frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 06 June 2025
DOI 10.3389/fmars.2025.1605996

OPEN ACCESS

EDITED BY
Mehran Idris Khan,
University of International Business and Economics, China

REVIEWED BY
Khadija Zulfiqar,
Dalian Maritime University, China
Muhammad Fahad Anwar,
University of Sahiwal, Pakistan

*CORRESPONDENCE
Yi-Che Shih
shih@gs.ncku.edu.tw

RECEIVED 04 April 2025
ACCEPTED 06 May 2025
PUBLISHED 06 June 2025

CITATION
Shih Y-C (2025) A study of marine environmental protection and biodiversity observation and monitoring mechanisms in Taiwan.
Front. Mar. Sci. 12:1605996.
doi: 10.3389/fmars.2025.1605996

A study of marine environmental protection and biodiversity observation and monitoring mechanisms in Taiwan

Yi-Che Shih*

Institute of Marine Technology and Affairs, National Cheng Kung University, Tainan, Taiwan

Taiwan's marine ecosystems are increasingly vulnerable to anthropogenic and environmental pressures, highlighting the urgent need for effective biodiversity monitoring. This study investigates existing marine biodiversity observation and monitoring mechanisms in Taiwan to inform future conservation and policy development. The study analyzes three long-term ecological datasets: (1) plankton assemblages in western coastal waters (1993–2021), (2) fish assemblages in northern rocky tide pools, and (3) fish assemblages in southern tide pools. Additionally, it evaluates the Taiwan Marine Environment Monitoring Service (TwMEMS), which integrates real-time and historical oceanographic data for ecological assessment and disaster preparedness. The findings reveal distinct seasonal and regional biodiversity patterns. Plankton communities exhibited peak chlorophyll-a concentrations in the third quarter, indicating nutrient enrichment likely from upwelling or runoff. Fish assemblages showed site-specific species richness, with notable dominance of *Bathygobius fuscus* and *Istiblennius* species. TwMEMS data demonstrated improved tsunami detection through advanced filtering techniques, supporting ecosystem risk monitoring. Taiwan's monitoring systems provide valuable baseline data for assessing long-term ecological change but face challenges in data integration and indicator standardization. Strengthening these frameworks through regional monitoring hubs, standardized biodiversity indicators, and alignment with international platforms such as GBIF and BONs will enhance marine conservation effectiveness. This study emphasizes the role of integrated observation mechanisms in supporting ecosystem-based management and Taiwan's contribution to global biodiversity goals.

KEYWORDS

marine environmental protection, oceanographic data, marine biodiversity, monitoring mechanism, monitoring indicators

1 Introduction

Marine biodiversity observation and monitoring mechanisms offer instrumental insights for setting effective baseline for detection of human-induced and environmental-induced impacts on the marine environment and modelling of future scenarios based on the ever dynamic global and environmental contexts (Sawh et al., 2024;Turschwell et al., 2023; Ward et al., 2022; Poloczanska et al., 2013). In recent years, there has been a significant demand for oceanographic data especially among blue economies such as Taiwan (Chen et al., 2024; Shih, 2024; Chen and Shih., 2021; Huang and James, 2014) and have been used to achieve a wide range of objectives including engineering design, mitigation of marine hazards, navigation, and environmental protection (Shih, 2024; Doong et al., 2021; Chen, 2019; Huang et al., 2018; Lin et al., 2015; Cheng et al., 2016). The collected oceanographic data are important in marine biodiversity observation and formulation of monitoring mechanisms using numerical models and simulation data that covers a wide geographical area over long periods of time (Libralato, 2024; Doong et al., 2021; Batten et al., 2019). Presently, there are a wide range of marine related data centers that collect, process and analyze data that are presented in a friendly and visualization environment that can be efficiently used for marine biodiversity observation and monitoring of the related ecosystems (Güntsch et al., 2024; Takeuchi et al., 2021; Fujioka and Halpin, 2014). Considering the large diversity of species in the marine environments of countries such as Taiwan, it is necessary to formulate and adopt a multi-faceted marine biodiversity observation and monitoring mechanism that incorporates diverse strategies ranging from educational to legal frameworks for efficient mitigation of environmental impacts and improve public awareness on conservatory practices (Chen et al., 2024; Shih et al., 2023; Ministry of Foreign Affairs, 2022). As such, in Taiwan, there is a need for further understanding of the existing and potential marine biodiversity observation and monitoring mechanisms for effective policy and decision-making support for sustainable development, economic resilience and environmental conservation in the country.

Taiwan has a coastline of 1,988 kilometers and is surrounded by the Pacific Ocean to the east, the East China Sea to the north, and the South China Sea to the southeast. Over 90% of the country's population lives within 100 kilometers of the coast, and economic, traffic, and recreational activities in Taiwan are inextricably linked to the surrounding oceans (Shyu et al., 2020). However, Taiwan is one of the most vulnerable areas in the world, frequently suffering from natural disasters which have direct environmental impacts on marine biodiversity (Liu et al., 2022; Doong et al., 2021; Ribas-Deulofeu et al., 2021). In 1998, a coastal ocean monitoring network was established in Taiwan's waters to offer real-time oceanographic data for mitigation of the impacts of potential natural disasters and environmental change on marine biodiversity. With the expansion of numerous marine activities and industries along the coastlines, there has been an increase in the frequency of occurrence of tragedies that demands the intervention of government authorities and agencies to enhance the safety of marine operations through effective biodiversity observational programs and monitoring mechanisms. Between 2001 and 2003, the Executive Yuan's Council for Sustainable Development adopted the Biodiversity Promotion Program, Biodiversity Sustainable Development Action Plan, and Taiwan Sustainable Development Indicator System. In 2005, the Forestry Bureau recommended fourteen biodiversity monitoring indicators, and in 2012, the Sustainability Council reviewed and revised the biodiversity action plan to ensure it met the Aichi targets. Presently, the establishment of the Taiwan Biodiversity Observation Network (TaiBON) is expected to reflect the country's biodiversity implementation results and serve as a reference for future management and administration of the marine environment, as well as convergence with global databases.

Taiwan has had a long history of biodiversity studies and surveys. However, there is a lack of quality and quantity of relevant biodiversity information at the ecosystem level as well as an effective integration mechanism. Departmental data and government-commissioned survey projects are deeply fragmented which makes it difficult to be integrated to produce a coherent and accurate report on the status of marine biodiversity. As a result, there have been challenges to meet the Convention on Biological Diversity's Aichi Target as well as the illustration of the nation's long-term pattern of biodiversity change. In this regard, there is an urgent need for the formulation of a monitoring mechanism for national biodiversity observations and survey data to improve the transparency and integration of domestic biodiversity monitoring data, allowing for the development of significant and representative indicators for better understanding of the state and evolving trends in its marine biodiversity. Also, Taiwan could join other global biodiversity observation networks such as Global Biodiversity Information Facility (GBIF), Encyclopedia of Life (EOL) and Biodiversity Observation Network (BONs) if it establishes an effective national biodiversity monitoring system and indicators. To align Taiwan's biodiversity growth with global trends, it is imperative for the government to work together with the private sector to adjust the existing policy plans to improve existing biodiversity indicators, address concerns, assess data quality, and increase indicator accuracy for better biodiversity development. The present research study provide a detailed analysis of specific marine biodiversity observation and monitoring mechanisms in Taiwan to provide policy insights for the development of the country's marine biodiversity.

