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INTEGRATING NATURE-BASED SOLUTIONS INTO COASTAL INFRASTRUCTURE — LIMITS, UNCERTAINTY, AND POLICY CHALLENGES

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Backdrop

This article seeks to provide critical albeit baseline inputs for policy-formulation with regard to the adoption nature-based solutions (NbS) for the enhancement of resilience of coastal infrastructure. Although NbS is often intuitively perceived to be a more attractive option than conventional- or hard infrastructure (commonly referred-to as "grey" infrastructure) the adoption of NbS as a policy measure requires policymakers in the Government of India to be intimately familiar with the challenges inherent in NbS, in order that policy-responses to these challenges may be properly formulated and executed.

The 2004 Indian Ocean tsunami caused a catastrophic loss of life and infrastructure, with over 200,000 fatalities, and economic damages estimated at nearly USD 6 billion across affected regions. In India, the coastal states of Kerala and Tamil Nadu, along with the Union Territories of the Andaman and Nicobar Islands, and Puducherry, experienced severe impacts. However, the destruction was not uniform. Post-disaster assessments indicated that coastal settlements shielded by mangroves and wetlands experienced comparatively lower damage and loss of life.[1] A similar pattern was observed during Cyclone *Amphan* in 2020, where the Sundarbans acted as a natural buffer, absorbing a significant portion of the storm's energy and reducing impacts on inland habitations.[2]

These events highlight both the protective potential of coastal ecosystems and a critical limitation: their performance is variable,[3] contingent on ecological condition, spatial extent, and event intensity. This variability lies at the core of ongoing debates on the role of nature-based solutions (NbS) in the resilience of critical infrastructure.

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[1] Kandasamy Kathiresan and Narayanasamy Rajendran, "Coastal Mangrove Forests Mitigated Tsunami," *Estuarine, Coastal and Shelf Science* 65, no. 3 (2005): 601–606, https://doi.org/10.1016/j.ecss.2005.06.022

[2] Livelihoods, "Amphan Cyclone, Sundarbans: Mangroves Played a Bio-Shield Role & Protected Coastal Communities," 29 May 29 2020, https://livelihoods.eu/amphan-sundarbans-india-mangroves-bio-shield/

[3] Anoop Raj Singh and Nehru Prabakaran, "The Fall and Rise of the Andaman Islands' Mangroves, and its Impact on the People", *Sanctuary Nature Foundation*, 10 July 2024, https://www.sanctuarynaturefoundation.org/article/the-fall-and-rise-of-the-andaman-islands%E2%80%99-mangroves%2C-and-its-impact-on-the-people

The resilience of critical infrastructure and coastal settlements has emerged as a central concern in national[4] and international[5] policy frameworks, particularly in the context of climate change. Coastal regions, which host nearly forty per cent of the global population, are exposed to a wide range of hydrometeorological hazards—including cyclones, storm surges, and tsunamis—as well as long-term threats such as sea-level rise. Infrastructure in these regions—such as ports, shipyards, undersea cable landing stations, and naval facilities—is integral to national economic and strategic systems, while also being exposed to security risks due to their location along maritime frontiers.

Conventional or 'grey' infrastructure approaches, such as seawalls and breakwaters, remain the primary means of coastal protection. However, they are often capital-intensive,[6] resource-demanding, and in some contexts—such as island territories—technically or economically impractical to implement at scale. In response, NbS are increasingly being explored as complementary or alternative measures.[7] In coastal settings, NbS function by attenuating wave and wind energy, reducing coastal flooding, and stabilising shorelines. These services are provided by ecosystems such as mangroves, salt marshes, tidal wetlands, and coral reefs, which have historically contributed to the natural protection of coastal settlements and harbours.

In addition to mitigating hazards, such ecosystems offer co-benefits including support to fisheries,[8] provision of forest-based resources, and pollutant attenuation,[9] while requiring relatively lower long-term maintenance once established. These advantages have driven increasing interest in their adoption within resilience planning frameworks.

However, despite their demonstrated potential, the integration of NbS into planning and design for critical infrastructure presents a distinct set of challenges. These challenges do not negate the value of such systems but rather, reflect the complexities associated with their feasibility, performance, and governance—particularly when applied within engineering and policy frameworks that are traditionally predicated on predictability and certainty.

