MARITIME PERSPECTIVES 2025

Blue Economy and Resilience

Edited by

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National Maritime Foundation

MARITIME PERSPECTIVES 2025: BLUE ECONOMY AND RESILIENCE

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First Published in 2025

Cover Picture Credit: Design created using Canva

ISBN: 978-81-994377-3-9

Rs: 300.00

Maritime Perspectives, published since 2014, is an annual publication of the National Maritime Foundation (NMF) which compiles thematically arranged research articles that have been published on the NMF website on issues related to holistic maritime security. The current editions of the Maritime Perspectives 2025, compile articles covering the period 15 September 2024 to 30 September 2025 in six thematically focused areas. Some articles published by the NMF Research Faculty elsewhere, are also reproduced with the permission of the original publisher.

The editors would like to acknowledge the special contributions of the production team comprising the following:

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Published by:
NATIONAL MARITIME FOUNDATION
Varuna Complex, Airport Road,
NH-8, New Delhi-110 010

Printed by:
Alpha Graphics
6A/1, Ganga Chambers, W.E.A.,
Karol Bagh, New Delhi-110005

Foreword

The oceans represent immense opportunities as well as unprecedented challenges. On the one hand, they are the arteries of global commerce, carrying the bulk of international trade, while also serving as sites of ecological, technological, and geopolitical transformation. Their importance is unmatched: they connect nations, sustain livelihoods, provide vital resources, and underpin both global security and prosperity. On the other hand, alongside this promise lies another reality, albeit a darker one. The world ocean and its four constituent basins are groaning under the enormous pressure of unsustainable human activity — activity that is threatening the acoustic habitat of marine life, generating ever greater concentrations of greenhouse gases that result in higher sea-surface temperatures and cause significant changes to global precipitation cycles, and driving exponential increases in oceanic pollution. How to balance economic opportunities with the pressing need to prevent any further ecological destruction and environmental degradation is precisely the question that has given birth to the concept of the "blue economy", one that recognises and acknowledges that the world ocean is the font of all life on earth.

This volume of Maritime Perspectives focuses upon the *Blue Economy and Resilience* and makes its intellectual offerings and policy recommendations in three sections. There is a fourth section that offers reviews by members of the NMF's research faculty of books that address a wide range of issues spanning ecological, economic, technological, and legal aspects.

The first section, *India's Marine Frontier: Balancing Growth, Ecology and Human Health*, explores the manner in which the intensifying effects of climate change have added an unprecedented layer of complexity to ocean governance. The impact is not limited to the environment alone; it extends to the lives of millions who depend on the ocean for their livelihood. The growing presence of plastic pollution, especially microplastics, has compounded this crisis. The consequences are far-reaching: threatening food security, undermining nutrition, and presenting long-term health risks for coastal communities. Equally concerning are the effects of unchecked anthropogenic activities. The push for seabed mining to extract critical minerals and raw materials needed for modern technology, poses serious ecological risks. The garbage accumulating in the Indian Ocean and its impact on native marine species, biodiversity, and the livelihoods of coastal communities, highlights the urgent need for comprehensive scientific assessment and policy action.

The second section, *Fortifying India's Critical Seabed Infra*, addresses how climate change has amplified the frequency and intensity of extreme weather events, threatening not only coastal populations but also critical maritime infrastructure. Submarine communication cables, which carry an overwhelming majority of global digital traffic, as also seabed pipelines, are particularly vulnerable. The incident involving *The New New Polar Bear* and similar episodes serve as a stark reminder that damage to seabed infrastructure can disrupt global economies, affect international security, and destabilise financial markets. The resilience of this hidden yet vital infrastructure must therefore be prioritised through improved governance, technological innovation, and multilateral cooperation.

The third section, *India's Global Reach: Securing Energy, Connectivity and Minerals*, underscores the fact that States are still grappling with the urgent need to secure their energy demands. The vulnerability of chokepoints to increasing congestion, accidents, and geopolitical instability, impact maritime supply chains. This increases the preference of States to trade via multimodal transport corridors such as the IMEC and to actively explore alternative sea routes.

The book reviews that comprise the fourth and last section of this volume reveal that the idea of the 'Blue' economy has emerged as both a necessity and an opportunity. It represents a framework that integrates economic growth, environmental sustainability, and societal wellbeing, ensuring that marine resources are harnessed responsibly and sustainably. Yet, the pursuit of a Blue Economy cannot be divorced from the fact that resources, both living and non-living, are overexploited and depleting at an alarming rate.

For India, of course, the stakes could not be higher. As a nation with a coastline of 11,098.81 km, an exclusive economic zone of over two million sq.km, and deep-rooted connections with the ocean, the health and security of maritime spaces directly influence our prosperity and national security. The challenges highlighted in each of the chapters, have direct implications for coastal communities, trade resilience, and India's leadership role in the Indian Ocean and the wider Indo-Pacific.

Perhaps the true significance of this book lies in the fact that its chapters bring together diverse perspectives that underscore the interconnectedness of maritime challenges and highlight the need for coordinated, cross-sectoral responses. This volume is, therefore, both timely and essential. It is hoped that it will serve as a valuable resource not only for policymakers and policy-shapers but also for academicians, researchers, strategic analysts, maritime practitioners, and the public at large.

Happy Reading! Sam no Varunah!

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India's Marine Frontier: Balancing Growth, Ecology and Human Health

From Exposure to Policy: Tracing Human Health Risks of Marine Microplastics and Their Regulatory Landscape

Dr Chime Youdon and Mr Soham Agarwal

Fifty to seventy-five trillion pieces of plastic and microplastics (MPs) populate the world's oceans, a number which grows by the day.[1] Albeit developed in 1907, the large-scale production of synthetic plastics during the 1940s and 1950s led to their proliferation in human society and consequently our environment due to their durability, cost-effectiveness, and manufacturing versatility.[2] As a result, global plastic production skyrocketed from just two million metric tonnes in 1950 to over 400 million metric tonnes by 2015. By 2021, cumulative production exceeded a staggering nine billion metric tonnes. If current trends persist, this figure is projected to reach an alarming 33 billion metric tonnes by 2050, and it is estimated that by this time there will be more plastic than fish in the sea.[3] This dramatic boom in plastic production has come at a profound environmental cost. Inadequate waste management systems have resulted in nearly 60 per cent of all plastic waste being either disposed in landfills or directly released into the environment.[4] Due to their synthetic nature, these polymers persist for centuries, with vast quantities ultimately making their way into marine ecosystems.

Since the 1980s, plastic waste has become the dominant form of marine litter.[5] Each year, between 12.8 to 14.8 million metric tonnes of plastic enter the marine environment,[6] much of it accumulating in large gyre-driven garbage patches such as the Great Pacific Garbage Patch, which spans roughly 1.6 million sq.km.[7] A significant portion of this plastic enters the ocean through rivers and breaks down into microplastics (1µm–5 mm) and even smaller nano-plastics as it degrades.[8] Coastal regions across the world have emerged as plastic pollution hotspots. For example, in India, coastal states such as Gujarat (Gulf of Kuchchh and Gulf of Khambhat) Mumbai, Kerala, Goa, Kanyakumari, Andaman and Nicobar Islands along with fishing harbours in Kerala and Karnataka – emerge as hotspots, fuelled by industrial discharge, tourism, fishing, and oceanic currents.[9]

Microplastics were first identified as a major ecological issue in 2004.[10] Since then, they have become a focus of environmental research due to their pervasive presence and associated health risks. These microscopic particles not only infiltrate ecosystems but also act as carriers of toxic pollutants and invasive species, exacerbating environmental damage.[11] Between 2015 and 2022, concentrations of plastic in the ocean rose sharply — from 2.9 kg to 14.2 kg per square kilometre — while microplastic hotspots expanded tenfold.[12] Today, microplastics are estimated to outnumber the stars in our galaxy by a factor of 500 times,[13] posing an unprecedented threat to biodiversity, ecosystem resilience, and human health. In terms of economic costs, microplastic pollution causes annual damage of around USD 8 billion to marine industries, while healthcare costs may rise due to links with chronic diseases.[14]

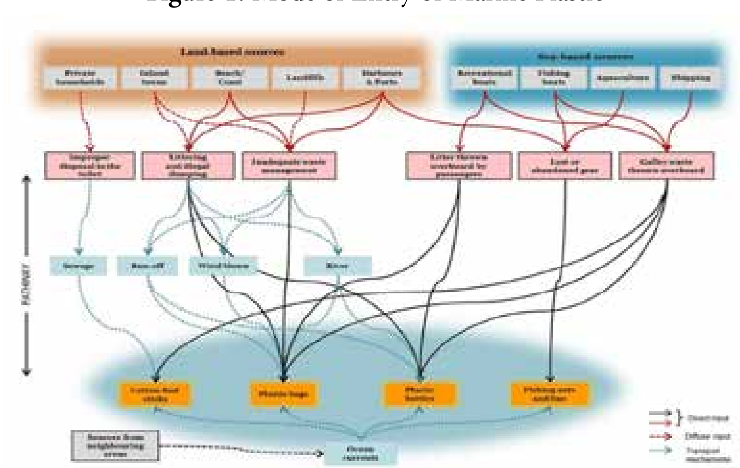
Addressal mechanisms includes policy and regulatory measures at the global, regional, and national level — such as the under-negotiation United Nations Environment Assembly's (UNEA) Global Plastics Treaty, and Europe's Restriction of Microplastics Initiative (2018 Plastics Strategy) — which are evolving to curb this crisis.[15] However, the lack of standardised detection methodologies hampers impact assessments.[16] This article begins by identifying microplastic pathways, sources, and their transformation in the ocean, and assessing the current state of research of their impact upon human health. Thereafter, policy and regulatory frameworks at the global, regional, and national level on microplastics are mapped. This article seeks to highlight the importance of improving health impact assessments and strengthening marine monitoring programs to ensure accurate data collection. The case is made for a robust, coordinated national implementation strategy supported by a legal framework for the reduction and spread of microplastics.