To strengthen the governance framework, Taiwan's approach to marine biodiversity observation and monitoring has been guided by several legal instruments. The Ocean Basic Act and Marine Conservation Act establish the general legal foundation, declaring marine environmental protection as a fundamental duty of the State. Building on this, the National Biodiversity Action Plan (NBAP) and the Taiwan Biodiversity Observation Network (TaiBON) embody soft law initiatives that exert significant normative influence while lacking direct enforceability. These instruments enhance Taiwan's legal soft power by shaping administrative practice and encouraging voluntary compliance from various stakeholders, consistent with contemporary theories of legal soft power.

2 Methods

The primary objective of the present research study is to investigate marine biodiversity observation and monitoring mechanisms in Taiwan. To achieve this objective, the study provides an analytical perspective of the statistical information and results of existing datasets that are focused on marine biodiversity observation and monitoring mechanisms. Considering the significant diversity of marine species, the study analyzes a wide range of datasets that have been collected over different periods of time and geographical locations with the goal of extracting insightful information that are associated with the topic of the research. Also, the study reviews existing academic and practical models that have been used in marine biodiversity observation and monitoring mechanisms both by the government and non-governmental institutions. The adopted research methodology focused on analysis of existing statistical information and models using both primary and secondary sources including bibliographic databases containing journals, proposed models, policy briefs, white papers, as well as the sources of cited references to provide detailed information on the topic of research. The methodology involved the identification of datasets and models that focused on research terms and keywords including 'marine biodiversity, 'monitoring mechanisms, 'species identification' and 'ocean biome'. Specifically, the chosen datasets focused on plankton assemblages in western Taiwan coastal water, fish assemblages in rocky tide pools on the northern coast of Taiwan and fish assemblages in rocky tide pools on the southern coast of Taiwan. The chosen model was the Taiwan Marine Environment Monitoring Service (TwMEMS) which is an integrated operational monitoring system for marine environmental parameters.

The first chosen dataset on plankton assemblages in western Taiwan coastal water was sourced from Lin et al. (2024) and was supported by the Ministry of Economic Affairs, Bureau of Industry. The dataset contains the results of the quarterly survey of the environmental factors and plankton population on eight transects along the coastline of western Taiwan from 1993 to 2021. The thirteen environmental parameters that were collected included temperature in °C, salinity in ‰, pH, concentration of chlorophyll a in mg × m−3, dissolved oxygen, concentration of, NO1−2, NO1−3, PO3−4, SiO4−4, biochemical oxygen demand BOD, and total suspended solids in mg × l−1, and transparency in m. The validation of the data was done through statistical checks and comparison with independent data. The statistical validation of the data was done by examining the distribution of the parameters using histograms of the chosen environmental variables. The second chosen dataset focused on fish assemblages in rocky tide pools on the northern coast of Taiwan and was sourced from Ho et al. (2020) and was supported by the Ministry of Science and Technology. The dataset consists of fish community composition that were collected from three sampling stations in rocky tide pools in the intertidal zone on the northern coast of Taiwan. The fish samples were collected across four seasons by counting the number of anesthetized fishes. The fish were gathered, packaged, and brought to the laboratory on ice. The captured fishes were identified and counted in the lab.

The third chosen dataset focused on fish assemblages in rocky tide pools on the southern coast of Taiwan and was sourced from Ho et al. (2020) and was supported by the Ministry of Science and Technology. The dataset consists of fish community composition that were collected from two sampling stations in rocky tide pools in the intertidal zone on the southern coast of Taiwan. The two stations were located near Kenting National Park, which provided habitat and shelter from human activity to coastal fish and were less disturbed by tourists due to the rocky paths to the tide pools and the strong reefs along the coast. As a results, the samples were considered as suitable for time series data on long-term species diversity. The fish samples were collected across four seasons by counting the number of anesthetized fishes. The fish were gathered, packaged, and brought to the laboratory on ice. The captured fishes were identified and counted in the lab. Lastly, the chosen model included in the study was the Taiwan Marine Environment Monitoring Service which is an integrated operational monitoring system for marine environmental parameters, as proposed by Doong et al. (2021). The model incorporates observational data which cover the range of the Northwest Pacific, from 110 degrees to 160 degrees east longitude and 5 degrees to 40 degrees north latitude. The model was developed by the Central Weather Bureau (CWB) of Taiwan and integrates *in-situ* data from 55 field stations that show real time conditions of the sea states across Taiwan.

3 Results

3.1 Monitoring of plankton assemblages in Western Taiwan coastal water

The findings of the long-term monitoring of plankton assemblages in Western Taiwan coastal water indicated that the distribution of the environmental parameters of interest were within reasonable ranges. According to the results, the pH ranged from 7.1 to 8.4, which corresponded to the range of coastal waters, and only a few metrics had exceptional levels, including salinity (8.1‰) and total suspended solids (877 mg × $^{1-1}$). The natural logarithm of plankton community density and abundance was also often symmetric or nearly symmetric which showed that they followed the log-normal distribution and, therefore, the most suitable empirical model for ecological analysis of marine environment. The results further found moderate fluctuation at all sites, although the levels of dissolved oxygen remain over 4.0 mg/l, which is critical for most marine life like fish and invertebrates. It is important to note that levels below the 4.0 mg/l level could lead to hypoxia which directly affect marine life. Also, the dataset results show that the third quarter of each year had the highest chlorophyll-a values which is an indication of algal biomass while the first quarter reported the lowest average at 0.53 ± 0.57 (range: 0.02-4.21). The findings imply that the third quarter experiences nutrient enrichment most likely from upwelling, riverine inputs, or

anthropogenic sources such agricultural runoff, which directly affects marine biodiversity. As shown in Figure 1, the distribution of key environmental parameters such as pH and chlorophyll-a reveals seasonal nutrient dynamics, providing important insights for detecting early signs of eutrophication and biodiversity stress in coastal ecosystems.

3.2 Monitoring of fish assemblages in rocky tide pools on the northern coast of Taiwan

The results from the first station of data collection indicated that the number of species collected per sample ranged between 4 and 18 and averaged 10.00 ± 2.84 (S.D.) while the number of while the number of physically collected species for every sample ranged between 22 and 184 and averaged 64.66 ± 34.80 (S.D). For the second station, the number of species collected per sample ranged between 5 and 20 and averaged 12.78 ± 3.79 (S.D) while the number of number of physically collected species was 632 for a total of 82 species. In the last station, the number of species collected per sample ranged between 4 and 20 and averaged 9.96 ± 3.71 (S.D) while the number of number of physically collected species was 468 for a total of 64 species. The dataset consisted of a total of 1,577 physically collected marine fish belonging to 106 species were collected at the three stations. According to the results, the most abundant species that were collected during the study included *Bathygobius fuscus*, *Abudefduf vaigiensis*, and *Istiblennius*, *Istiblennius dussumieri*, and *Istiblennius lineatus*. Figure 2 illustrates that fluctuations in fish species richness correlate with seasonal and multi-year environmental changes, highlighting areas vulnerable to habitat degradation and suggesting priority sites for conservation measures.

