



Mitigating Pacific rim marine radioactive contamination: A multilateral nuclear monitoring data governance perspective

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ABSTRACT

Marine radioactive pollution originates mainly from nuclear accidents combined with the dumping of radioactive waste. The dualistic nature of nuclear energy—combining economic potential with inherent risks—has been underscored by Japan's controversial Fukushima wastewater discharge initiative. Currently, nuclides simulation modeling and radioactive monitoring research indicate that Japan's discharge of Fukushima radioactive wastewater has led to a sharp increase in tritium (³H) concentrations in North and West Pacific Transition Zones with ocean currents in short term, resulting in radioactive accumulation in marine organisms. Rather than focusing on the traditional issues of marine pollution liability and transboundary compensation, this article highlights the low transparency of monitoring data in the governance of marine radioactive pollution. This article employs doctrinal research method concludes the marine pollution legal governance system encompassing the international conventions and regional legal instruments. Drawing the results that the legal governance framework for marine pollution faces challenges in terms of Non-State Actors Participation, legal binding enforcement, and radiative pollution monitoring transparency. Consequently, the article emphasizes the perspective of Pacific Rim multilateral cooperation on nuclear monitoring data. Nuclear monitoring data bears a critical nexus with marine radioactive pollution surveillance and governance, serving as the evidentiary foundation for source attribution and impact assessment. On this basis, Proposing legal-technical multilateral radioactive pollution monitoring cooperation mechanism, structured around four critical dimensions: legal supervision framework for nuclear monitoring data transparency, hierarchical risk assessment and conditional sharing regimes, institutionalize non-state actor participation, advanced nuclear pollution monitoring technologies.

1. Introduction

In August 2023, with the approval of the Japanese government, Tokyo Electric Power Company (TEPCO) initiated multiple rounds of radioactive wastewater discharge near the Fukushima Daiichi Nuclear Power Plant. From the initial planning stage to its official implementation, this action has continuously triggered widespread controversy among Pacific Rim countries over marine radioactive pollution. Currently, studies that examine Japan's discharge of radioactive wastewater in relation to marine radiological pollution are primarily focused on three dimensions: the transboundary physical impacts of radionuclide dispersion, the legal accountability under international law, cooperative theories and governance of marine pollution.

From a physical perspective, numerous studies indicate that the concentration of radionuclides in Fukushima's radioactive wastewater

far exceeds the “exemption level” set by the Japanese government and that the discharged water is not subject to further utilization, thereby constituting the disposal of radioactive waste (Men, 2021). Additionally, the Fukushima radioactive wastewater constitutes “abnormal waste” resulting from a nuclear accident, aligning with the definition of “radioactive waste” under Article 2 of the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management (Zhang, 2022).

The discharge of Fukushima's radioactive wastewater into the marine has elicited divergent policy responses from states and regions around the Pacific Rim, influenced by varying scientific assessments, geopolitical considerations, and public pressure. These responses form a complex spectrum of positions, ranging from strong opposition to explicit support. States that have explicitly expressed support include the United States and Canada. The United States has shown relatively

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high confidence in Japan's technical approach to wastewater treatment, such as the Advanced Liquid Processing System (ALPS). The U.S. government has issued a statement endorsing Japan's approach, asserting that it has thoroughly evaluated all available options and impacts while adhering to globally recognized nuclear safety standards (U.S. Department of State 2023–2024). The Canadian Nuclear Safety Commission (CNSC) has characterized the discharge as safe but nevertheless announced enhanced independent monitoring along Canada's west coast (CNSC, 2023). In contrast, strong opposition and trade restrictions have been exemplified by China, where the General Administration of Customs imposed a comprehensive ban on food imports from ten Japanese prefectures including Fukushima, stating the measure was adopted "to prevent potential risks and protect the health of Chinese consumers" (General Administration of Customs of China, 2024). Similarly, strict import bans were implemented by the special administrative regions of Hong Kong and Macau. States such as South Korea demonstrate an intermediate position: while the government officially acknowledges the International Atomic Energy Agency's review, significant domestic public concern has persisted, leading to ongoing protests. In response, the South Korean government launched a reinforced seawater radioactivity monitoring program and instituted 100 % intensive inspection of Japanese seafood imports (Korea Ministry of Oceans and Fisheries, 2024) to restore public trust. Pacific Island nations, whose economies depend heavily on fisheries and tourism, have vehemently criticized Japan's decision, warning of significant long-term risks and economic losses for future generations. Meanwhile, the Pacific Islands Forum (PIF), an international organization representing regions directly affected by oceanic pollution, has repeatedly called for a postponement of the discharge. It emphasizes that "our ocean is our identity and livelihood," and has demanded more thorough independent scientific assessment (Pacific Island Forum, 2023). Urging Japan to suspend the release until independent scientific assessments are fully conducted.

