

ECONOMIC AND LEGAL ANALYSIS OF ENVIRONMENTAL DAMAGES CAUSED BY THE DESTRUCTION OF THE KAKHOVKA HYDROELECTRIC POWER PLANT

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Abstract. The destruction of the Kakhovka Hydroelectric Power Plant on June 6, 2023, constitutes one of the largest technogenic-environmental catastrophes in European history, releasing the majority of the reservoir's 18 km³ volume, resulting in flooding that affected 80 settlements across four oblasts and directly impacted approximately 100,000 people. Despite the unprecedented scale of the disaster, existing damage assessments remain fragmented and methodologically limited. The official Post-Disaster Needs Assessment (PDNA), conducted by the Government of Ukraine and the United Nations, estimates total damage at 13.8 billion USD. However, the time horizon for ecosystem service losses is limited to 18 months, and a conservative 50% impact fraction is applied. Although alternative assessments by CEPR and the Centre for Economic Strategy provide sectoral data, they lack an integrated mechanism. This article presents a comprehensive mechanism for calculating the economic damage caused by the destruction of the Kakhovka dam. Drawing on an analysis of international judicial precedents (ICJ Costa Rica v. Nicaragua, UNCC F4 Panel), the methodologies of international organisations (World Bank DaLA, FAO, TEEB) and scientific approaches to the valuation of ecosystem services (Costanza et al.), the article proposes a five-component formula: $TD = D + L_{econ} + L_{eco} + I + R$, which encompasses direct damage, economic losses, losses of ecosystem services, indirect effects and recovery needs. A three-scenario approach (conservative, base case and high-end case) is appropriate for calculating environmental damage, applying a declining discount rate and time horizons of 30–100 years. The illustrative calculation shows that the total damage is in the range of 19–83 billion USD, which exceeds the PDNA estimate by between 1.4 and 6 times. The proposed mechanism can be applied to other cases of dam destruction in armed conflict or peacetime, providing a transparent and replicable framework for assessing damage in judicial, policy-making and scientific contexts.

Keywords: ecosystem services valuation, dam failure consequences, DaLA methodology, declining discount rate, post-disaster needs assessment, wetland restoration, armed conflict environmental liability, compensation for environmental harm.

JEL Classification: Q51, Q54, K32, H41

1. Introduction

The destruction of the Kakhovka Hydroelectric Power Plant on June 6, 2023, was one of the largest technogenic environmental catastrophes in European history. Over two weeks, the majority of the reservoir's 18 km³ volume was released as a result of the dam's destruction, flooding 80 settlements in four regions – Kherson, Mykolaiv, Dnipropetrovsk and Zaporizhzhia – and directly affecting approximately 100,000 people. Up to one million people lost

access to drinking water (PDNA, 2023). Exposing 1,944 km² of the reservoir bed transformed a mature aquatic ecosystem, which had functioned since the dam's construction in the early 1950s, into a riverine ecosystem in its initial developmental stage (Shumilova et al., 2025). According to UNEP estimates, a significant proportion of the environmental consequences are irreversible and it may take years or even decades for their full scale to become apparent (UNEP, 2023).

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With a volume of 18.2 km³ and an area of 2,155 km², the Kakhovka Reservoir was the largest in the Dnipro Cascade. The mean discharge of the Dnipro at the Kakhovka HPP site between 1956 and 2020 was 1,290 m³/s, equivalent to 40.7 km³ per year. The reservoir supplied water to three main canals: the Kakhovka Main Canal, the North Crimean Canal and the Dnipro-Kryvyi Rih Canal. These canals irrigated 350,000 hectares of agricultural land in the Kherson, Zaporizhzhia and Dnipropetrovsk regions. They also provided drinking water to the cities of Kryvyi Rih, Nikopol, Marganets, Beryslav, Enerhodar and Kamianka-Dniprovsk, as well as to dozens of rural settlements. The canals also cooled the Zaporizhzhia Nuclear Power Plant, which is Ukraine's largest nuclear power station with a capacity of 6 GW (Vyshnevskiy et al., 2023).

The official damage assessment, the Post-Disaster Needs Assessment (PDNA), was conducted by the Ukrainian government and the UN, with technical support from the World Bank and the EU. It estimates total damage at 13.8 billion USD, of which 2.79 billion USD constitutes direct damage to physical assets, while 11 billion USD represents losses in economic flows and ecosystem services (PDNA, 2023). However, this assessment has significant methodological limitations. Firstly, the losses to the ecosystem (6.4 billion USD, accounting for 58% of all losses) were calculated over a period of only 18 months, based on the conservative assumption that ecosystem services were impacted by 50%. Secondly, a significant portion of the territory affected on the left bank of the Dnipro remains occupied and inaccessible for assessment. Thirdly, the PDNA does not consider long-term cascading consequences, such as heavy metal contamination from exposed reservoir sediments.

Alternative assessments are also fragmented. CEPR estimates losses at approximately 6 billion USD (Djankov, 2023): 4 billion USD in direct costs and 2 billion USD in long-term costs. The Centre for Economic Strategy provides sectoral data: loss of irrigation on 584 thousand hectares (1.5 billion USD); loss to fisheries of up to 10.5 billion UAH; and loss to hydrotechnical land reclamation of over 150 billion UAH (CES, 2023). However, none of the existing assessments propose an integrated mechanism that combines all damage components with scientifically grounded time horizons and discount rates.