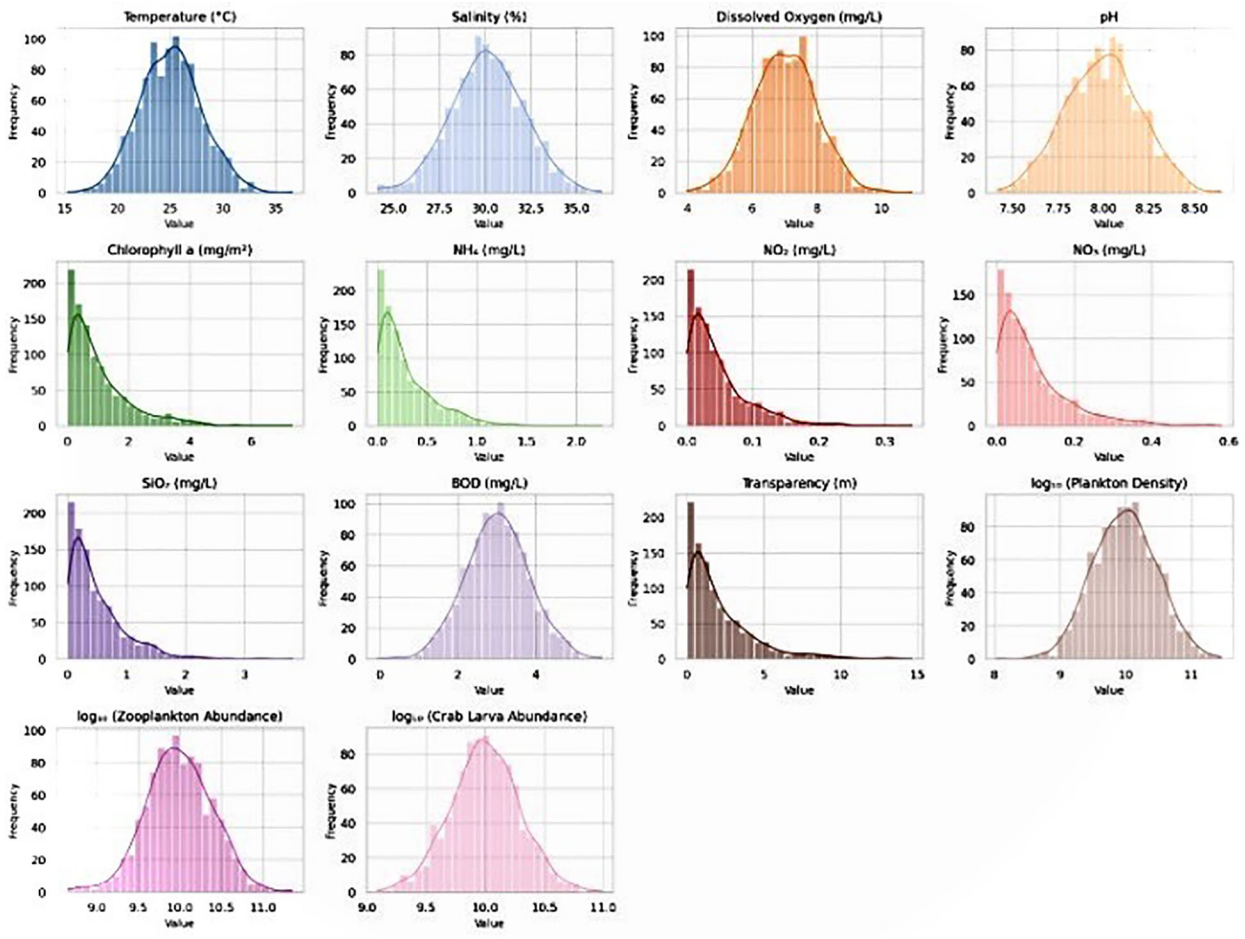

FIGURE 1
Histogram results for included environmental parameters. This figure Distribution of environmental parameters (pH, salinity, chlorophyll-a concentration, total suspended solids) recorded along the western Taiwan coastal waters (1993–2021). These baseline indicators are critical for assessing coastal ecosystem health, identifying nutrient enrichment trends, and informing coastal water quality management strategies. (Source: Adopted from Lin et al., 2024).

3.3 Monitoring of fish assemblages in rocky tide pools on the southern coast of Taiwan

The findings from the two stations of the monitoring of fish assemblages in rocky tide pools on the southern coast of Taiwan produced a total of 129 samples. The results indicated fluctuations in the number of species and physically collected samples at the two stations between 2000 and 2018. At the two locations, the average number of species taken per sample was 10.4 ± 3.3 (S.D), while the average number of physically collected samples was 59.7 ± 32.5. The most common species in the samples were *Istiblennius lineatus, I. edentulus*, and *Abudefduf sordidus, A. sordidus*, and *I. edentulous.* Long-term temporal variations in the number of individuals of these abundant species for each station was reported. As depicted in Figure 3, the observed fluctuations in species composition at the southern stations point to the cumulative effects of climate variability and coastal pressures, emphasizing the need for dynamic conservation strategies.

3.4 Taiwan marine environment monitoring service

The findings highlight the individual component models of the Taiwan Marine Environment Monitoring Service (TwMEMS) that specifically focus on tsunami monitoring and preprocessing of surface elevation data and analysis of swell warning. The surface elevation time series is recorded at the tidal station. The results indicate that elevation is raised by storm surges, astronomical tides, and other local factors. On the same note, abnormal instrumental electric currents or voltage fluctuations cause also cause surges in elevation levels. The results show that hat the three noticeable spikes have been eliminated, and following processing, the reference water level is closer to zero. Figure 4 demonstrates the refinement achieved through spike removal in TwMEMS data, ensuring more accurate detection of abnormal sea-level events that can impact marine and coastal ecosystems.

In terms of the data filtering method for the extraction of tsunami height, the results indicate that the low-pass filter does not completely exclude additional long wave period signals, and that the is a statistically significant difference between the results of low-pass filtering and those of high-pass filtering and band-pass filtering. Also, the model findings show that the high-pass filter cannot identify tsunami height since it produces high-frequency noise and may extract signals with shorter periods. To this end, therefore, the band pass filter is employed and proven to be a suitable technique for tsunami analysis in order to prevent misdiagnosis of tsunami signals by comparing real time results of observation data and historical data. This approach aligns with previous findings by Ala Amjadi and Mokhtari (2020), who demonstrated the effectiveness of wavelet techniques in distinguishing tsunami events from tidal data in historical tide gauge records. As shown in Figure 5, the application of band-pass filtering allows for precise identification of tsunami signals, thereby strengthening Taiwan's capacity to protect marine and coastal environments from extreme event impacts. Historical diagnostic analyses, like those for the Marshall Islands, offer critical insights for early warning and disaster resilience, while people-centered systems have proven essential for mitigating near-field tsunami risks in densely populated coastal cities (Smith and Juria, 2019; Rahayu et al., 2020).

