

Article

Oil-Spill Damage Valuation for Regional Sustainability Transitions in the Russian North: A Modular Institutional Framework

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Abstract

Environmental damage assessment has become an important institutional component of regional sustainability transitions, especially in resource-dependent northern territories where industrial risks, fragile ecosystems, sparse monitoring networks, and limited institutional capacity intersect. Existing oil-spill valuation approaches provide well-developed legal, economic, and ecosystem-service tools; however, their use as decision-support instruments for compensation governance, prevention investment, monitoring design, and regional resilience policy remains insufficiently operationalized. This article addresses this gap by developing a modular institutional framework for selecting and combining established environmental damage valuation methods under the ecological, legal, data-related, and socio-cultural constraints of the Russian North. The study applies a transparent narrative methodological review and framework-building design based on international and Russian literature, official regulatory sources, natural-resource damage assessment practice, ecosystem-service valuation studies, and publicly available evidence on the 2020 Norilsk diesel fuel spill. The analysis organizes six established valuation approaches into three complementary modules: direct harm, indirect and opportunity-related losses, and non-market ecosystem-service losses. The Norilsk case is used as an illustrative plausibility check rather than a full empirical recalculation. It shows that legally recognized compensation can provide a liability signal, but indirect losses and ecosystem-service components require separate evidence, sensitivity analysis, and double-counting control. The contribution of the article is to adapt established valuation methods into a transparent decision-support protocol that links environmental liability, compensation governance, prevention, monitoring, institutional resilience and regional sustainability transitions in Arctic and sub-Arctic resource regions.

Keywords: environmental damage valuation; oil spills; Russian North; ecosystem services; compensation governance; sustainability transitions



Academic Editors: Akim Mohsin and Markus Gerschberger

Received: 18 May 2026

Revised: 3 July 2026

Accepted: 7 July 2026

Published: 9 July 2026

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1. Introduction

Oil spills remain a global environmental and regional-development problem because they transform industrial risk into ecological degradation, public costs, lost ecosystem

services, and institutional conflicts. This problem is particularly acute in Arctic and sub-Arctic regions, where low temperatures, seasonal ice, long response distances, sensitive food webs, and limited infrastructure increase the persistence of oil and the uncertainty of ecological recovery [1–5]. Recent modelling, remote-sensing, and risk-assessment studies further show that spill trajectories, exposure zones, ecological sensitivity, and response priorities depend not only on pollutant mass, but also on spatial data, baseline assumptions, scenario design, and uncertainty treatment [6–15]. These findings make oil-spill damage valuation a governance issue as well as a technical task: valuation must be scientifically credible, legally defensible, and usable for prevention, restoration, compensation, and regional policy learning.

Internationally, several mature approaches already link environmental injury, compensation, and restoration. The United States Natural Resource Damage Assessment and Restoration (NRDA/NRDAR) framework connects injury assessment, lost public use, restoration planning, and recovery of damages from responsible parties [16–19]. The European Environmental Liability Directive (ELD) similarly emphasizes the prevention and remedying of environmental damage, while recent European policy analysis continues to develop the polluter-pays principle as a liability and prevention instrument [20,21]. Ecosystem-service and plural valuation research has further expanded the scope of environmental assessment by drawing attention to provisioning, regulating, cultural, relational, and non-market values that may be excluded from direct clean-up or restoration cost calculations [22–26]. Thus, the international literature already provides strong methodological and institutional foundations for environmental damage valuation.

The Russian North represents a specific regional case within this global challenge. Oil extraction, processing, storage, and transportation are concentrated in territories where ecosystems are vulnerable, infrastructure is spatially dispersed, monitoring networks are uneven, and some local and Indigenous communities depend on land and water systems for subsistence, mobility, and cultural continuity. The 2020 Norilsk diesel fuel spill illustrated this combination of industrial infrastructure risk, Arctic environmental vulnerability, legal compensation, and public concern [27,28]. Russian studies and regulatory practice provide important tools for calculating direct harm and compensation, especially through legally established procedures and expert appraisal mechanisms [29–41]. However, their capacity to capture delayed ecological recovery, indirect economic losses, non-market ecosystem-service losses, uncertainty, and socio-cultural effects remains uneven.

For regional sustainability transitions, oil-spill valuation is therefore broader than technical damage accounting. Resource-dependent northern territories cannot be understood only through the lens of decarbonization technologies or industrial modernization. Similar governance challenges have also been documented internationally in other resource-dependent economies, where dependence on oil rents and institutional complexity influence the pace and effectiveness of sustainability transitions [42]. These regions also face institutional challenges associated with strengthening environmental liability, monitoring, prevention, community inclusion, and regional resilience while remaining economically dependent on natural-resource extraction. Sustainability-transition and regional-resilience studies emphasize that transition pathways are spatially embedded and shaped by institutional capacity, governance arrangements, regional specialization, and policy learning [43–52]. In this context, environmental damage valuation can function as an institutional mechanism that influences whether environmental externalities are internalized, whether firms invest in prevention, whether affected communities and ecosystem services are recognized, and whether regional authorities can learn from accidents.

The literature gap addressed in this article is not the absence of valuation methods. Restoration cost, replacement cost, market price valuation, opportunity cost assessment,

avoided-cost logic, willingness-to-pay approaches, NRDA/NRDAR, ELD, and ecosystem-service valuation are already well established [16–26,53–58]. The gap lies in the weak operational connection between these approaches and their institutional use in remote northern resource regions. Existing studies often treat valuation either as a computational exercise, a legal compensation instrument, or an ecosystem-service assessment problem. Less attention has been paid to how established methods can be organized into a reproducible decision-support protocol that separates direct harm, indirect and opportunity-related losses, and non-market ecosystem-service losses; avoids double counting; and links each component to compensation governance, prevention investment, monitoring design, and institutional resilience.

The purpose of this article is to analyze the applicability of environmental damage valuation methods to oil-spill cases in the Russian North and to develop a modular institutional framework for using valuation as a support tool for regional sustainability transitions. The study addresses three research questions: (1) Which valuation approaches are most relevant for oil-spill damage under northern ecological, legal, socio-economic, and data constraints? (2) How can regional sustainable transformation be operationalized in relation to valuation results? (3) How can established valuation methods be combined in a transparent framework while limiting double-counting risks and avoiding overstatement of methodological novelty?

The contribution of the article is focused and institutional rather than formula-based. The paper does not seek to replace NRDA/NRDAR, ELD, Russian regulatory calculations, or established ecosystem-service valuation systems. Instead, it adapts established valuation approaches to the Russian North and organizes them into a modular framework that links valuation categories to institutional functions. This framework is intended to support compensation governance, prevention investment, monitoring design, ecosystem-service recognition, and regional resilience policy in Arctic and sub-Arctic resource regions.

The article is structured as follows. Section 2 explains the research design, evidence base, review protocol, spatial scope, key concepts, and framework-building procedure. Section 3 presents the results of the global and Russian methodological comparison and derives the modular framework. Section 4 provides an illustrative validation using the 2020 Norilsk diesel fuel spill. Section 5 discusses the theoretical, policy, and managerial implications. Section 6 presents the limitations and future research directions. Section 7 concludes.

2. Materials and Methods

2.1. Research Design, Evidence Base, and Review Protocol

The study was designed as a narrative methodological review combined with framework building. This design is appropriate because the article does not aim to estimate a single monetary value for one spill event. Instead, it compares heterogeneous valuation approaches and evaluates their institutional usability under northern ecological, legal, socio-economic, and data conditions. To improve transparency, the narrative review was implemented through an explicit search, screening, and coding protocol inspired by the logic of reproducible review reporting, while recognizing that the purpose is conceptual synthesis rather than a full systematic review or meta-analysis [57,58]. The methodological workflow and measures adopted to improve transparency and reproducibility are summarized in Table 1 and Figure 1, respectively.

