



Technological advances in monitoring ocean currents and marine pollutant transport

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Abstract

Monitoring ocean currents and pollutant transport is important for tracking environmental dynamics and forecasting pollutant movement, enabling pollution control measures to protect marine ecosystems. Technological improvements during the last few years have enabled tracking phenomena with greater precision, extent, and efficiency. This paper identifies the most recent technological advances in monitoring ocean currents and tracking marine pollutants, focusing on autonomous sensors, remote sensing, and data assimilation frameworks. Specifically, the paper discusses autonomous underwater vehicles, high-frequency radars, satellite remote sensing, and state-of-the-art sensors for pollutant monitoring. It lists the most salient insights regarding the advantages and drawbacks of the technologies above, especially the difficulties of real-time, on-the-fly calibration, complex pollutant tracking in oceanographic environments, and the pollutants themselves. The paper proposes integrating disparate technologies to formulate an operational system for monitoring and controlling marine pollution and cites the need for integrated systems to be the focus of future research efforts to improve the systems designed for this task. The findings showcase the need for an integrated approach to designing monitoring systems for marine pollution and to devise measures for effective marine pollution control.

Keywords: Ocean currents, Marine pollutant transport, Remote sensing, Autonomous sensors, Drifter technology, Ocean monitoring systems

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Introduction

Ocean currents are essential for transporting and distributing pollutants, plastics, oil, and other chemicals. All marine pollutants impact marine and coastal ecosystems and communities, and contribute to climate change (Ilyina *et al.*, 2006). Therefore, understanding the currents and predicting impacts becomes vital. Deviations and intricacies of the current flow system pose challenges for the pollutants monitoring and predictive modeling. The volume of the monitoring system and the ecological and environmental impacts of pollutants, particularly plastics, necessitate the development of advanced, robust monitoring systems (Wang *et al.*, 2023). The lack of monitoring systems for tracking pollutant transport and currents stems from the ocean's dynamic, vast nature, the lack of real-time monitoring, and numerous obstacles posed by the ocean itself. Monitoring the ocean using moorings, drifters, and ships greatly advanced understanding of ocean systems; however, these systems lack the necessary spatial and temporal parameters for large-scale, real-time monitoring of pollutants. And for tracking pollutants in remote, deep-ocean systems, these systems do not provide the necessary information (Kikaki *et al.*, 2024).

Recent advances in technology offer new opportunities for precisely and reliably tracking ocean currents and marine pollutants. Ocean flows are monitored and recorded in fine detail using autonomous underwater vehicles (AUVs), gliders, and high-frequency radar systems. Meanwhile, remote

sensing satellites, sophisticated modeling techniques (such as data assimilation and pollutant transport modeling), and advanced tracking of pollutants in a wide spatial range are all converging. Moreover, sensor networks with real-time tracking and integrated sensor data systems offer new opportunities for tracking marine pollutants (Röhrs *et al.*, 2023). However, ocean monitoring technologies and pollutant transport models remain poorly integrated, and there are minimal comprehensive real-time monitoring systems for diverse ocean environments. The purpose of this paper is to evaluate the latest technologies in monitoring ocean currents and assessing the transport of marine pollutants based on the most important achievements in these areas, as well as the varying strengths and weaknesses of the monitoring systems to fully understand these systems (Bean *et al.*, 2017). The paper also aims to propose a unified strategy for applying these systems to improve marine pollution monitoring (Xu, Shi and Sun, 2019) (Saparov *et al.*, 2024).

Materials and Methods

The expansion of both in situ and remote-sensing technologies facilitated significant advances in assessing ocean dynamics and pollutant transport (Suara *et al.*, 2020). In situ sensor platforms, such as moorings, drifters, ADCPs (Acoustic Doppler Current Profilers), and gliders, provide the tools necessary for direct measurement of ocean currents. Anchoring systems called moorings position sensors at various depths to provide reliable, long-term measurements of current velocity. Still,

