052-1.00024-3>
- [6] Seara, T., Owens, A., Pollnac, R., Pomeroy, R., & Dyer, C. (2022). Lessons learned from a natural resource disaster: The long-term impacts of the Long Island Sound lobster die-off on individuals and communities. *Marine Policy*, 136, 104943. <https://doi.org/10.1016/j.marpol.2021.104943>

- [7] Asif, Z., Chen, Z., An, C., & Dong, J. (2022). Environmental impacts and challenges associated with oil spills on shorelines. *Journal of Marine Science and Engineering*, 10(6), 762.
<https://doi.org/10.3390/jmse10060762>
- [8] Borja, Á., Dauer, D. M., Elliott, M., & Simenstad, C. A. (2010). Medium-and long-term recovery of estuarine and coastal ecosystems: patterns, rates and restoration effectiveness. *Estuaries and Coasts*, 33(6), 1249-1260. <https://doi.org/10.1007/s12237-010-9347-5>
- [9] Moreno, R., Jover, L., Diez, C., Sardà, F., & Sanpera, C. (2013). Ten years after the prestige oil spill: seabird trophic ecology as indicator of long-term effects on the coastal marine ecosystem. *PloS one*, 8(10), e77360. <https://doi.org/10.1371/journal.pone.0077360>
- [10] Venesjärvi, R., Jolma, A., & Helle, I. (2023). Sensitivity index for conservation priority ranking in the oil spill response: A case study for the coastal and marine species and habitat types in the Baltic Sea. *Ecotoxicology and Environmental Safety*, 257, 114936.
<https://doi.org/10.1016/j.ecoenv.2023.114936>
- [11] Schwing, P. T., Montagna, P. A., Joye, S. B., Paris, C. B., Cordes, E. E., McClain, C. R., ... & Murawski, S. A. (2020). A synthesis of deep benthic faunal impacts and resilience following the Deepwater Horizon oil spill. *Frontiers in Marine Science*, 7, 560012.
<https://doi.org/10.3389/fmars.2020.560012>
- [12] Bosco, K. J. (2025). Transforming Fisheries Sustainability: Smart Innovations for Resilient Aquatic Ecosystems. *National Journal of Smart Fisheries and Aquaculture Innovation*, 54-60.
- [13] Al-Majed, A. A., Adebayo, A. R., & Hossain, M. E. (2012). A sustainable approach to controlling oil spills. *Journal of environmental management*, 113, 213-227.
<https://doi.org/10.1016/j.jenvman.2012.07.034>
- [14] Frasier, K. E. (2019). Evaluating impacts of deep oil spills on oceanic marine mammals. In *Scenarios and responses to future deep oil spills: Fighting the next war* (pp. 419-441). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-12963-7_25