This research is relevant because there is no comprehensive mechanism that integrates international experience in assessing environmental damage in armed conflicts with contemporary scientific approaches to valuing ecosystem services, adapted to the specifics of the Kakhovka catastrophe.

This article aims to develop a comprehensive mechanism for calculating the economic damage caused by the destruction of the Kakhovka HPP, based

on a synthesis of international judicial precedents, the methodologies of international organisations and scientific approaches to valuing ecosystem services.

To achieve this aim, the following objectives have been set: 1) analyse existing methodologies and legal standards for assessing environmental and economic damage; 2) systematise international experience in compensating for environmental damage; 3) develop a formulaic apparatus for an integrated calculation mechanism; 4) conduct an illustrative calculation for the Kakhovka HPP under three scenarios.

2. Literature Review

2.1. Legal Basis for Compensation of Environmental Damage

The principle of full reparation is fundamental to international law. It originated from the ruling of the Permanent Court of International Justice in the *Factory at Chorzów* case (1928), which established that, wherever possible, reparation should eliminate all the consequences of the illegal act and restore the situation that would most likely have existed had the act not been committed (PCIJ, 1928). This principle is enshrined in the Articles on the Responsibility of States for Internationally Wrongful Acts (ILC ARSIWA, 2001). Article 31 establishes the obligation to provide full reparation, while Article 34 defines the three forms this can take: restitution, compensation and satisfaction. According to Article 36, compensation must cover 'any financially assessable damage, including loss of profits, provided it is established' (ILC, 2001).

The judgment of the International Court of Justice in *Costa Rica v. Nicaragua* (2018) is of fundamental importance to this research, as it was the first ICJ ruling on compensation for environmental damage. The Court ruled that environmental damage, and the subsequent impairment or loss of the environment's ability to provide goods and services, constitutes a compensable act under international law. This may include compensation for the loss or impairment of ecosystem goods and services during the period prior to recovery, as well as payment for restoration measures to repair the damaged environment (ICJ, 2018).

At the same time, the Court noted that international law does not prescribe any specific method of valuation for the purposes of compensating for environmental damage. Costa Rica proposed an ecosystem services approach, involving the transfer of value from analogous ecosystems in Mexico, the Philippines and Thailand. This approach used a 50-year time horizon and a 4% discount rate to value the damage to 6.19 hectares of Ramsar wetland at 2.88 million USD. In contrast, Nicaragua proposed a replacement cost approach based on its domestic environmental protection programme, valuing the damage at

27,000–35,000 USD. This approach used a 20–30 year horizon and a 4% discount rate. The court rejected both approaches, instead applying an overall valuation based on equitable considerations. It awarded 120,000 USD for loss of ecosystem services and 2,708 USD for restoration (Kindji & Faure, 2019). Kindji and Faure criticise this ruling for its narrow anthropocentric approach, as well as for its failure to explain the method used to calculate the awarded sum.

Another important decision was that of the F4 Panel of the United Nations Compensation Commission (UNCC, 2005), which reviewed 168 environmental claims arising from the Gulf War totalling 84.9 billion USD. The Panel recognised that the depletion or destruction of natural resources, including those without commercial value, is, in principle, compensable. It also stated that there is no justification for the contention that general international law precludes compensation for 'pure environmental damage' (UNCC, 2005). Regarding the Habitat Equivalency Analysis (HEA) methodology, the Panel recognised it as a 'relatively new methodology' with limited application, but did not reject it entirely. Instead, it was accepted in cases where 'the scope of damage and quantification of compensation were appropriate and reasonable in the circumstances of each claim'. A total of 5.26 billion USD was awarded. A key lesson was the critical role of the evidentiary basis. For example, Iran claimed 13.5 billion USD but received only 27 million USD due to insufficient evidence, and Saudi Arabia's claim of 20 billion USD for health damage was rejected entirely (Payne, 2016).

The principles of environmental protection in the context of armed conflicts are set out in the ILC Draft Principles on the Protection of the Environment in Relation to Armed Conflicts (ILC PERAC, 2022). In particular, Principle 9 establishes the obligation to provide full reparation for environmental damage caused in connection with an armed conflict (ILC, 2022). Article 56 of Additional Protocol I to the Geneva Conventions (1977) directly prohibits attacks on dams, dykes and nuclear electrical generating stations that may result in the release of dangerous forces and severe losses among the civilian population, even if these sites are military objectives (Protocol I, 1977). The ICRC Guidelines (ICRC, 2020) set out 32 rules and recommendations concerning the protection of the natural environment in armed conflicts. These include the obligation to consider the environmental impact of military operations when planning and carrying them out.

2.2. Methodologies for Damage and Loss Assessment

The Damage and Loss Assessment (DaLA) methodology, developed by the World Bank based on

the Economic Commission for Latin America and the Caribbean (ECLAC) approach, is the most widely used post-disaster assessment instrument. It has been applied in more than 20 countries over the past few decades. It distinguishes between two main components: 'direct damage', which is the replacement cost of destroyed or damaged physical assets assessed at pre-disaster prices; and 'losses', which are changes in economic flows resulting from the disaster, including reductions in production and income, as well as increased costs (World Bank, 2010). The assessment is conducted on a sectoral basis, in line with the country's system of national accounts. This ensures comparability and avoids double counting. The third component, 'needs', determines the financial resources required for recovery and reconstruction in line with the Build Back Better principle.

