



Strengthening Pacific Rim marine radioactive pollution governance: from nuclear data legal regulatory cooperative aspect

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Abstract

Nuclear data bears a critical nexus with marine radioactive pollution surveillance, serving as the evidentiary foundation for source attribution and impact assessment. This article adopts an empirical research approach, integrating nuclide simulation modeling with radioactive monitoring data, to demonstrate that Japan's discharge of Fukushima radioactive wastewater has resulted in the dispersion of radionuclides from inland waters into the North and West Pacific Transition Zones via ocean currents, thereby posing potentially irreversible, multigenerational threats to marine ecosystems. The current deficiencies in the international legal governance framework for marine pollution—combined with weak legal enforcement, a low level of cooperative consensus, and a transparency deficit in radioactive pollution monitoring—further exacerbate these risks. Accordingly, employing a doctrinal research method, this article examines the legal foundations for a Pacific Rim regional nuclear data regulatory framework and proposes a regional legal cooperation mechanism composed of legal principles, legal rules, organizational structures, and operational procedures. By constructing such a mechanism, the transparency of radioactive waste disposal monitoring data can be enhanced, the legal accountability challenges arising from Japan's wastewater discharge mitigated, and regional consensus strengthened on nuclear data classification, monitoring, and disclosure—ultimately improving the safety of nuclear energy development and utilization within the Pacific Rim.

Keywords Nuclear contaminated water · Nuclear data · Pacific Rim region · Legal cooperative mechanism

Introduction

The management of radioactive wastewater has emerged as one of the most complex and controversial challenges in the field of nuclear governance and environmental protection. This issue gained unprecedented global attention following the Fukushima Daiichi nuclear disaster in Japan. On March 11, 2011, a magnitude 9.0 earthquake struck off the northeastern coast of Japan, triggering a massive tsunami that inundated large areas of the Tōhoku region. The combined impact of these natural disasters severely damaged the Fukushima Daiichi Nuclear Power Plant, causing the failure of its core cooling systems. In particular, the tsunami flooded the plant's diesel generator buildings, resulting in a complete loss of power

and disabling the reactor cooling functions. The subsequent buildup of hydrogen gas led to multiple explosions, marking one of the most serious nuclear accidents since Chernobyl. In response to the imminent threat of a reactor core meltdown, emergency measures were taken to stabilize the situation. Approximately 400 tons of cooling water per day, including unconventional sources such as seawater, were injected into the reactor cores to prevent further overheating (Steinhauser et al. 2014). Over the years, this continuous injection generated vast quantities of contaminated water, which was subsequently processed through the Advanced Liquid Processing System (ALPS) to remove most radionuclides. However, certain radioactive isotopes—most notably tritium—remained in the treated wastewater. As of 2021, over 1.25 million tons of such treated radioactive wastewater had accumulated in storage tanks at the Fukushima site, placing increasing pressure on the facility's limited storage capacity. To address this issue, the Japanese government convened a cabinet meeting in April 2021 and officially approved a plan to gradually discharge the ALPS-treated wastewater into the Pacific Ocean. Preparatory construction work for the submarine discharge pipeline

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began in April 2022, with the Tokyo Electric Power Company (TEPCO) announcing that the discharge would commence in the spring of 2023. In May 2023, the International Atomic Energy Agency (IAEA) released a comprehensive report affirming that the discharge plan complied with international safety standards (IAEA 2023). Japanese authorities further contended that the treated wastewater met all regulatory requirements and posed no threat to human health, with some officials controversially claiming it was safe enough for direct consumption. Despite these assurances, the proposed ocean discharge has provoked widespread domestic and international opposition, particularly from neighboring coastal states, environmental organizations, and local fishing communities. Concerns persist regarding the long-term ecological impact, data transparency, and the adequacy of existing international legal frameworks governing marine radioactive pollution.

This article focuses on nuclear data regulation within the Pacific Rim region, approached from the perspective of cooperative nuclear data governance. By establishing a multilateral nuclear data regulatory cooperation mechanism for the Pacific Rim, it integrates radioactive pollution monitoring data with marine pollution governance, thereby alleviating the challenges in addressing marine radioactive pollution caused by Japan's discharge of radioactive wastewater. This article employs empirical research method and doctrinal research method, combining IAEA reports, Japan Nuclear Regulation Authority (NRA) report, JAEA database, TEPCO Fukushima Daiichi ALPS Treated Water Portal and FVCOM simulation model, analyzing the variations and dispersion of radionuclide concentrations, this study reveals the adverse environmental impacts of Japan's discharge of nuclear-contaminated wastewater on the Pacific Ocean region. Through a comprehensive review of international conventions, regional legal instruments on nuclear data regulation, the article identifies the challenges in addressing marine radioactive pollution in the Pacific region. Furthermore, it provides an international legal basis for establishing a regional multilateral cooperation mechanism on nuclear data oversight.

Early literature primarily viewed nuclear data as a subset of technical datasets relevant to nuclear physics, with emphasis on reactor modeling and nuclear energy research. However, recent studies have expanded the definition to include regulatory, environmental, safety, and emergency-related data (IAEA, 2015; NEA, 2020). In a broad sense, nuclear data encompasses not only traditional nuclear physical parameters but also all relevant data associated with nuclear energy and its applications. This comprehensive scope includes operational data from nuclear facilities, nuclear safety records, environmental radiation monitoring data, and radioactive waste management information (Flick 2021). International organizations, particularly the International Atomic Energy Agency (IAEA), have established a baseline for nuclear data collection and reporting. The IAEA's safeguards system under the Treaty on the Non-Proliferation

of nuclear weapons (NPT) mandates states to report data related to nuclear materials and facilities. Complementary mechanisms include the Convention on Nuclear Safety and the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, which require periodic national reports and peer review. Since nuclear data are generally considered part of national security, states like China, Russia, and America restrict the cross-border transmission and disclosure (Zhang and Kang 2020). Scholars 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 (Zhang and Xu 2024). Scholars contends that cross-border nuclear data transfer is significantly constrained by factors such as the diverse nuclear safety legal systems of different states, variations in technical standards for nuclear data, cybersecurity vulnerabilities (Georgieva et al. 2021). 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). Most of the studies are modelled on the Japanese discharge of Fukushima nuclear contaminated water, with physical practice studies examining the dispersal behavior of radionuclides, impacts on marine ecosystems and assessment of transboundary environmental issues. By combining observational data with computational simulations of atmospheric and oceanic currents, researchers have assessed the potential release of radioactive materials into marine and atmospheric systems due to Japan's wastewater disposal (Liang et al 2024). In the Pacific region, predictive models such as ROMS and POM have been applied to forecast ecological consequences stemming from Japan's release of treated nuclear wastewater. Further investigations into the treated effluent's isotopic signatures have provided insights into how key radionuclides accumulate in North Pacific marine life and their persistence in the ecosystem (Wu Men 2021).