Table 1. Review protocol and measures used to improve reproducibility.

Protocol Element	Implementation in This Study	Reason for Inclusion
Databases and sources	Scopus, Web of Science, ScienceDirect, Google Scholar, MDPI journals, eLIBRARY, official legal portals, NRDA/NRDAR sources, ELD documentation, company reports, and publicly available regulatory materials	Captures international and Russian scientific literature together with legal, methodological, and institutional evidence relevant to environmental damage valuation
Search period	Literature and regulatory sources published up to May 2026, with priority given to studies published between 2020 and 2026 whenever appropriate	Balances foundational valuation concepts with recent developments in oil-spill assessment, ecosystem-service valuation, and sustainability-transition research
Core search strings	“oil spill” AND “environmental damage valuation”; “natural resource damage assessment”; “ecosystem services” AND “oil spill”; “Arctic oil spill”; “Indigenous valuation”; “Russian North” AND “environmental harm”; “Norilsk diesel spill”, together with equivalent Russian-language terms	Improves transparency and facilitates replication of the literature search
Evidence coding	Each source was coded according to valuation method, damage component, institutional function, ecosystem-service coverage, data requirements, uncertainty treatment, Arctic applicability, and policy implications	Ensures systematic comparison of heterogeneous evidence and supports transparent framework development
Inclusion criteria	Studies addressing environmental damage valuation, oil-spill impacts, northern ecological constraints, ecosystem services, environmental liability, compensation mechanisms, sustainability transitions, regional resilience, or Russian environmental-damage methodology	Aligns evidence selection with the study objectives and research questions
Exclusion criteria	Sources focused exclusively on engineering clean-up technologies without valuation or governance relevance; duplicate publications; non-verifiable documents; and background sources superseded by more recent and authoritative evidence	Reduces selection bias and maintains methodological focus
Objectivity controls	Contrary evidence was retained and coded; official information was triangulated with peer-reviewed literature and publicly available data; methodological limitations and uncertainty sources were explicitly documented; no claim of full empirical validation was made	Improves transparency, reduces confirmation bias, and strengthens the credibility of the narrative review

Source: Compiled by the authors.

The evidence base included four source groups: (i) peer-reviewed international literature on oil spills, Arctic risk, ecosystem-service valuation, economic damage functions, and sustainability transitions; (ii) Russian peer-reviewed and methodological literature on ecological–economic damage assessment; (iii) official legal and regulatory materials, including Russian environmental legislation, NRDA/NRDAR rules, and the EU ELD; and (iv) publicly available case information for the 2020 Norilsk diesel fuel spill. Official sources were not treated as neutral empirical datasets. Their content was triangulated with peer-reviewed literature, company statements, remote-sensing studies, and regulatory documents when possible.

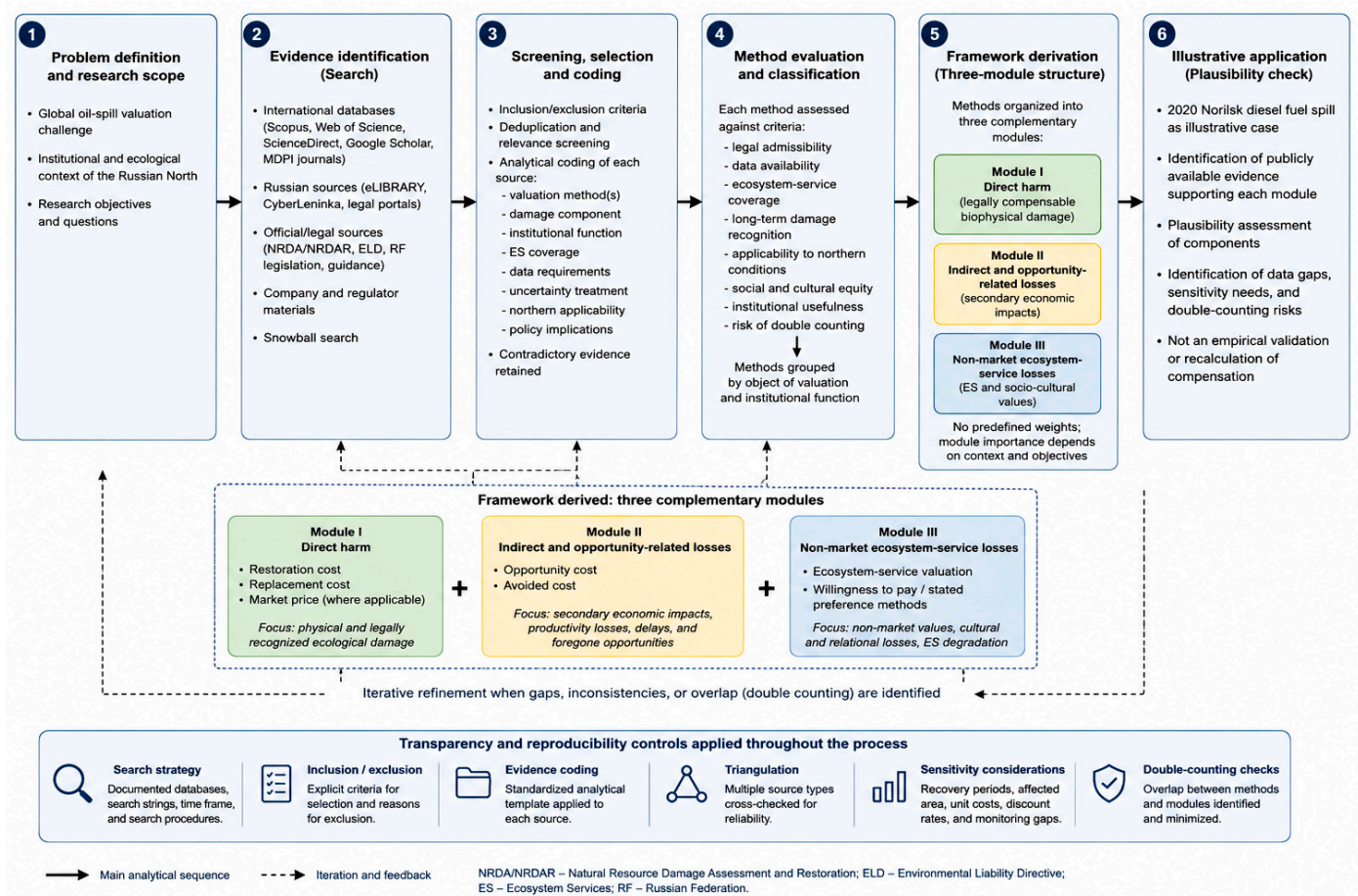


Figure 1. Research workflow illustrating evidence identification, screening, coding, method evaluation, framework derivation, and illustrative application. The framework was developed through sequential comparison of valuation methods according to their institutional function, environmental scope, data requirements, legal applicability, and risk of double counting. The transparency measures applied throughout the review process are shown below the workflow.