The FAO has developed a specialised methodology for assessing damage and losses in agriculture. This covers five sub-sectors: crops (C), livestock (L), forestry (FO), aquaculture (AQ) and fisheries (FI). The total impact is defined as follows: $\text{Impact} = \text{DL}(C) + \text{DL}(L) + \text{DL}(FO) + \text{DL}(AQ) + \text{DL}(FI)$. For each sub-sector, the methodology distinguishes between three components: production damage (the pre-disaster value of destroyed stocks); production losses (the difference between expected and actual production); and asset damage (the replacement cost of destroyed equipment). Discounting is applied for perennial crops and herd replenishment (FAO, 2020).

The DHS/ASDSO methodology for assessing the economic consequences of dam failures, developed in the United States, structures direct consequences into three categories: benefit losses, including irrigation, municipal and industrial (M&I) water supply, electricity generation, recreation, flood protection, fisheries, and navigation; remediation costs, including downstream property damage (using USACE depth-damage functions), environmental restoration, temporary structures, and emergency response; and costs of dam replacement or repair. The assessment of indirect consequences is facilitated by Input-Output Analysis or Computable General Equilibrium (CGE) models, which are capable of accounting for multiplier effects through inter-industry linkages (DHS, 2011).

2.3. Ecosystem Services Valuation

Costanza et al.'s pioneering work (1997) was the first to estimate the global value of 17 types of ecosystem service, including gas regulation, climate regulation, disturbance regulation, water regulation, water supply, erosion control, soil formation, nutrient cycling, waste treatment, pollination, biological control, refugia, food production, raw materials, genetic resources, recreation and cultural services, across 16 biomes. They estimated this value to be 33 trillion USD per year

(1994 USD), which exceeded the global GNP of that period (18 trillion USD). The value was found to be 14,785 USD/ha/year for wetlands, 19,580 USD/ha/year for floodplains, and 8,498 USD/ha/year for lakes and rivers (Costanza et al., 1997).

The 2014 update significantly increased the global value to 125 trillion USD per year (2007 USD), with the value of wetlands rising to 140,174 USD per hectare per year – the largest increase of all biomes. The authors estimated that the loss of ecosystem services due to land-use change between 1997 and 2011 was between 4.3 and 20.2 trillion USD per year (Costanza et al., 2014).

The TEEB (The Economics of Ecosystems and Biodiversity) programme systematised extant studies on wetland valuation based on a meta-analysis of hundreds of publications. For inland wetlands (floodplains, marshes, peatlands), the total value of ecosystem services ranges from 981 USD to 44,597 USD/ha/year (Int.USD/PPP 2007), with provisioning services ranging from 2 to 9,709 USD/ha/year; regulating services ranging from 321 to 23,018 USD/ha/year; habitat services ranging from 10 to 3,471 USD/ha/year; and cultural services ranging from 648 to 8,399 USD/ha/year (Table 1). For fluvial systems and lakes, the total value is 1,779 – 13,487 USD/ha/year (Russi et al., 2013).

The ISA guidance (Brander, 2023) systematised all extant methods of economic valuation of ecosystem services into three groups: market-based methods (market price, net factor income, replacement cost, damage cost avoided, social cost of carbon, opportunity cost); revealed preference methods (travel cost, hedonic pricing); and stated preference methods (contingent valuation, choice experiment). A separate category is the benefit/value transfer method, which involves the transfer of values from studies of analogous ecosystems. The selection of a particular method is contingent upon the nature of the ecosystem service in question, the accessibility of data, and the availability of research resources (Brander, 2023).

2.4. Existing Assessments and Their Methodological Limitations

The PDNA, conducted by the Ukrainian government and the UN, estimates total damage at 13.8 billion USD. This includes direct damage of 2.79 billion USD (of which 1.26 billion USD, or 45%, was caused by damage to the energy sector, and 1.1 billion USD, or 39%, was caused by damage to housing), and losses of 11 billion USD. Of these losses, 6.4 billion USD (58%) was caused by damage to ecosystem services. For the valuation of ecosystem services, the global values for wetlands from Davidson et al. (2019) were used: the total annual value of five Ramsar and seven Emerald

sites is 8.5 billion USD per year. With a conservative impact of 50% and a period of 18 months, this yields 6.4 billion USD. The total annual value of forests (11,294 hectares) was found to be 451 USD per hectare per year across five categories of services (recreation, hydrology, biodiversity, non-timber products and CO₂ absorption), yielding 5.1 million USD per year. Under the Build Back Better principle, recovery needs are estimated at 5.04 billion USD: 1.82 billion USD in the short term (2023–24); 2.2 billion USD in the medium term (2025–30); and 1 billion USD in the long term (up to 2033) (PDNA, 2023).

Shumilova et al. (2025) established that over two weeks, the majority of the reservoir's water, amounting to more than 18 km³, was released (Vyshnevskiy et al., 2023). This exposed 1,944 km² of the reservoir bed. Approximately 80% of the reservoir's biomass was lost and the entire 0+ juvenile fish stock was destroyed, as the flood occurred immediately after spawning. Additionally, approximately 450 tonnes of oil products were washed out and turbidity increased by a factor of around 50, resulting in concurrent increases in toxicity. During the first week, 9,000–17,000 tonnes of phytoplankton were washed out per day and approximately 10,000 tonnes of macroinvertebrates were lost. The primary long-term risk was identified as the presence of toxic contaminants, specifically heavy metals (Pb, Ni, Zn) and nitrogen-phosphorus compounds, in the exposed sediments. This constitutes 'a largely overlooked long-term threat to freshwater, estuarine, and marine ecosystems' (Shumilova et al., 2025).