Moreover, Taiwan's biodiversity observation framework aligns with the principle of supervision under constitutional environmental rights. Judicial Yuan Interpretation No. 803 emphasizes that the government must protect environmental

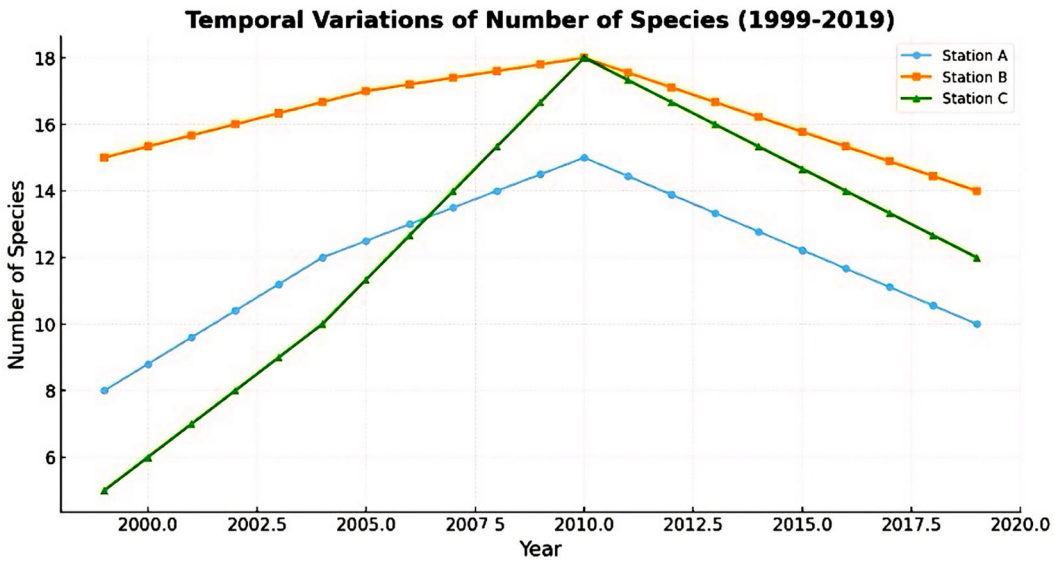

FIGURE 2
Temporal variations in fish species richness and abundance at three tide pool stations on the northern coast of Taiwan. The figure highlights changes over time and supports interpretation of ecosystem variability due to environmental or anthropogenic stressors. (Source: Adopted from Ho et al., 2020).

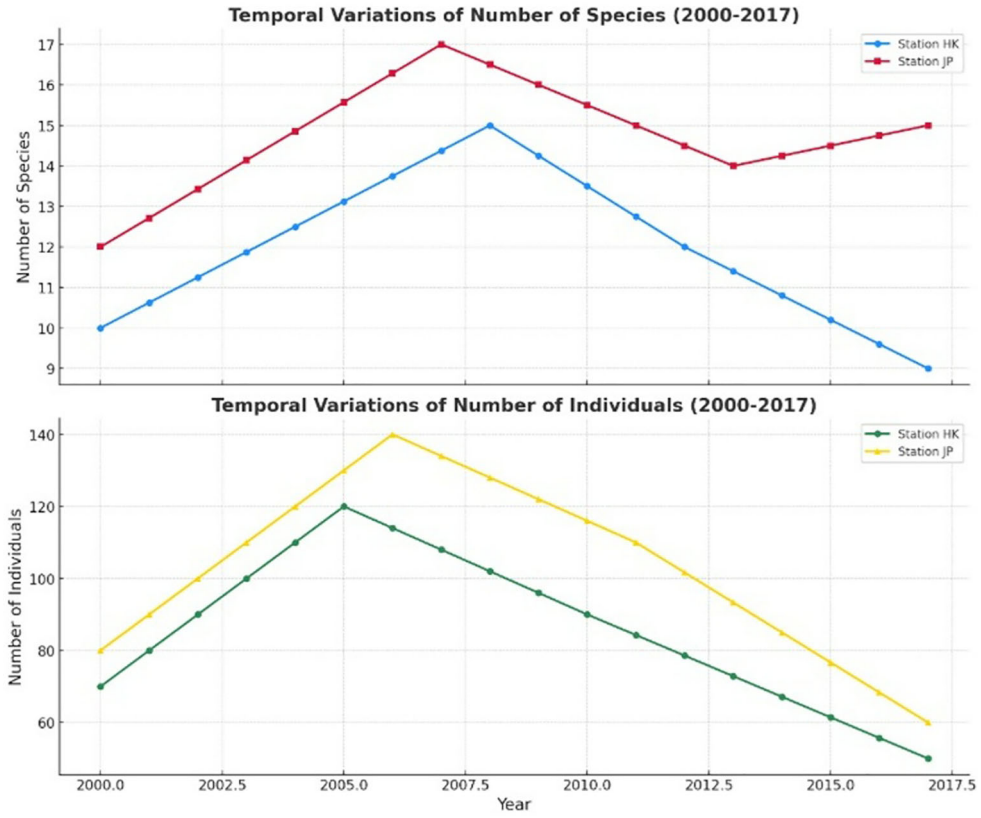

FIGURE 3
Long-term trends in species richness and abundance of fish assemblages from two rocky tide pool stations on the southern coast of Taiwan (2000–2018). These trends provide baseline data essential for evaluating the impact of environmental disturbances and guiding marine protected area planning. (Source: Adopted from Ho et al., 2020).

interests as part of its constitutional obligation. Although Taiwan lacks an extensive body of marine biodiversity-specific case law, administrative enforcement actions under the Marine Conservation Act, Environmental Impact Assessment Act and the Coastal Zone Management Act provide practical examples of legal supervision over marine and coastal biodiversity. These cases illustrate the embeddedness of biodiversity protection in Taiwan's evolving environmental jurisprudence.

4 Discussion

This study analyzed multiple long-term ecological datasets to identify patterns critical for guiding marine conservation strategies in Taiwan. The monitoring of plankton assemblages highlighted seasonal nutrient dynamics, while the assessment of fish communities in intertidal zones revealed biodiversity trends sensitive to human and environmental pressures. The following discussion integrates these findings, emphasizing their relevance to environmental management frameworks, policy planning, and Taiwan's alignment with international biodiversity commitments.