Microplastic Pathways, Sources, and Transformation in the Ocean

Categories of Microplastics based on Origin: Primary versus Secondary. Microplastics (<5 mm) are classified as primary or secondary based on their origin. Primary microplastics, i.e., those that are intentionally manufactured for products such as cosmetics, textiles, and industrial abrasives contribute 15–31 per cent of oceanic microplastic loads, with key sources including synthetic textile laundering (35 per cent) and tire abrasion (28 per cent).[17] Secondary microplastics, comprising 69–85 per cent of oceanic microplastic load, result from the degradation of larger plastics (e.g., single-use plastics, fishing gear) through photo degradation (ultraviolet exposure), mechanical degradation (wave action), and limited biological degradation (microbial colonisation).[18] This classification oversimplifies their interconnected lifecycle as primary microplastics can degrade further into smaller secondary forms and data variability across studies undermines precision. This diverts the focus from systemic drivers like industrial production and consumer behaviour which require integrated mitigation strategies.

Mode of Entry: Land-based versus Ocean-based. Microplastics enter the ocean predominantly from land-based sources, accounting for 80–90 per cent of marine plastic pollution (**Figure 1 refers**).[19] Among land-based contributors, synthetic

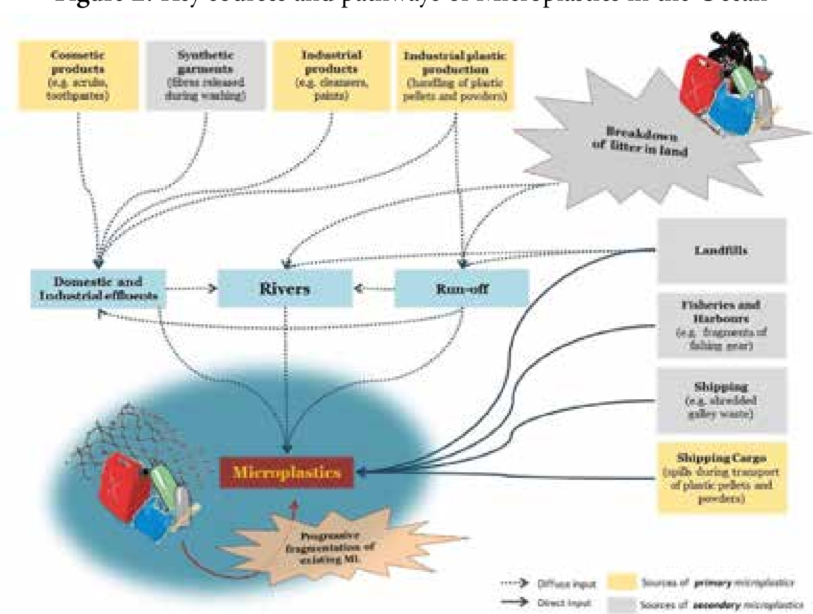
Figure 1. Mode of Entry of Marine Plastic



Source. Joana Mira Veiga et al. Identifying Sources of Marine Litter – Technical Report. European Commission, 2016 textiles are a major contributor. According to the United Nations Environment Programme (UNEP),[20] microplastics released from textiles washing account for around nine percent of total environmental discharges. However, when accounting for the fact that roughly half of the microplastics from tire wear, road markings, and urban dust are retained in soils or along riverbanks, the share of textile-derived microplastics reaching the ocean increases to 16 per cent.[21] Ocean-based sources such as discarded fishing gear, waste from ships, offshore platforms debris, and aquaculture operations contribute the remaining 10–20 per cent of marine plastic pollution.[22] However, research into marine microplastics is evolving with newer technologies and methodologies constantly updating our understanding on the sources of marine microplastics. Further, these figures differ regionally depending upon the level and type of discharge from the littorals of seas nd oceans.

Microplastics reach marine environments through multiple pathways—waterborne (e.g., rivers), airborne (e.g., wind deposition), and direct maritime discharge (**Figure 2 refers**). Rivers and surface runoff act as key transport pathways

Figure 2. Key sources and pathways of Microplastics in the Ocean

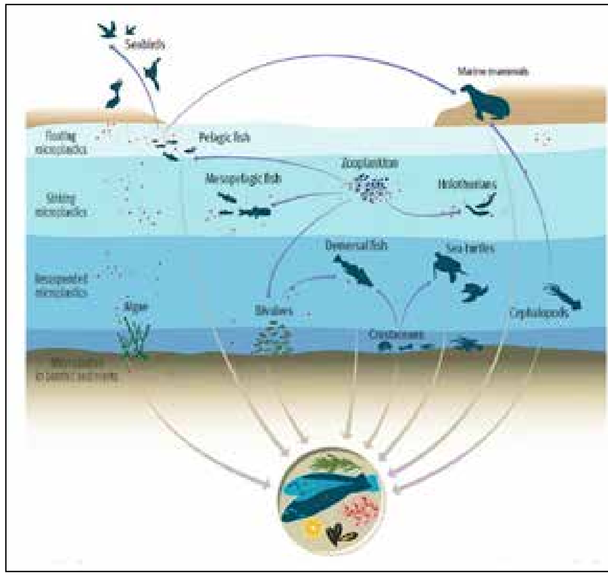


Source. Joana Mira Veiga et al. Identifying Sources of Marine Litter – Technical Report. European Commission, 2016 with an estimated 90 per cent of ocean plastics originating from just 10 rivers – nine of which are in Asia.[23] Once in the ocean, MPs undergo physical, chemical, and biological transformation, fragmenting into smaller particles, releasing toxic additives, and becoming increasingly bioavailable.[24] Climate change exacerbates these processes. Altered ocean currents redistribute MPs to previously uncontaminated areas while rising sea surface temperatures (SSTs) accelerate degradation and the leaching of toxic compounds intensifying interactions with marine organisms.[25] Additionally, coastal flooding flushes land-based MPs into aquatic systems increasing their persistence in food webs.[26]

The long-term impacts of microplastics on agriculture, fisheries, and livelihoods remain unclear, but concerns persist over their toxicity and ecological risks. As microplastics degrade, they can leach harmful chemicals and carry pathogens, potentially triggering inflammation, toxicity, and broader environmental harm.[27] Climate-induced fragmentation and dispersion further amplify the transport and bioaccumulation of POPs, heightening toxicity within marine food webs.[28] However, this linear source-to-impact model often overlooks regional variability and socio-economic drivers such as poor recycling infrastructure. Addressing these intertwined challenges calls for interdisciplinary frameworks that integrate ecological, social, and economic dimensions. The complex interplay of MPs, POPs, and climate change underscores the urgent need for adaptive, science-based strategies to mitigate their combined threat to marine ecosystems.

Pathways of Microplastic Exposure in Humans. Humans are exposed to microplastics through multiple pathways, primarily via ingestion, inhalation, and dermal contact. The most significant exposure routes include ingestion through seafood. Microplastics are ingested by all kinds of living organisms ranging from plankton, fish, and large mammals in the marine environment. Since the 1960s, it is documented that microplastics are ingested by marine species that affects seabirds, mammals, turtles, and fish, permeating food webs via direct ingestion and trophic transfer (**Figure 3 refers**).[29] Filter-feeders such as mussels and oysters are key contributors to human dietary exposure[30] to microplastics which carry along with them pollutants like persistent organic pollutants (POPs) and heavy metals.[31] Beyond seafood, microplastics contaminate salt, honey, drinking water, dairy, and beverages making exposure unavoidable. Inhalation and dermal contact further increase exposure, particularly in urban area.

Figure 3: Potential Pathways of Marine Microplastic into our Seafood



Source. UNEP 2021, Drowning in Plastic- Marine Litter and Plastic Waste Vital Graphics, GRID-Arenda

Health Risks Associated with Microplastic Exposure

The small size and chemical composition of microplastics facilitate their bioavailability leading to potential physiological and toxicological effects. Exposure to microplastics has been associated with cellular and tissue damage, chemical toxicity, endocrine disruption, immune dysfunction, and potential carcinogenic effects.

