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The Legal Restructuring of State Responsibility and Ecological Compensation for Transboundary Environmental Damage

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Abstract
As global environmental crises intensify, the legal regulation of transboundary ecological damage is undergoing a critical transition from a traditional private-law model of point-to-point compensation to a comprehensive global responsibility system centered on ecosystem integrity. Addressing the persistent challenges in determining and quantifying liability for transboundary environmental damage, this article critically examines the definitional dilemmas surrounding "pure environmental damage" and the fragmentation of current treaty practices. By abandoning rigid mathematical modeling in favor of strict legal dogmatics, this study establishes a dual-track normative framework distinguishing between State responsibility for internationally wrongful acts and international liability for injurious consequences arising from lawful activities. Furthermore, the article argues that the obligation of "due diligence" serves as the core jurisprudential criterion bridging this dual-track system. Through an empirical analysis of landmark international jurisprudence—including the Trail Smelter arbitration and recent advisory opinions by the International Court of Justice (ICJ) and the International Tribunal for the Law of the Sea (ITLOS)—this study exposes the limitations of traditional restoration cost methods and habitat equivalency analyses. Ultimately, the article proposes a legally grounded "Dual-Track Quantification Framework" that operationalizes the principle of Common But Differentiated Responsibilities (CBDR) and intergenerational equity. This framework aims to constrain excessive judicial discretion while providing a legally sound, predictable instrument for transboundary damage compensation that harmonizes scientific necessity with substantive legal justice.

Keywords: Transboundary Environmental Damage; State Responsibility; Internationally Wrongful Acts; Due Diligence; Ecological Compensation; Pure Environmental Damage

1 Introduction

Currently, the global community is confronting the unprecedented exacerbation of three interconnected planetary crises: climate change, biodiversity loss, and pervasive environmental pollution. Consequently, the global environmental governance deficit has widened significantly, necessitating an urgent normative shift in international environmental law. Against this backdrop, the legal frameworks governing transboundary ecological damage are approaching a critical transformative juncture. Historically rooted in traditional

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international law, the paradigm is shifting away from a private-law model—which exclusively focused on bilateral, "point-to-point" state compensation for immediate material losses—toward the establishment of a robust global responsibility architecture predicated on the preservation of ecosystem integrity.

This paradigm shift is increasingly supported by multidimensional jurisprudential developments. Notably, the International Law Commission (ILC) officially initiated a thematic study on "Reparation for injury caused by internationally wrongful acts" during its 76th session in 2025. Concurrently, the International Court of Justice (ICJ) and the International Tribunal for the Law of the Sea (ITLOS) have recently issued milestone advisory opinions regarding climate obligations and marine environment protection. Through these institutional actions, two novel legal consensuses have fundamentally materialized within the international community: first, that a substantially higher standard of judicial scrutiny must be applied to the "due diligence" obligations of States; and second, that "pure environmental damage" possesses independent, compensable legal value.

However, the crystallization of these jurisprudential consensuses has not yet resolved the formidable enforcement dilemmas present in international legal practice. The stark warnings articulated in the United Nations Environment Programme's (UNEP) 2025 Emissions Gap Report, coupled with the World Bank's estimation of an annual $8.1 trillion global pollution cost, underscore the inadequacy of existing compensatory mechanisms. Current legal instruments remain severely constrained by scientific uncertainties surrounding causation and the profound geoeconomic disparities among sovereign states.

To address these systemic deficiencies, this article advocates for the construction of a legally grounded, dual-track quantification model. Moving beyond pure economic calculations, this framework integrates legal valuation methods—such as the restoration cost method and habitat equivalency analysis—to accurately anchor ecological value. Moreover, it introduces jurisprudential adjustment coefficients based on comprehensive national development disparities and the legal standard of due diligence. By considering the practical realities of State and corporate liability allocation under international law, this model seeks to implement customary international rules and principles explicitly. Ultimately, this article endeavors to locate the optimal jurisprudential solution for transboundary environmental governance, balancing formal legal justice with practical enforceability.

2 The Meaning and Liability Typologies of Transboundary Environmental Damage

2.1 The Expansion of the Concept and Definitional Dilemmas

According to Article 2(c) of the ILC's Draft Principles on the Allocation of Loss in the Case of Transboundary Harm Arising out of Hazardous Activities (hereinafter the "Loss Allocation Draft"), transboundary damage is defined as harm originating in the territory or in places under the jurisdiction or control of a State, but producing detrimental consequences in the territory or under the jurisdiction of another State, or in areas beyond national jurisdiction such as the high seas, Antarctica, or outer space.

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From a legal perspective, this signifies that the locus of liability is not restricted to territorial installations (e.g., factories) but extends to state-registered vessels, aircraft, and extraterritorial activities conducted by nationals, such as deep-sea mining on the high seas.