From the perspective of international law, numerous scholars argue that Japan's actions constitute a breach of its international legal obligations, resulting in transboundary environmental harm. Consequently, existing research has largely focused on the issue of Japan's state responsibility. Procedurally, Japan has failed to comply with Article 198 of the United Nations Convention on the Law of the Sea (UNCLOS) and Article 2 of the Convention on Early Notification of a Transboundary Release of Hazardous Wastes. Specifically, it has neither engaged in timely consultations with potentially affected neighboring states nor publicly disclosed nuclear monitoring data related to radionuclides in the treated wastewater (Kim and Johnston

2022). Scholars further note that assessments of radionuclide concentration fluctuations near the Fukushima Daiichi Nuclear Power Station's harbor remain entirely reliant on data selectively released by the Japanese government and Tokyo Electric Power Company (TEPCO). Substantively, article 6 of the Draft Principles on the Allocation of Losses affirms that “international and domestic remedies” should function as parallel procedures, when transboundary nuclear pollution occurs, accountability procedures under both international and domestic law should be pursued simultaneously (Fu and Li 2024). Conversely, the absence of a long-term, effective monitoring mechanism for radioactive wastewater has resulted in extremely low transparency in environmental radioactive pollution monitoring data. Furthermore, radioactive contamination caused by nuclear waste disposal constitutes a protracted process across both temporal and spatial dimensions. Establishing causation between nuclear pollution activities and their resultant damages presents significant challenges in the absence of long-term monitoring and assessment data, thereby exacerbating the difficulties in governing marine radioactive pollution impacts.

Existing literature has identified the persistent challenge of low transparency in nuclear-related data, particularly concerning radioactive pollution monitoring and environmental damage assessment. However, current studies remain largely theoretical, focusing primarily on obstacles to cross-border nuclear data sharing and disclosure, without offering systematic analyses or actionable implementation pathways. Furthermore, a critical research gap persists in establishing the connection between nuclear data regulation and the mitigation of marine radioactive contamination. This study proposes to establish a multilateral legal framework for nuclear data governance in the Pacific region, which would enhance the transparency of authentic monitoring data regarding radionuclide concentrations and dispersion patterns from Japan's discharged nuclear-contaminated water, thereby preventing data monopolization by Japanese authorities; it establishes an evidentiary foundation for quantifying transboundary damage attribution, particularly regarding marine nuclear pollution resulting from acts not prohibited under international law. Ultimately, the binding nature of this cooperative legal architecture strengthens enforcement mechanism for holding states accountable for marine radioactive contamination.

Impact of Japan's radioactive wastewater discharge to the Pacific Rim marine environment

This study employs an empirical research approach to conduct a comprehensive analysis from dual perspectives. First, we systematically compare tritium (^3H) concentration variations in the North and West Pacific Transition Zones before

and after Japan's radioactive wastewater discharge, utilizing official monitoring reports published by the Japan Nuclear Regulation Authority (NRA) and the Tokyo Electric Power Company (TEPCO) during 2023–2024. Our analysis incorporates radionuclide dispersion modeling and US marine organism monitoring data, revealing that *Ulva lactuca* (sea lettuce) exhibits remarkable bioaccumulation capacity for cesium-137 (^{137}Cs) from Fukushima's wastewater. This finding suggests significant radiological risks across trophic levels, from primary producers to higher-order consumers. Second, through integrated assessment using the GTAP economic model and fisheries sector analyses from the Japan Fisheries Agency and Nomura Research Institute reports, we demonstrate substantial negative impacts on Japan's marine economy following the wastewater release.

Marine ecosystem pollution

Recent data released by Japan in 2023 indicate that nearly 70% of the nuclear-contaminated water treated by the Multi-Nuclide Removal System (MNRS) fails to meet regulatory standards. The discharge of such water into the ocean significantly degrades marine water quality. The contaminated water contains radioactive isotopes, including cesium (Cs), strontium (Sr), and iodine (I), which exhibit high levels of radioactivity and toxicity. Joint monitoring reports published by the Nuclear Energy Agency (NEA) and the Tokyo Electric Power Company (TEPCO) between July 2023 and June 2024 indicate a significant rise in tritium (^3H) concentrations near the discharge outlet within the harbor area of the Fukushima Daiichi Nuclear Power Station. Specifically, the concentration increased from approximately 1,000 Bq/L to between 5,000 and 10,000 Bq/L (NEA Report, 2020; JAEA Database, 2024; TEPCO ALPS Treated Water Portal, 2023–2024). Under Scenario 3, which simulates the total initial activity concentrations of radionuclides, studies indicate that isotopes such as ^{137}Cs , ^{90}Sr , and ^3H are highly concentrated in the waters surrounding Fukushima Coastal during the 1–2 years of discharge (Liu et al. 2022). 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; Liao and Yang 2023).

Furthermore, the discharge of nuclear-contaminated water poses significant risks to marine biodiversity. A 2024 study conducted by American biologists reported that 15% of collected *Ulva lactuca* (sea lettuce) samples from the US West Coast tested positive for cesium-137 (^{137}Cs). Over time, the concentration of ^{137}Cs in these samples declined to approximately 5.6%, suggesting that edible macroalgae possess a notable capacity to absorb and subsequently retain radioactive cesium. The bioaccumulation of radioactive elements in primary producers (such

as macroalgae) facilitates their transfer through food chains and food webs, ultimately affecting higher trophic levels, including primary, secondary, and tertiary consumers. This process not only threatens marine biodiversity but also has profound implications for seafood safety, nutritional quality, and the sustainability of seaweed aquaculture (Chang et al 2024).

Marine economy disruptions

The discharge of nuclear-contaminated water has elicited strong responses from key regional stakeholders, particularly China and South Korea, which have raised serious concerns over the safety of Japanese seafood and implemented stringent trade restrictions. In August 2023, the Chinese government imposed a ban on seafood imports from Fukushima and nine surrounding prefectures, while intensifying radiological testing for seafood from other regions of Japan. Importers must now provide comprehensive radiological test reports to ensure compliance with China's food safety standards (Zhao 2024).

Similarly, South Korea has banned seafood imports from Fukushima and adjacent areas, while pledging to collaborate with the international fishing community to address the environmental and economic repercussions of Japan's actions (Lee 2023). These trade restrictions have far-reaching economic consequences. Under the scenario of the GTAP model, Japan's discharge of nuclear-contaminated water is projected to cause significant declines in GDP (2.18%), imports (3.84%), exports (8.30%), household income (2.61%), and social welfare (a loss of \$130.7 billion) (Japan Fisheries Agency 2024; Lee and Nakamura 2024).

Notably, China's ban on Japanese fishery products has led to substantial welfare losses, with Japan incurring the

largest loss at \$13.31 billion, followed by China at \$687.77 million (Nomura Research Institute, 2023). Furthermore, the discharge has eroded public confidence in the safety of seafood products, such as sashimi and shellfish, across China, South Korea, and Japan (Hirose and Povinec 2019). This has intensified consumer aversion to seafood, disrupting regional seafood markets and exacerbating economic losses. As the fisheries market faces severe disruptions, the supply chains of related upstream industries are also adversely affected, further compounding the economic and social impacts of Japan's actions.