Broadly, the challenges associated with integrating nature-based solutions (NbS) into coastal resilience planning can be categorised into two domains: **(1)** planning and engineering constraints, and **(2)** policy and legislative limitations. This discussion focuses on the Indian

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[4] National Disaster Management Authority, *National Policy on Mitigation and Rehabilitation Measures for People Displaced by Coastal and River Erosion 2022* (New Delhi: National Disaster Management Authority, 2022), https://ndma.gov.in/sites/default/files/PDF/National_Policy_on_MRM_CRE.pdf

[5] United Nations, "Oceans and the Sustainable Development Goals", https://www.un.org/sustainabledevelopment/oceans/

[6] National Oceanic and Atmospheric Administration, "A Cost-Benefit Analysis of Green-Gray Infrastructure for Sea Level Rise Adaptation in the Pacific Northwest, Incorporating Externalities and Ecosystem Co-Benefits", 11 October 2023, https://coastalscience.noaa.gov/project/a-cost-benefit-analysis-of-green-gray-infrastructure-for-sea-level-rise-adaptation-in-the-pacific-northwest-incorporating-externalities-and-ecosystem-co-benefits/

[7] United Nations Office for Disaster Risk Reduction, "Words into Action: Nature-Based Solutions for Disaster Risk Reduction", https://www.undrr.org/words-action-nature-based-solutions-disaster-risk-reduction

[8] Pankaj Singha and Swades Pal, "Wetland Transformation and Its Impact on the Livelihood of the Fishing Community in a Flood Plain River Basin of India", *Science of The Total Environment* 858, No. 1 (2023): 159547, https://doi.org/10.1016/j.scitotenv.2022.159547

[9] BV Elsevier, "Wetlands May Remove or Reduce…", *Environmental Advances* (2023), https://www.sciencedirect.com/science/article/pii/S2468584423000363

context, with particular emphasis on critical infrastructure, where tolerance for uncertainty in performance is significantly lower than in the case of coastal settlements, resulting in more stringent planning- and design requirements. While the analysis centres on coastal wetland ecosystems due to their wider applicability, the underlying challenges are broadly relevant to coral reef-based systems as well.

A key step in the implementation of NbS is determining site applicability and selecting an appropriate ecosystem type. In this context, interventions can be broadly classified into two categories— "restorative" and "engineered"—a distinction that has direct implications for predictability, risk assessment, and policy acceptance.

Typological Distinction

Restorative Approach. In the "restorative approach", a coastal wetland or reef ecosystem previously existed at or near the project site, and the intervention seeks to restore it to a functional state. The prior presence of the ecosystem indicates that the site broadly satisfies the necessary environmental conditions, reducing the risk of ecological incompatibility. Historical evidence can also provide a basis for estimating performance, particularly where past settlement or infrastructure benefited from the ecosystem's protective functions. Importantly, however, restoration does not automatically imply a return to the original condition. Changes in land use, hydrology, and climate may alter system behaviour, and most interventions require targeted engineering inputs and landscape modification.

Engineered Approach. The "engineered approach" involves introducing ecosystems—or ecosystem-mimicking systems—into sites without historical precedent.[10] These interventions rely upon predictive modelling and inferred ecosystem behaviour to replicate known protective functions. These include ecological introductions, such as mangrove plantations, as also hybrid- or fully engineered systems such as artificial reefs or floating bio-structures. In such cases, feasibility and performance are derived primarily from modelling and analogues, rather than site-specific historical validation. As a result, the likelihood of successful establishment, maturation, and long-term persistence remains uncertain.

Comparative Overview. Table 1 offers a comparative overview of these two approaches.