As global society transitions from an industrial civilization to an ecological one, accompanied by rapid technological advancements, the international legal understanding of "environmental damage" has undergone a profound paradigm shift—transitioning from an anthropocentric societal view to a geocentric, global ecosystem perspective. Despite this theoretical evolution, the international community has thus far failed to establish a universally unified legal definition. Early international legal practice and foundational conventions did not provide a statutory basis for the compensation of "pure" environmental damage. Instruments such as the 1963 Vienna Convention on Civil Liability for Nuclear Damage and the 1972 Outer Space Treaty traditionally confined compensable liability to personal injury or direct property loss. Under this archaic framework of state responsibility, claims for environmental remediation could only be indirectly asserted as incidental consequences of economic or personal damage.

Beginning in the 1990s, the proliferation of high-risk, high-technology activities—including nuclear energy utilization, space launches, hazardous waste transportation, and deep-sea exploration—compelled international legal instruments to explicitly recognize the independent normative value of the environment itself. Despite this progressive recognition, defining the precise legal boundaries of transboundary environmental damage continues to pose a severe dual dilemma for international tribunals.

First, there remains deep doctrinal fragmentation regarding the legal definition of the "environment" itself. The ILC adopted an expansive trajectory in its Loss Allocation Draft, defining the environment to encompass both "living and non-living natural resources, such as air, water, soil, flora and fauna, and the interaction between these factors", extending even to landscape features. Secondly, within the intricate causal chains characteristic of transboundary harm, international courts face immense difficulties in isolating what legally constitutes "pure" environmental damage. According to the ILC's prevailing doctrine, pure environmental damage ought to encompass the intrinsic loss caused by environmental degradation, the costs of reasonable restorative measures, and the costs of reasonable response measures. Conversely, in specific treaty practices seeking to enhance actionable legal certainty and calculability, many liability treaties—such as the Basel Convention Protocol and the Kyiv Protocol—demonstrate a restrictive inclination. These treaties tend to limit environmental liability exclusively to the direct economic losses resulting from environmental impairment or the specific, quantifiable financial expenditures incurred through responsive measures. This severe conceptual inconsistency directly results in a fragmented jurisprudential landscape, mandating that the legal architecture for addressing transboundary environmental damage must be constructed upon disparate legal foundations.

2.2 The Dual-Track Typology of Liability

To adequately address the increasingly complex manifestations of transboundary harm, modern international law has established a dual-track architecture comprising State responsibility based on "internationally wrongful acts" and international liability for "injurious consequences arising out of acts not

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prohibited by international law". As the core product of the ILC's long-term codification efforts, the rules governing both frameworks have largely crystallized into customary international law, exerting binding legal force.

2.2.1 State Responsibility for Internationally Wrongful Acts

The legal norms governing State responsibility are primarily codified in the ILC's 2001 Draft Articles on Responsibility of States for Internationally Wrongful Acts (ARSIWA). The invocation of State responsibility is strictly predicated on the existence of an "internationally wrongful act", meaning that a State's conduct must constitute a breach of an international obligation binding upon it.

In extreme scenarios, such as armed conflicts, responsibility frequently stems from direct actions by State armed forces that violate international humanitarian law treaties. For instance, the deliberate destruction of oil fields during the Gulf War directly violated the prohibition against causing "widespread, long-term and severe damage to the natural environment" under Article 35(3) and Article 55 of the 1977 Additional Protocol I to the Geneva Conventions. However, during normalized peacetime, State responsibility typically arises not from direct, State-sponsored environmental destruction, but from the State's "omission" as a regulatory authority. By failing to exhaust all necessary regulatory mechanisms to manage hazardous activities within its jurisdiction, a State fails to meet the standard of "due diligence", thereby breaching the customary "obligation of prevention".

Once a State fails to fulfill its due diligence obligation—failing to deploy maximum efforts and appropriate means to prevent harm—it is deemed to have violated international law and must bear State responsibility. Under Article 31 of ARSIWA, the responsible State is under an obligation to make full reparation for any material or moral injury caused by the internationally wrongful act. The core objective of reparation is to wipe out all consequences of the illegal act and reestablish the situation which would have existed if that act had not been committed. In the Costa Rica v. Nicaragua case, because Nicaragua's dredging activities were legally characterized as an internationally wrongful act infringing upon sovereignty, the legal consequences fell squarely within the State responsibility framework, with the scope of compensation covering all direct losses, including environmental damage. Notably, such claims are typically initiated directly by the injured State government through diplomatic channels.

2.2.2 International Liability for Acts Not Prohibited by International Law

Determining whether a State has fulfilled its "due diligence" obligation does not rely on a rigid, abstract definition, but rather adopts a comprehensive "Factor Approach". The International Tribunal for the Law of the Sea (ITLOS), in its 2011 Advisory Opinion on Responsibilities and Obligations of States Sponsoring Persons and Entities with Respect to Activities in the Area and its 2024 Advisory Opinion on Climate Change and International Law, repeatedly emphasized that due diligence is a "variable", the content of which dynamically adjusts in response to changes in time, risks, technology, and State capacity. Based on the jurisprudence of the International Court of Justice (ICJ) and relevant arbitral tribunals, the determination of due diligence liability in transboundary environmental damage primarily relies on the following four core criteria.