O'Mahony (2021) argues that, for projects with long-term environmental consequences such as air pollution, climate change and ecosystem damage, the CBA time horizon should be 100+ years. The author demonstrates that the time horizon can have 'a much larger impact on the outcome than the discount rate', and that excluding long-term welfare gains and losses creates a systematic bias in favour of environmentally harmful projects (O'Mahony, 2021).

3. Method

3.1. General Formula

Based on the analysis conducted, the authors propose a five-component formula for calculating total damage:

$$TD = D + L_{econ} + L_{eco} + I + R$$

where TD – Total Damage; D – Direct Damage to physical assets; L_{econ} – Economic Losses of flows; L_{eco} – Ecosystem Services Losses; I – Indirect and Cascade Effects; R – Recovery and Restoration Needs.

The novelty of the proposed approach does not lie in the creation of new methods for assessing individual components, but rather in the integration of these methods into a unified mechanism adapted

to the specifics of the destruction of hydroelectric infrastructure under conditions of armed conflict. Specifically, the authors' contribution includes the following: (a) the integration of DaLA, ecosystem services and ICJ/UNCC legal standards into a single formula; (b) a three-scenario approach (conservative, base case and high-end case) instead of a single point estimate; (c) a declining discount rate for the environmental component; (d) the justification of time horizons of 50–100 years instead of 18 months; (e) adaptation to conditions where part of the territory is inaccessible for assessment.

3.2. Component D: Direct Damage

Direct damage is assessed at replacement cost at pre-disaster prices in accordance with the DaLA methodology (World Bank, 2010):

$$D = \sum D_s = \sum (Q_i \times RC_i)$$

where D_s – damage in sector s ; Q_i – quantity of destroyed units of asset i ; RC_i – replacement cost per unit. The Kakhovka HPP is divided into nine sectors, namely: energy (HPP 335 MW, electricity networks, substations); housing (37,000 buildings); culture (archaeological sites); municipal infrastructure (water supply, sewerage); water supply and sanitation (WSS); agricultural assets (irrigation systems); education (37 facilities); commerce/industry; and health.

3.3. Component L_{econ} : Economic Losses

Economic losses are calculated as the discounted sum of the difference between expected and actual production over the entire period until full recovery (World Bank, 2010; FAO, 2020):

$$L_s = \sum_{t=0}^{T_s} [(V_{\text{expected}_t} - V_{\text{actual}_t} + C_{\text{additional}_t}) / (1+r)^t]$$

where T_s – recovery period for sector s ; V_{expected} – baseline production; V_{actual} – actual production; $C_{\text{additional}}$ – additional costs; r – discount rate.

Nine sectors have been identified for the Kakhovka HPP: hydropower (335 MW, with a recovery period of six years or more), nuclear energy (with a risk of losses from the 6 GW Zaporizhzhia NPP, accounting for 43% of Ukraine's nuclear generation), agriculture (with over 350,000 hectares of land for irrigation and the potential to increase this to 1.5 million hectares), fisheries (with a potential yield of 95,000 tonnes of adult fish), industry (including ArcelorMittal and ferroalloy plants), housing, navigation (with approximately 50 vessels), water supply and health.

3.4. Component L_{eco} : Ecosystem Services Losses

This component is legally based on the rulings of the ICJ (2018) and the UNCC (2005), which recognised

the right to compensation for 'pure environmental damage'. The formula is as follows:

$$L_{eco} = \sum_{j=1}^J [A_j \times V_j \times IF_j \times \sum_{t=0}^{T_j} (RF_j(t) / (1+r)^t)]$$

where A_j – area of the affected ecosystem (ha); V_j – annual value of ecosystem services (USD/ha/year); IF_j – impact fraction (share of lost services, 0-1); T_j – recovery period; $RF_j(t)$ – recovery function; r – discount rate.

The areas are determined based on data from the PDNA (2023), the FAO and Shumilova et al. (2025). The protected territories cover 333,000 hectares, including five Ramsar sites and seven Emerald sites. The forests cover 11,294 hectares, the exposed reservoir bed covers 194,400 hectares and the flooded downstream territories cover 62,000 hectares.

The values of ecosystem services are determined using a three-scenario approach: a conservative scenario (PDNA/Davidson et al., 2019); a base case scenario (TEEB, 12,789 USD per hectare per year for inland wetlands; Russi et al., 2013); and a high-end case scenario (Costanza, 2014, 140,174 USD per hectare per year; Costanza et al., 2014).

The impact fraction is supported by scientific data: approximately 80% of the reservoir's biomass was lost (Shumilova et al., 2025), and the damage is 'very likely irreversible' (UNEP, 2023). The impact fraction is 0.50 for the conservative scenario, 0.65 for the base case and 0.80 for the high-end case.

The time horizon is 30 years for the conservative case, 50 years for the base case (by analogy with the ICJ Costa Rica case) and 100 years for the high-end case (following the recommendation of O'Mahony, 2021).

Discount rate – declining: 3.5% (years 0–30); 3.0% (years 31–75); 2.5% (years 76–125). For the conservative scenario, the discount rate is fixed at 5%.

Recovery function $RF_j(t)$ – logistic curve: $RF_j(t) = 1 - 1/(1 + e^{(-k(t - T_j/2))})$, where $k = 0.1$ (calibrated). For irreversible losses, $RF = 1$ for all t , meaning capitalisation of losses.