1. **Cellular and Tissue Damage.** Microplastics and nano plastics penetrate membranes accumulating in organs (e.g., liver, brain) and cause oxidative stress, inflammation, and mitochondrial dysfunction.[32]

2. **Toxicity and Chemical Exposure.** Microplastics adsorb and transport toxic substances such as polychlorinated biphenyls (PCBs), bisphenol A (BPA), phthalates, and heavy metals leading to endocrine disruption, metabolic disorders, and carcinogenesis.[33] Upon ingestion, microplastics may leach these chemicals into the digestive system contributing to systemic toxicity and inflammation.[34] The bioaccumulation of these toxicants in organs raises concerns about their long-term health impacts including neurological and immune system disorders which are associated with endocrine disruption, metabolic disorders, and inflammation.[35] Some microplastics are small

enough to cross the intestinal barrier and enter the bloodstream potentially accumulating in organs and inducing oxidative stress.[36]

3. **Endocrine Disruption and Reproductive Effects.** Microplastics and their associated chemicals interfere with hormonal regulation and reproductive health. Studies indicate that exposure to plastic-derived pollutants can reduce sperm quality, impact embryonic development, and alter gene expression related to fertility. Additionally, plastic additives such as BPA have been linked to developmental disorders and transgenerational health effects raising concerns about long-term reproductive consequences.[37]
4. **Potential Carcinogenic Effects.** Chronic exposure to microplastic-associated carcinogens (e.g. PAHs) may increase cancer risk.[38]
5. **Immune System Dysfunction.** Microplastic ingestion and inhalation have been linked to altered immune responses potentially leading to immune suppression or hyperactivation. Experimental studies on marine life indicate that microplastic exposure induces pro-inflammatory cytokine production and disrupts immune cell function.[39] These findings suggest that chronic exposure could weaken immune resilience, making individuals more susceptible to infections and inflammatory diseases.
6. **Neurological and Developmental Concerns.** Exposure to microplastic-associated neurotoxicants including BPA and phthalates has been associated with cognitive impairment, behavioural changes, and neurodevelopmental disorders.[40] There is growing concern that maternal exposure to microplastics during pregnancy could impact foetal brain development, potentially leading to neurodevelopmental deficits. As microplastics continue to accumulate in the environment and the food chain, the potential risks to neurological health warrant further investigation.

Empirical Evidence of Microplastic Contamination in Human Food Sources

Several studies have documented the presence of microplastics in various dietary sources, reinforcing concerns about human exposure (**Table 1 refers**). As

Table 1. Summary of Marine Species Documented to Have Ingested Plastics

Category	Study	Findings	Methodology	Health impact	Country
Fish	Comprehensive seafood study[41]	MPs in fish: 0.96 ± 0.08 MP/fish (herring, sardine, whiting, flathead)	Microplastic characterisation	Seafood as MP exposure pathway	Australia
	Golden anchovy study[42]	MPs in anchovies: 6.78 ± 2.73 MP/fish (fibres, films, pellets)	Tissue microplastic identification	Risk from whole-fish consumption	India
Canned Fish	Karami et al. (2018)[43]	Micro- and mesoplastics in canned sardines and sprats	Microscopic analysis	Increased exposure from canned seafood	Malaysia
	Canned fish study[44]	MPs in canned mackerel and tuna: 1.28 ± 0.04 MP/g (PET, PS, PVC)	Canned fish analysis	Higher exposure from processed seafood	Iran
Shellfish	Van Cauwenberghe & Janssen (2014)[45]	Microplastics in molluscs. Avg. 11,000 MPs/year (European consumption)	Soft tissue analysis	Gastrointestinal/systemic exposure	Japan
Shrimp	Indian white shrimp study [46]	MPs in shrimp: 0.04 ± 0.07 MP/g wet weight	Spectroscopy analysis	Exposure through shrimp consumption	India
Seaweed	Nori seaweed study[47]	MPs in nori seaweed: 1.8 ± 0.7 MP/g	Polymer/size analysis.	Contamination in seaweed	China
Sea Salt	Chinese study on salt (2015)[48]	MPs in sea salt: 550–681 particles/kg (fibres, fragments)	Microplastic content analysis	Regular MP exposure via salt	China

Source: Compiled by the Authors

microplastics continue to accumulate across environmental compartments and infiltrate the food chain, growing concerns have emerged regarding their potential impacts on neurological health. Early studies suggest that microplastics may induce neurotoxic effects through mechanisms such as oxidative stress, inflammation, and disruption of the blood-brain barrier. However, evidence remains limited and fragmented, underscoring the urgent need for systematic, multidisciplinary research to understand the extent and nature of these risks. In this context, improving the quality and scope of health impact assessments becomes critically important — not only to clarify potential neurological and systemic effects, but also to inform evidence-based regulatory responses. Equally vital is the strengthening of marine monitoring programs that can consistently track microplastic presence and behaviour in aquatic systems. Together, robust health assessments and enhanced monitoring will help generate reliable, high-resolution data that is essential for guiding targeted policy interventions and safeguarding public health in the face of this emerging environmental threat.

Impact of Microplastic Characteristics on Marine Ecosystems and Human Food Systems

Microplastics vary in size, colour, and shape, influencing their environmental fate, interactions with marine biota, and implications for human food systems.

Size: Bioavailability and Trophic Transfer. Microplastic size, ranging from nano plastics (<1 µm) to 5 mm, governs transport, bioavailability, and toxicity. Smaller particles, with higher surface-area-to-volume ratios, are more mobile, disperse widely via ocean currents, and absorb contaminants such as polychlorinated biphenyls acting as pollutant vectors.[49] Larger microplastics (1–5 mm) are ingested by filter feeders (e.g., mussels) and predators (e.g., fish), causing physical blockages and reduced feeding efficiency.[50] Smaller particles (<100 µm) penetrate cellular membranes, accumulate across trophic levels, and cause transgenerational effects such as reduced zooplankton reproduction.[51] In human food systems, smaller microplastics in seafood (e.g., shellfish, finfish) translocate into edible tissues, pose health risks.[52]

Colour: Selective Ingestion and Toxicity. Microplastic colour (e.g., white, blue) impacts ingestion and persistence. Darker plastics degrade faster under ultraviolet light, while lighter ones persist.[53] Bright colours (e.g., red) mimic prey and increase ingestion by fish, while transparent particles attract filter feeders. Species-specific preferences, such as larval fish favouring blue — vary.[54] In seafood, coloured microplastics introduce toxic additives (e.g., dyes), risking chemical transfer to humans.

Shape: Ingestion, Transport, and Retention. Microplastic shapes—fibres, fragments, spheres, films, foams — affect hydrodynamics and biological uptake. Fibres, often from textiles, entangle in gills or digestive tracts of marine species (e.g., crustaceans), while fragments and spheres are readily ingested due to compact shapes.[55] Fibers prolong gut retention, increasing contaminant release, whereas spheres translocate efficiently across tissues, enhancing bioaccumulation.[56] In human food systems, fibres dominate in shellfish and fragments in finfish reflecting habitat differences.

Challenges in Microplastic Detection, Characterisation, and Regulation

The pervasive nature of microplastics and nano plastics in environmental and biological systems poses significant scientific and regulatory challenges. Their physical and chemical heterogeneity — spanning sizes (<1 μm to 5 mm), shapes (fibres, fragments, spheres), colours, polymer types (e.g., polyethylene, polystyrene), and degradation states — complicates detection, quantification, and risk assessment. These challenges are compounded by the absence of standardised methodologies, regulatory gaps, and limitations in current analytical technologies hindering a comprehensive understanding of microplastic pollution and its implications.

Challenges in Detection and Characterisation

The accurate detection and characterisation of microplastics in environmental matrices (e.g., water, sediments, biota) are hindered by diverse particle properties and chemical additives (e.g., plasticizers, flame retardants). Existing microscopy techniques such as Optical, Scanning Electron (SEM) and Atomic Force Microscopy (AFM) offer morphological insights but are labour-intensive, error-prone, and lack chemical specificity.[57] Spectroscopy methods such as Fourier Transform Infrared (FTIR) and Raman Spectroscopy enable polymers identification but face limitations. For instance, FTIR struggles with particles below 20 µm, missing nano plastics, while Raman is highly sensitive to fluorescence interference from organic matter.[58] Advanced techniques such as Micro-FTIR Spectroscopy and Micro-Raman improve resolution but are time-consuming and require expertise, limiting scalability.[59] Mass spectrometry-based methods (e.g., Pyrolysis-GC-MS) provide detailed chemical profiling but are destructive, costly, and unsuitable for routine monitoring.[60] These methodological limitations are compounded by the dominance of non-plastic particles. For example, a study found that only 1.4 per cent of 404 sediment particles analysed via FTIR were microplastics, while 96 per cent were quartz, highlighting the challenge of distinguishing plastics from natural substrates.[61] The absence of standardised protocols for isolation, identification, and quantification limits comparability across studies, hindering spatial and temporal trend analysis.

1. **Inconsistencies in Sampling and Quantification.** The lack of uniform protocols in sampling and quantification across environments (marine versus terrestrial), depths and particle sizes results in irreproducible findings.[62] Additionally, inadequate contamination control measures, such as insufficient precautions against airborne microplastic deposition during collection and analysis, further compromise data integrity.[63] Natural degradation and transport variability, driven by factors such as polymer weathering rates, ocean currents, and sedimentation processes further obscure long-term pollution trends by affecting microplastic detectability.[64] These inconsistencies prevent the establishment of baseline pollution levels and accurate risk assessments, highlighting the urgent need for standardised methodologies that account for environmental and analytical variables.

2. **Emerging Technologies for Improved Detection.** Emerging technologies are advancing microplastic detection by improving efficiency, accuracy, and scalability. Machine learning and AI-driven tools such as PlasticNet have

demonstrated over 95 per cent identification accuracy, significantly reducing human error and expediting large-scale data processing.[65] However, their effectiveness depends on high-quality training datasets, limiting their reliability for novel or degraded microplastic particles. Portable detection tools — including fluorescence-based sensors, portable FTIR, and Raman spectroscopy — enable field-based analysis, reducing dependence on laboratory-based methods.[66] While these technologies hold promise, validation across diverse environmental matrices is essential to ensure reliability. Additionally, scalability and cost barriers remain significant challenges, restricting widespread adoption.