Challenges of marine radioactive pollution governance in the Pacific Rim region

Fragmentation and weak enforcement of the legal framework

The international legal framework governing marine radioactive pollution is fragmented across multiple regulatory domains, including the law of the sea, pollutant control, hazardous waste management, and international atomic energy law (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 Convention provides a precise definition of "pollution of the marine environment" as the introduction by humans, directly or indirectly, of substances or energy into the marine environment which results or is likely to result in deleterious

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

Domain	Convention/Protocol	Key Provisions
Law of the Sea	United Nations Convention on the Law of the Sea	Defines "pollution of the marine environment"; obliges states to prevent transboundary pollution, share information, and cooperate internationally
Pollution Prevention and Control	Convention on the Prevention of Marine Pollution by Dumping	Regulates marine pollution from dumping; bans dumping of radioactive waste except at IAEA-exempt concentration levels; applies a "list-based" system of waste classification
	Protocol to the London Convention	Modernizes the London Convention; establishes the precautionary principle; adopts a "reverse list" system allowing only explicitly listed substances to be dumped
Hazardous Waste Management	Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal	Regulates cross-border movement and disposal of hazardous and other wastes; introduces the Prior Informed Consent (PIC) procedure; aims to prevent illegal trafficking of hazardous waste
International Nuclear Energy Law	Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management	Governs safety of spent fuel and radioactive waste management; requires periodic state reporting; obligates states to notify transboundary radioactive release incidents

effects. Chapter 12 of UNCLOS, titled “Protection and Preservation of the Marine Environment,” outlines the obligations of States Parties to take precautionary measures and share relevant information (United Nations 1982). On one hand, states bear the obligation not to transfer pollution damage, which entails both prohibiting the passive allowance of pollution dispersion and actively preventing the transboundary displacement of contaminants to other jurisdictions. This fundamental duty precludes States from shifting their inherent marine environmental protection responsibilities to other nations. Concurrently, states are positively obligated to protect and preserve the marine environment through international cooperation, as established under customary international law and treaty regimes. Specifically, Articles 194(1) and (2) require States to implement measures to prevent pollution of the marine environment by harmful substances, while Articles 200 and 204–206 impose obligations on States Parties to exchange information and data in a timely manner to prevent the transboundary transfer of hazards (United Nations 1982, art. 194; art. 200–206).

In the domain of pollution prevention and control, the Convention on the Prevention of Marine Pollution by Dumping (hereinafter referred to as the London Convention) stands as one of the earliest global conventions designed to protect the marine environment from anthropogenic impacts. 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 (Convention on the Prevention of Marine Pollution by Dumping 1972). In principle, the dumping of radioactive waste into the sea would be banned, except for waste containing radioactive material that meets the IAEA minimum (exempt) concentration criteria. In 1996, the Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (hereinafter referred to as the London Protocol) was adopted to modernize the London Convention, entering into force in 2006. The Protocol establishes dual regulatory dimensions: first, it codifies the “application of the precautionary approach” as a general obligation for Contracting Parties, mandating marine environmental protection against dumping-induced pollution even in situations of scientific uncertainty; second, it implements a “reverse list” system that explicitly enumerates permissible wastes or other materials for ocean disposal while prohibiting all unlisted substances (Protocol

to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1996).

Regarding hazardous waste management, the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal (hereinafter the Basel Convention) was adopted at the Conference of Plenipotentiaries on the Control of Transboundary Movements of Hazardous Wastes in 1989, becoming effective in 1992. This Convention seeks to protect human health and the environment from adverse effects of hazardous wastes by regulating cross-border transfers and disposal operations, thereby preventing illegal transboundary waste trafficking between states. Its regulatory scope encompasses both “hazardous wastes” and “other wastes,” as technically defined in respective annexes. A cornerstone mechanism is the Prior Informed Consent (PIC) procedure, which systematically governs all transboundary movements of designated waste categories (Basel Convention 1989).

In the domain of international nuclear energy law, the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (hereinafter referred to as the “Joint Convention”) serves as the primary international treaty governing radioactive waste management. State parties are obligated to periodically provide detailed reports regarding the management and storage of radioactive materials, which must adhere to globally recognized safety protocols. Additionally, states parties are obligated to notify any incident that has caused or may cause a release of radioactive material resulting in a national release beyond national boundaries.

Although international conventions impose both procedural and substantive obligations on states regarding transboundary releases of radioactive materials, the obligations are set too broadly, and the provisions are limited in their operability and lack legal enforceability. Convention lacks strong legally binding provisions and primarily functions as a soft law instrument that encourages compliance rather than imposing strict enforcement mechanism. UNCLOS establishes the duty of States to prevent transboundary pollution, it does not explicitly define what constitutes “necessary measures” nor does it provide clear criteria for determining proportional responsibility and causation in cases of marine nuclear pollution. Similarly, the Convention on Early Notification of a Nuclear Accident establishes notification obligations for states parties. Nevertheless, the notification obligations under are not legally binding, limiting its effectiveness in ensuring timely and transparent information sharing (Gong 2024). Consequently, this article proposes the establishment of a regional multilateral legal mechanism for nuclear data regulatory cooperation, which defines the obligations of member States in areas such as nuclear data risk assessment and conditional disclosure, as well as the

punitive compensation obligations triggered by breaches of these fundamental duties. It further ensures the efficiency of accountability through both the establishment of regional supervisory and enforcement bodies and the formulation of specific institutional arrangements.

Lack of regional cooperative consensus on marine radioactive pollution governance

Due to the intersection of multiple variables—such as national interests, modes of risk perception, data independence and integrity, and interactions with public opinion—states within the Pacific Rim hold divergent views on Japan's discharge of radioactive wastewater. First, reflecting nuclear energy and environmental policy divergences driven by national interest considerations, the United States, as one of the world's major nuclear energy users and a long-standing partner of Japan in nuclear regulation and safety, has shown relatively high confidence in Japan's technical approach to wastewater treatment, such as the Advanced Liquid Processing System (ALPS). The US 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 (IAEA Safety Standards Series No. GSG-8). Compared with the United States, China, South Korea, and Pacific Island states tend to place greater emphasis on the “precautionary principle” and “environmental justice.” States like Korea and China argue that the IAEA's capacity to fulfill its mandate—particularly in regulating atomic safety, conducting independent assessments, and enforcing Primary verification protocols—has been constrained by the geopolitical interests of major powers. China regards the discharge of Fukushima's radioactive wastewater into the ocean as a matter of regional public risk and advocates for “international consultation,” “environmental democracy,” and “multilateral supervision” in addressing this issue. The South Korean government has adopted a conditional stance, stating that it will demand an immediate cessation of discharge and pursue international litigation if radioactive element concentrations exceed permissible standards. 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. Second, based on differences in risk perception models, the United States prefers a probabilistic risk assessment that low-dose, controlled releases will not result in marine radioactive contamination. An integrated analysis of the IAEA's 2023 safety assessment report and oceanic dispersion modeling conducted by the University of Tokyo indicates that tritium (^3H) concentrations in open Pacific waters, at distances exceeding 100 km from the discharge point, increase by only approximately 0.1% relative to

background levels (≈ 0.00003 – 0.0002 Bq/L). Furthermore, 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 (Beck 2023). Conversely, China demonstrates a results-based risk aversion approach, maintaining that even low-probability events warrant stringent precautions given the irreversible consequences of marine ecological contamination. This rationale underpins China's advocacy for a “zero-risk” or “minimal-risk” strategy. Furthermore, citing limitations in data transparency, China has raised substantive concerns regarding potential compromises to the IAEA's assessment independence due to major power influence, while simultaneously questioning the integrity of Japan's reported data. Following extensive bilateral consultations in September 2024, Japan expressed its willingness to establish a long-term international monitoring mechanism under the auspices of the International Atomic Energy Agency. This framework would encompass key aspects of the sea discharge process, including provisions for stakeholder nations to independently collect and analyze samples.

Although China and Japan have reached a consensus on the discharge of nuclear-contaminated water from the Fukushima Daiichi Nuclear Power Plant, allowing China to conduct independent sampling and monitoring, there remains an absence of binding bilateral legal instruments. Technical details—such as the types of radionuclides to be monitored, the detection methodologies, and the establishment of a long-term and effective mechanism for supervising the transparency of monitoring data—still require further negotiation. Finally, considering the interaction between domestic politics and public opinion, awareness of nuclear contamination risks remains generally low across the Pacific Rim. This limitation stems in part from the inadequate reporting by certain Japanese media outlets, which have neither transparently disclosed the radionuclide content in the discharged water nor objectively assessed its ecological consequences. This article establishes a regional multilateral legal framework for nuclear data governance, anchored by the legally binding Pacific Rim Nuclear Data Regulatory Cooperation Accord. The proposed mechanism institutionalizes three core procedural pillars—joint information-sharing, joint risk assessment, and joint decision-making—while clearly defining common objectives for regional cooperation, and fundamental legal principles to be observed by participating states.