The focus of the study was to analyze the findings of marine biodiversity observation and monitoring mechanisms in Taiwan. The findings provide a wide range of long-term monitoring data that can be used to set effective baseline for detection of human-induced and environmental-induced impacts on the marine environment and modelling of future scenarios based on the ever dynamic global and environmental contexts. Detecting ecosystem-level changes also requires appropriate sampling design and resolution, as poor sampling strategies can obscure important biodiversity shifts, particularly under rapid environmental change (Bruel and White, 2021). The findings from the first set of the collected data highlight the significant role of plankton in marine environments by providing a detailed analysis of the effect of changes in plankton assemblages in western Taiwan coastal water. According to the findings, plankton are the foundation of the marine food web and significant producers of primary production, and essential elements of the global biogeochemical cycles (Lin et al., 2024). The findings show that the natural logarithm of plankton community density and abundance is symmetric which showed that they followed the log-normal distribution and, therefore, are a suitable empirical model for ecological analysis of marine environment (Lin et al., 2024). The findings imply that the third quarter of the year experiences nutrient enrichment most likely from upwelling, riverine inputs, or anthropogenic sources such agricultural runoff, which directly affects the plankton assemblages in western Taiwan coastal waters

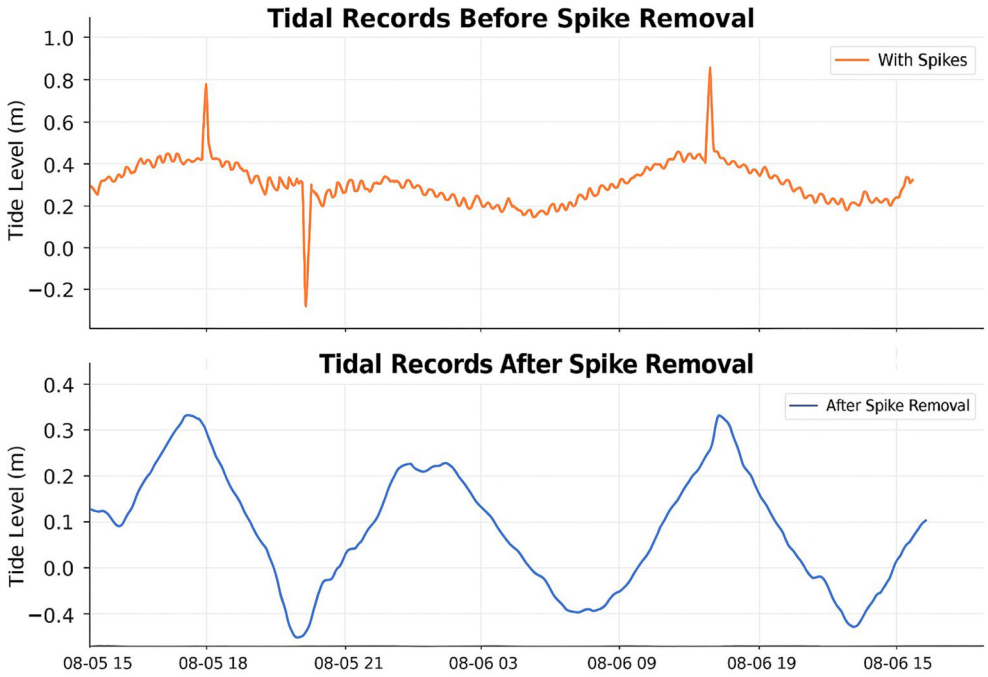

FIGURE 4
Surface elevation data before and after spike removal in the Taiwan Marine Environment Monitoring Service (TwMEMS) tidal monitoring system. Effective data preprocessing is vital for improving tsunami risk detection accuracy and supporting coastal hazard mitigation planning. (Source: Adopted from Doong et al., 2021).

which directly affects the marine environment (Kuo et al., 2022). Based on the findings, a comprehensive understanding of the population of marine plankton, with an emphasis on the possible effects of human activities and advancements provide an opportunity for promotion of ecosystem-based management which can be crucial in the preservation and conservation of marine environments.

The study findings further highlight the significance of understanding the changes of fish assemblages within in the rocky tide pools on the coastal areas of Taiwan. According to the findings, the detrimental effects of human activity have a significant impact on the assemblage of fish species in the rocky intertidal zone which directly affects land-sea interactions and the different marine fish

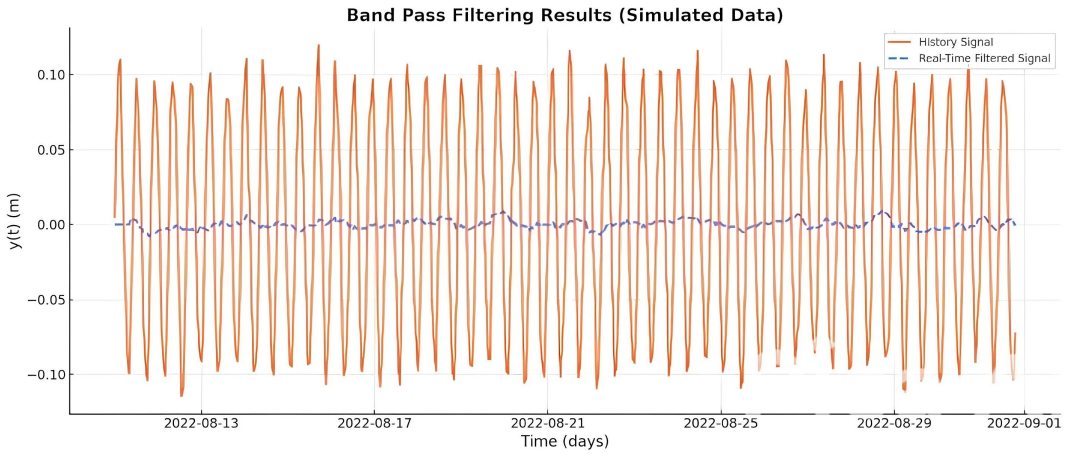

FIGURE 5
Results of band-pass filtering applied to surface elevation data to isolate tsunami signals within TwMEMS datasets. Enhanced signal processing contributes to early warning capabilities and safeguards marine biodiversity by improving coastal disaster preparedness. (Source: Adopted from Doong et al., 2021).

species within the Taiwanese coastlines (Ho et al., 2022). Taiwan has not yet made enough investments in long-term ecological monitoring of fish communities. There is a lack of baseline ecological data since surveys and data are typically brief, dispersed, insufficient, and poorly archived. The findings show that the quantity of species is directly impacted by the tide pool volume. Also, the position of the tide pool within the intertidal zone affects the fish assemblage in terms of the amount of dissolved oxygen, wave exposure, and other local conditions, which directly influence the degree of marine biodiversity along the coastlines. Based on the findings, it can be hypothesized that long-term temporal datasets of species richness and abundance are a necessary requirement in the assessment of the efficacy of conservation efforts and investigation of the underlying causes of changes in fish assemblages (Ho et al., 2022). Recent studies show that combining molecular methods like environmental DNA (eDNA) with traditional visual surveys improves the understanding of fish communities and overall marine biodiversity (Alexander et al., 2022). New approaches, such as using spider webs to collect eDNA, highlight its growing versatility across different species and habitats (Gregorič et al., 2022). When applied carefully, eDNA and iDNA can effectively assess vertebrate diversity and abundance across environments (Carvalho et al., 2022). eDNA is also considered a reliable tool for detecting human impacts in coastal ecosystems, offering early warnings of degradation and aligning well with traditional survey methods (Doi et al., 2021; Liber et al., 2021; DiBattista et al., 2020). Still, accurate interpretation depends on rigorous methods and awareness of potential detection biases (Rourke et al., 2022; Burian et al., 2021). The marine biodiversity observation and monitoring mechanisms area useful tool for the determination of the long-term patterns in the ecology of marine species and the intertidal ecosystem in the Taiwanese coastlines. The data can also be used by ecologists and fishery biologists with intentions of understanding the temporal patterns of species abundance and composition in relation to environmental factors, climate change, and human activities. (Ratnarajah et al., 2023; Pawlowski et al., 2020; Palazov et al., 2019). Furthermore, recent comparative studies have demonstrated that the choice of eDNA sampling method significantly influences biodiversity detection around marine infrastructure, reinforcing the need for methodologically optimized approaches in future monitoring efforts (Alexander et al., 2023).