The search covered literature and regulatory sources available up to May 2026. International databases and search platforms included Scopus, Web of Science, ScienceDirect, and Google Scholar, along with targeted searches of publisher websites (including MDPI) and official regulatory resources. Search strings combined terms such as oil spill, environmental damage valuation, natural resource damage assessment, ecosystem services, Arctic, sub-Arctic, Indigenous valuation, avoided cost, replacement cost, willingness to pay, environmental liability, Russian North, Norilsk, and their Russian equivalents. Snowball searches were conducted from reference lists of highly relevant papers and official documents. To improve methodological transparency and reproducibility, each included publication or document was coded using a structured analytical template adapted from narrative evidence synthesis approaches [57,58]. The coding procedure recorded: (i) valuation method(s) discussed; (ii) environmental damage component addressed (direct, indirect, or ecosystem-service related); (iii) legal or institutional applicability; (iv) ecosystem-service coverage; (v) data requirements; (vi) treatment of uncertainty; (vii) relevance to Arctic or sub-Arctic conditions; and (viii) implications for environmental governance and regional sustainability transitions [23,24,43,48]. Rather than statistically synthesizing evidence, the coded information was compared across sources to identify recurring methodological patterns, institutional functions, areas of consensus, and unresolved limitations. Contrary findings were retained throughout the analysis to reduce confirmation bias and ensure that both the strengths and weaknesses of existing valuation approaches informed framework

development [23,24,57]. Approximately 230 potentially relevant publications, reports, legal documents, methodological guidelines, and publicly available datasets were identified during the initial search. After screening for topical relevance, methodological quality, duplication, and evidential value, 92 sources formed the analytical evidence base used for framework construction. During the screening process, records were excluded because they (i) focused exclusively on engineering spill response technologies without relevance to environmental damage valuation or governance; (ii) duplicated information already represented in higher-quality sources; (iii) lacked sufficient methodological description or verifiable bibliographic information; or (iv) addressed environmental pollution in general without providing evidence relevant to oil-spill valuation, institutional assessment, or sustainability transitions.

The inclusion criteria were: direct relevance to environmental damage valuation, oil-spill impact assessment, Arctic or northern ecosystem vulnerability, ecosystem-service or non-market valuation, environmental liability, compensation mechanisms, regional sustainability transitions, regional resilience, or Russian environmental-damage methodology. The exclusion criteria were: sources focused only on engineering clean-up technologies without valuation or governance implications; duplicate or non-verifiable sources; sources without methodological relevance; and sources used only for general background when more recent or authoritative evidence was available. Contrary evidence was retained when it highlighted the limits of valuation methods, legal admissibility, data scarcity, uncertainty, or risks of double counting.

Potential errors and temporal gaps in official documents were managed by separating legally established evidence from analytical interpretation. For example, official compensation amounts in the Norilsk case are used only to identify the legally recognized direct-compensation core, not to infer a universal per-ton coefficient. Because official documents may describe past decisions rather than real-time ecological dynamics, the framework requires sensitivity analysis for recovery periods, the affected area, unit costs, discount rates, and monitoring gaps before any empirical application. Although the review protocol follows principles commonly associated with transparent evidence synthesis, this study should not be interpreted as a systematic review or meta-analysis. Its objective is conceptual integration and institutional framework development rather than statistical aggregation of empirical findings. Consequently, expert judgement inevitably influenced evidence selection and interpretation. To mitigate this limitation, explicit reporting of the search strategy, inclusion criteria, coding procedure, triangulation, and analytical steps was adopted to maximize transparency and reproducibility [57,58].

2.2. Spatial Scope and Location of the Illustrative Case

The spatial focus of the article is the Russian North, understood here as a set of Arctic and sub-Arctic resource-dependent territories where oil and petroleum-product infrastructure interacts with cold-climate ecosystems, long transport distances, sparse settlement patterns, and uneven environmental-monitoring capacity. The framework is not restricted to one administrative region, because the valuation problem is shaped by cross-regional northern conditions: remoteness, ice and snow cover, permafrost-related infrastructure risk, low temperatures, low population density, and the socio-cultural importance of ecosystem services for local and Indigenous communities.

The 2020 Norilsk diesel fuel spill is used as an illustrative validation case because it combines several features that make northern oil-spill valuation difficult: a large release of petroleum product, affected soils and water bodies, remote Arctic conditions, publicly reported compensation, and independent remote-sensing analysis. The map in Figure 2

locates Norilsk within the broader Russian North focus area. The map is used for orientation only and does not define legal spill boundaries.



Figure 2. Location map of the Russian North focus area and the Norilsk illustrative case. The dashed box provides an approximate analytical focus area rather than an administrative boundary.

2.3. Key Concepts and Operational Definition of Regional Sustainable Transformation

For conceptual clarity and methodological consistency, this subsection defines the key concepts used throughout the analysis and explains how the central concept of regional sustainable transformation is operationalized for the purposes of the proposed analytical framework. Environmental damage is understood as legally and institutionally recognized harm to environmental components, natural resources, public welfare, property, productive assets, and protected environmental interests. Ecological damage refers more narrowly to biophysical degradation of ecosystems, species, habitats, soils, water bodies, and ecological functions. Economic loss refers to monetary losses borne by firms, households, public authorities, or resource users, including lost income, lost profits, additional costs, and foregone opportunities. Ecosystem-service loss refers to reductions in provisioning, regulating, supporting, cultural, and relational benefits provided by ecosystems.

Regional sustainable transformation is operationalized in this study through a set of measurable institutional outcomes that connect environmental damage valuation with governance performance. Rather than treating sustainability transition as an abstract policy objective, the proposed operationalization identifies observable dimensions through which valuation results may contribute to environmental risk reduction, liability enforcement, monitoring capacity, ecosystem-service protection, social inclusion, and institutional learning. The corresponding dimensions, illustrative indicators, and their relationship to valuation outcomes are summarized in Table 2 [43–52].

Table 2. Operationalization of regional sustainable transformation in relation to oil-spill damage valuation.

Dimension	Indicative Variables or Evidence	Possible Indicators	Link with Valuation Results
Environmental risk reduction	Frequency and severity of oil spills; infrastructure renewal; emergency preparedness; avoided-damage estimates	Number of spills per year; contaminated area (ha); emergency response time; share of modernized infrastructure (%)	Avoided-cost and prevention-benefit estimates support investment prioritization and justification of preventive measures
Liability and compensation governance	Legal admissibility; timeliness of compensation claims; restoration planning; compensation payments; expert assessment procedures	Compensation recovery rate (%); claim processing time; restoration plans implemented; enforcement actions	Direct-harm valuation supports legally defensible compensation and implementation of the polluter-pays principle
Monitoring and evidence capacity	Baseline ecological information; remote sensing; water and soil monitoring; uncertainty assessment	Monitoring density; baseline coverage; frequency of observations; uncertainty intervals	Improves reliability of valuation results and supports sensitivity analysis and adaptive monitoring
Ecosystem-service protection	Provisioning, regulating, cultural, and relational ecosystem services; recovery periods; ecosystem-service baselines	Ecosystem-service value estimates; recovery time; affected ecosystem area	Prevents systematic omission of non-market ecosystem-service losses and improves comprehensive damage assessment
Social inclusion and equity	Participation of Indigenous and local communities; subsistence losses; benefit distribution; grievance mechanisms	Number of consultations; participation rate; livelihood-loss estimates; resolved grievances	Supports recognition of social and cultural losses through participatory and stated-preference valuation approaches
Regional resilience and institutional learning	Regulatory change; insurance mechanisms; prevention investments; inter-agency coordination	Regulatory amendments; environmental expenditure; insurance coverage; monitoring improvements	Valuation becomes a feedback mechanism supporting institutional learning, prevention, and long-term regional resilience

Source: Compiled by the authors.