3.5. Components I and R

Indirect and cascade effects (I) include: macroeconomic impact on GRP (assessed through CGE or Input-Output; DHS, 2011); social costs (approximately 100,000 displaced persons, up to 1 million without drinking water); long-term health costs from Pb, Ni, Zn contamination (Shumilova et al., 2025); security costs (demining by analogy, UNCC awarded Kuwait 688 million USD for the removal of 1.6 million mines; Payne, 2016).

Recovery and restoration needs (R) under the Build Back Better principle: $R = \sum (D_s \times BBB_{\text{factor}} + C_{\text{new}})$, where $BBB_{\text{factor}} = 1.15–1.50$ (World Bank, 2010).

4. Results

4.1. Component D: Direct Damage

According to PDNA (2023) data, direct damage amounts to 2.79 billion USD:

Sector	Damage, million USD	%
Energy	1 260	45.1
Housing	1 101	39.4
Culture	156.8	5.5
Municipal infrastructure	127.82	4.5
Water supply	65.92	2.4
Education	51.97	1.9
Agriculture	23.87	0.9
Commerce/industry	7.40	0.28
Health	0.95	0.02
Total	2,795	100

4.2. Component L_{econ}: Economic Losses

L_{econ} is calculated on a sectoral basis using the formula $L_s = \sum_{t=0}^{T_s} [(V_{\text{expected}_t} - V_{\text{actual}_t} + C_{\text{additional}_t}) / (1+r)^t]$.

L1. Hydropower. With a capacity of 335 MW, the Kakhovka HPP provided generation of approximately 1,400 GWh/year. According to PDNA data, Ukrhydroenergo's annual revenue from the HPP was 96 million USD, while the value of lost electricity and ancillary services amounted to 138 million USD per year, totalling 234 million USD per year in total. Using a conservative recovery horizon of six years (based on Ukrhydroenergo's estimates) and a discount rate of 5%, the NPV of hydropower losses is approximately 1.2 billion USD. Under the base case scenario of 10 years and a 3.5% discount rate, the NPV is approximately 1.9 billion USD. Under the high-end case scenario of 15 years and a 3.5% discount rate, the NPV is approximately 2.7 billion USD.

L2. Nuclear energy. The Zaporizhzhia NPP (6 GW, accounting for 43% of Ukraine's nuclear generation capacity) depends on the reservoir for cooling purposes. According to PDNA data, potential losses from ZNPP downtime are estimated at up to 3.6 billion USD. In the conservative scenario, the authors only account for partial losses associated with changes to the cooling system (2.6 billion USD); in the base case, the total losses from electricity generation over five years are accounted for (3.6 billion USD); and in the high-end case, an extended ten-year horizon that accounts for the risk of decommissioning is considered (4.3 billion USD).

L3. Agriculture. Losses are calculated using the FAO (2020) methodology as the difference between baseline and actual production. The PDNA estimates direct agricultural losses at 382.71 million USD for the first 18 months. CES provides a broader estimate, calculating the loss of irrigation on 584 thousand hectares (with the potential for this figure to increase to 1.5 million hectares), which corresponds to a decline

in irrigated crop yields of between 50 and 70%. CES estimates that annual agricultural production losses amount to approximately 1.5 billion USD. Under the conservative scenario (irrigation recovery in 5 years, 50% area recovery, 5% discount): NPV \approx 0.38 billion USD; in the base case (10 years, 70% of area, 3.5%) approximately 1.0 billion USD; in the high-end case (15 years, complete loss of irrigated farming, 3.5%) approximately 2.0 billion USD. For perennial plantings (vineyards, orchards), an additional productivity recovery horizon of 5-7 years is applied in accordance with FAO (2020) recommendations.

L4. Fisheries. According to CES data, the destruction of the dam resulted in the loss of 95 thousand tonnes of adult commercial fish (valued at approximately 4 billion UAH), with total losses to the fisheries sector estimated at up to UAH 10.5 billion (equivalent to around 280 million USD at 2023 exchange rates). Shumilova et al. (2025) documented the destruction of 100% of 0+ juvenile fish (the flood occurred immediately after spawning), indicating an interruption to stock replenishment of 5–10 years. The conservative scenario (0.25 billion USD) only accounts for primary biomass losses. The base case (0.5 billion USD) additionally includes ten years of lost reproduction, while the high-end case (1.0 billion USD) includes a twenty-year horizon, covering aquaculture losses and the impact on the Dnipro-Buh Estuary.

L5. Industry. The technical water deficit affected the operations of major industrial enterprises: Arcelor Mittal (Kryvyi Rih) suspended some of its production processes and Nikopol ferroalloy plants reduced their capacity (CES, 2023). This estimate is based on data showing a decline in industrial production volumes in the Kherson and Dnipropetrovsk oblasts. The conservative scenario (0.2 billion USD) assumes the restoration of the water supply within three years. In the base case (0.5 billion USD), this is within five years. In the high-end case (0.8 billion USD), losses in investment attractiveness and the relocation of production facilities are included.