3. **Policy and Regulatory Gaps.** Policy frameworks lag behind scientific progress due to insufficient data and inconsistent methodologies and the absence of global monitoring standards. Most policies focus on microplastics such as bans on their primary sources, while microplastic contamination in food, water, and ecosystems remains largely unregulated. Data gaps on long-term ecological and human health impact partially due to analytical challenges — delay proactive policy and regulations perpetuating a reactive approach rather than proactive approach. These gaps reflect a broader disconnect between scientific urgency and regulatory inertia. A more detailed exploration of these gaps will be undertaken here forth.

Policy and Regulatory Frameworks

Policy and regulatory mechanisms are an effort to respond to the challenges posed by marine litter especially microplastics. With developing literature and better scientific understanding of the environmental, ecological, and economic impacts, both voluntary and binding mechanisms are being developed at the international, regional, and national levels to address the lifecycle of plastic in attempts to address the proliferation of microplastics in the marine environment. The regulatory structure has evolved to distinctly address primary and secondary microplastics.

Primary Microplastics

The most recent regulatory mechanism to address primary microplastics is seen within the European Union (EU). While it is acknowledged that primary microplastics represent a relatively smaller proportion of microplastic in the sea, yet they form the only type of microplastic which has been directly and explicitly regulated. This is because they are relatively easy to address and can allow for targeted action.

Drawing from the European Strategy for Plastics in a Circular Economy, and the Zero Pollution Action Plan — which mandates a 30 per cent reduction in microplastics release into the sea by 2030 — the European Commission released Commission Regulation (EU) 2023/2055.[67] This legislation introduced "synthetic polymer microparticles" (SPM) within Annex XVII of the Regulation concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), which is the primary EU law to protect human health and the environment from the risks posed by chemicals.[68] Inclusion of SPMs into REACH has enabled their regulation at a European Union level through which a general ban has been imposed on the "placing on the market" of SPMs, either on their own or intentionally introduced into "mixtures".[69] Size limits are established to gauge applicability of the restriction. This includes particles equal to or less than five mm in diameter but also includes those particles the "length of which is equal to or less than 15 mm and their length to diameter ratio is greater than three" when found in a concentration equal to or greater than 0.01 per cent by weight of the mixture. Particles up to 15 mm in length are brought within the scope of the restriction for those which are used for reinforcement of adhesives and concrete which are "very persistent and contribute to the identified risk".[70] The minimum concentration value of 0.01 per cent is identified as it is the minimum level where SPMs can confer a sought-after characteristic to the product and may be intentionally added. Therefore, these SPM (polymers as defined in the regulation) may not be "supplied or made available…to a third party" (including imports within the Union) either as themselves or within a product to which they are added to alter its properties.[71]

The aim is to capture all those cases which inevitably lead to the release of these SPMs into the environment. It is estimated that this restriction will lead to a cumulative emission reduction of nearly 500,000 tonnes of microplastics over a 20-year period following the implementation of the regulation.[72] While this may sound significant, it must be compared to 200,000 – 500,000 tonnes of microplastic released into the marine environment each year from the textile industry alone.[73]

This can stem from the extremely limited scope of this regulation with significant derogations from this ban which in any case is sought to be implemented gradually over a period of time. In cases where the product does not release SPMs, their release can be prevented/minimised or regulated by other legislation are excluded from the application of this ban.[74] There are two significant exclusions from these restrictions.

First, the scope of the term 'SPMs' is restricted to include only solid, synthetic/chemically modified, non-degradable, and insoluble polymers given the lower environmental impact of liquid, natural, degradable, and soluble polymers. This also promotes investment in developing environmentally friendly polymers. Recent research, however, has highlighted that "biodegradable" plastics do not do so in the marine environment as they require specific conditions such as heat and microbes which otherwise are not prevalent at sea.[75] Even if they do degrade, it is often at an extremely slow pace, or they degrade into smaller and more persistent particles.[76] Only specific types of plastics have shown to be biodegradable by microbes in seawater, but legislation does not make any distinction between the two. This highlights the importance of informed decision-making and bridging the gap between science and regulation.

Second, is the permitting of derogations from the ban for those SPM "for use at industrial sites" among other uses and those which can be contained from release either by technical means are permanently modified at end use, or permanently incorporated in a solid matrix at end use.[77] For these categories of SPMs, instructions for use and disposal (IFUD) are to be provided to industrial downstream users and end users and estimated SPM emissions are to be reported each year by the SPM supplier.[78] The rationale is that such instructions can prevent or at least significantly minimise SPM release into the environment given that industries that are well-regulated will follow and implement the IFUD.[79] However, this presumes that the supplier is aware of the different emission pathways for microplastics. While reporting requirements place an obligation on the supplier to undertake emission assessments, significant gaps in research and understanding may preclude accurate reporting and disposal mechanisms, making the framework inefficient. This demonstrates the challenges and competing interests often must be balanced by policymakers when developing legislation on such issues. Therefore, while this legislation may capture consumer products to which SPMs are intentionally added, its industrial use has currently been subjected to IFUD and reporting requirements. This broadly corresponds to the legislation in the United States of America attempting to restrict the manufacture and distribution of microbeads in "rinse-off cosmetics" under the Microbead-Free Waters Act 2015 broadly limited to cosmetics and non-prescription drugs.[80] The objective of this Act is to prevent run-off into lakes and oceans of microplastics which cannot currently be filtered and not to address microplastic impact on human health. This stems from the fact that research on the impact of microplastics on marine ecosystems is better documented than the impact of microplastics on human health.

Hence, legislation is designed in such a way that it aims to restrict specific emission pathways and reduce impact on human health indirectly. A notable example may be the exception in the EU regulation for fibre-like particles in concrete which are incorporated in a solid matrix at end use. However, research suggests that concrete products will likely emit microplastics in the future due to erosion and demolition via leaching and airborne dust.[81] While options such as the use of high strength to ultra-high strength concrete and surface hardening agents exist, they do not necessarily reflect in the legislation. Hence, research is required not only to better understand the impact on human health, which may potentially lead to more stringent regulation, but also to frame better law.

Secondary Microplastics

Since secondary microplastics are formed due to the fragmentation and degradation of larger plastics, addressing this source of microplastics would requires addressing the problem of marine litter as a whole. The challenges and competing interests that were faced while regulating intentional microplastics attain an order of magnitude of significant proportion as the whole plastic industry needs to be addressed. Further, lack of viable cost-effective alternatives to plastic precludes an outright prohibition on plastic production and use. Therefore, piecemeal restrictions are being discussed and negotiated to identify the least restrictive measure with the greatest impact. Greater emphasis is placed on addressing the entire plastic lifecycle to promote plastic circularity and prevent leakage into the environment.[82]

The global community has committed to adopting an international legal binding instrument on plastic pollution including in the marine environment through Resolution 5/14 of the United Nations Environment Assembly in 2022.[83] This treaty, when adopted, would be the first global legally binding instrument explicitly addressing plastic pollution. Current attempts, including through this treaty, are on developing a mix of voluntary and binding approaches at the global, regional, and national level. Since the majority of microplastics in the oceans come from land-based sources, addressing upstream activities including manufacturing, use, and waste management within states has become an important tool in the battle against microplastics. However, the principle of sovereignty of States and their right to pursue their economic development, especially for developing economies requires that these measures are non-intrusive and facilitative in nature. Any measure which places an undue burden on the states is unlikely to be agreed to and will affect the effectiveness of global measures. Since the oceans are a global common, leakages of plastic from any source will have an impact on everybody. It is in this context that voluntary mechanisms play an important role in balancing these competing interests.

Regulation of plastic and consequently microplastics does not feature as the primary objective of any international treaty. Rather, fragmented measures which have as their objective the prevention of pollution, protection of marine biodiversity and regulation of chemicals find application to the issue of plastics. Each of these treaties (**Table 2 refers**) has a differing scope of application and seek to address the problem at the source.

Table 2: International Legally Binding Mechanisms on Microplastics

Treaty	Provision	Theme	Remarks
United Nations Convention on the Law of the Sea, 1982 (UNCLOS)[84]	Article 192	General obligation on States to protect and preserve the marine environment	-
	Article 194	Measures to prevent, reduce and control pollution of the marine environment	Applicable to all sources of 'pollution'. States are to do so in accordance with their capabilities and shall endeavour to harmonise their policies on a global or regional basis acting through competent international organisations.
	Article 1 (4)	Definition of pollution. '*Introduction of…substances into the marine environment which results or is likely to result in harm to marine life, hazards to human health…*"	The broad definition of pollution under UNCLOS will likely include microplastics. Consequently, documented research on the deleterious impact of microplastics on marine life and human health brings it within the ambit of the states' obligations to prevent or reduce their introduction into the marine environment.
	Article 207	Obligation to adopt laws and regulations to prevent, reduce, and control pollution from land-based sources including rivers.	Explicitly identifies land-based sources of pollution. Reiteration of obligation to adopt laws and harmonise policies.
	Article 211	Pollution from vessels	Establishment of global norms and effective exercise of flag State and port State jurisdiction to control pollution from vessels.
	Article 210	Pollution from dumping	Duty to regulate
	Section 6	Enforcement	A distinct obligation on States to undertake enforcement measures for the laws undertaken to prevent pollution.