Based on the diverse attitudes of countries in the Pacific Rim region toward Japan's marine discharges, academics also hold different views on the transboundary environmental impacts of Japan's radioactive wastewater discharges. Few research argues that the Fukushima ALPS-treated and diluted radioactive wastewater contains radionuclide concentrations significantly below international safety standards. An integrated analysis of the IAEA's 2023 safety assessment report and oceanic dispersion modeling conducted by the University of Tokyo indicates that tritium (^{3}H) concentrations in open Pacific waters, at distances exceeding 100 km from the discharge point, increase by only approximately 0.1 % relative to background levels (IAEA's, 2023 safety assessment report). These concentrations consistently remain below detection limits and are several orders of magnitude lower than the World Health Organization's safety standard for drinking water (Kaizer et al., 2024b; Beck, 2023). Conversely, the prevailing perspective among scholars holds that up to 30 years of sustained discharge will lead to the dispersion of radionuclides from Japan's coastal waters into the Pacific Ocean via ocean currents, causing irreversible damage to marine ecosystems. Researchers use ROMS and POM models to predict the environmental damage caused by nuclear contamination from Japan's seawater discharge in the Pacific Ocean (Smith and Kim, 2020). The FVCOM simulation model for nuclides has been employed to study dispersion pathways in the Northwest Pacific Ocean, revealing that the convergence zone of the Kuroshio and Kibo tides serves as a critical node for the dispersion of radionuclides. (Liang et al., 2024). To evaluate the transport and fate of radionuclides, three scenarios were developed: Scenario 1 considers advection and diffusion processes only ; Scenario 2 builds upon Scenario 1 by incorporating radioactive decay; Scenario 3 represents the total initial activity concentration immediately after discharge, serving as a baseline to evaluate the theoretical maximum concentration without any environmental mitigating factors (Behrens et al., 2019). It assumes that the concentration of radioactivity in seawater in the vicinity of the discharge point is determined solely by the discharge itself, which is equivalent to depicting the theoretical

maximum concentration at the outfall 'instantaneously' after the discharge (Periáñez et al., 2019). Under Scenario 3, inputting the total activity of each nuclide and the emissions per unit of time for the planned emissions published by the Tokyo Electric Power Company of Japan, which indicates that isotopes such as cesium-137, strontium-90 and ^{3}H are highly concentrated in the waters surrounding Fukushima Coastal during the 1–2 years of discharge (Kaizer et al., 2024a). Over time, radionuclides will enter the North Pacific circulatory system with the Kuroshio Tide within three years, which could eventually affect ecologically sensitive areas such as Alaska, the west coast of Canada, Hawaii (Liu et al., 2024). Joint monitoring reports issued by the Japan Nuclear Regulation Authority (NRA) and Tokyo Electric Power Company (TEPCO) (July 2023–June 2024), researchers reveal a marked increase in ^{3}H concentration near the discharge outlet of Fukushima Daiichi Nuclear Power Station's harbor, rising from approximately 1000 Bq/L to 5000–10,000 Bq/L. (NRA report, JAEA database, TEPCO, 2023–2024). Subsequently, in the 2024 Japanese Ministry of the Environment monitoring report for the Pacific Rim, ^{3}H growing rapidly in the Fukushima Coastal and North Pacific Transition Zones, reaching a substantial increase of more than fourfold. (Zhao and Wang, 2025). Notably, a 2024 report by American biologists on algae samples collected from the U.S. West Coast revealed that 15 % of cesium-137 was detected in *Ulva lactuca*. Over time, the concentration of cesium-137 in these samples declined to 5.6 %, indicating that edible seaweeds possess a significant capacity to absorb cesium-137 (Zhou, 2024). Radionuclide monitoring in marine biota reveals pronounced bioaccumulation in primary producers (particularly macroalgae), with subsequent trophic transfer elevating concentrations in secondary and tertiary consumers, confirming the persistence of these contaminants in marine food webs (Chang et al., 2024).

Comparing traditional state responsibility for internationally wrongful acts under international law with the liability for transboundary harm caused by acts not prohibited by international law. Scholars contend that Japan's discharge falls under the latter category, obligating it to bear responsibility for transboundary harm due to its improper conduct (Chang and Zhao, 2012). Scholars have examined Japan's international legal obligations through both procedural and substantive dimensions. Regarding procedural obligations, Japan has failed to comply with Article 198 of the United Nations Convention on the Law of the Sea and Article 2 of the Convention on Early Notification of a Transboundary Release of Hazardous Wastes. Especially in conducting comprehensive environmental impact assessments (EIAs), engaging in transparent risk communication, and obtaining the prior informed consent of potentially affected states (Chang and Zhao, 2012; Wu and Gong, 2023; Zhao and Wang, 2025). Subsequently, international conventions such as the Paris Convention on Third Party Liability in the Field of Nuclear Energy, the Vienna Convention on Civil Liability for Nuclear Damage, and the Supplementary Convention on Compensation for Nuclear Damage primarily address compensation for damages arising from nuclear accidents and do not specifically cover compensation mechanisms for nuclear pollution-related damage (Li et al., 2023 ; Duan and Tang, 2024). Research focusing on China's domestic nuclear damage compensation mechanism reveals structural deficiencies in the state's legal policies and institutional frameworks for nuclear damage compensation, primarily attributable to the long latency period characteristic of radioactive pollution. These deficiencies are particularly manifested in: (1) the inadequately defined liability limits for nuclear damage compensation, and (2) the ambiguous ecological damage assessment standards.