L6-L9. Other sectors. Housing losses (L6) include demolition costs, temporary housing and lost rental income for 37,000 buildings (PDNA: 66.6 million USD; this is an incomplete estimate due to limited access to occupied territories). In terms of navigation (L7), there has been a loss of river transport on the Dnipro below Zaporizhzhia for approximately 50 vessels (Vyshnevskiy et al., 2023). Water supply (L8): the cost of an alternative water supply for Kryvyi Rih, Nikopol, Marganets, Beryslav, Enerhodar and dozens of rural settlements (PDNA: 82.82 million USD). Health (L9): treatment, screening, prevention and mental health (PDNA: 64.6 million USD). Combined for other sectors: 0.3 billion USD (conservative estimate), 0.5 billion USD (base case estimate), 1.2 billion USD (high-end estimate).

Summary table for L_{eco}:

Sector	Conservative	Base case	High-end case	Horizon
L 1 Hydropower	1.2 billion USD	1.9 billion USD	\$2.7 billion USD	6–15 yr
L 2 Nuclear energy	2.6 billion USD	3.6 billion USD	\$4.3 billion USD	5–15 yr
L 3 Agriculture	0.38 billion USD	1.0 billion USD	\$2.0 billion USD	5–15 yr
L 4 Fisheries	0.25 billion USD	0.5 billion USD	\$1.0 billion USD	10–20 yr
L 5 Industry	0.2 billion USD	0.5 billion USD	\$0.8 billion USD	3–10 yr
L6-L9 Other	0.3 billion USD	0.5 billion USD	\$1.2 billion USD	5–15 yr
Total L_{eco}	≈5 billion USD	≈8 billion USD	≈12 billion USD	

The L_{eco} structure demonstrates the dominance of the energy sector (L1 + L2), which accounts for between 58% and 76% of total economic losses. The figures are as follows: conservative case – 76% (3.8 billion USD out of 5 billion USD); base case – 69% (5.5 billion USD out of 8 billion USD); high-end case – 58% (7 billion USD out of 12 billion USD). This is due to the strategic importance of the Kakhovka Reservoir to the operation of both the HPP and the ZNPP.

4.3. Component L_{eco}: Ecosystem Services Losses

Parameter	Conservative	Base case	High-end case
V _j (USD/ha/year, wetlands)	12,789 USD	25,500 USD	140,174 USD
IF _j	0.50	0.65	0.80
T _j (years)	1.5	50	100
Discount rate	5% fixed	3.5% declining	2.5% declining
Area	333,000 ha	333,000 ha	527,400 ha
NPV L _{eco}	6–8 billion USD	~65 billion USD	2+ trillion USD

4.4. Overall Assessment

Scenario	D	L _{eco}	L _{eco}	R	TOTAL
conservative	2.8 USD	5 USD	6–8 USD	\$5	19–21 billion USD
base case	2.8 USD	8 USD	~65 USD	\$7	~83 billion USD
high-end case	2.8 USD	12 USD	2000+ USD	\$10	2+ trillion USD

The high-end scenario is a theoretical maximum, illustrating how sensitive the assessment is to the input parameters. The range that can be practically applied lies between the conservative and base cases.

4.5. Sensitivity Analysis

The range of results, from 19 billion USD to 98 billion USD (with a theoretical upper limit of over 2 trillion USD), demonstrates the significant sensitivity of the mechanism to its input parameters. To ensure transparency in the assessment, sensitivity analysis was conducted on four key parameters.

Sensitivity to unit value of ecosystem services (V_j). This parameter is the most influential: changing

V_j from PDNA/Davidson values (approximately 25,500 USD/ha/year for wetlands) to Costanza 2014 (140,174 USD/ha/year) increases L_{eco} by 5.5 times, ceteris paribus. For the base case scenario (TEEB 12,789 USD/ha/year), L_{eco} is approximately 65 billion USD; at PDNA values while maintaining other base case scenario parameters – approximately 130 billion USD; at Costanza 2014 – approximately 712 billion USD. Thus, the elasticity of L_{eco} with respect to V_j is approximately 1:1 – proportional change.

Sensitivity to impact fraction (IF_j). Changing IF from 0.50 to 0.80 (i.e., by 60%) increases L_{eco} also by 60%. At IF = 0.50 for the base case scenario, L_{eco} ≈ 50 billion USD; at IF = 0.65 - approximately 65 billion USD; at IF = 0.80 - approximately 80 billion USD. The choice of IF should be supported by empirical data: Shumilova et al. (2025) document the loss of approximately 80% of biomass, supporting IF ≥ 0.65 for desiccated territories.

Sensitivity to time horizon (T_j). Extending the horizon from 30 to 50 years at a 3.5% rate increases the annuity factor from 18.4 to 23.5 (+28%). Extending to 100 years increases it to 27.7 (an additional +18% relative to 50 years). Thus, the transition from PDNA (18 months, or an annuity factor of approximately 1.5) to a 50-year horizon increases L_{eco} by approximately 16 times, then, this is the primary factor explaining the divergence between the authors' assessment and PDNA.

Sensitivity to discount rate (r). For a 50-year horizon: at r = 5%, the annuity factor = 18.3; at r = 3.5% - 23.5; at r = 2% - 31.4. Reducing the rate from 5% to 2% increases NPV by 72%. Using a declining discount rate (3.5%→3.0%→2.5%), as justified by O'Mahony (2021) and adopted in the UK Green Book, increases NPV by approximately 1-4% compared to a fixed 3.5% rate over horizons of 50–100 years.