Taiwan's regulatory approach to marine biodiversity supervision also draws upon sectoral laws such as the Marine Conservation Act, Environmental Impact Assessment Act, which mandates biodiversity considerations for development projects affecting coastal and marine environments, and the Coastal Zone Management Act, which designates and regulates protected coastal zones. Judicial interpretation further strengthens these duties; notably, Judicial Yuan Interpretation No. 803 explicitly recognizes environmental protection as a constitutional obligation, thereby framing biodiversity monitoring as an expression of fundamental rights.

In addition, building marine biodiversity monitoring into Taiwan's constitutional framework of environmental rights not only strengthens domestic protection and governance but also enhances Taiwan's credibility and capacity to participate in international platforms such as the Global Biodiversity Information Facility (GBIF) and the Biodiversity Observation Network (BON). Recognizing the legal underpinnings of observation mechanisms, even in the absence of abundant case law, is crucial for demonstrating Taiwan's commitment to international environmental legal norms and soft law instruments like the Aichi Biodiversity Targets and the post-2020 Global Biodiversity Framework.

The Taiwan Marine Environment Monitoring Service (TwMEMS) is identified as an important tool in marine biodiversity observation and monitoring. The service is designed to integrate maritime environmental data from ship reports, numerical models, and *in-situ* and remote sensing observations to enhance the safety of various marine-related operations in Taiwanese seas (Doong et al., 2021; Huang et al., 2020; Le Traon et al., 2019; Storto et al., 2019). The model consists of separate modules that are incorporated within a single platform to facilitate advanced research using a wide range of techniques including the particle tracking, oil spill simulation, tsunami warning (TW), sea level rise, dangerous swell warning (DSW), extreme waves, and SST drop modules (Hsiao et al., 2020a, b; Voronina et al., 2019; Yu et al., 2019). According to the results, tidal elevation is raised by storm surges, astronomical tides, and other local factors, and abnormal instrumental electric currents or voltage fluctuations cause also cause surges in elevation levels. By taking into account the large diversity of species in the marine environments of countries such as Taiwan, it is important to formulate and adopt a multi-faceted marine biodiversity observation and monitoring mechanism that incorporates diverse strategies ranging from educational to legal frameworks for efficient mitigation of environmental impacts and improve public awareness on conservatory practices. Presently, a lot of marine biodiversity observations have been gathered and are publicly available in different databases that are kept up to date by the Taiwanese government agencies, which scientists and marine engineers can greatly benefit from (Takeuchi et al., 2021). Since the development of high-resolution numerical modeling methods in recent decades, the databases have grown from single point observations to encompass wider spatial coverage. Appropriate database use and a system that is appropriately built to serve the public can effectively enhance the accuracy of marine biodiversity observation and monitoring mechanisms.

5 Conclusion

The study provided a detailed analysis of specific marine biodiversity observation and monitoring mechanisms in Taiwan to provide policy insights for the development of the country's marine biodiversity. Marine biodiversity observation and monitoring mechanisms offer instrumental insights for setting

effective baselines for detection of human-induced and environmental-induced impacts on the marine environment and formulation of future scenarios that account for the dynamic global and environmental contexts.

Additionally, the datasets analyzed offer actionable insights for marine spatial planning, pollution management, and coastal conservation. We recommend the development of a national biodiversity data platform, the implementation of regional monitoring hubs, integration of citizen science, and alignment with global networks such as GBIF, GOOS, and BONs. These strategies will improve indicator development, data transparency, and the accuracy of biodiversity assessments in Taiwan.

Furthermore, the marine biodiversity observation and monitoring mechanisms discussed in this study can serve as a critical foundation for advancing ecosystem-based management (EBM) approaches in Taiwan. By systematically collecting and integrating long-term ecological data, Taiwan is better positioned to move beyond species-specific management towards holistic, ecosystem-level governance. In addition, the establishment of robust monitoring frameworks supports Taiwan's ability to align with international commitments, such as the Aichi Biodiversity Targets under the Convention on Biological Diversity (CBD) and the United Nations Sustainable Development Goals (SDGs), particularly Goal 14 (Life Below Water). Strengthening these observation mechanisms will also facilitate Taiwan's deeper participation in global biodiversity platforms such as the Global Biodiversity Information Facility (GBIF) and the Biodiversity Observation Network (BON), enhancing both national conservation planning and international data sharing efforts. These developments are essential steps toward promoting biodiversity resilience, improving marine policy integration, and contributing to global biodiversity conservation initiatives.

To enhance Taiwan's marine biodiversity monitoring system, several targeted actions are recommended. First, establishing regional biodiversity monitoring hubs would enable more localized, high-resolution data collection, particularly in ecologically sensitive coastal areas. Second, developing standardized biodiversity indicators aligned with international frameworks, such as the Essential Biodiversity Variables (EBVs), would improve data comparability and facilitate reporting to global databases like GBIF and BON. Third, integrating citizen science programs, such as community-based reef monitoring and intertidal biodiversity surveys, could significantly expand data coverage while enhancing public engagement. Fourth, Taiwan should prioritize the creation of a centralized, publicly accessible national marine biodiversity data platform to improve transparency, support academic research, and inform management decisions. Lastly, fostering cross-sectoral collaboration between governmental agencies, research institutions, and NGOs will be essential to ensure a cohesive, ecosystem-based approach to marine conservation planning and policy development.

In conclusion, marine biodiversity observation and monitoring mechanisms are a useful tool for the determination of the long-term patterns in the ecology of marine species and the intertidal ecosystem in the coastlines of Taiwan.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

Y-CS: Writing – review & editing, Writing – original draft.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This study was financed by grants from the Taiwan National Science and Technology Council (NSTC 114-2119-M-004-003, NSTC 113-2119-M-004-001).