2.4. Analytical Procedure and Framework Derivation

The analysis proceeded in six stages. First, the core valuation concepts were clarified by comparing their use in environmental economics, legal regulation, ecosystem-service valuation, Russian methodology, and expert practice. Second, international liability systems and Russian compensation practice were compared to identify commonalities and differences. Third, valuation approaches were grouped according to methodological logic and institutional function. The modular structure was derived through a two-dimensional classification rather than by statistical weighting. The first-dimension distinguished methods according to the primary object of valuation (direct ecological damage, indirect economic consequences, or non-market ecosystem-service losses). The second dimension classified methods according to their dominant institutional function, including legal compensation, environmental restoration, preventive decision support, ecosystem-service recognition, and regional policy learning [16–24,43–50]. Only valuation methods demonstrating both conceptual distinctiveness and practical complementarity were retained as separate framework components. Other valuation approaches identified during the review (e.g., hedonic pricing, productivity-based valuation, and recipient-specific assessment methods) were considered but not retained as independent modules because they were considered spe-

cialized variants of broader valuation categories, required context-specific datasets rarely available for northern oil-spill cases, or substantially overlapped with the selected methods in terms of institutional function. This procedure minimizes overlap between valuation categories while reducing the risk of double counting when several methods are applied simultaneously. Fourth, each method was assessed against criteria of data availability, legal admissibility, ecosystem-service coverage, long-term damage recognition, applicability to remote northern conditions, social and cultural equity, institutional usefulness, and double-counting risk. These analytical criteria are summarized in Table 3.

Table 3. Analytical criteria used to assess valuation methods for northern oil-spill damage.

Criterion	Meaning	Relevance to Regional Sustainability Transitions
Data availability	Whether the method can be applied in the case of sparse monitoring data and limited baseline information	Determines whether valuation can support evidence-based regional policy
Legal admissibility	Whether the method can support compensation claims, expert appraisal, administrative procedures, or litigation	Links valuation with environmental liability and polluter-pays enforcement
Ecosystem-service coverage	Whether the method captures provisioning, regulating, supporting, cultural, and relational ecosystem services	Prevents underestimation of non-market ecological and social losses
Long-term damage recognition	Whether delayed, cumulative, and slow-recovery effects are included	Reflects resilience challenges in Arctic and sub-Arctic ecosystems
Applicability to remote northern conditions	Whether the method remains feasible in the case of remoteness, ice cover, logistical constraints, and weak infrastructure	Connects valuation with place-based regional policy
Social and cultural equity	Whether the method can include losses borne by Indigenous and local communities	Supports inclusion and equity in sustainable regional governance
Institutional usefulness	Whether the method improves compensation, prevention, monitoring, insurance, or policy coordination	Strengthens institutional resilience and transition governance
Risk of double counting	Whether the method overlaps with other valuation components when several methods are combined	Ensures methodological transparency and prevents overestimation or duplication of compensation claims

Source: Compiled by the authors.

Fifth, the six most relevant methods were assigned to three modules: direct harm, indirect and opportunity-related losses, and non-market ecosystem-service losses. The modules were derived from the damage object and institutional function of each method, not from a statistical weighting procedure. No fixed weights are proposed, because the relative importance of the modules depends on spill location, affected media, legal purpose, data quality, recovery period, and affected communities. Sixth, the framework was checked using an illustrative application to the Norilsk spill to identify which components are supported by public evidence and which require additional empirical data.

3. Results

3.1. Global Liability and Valuation Systems as a Macro-Level Benchmark

A macro-level review shows that oil-spill damage valuation is already embedded in several mature international systems. NRDA/NRDAR procedures emphasize injury assessment, lost use, restoration planning, and recovery of costs from responsible parties [16–19].

The EU ELD emphasizes prevention and remedying of environmental damage, while the polluter-pays principle frames liability as both a compensation and prevention instrument [20,21]. Ecosystem-service valuation and plural valuation literature broaden this logic by recognizing values that may be absent from markets, including cultural, subsistence, relational, and public-welfare values [22–26].

These international systems provide an important benchmark for the Russian North, but they cannot be transferred mechanically. NRDA is institutionally tied to US trustee practice and restoration planning, while the ELD reflects European legal and administrative contexts. Russian compensation practice has its own legal instruments and normative calculation procedures. Therefore, the central task is not to replace international systems, but to use them as reference points for building a context-specific framework that is transparent, operational, and suitable for northern Russian constraints. The principal characteristics, strengths, limitations, and institutional roles of these mature international systems, together with Russian regulatory practice and the proposed modular framework, are summarized in Table 4.

Table 4. Comparison of mature international systems, Russian practice, and the proposed modular framework.

System or Approach	Main Valuation Logic	Strengths	Limitations for the Russian North
US NRDA/NRDAR	Injury assessment, lost public use, restoration planning, and recovery of damages	Strong restoration orientation; explicit resource and service injury logic; established procedures	Institutionally specific to US trustee and legal practice; not directly transferable to Russian courts and regulators
EU Environmental Liability Directive	Prevention and remedying of environmental damage under liability rules	Clear link between liability, prevention, and remediation; compatible with polluter-pays logic	European administrative context differs from Russian legal and expert practice
Ecosystem-service and plural valuation	Valuation of provisioning, regulating, cultural, relational, and non-market values	Captures losses excluded from direct-cost approaches; supports social equity	Requires survey, participatory, or benefit-transfer evidence; legal acceptance may be uneven
Russian regulatory and expert practice	Normative harm calculation, compensation claims, restoration and remediation costs	Legally relevant and operational for direct harm; compatible with administrative and judicial procedures	Can understate indirect, long-term, and socio-cultural losses if used alone
Proposed modular framework	Three complementary modules: direct harm, indirect loss, and non-market ecosystem-service loss	Links methods to institutional functions; supports double-counting control and policy use	Conceptual decision-support framework; requires empirical testing and case-specific data

Source: compiled by the authors based on [16–26,39–41].

Overall, the comparison demonstrates that mature international liability systems already integrate environmental valuation with compensation and restoration planning, but they differ substantially in their institutional architecture and legal implementation. Consequently, rather than replacing existing approaches, the present study seeks to organize established valuation methods into a transparent decision-support framework adapted to the ecological, legal, and governance conditions of the Russian North.

3.2. Classification of Valuation Approaches in Global and Russian Contexts

The reviewed literature provides a broad set of approaches to environmental damage valuation. The main distinction is not only methodological but also institutional. Cost-based and market-based approaches are usually closer to those used to determine legally admissible compensation, while ecosystem-service, stated-preference, and integrated approaches are more useful for identifying losses that are difficult to monetize or litigate. In the Russian North, the choice of method must account for both global commonalities and regional particularities: global oil-spill valuation faces uncertainty and non-market losses, whereas northern Russian cases additionally face long distances, weak baseline monitoring, slow ecological recovery, regulatory admissibility constraints, and socio-cultural losses that may be institutionally invisible.

Table 5 distinguishes the main approaches and summarizes how each approach performs in the global valuation context and in the Russian North. This structure responds to the need to separate common global issues from the specific Russian case.

Table 5. Classification of valuation approaches and their relevance to the Russian North.