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First, "knowledge" serves as the logical starting point for triggering the due diligence obligation. A State cannot prevent risks of which it is unaware, yet it cannot use "ignorance" as an excuse to evade responsibility. International judicial practice has established a parallel evidentiary standard of "actual knowledge" and "constructive knowledge". In the Corfu Channel case, although the ICJ held Albania responsible for the presence of naval mines, it did not require the State to be omniscient regarding everything occurring within its territory; rather, the Court deduced that the Albanian government "must have known" through circumstantial evidence, such as the scale of the mine-laying, the width of the channel, and the strictness of coastal defenses. This logic of presumption is particularly crucial in international environmental law. In the modern era of satellite monitoring and big data, it is exceedingly difficult for a State to claim complete ignorance of large-scale industrial emissions or ecological destruction.

More critically, the due diligence obligation requires States to establish mechanisms to proactively acquire knowledge. In the Pulp Mills on the River Uruguay case, the ICJ explicitly noted that conducting an Environmental Impact Assessment (EIA) has become a legal obligation under international law. An EIA is not merely a tool for a State to acquire information regarding project risks; it is a constituent element of fulfilling its due diligence obligation. If a State fails to conduct an EIA prior to approving a project that could cause significant transboundary impact, or if the content of the EIA is severely deficient, a court may directly determine that the State has failed to exercise due diligence, thereby ordering it to bear responsibility. This implies that "knowledge" is no longer merely a psychological state, but has been objectified into a set of procedural obligations that must be fulfilled. Furthermore, the nature of the risk dictates the intensity of the obligation. For "ultra-hazardous activities" involving nuclear energy, hazardous waste disposal, or deep seabed mining, international law tends to apply a stricter standard of constructive knowledge; merely by engaging in such activities, a State is presumed to be aware of their immense potential risks and must therefore maintain the highest level of vigilance.

Second, the Proportionality Between Risk and Conduct: Advanced Insights from the ITLOS 2024 Advisory Opinion. The "principle of risk proportionality", initially established in the Alabama Claims arbitration, has been substantially reinforced and radically expanded in contemporary environmental jurisprudence. Evaluating whether the measures adopted by a State are appropriate necessitates weighing them within a specific, dynamic risk context. The International Tribunal for the Law of the Sea (ITLOS) provided a highly forward-looking and unprecedented interpretation of this standard in its 2024 Advisory Opinion on Climate Change and International Law. Addressing the existential threat posed by global warming, ITLOS fundamentally reinterpreted the scope of "pollution of the marine environment" under Article 1, paragraph 1(4), of the United Nations Convention on the Law of the Sea (UNCLOS), explicitly categorizing anthropogenic greenhouse gas (GHG) emissions as marine pollutants. The Tribunal noted that, given the severe, cumulative, and largely irreversible harm caused by GHG emissions—such as ocean acidification, sea-level rise, and the mass bleaching of coral reefs—the standard of due diligence required for a State to fulfill its obligation under Article 194 to prevent, reduce, and control marine pollution must be exceptionally "stringent". This groundbreaking jurisprudential shift signifies that for high-risk, globalized environmental issues, routine legislative enactments or standard administrative measures are legally insufficient to secure exoneration from State responsibility. The Tribunal emphasized that the obligation of

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due diligence is not merely an obligation of conduct but a rigorous requirement to deploy "all necessary measures" and to exercise a high degree of vigilance. Crucially, the ITLOS opinion established that even when scientific evidence remains partially inconclusive regarding the exact localized impact of specific emissions, States are legally bound to adopt defensive actions based on the "precautionary approach".

Furthermore, this stringent standard dramatically alters the evidentiary landscape of transboundary harm. Historically, establishing causation required tracing a direct, linear path from a specific point-source polluter to a localized victim. However, in the context of diffuse risks like climate change or large-scale marine degradation, the ITLOS framework suggests that a State's systemic failure to enforce rigorous emission controls or to implement robust environmental impact assessments itself constitutes a breach of the proportionality requirement. For example, regarding risks involving the protection of vulnerable marine ecosystems, a State must not only enact robust domestic environmental legislation but also demonstrate a high level of continuous enforcement efficacy. Paper-based prohibitions lacking actual monitoring, patrols, and punitive mechanisms against non-compliant corporations are inherently insufficient to prove proportionality between the catastrophic risk and the State's conduct. Consequently, this stringent interpretation of proportionality arms international tribunals with the doctrinal authority to hold States accountable for regulatory complacency in the face of escalating ecological threats.

Third, the principle of Common But Differentiated Responsibilities (CBDR) must be integrated. As a flexible standard, due diligence requires consideration of a State's actual governance capacity, reflecting the CBDR principle within international environmental law. Due to a scarcity of technological, financial, and administrative resources, the specific requirements for developing countries to fulfill due diligence should theoretically be lower than those for developed countries. However, this "capacity defense" is not without a baseline. In the Advisory Opinion on Responsibilities and Obligations of States Sponsoring Persons and Entities with Respect to Activities in the Area, ITLOS clarified that while developing sponsoring States may enjoy certain preferential treatment, this primarily manifests in technical assistance and financial support, and does not imply an exemption from the obligation to establish a basic regulatory framework. For core obligations concerning the interests of the global commons, such as the protection of the marine environment, all States must achieve a "minimum standard of diligence". If a State fails to establish even the most fundamental environmental protection agencies or turns a blind eye to blatant pollution, it cannot cite "lack of capacity" as a ground for exoneration. In the ICJ's advisory opinion on climate change, the Court considered that developed nations, based on their historical emission responsibilities and robust technological capacities, must undertake earlier and more substantial emission reduction obligations and provide support to developing nations; this in itself constitutes part of fulfilling their "due diligence". Conversely, for developing countries, the due diligence requirement may focus more heavily on gradually enhancing their capacities for climate change adaptation and mitigation, premised upon receiving support.