Based on the previous research, scholars gradually focused on international cooperation in the governance of marine radioactive pollution. Summarizing the theoretical basis of the risk precautionary principle, the international cooperation principle. The precautionary principle as a cornerstone of international environmental law, underpins a wide range of procedural and substantive legal obligations. Procedural mechanisms derived from this principle include environmental impact

assessments, notification requirements, information collection and exchange systems, and prior informed consent protocols. It comprises four fundamental elements: anticipation of harm, uncertainty, preventive measures, and burden of proof mechanisms (Sieckmann, 2018). Even in the early stages of radioactive pollution, where conclusive empirical evidence is lacking to demonstrate that radionuclides have already caused harm to marine life and human health, scientific projections based on realistic conditions indicate that, to prevent potentially irreversible adverse consequences, it remains necessary to adopt preventive and cooperative measures (Hunt et al., 2023; Sands et al., 2018). The principle of international cooperation, in the field of marine pollution governance, is reflected in the joint efforts of sovereign states, international organizations, and other actors to address global marine issues through international regulation and coordinated collaboration, aiming to achieve the sustainable development of the oceans. The United Nations Convention on the Law of the Sea, as the core of the marine governance framework, establishes the obligation of states to cooperate in controlling marine pollution. Some scholars advocate for a normative rethinking of marine pollution governance. Proposals such as the "Maritime Community with a Shared Future" envision a cooperative approach that transcends sovereign interests and prioritizes ecological security for all Pacific Rim states (Zhang and Xu, 2024). From the radioactive pollution monitoring cooperation aspect, nuclear monitoring data refer to a comprehensive set of information obtained through the surveillance of the entire process of nuclear activities, including the monitoring of nuclear materials, nuclear facilities, nuclear reactions, radiation levels, and the release and dispersion of radioactive substances. These data form the foundation for radioactive regulation across various environmental systems, including the marine environment. Scholars contend that nuclear monitoring data is significantly constrained by factors such as the diverse nuclear safety legal systems of different countries, variations in technical standards for nuclear data, the influence of policy measures, safety cooperation agreements, and privacy protection frameworks (Flick, 2021). Proposing establish regional marine radionuclide monitoring networks and legally binding pollutant thresholds (Zhang and Xu, 2024). From the technical cooperation aspect, researchers contend that artificial intelligence technology and systematic regulatory modeling can be applied to the prediction of marine environmental pollution. Enhancing predictive capabilities for marine pollution involving radioactive materials through real-time simulation of ecological impacts (Liu et al., 2025).

Existing literature underscores that while Japan's discharge plan may comply with certain technical standards, it exposes significant deficiencies in the international transboundary legal accountability, marine pollution governance, and public engagement mechanism. Currently, several important research gaps remain. Primarily, it is widely emphasized cross-border liability claims, while largely overlooking procedural challenges in establishing a causal link between harmful conduct and its substantive consequences. Secondly, although some studies emphasize the necessity of multilateral cooperation in the international governance of marine radiological pollution, such discussions largely remain at a theoretical level and pay insufficient attention to the dynamics of regional cooperation. While most research identifies key challenges in international collaboration—such as the complexity of national interests, low levels of information transparency, and limited public awareness—it often falls short of providing systematic analyses or practical pathways for implementation. Finally, there is a noticeable gap in the literature regarding the integration of nuclear monitoring data regulation into the mitigation of marine radioactive contamination.

2. Doctrinal research method

Doctrinal analysis is conducted through three interrelated dimensions: (1) textual interpretation, which clarifies the scope and content of treaty provisions; (2) systemic analysis, which identifies coherence or fragmentation across different regimes such as the law of

the sea, pollution control, and nuclear safety; and (3) teleological reasoning, which evaluates how the objectives of each legal instrument align with the overarching principles of precautionary, international cooperation and transparency.

2.1. International conventions and guidelines

Currently, a legal system that incorporates both binding (hard law) and non-binding (soft law) instruments to control marine radioactive pollution (see Table 1).

In the context of marine environmental protection, the most representative international convention is the United Nations Convention on the Law of the Sea (UNCLOS), adopted during the Third United Nations Conference on the Law of the Sea in 1982. The United Nations Convention on the Law of the Sea (UNCLOS) establishes the foundational legal framework for marine environmental protection and embodies core doctrines of international environmental law, including the duty to prevent, reduce, and control pollution articulated in Article 194. This obligation is further refined through the lens of the precautionary principle, which not explicitly named in UNCLOS, is widely regarded as having crystallized into a norm of customary international law and is invoked in the implementation of Articles 194(1) and (2). Urging states to take the necessary measures to avoid or reduce the potential for pollution of the marine environment through, *inter alia*, the use of judgement based on internationally agreed scientific standards. Articles 200–206 impose specific duties concerning monitoring, environmental assessment, and information exchange (United Nations, 1982, art. 194; art. 200–206), which have been interpreted in international jurisprudence (In the Responsibilities and Obligations of States Sponsoring Persons and Entities with Respect to Activities in the Area Advisory Opinion) as reflecting due diligence obligations requiring states to adopt best available techniques and internationally agreed rules and standards.