Low transparency of marine ecological nuclear contamination monitoring data

From a structural perspective, deficiencies in transparency arise from several interrelated factors. On one hand, jurisdictional constraints and sovereign control over nuclear data

enable states to determine what monitoring data is released. 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, in what form, and on what timeline. This often results in politically filtered disclosures that omit raw datasets, limit methodological details, or withhold temporal continuity necessary for independent verification. On the other hand, the absence of legally “monitoring–disclosure–remedy” trinity-based transparency supervision framework, increasing the risk of malicious nuclear data leakage in regional regulatory cooperation. This article unifies the classification standard and regional sharing format of nuclear data by building a regional legal mechanism for multilateral nuclear data regulatory cooperation and combining the nuclear data risk assessment and classification system with blockchain technology. Aiming to break the trust deficit of regional states in cross-border safe nuclear data transmission and enhance data transparency and traceability.

Feasibility for the establishment of Nuclear Data Regulatory Legal Cooperative mechanism in the Pacific Rim Region

Analysis of the Imperative for Multilateral Nuclear Data Regulatory Legal Cooperative mechanism

Remedying legal Enforcement Deficits in Nuclear Pollution Liability

As the mentioned above, The IAEA safeguards regime primarily focuses on nuclear material accounting and non-proliferation, lacking a mandatory multilateral real-time sharing mechanism for operational data from nuclear facilities or radiation environmental monitoring. Regional cooperation frameworks predominantly rely on voluntary participation and soft law instruments, absent binding regional agreements. Regarding Japan's discharge of radioactive wastewater, while multiple states consider it a breach of obligations under acts not prohibited by international law, the current system lacks enforceable accountability measures. Adopting the Regional Nuclear Data Governance Cooperation Agreement to institutionalize a comprehensive legal framework. Under this agreement, the substantive scope is explicitly defined to include four critical categories of nuclear-related data: nuclear pollution monitoring data, radioactive regulatory data, radiation source monitoring data, and environmental impact assessment data. Signatory states assume binding rights and obligations, which encompass adherence to standardized risk assessment protocols, the implementation of transparent data-sharing mechanisms, and mandatory

disclosure requirements. To ensure accountability, the agreement integrates enforceable liability provisions that outline specific remedial actions and compensation obligations in cases of non-compliance. Effective implementation of these measures relies on the oversight authority of a designated regional body—the Trans-Pacific Nuclear Data Regulatory Commission—which is tasked with verifying compliance, mediating disputes, and facilitating technical coordination among member states. Additionally, the Pacific Rim Nuclear Data Regulatory Cooperation Mechanism enables participating states to conduct systematic evaluations using ecological monitoring data, while advancing damage assessment methodologies through ecological service valuation, restoration cost analysis, and virtual abatement cost approaches (Wang, Zhang, Huang 2022).

Enhancing transparency in radioactive waste discharge monitoring through regional trust-building

In the absence of a multilateral legal framework, major nuclear powers in the region remain concerned that nuclear data could be attacked, leaked, and subsequently misused during cross-border transmission. The Pacific Rim Nuclear Data Regulatory Cooperation mechanism centers on a risk-based classification system combined with a conditional data-sharing framework. On one hand, the Risk Assessment Agency under the Pacific Rim Nuclear Data Regulatory Cooperation Committee (PRNRC) is tasked with overseeing the disclosure of nuclear waste monitoring data, records of radioactive activities, and inventories of radiation sources. It is also empowered to establish unified risk assessment standards, implement standardized confidentiality protocols and cross-border data transfer procedures, and adopt measures to prevent cyber intrusions. Based on risk identification, nuclear data will be classified into three levels according to their strategic significance: (1) data that could endanger national security, public safety, or critical infrastructure will be assigned a top-secret classification; (2) data affecting the operation of nuclear facilities or corporate interests will be designated as internal use only; and (3) data with global public health or ecological relevance—such as radiation protection indicators and waste disposal records—will be placed in the public access category. On the other hand, the conditional monitoring sharing regime requires regional states to collaborate in monitoring the disposal of radioactive nuclear waste and environmental conditions, with real-time conditional data sharing on pollution sources. The supporting “Full-Cycle Monitoring System for Radioactive Materials” and the “Mutual Recognition Mechanism for Monitoring Data” improving the security of cross-border transmission processes (Rodell et al. 2024).

Legal basis for the Nuclear Data Regulatory Cooperation mechanism

This article adopts the doctrinal research method to systematically analyze the legal framework for nuclear data regulation in the Pacific Rim region. At present, neither international conventions nor regional legal instruments contain legal provisions specifically and directly addressing nuclear data regulation. Nevertheless, issues concerning the secure regulation of relevant data can be found in the legal regimes governing nuclear energy development and utilization, nuclear accident emergency response, and the disposal of radioactive waste.

International conventions

International conventions primarily regulate the safety management of data related to nuclear energy development and utilization, the radiological impacts of nuclear accidents, and the disposal of radioactive waste (See Table 2). The Convention on Environmental Impact Assessment in a Transboundary Context stipulates that member states must conduct environmental impact assessments for hazardous activities likely to cause transboundary environmental effects. In the nuclear energy sector, it requires contracting parties to promptly assess data on radiation and nuclear risks arising from the operation of nuclear facilities (Espoo Convention, 1991). The Convention on Nuclear Safety, while not specifically targeting nuclear data regulation, establishes a national reporting system and accident reporting obligations for contracting

parties, and calls for the creation of an information exchange mechanism concerning nuclear energy development and utilization (Nuclear Safety Convention 1994). Articles VIII.B and VIII.C of the Statute of the International Atomic Energy Agency (IAEA) emphasize the establishment of a comprehensive nuclear database encompassing nuclear material management, nuclear facility safety, and environmental monitoring. Mechanisms under the IAEA, including the Nuclear Safety Information Exchange (NUSEC), the International Nuclear Information System (INIS), the Emergency Preparedness and Response Information Management System (EPRIMS), and the International Radiation Monitoring Information System (IRMIS), provide a cooperative foundation for nuclear data governance. The Convention on Nuclear Safety further requires member states to periodically submit national reports for peer review on nuclear safety regulation. The Comprehensive Nuclear-Test-Ban Treaty, through its International Monitoring System (IMS), operates an extensive network of nuclear test monitoring stations across the Pacific Rim, enabling the collection of radiological and other nuclear-related data. The treaty provides for the use and scientific sharing of such monitoring data by contracting parties (CTBT, 1996). The Preparatory Commission for the CTBT (CTBTO) offers global nuclear monitoring data, including radioactive aerosol and seismic data, which were used to trace nuclear releases during the Fukushima accident and shared with tsunami warning systems. The Convention on Early Notification of a Nuclear Accident mandates that states promptly provide detailed data in the event of a nuclear accident, including radiation levels,

Table 2 International conventions for nuclear data regulatory

Domain	Convention	Key Provisions on Nuclear Data
Transboundary Environmental Impact	Convention on Environmental Impact Assessment in a Transboundary Context	Requires environmental impact assessments for hazardous activities likely to cause cross-border effects, including radiation and nuclear risks
Nuclear Safety	Convention on Nuclear Safety	Establishes national reporting and accident reporting obligations; promotes information exchange on nuclear energy development and safety
	Statute of the International Atomic Energy Agency	Mandate the creation of nuclear databases; IAEA mechanisms include NUSEC, INIS, EPRIMS, and IRMIS for cooperative data governance
	Convention on the Physical Protection of Nuclear Material	Requires member states to report and cooperate regarding the protection and safety of nuclear materials (including data-sharing obligations)
	Comprehensive Nuclear-Test-Ban Treaty	Establishes the International Monitoring System (IMS) for radiological and seismic data; provides global data sharing, including CTBTO monitoring outputs
Accident Notification	Convention on Early Notification of a Nuclear Accident	Requires prompt provision of detailed accident data to enable risk assessment and protective action
Radioactive Waste Management	Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management	Obligates parties to submit data on radioactive waste disposal and storage, ensuring compliance with safety standards

the status of nuclear facilities, and the type and quantity of released materials, enabling affected states to assess risks and implement protective measures. Finally, the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management requires contracting parties to regularly submit data on radioactive waste disposal methods and storage facilities, ensuring compliance with international safety standards.