Approach	Representative Methods	Global Use	Russian North Relevance and Limits
Aggregated and normative	Aggregated assessment, direct counting, analogy, coefficients	Operational when data are limited; useful for administrative standardization	Fits regulatory practice but may understate actual restoration costs and long-term ecosystem-service losses
Cost-based	Restoration cost, replacement cost, terminal cost, clean-up and reclamation budgets	Legally persuasive because it uses observable expenditures and project estimates	Strong direct-harm core, but insufficient for representing indirect, cultural, and delayed losses if used alone
Market-based	Market price, hedonic pricing, lost resource value	Useful for traded resources and measurable property or production effects	Limited where ecosystem services lack market prices or where remote areas have few comparable markets
Rent and opportunity-based	Opportunity cost, lost profit, natural-rent capitalization	Shows long-term losses from foregone resource use	Sensitive to discount rates, baseline assumptions, and future use scenarios
Expert-sociological and stated-preference	WTP, WTA, contingent valuation, expert judgement, benefit transfer	Captures non-market values, public preferences, and cultural ecosystem services	Requires representative or carefully weighted evidence; risk of hypothetical bias and legal uncertainty
Recipient-based	Control-area comparison, recipient-specific damage assessment	Links damage to affected components, users, and communities	Difficult when monitoring stations, baselines, or control territories are absent
Integrated/comprehensive	Scenario modelling, ecological risk assessment, ecosystem models, combined valuation	Suitable for complex cumulative impacts and restoration planning	Requires extensive data, modelling assumptions, and sensitivity analysis

Source: compiled by the authors based on [1–15,22–38,53–58].

The comparison confirms that no individual valuation approach adequately captures the full spectrum of ecological, economic, institutional, and socio-cultural losses associated with major oil spills in northern environments. This finding provides the conceptual justification for combining complementary valuation methods within a modular institutional framework rather than selecting a single preferred technique.

3.3. Northern Constraints and Their Parameterization in Valuation

A frequent weakness in oil-spill valuation is the general statement that northern conditions are specific without translating this specificity into valuation parameters. Table 6 addresses this issue by linking northern characteristics to variables, assumptions, or methodological decisions. The table shows that low temperature, ice, remoteness, sparse monitoring, permafrost-related infrastructure risk, and Indigenous or local dependence on ecosystem services do not merely provide a descriptive background. They affect recovery periods, affected-area uncertainty, unit costs, discounting, survey design, data reliability, and the choice of valuation method.

Table 6. Parameterization of northern specificity in oil-spill damage valuation.

Northern Characteristic	Valuation Parameter Affected	Implication for Method Selection
Low temperatures and slow degradation of petroleum products	Recovery period T; monitoring duration; restoration success probability	Use longer time horizons and sensitivity tests for restoration, replacement, and ecosystem-service losses
Seasonal ice, snow cover, and hydrological transport	Affected area A; exposure pathways; uncertainty interval U	Combine field evidence, remote sensing, scenario modelling, and conservative uncertainty reporting
Remoteness and weak logistics	Unit cost C for clean-up, transport, equipment, labor, and monitoring	Restoration and replacement costs should include northern logistics and contingency components
Sparse baseline monitoring	Baseline B0; confidence in counterfactual no-spill scenario	Avoid single-point estimates; report data gaps and use sensitivity or scenario ranges
Permafrost-related infrastructure vulnerability	Probability of accident P; avoided damage; preventive investment cost	Use avoided-cost logic for risk reduction, infrastructure renewal, and environmental insurance decisions
Low population density with high ecosystem dependence	Affected user groups; subsistence and cultural losses L	Use participatory identification of services and carefully designed WTP, WTA, or qualitative valuation
Uneven legal acceptance of non-market values	Legal admissibility score; evidentiary status	Separate legally compensable components from policy-relevant complementary evidence

Source: compiled by the authors.

This parameterization also clarifies why a single method is insufficient. Direct restoration costs are essential, but they may not capture delayed ecosystem recovery. Market prices may capture some resource losses, but not cultural or subsistence values. WTP and participatory valuation can identify non-market losses, but require careful design under income, cultural, and representation constraints. Therefore, northern specificity is operationalized as a set of method-selection and sensitivity-analysis requirements.

Parameterizing northern conditions in this way shifts the discussion from descriptive regional characteristics toward operational valuation variables. This translation enables valuation methods to be selected and calibrated according to measurable ecological, institutional, and socio-economic conditions rather than broad regional generalizations.

3.4. Relevant Valuation Methods for Northern Oil-Spill Cases

The review indicates that six methods are most relevant for oil-spill cases in the Russian North: restoration cost, replacement cost, opportunity cost, avoided cost, market price, and willingness to pay. These methods should not be interpreted as competing alternatives from which one universal method must be chosen. They correspond to different damage objects and institutional purposes. Restoration and replacement costs support direct compensation

and remediation planning. Opportunity cost, avoided cost, and market price help identify indirect economic consequences and prevention benefits. WTP and related approaches help identify non-market ecosystem-service and public-welfare losses.

The calculation expressions in Table 7 are generalized valuation logics rather than legally binding formulas. In any practical case, variables must be adapted to the affected media, legal context, baseline data, recovery period, and available monitoring evidence. When data are weak, results should be reported as ranges or complementary evidence rather than as a mechanically aggregated total.

Table 7. Methods, generalized formulas, data needs, and institutional uses.

Method	Generalized Valuation Logic	Northern Data and Parameterization Needs	Institutional Use and Overlap Control
Restoration cost	$U_{RC} = \sum_{i=1}^n C_i^{rest} + C_{adm} + C_{mon} + C_{cont}$	Remediation project estimates, logistics costs, monitoring duration, contingency for remote access	Legally persuasive direct-harm core; avoid overlap with replacement costs for the same actions
Replacement cost	$U_{RCp} = C_{clean} + C_{recult} + C_{rehab} + C_{subst}$ for equivalent ecological functions or resources	Costs of habitat rehabilitation, compensatory measures, artificial substitutes, or equivalent restoration	Useful when functions cannot be restored immediately; separate from restoration cost
Opportunity cost	$U_{OC} = \sum_{t=1}^T \frac{(B_t^0 - B_t^1)}{(1+r)^t}$	No-spill baseline, post-spill income, duration of restrictions, discount rate, affected users	Compensates lost use and lost income; avoid overlap with market-price losses for the same resource
Avoided cost	$U_{AC} = \sum_{t=1}^T \frac{(D_t^0 - D_t^1)}{(1+r)^t}$ or justified prevention cost when avoided damage cannot be observed	Scenario of expected damage without prevention, residual damage after prevention, accident probability	Supports prevention investment, insurance, and infrastructure modernization; not normally added to ex post damage totals
Market price	$U_{MP} = \sum_{i=1}^n \Delta Q_i \cdot P_i$	Quantity of lost/degraded resource, relevant market price, quality adjustment, time period	Transparent for traded resources; limited for services without markets
Willingness to pay	$U_{WTP} = \sum_{h=1}^H \frac{W\hat{T}P_h \cdot w_h}{(1+r)^t}$ with weighting and time adjustment where appropriate	Representative survey, affected population, income/cultural context, benefit-transfer validity	Captures non-market public welfare and cultural services; report separately if legal admissibility is uncertain

Source: compiled by the authors based on [22–38,53–58].

3.5. Modular Institutional Framework

The proposed framework organizes the six methods into three modules. Module 1 covers direct harm and includes restoration and replacement costs. Its primary function is legal compensation, remediation budgeting, and implementation of the polluter-pays principle. Module 2 covers indirect and opportunity-related losses and includes opportunity cost, avoided cost, and market price methods. Its primary function is to connect valuation with lost resource use, prevention investment, insurance, and regional-economic resilience. Module 3 covers non-market ecosystem-service losses and includes WTP, benefit transfer, participatory valuation, and qualitative evidence. Its primary function is to recognize welfare, cultural, subsistence, and relational values that are not fully represented in markets or direct-cost calculations.

The modules are independent in the sense that they refer to different primary damage objects, but they are complementary because a major oil spill can affect all three categories simultaneously. Their weights are not fixed *ex ante*. Instead, the framework requires a damage-component matrix in which each component is assigned to one primary module, with explicit identification of the affected object, user group, time period, evidence base, and legal or policy status. Aggregation is appropriate only after overlap has been excluded. Where overlap cannot be excluded, the components should be reported separately as complementary evidence.