Fourth, the effectiveness of institutional measures and control is paramount. Determining whether a State has breached its due diligence obligation typically does not involve scrutinizing a specific, isolated private violation, but rather assessing whether the State has established and effectively operated a system of "institutional measures". In the Pulp Mills on the River Uruguay case, Argentina alleged that Uruguay

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violated its obligation of prevention, yet the ICJ ultimately did not find a breach by Uruguay. The Court examined Uruguay's regulatory framework, concluding that despite procedural flaws in its notification obligations, it had formulated emission standards aligned with international norms in its substantive regulation and had conducted continuous monitoring of the plant. This indicates that the ICJ favors a "holistic assessment"; as long as a State maintains a reasonably functioning legal, administrative, and law enforcement system, it should not be readily deemed to have violated due diligence, even if an incidental pollution event occurs. Conversely, in the Costa Rica v. Nicaragua case, the Court found that Nicaragua violated its obligation to conduct an environmental impact assessment, as it failed to perform any form of transboundary impact assessment prior to undertaking river dredging—a project with obvious transboundary risks; this institutional deficiency constituted a fundamental breach of due diligence.

Furthermore, the effectiveness of control is a critical factor. For activities occurring within its territory, a State enjoys exclusive jurisdiction and therefore bears the highest regulatory obligation. However, for activities occurring outside its jurisdiction but conducted by its nationals or registered vessels—such as high seas fishing or deep seabed mining—the State's control is relatively weaker; consequently, the content of the due diligence obligation primarily transforms into an "obligation to ensure", namely, restricting the conduct of its nationals through domestic legislation and sanction mechanisms. ITLOS explicitly stated in the Request for an Advisory Opinion submitted by the Sub-Regional Fisheries Commission (SRFC) that a flag State must investigate and penalize vessels suspected of illegal fishing, and this "subsequent punishment" itself is a vital component of fulfilling the due diligence obligation.

3 Determination of Loss in Transboundary Environmental Damage

The core of the transboundary environmental damage compensation system lies in accurately defining the scope of damage from both legal and scientific dimensions, and employing rational methodologies to monetize and quantify these damages. From the early Trail Smelter arbitration to recent judgments by the International Court of Justice (ICJ), international judicial practice regarding the identification of damage types, the evidentiary standards for causation, and valuation methodologies has undergone a significant evolution—transitioning from a "property-damage-centric" approach to an "ecosystem-function-centric" paradigm. This evolution reflects the gradual acceptance and normative standardization of remedies for "pure environmental damage" within international environmental law.

3.1 Types of Transboundary Environmental Damage and Causation

In international legal practice, not all negative changes related to the environment constitute compensable damage. When adjudicating such cases, courts and arbitral tribunals typically rely on legal principles such as "directness", "certainty", and "reasonableness" to filter compensable types of damage and subsequently allocate the burden of proof.

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3.1.1 Judicial Recognition of Compensable Damage Types

First, environmental restoration and clean-up costs currently represent the most widely accepted type of damage in international judicial practice. The United Nations Compensation Commission (UNCC), in addressing environmental damage caused by Iraq's invasion of Kuwait, established a core principle: the costs of any reasonable measures aimed at restoring the damaged environment to its "baseline condition" shall be fully compensated. For instance, in the Kuwaiti oil lakes clean-up case, the Commission supported the costs associated with removing soil contamination caused by oil spills. The jurisprudential foundation of this category is that physically removing pollutants is the most direct method to eliminate the consequences of an unlawful act.

Second, monitoring and assessment costs have been recognized as an independent category of compensable damage. Even if monitoring results ultimately reveal no severe environmental damage, as long as the monitoring activity was based on reasonable scientific hypotheses and targeted a significant potential risk (such as public health risks), the associated financial costs are compensable. This embodies the precautionary principle, dictating that when facing complex environmental risks, the injured State possesses both the right and the legal obligation to conduct scientific assessments to determine the nature and scope of the damage.

Furthermore, the temporary loss of ecosystem service functions has also been incorporated into compensable damage types. In the Costa Rica v. Nicaragua case, the ICJ confirmed that compensation for environmental damage must include not only the costs of restoring the damaged environment but also the value of the lost ecosystem services during the period from the impairment until full recovery. This ruling, echoing the established practices of the UNCC, affirmed the compensability of "pure environmental damage", establishing that the environment itself and its service functions possess legal value independent of human property interests.