In the domain of pollution prevention and control, The Convention on the Prevention of Marine Pollution by Dumping (London Convention, 1972) and its 1996 Protocol illustrate the evolution of normative standards through interpretive practice. The London Convention specifically aims to regulate and mitigate marine pollution resulting from waste disposal activities by establishing comprehensive controls over the dumping of wastes and other substances into the marine environment. A distinctive feature of the Convention is its adoption of a "list-based" regulatory approach, whereby wastes are categorized and their permissible disposal methods in the marine environment are determined according to the severity of their potential harm to marine ecosystems. In principle, the dumping of radioactive waste into the sea would be banned, except for waste containing radioactive material that meets the

Table 1
International legal system for the governance of marine radioactive pollution.

International Legal System	Domain	International Conventions and Guidelines
International Conventions	Marine environmental protection	United Nations Convention on the Law of the Sea
International Conventions	Pollution prevention and Control	Convention on the Prevention of Marine Pollution by Dumping 1996 Protocol to the Convention on the Prevention of Marine Pollution by the Dumping of Wastes and other Matter
International Conventions	Nuclear radioactive waste management	<i>Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, 1997</i> Convention on Early Notification of a Nuclear Accident
International Guidelines	Basic principles and technical guidelines	Security Series No. 111-F Safety Standards for Radioactive Waste Management

IAEA minimum (exempt) concentration criteria. Nevertheless, the London Convention establishes a general obligation to prevent marine pollution by dumping, its permissive approach regarding certain types of waste has been progressively superseded by the precautionary and preventive orientation of the 1996 Protocol. The Protocol's "reverse list" approach effectively prohibits all dumping except for a limited number of permissible substances, thereby instantiating a doctrinal shift toward a more restrictive interpretation of what constitutes permissible ocean disposal.

Under the atomic energy law, the *Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management* (1997) articulates a comprehensive doctrinal framework for radioactive waste management. Its provisions—particularly the principles of inter-generational equity, safety culture, and continuous regulatory control—represent the crystallization of emerging norms into treaty form. The reporting and peer-review regimes under Chapter IV operationalize these doctrines through transparency and accountability, reinforcing the convention's normative force (*Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management*, 1997). The *Convention on Early Notification of a Nuclear Accident* (1986) reflects the principle of precautionary and transparency. Adopted in the aftermath of the Chernobyl disaster, the Convention was designed to ensure that states provide timely, accurate, and comprehensive information on nuclear accidents that may have transboundary radiological consequences. Article 2 stemming from the precautionary principle include notification requirements, information exchange, and prior informed consent (*Early Notification Convention*, 1986). By mandating the real-time exchange of technical and environmental data, the article 4 and 5 of the Convention institutionalizes transparency as a legal obligation rather than a matter of diplomatic discretion. Which reflects a doctrinal shift in international law from traditional state sovereignty toward cooperative risk governance (Liu and Mark, 2023).

Supplementing these conventions, the IAEA Safety Standards constitute an authoritative body of soft law that informs the interpretation and application of hard law obligations. Principles like inter-generational equity as outlined in Safety Series No. 111-F. Although non-binding, these instruments exert persuasive authority in shaping customary law and guiding national regulatory frameworks.

2.2. Regional legal instruments

Although the Pacific Rim region has not yet established a dedicated regional agreement specifically addressing marine pollution, existing regional legal instruments play a significant role in shaping state practice and fostering normative convergence (See Table 2). The *South Pacific Nuclear Free Zone Treaty* (Treaty of Rarotonga) establishes a

normative structure grounded in the principles of environmental protection and regional security. Comprising a preamble, 16 articles, 4 annexes, and 3 additional protocols, has been ratified by 13 Pacific nations. While Article 2 defines the geographical scope of the zone, Articles 6 through 10 articulate substantive obligations concerning verification and consultation. Crucially, the treaty reflects the principle of regional precautionary governance, requiring states to proactively prevent the introduction of radioactive waste into the marine environment. Which not only textualizes these prohibitions but also institutionalizes them through reporting and consultation mechanism, thereby operationalizing the customary international law principle that states shall not cause transboundary environmental harm.