Sensitivity matrix for L_{eco} (billion USD), area 333,000 ha, IF = 0.65:

V _j \ T _j , r	30 yr, 5%	50 yr, 3.5%	100 yr, 2.5%
PDNA ~25,500 USD	85 USD	130 USD	202 USD
TEEB 12,789 USD	43 USD	65 USD	101 USD
Costanza 140,174 USD	466 USD	712 USD	1,111 USD

The matrix results show that, for all V_j values and time horizons, L_{eco} is much higher than the PDNA estimate of 6.4 billion USD, since the PDNA is only valid for 18 months. Using PDNA's own unit values (25,500 USD/ha/year) and extending the time horizon to 30 years yields a figure of 85 billion USD – over 13 times higher than the PDNA estimate.

Recommended range. In light of the sensitivity analysis, the following recommendations are put forward: for legal claims – conservative (19–21 billion USD) as a lower bound with a high level of evidentiary support; for policy-making – base case scenario (~83 billion USD); for scientific purposes – the full range of all three scenarios with Monte Carlo simulation for quantitative uncertainty assessment.

5. Discussion

5.1. Comparison with PDNA and Alternative Assessments

A comparison of the authors' results with the existing PDNA estimate of 13.8 billion USD demonstrates a substantial divergence: even the most conservative scenario exceeds the PDNA estimate by 38–52%, while the base case scenario exceeds it by around sixfold. The primary reason for this is the difference in the temporal scope of the assessment of ecosystem loss: PDNA is limited to 18 months, whereas the authors' mechanism applies a horizon of 30–50 years, which is supported by both international precedents (e.g., ICJ Costa Rica – 50 years) and scientific recommendations (e.g., O'Mahony, 2021 – 100+ years).

The second factor of divergence is the choice of unit value for ecosystem services. The PDNA uses the values provided by Davidson et al. (2019), whereas the updated values for wetlands provided by Costanza et al. (2014) are substantially higher at 140,174 USD/ha/year. TEEB (Russi et al., 2013) provides a range of intermediate values of between 981 and 44,597 USD per hectare per year. Such uncertainty is typical of the valuation of ecosystem services in general. For this reason, a three-scenario approach is proposed instead of a point estimate, ensuring transparency of assumptions and enabling sensitivity analysis.

The third factor is the impact fraction. PDNA conservatively adopts 50% for protected territories, whereas scientific data from Shumilova et al. (2025) indicates a loss of approximately 80% of reservoir biomass and the complete destruction of juvenile fish. UNEP characterises the damage as 'very likely irreversible' (UNEP, 2023). For the base case scenario, the authors apply an IF of 0.65, and for the high-end case, an IF of 0.80.

A comparison with the CEPR assessment (approximately \$6 billion; Djankov, 2023) shows

that the CEPR only considers direct and short-term losses, without providing a quantitative assessment of ecosystem services. This makes it the most limited of all existing estimates. The CES (2023) provides more detailed sectoral data (584 thousand hectares of irrigation, agricultural losses of approximately 1.5 billion USD, and losses in fisheries of up to 10.5 billion UAH, as well as land reclamation exceeding 150 billion UAH). However, it also does not integrate this data into a unified mechanism.

5.2. A Comparison with International Precedents

A comparison with international precedents reveals a systematic pattern. In the UNCC case, 6.2% of the claimed amount was awarded (5.26 out of 84.9 billion USD), whereas in the ICJ Costa Rica case it was just 4.2% (120,000 out of 2.88 million USD). The main reason for this is an insufficient evidentiary basis. This generates a critical practical recommendation: any calculation mechanism must be accompanied by a strategy for establishing a solid evidentiary foundation. The principle of the Trail Smelter Arbitration (Trail Smelter, 1941), as set out in the UNCC (2005), allows compensation to be awarded based on 'just and reasonable inference', even in cases of incomplete certainty, provided that the available evidence is sufficient.

The UNCC experience is particularly instructive regarding the role of evidence: Iran claimed 13.5 billion USD, yet received only 27 million USD (0.2%) due to insufficient documentary evidence. Saudi Arabia claimed 20 billion USD for health damage, but this claim was rejected on the grounds that there was an absence of epidemiological data (Payne, 2016). Concurrently, Kuwait received 688 million USD in funding for demining operations, facilitated by comprehensive documentation detailing the quantity and location of mines. This experience indicates that for the Kakhovka HPP, the following are critical: satellite imagery in chronological sequence, field studies of water and soil quality, independent expert assessments, and baseline data on ecosystem conditions prior to destruction.

The ICJ Costa Rica v. Nicaragua (2018) case highlighted another issue: the court rejected the two approaches put forward by the parties (Costa Rica's ecosystem services approach and Nicaragua's replacement cost approach) and instead applied its own 'overall assessment based on equitable considerations', without providing an explanation of the calculation method (Kindji & Faure, 2019). For large-scale cases such as the Kakhovka HPP, there is a risk that the awarded amount will be significantly reduced compared to the calculated figure. The three-scenario approach in the proposed mechanism addresses this

risk, enabling the court to select the most justified scenario without rejecting the approach entirely.

5.3. Methodological Innovations and Contribution

The proposed mechanism introduces several methodological innovations compared to existing approaches. Firstly, it integrates three previously disparate methodological streams – DaLA (World Bank), ecosystem services valuation (Costanza, TEEB) and legal compensation standards (ICJ, UNCC and ILC PERAC) – into a unified five-component formula. None of the existing assessments of the Kakhovka catastrophe have undertaken such integration. While Killean (2023) examines the issue of reparations in the context of ecocide, their focus is on legal mechanisms rather than developing a quantitative damage assessment instrument.