However, judicial practice also imposes strict limitations on the scope of such claims. Purely theoretical or speculative damage claims are generally not supported. For example, the UNCC rejected Syria's claim regarding acid rain in its territory allegedly caused by the Kuwaiti oil well fires, reasoning that meteorological models indicated the smoke plumes primarily drifted southward, and the claimant lacked field measurement data to substantiate its theoretical projections. Additionally, recreational value losses calculated based on the "travel cost method" are often dismissed due to ambiguous causation. In the Kuwaiti beach pollution case, the Commission held that the public's reduced beach attendance in the immediate post-war period was caused not solely by oil pollution, but primarily by the presence of landmines and security checkpoints, making it impossible to isolate the loss of value caused exclusively by "environmental pollution".

3.1.2 The Burden and Standard of Proof for Causation

In transboundary environmental damage cases, establishing the causal chain between the unlawful act and the resulting damage is crucial for obtaining compensation, with the burden of proof generally following the procedural principle of "he who asserts must prove". In the Pulp Mills on the River Uruguay case, the ICJ reiterated this principle; because Argentina failed to provide conclusive scientific evidence proving that

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the water quality deterioration was directly caused by the pulp mill, the Court dismissed its compensation claim, indicating that the plaintiff bears a strict burden of scientific proof. However, in specific contexts, the burden of proof may be reversed. In the Armed Activities on the Territory of the Congo (Democratic Republic of the Congo v. Uganda) case, the ICJ established an important legal rule: regarding resource plunder and environmental destruction occurring within occupied territories under Uganda's effective control, Uganda, as the occupying power, bore the obligation of "vigilance" and maintaining order. Consequently, the burden shifted to Uganda, as the defendant, to prove that the environmental damage in that area was not caused by its failure to fulfill its obligations as an occupying power. This reversal of the burden of proof significantly alleviated the injured State's evidentiary burden when collecting evidence in a war-torn environment.

Furthermore, when confronting complex scientific uncertainty, the standard of proof demonstrates a degree of judicial flexibility. The arbitral tribunal in the Trail Smelter case noted that when the nature of the tortious act makes it difficult to ascertain the exact amount of damage, evidence demonstrating a "just and reasonable inference" of the extent of the damage is sufficient to form the legal basis for compensation. This reflects international law's pragmatic balance between pursuing rigorous scientific certainty and ensuring the injured State receives substantive legal relief.

3.2 Methodologies for the Determination of Damage Values

3.2.1 The Restoration Cost Method and Its Reasonableness Limitations

The restoration cost method is the mainstream approach for addressing physical environmental damage; its logic involves calculating the engineering costs required to restore the environment from a damaged state to its baseline condition. However, the application of this method is strictly constrained by the legal principle of "reasonableness". In the Kuwaiti oil lakes case, Kuwait proposed using high-temperature thermal desorption technology to treat the contaminated soil. The UNCC's panel of experts reviewed the proposal and concluded that while this technology could completely eradicate the oil, it was exorbitantly expensive and would destroy soil biological activity, causing secondary ecological harm. Consequently, the expert panel utilized a more economical and ecologically friendly bioremediation and landfill technology as the basis for calculation, substantially reducing the compensation amount. This case established that when applying the restoration cost method, a judicial balance must be struck among technical feasibility, cost-benefit rationality, and ecological safety.

3.2.2 Habitat Equivalency Analysis (HEA)

To address the temporary loss of ecosystem service functions, traditional market valuation methods often fail, prompting the introduction of Habitat Equivalency Analysis (HEA). The core rationale of this method is "service-to-service" compensation, meaning that the ecological service functions lost to the public due to environmental impairment can be offset by implementing compensatory restoration projects of an equivalent magnitude. The UNCC applied this method in processing claims from Jordan and Kuwait, determining the scale of compensatory projects by calculating the "discounted service acre-years" of the impaired ser-

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vices. The application of HEA marks international law's formal acceptance of addressing pure environmental damage through non-monetized ecological compensation mechanisms.

3.2.3 The Overall Assessment Method and the Global Sum Method

When it is impossible to precisely calculate the specific financial amount of each individual damage, international courts tend to exercise judicial discretion and adopt macroscopic valuation methods. In the Costa Rica v. Nicaragua case, the ICJ rejected both the "ecosystem services approach" advocated by Costa Rica, which attempted to price and accumulate each specific service individually, and the "replacement cost approach" proposed by Nicaragua, which only calculated the cost of replanting trees. The Court found that the former lacked sufficient evidence for certain parts, while the latter's valuation was excessively low. Therefore, the Court adopted an overall assessment method, comprehensively considering the nature of the damaged ecosystem, the severity of the damage, and its restorative capacity, to directly award an overall compensation figure encompassing both restoration costs and the loss of ecological services.

Similarly, in the Armed Activities on the Territory of the Congo case, facing the predicament of detailed evidence being destroyed by warfare, the Court employed the global sum method. The Court did not mechanically track every single plundered natural resource; instead, based on expert reports and UN investigations, it awarded a global compensation sum of $60 million covering all natural resource losses. This method eschews precise arithmetic accumulation in favor of the principle of fairness and reasonableness, resolving the dilemma of the "inability to produce evidence" in conflict environments.