Treaty	Provision	Theme	Remarks
International Convention for the Prevention of Pollution from Ships (MARPOL)	Annex V Regulation 3	Prohibition of plastic disposal into the sea	Adopted by the International Maritime Organisation acting on the mandate on the 'competent international organisation' under UNCLOS Addresses a major sea-based source of secondary microplastic in the oceans i.e., from ships including fishing vessels. Explicitly prohibits the disposal into sea of all plastics including synthetic fishing nets and plastic garbage bags from all ships including plastic mixed with other garbage
Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (London Convention)	Article 3	Regulation of 'deliberate disposal' at sea of waste.[85]	Addresses intentional dumping as opposed to the discharge into the sea of waste during the normal operations of vessels regulated under MARPOL. This treaty, however, has not received widespread ratification with currently only 87 state parties.[86]
Convention on Biological Diversity (CBD).	Decision XIII/10 adopted by its Conference of Parties (COP) Paragraph 8 (f)	Addressing the impacts of marine debris on marine and coastal biodiversity.[87]	While the CBD has as its primary objective the conservation of biodiversity in general, this decision focuses explicitly on marine debris impact on marine biodiversity. It records as a priority action for states to "*assess whether different sources of microplastics that include both primary and secondary microplastics and different products and processes, are covered by legislation, and strengthen, as appropriate, the existing legal framework so that the necessary measures*

Treaty	Provision	Theme	Remarks
			are applied, including through regulatory and/or incentive measures to eliminate the production of microplastics that have adverse impacts on marine biodiversity"
Stockholm Convention 2001		Protection of human health and the environment from persistent organic pollutants (POPs)	Plastic regulation is limited to the extent of POPs produced and used in the production of certain types of plastics (e.g.: polychlorinated biphenyls (PCBs) as opposed to the production and use of plastics.[88]
Basel Convention	Partnership on plastic waste was established in 2019.[89]	Transboundary movement of hazardous and 'other wastes' mandating state parties to ensure adequate disposal facilities for environmentally sound management (ESM) of hazardous and other wastes	The goal of the partnership is to improve the ESM of plastic waste in the context of addressing and reducing its transboundary movement.

Source: Compiled by Authors

Voluntary Mechanisms

The primary purpose of these mechanisms is to play an enabling role to allow states, through regional cooperation, to implement national and regional plans to address plastic pollution. While there is a litany of voluntary and non-profit programs to tackle marine litter, there are a few significant global and regional mechanisms (**Table 3 refers**).

Tracing legal and policy initiatives to tackle marine litter demonstrates that microplastics do not fall in a regulatory void. While there is no specific legislation concerning plastics/secondary microplastics (**Figure 4 refers**), the general provisions in UNCLOS 1982 are broad enough to encapsulate within their scope microplastics. However, it must be demonstrated that microplastics are indeed harmful to the marine environment and are a "land-based" source of pollution. That is why the initial focus of the international community was to establish the deleterious effect

Table 3: Global Voluntary Mechanisms on Microplastics

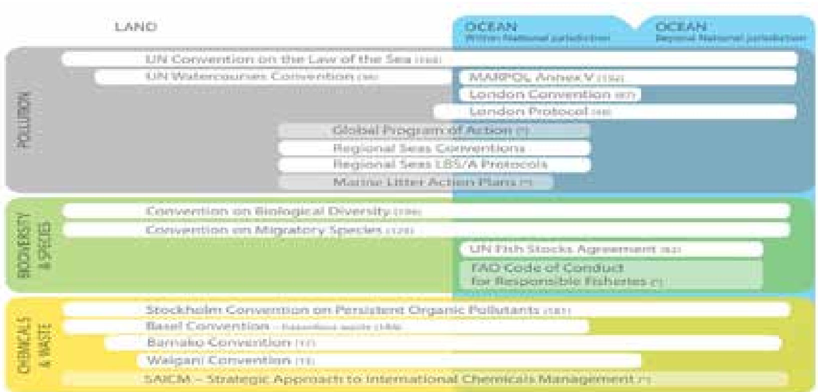
S. No.	Mechanism	Objective
	The Global Program of Action for the Protection of the Marine Environment from Land-Based Activities (GPA). – Led by a steering committee with secretarial services by the United Nations Environment Program – Seeks to implement the commitments of the 1992 United Nations Conference and Agenda 21 – Manila Declaration on Furthering the Implementation of the GPA included marine litter within the ambit of the GPA in 2012 (Manila Declaration).[90] – Works actively with the Regional Seas Program.	Established in 1995 as an intergovernmental mechanism that issues guidelines for addressing land-based sources of pollution. The GPA sought to identify specific problems for specific regions and recommend priorities for action.[91] Enable development of regional action plans with steps towards harmonisation of standards, capacity building, and contingency planning.[92]
	Global Partnership on Marine Litter (GPML) – Established in 2012 after the Manila Declaration with a mission to protect the global environment and human wellbeing by addressing marine litter. – Voluntary open-ended partnership for state and non-state actors alike. – Framework documents were adopted in October 2018.[93] – Managed by a steering committee drawn from partners with secretarial services provided by UNEP.	Seeks to: (a) create an informed global community working together; (b) eliminating discharges; and (c) carrying out targeted removal. Aim is to provide a platform for knowledge-sharing between all stakeholders including the private sector, NGOs, and the civil society. More specifically, GPML seeks to (a) reduce the plastic in the ocean through improved design; (b) application of the 3R's principle to plastics; (c) promote circular production cycles; and (d) maximisation of resource efficiency.
	Regional Seas Program (RSP) – Established in 1974 by the UNEP – Currently it covers 18 regions, seven of which are directly administered by the UNEP,[94] seven of which are established under the UNEP, but non-UNEP administered,[95] while four are independently established.[96] – The program is underpinned by a 'regional convention' and protocols on specific issues for each region which are collectively referred to as Regional Seas Conventions and Action Plans (RSCAPs).	Primary objective to address the "*accelerating degradation of the coastal and marine environment through a shared seas approach*".[99] Consequently, it seeks to build regional frameworks for cooperation, management, and protection of "shared seas". The convention sets out broad obligations for states with protocols and annexes detailing specific plans of action. However, not all protocols have entered

	– Each convention and land-based protocol (if one exists to address marine litter) has differing obligations including their scope of application.[97] The Mediterranean, the Western Indian Ocean, and the East Asian Sea are one of the few RSCAPs to have a dedicated protocol on Marine Litter.[98]	into force and are not binding in nature with many Marine Litter Action Plans yet to be finalised.[100]
	Clean Seas Program[101] – Established by the UNEP in 2017 – Mandate extended with the launch of Clean-Seas 2.0 – Flagship program is the CounterMEASURE project administered by UNEP and funded by the Government of Japan. – The project seeks to map out the places and manner in which plastic waste enters waterways, with the Ganga and Mekong rivers as pilot projects. It utilises tools of citizen science, drone imaging, machine learning, and GIS algorithms to identify and map plastic waste (including microplastic) hotspots.[102]	Primarily focused on the elimination of single-use plastic in the first edition. The second edition will focus on advocacy and promote urgency for action by using data-collection tools to identify key sources, pathways and hazards.
	FAO Code of Conduct for Responsible Fisheries	Voluntary instrument which governs issues related to fishing activities. This includes abandoned, lost, or otherwise discarded fishing gear including the development of "selective and environmentally safe fishing gear and practices".
	The Cross Industry Agreement – Voluntary collaboration of five European industry associations representing the global value chain of the textile industry including manufacturing and maintenance.[103]	Aims to leverage industry expertise to deploy solutions within the textile industry including in design, washing and use, and wastewater treatment.

Source: Compiled by Authors

of plastic waste on the marine environment. Similarly, the impacts of microplastics on matters which were the subjects of other international conventions such as the one on protection of biological diversity and regulation of transboundary waste had to first be sufficiently established. It was only in 2012, (8 years after microplastics were identified as a major ecological concern) after it was recognised in the Manila Declaration that marine litter is an underestimated problem with profound effect on marine ecology and human health that global action was sought to be catalysed. Notable was the recognition that land-based sources contribute a significant portion of marine litter. Therefore, action must be taken at the national level. This is reaffirmed by the fact that in 2014, the first United Nations Environment Assembly (UNEA) resolution on this subject — out of a total of four — "noted with concern" this issue was recognised as a compounding nature of the problem due to the formation of secondary microplastics.[104]

Figure 4. Summary of the Legal Framework applicable to Microplastics



Source. United Nations Environment Program, "Combating Marine Plastic Litter and Microplastics: An Assessment of the Effectiveness of Relevant International, Regional and Subregional Governance Strategies

However, even though the international community identifies the problem, the question of how to address it remains. This is a problem mostly because land-based policies can only be adopted by nation states domestically and require addressing major systemic issues such as waste management and disposal of plastic within national territory. Environmentally sound management practices that are cost-effective are still being developed and so effectively addressing plastic at source has been challenging. Sea-based sources on the other hand, such as fishing gear and discharge from vessels, were relatively easily addressed in the MARPOL Convention as it did not require costly mechanisms to address these. Hence, the first UNEA resolution asked for further reports on the identification of the key sources, more research on impact — to gauge the scale of remedial action — and measures to address the issue.

By the second UNEA resolution in 2016, there was a greater understanding of potential harm so the effort was directed toward identifying the different agencies e.g., the International Maritime Organisation (IMO) and the Food and Agriculture Organisation (FAO) that are involved in addressing this issue, bringing together additional stakeholders such as civil society and industry, and how national and regional mechanisms can be developed.[105] By the third and fourth resolutions, it was clearer that national measures are important. However, very slow progress had been made on that front. Hence, the focus shifted to raising awareness about the impact, collecting data to establish urgency, and comparing different cost implications for potential measures — especially for developing countries — so that their concerns can be addressed. Moreover, there was also a realisation that there are scattered agencies with different mandates and hence inter-stakeholder coordination is important to develop synergy between multiple prongs of action towards a common end.