Secondly, the three-scenario approach is an adaptation of the IPCC's scenario modelling practice for the purposes of damage assessment. Unlike point estimates (13.8 billion USD according to the PDNA and approximately 6 billion USD according to the CEPR), the three-scenario approach provides the following: (a) transparency of assumptions for each scenario, (b) adaptability to the application context (e.g., judicial, policy or scientific) and (c) a quantitative assessment of uncertainty.

Thirdly, using a declining discount rate (3.5% → 3.0% → 2.5%) for the environmental component is theoretically justifiable. This approach is adopted in the UK Green Book and the Quinet Report for long-term projects with intergenerational consequences (O'Mahony, 2021). However, PDNA does not apply this approach, instead using a fixed rate.

Fourthly, the logistic recovery function $RF_j(t)$ enables the modelling of nonlinear ecosystem recovery dynamics, including slow initial recovery, acceleration in the middle phase and an asymptotic approach to full recovery. For irreversible losses ($RF = 1$ for all t), this provides capitalisation consistent with the principle of 'perpetual flow of services' in ecosystem services theory.

5.4. Practical Recommendations

For the practical application of the mechanism, the following recommendations are made: for legal claims (ICJ, ICC) the Conservative or lower bound of the Base case scenario with evidentiary support (satellite data, field surveys, expert reports); for policy-making and negotiating positions, the base case scenario with sensitivity analysis is recommended; for scientific justification, all three scenarios with transparent methodology are recommended.

It should be noted separately that the mechanism is applicable not only to the Kakhovka HPP, but also to

other cases of dam destruction. These include: the failure of the Fundão dam in Brazil in 2015, which was assessed by Scarpelin et al. (2022) using an energy-based approach; the Banqiao dam disaster in China in 1975; and potential catastrophes for which DHS/ASDSO (2011) developed a specialised methodological guide. Adapting the mechanism to a specific case requires only the calibration of the relevant parameters (A_j, V_j, IF_j and T_j) for the ecosystem and territory in question.

5.5. Limitations of the Study

Firstly, the illustrative calculation is based primarily on secondary data (PDNA, CES and scientific publications) due to the absence of the authors' own field research. Secondly, part of the affected territory remains occupied and inaccessible, meaning the assessment is subject to systematic underestimation. Thirdly, indirect and cascade effects (Component I) require separate CGE modelling, which is beyond the scope of this study. Fourthly, the impact on the marine environment (the Dnipro-Buh Estuary and the Black Sea) has not yet been assessed quantitatively due to a lack of data. While Shumilova et al. (2025) and Vyshnevskiy et al. (2023) document secondary pollution and salinity changes, sufficient information for a monetary assessment is not yet available. Fifthly, the recovery function $RF(t)$ requires calibration based on field data from the Dnipro wetlands; the value of the parameter $k = 0.1$ is an assumption that requires empirical verification.

Additionally, the absence of complete baseline data on the state of the Kakhovka Reservoir's ecosystem services prior to its destruction is a limitation. Although the PDNA uses global values from Davidson et al. (2019), a site-specific assessment (through contingent valuation or a choice experiment) could substantially refine V_j for specific ecosystems. Finally, although Component I (indirect effects) is included conceptually in the mechanism, its numerical estimation requires a separate study employing CGE or input-output modelling (DHS, 2011).

6. Conclusions

The present article has developed a comprehensive five-component mechanism for calculating damage from the destruction of a hydraulic structure under conditions of armed conflict. The proposed formula $TD = D + L_{econ} + L_{eco} + I + R$ represents a significant integration of the World Bank DaLA methodology, the ecosystem services valuation approach (Costanza et al., 1997, 2014; Russi et al., 2013), and the legal standards for compensation of environmental damage established by the International Court of Justice (ICJ, 2018) and the United Nations

Compensation Commission (UNCC, 2005) into a unified, formalised instrument. A review of international case law reveals that international law recognises the compensability of 'pure environmental damage', including damage to non-commercial resources and interim losses. However, it does not prescribe a single mandatory valuation method. This finding justifies the necessity and legitimacy of developing integrated mechanisms.

An illustrative calculation was conducted for the Kakhovka HPP under three scenarios with a declining discount rate (3.5%, 3.0%, 2.5%) and time horizons of 30–100 years for environmental damage. This demonstrated total damage in the range of 19–83 billion USD, which exceeds the PDNA estimate of 13.8 billion USD by between 1.4 and 6 times. The main reason for this difference is that the PDNA's assessment of ecosystem loss is limited to 18 months instead of decades. This is inconsistent with scientific data on the scale of the damage (Shumilova et al., 2025) and international judicial practice (ICJ Costa Rica, 50 years).

The three-scenario approach ensures methodological transparency and the capacity for sensitivity analysis. It is also adaptable to various application contexts, including legal, policy-making and scientific ones.

At the same time, the study has a number of limitations that inform the direction of future work. The calculation is based on secondary data due to the absence of the authors' own field research, and part of the affected territory remains occupied and inaccessible for assessment. Priority areas for future research include field studies of affected ecosystems following de-occupation, calibration of recovery functions for the Dnipro wetlands, CGE modelling of the macroeconomic consequences of the conflict, and assessment of the impact on the marine environment of the Dnipro-Buh Estuary and the Black Sea. The proposed mechanism is not only applicable to the Kakhovka HPP, but also to other cases of dam destruction. This makes its contribution to the methodology of environmental damage assessment universally applicable.

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