3.2.4 Summary

Although the aforementioned methodologies have played a critical role in resolving specific transboundary environmental disputes, they still exhibit significant limitations in terms of universality and precision. The restoration cost method is constrained by technical feasibility and cost-benefit considerations, and is often powerless in the face of irreversible ecological damage. While HEA is theoretically advanced, its precise application in transboundary damage scenarios is frequently hindered by a severe lack of detailed baseline ecological data. Furthermore, although the global sum method and the overall assessment method resolve the issue of missing evidence, they inherently rely on the discretionary power of judges, lack uniform calculation standards and transparent mathematical models, and easily lead to unpredictability in compensation outcomes.

Moreover, the existing system primarily focuses on ex post remedies and lacks a standardized quantification tool capable of integrating the dual-track liability architecture of "internationally wrongful acts" and "acts not prohibited by international law" while making differentiated adjustments for States at varying stages of development. Consequently, constructing a more inclusive and scientifically rigorous quantification model for transboundary environmental damage compensation is particularly necessary, representing the core jurisprudential problem this study attempts to resolve in the subsequent chapter.

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4 The Dual-Track Quantification Model for Transboundary Environmental Damage Compensation

4.1 Principles of Model Construction and Variable Configuration

Given the established dual-track jurisprudential distinction in international law between State responsibility for internationally wrongful acts and international liability for injurious consequences arising out of acts not prohibited by international law, this study constructs a dual-track quantification model predicated on "standardized mean assessment" and "comprehensive development disparity adjustment". To eliminate the incidental interference of single-year climatic fluctuations and economic data anomalies, all physical quantities and economic parameters within the model utilize a five-year arithmetic mean.

4.1.1 The Scientific Baseline of Present Damage Value

Based on the ecosystem service restoration cost method, the model introduces a discount rate from the perspective of intergenerational equity to construct the baseline damage calculation. The scientific baseline of the present damage value is determined by integrating the mean physical damage attributable to the State of origin over the restoration period, the cross-border transmission attribution coefficient, and the mean unit cost of ecological restoration.

Crucially, the social discount rate is locked at 3%, adhering to the recommendations of the U.S. National Oceanic and Atmospheric Administration (NOAA) for Natural Resource Damage Assessment (NRDA). This legally mandated rate is significantly lower than commercial capital return rates. This specific configuration serves the critical jurisprudential purpose of preventing the ecological rights of future generations from being unduly diluted by temporal compound interest effects, thereby legally operationalizing the principle of intergenerational equity within international environmental law.

4.1.2 The Comprehensive National Development Disparity Assessment

To legally operationalize the principle of Common But Differentiated Responsibilities (CBDR) within the compensatory architecture, this study proposes a structured normative test—the Comprehensive National Development Disparity Assessment. Rather than relying on a rigid arithmetic formula, this framework establishes a proportionality-based legal assessment that integrates three core jurisprudential elements: economic capacity, societal reliance on natural resources, and inherent ecological vulnerability.

First, the economic capacity to provide compensation serves as the threshold inquiry. Measured through the metric of mean Gross National Income (GNI) per capita, it reflects the marginal utility of the financial burden imposed on the responsible State. This ensures that compensatory mandates do not violate the principle of economic proportionality or compromise the State's fundamental sovereign functions.

Second, this baseline is subjected to a normative adjustment based on the injured State's societal resource dependency. Evaluated through the proportion of the national economy derived from primary sectors, this criterion legally translates the impact of environmental degradation on fundamental human rights

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and social welfare. A profound dependency dictates a corresponding upward corrective adjustment in the compensatory burden of the State of origin, reflecting the imperatives of distributive justice.

Finally, the assessment incorporates the ecosystem's inherent vulnerability—its resistance to anthropogenic interference and the objective difficulty of remediation. In balancing these factors, the framework assigns normative primacy to the overarching principle of fairness as the foundational determinant of liability allocation. The material considerations of societal dependency and ecological fragility serve as co-equal, secondary adjusting factors. Through this structured legal hierarchy, the compensatory mechanism is constrained by economic enforceability while robustly safeguarding baseline social welfare and international ecological security.

4.2 The Quantification Model for State Responsibility

This legal pathway applies exclusively to scenarios where a State has failed to fulfill its regulatory due diligence obligations or where subjective fault exists, constituting an internationally wrongful act. This pathway adheres to the principle of "full reparation" while incorporating delay interest as a punitive mechanism and establishing a social welfare "circuit breaker" threshold.

The total theoretical compensation encompasses the baseline damage value adjusted by a delay interest rate, a contributory negligence coefficient, a due diligence coefficient, and the development disparity index. The delay interest rate is intentionally set higher than commercial lending rates to penalize dilatory compensation behaviors and compel the responsible State to fulfill its legal obligations promptly.

Crucially, under the State responsibility pathway, because the conduct has already been legally characterized as an "internationally wrongful act"—indicating that the State objectively failed to exercise due diligence—no fault-free mitigation logic applies. Therefore, the due diligence coefficient is strictly locked at 1.0, mandating full baseline liability. Furthermore, a social welfare circuit breaker is established in accordance with international human rights law principles concerning the "non-deprivation of means of subsistence", ensuring that compensation does not precipitate state collapse or the defunding of essential public health and education services.