Beyond binding treaties, regional soft-law instruments contribute to the formation of normative expectations and state practice. The Action Plan for the Protection, Management and Development of the Marine and Coastal Environment of the Northwest Pacific Region (NOWPAP) and the Action Plan for the Protection and Sustainable Development of the Marine and Coastal Areas of the East Asian Seas (COBSEA) extend beyond technical cooperation to institutionalize transparency and information-sharing obligations. Facilitating harmonized national policies and foster technical cooperation in monitoring and emergency response, which doctrinally underpin the principle of procedural participation, ensuring that scientific data and monitoring results are available for regional scrutiny. Regional legal instruments move regional governance beyond "soft" coordination toward a regime were data disclosure and mutual verification form binding components of cooperative environmental protection.

3. Results

Through the above analysis, it becomes evident that both at the international and regional levels, there exist systematic legal frameworks for the governance of marine pollution. However, in terms of actors, international legal framework remains primarily state-centric, with contracting parties as the core subjects, and lack explicit provisions for the participation of non-governmental actors. In terms of national obligation, while conventions in both the law of the sea and international nuclear law emphasize the procedural and substantive obligations of contracting states, such obligations are often formulated in general terms and lack binding force, with the mechanisms for holding states accountable for breaches of treaty obligations remaining vague. Regarding marine environmental monitoring cooperation, regional legal instruments emphasize the establishment of monitoring databases but fail to develop institutional structures or legal mechanism. Consequently, the governance of trans-Pacific radioactive pollution continues to face significant systemic challenges.

3.1. Weak legal enforcement

Drawing on previous research, we find that approximately 90 % of Pacific Rim states—excluding the United States and North Korea—have ratified the United Nations Convention on the Law of the Sea (UNCLOS). Nevertheless, the Convention fails to provide clear definitions regarding the substantive scope and jurisdictional boundaries of the "necessary measures" required of State Parties. It similarly lacks precise legal standards for determining liability apportionment and establishing causation in cases of marine radioactive pollution damage (Wang et al., 2025 ; Xu, 2025). While Part XII mandates obligations for timely information sharing and data exchange among signatories, the treaty framework omits punitive measures for non-compliance. Furthermore, the dispute resolution mechanisms under Part XV remain confined to traditional judicial and arbitral processes. Although UNCLOS institutions are frequently invoked, geopolitical considerations often impede the enforcement of rulings.

Unlike the Joint Convention, which has seen uneven ratification across the Pacific Rim, the Early Notification Convention has been

Table 2
Regional legal instruments for the governance of marine radioactive pollution.

Regional Provisions	Signatory States	Specific Content
South Pacific nuclear-free-zone treaty	Australia, New Zealand, Cook Islands, Fiji and other 13 Pacific countries	Ban on nuclear testing, dumping of radioactive waste in the South Pacific region Emphasize states to cooperate in nuclear safety and marine environmental protection
NOWPAP: Northwest Pacific Action Plan	China, Japan, South Korea, and Russia	Establish an effective database for the monitoring of the marine environment
Action Plan for the Protection and Sustainable Development of the Marine and Coastal Areas of the East Asian Seas	Cambodia, China, Indonesia, South Korea, Malaysia, Philippines, Thailand	Primary emphasis on cooperation among States in the sharing of monitoring data

widely adopted in the region, with only North Korea and certain Pacific Island states remaining non-parties. The recent phased discharge of radioactive wastewater by Japan underscores the legal implications of these treaties. As a party to both conventions, Japan bears the ultimate responsibility for ensuring the safe management of spent fuel and radioactive waste, as well as a continuing obligation to provide timely notifications regarding its handling of contaminated water (Liang, 2021). However, the Japanese government failed to disclose critical environmental monitoring data prior to the discharges and did not engage in meaningful consultations with other Pacific Rim states (Yue and Yang, 2023). The prevailing framework for addressing marine radioactive pollution in the Pacific Rim region remains predominantly structured through cooperative programs rather than binding legal instruments. This institutional design inherently lacks punitive enforcement mechanisms, rendering the effectiveness of such arrangement's contingent upon state voluntarism and susceptible to geopolitical considerations. The absence of compulsory compliance measures creates a governance paradigm where implementation efficacy correlates directly with transient political goodwill and the fluctuating intensity of diplomatic pressure, rather than operating through predictable, rules-based mechanisms characteristic of robust international environmental regimes (Wang et al., 2022).

3.2. Inadequate engagement of non-state actors

Despite the transboundary nature of radionuclide dispersion, most institutional arrangements continue to privilege state-centric mechanism, offering limited channels for NGOs, scientific communities, and coastal populations to influence decision-making. On the one hand, it is reflected that the absence of institutionalized participation mechanisms. Core international instruments such as the United Nations Convention on the Law of the Sea (UNCLOS) and the London Convention continue to center on states as the primary actors, while non-governmental organizations (NGOs), public interest groups, and academic institutions are allowed to participate only as observers, advisors, or in other informal capacities, without decision-making or voting rights. Although some states have established public participation mechanisms—such as *environmental impact assessment (EIA) public disclosures*—these processes often lack substantive influence on policy outcomes. On the one hand, it is reflected that the lack of nuclear pollution information-sharing platform. The information deficiency has led to widespread misconceptions and cognitive biases. Nuclear discharge activities and environmental monitoring data are predominantly state controlled in most jurisdictions, creating systemic barriers for non-governmental organizations to access real-time, transparent, and verifiable information. Additionally , Public perception and social trust have emerged as critical dimensions of the cooperation challenges. Survey-based research demonstrates that public opinion in Japan and neighboring countries is not solely driven by scientific risk assessments but is heavily influenced by emotional, historical, and communicative factors (Liu et al., 2025). The inadequate reporting by several Japanese media outlets, which have neither accurately covered the government's actions regarding radioactive wastewater discharge nor provided transparent data on radioactive nuclide content and its environmental implications.