Regional legal instruments

Although the Pacific Rim region currently lacks a dedicated regional agreement or legal instrument specifically governing nuclear data cooperation, existing regional legal frameworks addressing radioactive waste disposal, marine radioactivity monitoring, and technical collaboration provide foundational legal support for establishing a nuclear data governance mechanism (See Table 3). Notably, the South Pacific Nuclear Free Zone Treaty, as a cornerstone regional nuclear control regime, emphasizes on the prevention of marine environmental pollution in the region from radioactive waste and other radioactive materials. The Treaty obligates State Parties to periodically exchange nuclear activity data and establish consultative committees for dispute resolution (Treaty of Rarotonga 1985). Under the IAEA framework, the Regional Cooperative Agreement for Asia, and the Pacific mandates technical cooperation among parties, encompassing nuclear science research, capacity building, and regulated data sharing. It specifically requires IAEA-facilitated nuclear data exchange, particularly real-time monitoring data sharing during nuclear emergency responses (RCA, 1987). The Convention for a North Pacific Marine Science Organization institutionalizes a Data Management Policy that operationalizes FAIR (Findable, Accessible, Interoperable, Reusable) and CARE (Collective Benefit,

Authority to Control, Responsibility, Ethics) principles, creating an open, interoperable, and auditable transnational data-sharing framework (PICES Convention 1990). Pursuant to this Convention, the North Pacific Marine Science Organization comprises a decision-making body, a Council, and an Executive Committee. The Council oversees major decisions related to the organization's activities, policies, and programs, while the Executive Committee—consisting of a Technical Committee and a Scientific Committee—manages domain-specific affairs (PICES Convention, 1992). Following the Fukushima nuclear disaster, the Organization facilitated cross-border cooperation among its members to monitor and address the dispersion of nuclear contaminants such as cesium-137. The Monitoring Committee tracks the dispersion pathways of such contaminants, providing critical data for analysis, while the Data Exchange Committee consolidates member states' marine nuclear pollution monitoring data into a centralized multinational database to enable integrated research and environmental impact assessments.

Additionally, China, Japan, South Korea, and the Russian Federation jointly adopted The Action Plan for the Protection, Management, and Development of the Marine and Coastal Environment of the Northwest Pacific Region (NOWPAP) under the UNEP Regional Seas Programme. During the Fourth Intergovernmental Meeting in 1999, four Regional Activity Centers (RACs) were established: Special Monitoring and Coastal Environmental Assessment Regional Activity Centre (CEARAC); Data and Information Network Regional Activity Centre (DIN-RAC); Marine Environmental Emergency Preparedness and Response Regional Activity Centre (MERRAC); Pollution Monitoring Regional Activity Centre (POMRAC). Focusing on establishing an effective database for the monitoring of the marine environment (Northwest Pacific Action Plan, 1994).

Table 3 Regional legal instruments for nuclear data regulatory

Domain	Legal instrument	Key provisions on nuclear data
Nuclear Control	South Pacific Nuclear Free Zone Treaty	Prohibits radioactive waste dumping; requires states to exchange nuclear activity data periodically; establishes consultative committees for dispute resolution
Technical Cooperation	Regional Cooperative Agreement for Asia and the Pacific under IAEA	Facilitates nuclear science collaboration; mandates IAEA-supported nuclear data exchange; requires real-time monitoring data sharing during nuclear emergency responses
Data Governance	Convention for a North Pacific Marine Science Organization	Institutionalizes a data management policy based on FAIR and CARE principles; consolidates marine nuclear pollution monitoring data into a multinational database
	Northwest Pacific Action Plan	focuses on building a regional marine environmental monitoring database

Establishment of the Nuclear Data Cooperation Governance Mechanism in the Pacific Rim Region

Legal principles for Nuclear Data Regulatory Cooperation

Concurrently, efforts are underway to facilitate regional high-level intergovernmental dialogue on nuclear safety governance, seeking to harmonize regional priorities and negotiate a comprehensive regulatory framework. Specifically, the Pacific Rim states 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 nuclear data cooperation. To mitigate risks of malicious cyber-attacks and leaks in nuclear safety data during regulatory cooperation, it is imperative to codify binding legal principles for regional collaboration.

The principle of security

The principle of security in regional nuclear data governance cooperation manifests as safeguards against the misuse of nuclear safety data for illicit purposes. This principle operates through three technical dimensions: data encryption, access control, and security auditing. At the data transmission stage, robust encryption algorithms and stringent key management protocols must be implemented for cross-border nuclear data transfers. For data storage and visualization platforms, restricted access measures should be enforced, enhanced by role-based access control (RBAC) systems and multi-factor authentication (MFA) technologies to secure login procedures. The framework further requires regular compliance audits of nuclear data usage, coupled with continuous vulnerability monitoring and remediation for visualization platforms. A practical application of this security framework can be observed in Japan's release of treated nuclear wastewater. The radionuclide dispersion monitoring data is protected through advanced encryption during transmission to regional states. When stored on the Disclosure Visualization Platform, while permitting legitimate access by authorized stakeholders, the system implements rigorous periodic review mechanisms to prevent data acquisition and exploitation by hazardous organizations.

The principle of reasonable use

The Principle of Reasonable Use in data governance ensures compliance with ethical standards, legal requirements, and public interests throughout data collection, storage, processing, and utilization. This principle operates through two key dimensions: First, adherence to international treaties and agreements such as the Convention on Nuclear Safety and the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. Second, guaranteeing that access to and use of nuclear data requires prior legal authorization, ensuring all entities handling such data possess appropriate permissions and qualifications.

The principle of procedural fairness

Procedural fairness serves as the foundation for establishing the authority and legitimacy of nuclear data governance cooperation in the Pacific Rim region. This principle requires that all processes—including nuclear data risk assessments and prior informed consent for data sharing—be grounded in established procedural norms or rules. Specifically, risk assessment functions as a prerequisite procedure for nuclear data regulation. Given the complexity of nuclear-related data, a standardized risk assessment protocol must classify and categorize data accordingly. Furthermore, since nuclear data broadly encompasses sensitive information—including nuclear materials and technologies that may threaten national security—cross-border data transfer and sharing requires explicit consent from relevant nations. For instance, post-risk assessment classification of Japan's radioactive wastewater discharge monitoring data revealed its potential global impact on human health and ecological sustainability. Consequently, such data should in principle be publicly accessible and subject to review by affected states, while maintaining appropriate safeguards for sensitive information.