these measurements are constrained to a single location, and moorings are subject to environmental degradation. Floating drifters provide useful information on surface current patterns for as long as they remain operational. ADCPs estimate water velocity at various depths using sound and are well-suited for profiling deep-ocean currents, but they are expensive and require significant maintenance. As autonomous underwater vehicles, gliders can travel long distances and collect high-resolution information on ocean currents and other environmental variables. Though they are highly useful in this regard, gliders are constrained by real-time data transmission, low speed, and long endurance. Alongside in situ methods, ocean current monitoring can also be accomplished using remote sensing technologies, including satellite altimetry, high-frequency (HF) radar, synthetic aperture radar (SAR), and optical sensors. Altimeter satellites, which capture and store numerous satellite images of Earth from space, track variations in sea surface height and provide global coverage, monitoring large-scale patterns in ocean currents. However, tracking surface currents, discontinuous altimetry data sampling, and variations in weather conditions, independent of human actions, pose major limitations (Prakash and Zielinski, 2025).

HF radar systems monitor and provide real-time information on coastal currents and can cover enormous areas, but are limited by adverse saltwater environments and corrosion. For instance, the detection and monitoring of oil spills and oil slicks on the water

surface can be accomplished using SAR systems regardless of the weather. However, SAR systems are expensive and complex to use since the image data requires sophisticated analysis. Optical sensors, on the other hand, can monitor surface currents, surface water properties, and water and atmospheric conditions; however, they are affected by clouds. Lastly, the use of data assimilation in combination with real-time monitoring systems, active monitoring networks, and various data sources is indispensable for integrating real-time observations into numerical ocean models. Ocean models, using data assimilation, improve the prediction of current movements by actively assimilating real-time data and adjusting the models; in turn, pollutant transport models predict and simulate current movements while accounting for ocean contaminants. Active monitoring networks combine in situ sensors and models to monitor and provide continuous data to support responses to marine pollution. The integrated systems offer extensive monitoring capabilities; however, they face challenges integrating various systems and technologies, ensuring data integrity, and achieving operational efficiency across a wide range of ocean environments, as illustrated in Figure 1.