4.3 The Normative Framework for International Liability Allocation

For transboundary damage arising from lawful yet inherently hazardous activities, this study proposes a tiered allocation mechanism that operationalizes the dichotomy between private operator liability and State supplementary obligations. This framework is governed by a tripartite legal logic: primary enterprise liability, supplementary State liability, and equitable risk-sharing.

The Primary Threshold: Enterprise Liability Limit Grounded in the "polluter pays" principle, the initial burden of compensation falls exclusively upon the private enterprise. However, to prevent the compensatory regime from producing disproportionate economic devastation, this primary liability is capped by a strict legal ceiling. This limit is determined by synthesizing the enterprise's mandatory environmental liability insurance coverage with a reasonable, audited fraction of its historical net profits. By imposing

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a legally binding financial safety margin, the framework ensures that compensatory obligations do not precipitate severed capital chains or systemic unemployment, thereby adhering to the principle of economic proportionality.

The Secondary Safeguard: State Supplementary Liability When the baseline ecological damage exceeds the private enterprise's liability ceiling, the framework triggers the secondary obligation of State supplementary liability. Crucially, because the State of origin has, ex hypothesi, fulfilled its due diligence obligations—thus precluding the finding of an internationally wrongful act—its supplementary liability is not punitive. Instead, it is characterized by the legal doctrine of risk-sharing.

Consequently, the State's compensatory burden is mitigated by a due diligence recognition factor, acknowledging its adherence to normative regulatory standards. The final allocation of this supplementary burden is dynamically governed by the aforementioned Development Disparity Assessment. Under this paradigm, a pronounced geoeconomic asymmetry—where the State of origin possesses robust financial capacity while the injured State suffers high resource dependency—mandates a regime of "strong compensation", compelling the State of origin to internalize the residual environmental costs. Conversely, a parity in development indicators invokes a logic of reciprocal compensation. In extreme scenarios where the State of origin experiences severe economic distress and the injured State exhibits low ecological vulnerability, a "survival exemption" may be activated, equitably distributing a fraction of the residual risk to the injured State.

4.4 Empirical Application and Scenario Simulation: A Deep-Sea Mining Case Study

To demonstrate the practical enforceability and judicial utility of the "Dual-Track Quantification Model", this section constructs a highly realistic scenario simulation based on contemporary transboundary environmental risks. The scenario examines an ecological disaster stemming from deep-sea polymetallic nodule mining, a rapidly emerging frontier in international environmental law.

4.4.1 Scenario Parameters and Factual Matrix

Assume a hypothetical scenario where an entity registered in and sponsored by a developed nation (State A) conducts deep-sea mining operations in the Clarion-Clipperton Zone. Due to operational failures, a toxic discharge causes catastrophic, irreversible ecological harm to the Exclusive Economic Zone of a Small Island Developing State (State B), a nation characterized by high ecological vulnerability and profound societal dependence on marine ecosystems. An independent investigation confirms that while the private operator violated safety protocols, State A had fully discharged its due diligence obligations by enacting stringent domestic regulations and requiring comprehensive environmental impact assessments prior to sponsorship. The accident was ultimately precipitated by unforeseeable mechanical fatigue.

4.4.2 Step 1: Ascertaining the Scientific Baseline of Present Damage

Under judicial supervision, ecological experts apply Habitat Equivalency Analysis and the restoration cost method to determine the scientific baseline of the damage. By calculating the costs necessary for

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physical ecological restoration and the temporary loss of ecosystem services over the projected recovery period, a preliminary gross damage valuation is established. This valuation is subsequently adjusted using a legally mandated social discount rate rooted in intergenerational equity, ultimately yielding the finalized present value of the baseline ecological damage.

4.4.3 Step 2: Applying the International Liability Pathway and Tier 1 Allocation

Because State A has demonstrably fulfilled its due diligence obligations, its conduct precludes the invocation of State responsibility for internationally wrongful acts, thereby barring punitive measures such as delay interests or strict liability without fault. Consequently, the tribunal applies the framework for international liability arising from lawful activities.Under the first tier of this framework, the private operator bears the primary compensatory burden pursuant to the "polluter pays" principle. However, to prevent disproportionate economic disruption and corporate insolvency, this primary liability is capped by a strict statutory ceiling. This ceiling is derived by synthesizing the operator's compulsory environmental liability insurance coverage with a legally prescribed, safe proportion of its historical net profits, establishing the absolute limit of the enterprise's financial obligation.

4.4.4 Step 3: Activating Tier 2 State Supplementary Liability and the Disparity Index

Upon exhausting the enterprise’s maximum liability, a substantial portion of the baseline ecological damage remains uncompensated, thereby triggering the second tier of State supplementary liability. At this juncture, the tribunal conducts a Comprehensive National Development Disparity Assessment to operationalize the principle of Common But Differentiated Responsibilities (CBDR). Given the profound geoeconomic asymmetry between the highly developed State of origin and the ecologically vulnerable, resource-dependent injured State, the jurisprudential evaluation yields a significant development disparity multiplier.Although State A’s supplementary liability is initially mitigated by its adherence to due diligence standards—reflecting a logic of equitable risk-sharing rather than penalization—this reduction is ultimately superseded by the aforementioned disparity multiplier. This normative adjustment mandates a regime of strong compensation, amplifying State A's theoretical liability to a level that exceeds the residual uncompensated damage. Consequently, State A is legally compelled to fully absorb the remaining ecological costs through its national environmental compensation funds. Through this simulation, the Dual-Track Quantification Model effectively guarantees that the vulnerable injured State receives complete ecological remediation without precipitating private sector insolvency, formally anchoring the State's supplementary burden within the objective tenets of international equity and CBDR.