Therefore, clearly, national, and regional legislative frameworks and plans are crucial to the effective addressal of this issue. Even the new plastic treaty will be unable to make any significant impact unless states are swift to act in curbing the plastic menace at a war footing. Therefore, greater attention needs to be place on operationalising regional strategies at the national level.

National Measures

As part of its endeavour to support state action on adopting national legislation, the UNEP released a toolkit for national legislation.[106] The key findings focus on addressing single-use items and developing an inter-agency mechanism to co-ordinate the development, implementation, and review of national plans and strategies. However, mere legislation without active implementation and monitoring strategy is likely to be ineffective. Such strategies need to establish baseline conditions, set targets, and develop market-based incentives for the collection of plastic waste to enable effective review.

For example, India does have the Plastic Waste Management (Amendment) Rules 2021 under the Environment (Protection) Act 1986 to specifically deal with plastic waste management.[107] It has banned the manufacture, import, stocking, distribution, sale and use of plastic carry bags of thickness less than 120 microns and 19 single-use plastic products. Additionally, the rules even prescribe the colours and pigments that may be used in carrying plastic bags (even if only in the context of those plastic bags in contact with food, pharmaceuticals, and drinking water). This list should be updated to account for the way marine biodiversity interacts with these colours which eventually enter the food chain. The Government of India has also established a Special Task Force and National Level Task Force to implement and coordinate these rules.[108] In addition to an incomprehensive addressal of microplastics — the textile and tyre industry has not been addressed. Four years later, there is poor implementation of these norms.[109] This is primarily because of: (a) the lack of an action/implementation plan; (b) the lack of viable alternatives; (c) poor compliance from manufactures due to effective lobbying; (d) poor union state coordination; and (e) lack of behavioural change on plastic consumption. All this combined leads to poor compliance, monitoring, and enforcement.

This also highlights the need for all stakeholders from raw material producers, manufacturers, state officials, and end-consumers to ensure the success of any strategy. While there is a distinction between consumer plastic litter and manufacturer plastic litter, environmentally conscious consumption patterns will have an impact on business practices too. Therefore, national strategies also need to focus on public advocacy as reducing consumption of plastic goods can go a long way in reducing generation of plastic waste. Advocacy can also be useful in assisting the state to ensure proper waste management. Additionally, simply regulating this issue without supporting waste management and recycling infrastructure is unlikely to make a dent.

Conclusion

Marine microplastic pollution represents a complex and intensifying global crisis that transcends ecological boundaries, threatening marine biodiversity, compromising food systems, and posing potential risks to human health. Its persistence reflects a cyclical challenge. Limitations in current detection methodologies hinder robust data collection, which in turn delays regulatory responses and perpetuates fragmented, reactive interventions. This complexity is further deepened by the heterogeneity of microplastics—their varying sizes, shapes, chemical additives, polymer types, and degrees of degradation—all of which influence environmental behaviour, bioavailability, and trophic transfer.

An overemphasis on downstream technological solutions including AI and portable detection tools often detracts from addressing upstream systemic drivers such as unsustainable production models and inadequate waste governance. Simultaneously, the prevailing marine-centric focus frequently neglects terrestrial and atmospheric pathways, resulting in incomplete risk assessments and significant policy blind spots. Addressing these multifaceted challenges demands that standardisation precedes innovation to ensure data consistency and comparability. Regulatory frameworks must adopt precautionary, life-cycle-based approaches rather than waiting for conclusive human health evidence to be obtained.

Without confronting these interlinked scientific, structural, and governance gaps, mitigation efforts will remain piecemeal, reactive, and ultimately insufficient — placing ecosystems and public health at continued risk. Escalating healthcare costs tied to potential microplastic exposure underscore the urgency of investing in long-term toxicity research. Meanwhile, projections indicating that global waste generation will exceed current management capacities highlight the need for stringent industrial regulations and corporate accountability across the plastic value chain.

A paradigm shift toward holistic, system-based solutions is essential. This includes integrating scientific innovation with regulatory foresight and societal engagement. Strengthening marine monitoring systems, improving waste infrastructure, and enhancing coordination across national, regional, and global governance mechanisms are critical to controlling microplastic proliferation. In addition to a legislative framework, a supporting implementing strategy with defined goals, clear institutional roles, and enforceable timelines is necessary to galvanise collective action and enable everyone to play their part.

As global plastic production continues to accelerate, the window for effective intervention is narrowing. Reactive, siloed responses are no longer sufficient.

What is urgently needed is a cohesive, globally coordinated strategy — anchored in precaution, informed by robust science, and aligned with regional and national legal frameworks as it is imperative to safeguard ocean health, food security, and human wellbeing for current and future generations.

05 July 2025

Acknowledgement

This paper was originally published in the edited volume 'Health and Climate Change: Promoting Health and Wellbeing', edited by Dr Saroj Pachauri and Dr Ash Pachauri, and released by the Protect Our Planet (POP) Academy, New York, in 2025.

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Coastal Water Dynamics and Human Health: Vulnerabilities and Resilience

Dr Gulshan Sharma and Mr Tariq Ahmad

The intricate relationship between coastal and marine ecosystems, and human health represent one of the most critical yet understudied areas of environmental health science. These dynamic interfaces between land and sea not only support extraordinary biodiversity but also provide essential services that sustain human communities worldwide. As anthropogenic pressures intensify through climate change, pollution, and habitat destruction, the implications for both ecosystem integrity and human wellbeing have become increasingly pronounced.

Moreover, coastal water systems are increasingly threatened by anthropogenic pollution and climate-driven alterations, creating significant challenges for human health and coastal ecosystem integrity. This article explores the multifaceted relationship between coastal water dynamics, pollution patterns, and associated health outcomes in coastal communities. Industrial contaminants, including heavy metals from activities such as mining, introduce toxins such as lead and arsenic into groundwater systems that eventually discharge into marine environments. These pollutants have numerous health impacts including salmonellosis, typhoid fever, hepatitis, cholera, and dysentery through direct contact or by the consumption of contaminated seafood associated with bioaccumulation of marine toxins.

The authors of this article argue that coastal water quality requires coordinated action across multiple sectors, with particular attention to vulnerable populations in coastal areas where monitoring and infrastructure remain inadequate. A PRISMA review is conducted to analyse and explore the intricate relationship between coastal water pollution, warming waters, and human health. Management and governance approaches, including water quality monitoring and wastewater treatment technologies, as well as adaptation strategies for mitigating these health risks are examined.

Importance of Coastal Water Ecosystems: Ecological and Economic Roles of Marine Environments

Coastal and marine ecosystems represent some of the most productive and diverse environments on Earth, providing a range of essential services that support both ecological processes and human activities. Research on marine and coastal ecosystem services (MCES) has grown exponentially in recent decades, revealing the critical importance of these environments for global wellbeing. A comprehensive systematic review identified 476 indicators for assessing MCES, highlighting the complexity and breadth of benefits derived from these systems. Food provision, particularly through fisheries, remains the most extensively analysed service, reflecting the crucial role of marine environments on global food security.

Interconnectedness of Marine and Human Health: Exploring the Complex Relationships between Marine Ecosystems and Human Wellbeing

The relationship between marine environments and human health encompasses multidimensional connections that influence physical, mental, and social wellbeing. Contrary to common perceptions that associate health inequalities primarily with inner-city environments, coastal communities often experience significant health challenges that have received insufficient attention. Recent mapping of key health indicators reveals a distinct core-periphery pattern in disease prevalence, with coastal communities bearing a disproportionately high burden of ill health across multiple conditions.

Marine environments affect human health through numerous pathways including nutrition, exposure to pathogens and toxins, natural disaster mitigation, and opportunities for recreation and psychological restoration. The quality of coastal waters directly influences human health through exposure during recreational activities and consumption of seafood. Harmful algal blooms, bacterial contamination, and chemical pollutants can lead to acute illnesses and chronic health conditions among coastal populations. Conversely, access to healthy marine environments provides opportunities for physical activity, stress reduction, and improved mental health outcomes.

Of particular concern are the emerging patterns of health outcomes for children and young people in coastal areas. These patterns potentially reflect a shift in the distribution of child poverty since the 1990s and may signal an impending public health crisis in coastal communities without appropriate intervention.

The economic value of these ecosystem services is substantial with estimates suggesting that marine and coastal ecosystems contribute trillions of dollars annually to the global economy through direct and indirect benefits. Mangroves and coastal wetlands emerge as particularly important habitats, providing key functions for marine ecosystems and substantial economic benefits. Unfortunately, these habitats are disappearing at alarming rates — 35 per cent of mangroves have been lost in recent decades, while some regions report annual coastal wetland losses of up to 20 per cent. Such losses threaten not only biodiversity but also the livelihoods and wellbeing of hundreds of millions of people worldwide.

Coral reefs represent another critical coastal ecosystem, providing habitat for commercially important fish species while offering coastal protection from storms and erosion. Similarly, seagrass meadows deliver essential services through their roles in carbon storage, erosion control, and as nursery habitats for marine species. The diversity of services provided by these various coastal ecosystems underscores their irreplaceable value to human societies globally.

Coastal Water Pollution Sources and Impacts

Degradation of water resources is a major challenge across the world, with a critical impact on human health, food security, sanitation and hygiene as a first order impact. Coastal regions as an interface between the oceans — a foundational media for major biogeochemical cycles — and coastal lands which are inhabited by a major portion of the population become extremely vulnerable to impacts of water pollution. Water pollution in a coastal settlement impacts not only the health of its inhabitants but also poses risk to local oceanic fauna which might be the major food or protein source for the settlement. Furthermore, the ocean — being a major conduit for matter and energy — circulating resources across the world, the same pollutants can have a much wider spatial range of impact.