Dimension	**Restorative Approach**	**Engineered Approach**
Definition	Restoration of a historically existing coastal ecosystem	Introduction or construction of an ecosystem (or bio-inspired system) without historical precedent
Basis of Design	Historical presence and ecological memory of the site	Predictive modelling and inferred ecosystem behaviour
Performance Expectation	Relatively more predictable due to past functioning	Inherently uncertain and model-dependent

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[10] United States Environmental Protection Agency, "Constructed Wetlands", https://www.epa.gov/wetlands/constructed-wetlands

Dimension	**Restorative Approach**	**Engineered Approach**
Ecological Risk	Lower (though not negligible), as system existed previously	Higher, due to potential mismatch with site conditions
Examples	Mangrove restoration in previously degraded coastal belts	Artificial reefs, bio-engineered systems (e.g., Emerald Tutu)
Policy and Design Implication	Easier integration into planning frameworks	Requires higher scrutiny, validation, and risk buffering

Table 1: Comparative Overview

Implications for Uncertainty and Planning. In practice, the distinction between these restorative and engineered approaches is not absolute, and most interventions incorporate elements of both. The key difference lies in the degree of predictability: *restorative* approaches benefit from partial historical validation, whereas *engineered* approaches rely largely on projections. However, neither approach eliminates uncertainty.[11] Even restored ecosystems remain sensitive to changing environmental conditions, particularly under climate change. This distinction is therefore critical for planning and policy, as it directly influences how NbS interventions can be evaluated and integrated into infrastructure design—especially for critical facilities where tolerance for uncertainty is limited.

Feasibility of Nature-Based Solutions

The next stage in implementing an NbS is the assessment of ecological feasibility—whether the proposed ecosystem can exist and sustain itself at the identified site. This assessment focuses on underlying environmental conditions rather than construction or engineering considerations. In broad terms, feasibility is governed by two interdependent factors: "hydro-geomorphological conditions" and "biochemical characteristics".

Hydro-geomorphological Conditions. Coastal wetland ecosystems—such as mangroves, tidal flats, salt marshes, and seagrass meadows—are shaped by site-specific hydrology, bathymetry, and geomorphology. Key determinants include tidal range, inundation patterns, sediment dynamics, and shoreline configuration.[12] A critical implication for planning is that ecosystem development is stage dependent. The feasibility of a proposed intervention depends on the existing ecological state of the site, and ecosystems cannot be arbitrarily introduced at any desired stage. For example, planting mangroves in an unstabilised mudflat that lacks appropriate sedimentary and microbial conditions is unlikely to result in a functional wetland system.[13] Similarly, reef systems require a stable substrate capable of withstanding wave action.

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[11] Haye H Geukes, Eva S Visser, Elena V Bondarouk, Peter M van Bodegom, and Alexander PE van Oudenhoven, "Navigating the Unknown: Nature-Based Solutions for Coastal Climate Adaptation under Deep Uncertainty", *Journal of Environmental Management* 398 (2026): 128483, https://doi.org/10.1016/j.jenvman.2025.128483

[12] Eric Wolanski, Mark M Brinson, Donald R Cahoon, and Gerardo M E Perillo, "Coastal Wetlands", in *Coastal Wetlands: An Integrated Ecosystem Approach*, ed. Gerardo ME Perillo *et al.* (Amsterdam: Elsevier, 2009), 9.

[13] Wolanski et al., "Coastal Wetlands," 6.

Biochemical Conditions. Closely linked to physical conditions are the biochemical parameters governing ecosystem growth. Salinity, acidity or alkalinity (pH value), and nutrient availability, all determine species composition and ecological function. In coastal wetlands, salinity levels directly influence vegetation types, while in coral reef systems, the pH value governs calcification processes.[14] Nutrient availability is often regulated by upstream hydrological processes. For instance, interventions such as dams or diversions can alter sediment and nutrient flows, thereby constraining ecosystem development and long-term sustainability.[15]

Potential Externalities. In addition to site suitability, NbS interventions may introduce ecological externalities. One such concern is the introduction of "invasive species", particularly in engineered approaches, making the selection of locally adapted species essential. Wetland systems may also alter downstream ecological processes by acting as nutrient sinks or sources.[16] Such changes can influence water chemistry, including pH levels, with potential impacts on downstream ecosystems such as molluscs and coral reefs.