Legal rules for nuclear data regulatory cooperation

The foundation for transnational coordination on nuclear information governance in the Pacific region rests upon the multilateral Pacific Rim Nuclear Data Regulatory Cooperation Accord. The accord establishes the enhancement of regional nuclear energy development safety and the improvement of nuclear data security and transparency as its primary cooperative objectives, thereby clarifying the shared goals among Contracting Parties and strengthening consensus for regional collaboration. Firstly, the Agreement's scope of application encompasses nuclear data regulation in a broad

sense, extending beyond core nuclear physics and engineering data to include various types of data generated during radioactive waste disposal activities. Comprising radiological contamination metrics, regulatory oversight records, radiation source surveillance statistics, and ecological monitoring datasets.

Secondly, it explicitly outlines the obligations of member states regarding the storage, cross-border transfer, and sharing of nuclear data. These obligations include conducting risk assessments and adhering to transparent data-sharing procedures and disclosure protocols. To ensure enforceability, the agreement also incorporates remedial measures and enforceable liability clauses that specify remedies and compensation obligations for breaches of the agreement.

Finally, the agreement establishes a clear organizational structure and operational system. The Pacific Rim Nuclear Data Regulatory Cooperation Committee (PRNDRCC) serves as the central coordinating body, with a Plenary Conference of signatory nations functioning as the supreme policy-making forum. Within this structure: The Conference of the Parties operates as the highest decision-making organ; The Pacific Rim Secretariat for Nuclear Data Governance coordinates regional collaborative affairs, aligning national policies on nuclear data supervision, technical standards, and emergency response to promote regulatory harmonization; The Nuclear Data Supervisory Committee monitors compliance with the Agreement's provisions among regional signatories; A dedicated Dispute Resolution Body provides multilateral settlement mechanisms when radioactive pollution damage results from breaches of contractual obligations.

Organizational structure for nuclear data regulatory cooperation

Decision-making and deliberative body

The Pacific Rim Nuclear Data Regulatory Cooperation Mechanism's decision-making and deliberative body is its focal point. Senior representatives from the governments of the nations that make up the Pacific Rim comprise the highest decision-making body, the Pacific Rim Nuclear Data Regulatory Council. The Council's primary mandate would be to develop and issue overarching plans, strategies, and policies related to nuclear data governance, thereby ensuring coherence in collective objectives and regulatory alignment among participating nations. Due to differences in data privacy policies among states in the Pacific Rim, the United States encourages the free cross-border flow of data and imposes restrictions only when specific commercial transactions pose a "national security risk." In contrast, China, under the Cybersecurity Law, the Data Security Law, and the Personal Information

Protection Law, strengthens the principles of "cyber sovereignty" and "data localization," viewing data security as a core component of national security, and requiring sensitive data to remain within its borders. For "important data," outbound transfer is permitted only after undergoing a security assessment by the Cyberspace Administration of China (CAC), obtaining PIP certification, and filing a standard contractual clause record. Considering the nexus between nuclear data and national security (Chapman and McCombie, 2023). It is necessary to establish a neutral third-party technical verification body under the Council. The verification body operates on a two-tiered assessment framework: primary classification according to the originating state's domestic nuclear data sensitivity grading system, supplemented by secondary regional technical evaluation. For regulatory decisions concerning highly sensitive nuclear data, unanimous consensus among all Contracting Parties is required as a mandatory procedural safeguard.

The coordination of cooperation affairs body

As the coordination organization, the Pacific Rim Nuclear Data Regulatory Secretariat is in the role of standardizing technical procedures, coordinating emergency response plans, coordinating intraregional cooperation, and coordinating national nuclear data regulatory policies. Through formulating tangible implementation plans to operationalize the Pacific Rim Nuclear Data Regulation Cooperation Agreement, the Secretariat guarantees regional coherence and interoperability. Furthermore, it tackles and settles important problems and disagreements that could come up during collaboration, guaranteeing the ongoing advancement of joint endeavors.

Cooperative supervisory enforcement body

Implementing a collaborative supervisory body that incorporates review, assessment is vital for guaranteeing member states' transparency and compliance regarding nuclear data. The core of this body is the Nuclear Data Supervisory Committee (NDSC), which is responsible for formulating, implementing, and overseeing regulatory policies. Its responsibilities include: (a) developing uniform technological requirements, standards, and regulatory rules for nuclear data. (b) monitoring member states' adherence to legal procedures and cooperation agreements. (c) releasing the Pacific Rim Nuclear Data Compliance Report annually.

Dispute resolution body

On one hand, an independent dispute resolution body for nuclear data regulatory governance could be established

under the IAEA's institutional framework. Alternatively, specialized adjudicative institutions could be designed to address disputes arising in specific cooperative domains. For instance, a dedicated chamber for nuclear pollution cases might be constituted within the International Tribunal for the Law of the Sea (ITLOS), leveraging its jurisdictional expertise in maritime environmental disputes. However, considering the jurisdictional limitations of the International Tribunal for the Law of the Sea, together with geopolitical frictions arising from Sino–Japanese maritime boundary disputes and unresolved wartime historical issues, it is advisable to encourage non-parties to the United Nations Convention on the Law of the Sea (UNCLOS) to accept the tribunal's jurisdiction through selective agreements or provisional arbitration clauses. Furthermore, a pre-arbitration technical working group—encompassing joint environmental monitoring initiatives and a shared nuclear data repository—should be established to mitigate mutual distrust, while secure handling protocols are implemented to safeguard highly sensitive nuclear data. On the other hand, a “preventive dispute resolution” approach could be enhanced by implementing a three-tier progressive mechanism encompassing risk prevention, negotiation and mediation, and judicial remedies. This framework would prioritize amicable consultation as the normative baseline while retaining judicial recourse for intractable disputes, balancing procedural flexibility with enforceability.

Specific implementation regimes for regulatory cooperation

Risk assessment hierarchical regime

Utilizing effectively preventing and controlling risks like malicious assaults and leaks in the regional cross-border transmission and sharing of nuclear data, the nuclear data risk assessment regime raises the legitimacy of regional cooperation. The standards for classifying and evaluating nuclear data constitute the foundation of the regime. Building on the risk identification framework for nuclear data, classification is established based on importance and sensitivity, dividing the data into three categories. Highly sensitive nuclear data that pose potential threats to national security, public safety, or critical infrastructure are designated as top secret. Information that influences the interests and internal operations of a state's nuclear facility operators falls under the internal category. Meanwhile, data impacting global public health and the sustainable development of the ecological environment are categorized as public (e.g., Japanese radioactive wastewater disposal monitoring data). Further distinctions are made based on the nature and application of nuclear data, encompassing information related to nuclear technology in energy development and utilization,

diagnosis, operation, and maintenance of nuclear facilities, radiation protection, monitoring of nuclear waste disposal activities, and emergency response mechanisms for nuclear accidents (CTBTO 2023). To ensure effective governance, regulatory frameworks have been established to guide the processing and sharing of nuclear data across different classification levels and categories, enhancing security, accessibility, and international cooperation in nuclear data management.

A specialized risk assessment body should be established under the Pacific Rim Nuclear Data Regulatory Cooperation Committee (PRNRC) to oversee the regulation of the collection, transmission and disclosure of nuclear data related to the monitoring of nuclear waste disposal, nuclear radiological activities, and radiation sources. When confronting potential cyber threats targeting nuclear information systems, the unit would implement proactive security evaluations and mitigation protocols. A critical function of this body would involve formulating harmonized evaluation criteria, comprising both methodological guidelines and technical specifications. The methodological component would involve creating a regional risk analysis model incorporating advanced analytical techniques such as probabilistic safety assessment and failure mode analysis. Technical standardization efforts would focus on establishing uniform protocols for data encryption, transnational data sharing, and the development of an integrated monitoring platform capable of simultaneous data analysis, threat detection, and risk evaluation—thereby optimizing regulatory coordination across jurisdictions. This multi-faceted approach would significantly improve the robustness of regional nuclear data oversight mechanisms while maintaining necessary safeguards for sensitive information.