Anthropogenic sources contribute to water pollution in the most significant manner and are much more feasible to mitigate in theory. Geogenic sources also exist, which can alter the composition of various chemicals in the water above the safe prescribed limits. Geogenic pollution can pose a problem ranging from minor treatment methods for certain uses (drinking) to absolute prohibition on water usage and intensive treatment, if possible, as in case of arsenic contamination.

Water pollution (anthropogenic) can be understood in terms of type of pollutants – municipal sewage and solid waste, agricultural, industrial, thermal, etc. to name a few. It can be also classified in terms of the nature of discharge – point sources, which as the name suggests are sources which can be identified to be originating from a point, such as a drain opening or a landfill. This is contrasted by non-point sources, which can't be attributed to a single point, but rather are a spatially distributed phenomenon such as a surface runoff or percolation from an already contaminated area like agricultural fields with intensive farming methods. Hence, in the case of a non-point source, one must address a practice (e.g. use of chemical fertilizers) rather than any specific point. Lastly, water pollution must also be understood from the perspective of the type of water being impacted. Typically, surface water which includes rivers, canals, lakes, ponds, etc. is the most vulnerable water sources as it is exposed to all types of pollution through many pathways. Surface runoffs, contaminated precipitation (e.g. acid rain), contamination through soil as well as anthropogenic discharge into these sources makes them most vulnerable. Furthermore, due to the general nature of these systems, which ensure a certain degree of interconnectivity with each other as well as with groundwater and ocean water, contamination of these sources can leak into any downstream water body as well. Groundwater, which in India, tends to be a major water source even in the coastal region is a slowly replenishing resource, which can be treated as non-renewable in certain cases within human timeframes. Coastal groundwater is vulnerable to both anthropogenic contamination and over exploitation along with seawater contamination affecting salinity and chemical composition. Ocean water, which as mentioned previously, is a globally connected entity and hence can be potentially susceptible to being polluted from a geographically farther area. However, the ocean has its own complex mechanism of mixing materials and energy, and the situation can be exacerbated or mitigated depending on prevalent currents and other conditions. From the perspective of an ocean settlement though, problems can be more localised. Firstly, it will affect the flora and fauna of the immediate coastal area, threatening local food security. The impact of contamination can also negatively impact human health. Biomagnification can be seen as such an impact. Finally, degradation of coastal waters can further affect economic activities such as tourism which in turn can threaten the local economy. These issues are mere first order effects and several externalities have been observed due to poor coastal water health.

Municipal Waste

Municipal waste refers to waste collected by municipal entities such as local governing bodies. It can exist in the form of municipal sewage and stormwater or as municipal solid waste, which is colloquially understood as 'garbage'.

Municipal wastewater, which can refer to wastewater collected from sewage and in several cases to stormwater as well. In piped sewerage systems (as opposed to in situ systems such as discharge pits), wastewater, consisting of blackwater (discharge from kitchen and toilets) and greywater (discharge from other domestic and non-industrial use not described as blackwater) form major hazardous components of wastewater. Stormwater, which originates from the precipitation runoff over the surfaces of settlements, can be discharged through a separate system even allowing storage and groundwater recharge. In that case surface contamination and sediment flow are the major water pollution challenges. However, in several cases, the practice is to have a single system, used to carry both wastewater and stormwater, rendering them essentially the same in terms of pollution management. It is to be noted in various cases; this practice is a design necessity and not an oversight.

Municipal wastewater has been classified as a single biggest contributor to coastal water pollution from land-based activities in India. It comprises biological contaminants such as faecal matter, nutrient and food particulates and other organic matter providing fertile ground for pathogen growth, which are also a significant component of the discharge. Pathogens such as E. Coli can thrive in such environments and lead to waterborne diseases. It also includes chemical pollutants from household items like detergents, disinfectants and other cleaning agents along with medicine compounds released as part of human waste. Heavy metals and toxic compounds from unintended sources such as poor waste disposal practices are a significant threat in India, where hazardous waste disposal practices are not implemented rigorously at household level.

Municipal solid waste (MSW) has been found to have limited impact on coastal water pollution. However, it can nevertheless affect freshwater sources both on the surface and groundwater. MSW is typically collected at the household level by the local governing body and stored at location, from where it can be eventually sent to a long-term storage at a landfill or destroyed via methods like incineration, after any processing and recycling (if done). It is the landfill which in the form of leachate, especially when managed improperly, leads to contamination of water sources. Typical composition of MSW leachate can include dissolved organic matter (DOM) along with suspended particulates, inorganic compounds, ammonia, heavy metals, etc. While the impact of leachate is generally localised, surface runoff and groundwater movements can transport contaminants much farther.

Industrial Discharge

Industrial discharges are the most 'popular' threats to water sources, and their impacts have been well documented in cases of pollution borne diseases such as Minamata in Japan. In India, primarily heavy metals and other industrial chemicals such as acids, bases, etc., can be found in linked water bodies. The practice in India is to prohibit direct release of effluents into water bodies. A common effluent treatment plant (CETP) is used in most cases, especially when it comes to releasing wastewater into coastal waters. However, literature indicates that upstream contamination along the drainage of the rivers systems leading into coastal waters can still carry those effluents into coastal waters.

Industrial effluents in coastal waters can significantly change the local coastal ecosystem, leading to prominence of organisms which can survive the presence of the contaminants. Phytoplankton blooms near the local coast can severely degrade and alter the local ecosystem affecting food supply. Furthermore, the presence of heavy metals and other effluents susceptible to biomagnification can contaminate the upstream food supply. Local contamination of freshwater surface and ground sources due to effluent discharge remains a traditionally understood risk of industrial activities.

Agricultural Discharge

Contemporary agricultural practices are a significant and diverse source of ecological degradation. Due to the nature of the practices, water resource degradation, both in terms of overexploitation and pollution, is a serious threat. Agricultural activities contribute to water pollution across a spectrum of dimensions, some more obvious than the others.

The most obvious and well-known impact is agricultural runoff. Pesticides and fertilizers runoff (chemical ones) is a well-documented and popularly known challenge of intensive farming. Organochlorine based pesticides such as dichlorodiphenyltrichloroethane (DDT), hexachlorocyclohexane (HCH), Endosulfan, etc. are banned or regulated within the country, even though studies have indicated the presence of these compounds exceeds the safe limits defined by international and domestic bodies. It should be noted that several pesticides are allowed as malaria control measures and can still be found in the water supply. A lot of contamination is from residual pesticides left before the bans, which highlights the challenge posed. Most of these compounds are persistent, bio accumulative, and toxic leading to a myriad of health effects including development disorders, cancers, immunosuppression, hormone disruption, and reproductive distortion. The health impacts are both chronic and acute depending on exposure. Pesticide residue is not limited to the water supply as it also enters the food chain as a residual entity on food products that are used.

Chemical fertilizers have significant first and second order impacts on water resources and human health. Industrial processes required in manufacture also add harmful substances such as arsenic, cadmium, lead, uranium, etc. as a by-product of the process. Nitrates and calcium can act as a wide range of irritants that can cause renal damage and negatively impact bone structure. The second order effect of overabundance of plant macronutrients from surface runoff into local drainage basins can lead to algal blooms in water reservoirs used for human or livestock use. The algal bloom outcompetes pre-existing flora and fauna within the water body leading to oxygen, sunlight, and nutrient deprivation which, in turn, leads to death and decay of those organisms leading to pathogenic and chemical contamination. Such water might end up being unfit for use and along with pesticide and fertilizer runoff become hazardous for most purposes.

Another significant impact of agriculture comes from animal waste, specifically manure, which is a fertile ground for various pathogens like coliforms, salmonella, etc. Improperly isolated discharge pits for human faecal waste disposal can also leach pathogens in the surrounding soil and can have similar effects. Assessment of upstream sources of such contaminants combined with analysis of local drainage patterns, must be done to mitigate this issue.

Lastly, antibiotic usage in livestock feed and other prophylactic methods lead to discharge of the same in the soil and water supply resulting in the rapid emergence of antibiotic-resistant strains of various diseases. India consumes three percent of global antimicrobials used for food animals, which includes aquaculture as well.

Climate-Change Effects

Sea Level Rise and Ocean Warming: Impacts on Marine Ecosystems and Water Quality. Climate-change exerts a profound influence on marine ecosystems through multiple pathways with ocean warming and sea level rise being among the most significant. Unlike atmospheric temperatures that fluctuate considerably, ocean temperatures show steady and consistent warming trends. Recent research indicates that the rate of ocean warming has doubled over the past 20 years, with 2023 recording one of the highest increases since the 1950s. While the Paris Agreement aimed to limit global warming to below 2°C above pre-industrial levels, ocean temperatures have already increased by an average of 1.45°C globally, with hotspots exceeding 2°C in the Mediterranean, Tropical Atlantic, and Southern Oceans.

This accelerated warming drives numerous ecological changes including shifts in species distributions, altered phenology (timing of life cycle events), increased disease prevalence, and reduced productivity in some regions. Marine heatwaves — extended periods of high ocean temperatures — have increased in frequency and intensity causing mass mortality events and potentially irreversible ecosystem changes. These temperature anomalies threaten thermally sensitive organisms such as corals, leading to mass bleaching events that compound existing pressures on reef ecosystems.