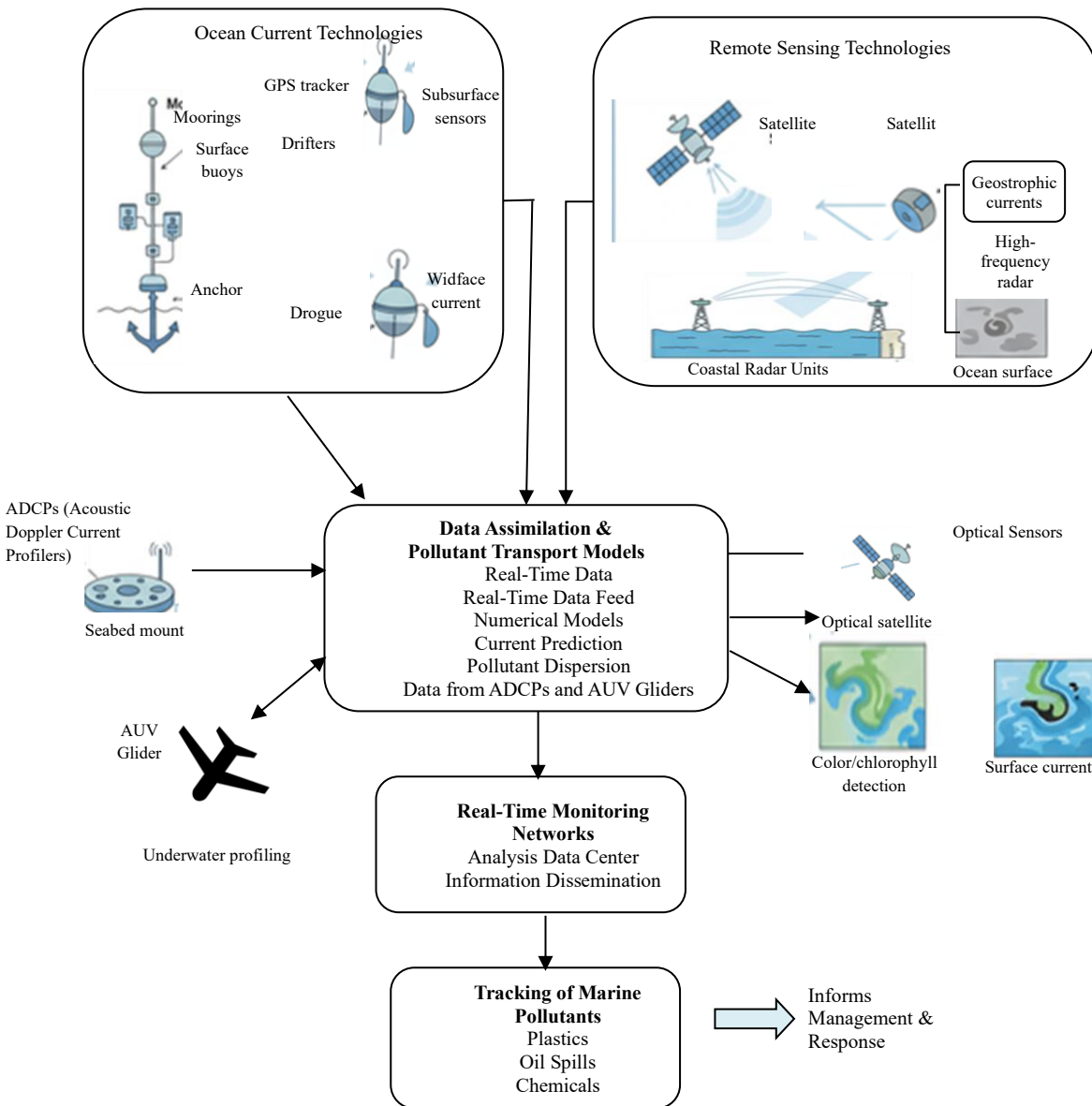


Figure 1: Molecular motion representation.

Technologies used to track marine pollutants monitor the movement and dispersion of pollutants, including plastics, oil, and chemicals, in marine currents (Liu *et al.*, 2025). The movement of pollutants is studied using drifters and chemical tracers. Drifters provide real-time data on surface currents, while chemical tracers simulate pollutant behavior, providing valuable information for understanding pollutant dispersion. Drifters are a viable option for tracking surface currents, but their overall effectiveness may be compromised by

limited lifetimes and exposure to unpredictable environmental conditions. Documented evidence shows the use of passive and active sensors for direct detection of pollutants while 'Drifters' track surface currents. Microplastic sensors use optical and infrared techniques to detect small plastic particles, while optical and infrared techniques are used to detect oil slicks. Toxic pollutants in the oil are determined by measuring the concentrations of different chemical pollutants, and infrared radar sensors are used to detect

so-called oil slicks. Real-time sensors can indeed monitor marine pollutants in situ, but calibration and sensitivity issues persist (Ma *et al.*, 2023). The combination of tracking ocean currents with modeled pollutant forecasts predicted that pollutants would be dispersed across vast regions of the ocean. The purpose of Lagrangian models is to predict pollutant dispersion.

In contrast, transport models predict the current hydrodynamic and chemical processes of the system by merging model data with real-time data (Tsanis *et al.*, 2007). Complex, interrelated patterns are discovered by machine learning to improve the predictive capabilities of real-time monitoring systems, which serve as the primary technology for integrating systems to promote the efficient management of marine pollution. The movement of pollutants can be monitored and forecasted with greater efficiency using an integrated system (Idžanović, Rikardsen and Röhrs, 2023).

The application of technology for monitoring ocean currents and analyzing pollutant distribution in the sea is of utmost importance for efficient pollution management, as shown in Figure 2. This technology combines in-situ (drifters, moorings, ADCPs, gliders) and remote sensors (satellite altimetry, HF radar, SAR) to provide real-time currents and pollutant concentrations. This information, in combination with Lagrangian tracking of pollutant transport and 3D (hydrodynamic) modeling, facilitates the estimation of pollutant transport and the pollution potential in large oceanic regions.