Nuclear data monitoring regime

The establishment of a unified and efficient nuclear data monitoring system in the Pacific Rim is a fundamental part of addressing the risk of transboundary radioactive nuclear contamination and improving the regional environmental safety management capacity. Nuclear data monitoring inherently involves sensitive information concerning national nuclear facility operations, radioactive waste disposal practices, and related quantitative metrics. The current absence of unified regional standards for data classification, confidentiality periods, and disclosure scopes frequently triggers compliance conflicts. For instance, while the United States typically categorizes such data under Critical Infrastructure Protection frameworks, China prioritizes sovereign control mechanisms coupled with rigorous review systems (Smith and Kim 2020). Furthermore, significant technological disparities exist among Pacific Rim nations. Advanced economies like the United States, Japan, and South Korea maintain

leadership in automated monitoring sensors and AI-driven analytics platforms, whereas many Pacific Island nations and developing states face substantial gaps in digital infrastructure, network coverage, and data standardization capabilities.

On the one hand, a monitoring center should be established under the Pacific Rim Nuclear Data Regulatory Council to address the challenge of inconsistent technical standards by formulating a trans-Pacific nuclear data collection and monitoring protocol in reference to International Atomic Energy Agency (IAEA) standards. The monitoring participants would include national nuclear regulatory authorities, research institutions, fishery associations, and local communities within the region, while the monitoring scope would cover nuclear facility operation data, environmental radiation dispersion data, and radioactive waste tracking data. On the other hand, blockchain and artificial intelligence technologies should be employed in accordance with the graded standards for nuclear data risk assessment. The integration of blockchain and artificial intelligence (AI) technologies with regional monitoring database on the Northwest Pacific Action Plan (NOWPAP) could establish a synergistic modeling system. At the data-chain level, 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 monitoring radioactive dispersion data, AI-driven regulatory modeling systems could be integrated into the backend infrastructure of the Data and Information Network Regional Activity Centre (DINRAC) under the Northwest Pacific Action Plan (NOWPAP). Leveraging long short-term memory (LSTM) neural networks in conjunction with satellite-derived ocean current visualization data, these systems would facilitate real-time simulations and forecasts of radionuclide migration pathways, as well as dynamic trend analyses of monitoring datasets (Chang et al. 2024).

Conditional data disclosure regime

Building upon the established risk classification framework, a Conditional data disclosure Regime could be instituted to enhance real-time regional cooperation in tracking fluctuations in marine radioactive concentrations. Within this regime, Top-Secret category data would be safeguarded through stringent security measures, including advanced encryption techniques and localized data storage protocols (Georgieva et al. 2021). Internal classification data could be selectively disclosed to designated authorized entities via controlled access channels, ensuring both targeted

information flow and protection against unauthorized dissemination. In contrast, public classification data—particularly monitoring results pertaining to environmental radioactive contamination—would be subject to mandatory, periodic disclosure through regional nuclear data disclosure Visualization Platform, thereby promoting transparency, environmental accountability, and international confidence-building. The disclosure Visualization Platform serves as a crucial fundamental for facilitating civic engagement, which incorporates application programming interfaces (APIs) that permit integration with external software solutions, thereby broadening the potential applications of shared nuclear information resources (Chang and Zhao 2024). Drawing on the public access provisions of Article 5 of the Aarhus Convention, the platform allows non-governmental organizations (NGOs) such as the Pacific Islands Forum (PIF), the Pacific Nuclear Safety Network (PNSN), and The Pacific Islands Association of Non-Governmental Organizations (PIANGO) and the public to register free of charge; affected communities are only required to meet minimum identification criteria (Aarhus Convention, art. 5., 1998). To ensure secure public access, the platform implements a multi-factor authentication (MFA) system—including passwords, dynamic tokens, and biometric verification—to validate user identities (Urso et al. 2012). Furthermore, a feedback module is available on the platform, allowing non-governmental organizations and representative local communities, to question the authenticity and neutrality of data disclosure and to provide their opinions. The system will regularly compile this feedback and present it through text reports, downloadable datasets, and data visualization charts.

Conclusion

This article adopts an empirical research approach by analyzing the IAEA's 2023 Safety Assessment Report, the NRA Report, the JAEA database, the TEPCO Fukushima Daiichi ALPS Treated Water Portal, and FVCOM simulation modeling, to determine that Japan's discharge of radioactive wastewater poses a radioactive contamination threat to the marine ecosystem of the Pacific Rim. However, the current marine pollution governance framework faces persistent challenges in legal enforceability, regional cooperation consensus, and transparency of environmental radiation diffusion monitoring data. Accordingly, this paper proposes the establishment of a Pacific Rim Nuclear Data Regulatory Cooperation Mechanism, which, by fostering regional consensus, aims not only to enhance the transparency of radioactive waste disposal activities but also to strengthen the transparency of monitoring data while addressing deficiencies in the legal enforceability of liability for radioactive pollution damage. The research further employs

the doctrinal research method to examine international treaties and regional legal instruments concerning nuclear data regulation, thereby laying a solid legal foundation for the proposed mechanism. The mechanism is systematically designed around four dimensions: the formulation of legal principles, the construction of legal rules, the establishment of organizational structures, and the refinement of regimes. From a theoretical perspective, the paper clarifies the legal principles and specific rules for building a Pacific Rim nuclear data regulatory cooperation mechanism. From a practical perspective, it integrates blockchain and AI-driven modeling to enhance data transparency and traceability. Nevertheless, the proposed mechanism still faces constraints at the implementation stage. Due to the absence of empirical testing under real operational conditions, its immediate applicability remains limited. Future research should focus on launching pilot cooperative monitoring projects to assess feasibility, engaging in interdisciplinary exploration that combines law, cybersecurity, and marine environmental science.