Acknowledgments

The author thanks the reviewers from this journal for their valuable comments and all the individuals who assisted in this study.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

References

Ala Amjadi, A., and Mokhtari, M. (2020). Application of wavelets for specifying tsunami from tide: A comprehensive study on the 1945 Makran tide gauge records. *Phys. Earth Planetary Interiors* 299, 106425. doi: 10.1016/j.pepi.2019.106425

Alexander, J. B., Marnane, M. J., Elsdon, T. S., Bunce, M., Songploy, S., Sitaworawet, P., et al. (2022). Complementary molecular and visual sampling of fish on oil and gas platforms provides superior biodiversity characterisation. *Marine Environ. Res.* 179, 105692. doi: 10.1016/j.marenvres.2022.105692

Alexander, J. B., Marnane, M. J., McDonald, J. I., Lukehurst, S. S., Elsdon, T. S., Simpson, T., et al. (2023). Comparing environmental DNA collection methods for sampling community composition on marine infrastructure. *Estuarine Coastal Shelf Sci.* 283, 108283. doi: 10.1016/j.ecss.2023.108283

Batten, S. D., Abu-Alhaija, R., Chiba, S., Edwards, M., Graham, G., Jyothibabu, R., et al. (2019). A global plankton diversity monitoring program. *Front. Marine Sci.* 6. doi: 10.3389/fmars.2019.00321

Bruel, R., and White, E. R. (2021). Sampling requirements and approaches to detect ecosystem shifts. *Ecol. Indic.* 121, 107096. doi: 10.1016/j.ecolind.2020.107096

Burian, A., Mauvisseau, Q., Bulling, M., Domisch, S., Qian, S., and Sweet, M. (2021). Improving the reliability of eDNA data interpretation. *Mol. Ecol. Resour.* 21, 1422–1433. doi: 10.1111/1755-0998.13367

Carvalho, C. S., De Oliveira, M. E., Rodriguez-Castro, K. G., Saranholi, B. H., and Galetti, P. M. (2022). Efficiency of eDNA and iDNA in assessing vertebrate diversity and its abundance. *Mol. Ecol. Resour.* 22, 1262–1273. doi: 10.1111/1755-0998.13543

Chen, S.-T. (2019). Probabilistic forecasting of coastal wave height during typhoon warning period using machine learning methods. *J. Hydroinformatics* 21, 343–358. doi: 10.2166/hydro.2019.115

Chen, V. Y., Lu, D.-J., and Han, Y.-S. (2024). Hybrid intelligence for marine biodiversity: Integrating citizen science with ai for enhanced intertidal conservation efforts at cape santiago, Taiwan. *Sustainability* 16, 454. doi: 10.3390/su16010454

Chen, T.-A. P., and Shih, Y.-C. (2021). Blue Economy based on Local DNA in Taiwan: Marine Regional Revitalization under collaboration between local and central government. *Marine Policy*. 132, 104668. doi: 10.1016/j.marpol.2021.104668

Chen, P.-J., Yeh, T.-C., Hsieh, J.-C., and Lee, B.-H. (2024). Performance and economic analysis of various geothermal power plant systems: Case study for the Chingshui geothermal field in Taiwan. *Energy Rep. Vol.* 12, 4539–4554. doi: 10.1016/j.egyr.2024.10.027

Cheng, S.-N., Shaw, C.-F., and Yeh, Y.-T. (2016). Reconstructing the 1867 keelung earthquake and tsunami based on historical documents. *Terrestrial Atmospheric Oceanic Sci.* 27, 431–449. doi: 10.3319/tao.2016.03.18.01(tem

DiBattista, J. D., Reimer, J. D., Stat, M., Masucci, G. D., Biondi, P., De Brauwer, M., et al. (2020). Environmental DNA can act as a biodiversity barometer of anthropogenic pressures in coastal ecosystems. *Sci. Rep.* 10, 8365. doi: 10.1038/s41598-020-64858-9

Doi, H., Inui, R., Matsuoka, S., Akamatsu, Y., Goto, M., and Kono, T. (2021). Estimation of biodiversity metrics by environmental DNA metabarcoding compared with visual and capture surveys of river fish communities. *Freshwater Biol.* 66, 1257–1266. doi: 10.1111/fwb.13714

Doong, D.-J., Fan, Y.-M., Chen, J. Y., and Kao, C. C. (2021). Analysis of long-period hazardous waves in the Taiwan marine environment monitoring service. *Front. Marine Sci.* 8. doi: 10.3389/fmars.2021.657569

Fujioka, E., and Halpin, P. N. (2014). Spatio-temporal assessments of biodiversity in the high seas. *Endang Species Res.* 24, 181–190. doi: 10.3354/esr00591

Güntsch, A., Overnann, J., Ebert, B., Bonn, A., Bras, Y.L, Engel, T., et al. (2024). National biodiversity data infrastructures: ten essential functions for science, policy, and practice. *BioScience* 75 (2), 139–151. doi: 10.1093/biosci/biae109

Gregorič, M., Kutnjak, D., Bacnik, K., Gostinčar, C., Pecman, A., Ravnikar, M., et al. (2022). Spider webs as eDNA samplers: Biodiversity assessment across the tree of life. *Mol. Ecol. Resour.* 22, 2534–2545. doi: 10.1111/1755-0998.13629

Ho, L.-T., Wang, S.-C., Shao, K.-T., Chen, I.-S., and Chen, H. (2020). A long-term monitoring dataset of fish assemblages in rocky tidepools on the northern coast of Taiwan. *Sci. Data* 7, 84. doi: 10.1038/s41597-020-0425-7

Ho, L.-T., Wang, S.-C., Shao, K.-T., Chen, I.-S., and Chen, H. (2022). Long-term monitoring dataset of fish assemblages in rocky tidepools on the southern coast of Taiwan. *Sci. Data* 9, 639. doi: 10.1038/s41597-022-01778-5

Hsiao, L.-F., Chen, D.-S., Hong, J.-S., Yeh, T.-C., and Fong, C.-T. (2020a). Improvement of the numerical tropical cyclone prediction system at the central weather bureau of Taiwan: Twrf(Typhoon wrf). *Atmosphere* 11, 657. doi: 10.3390/atmos11060657

Hsiao, S.-C., Chen, H., Wu, H.-L., Chen, W.-B., Chang, C.-H., Guo, W.-D., et al. (2020b). Numerical simulation of large wave heights from super typhoon nepartak, (2016) in the eastern waters of Taiwan. *J. Marine Sci. Eng.* 8, 217. doi: 10.3390/jmse8030217

Huang, C.-J., Chang, Y.-C., Tai, S.-C., Lin, C.-Y., Lin, Y.-P., Fan, Y.-M., et al. (2020). Operational monitoring and forecasting of wave run-up on seawalls. *Coastal Eng.* 161, 103750. doi: 10.1016/j.coastaleng.2020.103750

Huang, W. P., Hsu, J. C., Chen, C. S., and Ye, C. J. (2018). The study of the coastal management criteria based on risk assessmeant: a case study on Yunlin Coast, Taiwan. *Water* 10, 988. doi: 10.3390/w10080988

Huang, C.-H., and James, P. (2014). Blue, green or aquamarine? Taiwan and the status quo preference in cross-strait relations. *China Q* 219, 670–692. doi: 10.1017/s0305741014000745

Kuo, Y.-C., Lee, M.-A., and Chang, Y. (2020). Satellite observations of typhoon-induced sea surface temperature variability in the upwelling region off northeastern Taiwan. *Remote Sens.* 12, 3321. doi: 10.3390/rs12203321

Le Traon, P. Y., Reppucci, A., Alvarez Fanjul, E., Aouf, L., Behrens, A., Belmonte, M., et al. (2019). From observation to information and users: The copernicus marine service perspective. *Front. Marine Sci.* 6. doi: 10.3389/fmars.2019.00234

Liber, J. A., Bonito, G., and Benucci, G. M. N. (2021). CONSTAX2: Improved taxonomic classification of environmental DNA markers. *Bioinformatics* 37, 3941–3943. doi: 10.1093/bioinformatics/btab347

Libralato, S. (2024). Numerical Models for Monitoring and Forecasting Ocean Ecosystems: a short description of present status. *State Planet* 2024. Available at: https://doi.org/doi: 10.5194/sp-2024-42 (Accessed December 13, 2024).