Additionally, the use of machine learning and data-driven approaches enables fundamental improvements to models through large-scale data analysis, revealing patterns and predicting, a necessity for real-time routing. However, combining various systems to achieve seamless real-time functionality remains a core challenge. These challenges include mismatches in sensor spatial and temporal resolution, sensor cost, and the system's data-handling, calibration, and validation complexity. Storms and rough seas will influence sensor performance and the quality of collected information. Incorporating monitoring data and pollutant transport models is also challenging due to limited and inaccurate input data. For such issues, we put forth an integrated system of monitoring layered sensor networks, assimilation of data in real time, and predictive models of pollutant transport. Such a system would encompass various types of sensors in the main regions of the ocean, remote sensing systems for broader surveillance, and a real-time data assimilation system that performs active updates of the predictive model. A core dashboard should show real-time information on pollutant tracing, which will support pollution response. An example of such a system might be implemented in the Gulf of Mexico, where integrating real-time information on ocean currents with drifters, gliders, and satellite images could create a predictive model of an oil slick's trajectory. This would improve the ability to predict, and thus better manage, the response to the pollutants and control marine pollution (Trevathan and Schmidtke, 2022).

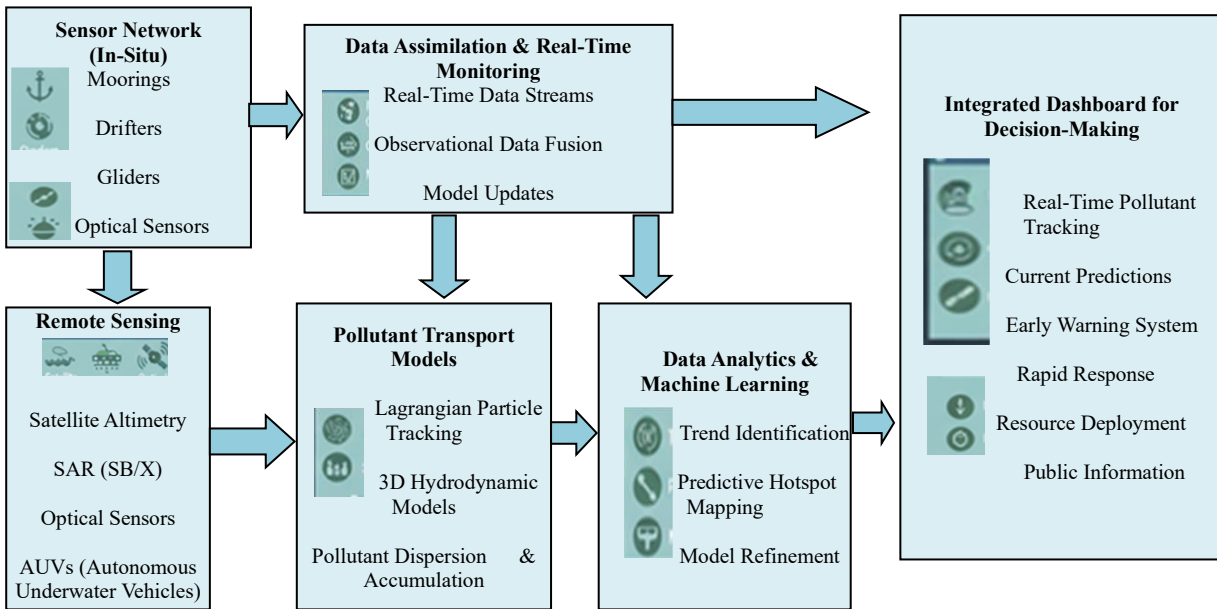


Figure 2: Proposed framework for an integrated monitoring system.

Results

Analysis demonstrates the complexities of the mechanisms of the spreading of contaminants in the sea. The various visualization approaches through time and space, cumulative tracking, heat maps, and 3D models, provided trends and concentration patterns for various streams of contaminants, oil spills, plastic

debris, and chemical waste. The findings indicate the significant roles of currents and weather in the dispersion of contaminants and the geographical features. The comprehensive dataset provides the foundation for developing strategies on monitoring and remediation of sea-borne pollutants, focusing on the urgent need for real-time tracking and predictive models.