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References

- Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal. 1989, March 22. *United Nations Treaty Series*, 1673, 57.
- Beck HP (2023) Fukushima tritiated water release--What is the polemic all about? arXiv preprint arXiv:2309.07083
- Chang YC, Zhao X, Jian A, Tan Y (2024) Frontier issues in international ocean governance: Japan's discharge of nuclear contaminated water into the sea. *Mar Pollut Bull*. <https://doi.org/10.1016/j.marpolbul.2023.115853>
- Chang YC, Zhao X (2024) Addressing Japan's disposal of radioactive wastewater from the perspective of international human rights law. *Chin J Popul Resour Environ* 22(1):1–9
- Chapman N, McCombie C (2023) Multinational repositories (MNRs) highlight the need for transnational information management in geological disposal. *Front Nucl Eng* 2:1208524. <https://doi.org/10.3389/fnue.2023.1208524>
- Comprehensive Nuclear-Test-Ban Treaty*, Sept. 10, 1996, U.N. Doc A/50/1027
- Convention for a North Pacific Marine Science Organization*, Dec. 12, 1990, PICES Doc. 1990–1.
- Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters*, art. 5, June 25, 1998, 2161 U.N.T.S. 447.
- Convention on Environmental Impact Assessment in a Transboundary Context*, Feb. 25, 1991, 1989 U.N.T.S. 309.
- Convention on Nuclear Safety*, June 17, 1994, 1963 U.N.T.S. 293.
- Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter*. 1972, November 13. *United Nations Treaty Series*, 1046, 120.
- CTBTO (2023) Verification regime. <https://www.ctbto.org/our-work/verification-regime>. ctbto.org/our-work/verification-regime.
- Flick G (2021) The Evolution of Nuclear Security Cooperation in the 21st Century. Nuclear Security Governance Experts Group, Stimson Center.
- Fu B, Li H (2024) Marine environmental governance for nuclear pollution: from the perspective of China's response to Japan's Fukushima nuclear wastewater discharge. *Mar Policy* 167:106242
- Georgieva Z, Campi A, Nakayama M (2021) Cross-border nuclear security cooperation: conceptual framework and potential mechanisms. *Int J Nucl Secur* 7:1–19
- Gong W (2024) International law obligations for the disposal of Fukushima nuclear-contaminated water under the principles of nuclear safety. *Chin J Popul Resour Environ* 22:10–19. <https://doi.org/10.1016/j.cjpre.2024.03.002>
- Hirose K, Povinec P (2019) ¹³⁷Cs and ⁹⁰Sr in surface waters of the Sea of Japan: variations and the Fukushima Dai-ichi Nuclear Power Plant accident impact. *Mar Pollut Bull* 146:645–652. <https://doi.org/10.1016/j.marpolbul.2019.07.024>
- International Atomic Energy Agency (2015) The Fukushima Daiichi Accident: Report by the Director General. IAEA, Vienna
- International Atomic Energy Agency. (2018) IAEA Safety Standards Series International Atomic Energy Agency. (2023) Fukushima Daiichi ALPS Treated Water Discharge – Reports. <https://www.iaea.org/topics/response/fukushima-daiichi-nuclear-accident/fukushima-daiichi-alps-treated-water-discharge/reports>

- Japan Atomic Energy Agency. (2024) Database for Radioactive Substance Monitoring Data.
- Japan Fisheries Agency. (2024) *Report on the Impact of Fukushima Water Release on Domestic Fisheries Industry*. Retrieved from <https://www.jfa.maff.go.jp/>
- Kim S, Johnston AI (2022) Transboundary Risk Governance and the Fukushima Wastewater Controversy: Legal Norms, Scientific Uncertainty, and Regional Responses. *Ocean Development & International Law* 53(2):123–145. <https://doi.org/10.1080/00908320.2022.2057711>
- Lee H (2023) Risk perception and seafood trade: a South Korean perspective on Japan's water discharge. *Pac Aff* 96(3):403–426
- Lee H, Nakamura T (2024) Economic consequences of the Fukushima water release: a regional input-output analysis. *Asian Econ J* 38(1):22–41. <https://doi.org/10.1111/asej.12345>
- Liang X, Yang S, Lou Z, Ali A (2024) The impact of Japan's discharge of nuclear-contaminated water on aquaculture production, trade, and food security in China and Japan. *Sustainability* 16:1285. <https://doi.org/10.3390/su16031285>
- Liao H, Yang Z (2023) Health impact of nuclear wastewater discharge from the Fukushima Daiichi nuclear plant. medRxiv. <https://doi.org/10.1101/2023.04.23.23288984>
- Liu J, Yuan H, Xia Z, He P (2024) Paying attention to the safety of global edible seaweeds after the discharge of nuclear-contaminated water from Japan. *Algal Res* 23:103811
- Liu Y, Guo XQ, Zhang J, Hu Z (2022) Discharge of treated Fukushima nuclear accident contaminated water: macroscopic and microscopic simulations. *Natl Sci Rev* 9:nwab209. <https://doi.org/10.1093/nsr/nwab209>
- Men W (2021) Discharge of contaminated water from the Fukushima Daiichi Nuclear Power Plant Accident into the Northwest Pacific: what is known and what needs to be known. *Mar Pollut Bull* 173:112984. <https://doi.org/10.1016/j.marpolbul.2021.112984>
- Nomura Research Institute. (2024). Economic Forecast: Impact of Chinese Import Ban on Japanese Seafood Industry. *NRI Economic Review*, 56(3), 44–58.
- Nuclear Energy Agency (2020a) Radioactive Waste Management and Decommissioning: Annual Report 2020. OECD Publishing, Paris
- Nuclear Energy Agency. (2020). Status Report on Spent Fuel and Radioactive Waste Management in NEA Member states. OECD Publishing. https://www.oecd-nea.org/jcms/pl_31681
- Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter. 1996, November 7. *International Legal Materials*, 36(1), 1–45.
- Regional Cooperative Agreement for Asia and the Pacific*, June 10, 1987, IAEA INFCIRC/331.
- Rodell M, Barnoud A, Robertson FR, Allan RP, Bellas-Manley A, Bosilovich MG, Seneviratne SI (2024) An abrupt decline in global terrestrial water storage and its relationship with sea level change. *Surv Geophys* 45(6):1875–1902
- Smith JA, Kim S (2020) Cybersecurity risks in cross-border nuclear data exchange. *J Nucl Mater Manag* 48(3):45–59
- South Pacific Nuclear Free Zone Treaty*, Aug. 6, 1985, 1445 U.N.T.S. 177.
- Steinhauser G, Brandl A, Johnson TE (2014) Comparison of the Chernobyl and Fukushima nuclear accidents: a review of the environmental impacts. *Sci Total Environ* 470:800–817. <https://doi.org/10.1016/j.scitotenv.2013.10.029>
- TEPCO. (2023–2024). Discharging from ALPS treated water dilution/discharge facilities at the Fukushima Daiichi Nuclear Power Station.
- UNEP, Action Plan for the Protection, Management and Development of the Marine and Coastal Environment of the Northwest Pacific Region (NOWPAP), Sept. 1994.
- United Nations Convention on the Law of the Sea*. Montego Bay, 10 December 1982. United Nations.
- United Nations Economic Commission for Europe. (1998). *Convention on Access to Information, Public Participation in Decision-making, and Access to Justice in Environmental Matters (Aarhus Convention)*. Aarhus, Denmark: United Nations. Retrieved from <https://unece.org/environment-policy/public-participation/aarhus-convention>
- Urso L, Astrup P, Helle KB, Raskob W, Rojas-Palma KC (2012) Improving evaluation criteria for monitoring networks of weak radioactive plumes after nuclear emergencies. *Environ Model Softw* 38:108–116. <https://doi.org/10.1016/j.envsoft.2012.05.001>
- Wang Qiuwen Hu, Zhang JH (2022) Japan's nuclear wastewater discharge: Marine pollution, transboundary relief, and potential implications from a risk management perspective. *Ocean Coast Manag* 228:106322. <https://doi.org/10.1016/j.ocecoaman.2022.106322>
- Zhang, S. (2022). International legal issues of the Fukushima nuclear wastewater discharge plan: An examination from the perspective of radioactive waste disposal. *Japanese Studies*, (06), 49–81+150.
- Zhang T, Kang J (2020) Nuclear data regulation in China: balancing secrecy and safety. *J Risk Res* 23(10):1301–1316. <https://doi.org/10.1080/13669877.2019.1628090>
- Zhang X, Xu Q (2024) Reflections on governing Japan's discharge of Fukushima radioactive wastewater: from the perspective of building a Maritime Community with a Shared Future. *Marine Development* 2(1):20
- Zhao Y (2024) China's seafood import ban on Japan and its legal basis under WTO law. *Asian J Int Law* 14(1):87–109. <https://doi.org/10.1017/S2044251324000042>

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