Feasibility and Uncertainty. A fundamental limitation of a feasibility-assessment is that it establishes conditions for *possibility*, not *certainty*. While these parameters can indicate when an ecosystem is unlikely to succeed, they do not guarantee its establishment or long-term stability. Even where all criteria are satisfied, the development of a mature NbS remains probabilistic. This uncertainty is particularly pronounced in engineered scenarios, although it persists even in restorative approaches under changing environmental conditions. From a planning perspective, feasibility should, therefore, be understood as a necessary condition— but not a sufficient one— for successful implementation of NbS.

Impact of Climate Change on Feasibility Requirements. The feasibility of coastal wetland ecosystems is inherently dynamic and sensitive to evolving climatic and environmental conditions. As a result, sites that currently satisfy feasibility criteria may not remain suitable over the lifespan of an infrastructure project. Climate change influences coastal ecosystems through three primary pathways: **(1)** sea-level rise, **(2)** changes in meteorological conditions, and **(3)** alterations in upstream hydrological regimes. These processes affect the hydro-geomorphological and biochemical conditions that underpin ecosystem viability.[17] Sea-level rise, for instance, alters coastal bathymetry, tidal regimes, and inundation patterns, while also shifting salinity gradients. Meteorological changes—including variations in temperature and precipitation—affect species behaviour, ecosystem stability, and local hydrodynamics.[18] Concurrently, changes in upstream riverine systems influence sediment transport and nutrient availability, both of which are critical for ecosystem development. In addition to these gradual changes, an increase in the frequency and intensity of extreme weather events introduces episodic disturbances that can damage or reset ecosystems, affecting both establishment and

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[14] Wolanski et al., "Coastal Wetlands", 13.

[15] Wolanski et al., "Coastal Wetlands", 23–26.

[16] Xue-rong Wu, Tjeerd J Bouma, Francesco Cozzoli, Johan van de Koppel, and Jim van Belzen, "Effect of Upscaling Nature-Based Coastal Protection on Estuarine Biodiversity Using Foreshores and Transitional Polders", Journal of Applied Ecology (2025): DOI:10.1111/1365-2664.70029.

[17] Woodroffe and Davies, "The Morphology and Development of Tropical Coastal Wetlands", 71–76.

[18] Wolanski et al., "Coastal Wetlands," 13.

long-term stability. As a consequence of all this, a key implication is that *feasibility* must be treated as a time-dependent condition rather than a fixed site attribute. For example, rising sea levels may drive landward migration of mangrove ecosystems in response to changing tidal and salinity regimes. Where such migration is constrained by natural barriers or human land use, the ecosystem may fail to persist, rendering a previously feasible site unsuitable over time. This temporal variability introduces additional complexity into NbS-based planning. It challenges the validity of long-term design assumptions and underscores the need to incorporate dynamic environmental change into feasibility assessments.

Performance

Once an NbS is deemed to be ecologically feasible, the next step is to evaluate its performance—that is, its ability to deliver the intended level of hazard-mitigation under design conditions. Unlike conventional infrastructure, whose behaviour can be specified within defined limits, NbS performance is inherently variable. This creates a fundamental challenge when integrating such systems into critical infrastructure design, where reliability requirements are typically deterministic.

For analytical clarity, performance can be understood along two dimensions, namely, *structural integrity* and *mechanical performance*.

Structural Integrity. An NbS must withstand the very hazards it is intended to mitigate. If it fails structurally, its mitigative function is lost and it may, instead, introduce secondary risks. High-energy events can uproot mangrove systems or destabilise wetland substrates, altering site conditions and inhibiting ecosystem recovery. In extreme cases, vegetation itself can become a hazard. Evidence from the 2004 Indian Ocean tsunami illustrates this variability: while some mangrove belts attenuated wave energy, others were completely uprooted. The resulting debris acted both as high-velocity projectiles and as obstructive litter within coastal and harbour environments, thereby amplifying damage. Such behaviour contrasts with conventional "grey infrastructure", which is designed with defined failure modes and often incorporates sacrificial elements to dissipate energy while maintaining safety. In ecological systems, failure is less predictable and may not conform to controlled patterns. It is obvious that "scale" is a critical factor in this context. The survivability and effectiveness of an NbS depend on its spatial extent and density. Narrow or fragmented systems are more susceptible to failure, whereas wider, mature systems may provide both attenuation and structural resilience. However, defining such thresholds remains context specific.