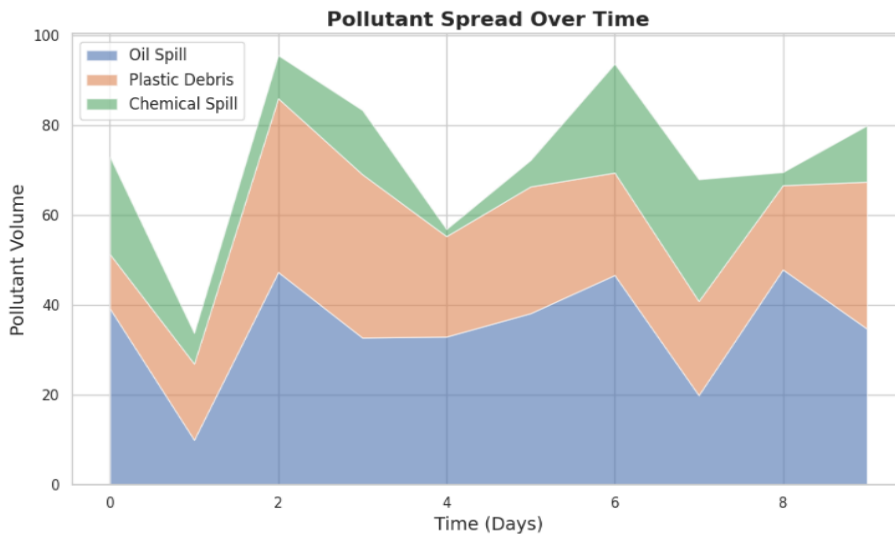


Figure 3: Temporal dynamics of pollutant spread in ocean waters.

Data depicted in Figure 3 demonstrates the two-week inter-temporal distribution of the three major

relevant pollutants for the 3 Spill Models under study: Oil, plastics, and damaging chemicals. This shows the relative

degrees of each pollutant constituent's weight to the overall ocean leached pollution over the given period. The relative size changes of each pollutant constituent demonstrate the volatility in each pollutant's dissolution. The volatility is likely due to a variety of

reasons: oceanic currents and climate conditions, as well as the lack of parceling. The pollutants overdosing over the given period is instructive in strategically timing the pollutant extraction efforts.

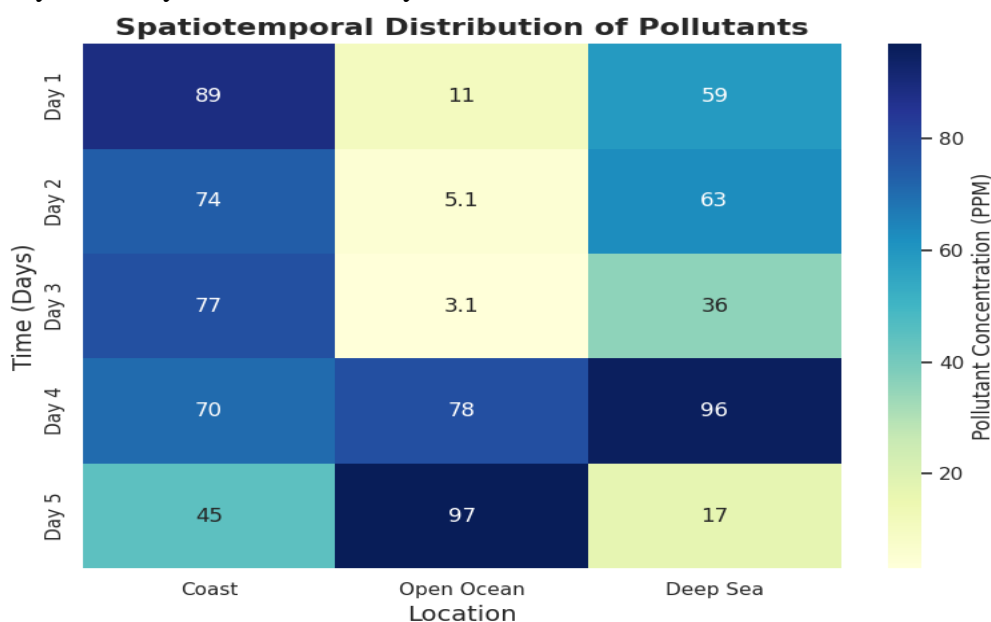


Figure 4: Spatiotemporal distribution of pollutant concentrations in the ocean.