Figure 3 improves the earlier conceptual scheme by adding operational variables, northern constraints, cross-module double-counting rules, and feedback loops from valuation outputs back to monitoring, prevention, and regional policy learning. This avoids presenting the framework as a one-directional list of recommendations.

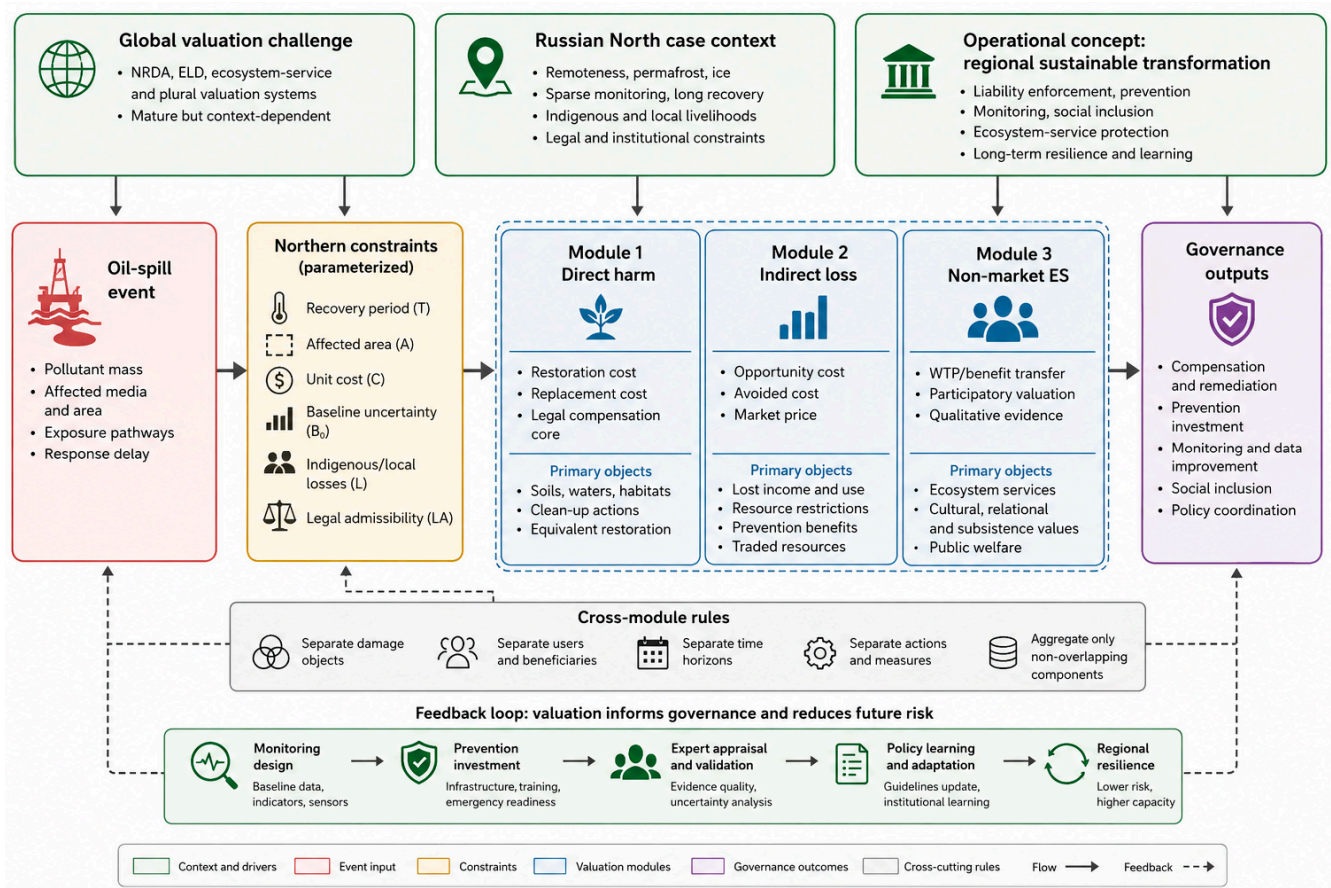


Figure 3. Modular institutional framework for oil-spill damage valuation in northern resource-dependent territories. The framework links global valuation practice, Russian North constraints, operational variables, valuation modules, governance outputs, double-counting controls, and feedback to monitoring and prevention policy.

The allocation of valuation methods to the three modules was derived through a two-stage analytical procedure rather than expert intuition alone. First, each valuation method was classified according to its primary damage object (direct ecological damage, indirect economic consequences, or ecosystem-service losses). Second, methods were compared according to their dominant institutional function, including legal compensation, restoration planning, preventive decision support, or recognition of non-market values. Only methods demonstrating both conceptual distinctiveness and practical complementarity were retained as independent framework components. This procedure minimizes overlap between valuation categories while strengthening transparency and reducing the potential

for double counting. The outcome of this classification procedure, including the allocation of the six valuation methods to the three institutional modules, together with their primary damage objects, conceptual rationale, institutional functions, and aggregation rules, is summarized in Table 8.

Table 8. Derivation of the three modules from the six valuation methods.

Module	Methods	Primary Damage Object	Conceptual Rationale	Institutional Function	Aggregation Rule
Module 1. Direct harm	Restoration cost; replacement cost	Physical environmental damage requiring restoration	Legally recognized ecological damage directly attributable to the spill	Compensation; remediation budgeting; expert appraisal	Aggregate-only non-overlapping restoration activities
Module 2. Indirect loss	Opportunity cost; market price; avoided cost	Secondary economic losses and foregone benefits	Captures economic consequences beyond immediate ecological restoration	Risk management; infrastructure planning; prevention investment	Separate ex post losses from ex ante prevention benefits
Module 3. Non-market ecosystem services	WTP; WTA; benefit transfer; participatory valuation	Cultural, relational, subsistence, and ecosystem-service losses	Recognizes values not reflected in market transactions	Social equity; community recognition; ecosystem-service governance	Report separately whenever legal admissibility remains uncertain

Source: compiled by the authors.

Taken together, the results demonstrate that existing environmental damage valuation methods should be regarded as complementary rather than mutually exclusive. Their organization into three institutional modules enables environmental assessment to extend beyond compensation calculations toward prevention planning, ecosystem-service recognition, monitoring design, and regional sustainability governance. The framework therefore provides a transparent decision-support structure while leaving quantitative parameterization and monetary estimation to future empirical case studies.

4. Illustrative Application of the Proposed Framework

This section is presented separately from the Results because its purpose is not to provide independent empirical validation of the proposed framework. Instead, it demonstrates how the framework can be applied to a well-documented oil-spill event using publicly available evidence. Accordingly, the Norilsk spill is treated as an illustrative application and plausibility check rather than as a quantitative validation exercise. The Norilsk spill is not presented as a full empirical case study and does not validate the accuracy of a numerical model. It is used as an illustrative validation and plausibility check: the case shows whether the proposed modules can organize publicly available evidence, reveal missing data, and identify where additional empirical work would be required.

The spill occurred on 29 May 2020 after the failure of a fuel storage tank at Norilsk-Taimyr Energy Company facilities. Published scientific work reports the release of approximately 21,000 tons of diesel fuel and impacts on soils, water bodies, and biota in Arctic conditions [27,28]. Publicly available company information reports compensation payments of approximately RUB 145.49 billion for damage to water bodies and RUB 0.685 billion for damage to soils, or approximately RUB 146.18 billion in total legally recognized compensation [41]. These values are used only as case evidence for the direct-compensation module.