Lin, Y.-J., Chen, T.-C., Chen, C.-T. A., Wong, S.-L., Meng, P.-J., and Chen, M.-H. (2024). Long-term monitoring dataset of plankton assemblages in western Taiwan coastal water. *Sci. Data* 11, 917. doi: 10.1038/s41597-024-03784-1

Lin, S. C., Wu, T. R., Yen, E., Chen, H. Y., Hsu, J., Tsai, Y. L., et al. (2015). Development of a tsunami early warning system for the South China Sea. *Ocean Eng.* 100, 1–18. doi: 10.1016/j.oceaneng.2015.02.003

Liu, T.-C., Wu, T.-R., and Hsu, S.-K. (2022). Historical tsunamis of Taiwan in the 18th century: the 1781 Jiateng Harbor flooding and 1782 tsunami event. *Natural Hazards Earth System Sci.* 22, 2517–2530. doi: 10.5194/nhess-22-2517-2022

Ministry of Foreign Affairs (2022). "Learning lessons from the sea: the race to protect our marine biodiversity," in *New southbound policy portal*. Available at: https://nspp.mofa.gov.tw/nsppe/news.php?post=223057&unit=410 (Accessed October 11, 2024).

Palazov, A., Ciliberti, S., Peneva, E., Gregoire, M., Staneva, J., Lemieux-Dudon, B., et al. (2019). Black sea observing system. *Front. Marine Sci.* , 6. doi: 10.3389/fmars.2019.00315

Pawlowski, J., Apothéloz-Perret-Gentil, L., and Altermatt, F. (2020). Environmental DNA: What's behind the term? Clarifying the terminology and recommendations for its future use in biomonitoring. *Mol. Ecol.* 29, 4258–4264. doi: 10.1111/mec.15643

Poloczanska, E. S., Brown, C. J., Sydeman, W. J., Liessling, W., Schoeman, D. S., Moore, P. J., et al. (2013). *Global imprint of climate change on marine life. Nat. Climate Change* 3, 919–925. doi: 10.1038/nclimate1958

Rahayu, H. P., Comfort, L. K., Haigh, R., Amaratunga, D., and Khoirunnisa, D. (2020). A study of people-centered early warning system in the face of near-field tsunami risk for Indonesian coastal cities. *Int. J. Disaster Resilience Built Environ.* 11, 241–262. doi: 10.1108/IJDRBE-10-2019-0068

Ratnarajah, L., Abu-Alhaija, R., Atkinson, A., Batten, S., Bax, N. J., Bernard, K. S., et al. (2023). Monitoring and modelling marine zooplankton in a changing climate. *Nat. Commun.* 14, 564. doi: 10.1038/s41467-023-36241-5

Ribas-Deulofeu, L., Denis, V., Château, P. A., and Chen, C. A. (2021). Impacts of heat stress and storm events on the benthic communities of Kenting National Park (Taiwan). *PeerJ* 9, e11744. doi: 10.7717/peerj.11744

Rourke, M. L., Fowler, A. M., Hughes, J. M., Broadhurst, M. K., DiBattista, J. D., Fielder, S., et al. (2022). Environmental DNA (Edna) as a tool for assessing fish biomass: A review of approaches and future considerations for resource surveys. *Environ. DNA* 4, 9–33. doi: 10.1002/edn3.185

Sawh, S. K., Gilani, I. E., Siddique, A., Khatir, Z., Range, P., Mohamed, N. Y., et al. (2024). Evaluating climate change impacts to Qatar's marine life: A risk assessment for SDG 14 (Life below water). *J. Mari Scie Res. Ocean* 7, 01–10. doi: 10.33140/JMSRO.07.04.02

Shih, Y.-C. (2024). Ocean governance in practice: A study of the application of marine science and technology research techniques to maritime law enforcement in Taiwan. *Marine Policy*. 163, 106081. doi: 10.1016/j.marpol.2024.106081

Shih, Y.-C., Chen, W. C., Chen, T.-A. P., and Chang, C.-w. (2023). The development of ocean governance for marine environment protection: Current legal system in Taiwan. *Front. Marine Science Front. Mar. Sci.* 10. doi: 10.3389/fmars.2023.1106813

Shyu, G-S., Fang, W-T., and Cheng, B-Y. (2020). Recreation and tourism service systems featuring high riverbanks in Taiwan. *Water* 12, 2479. doi: 10.3390/w12092479

Smith, G., and Juria, N. (2019). Diagnosis of historical inundation events in the Marshall Islands to assist early warning systems. *Natural Hazards* 99, 189–216. doi: 10.1007/s11069-019-03735-9

Storto, A., Masina, S., Simoncelli, S., Iovino, D., Cipollone, A., Drevillon, M., et al. (2019). The added value of the multi-system spread information for ocean heat content and steric sea level investigations in the CMEMS GREP ensemble reanalysis product. *Climate Dynamics* 53, 287–312. doi: 10.1007/s00382-018-4585-5

Takeuchi, Y., Muraoka, H., Yamakita, T., Kano, Y., Nagai, S., Bunthang, T., et al. (2021). The Asia-Pacific Biodiversity Observation Network: 10-year achievements and new strategies to 2030. *Ecol. Res.* 36, 232–257. doi: 10.1111/1440-1703.12212

Turschwell, M. P., Brown, C. J., Lacharité, M., Melbourne-Thomas, J., Hayes, K. R., Bustamante, R. H., et al. (2023). Co-designing a multi-criteria approach to ranking hazards to and from Australia's emerging offshore blue economy. *Environ. Sci. Policy. Vol.* 147, 154–168. doi: 10.1016/j.envsci.2023.06.008

Voronina, T. A., Voronin, V. V., and Cheverda, V. A. (2019). The 2015 illapel tsunami source recovery by inversion of dart tsunami waveforms using the r-solution method. *Pure Appl. Geophysics* 176, 2985–2993. doi: 10.1007/s00024-019-02100-y

Ward, D., MelbourneThomas, J., Pecl, G. T., Evans, K., Green, M., McCormack, P. C., et al. (2022). Safeguarding marine life: conservation of biodiversity and ecosystems. *Rev. Fish Biol. Fisheries.* 32, 65–100. doi: 10.1007/s11160-022-09700-3

Yu, Y.-C., Chen, H., Shih, H.-J., Chang, C.-H., Hsiao, S.-C., Chen, W.-B., et al. (2019). Assessing the potential highest storm tide hazard in Taiwan based on 40-year historical typhoon surge hindcasting. *Atmosphere* 10, 346. doi: 10.3390/atmos10060346