Mechanical Performance. Beyond survivability, performance depends on the ability of the NbS to provide measurable mitigation. While attenuation effects are well studied and modelled, integrating them into engineering design introduces a fundamental challenge. In conventional design, the mitigation provided by a structure such as a seawall may be expressed as:

$$Mitigation\ = f(seawall)$$

With the introduction of an NbS element—such as a mangrove belt—the expected performance may be conceptualised as:

$$Mitigation\ = f(seawall) + f(mangrove)$$

Here, $f(\text{mangrove})$represents the estimated contribution of the ecosystem based on modelling or historical evidence. However, this formulation implicitly assumes that the ecosystem will establish, mature, and persist over the design life of the infrastructure. In practice, these very assumptions introduce uncertainty. The mangrove system may not reach the intended maturity, or it may degrade or disappear over time due to environmental or anthropogenic factors. Incorporating these uncertainties, the relationship can be more appropriately expressed as:

$$Mitigation\ = f(seawall) + \alpha\ \times\ \beta\ \times f(mangrove)$$

where α represents the probability that the ecosystem reaches the desired level of maturity, and β represents the probability that it persists and remains functional at the time of a hazard event. This formulation highlights a key distinction: while the performance of engineered structures is treated as deterministic within design limits, the contribution of NbS is inherently probabilistic.

Design Implications. This leads to a fundamental design dilemma. One approach is to distribute the mitigation load between the engineered structure and the NbS, reducing structural requirements but introducing probabilistic dependence into a deterministic framework—something current design codes do not readily accommodate. A second approach is to design the engineered system for the full mitigative load, treating the NbS as a supplementary layer. While conservative, this approach does have the advantage that it aligns with existing engineering practice. A third approach involves allowing the NbS to mature before finalising structural design. However, given the long maturation periods of ecosystems such as mangroves, this is often impractical for infrastructure projects. These considerations illustrate that, even where ecological feasibility is established, uncertainty in performance constrains the integration of NbS into core design frameworks. While partial benefits may accrue during early stages of ecosystem development, their use as primary mitigation measures remains difficult to justify within current engineering and regulatory contexts.

Implementational Challenges

Governance and Finance Challenges. Even where ecological feasibility and technical performance considerations are addressed, the implementation of NbS remains constrained by governance and financial barriers. These challenges arise not only from cost, but from a structural mismatch between the characteristics of NbS—uncertain, long-term, and spatially extensive—and those of conventional infrastructure systems, which operate within clearly defined boundaries of ownership, accountability, and risk. Broadly, these challenges can be grouped into three issues: (**1)** those of land ownership and spatial requirements, **(2)** those of project financing and actuarial constraints, and **(3)** those involving jurisdictional governance and long-term stewardship.

Land Ownership and Spatial Constraints. A fundamental constraint in implementing coastal NbS, particularly wetland systems, is their spatial requirement. Effective interventions typically require land areas on the order of several hectares, in contrast to the relatively compact footprint of conventional infrastructure. While publicly funded projects may have greater flexibility, privately developed projects or public–private partnership (PPP) ones face significant barriers in acquiring and allocating such land, especially in high-value and highly regulated coastal zones. In restorative scenarios, land may already be classified as wetlands or mangroves, reducing acquisition challenges but introducing regulatory restrictions on their use and modification. In engineered scenarios, the burden of land acquisition and associated costs becomes more pronounced. These spatial constraints limit the applicability of NbS, particularly in densely developed coastal regions and near critical infrastructure.

Project Financing and Actuarial Constraints. Although NbS interventions are generally less capital-intensive than grey infrastructure, their financial viability is complicated by the temporal mismatch between costs and benefits, and by uncertainty in performance. While investments are made upfront, benefits—especially for ecosystems such as mangroves—may take decades to materialise. This misalignment is particularly problematic in infrastructure projects operating under fixed concession periods, where private entities may not realise the full value of the intervention. From an actuarial perspective, NbS presents a more fundamental challenge. Financial and insurance frameworks rely on quantifiable and historically validated risk parameters. The probabilistic nature of NbS performance—arising from uncertainties in establishment, maturation, and persistence—makes it difficult to incorporate these systems into conventional risk models.[19] In the absence of standardised benchmarks or validated performance data, projects incorporating NbS may be perceived as carrying higher risk. This can translate into higher insurance costs, reduced investor confidence, or reluctance to adopt such measures altogether.