No per-ton compensation coefficient is calculated in the revised manuscript. Dividing total compensation by pollutant mass would conflate soil and water components, ignore site-specific hydrological and ecological assumptions, omit the cost structure of restoration

and monitoring, fail to adjust for timing and inflation, and create a risk of double counting. Such a calculation would therefore be inappropriate for a scientific journal article unless supported by independent case data and sensitivity analysis.

The illustrative validation confirms the functional logic of the framework. The direct-harm module is supported by publicly recognized compensation. The indirect-loss module identifies categories that require additional data, such as emergency response costs, resource-use restrictions, reputational effects, and prevention investments. The non-market ecosystem-service module identifies additional categories that may be material but are not fully monetized in public legal compensation evidence, including water regulation, biodiversity, subsistence practices, landscape values, and public welfare. Thus, the case supports the usefulness of the framework for structuring evidence, not the accuracy of a specific monetary estimate. The results of this illustrative application, together with the evidence supporting each framework module, the functions demonstrated, the additional information required for operational implementation, and the current level of evidential confidence, are summarized in Table 9.

Table 9. Illustrative application of the proposed modular framework to the 2020 Norilsk diesel fuel spill.

Framework Module	Publicly Available Evidence	Framework Function Demonstrated	Additional Evidence Required for Operational Application	Current Confidence *
Module 1. Direct harm	Publicly reported compensation for damage to water bodies and soils totaling approximately RUB 146.18 billion [41]	Demonstrates that the framework successfully identifies the legally recognized core of environmental compensation and supports implementation of the polluter-pays principle	Detailed restoration budgets; long-term ecological monitoring; affected-area delineation; ecosystem recovery indicators	High
Module 2. Indirect economic losses	Public reports describe emergency response activities, monitoring requirements, temporary restrictions on resource use, infrastructure rehabilitation, and prevention investments [27,28,41]	Demonstrates that substantial regional economic consequences extend beyond legally compensated direct damage and require complementary valuation methods	Sector-specific economic losses; costs by stakeholder group; lost income; resource-use restrictions; baseline economic data; discount rates; prevention scenarios	Moderate
Module 3. Non-market ecosystem-service losses	Scientific literature identifies potential impacts on biodiversity, water regulation, landscape quality, subsistence practices, and public welfare [22–28]	Demonstrates that ecosystem-service losses constitute an important but largely unmonetized component of environmental damage and should be considered separately from direct compensation	Participatory valuation; Indigenous and local knowledge; representative WTP/WTa surveys; benefit-transfer validation; cultural ecosystem-service assessment	Low–Moderate
Cross-module uncertainty and double-counting control	Remote Arctic conditions, heterogeneous monitoring coverage, and satellite observations indicate substantial spatial and temporal uncertainty [28]	Demonstrates the need to separate damage objects, beneficiaries, valuation methods, and time horizons before aggregation to avoid double counting	Sensitivity analyses for affected area, recovery period, restoration effectiveness, discount rates, valuation assumptions, and alternative baselines	High

Source: compiled by the authors based on [27,28,41]. * Confidence refers to the strength of currently available public evidence supporting the illustrative application of each framework module and does not represent confidence in environmental recovery or compensation adequacy.

Overall, the illustrative application demonstrates that the proposed framework is capable of organizing heterogeneous environmental evidence into a coherent institutional structure without claiming quantitative completeness. The exercise also identifies where additional ecological monitoring, socio-economic information, and ecosystem-service valuation would be required before comprehensive monetary assessment could be undertaken. Accordingly, the Norilsk case should be interpreted as a demonstration of framework applicability rather than empirical proof of its predictive performance. Future research should apply the framework to independent empirical case studies incorporating primary ecological, economic, and stakeholder data in order to evaluate its operational performance under different institutional settings.

5. Discussion and Implications

5.1. Contribution Relative to Existing Valuation Systems

The findings indicate that environmental damage valuation in northern resource-dependent regions cannot be reduced to the selection of a single preferred economic valuation technique. Instead, the effectiveness of valuation depends on the ability to combine complementary methods according to the ecological characteristics of the spill, institutional objectives, legal requirements, and the availability of reliable environmental evidence. This observation is particularly important for Arctic and sub-Arctic territories, where long ecological recovery periods, sparse monitoring networks, logistical constraints, and heterogeneous ecosystem services substantially increase uncertainty throughout the valuation process [1–15].

The proposed framework should therefore be viewed as an institutional integration of established valuation approaches rather than as a methodological replacement for existing systems. Mature international frameworks such as the U.S. Natural Resource Damage Assessment (NRDA) and the European Environmental Liability Directive (ELD) already provide comprehensive procedures linking environmental injury, restoration planning, liability, and compensation [16–21]. Likewise, ecosystem-service valuation and plural valuation research have considerably expanded the ability to account for regulating, provisioning, cultural, and relational ecosystem values that are not adequately represented by conventional market-based approaches [22–24,54,55].

The contribution of the present study lies in translating these well-established concepts into a transparent decision-support protocol specifically designed for northern resource regions characterized by limited baseline information, prolonged ecological recovery, institutional heterogeneity, and uneven legal recognition of non-market environmental values. Rather than proposing another valuation methodology, the framework organizes existing methods according to their primary institutional functions, thereby facilitating consistent method selection while reducing the risk of overlap and double counting.

This distinction is particularly relevant because valuation methods frequently serve different governance objectives. Restoration and replacement costs primarily support legal compensation and remediation planning, whereas opportunity-cost and avoided-cost approaches inform preventive investment and regional risk management. In contrast, willingness-to-pay and ecosystem-service valuation methods contribute to recognizing public welfare, Indigenous subsistence, cultural identity, and other values that often remain invisible within conventional compensation procedures [22–26]. Organizing these approaches into complementary institutional modules therefore improves transparency without challenging the methodological foundations of existing international valuation systems.

The proposed framework also extends current sustainability-transition research by explicitly connecting environmental damage valuation with institutional learning. Previous

studies have emphasized that sustainability transitions depend not only on technological innovation but also on governance capacity, regional institutions, policy coordination, and adaptive learning processes [43–50]. In this context, environmental damage valuation becomes more than a mechanism for estimating financial losses. It functions as an institutional feedback mechanism through which environmental accidents generate information that supports prevention, infrastructure modernization, environmental monitoring, compensation procedures, and long-term regional resilience.

5.2. Implications for Regional Sustainability Transitions

The results suggest that environmental damage valuation should be considered an enabling component of regional sustainability transitions rather than a purely technical accounting exercise. Resource-dependent northern regions face the simultaneous challenge of maintaining economic activity while reducing environmental risk and strengthening institutional resilience. Under such conditions, valuation influences transition processes by determining how environmental externalities are recognized, internalized, and incorporated into public decision-making.

Specifically, the proposed framework links valuation outputs to measurable institutional outcomes, including improved environmental monitoring, stronger liability enforcement, enhanced prevention planning, broader recognition of ecosystem services, greater stakeholder participation, and increased policy learning. In this respect, valuation contributes indirectly to sustainability transitions by improving the quality of environmental governance rather than by producing transition outcomes on its own. In practical terms, repeated valuation exercises generate comparable evidence that can inform regulatory revision, monitoring priorities, infrastructure investment, and adaptive governance, thereby creating an institutional learning cycle beyond the immediate compensation process. This interpretation is consistent with contemporary regional-transition literature emphasizing that institutional capacity and governance quality shape the success of sustainability transformations, while recent empirical evidence further demonstrates that governance quality and institutional effectiveness strongly influence environmental performance and sustainability outcomes, reinforcing the importance of integrating valuation into broader institutional decision-making processes [47–52,59].