3.3. Lacking long-term independent third-party radioactive pollution monitoring body

Lacking a long-term international monitoring mechanism for radioactive wastewater, the Pacific Rim states unable to independently verify Japan's discharged effluent, relying instead on Japan's own disclosures and IAEA reports—an arrangement that has proven insufficient. The Japanese government also claimed that wastewater treated through ALPS met discharge standards and was considered safe, even for direct consumption. As the mentioned above, the assessment of radionuclide concentration fluctuations in the vicinity of Fukushima Daiichi Nuclear

Power Station's harbor remains exclusively dependent on data disclosed by the Japanese government and Tokyo Electric Power Company (TEPCO). This monopoly over critical environmental information has generated international skepticism, while other nations lack viable mechanisms to independently verify the reported measurements. (Gong, 2024). Nevertheless, the IAEA's capacity to fulfill its mandate—particularly in regulating atomic safety, conducting independent assessments, and enforcing verification protocols—has been constrained by the geopolitical interests of major powers. Furthermore, the International Atomic Energy Agency (IAEA), although involved in verification, does not function as a fully autonomous environmental watchdog with binding enforcement power. Consequently , the lack of a third-party monitoring architecture significantly weakens regional trust , hampering the development of a unified response framework among Pacific Rim nations.

3.4. Transparency deficit in radioactive pollution monitoring data

Current radioactive pollution monitoring efforts are predominantly state driven, with data collection, risk assessments, and public disclosures controlled by national authorities or entities affiliated with polluting states. Notably the United States and Canada, regard nuclear waste radioactive pollution monitoring data as a critical subset of national nuclear data and invoke the national security exception clause under Article 21 of the General Agreement on Tariffs and Trade (GATT), which permits the protection of essential security interests in areas involving nuclear materials, weapons, and other sensitive domains. As a result, these countries impose strict limitations on the cross-border transfer and disclosure of such data.

4. Discussions

This article improves the governance of radioactive pollution in the Pacific Rim from the perspective of regional nuclear monitoring data cooperation, establishing a legal- technical multilateral systematic radioactive pollution monitoring cooperation mechanism.

4.1. Establishing nuclear monitoring data transparency supervision legal framework

Adopting the Regional Nuclear Data Governance Cooperation Agreement to institutionalize a comprehensive “monitoring-disclosure-remediation” legal framework. Firstly, this agreement delineates its substantive scope to encompass four critical data categories: nuclear pollution monitoring data, radioactive regulatory data, radiation source monitoring data, and environmental impact assessment data. Secondly, establishing rights and obligations for signatory states, particularly regarding risk assessment protocols, transparent data-sharing procedures, and compulsory disclosure. Thirdly, it incorporates enforceable liability provisions, specifying remedial measures and compensation obligations for non-compliance. Ensuring consistent implementation, oversight authority should be delegated to a regional monitoring supervision body—the Trans-Pacific Nuclear Data Regulatory Commission—empowered to verify compliance, mediate disputes, and facilitate technical coordination among member states.

However , the Pacific Rim is a highly complex geopolitical region, characterized by territorial disputes, strategic competition, and shifting alliances, all of which hinder the development of the legal framework. On the one hand, longstanding hotspot issues persist in the region , involving disputes over territorial sovereignty and maritime rights between China and several Southeast Asian countries. On the other hand, great power rivalries also interfere with regional nuclear monitoring data transparency. Since each nation places a strong emphasis on the independence and autonomy of its nuclear data and facilities, viewing sensitive information, such as nuclear monitoring data, as a critical component of national sovereignty. The cross-border transmission and

sharing of nuclear monitoring data are often perceived as concessions of sovereignty. The United States has reinforced its military and economic control over the Pacific Rim through the Indo-Pacific mechanism, while China has expanded its regional influence through initiatives such as the Belt and Road Initiative and the Regional Comprehensive Economic Partnership (RCEP). The Pacific Rim region could initiate a multilateral confidence-building agenda by leveraging existing platforms such as the environmental forum of the Asia-Pacific Economic Cooperation (APEC), the Blue Pacific initiative under the Pacific Islands Forum (PIF), and the Tripartite Environment Ministers Meeting (TEMM) among China, Japan, and South Korea, to facilitate high-level governmental dialogue and forge regional consensus on cooperation.