Figure 4 displays pollutant concentration values for specific places at given times during a five-day sampling period. Values of concentrated pollutants are depicted in cells represented geographically, while variations in concentration for a given pollutant at a location are displayed using a color gradation scheme. Higher concentration values are portrayed in darker shades, while lower concentration values are portrayed in lesser shades. The heatmap demonstrates how and where pollutants

are dispersed. It is safe to assume that pollutants are concentrated in coastal environments. This type of display is invaluable for the recognition of pollution concentration and for a strategic pollution dispersion understanding to develop an appropriate monitoring scheme and resource allocation for the area of interest. The hotspots and dynamism of concentration dispersion are fundamental to the development of resource-conserving pollution monitoring plans.

Pollutant Transport Modeling

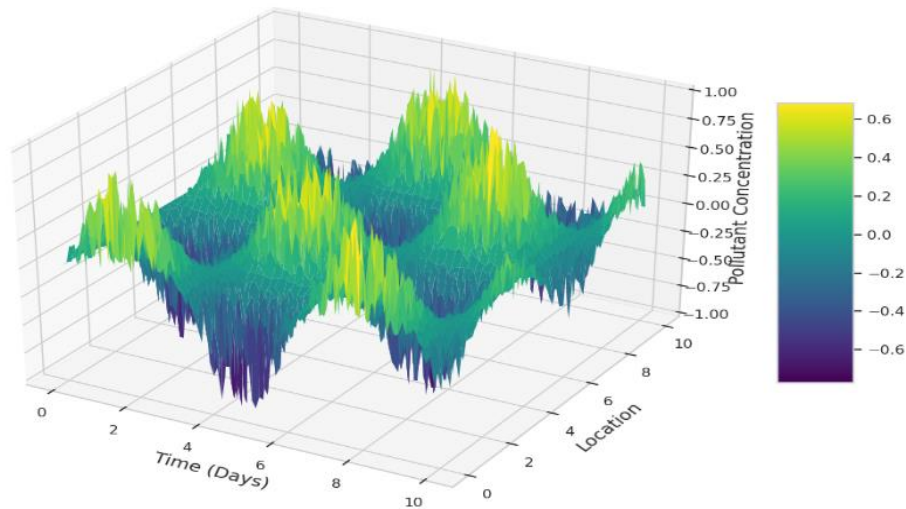


Figure 5: 3D Modeling of pollutant transport in ocean current.

As illustrated in Figure 5, pollutants disperse in the ocean both in space and time. The x and y axes depict time and space, while the z-axis illustrates the concentration of the pollutant. The varying heights of the surface on the plot represent differing pollutant concentrations; taller surfaces represent greater pollutant concentration. The plot demonstrates the interplay of ocean currents, pollutant characteristics, and other environmental factors for time and depth dispersion of pollutants. The visualization aids in identifying zones of pollutant accumulation, and the predictor aids in anticipating future pollutant concentrations, facilitating pre-emptive action for pollution mitigation and environmental management.

Discussion

In maintaining technological tracking and predicting advancement and potential contaminant distribution, tracking and predicting technology readings concerning contaminant distribution and tracking, a review concerning handling infrastructural technological thresholds

concerning handling contaminant distribution tracking and predicting potential dispersal. Gliders and high-frequency (HF) radar, and machine learning (ML) models are particularly useful. Gliders facilitate long-range and high-resolution monitoring of the ocean at multiple strata of the water. HF tracking radars also help provide real-time and extensive coverage of surface currents, making them useful in monitoring the movement of pollutants (especially oil slicks and debris) and tracking their dispersal (Nooteboom *et al.*, 2020; Chen *et al.*, 2024). The combination of the technologies and ML models improves the tracking of pollutants in real-time and predictive tracking by pattern formation of complex datasets and predictive learning of the pollutant movement (Xu, Irigoien and Alouini, 2024). However, there are a variety of deficiencies and gaps. The detection of microplastics remained a significant challenge for current monitors and detection methods of lower water columns, specifically designed to revolutionize surface monitoring and

methods of detection of lower column shallow waters (Al-Rashid and Greaves, 2025). Also, real-time detection of pollutants, especially in remote/deep sea, remains a major challenge, where real-time continuous transmission of data is impossible. The integration of monitoring ocean currents and pollutant transport focuses on the heterogeneity of real conditions (ocean temperature and currents) functioning.