4.5 Institutional Safeguards and Future Perspectives

While the Dual-Track Quantification Model provides a robust jurisprudential and mathematical framework for resolving transboundary environmental disputes, its theoretical elegance cannot operate in a procedural vacuum. For this framework to be effectively operationalized within the existing architecture of international tribunals, such as the International Court of Justice (ICJ) or the International Tribunal for the Law of the Sea (ITLOS), a series of corresponding institutional safeguards and procedural mechanisms

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must be established at the global level.

First, overcoming the evidentiary barriers associated with the Habitat Equivalency Analysis (HEA) and the baseline scientific damage calculation requires the establishment of a centralized international environmental data-sharing mechanism. Currently, developing nations frequently lack the historical ecological baseline data necessary to prove the full extent of pure environmental damage. To rectify this structural evidentiary asymmetry, it is highly recommended that the United Nations Environment Programme (UNEP) spearheads the creation of a "Global Ecological Baseline Registry". Such a registry would securely compile and standardize environmental monitoring data, satellite imagery, and biodiversity inventories, providing international judges with objective, third-party scientific benchmarks when adjudicating the actual physical damage variable within the model.

Second, the rigorous application of the "Factor Approach" to evaluate a State's due diligence—particularly regarding complex technical thresholds and risk proportionality—demands specialized epistemic support. International judges, primarily trained in public international law, face inherent limitations when reviewing highly technical environmental impact assessments or chemical pollution trajectories. Therefore, international judicial bodies should transition from ad hoc expert appointments to the institutionalization of a "Permanent Roster of Independent Scientific and Economic Experts". This roster would actively assist the tribunal in cross-examining corporate technical defenses and verifying the appropriateness of the development disparity index parameters, ensuring that the judicial presumptions applied within the quantification model are scientifically incontrovertible.

Finally, looking toward the progressive development of international law, the quantification model proposed in this study offers a tangible legislative blueprint. As the International Law Commission (ILC) advances its newly adopted thematic study on "Reparation for injury caused by internationally wrongful acts" throughout the late 2020s, the Commission must move beyond abstract principles of restitution. It is imperative that future ILC drafts formally codify specific quantitative adjustment mechanisms—such as the "Comprehensive National Development Disparity Index"—into soft law instruments or draft guidelines. By explicitly translating the customary principle of Common But Differentiated Responsibilities (CBDR) into an operational metric for liability allocation, international law can transition from fragmented, case-by-case equitable estimations to a standardized, predictable, and structurally just regime for global ecological compensation. Ultimately, equipping international environmental governance with these institutional safeguards will ensure that the legal restructuring of state responsibility effectively deters high-risk ecological negligence while safeguarding the sustainable development of vulnerable nations.

5 Conclusion

The dual-track quantification model constructed in this study aims to dismantle the "black box" dilemma inherent in the judicial determination of compensation amounts within current international practice. By translating physical damage attribution, restoration cost assessment, and national development disparities into standardized legal formulas, this model establishes a "baseline anchor" for compensation calculations.

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This quantitative mechanism effectively restricts arbitrary judicial discretion, compelling compensation figures to align with scientific facts and legal logic, thereby ensuring the objective fairness of judgments. Simultaneously, acknowledging the extreme political, economic, and ecological complexities of transboundary environmental damage cases, this model deliberately avoids rigid mechanical calculations, preserving a controlled space for judicial adjustment. Judges retain the authority to make legally sound adjustments to critical coefficients based on the specifics of the case, such as the due diligence coefficient reflecting the degree of subjective fault or the development disparity weights reflecting specific geopolitical contexts. This institutional design—predicated on "scientific quantification supplemented by judicial discretion"—restricts the abuse of power while retaining the flexibility necessary to adjudicate complex individual cases, ultimately achieving a dynamic equilibrium between legal certainty and substantive justice.

Furthermore, the implementation of this model signifies a crucial paradigm shift in international environmental governance. By explicitly embedding the principle of Common But Differentiated Responsibilities (CBDR) and the concept of intergenerational equity into measurable variables, the framework transcends the traditional, fragmented paradigm of ex-post remediation. Instead, it serves as a powerful ex-ante deterrent, compelling sovereign States and transnational corporations to fully internalize the true costs of their ecological risks before engaging in ultra-hazardous activities. As the international community confronts escalating planetary crises, transitioning from ambiguous equitable estimations to this mathematically grounded, legally robust architecture is not merely a procedural upgrade. It is an indispensable evolution toward a more resilient, accountable, and ecologically sustainable global legal order.

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