Jurisdictional and Governance Challenges. NbS interventions often extend beyond the operational boundaries of infrastructure assets, creating challenges in assigning responsibility for their maintenance and protection. Under regulatory frameworks such as the Coastal Regulation Zone (CRZ), many coastal ecosystems fall under government jurisdiction, requiring infrastructure operators to depend on external agencies for long-term stewardship. This dependency introduces uncertainty, as the effectiveness of the NbS now becomes contingent not only on ecological conditions but also on administrative capacity, coordination, and sustained institutional commitment. Conversely, assigning responsibility to private entities imposes additional financial and operational burdens, further discouraging adoption. A critical unresolved issue is that of liability. In the event of NbS failure—whether due to ecological degradation, extreme events, or inadequate maintenance—it is often unclear which entity bears responsibility. This ambiguity creates legal and financial risks that are difficult to quantify, reinforcing conservative design choices and deterring both public and private actors from integrating NbS into core infrastructure strategies.

Conclusion and Way Forward

An NbS-based approach to protecting critical coastal infrastructure and settlements must be evaluated against a fundamental constraint, which is that while such systems provide demonstrable mitigation benefits, their performance remains inherently probabilistic. In

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[19] Lorraine Blackwood and Fabrice G Renaud, "Barriers and Tools for Implementing Nature-Based Solutions for Rail Climate Change Adaptation", *Transportation Research Part D: Transport and Environment* 113 (2022): 103529, https://doi.org/10.1016/j.trd.2022.103529

contrast, conventional infrastructure design frameworks are based on deterministic safety and reliability standards. As a result, NbS cannot currently serve as primary, design-grade defence systems for critical infrastructure but are more appropriately positioned as supplementary or risk-modulating layers within a broader resilience strategy.

Although global practices have progressed in incorporating ecological feasibility into NbS planning, these approaches remain largely uncodified in the Indian context. In the absence of standardised frameworks, the integration of NbS into infrastructure systems remains constrained across the planning–design–operation continuum. This limits their adoption to peripheral roles—such as environmental offsets or discretionary interventions—rather than embedding them within core risk mitigation strategies.

A further structural constraint arises from the temporal mismatch between infrastructure development cycles and ecosystem maturation. Critical infrastructure is typically designed and commissioned within defined timelines, whereas coastal ecosystems such as mangroves may require decades to achieve functional maturity. While pilot projects are essential for building empirical understanding, they are unlikely to generate evidence at a pace commensurate with current infrastructure expansion, particularly in the context of India's maritime development trajectory.

Addressing these constraints requires a coordinated institutional and policy response centred on four priorities:

- First, there is a need to develop standardised design frameworks that enable the integration of NbS into engineering practice while explicitly accounting for uncertainty in performance.[20]
- Second, risk assessment and actuarial methodologies must evolve to incorporate probabilistic mitigation systems, supported by validated datasets and performance benchmarks.
- Third, governance structures must clearly define jurisdiction, responsibility, and liability across the lifecycle of NbS interventions, particularly where such systems extend beyond project boundaries or fall within regulated coastal zones.
- Finally, financing mechanisms must be aligned with the long-term and uncertain nature of NbS, including incentives, risk-sharing instruments, and models for sustained maintenance and stewardship.

In the absence of such reforms, NbS adoption in critical coastal infrastructure will remain limited to supplementary applications. However, with the development of robust methodologies, regulatory clarity, and institutional capacity, NbS can be systematically integrated into hybrid coastal defence systems. In such a framework, they do not replace engineered infrastructure but enhance overall system resilience—contributing to hazard mitigation while delivering broader ecological and socio-economic benefits.

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[20] Bureau of Indian Standards, *Code of Practice for Planning and Design of Ports and Harbours: Part 5 Layout and Functional Requirements (IS 4651: Part 5: 1980)* (New Delhi: Bureau of Indian Standards, 1980), https://law.resource.org/pub/in/bis/S03/is.4651.5.1980.pdf

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