4.2. Developing hierarchical risk assessment and conditional sharing regimes

The prevailing opacity surrounding marine nuclear monitoring data largely stems from states' legitimate concerns regarding national security sensitivities, as evidenced in prior research. Pacific Rim states institutionalize risk-tiered assessment of nuclear monitoring data as a mandatory preliminary procedure. The Pacific Rim Nuclear Data Regulatory Committee (PRNDRC) serves as the central coordinating body, with a Plenary Conference of signatory nations functioning as the supreme policy-making forum. The PRNDRC establishes a dedicated risk assessment body to oversee the disclosure of nuclear waste monitoring data, radioactive activity logs, and radiation source inventories, with mandated authority to develop uniform risk assessment standards, implement unified confidentiality technology and data cross-border transmission procedures, implement protective measures against cyber intrusions. Based on the risk identification, nuclear monitoring data would be classified into a three-tiered risk categories according to its strategic significance: Top-Secret classification for information potentially compromising national security, public safety, or critical infrastructure; Internal classification for data affecting nuclear facility operations or corporate interests; and public classification for information bearing global health and ecological implications (radiation protection metrics, waste disposal records).

Building upon the risk classification framework, a conditional monitoring data-sharing regime could be established to enhance real-time regional cooperation in tracking marine radioactive concentrations. Given the variations in data privacy policies among Pacific Rim states, it is recommended that states engage in high-level intergovernmental consultations to negotiate and sign conditional data-sharing protocol, which would clearly define rules for sharing nuclear monitoring data according to different risk classification. Top-Secret classification data would require stringent protections, including advanced encryption and localized storage protocols (Georgieva et al., 2021). Internal classification data could be selectively disclosed to authorized entities through controlled access channels, while public classification data-monitoring data related to environmental radioactive contamination-would be subject to mandatory periodic disclosure through IAEA-administered platforms.

Upon official receipt of a Nuclear Emergency Declaration from a member state (via designated contact points) or through the IAEA's emergency notification system, the Secretariat under the Pacific Rim Nuclear Data Regulatory Committee immediately verifies the event against pre-defined criteria. The conditional data-sharing protocol granting the Secretariat temporary elevated authority to coordinate and compel data sharing under emergency crisis. The Secretariat switches the data-sharing system to Emergency Mode, overriding standard access restrictions for relevant datasets as defined in the Protocol's Annex on Emergency Procedures. Additionally, The Secretariat convenes an emergency data coordination panel with representatives from all member states to: monitor data accuracy and relevance; approve exceptions or additional data requests; ensure adherence to the Protocol's privacy and security safeguards.

4.3. Institutionalize non-state actor participation

Non-State Actors (NSAs), while lacking sovereign state status, exert substantive influence in both international and domestic affairs. Environmental non-governmental organizations (NGOs), research institutions, fishery associations, local communities, and the public constitute critical NSA components. Legal analysis under the *International Covenant on Civil and Political Rights* and *The Maastricht Principles on Extraterritorial Obligations of States in Economic, Social and Cultural Rights* demonstrates that Japan's Fukushima wastewater discharge violates fundamental human rights – including environmental rights, subsistence rights, and development rights - for both its domestic population and extraterritorial affected groups (Chang and Zhao, 2024). However, prevailing international environmental laws and domestic nuclear regulatory regimes predominantly recognize only states and expert bodies as legitimate participants, relegating grassroots communities to "stakeholders" rather than "rights holders." Primarily, the authorization mechanism under the United Nations framework should be improved by establishing Non-State Actors Alliance for marine radioactive pollution Response under the United Nations Environment Programme (UNEP), mandating three substantive entitlements for qualified NSAs: (1) real-time data access rights, (2) participatory investigation rights, and (3) formal policy recommendation rights. Subsequently, supervisory procedures for non-governmental organizations could be incorporated into the United Nations Convention on the Law of the Sea (UNCLOS) and the London Convention. The Pacific Islands Forum (PIF), Pacific Nuclear Safety Network (PNSN), The Pacific Islands Association of Non-Governmental Organizations (PIANGO) are typical NGOs in the Pacific Rim, focusing on nuclear safety, environmental protection, and transnational cooperation. A review committee could be established jointly by the International Atomic Energy Agency (IAEA) and non-governmental organizations to conduct third-party verification and oversight of decisions and procedures related to the discharge or disposal of radioactive pollutants.

Furthermore, drawing on the Aarhus Convention, a representative mechanism for affected communities could be introduced. During the pre-release phase of radioactive pollution activities, this would involve organizing *community-level briefing sessions* and *local risk awareness hearings*, with the feedback systematically incorporated into formal Environmental Impact Assessment (EIA) reports. For the post-release governance phase, an *environmental rights grievance mechanism* should be established, enabling affected individuals or communities to file claims before national or regional arbitration platforms regarding violations of their subsistence and environmental rights.