The future enhancements of the monitoring system include self-adapting AI sensors for detecting pollutants and swarm autonomous vehicles for extensive ocean coverage. Advanced remote sensing technologies, such as next-generation SAR satellites and hyperspectral imagers, will enable dynamic pollutant monitoring. These innovations will support policy and management in making rapid, real-time decisions regarding marine pollution control. The effectiveness of these technologies varies by marine environment; high-frequency radar and local sensor networks will be most effective in coastal areas, while satellite-based remote sensing and autonomous underwater vehicles will better serve vast open ocean regions. In developing areas like Tamil Nadu, India, where pollution is high and resources are limited, cost-effective solutions such as low-cost drifters and sensor networks can improve local monitoring capacities for ocean pollution management.

Conclusion

This paper examined new methods to observe ocean currents and the transportation of marine pollutants. The research demonstrates the use of self-

sustaining automated sensors, remote detection systems, and assimilation of real-time, harmonized predictive models. The combination of these systems provides the opportunity to track and forecast pollutant dispersion in the ocean. Using models of pollutant transport in conjunction with real-time ocean current surveillance and pollutant transport models, we can address the pollutant dispersion dynamics and develop appropriate mitigation measures. The combination of gliders, high-frequency radar, machine learning models, and satellite remote sensing technologies provides one of the best solutions for ocean monitoring systems. Nevertheless, the costs associated with the sensors, data relay systems, real-time pollutant detection systems, and the technologies required to monitor inactive zones of the ocean are among the most important obstacles these technologies face. An advanced monitoring network is built on an ensemble of disparate sensors, assimilating real-time measurements and liaising with predictive frameworks. Streamlined sensor deployment, sensor bias and accuracy assessments, and frame-worked interoperable data discourses will render monitoring networks economically viable and efficient to solve marine pollution. Furthermore, system operational capability will address marine pollution on a global scale, especially systems designed and developed to address pollution in low-income nations. The ability to use technology to manage predictive responses, tool efficiencies, and targeted approaches to mitigate pollution is the essence of the technology's ability to manage pollution.

Conservatively and interactively redirecting technology. Ocean and marine pollution technologies will advance research aimed at specific investments in the real-time monitoring of marine pollution, the optimization of marine pollution detection systems, and the interconnectedness of disparate marine systems.

References

- Al-Rashid, A. and Greaves, J., 2025.** Evaluating Microplastic Pollution in Coastal Waters and Its Impact on Aquatic Food Webs. *Aquatic Ecosystems and Environmental Frontiers*, 3(3), pp.1-5.
- Bean, T.P., Greenwood, N., Beckett, R., Biermann, L., Bignell, J.P., Brant, J.L., Copp, G.H., Devlin, M.J., Dye, S., Feist, S.W. and Fernand, L., 2017.** A review of the tools used for marine monitoring in the UK: combining historic and contemporary methods with modeling and socioeconomics to fulfill legislative needs and scientific ambitions. *Frontiers in Marine Science*, 4, p.263.
<https://doi.org/10.3389/fmars.2017.00263>
- Chen, Z., Wang, X., Cao, H. and Song, X., 2024.** Mapping high-resolution surface current by incorporating geostrophic equilibrium with surface quasigeostrophic theory using multi-source satellite observations. *Remote Sensing of Environment*, 304, p.114058.
<https://doi.org/10.1016/j.rse.2024.114058>
- Idžanović, M., Rikardsen, E.S. and Röhrs, J., 2023.** Forecast uncertainty and ensemble spread in surface currents from a regional ocean model. *Frontiers in Marine Science*, 10, p.1177337.
<https://doi.org/10.3389/fmars.2023.1177337>
- Ilyina, T., Pohlmann, T., Lammel, G. and Sündermann, J., 2006.** A fate and transport ocean model for persistent organic pollutants and its application to the North Sea. *Journal of Marine Systems*, 63(1-2), pp.1-19.
<https://doi.org/10.1016/j.jmarsys.2006.04.007>
- Kikaki, K., Kakogeorgiou, I., Hoteit, I. and Karantzalos, K., 2024.** Detecting marine pollutants and sea surface features with deep learning in sentinel-2 imagery. *ISPRS Journal of Photogrammetry and Remote Sensing*, 210, pp.39-54.
<https://doi.org/10.1016/j.isprsjprs.2024.02.017>
- Liu, Z., You, S., Xing, L., Durand, G., Moccia, L.P., Mercier, V., Pan, Y. and Zhang, X., 2025.** OPMS-A web-based ocean pollution monitoring system. *Marine Pollution Bulletin*, 212, p.117510.
<https://doi.org/10.1016/j.marpolbul.2024.117510>
- Ma, J., Ma, R., Pan, Q., Liang, X., Wang, J. and Ni, X., 2023.** A global review of progress in remote sensing and monitoring of marine pollution. *Water*, 15(19), p.3491.
<https://doi.org/10.3390/w15193491>