An additional contribution concerns Arctic governance. Previous studies have repeatedly identified remoteness, low temperatures, seasonal ice, limited monitoring infrastructure, and Indigenous dependence on ecosystem services as major challenges for environmental management in northern regions [1–5,25,26]. However, these characteristics are often described qualitatively without being explicitly incorporated into valuation methodology. The present framework addresses this gap by translating northern environmental conditions into operational criteria affecting method selection, uncertainty analysis, recovery periods, monitoring requirements, and evidence quality. This parameterization improves methodological transparency and facilitates adaptation of valuation procedures to region-specific environmental conditions.

5.3. Policy and Managerial Implications

The findings have practical implications for environmental regulators, infrastructure operators, regional governments, and Indigenous organizations involved in environmental governance.

First, environmental authorities should move beyond reliance on single-method compensation procedures and instead adopt modular valuation protocols that distinguish direct ecological damage, indirect socio-economic losses, and non-market ecosystem-service impacts. Such differentiation improves transparency, reduces the likelihood of double

counting, and clarifies which valuation components are legally compensable and which should inform broader policy development.

Second, monitoring systems should be designed not only to detect environmental contamination but also to provide evidence suitable for compensation procedures and long-term environmental management. Investment in baseline monitoring, remote sensing, ecological recovery indicators, and spatially explicit environmental databases would substantially improve the reliability of future valuation exercises [6–15].

Third, infrastructure operators and industrial companies may benefit from integrating avoided-cost approaches into investment planning. Under Arctic conditions, preventive investments in infrastructure modernization, monitoring technologies, emergency preparedness, and environmental risk management may generate substantially greater long-term economic benefits than post-accident remediation alone.

Fourth, greater incorporation of local and Indigenous knowledge may improve both scientific completeness and procedural legitimacy. Participatory identification of ecosystem services can reveal subsistence, cultural, and relational values that are frequently omitted from conventional cost-based valuation while simultaneously strengthening stakeholder trust and reducing potential conflicts surrounding compensation decisions [23–26].

Finally, regional policymakers may consider developing dedicated valuation guidelines for Arctic and sub-Arctic territories. Such guidance could incorporate region-specific recovery periods, uncertainty reporting requirements, ecosystem-service modules, sensitivity-analysis procedures, and standardized approaches to avoiding double counting. Rather than functioning solely as a post-disaster compensation mechanism, environmental damage valuation could thereby become an institutional instrument supporting preventive governance, adaptive regional planning, and long-term sustainability transitions.

6. Limitations and Future Research

The framework proposed in this study is conceptual and decision-oriented rather than predictive. It is intended to support the selection and combination of valuation methods under different institutional and ecological conditions rather than to generate universal monetary estimates of environmental damage.

No universal weighting coefficients are assigned to the three valuation modules because their relative importance depends on spill characteristics, ecosystem vulnerability, legal objectives, monitoring quality, data availability, and socio-cultural context. Consequently, the framework should be interpreted as a flexible decision-support protocol rather than as a fixed valuation algorithm.

The illustrative application to the 2020 Norilsk diesel fuel spill serves exclusively as a plausibility check demonstrating how the framework can be applied using publicly available information. It should not be interpreted as an empirical validation or recalculation of officially established compensation values. Independent regional case studies, expert elicitation, and quantitative calibration remain necessary before the framework can be used for operational environmental damage assessment [27,28,30,31,37].

Additional limitations should also be acknowledged. First, the framework was developed primarily for oil-spill damage valuation in the Russian North and should not be assumed to be directly transferable to other environmental hazards, regions, or institutional contexts without adaptation. Second, the framework has not yet been tested using independent empirical datasets, field monitoring, stakeholder surveys, or expert elicitation. Third, institutional and legal practices continue to evolve, which means that the proposed decision-support protocol will require periodic revision. Finally, ecosystem-service valuation remains constrained by data availability, methodological uncertainty, and differences in the legal recognition of non-market values across jurisdictions.

7. Conclusions

This study reframed environmental damage valuation for oil spills in the Russian North as both a methodological challenge and an institutional component of regional sustainability transitions. Rather than focusing on the calculation of a single compensation value, the article examined how different valuation approaches can be systematically combined to support environmental governance, liability, prevention, and long-term regional resilience in resource-dependent northern territories.

The first research question addressed which valuation methods are most appropriate under Arctic and sub-Arctic conditions. The review demonstrated that restoration cost, replacement cost, opportunity cost, avoided cost, market-price approaches, and willingness-to-pay methods each capture different dimensions of environmental damage. None of these methods provides a comprehensive assessment when applied independently. Their strengths and limitations depend on ecological conditions, data availability, legal objectives, monitoring capacity, and the nature of affected ecosystem services.

The second research question examined how regional sustainable transformation can be operationalized in relation to environmental damage valuation. The proposed framework conceptualizes sustainability transitions as an institutional process through which valuation supports environmental risk reduction, liability enforcement, ecosystem restoration, monitoring improvement, stakeholder participation, policy learning, and regional resilience. In this interpretation, valuation becomes not merely a mechanism for estimating financial losses but an institutional instrument capable of strengthening adaptive environmental governance.

The third research question concerned how established valuation approaches can be combined without creating methodological overlap or overstating scientific novelty. The proposed three-module framework addresses this challenge by separating direct ecological damage, indirect economic losses, and non-market ecosystem-service losses according to their primary damage objects and institutional functions. This modular structure facilitates transparent method selection, reduces the risk of double counting, and allows valuation results to be interpreted consistently across different decision-making contexts.

The principal contribution of the study therefore lies not in proposing a new valuation methodology but in integrating established approaches into a transparent decision-support framework adapted to the institutional and environmental conditions of northern resource regions. The illustrative application to the 2020 Norilsk diesel fuel spill demonstrates how the framework can organize publicly available evidence, distinguish between legally established and complementary valuation components, and identify where additional empirical information is required before comprehensive environmental assessments can be undertaken.

More broadly, the proposed framework contributes to current debates on regional sustainability transitions by demonstrating that environmental damage valuation can function as an enabling governance instrument rather than solely as a post-disaster compensation mechanism. By linking environmental assessment with prevention, monitoring, institutional learning, and ecosystem-service recognition, the framework provides a practical basis for strengthening institutional resilience and improving environmental decision-making in Arctic and other resource-dependent regions facing similar sustainability transition challenges.

Author Contributions: Conceptualization, O.S.S. and O.L.C.; methodology, O.S.S. and O.L.C.; validation, R.Y.B. and O.S.S.; formal analysis, R.Y.B., M.I.I. and O.S.S.; investigation, R.Y.B., M.I.I. and O.S.S.; resources, O.S.S. and O.L.C.; data curation, R.Y.B. and M.I.I.; writing—original draft preparation, R.Y.B. and O.S.S.; writing—review and editing, M.I.I. and O.L.C.; visualization, R.Y.B.; supervision,

O.S.S. and M.I.I.; project administration, O.S.S.; funding acquisition, O.L.C. All authors have read and agreed to the published version of the manuscript.

Funding: The reported study was funded by the Foundation for Scientific and Technological Development of Yugra according to the research project № 2025-628-08.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ELD	Environmental Liability Directive
ES	Ecosystem services
NRDA	Natural Resource Damage Assessment
NRDAR	Natural Resource Damage Assessment and Restoration
RUB	Ruble
WTA	Willingness to accept compensation
WTP	Willingness to pay

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