4.4. Reinforcing marine radioactive monitoring technological

The integration of blockchain and artificial intelligence (AI) technologies with regional monitoring database on the Northwest Pacific Action Plan (NOWPAP) could establish a synergistic framework comprising an immutable monitoring data chain and intelligent modeling systems to address critical challenges in marine radioactive pollution monitoring, including data trustworthiness, real-time analysis, and transboundary coordination. At the data-chain level, the NOWPAP Secretariat would manage node access rights with strict oversight, ensuring that only authorized contributors may upload monitoring data. Utilizing blockchain platforms such as Ethereum or Hyperledger, the traceability of submitted marine radioactive pollution data can be enhanced by generating hashed records containing timestamps, geographic coordinates, radionuclide concentrations, sampling institutions, and responsible actors. Any attempt to tamper with the data would alter the hash values, and verification would require joint confirmation by at least two designated nodes.

In terms of spatiotemporal modeling of radioactive dispersion, AI-powered regulatory modeling systems could be deployed in the back-end of NOWPAP's Data and Information Network Regional Activity

Centre (DINRAC). These systems, based on long short-term memory (LSTM) neural networks and satellite-based ocean current visual data, would enable real-time simulation and forecasting of radionuclide migration pathways and dynamic trends in monitoring data (Chang and Zhao, 2024). Additionally, integrating data mutual recognition technology with blockchain systems would establish comprehensive life-cycle monitoring of radioactive materials, creating traceability mechanisms, unified classification standards, and regional data-sharing formats.

Building upon the security of the monitoring data chain infrastructure, a complementary data visualization and collaboration platform should be developed. By integrating smart contracts with a secure auditing system, the platform can automatically trigger a red alert and notify neighboring countries when the monitored concentration of radionuclides exceeds a predefined regional threshold. Simultaneously, it would activate a verification mechanism involving NGOs or research institutions for independent re-sampling and data confirmation. While incorporating both intrusion detection (IDS) and prevention systems (IPS) to mitigate potential data misuse through real-time threat neutralization and system remediation capabilities. Furthermore, the platform incorporates a public participation incentive mechanism, enabling public to submit monitored data regarding radionuclides and contaminated marine areas. Upon AI-based verification, validated data would be recorded on the blockchain. Correspondingly, contributors would receive marine governance tokens redeemable for subsidies or governance voting rights. Finally, the platform integrates a transparent information disclosure module, providing verified radionuclide monitoring data to the public, researchers, and NGOs through standardized access protocols. It involves regular dissemination of collaborative project updates, research findings, and evaluative analyses through multiple media formats—including textual reports, downloadable datasets, and graphical representations employing diverse data visualization techniques. Additionally, the platform features a dedicated secure portal for an “Emergency Data Operating Picture,” which employs ensemble hydrodynamic-Lagrangian models (such as FVCOM/HYCOM coupled with particle tracking) integrated with real-time data assimilation (Zhao et al., 2022). This system generates forecasts of plume extent, time-of-arrival, isopleth maps, and uncertainty cones. Acting as a fusion center, the PRNDRC would synthesize heterogeneous data streams—from fixed monitoring stations, mobile platforms, satellite remote sensing, and member states’ reports—into a unified and accessible Common Operational Picture (Liu and Mark, 2023). This geospatial dashboard visualizes real-time radiation levels, model predictions, and the locations of sensitive marine ecosystems, providing indispensable support to emergency commanders in decision-making.

5. Conclusion

Marine radioactive pollution represents a significant transboundary challenge within the realm of global ocean governance. This article combines the Japanese act of discharging Fukushima radioactive wastewater, examining the critical issue of nuclear monitoring data governance through the prism of trans-Pacific regulatory cooperation. Nuclear monitoring data, defined as systematically collected, observed, and analyzed information sets, serves as the fundamental basis for assessing the radiological impact of nuclear activities—particularly radioactive waste disposal—on marine ecosystems. Employing doctrinal research method, results analysis reveals marine radiative pollution governance challenges in the Pacific Rim region: inadequate enforcement of existing legal frameworks, inadequate engagement of non-state actors, absence of long-term independent third-party monitoring body, insufficient transparency in monitoring data disclosure. These structural deficiencies necessitate the development of an innovative legal-technical collaborative mechanism. Focusing on legal framework, centered on trans-pacific nuclear data regulatory commission, establishing the “monitor-disclose-remediate” transparency supervision

framework, which would be complemented by nuclear data risk assessment and conditional data-sharing regime. Additionally, institutionalizing the participation of non-state actors such as NGOs, grassroots communities. From the technical cooperation aspect, the integration of blockchain and artificial intelligence technology for monitoring system would significantly enhance regional marine pollution monitoring effectiveness.

Declaration of generative AI and AI-assisted technologies in the writing process*

During the preparation of this work the author(s) used DeepSeek/Chatgpt for Proofreading. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Author statement

We declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

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CRediT authorship contribution statement

Shumei Yue: Conceptualization, Funding acquisition, Resources, Supervision, Validation, Writing – review & editing. **Wenna Fan:** Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Writing – review & editing.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

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