- Nooteboom, P.D., Delandmeter, P., van Sebillé, E., Bijl, P.K., Dijkstra, H.A. and von der Heydt, A.S., 2020.** Resolution dependency of sinking Lagrangian particles in ocean general circulation models. *PloS one*, 15(9), p.e0238650. <https://doi.org/10.1371/journal.pone.0238650>
- Prakash, N. and Zielinski, O., 2025.** AI-enhanced real-time monitoring of marine pollution: part 1-A state-of-the-art and scoping review. *Frontiers in Marine Science*, 12, p.1486615. <https://doi.org/10.3389/fmars.2025.1486615>
- Röhrs, J., Sutherland, G., Jeans, G., Bedington, M., Sperrevik, A.K., Dagestad, K.F., Gusdal, Y., Mauritzen, C., Dale, A. and LaCasce, J.H., 2023.** Surface currents in operational oceanography: Key applications, mechanisms, and methods. *Journal of Operational Oceanography*, 16(1), pp.60-88. <https://doi.org/10.1080/1755876X.2021.1903221>
- Saparov, K., Yakhshieva, Z., Kholdorova, G., Sangirova, M., Dadaeva, G., Rajabov, K., Asallaev, U. and Safarova, N., 2024.** Advanced Materials for Pollution Control that Integrate Engineering Science with Environmental Conservation. *Natural and Engineering Sciences*, 9(3), pp.77-87. <https://doi.org/10.28978/nesciences.1581548>
- Suara, K., Khanarmuei, M., Ghosh, A., Yu, Y., Zhang, H., Soomere, T. and Brown, R.J., 2020.** Material and debris transport patterns in Moreton Bay, Australia: The influence of Lagrangian coherent structures. *Science of The Total Environment*, 721, p.137715. <https://doi.org/10.1016/j.scitotenv.2020.137715>
- Trevathan, J. and Schmidtke, S., 2022.** Open-source Internet of Things remote aquatic environmental sensing. *HardwareX*, 12, p.e00336. <https://doi.org/10.1016/j.ohx.2022.e00336>
- Tsanis, I., Wu, J., Shen, H. and Valeo, C., 2007.** *Environmental hydraulics: hydrodynamic and pollutant transport models of lakes and coastal waters* (Vol. 56). Elsevier.
- Wang, N., Cao, R., Lv, X. and Shi, H., 2023.** Research on the transport of typical pollutants in the yellow sea with flow and wind fields. *Journal of Marine Science and Engineering*, 11(9), p.1710. <https://doi.org/10.3390/jmse11091710>
- Xu, G., Shi, Y., Sun, X. and Shen, W., 2019.** Internet of things in marine environment monitoring: A review. *Sensors*, 19(7), p.1711. <https://doi.org/10.3390/s19071711>
- Xu, J., Irigoien, X. and Alouini, M.S., 2024.** State-of-the-Art Underwater Vehicles and Technologies Enabling Smart Ocean: Survey and Classifications. <https://doi.org/10.48550/arXiv.2412.18667>