Sea level rise represents another critical climate change impact with global sea levels rising at accelerating rates. Ocean warming contributes approximately 40 per cent to global sea level rise through thermal expansion with the rate of rise doubling over the past 30 years to reach a total of nine cms. This seemingly modest increase has already enhanced coastal flooding risks in many regions with significant implications for coastal infrastructure, freshwater supplies, and human settlements. Rising seas infiltrate coastal aquifers with saltwater compromising drinking water supplies and agricultural productivity in coastal zones worldwide.

Extreme Weather Events: Increased Pollution, Ocean Acidification.

Climate-change intensifies the hydrological cycle, leading to more frequent and severe extreme weather events that disproportionately affect coastal regions. Hurricanes, typhoons, and cyclones draw energy from warming ocean surfaces, potentially increasing in intensity while delivering more precipitation per event. These storms mobilise pollutants through flooding, combined sewer overflows, and damage to industrial facilities and waste management infrastructure, creating acute pollution pulses in coastal waters.

Beyond storms, changing precipitation patterns alter the timing and magnitude of terrestrial runoff, affecting the delivery of nutrients, sediments, and contaminants to coastal environments. In regions experiencing more intense rainfall, increased erosion mobilises soil-bound contaminants and overwhelms wastewater treatment systems leading to more frequent contamination events. Conversely, drought conditions concentrate pollutants in reduced water volumes while potentially increasing reliance on contaminated water sources when preferred supplies become limited.

Ocean acidification represents a direct chemical consequence of increased atmospheric carbon dioxide. With 25-30 per cent of fossil fuel emissions absorbed by oceans, the resulting chemical changes reduce seawater pH and carbonate ion availability. These changes threaten calcifying organisms including commercially important shellfish and coral reef builders, while potentially altering the bioavailability and toxicity of certain pollutants. Since the 1960s, oceans have lost approximately two per cent of their oxygen content due to warming temperatures and pollutants, with coastal areas experiencing particularly severe impacts. Research has identified roughly 500 coastal "dead zones" worldwide where depleted oxygen levels have eliminated almost all marine life.

Vulnerable Populations and Environmental Challenges: Limited Access to Clean Water and Healthcare for Vulnerable Communities. Access to clean water and adequate healthcare represents a particular challenge for vulnerable coastal communities. Despite coastal locations, many communities struggle with freshwater scarcity due to saltwater intrusion, contamination, or inadequate infrastructure. Socioeconomic status strongly influences vulnerability to coastal environmental hazards with disadvantaged communities often occupying higher-risk locations and lacking resources for adaptation or relocation. Historical patterns of development and discrimination have frequently concentrated marginalised populations in areas most exposed to flooding, erosion, and industrial pollution. Climate change exacerbates these challenges through sea level rise, changing precipitation patterns, and increasing the frequency of extreme events that disrupt water supply and damage infrastructure.

Case Studies of Pollution-related Health Outbreaks

Examples from Coastal Communities: Documented Health Impacts. Numerous documented cases illustrate the health impacts of waterborne disease and environmental degradation. Waterborne diseases are a concern in areas where industrial operations, coastal development, and poor wastewater management lead to the pollution of marine and coastal waters. The primary causes of waterborne disease outbreaks in marine ecosystems are pollutants that introduce bacteria, viruses, and parasites through untreated sewage, industrial chemicals, and agricultural runoff. These pathogens can enter human beings through the consumption of contaminated seafood and through exposure to contaminated water. These pathogens also affect marine organisms. The most common waterborne illnesses include cholera, hepatitis A, gastroenteritis, and typhoid fever which poses a major threat to public health by seriously jeopardising it, especially in coastal communities which rely on fishing and tourism.

In Minamata, Japan, industrial discharge of methylmercury into coastal waters led to devastating neurological damage in local communities consuming contaminated seafood. This landmark case, identified in the 1950s, continues to provide lessons about bioaccumulation, delayed health effects, and the need for precautionary approaches to chemical management in coastal environments.

More recently, harmful algal blooms have triggered multiple health emergencies in coastal communities worldwide. Florida's recurrent red tide events cause respiratory irritation among beachgoers, economic losses in tourism and fishing industries, and potential neurological impacts from the consumption of contaminated shellfish. Research indicates that these events that have intensified in frequency and duration are potentially linked to nutrient pollution and climate change.

Vibrio bacterial infections represent another emerging threat with warming coastal waters expanding the geographic range and seasonal windows for pathogenic species. The U.S. Gulf Coast has documented (**Figure 1 refers**) increasing cases of wound infections and seafood-associated illness, particularly following extreme weather events that disrupt water and sanitation infrastructure.

Oil spills provide examples of acute pollution impacts on coastal community health. Studies following the Deepwater Horizon disaster documented respiratory symptoms, psychological distress, and endocrine disruption among cleanup workers and coastal residents. Long-term monitoring continues to reveal subtle impacts on community wellbeing including effects on mental health, social cohesion, and economic stability years after the initial event.

Figure 1. Pollution devastales everything and human health

(a) Minamata disease from mercury contamination in Japan highlights neurological damage

(b) red tides caused by harmful algal blooms disrupt marine biodiversity and poison seafood

(a) Minamata disease from mercury contamination in Japan highlights neurological damage

(b) red tides caused by harmful algal blooms disrupt marine biodiversity and poison seafood

Source: The Japan Times

Management and Governance Approaches

Water resource management, which also covers the water quality and pollution aspects, is an important concept for the holistic management of water resources. The integrated water resource management (IWRM) approach is used to acquire more freshwater resources via rainwater harvesting and watershed management. Land use planning considering environmental conditions, is gaining traction to prevent contamination via both point and non-point sources. Governance plays a major role in the management of various water quality monitoring regimes.

Water Pollution Monitoring

In the United States of America, water pollution and safe drinking water is managed by the federal body, the US Environmental Protection Agency (EPA), empowered under the Clean Water Act (1972) and Safe Drinking Water Act (1974) along with various other legislations. Water quality standards are set by individual states. In contrast, in India, a single minimum water quality standard has been prescribed in BIS: 10500.

The Central Pollution Control Board (CPCB) is the apex body for monitoring pollution in India. CPCB along with the State Pollution Control Boards (SPCBs) are responsible for monitoring water quality across the country. These bodies maintain a water quality testing regime and are responsible for monitoring industrial discharges. However, at district level the District Water Sanitation Committee (DWSC) is responsible for monitoring and regulating the domestic water quality. It should be noted that CPCB and SPCB are under the Ministry of Environment, Forest and Climate Change as a statutory body, whereas DWSC is under the Ministry of *Jal Shakti*. The Water Quality Monitoring and Surveillance Framework (WQMS) was established under the National *Jal Jeevan* Mission (JJM) in 2019. It aims to streamline the water quality monitoring regime especially for rural areas by empowering the Village Water/Sanitation Committee (VWSC) under the district counterpart (DWSC). JJM is focused on ensuring domestic water supply quality, whereas CPCB and SPCB still cover other domains maintaining their own network regime.

Water Quality Management Information System (WQMIS) compiles all the data provided by respective bodies under JJM, tracking quality and taking preventative measures for averting disease outbreaks.

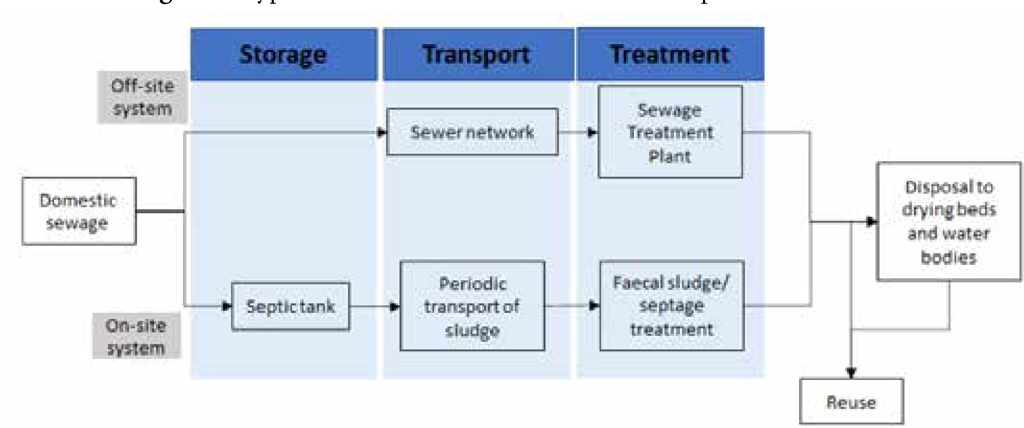
Local governing bodies (urban and rural local bodies) are mandated to conduct water quality surveillance every month at the grassroot level, compiling the data into WQMIS. The JJM mandates monitoring drinking water at least once a year for chemical contamination and twice a year for biological contamination, setting a mandatory minimum surveillance requirement. Furthermore, it also specifies that no village can be left behind, providing a tool for financial support.

JJM also specifies standard operating procedure (SOP) for disease outbreaks, which must be framed by the respective State Water/ Sanitation Committee (SWSC). It also identifies water quality monitoring hotspots, specifically for chemical contamination either natural or anthropogenic. Any water supply infrastructure is scrutinised and approved by the local VWMS before development.

Wastewater Treatment Method

Wastewater treatment involves removal of harmful substances and reconstitution of specified parameters below a prescribed criterion. Typically, it is desirable to recover water from waste through a sewage treatment plant (STP) and recirculate the water recovered. 80 per cent water can be recovered by this approach, with remaining lost along with the undesirable components. Regardless of the method used in between, a certain amount of wastewater must be released in a water body or disposed of on a drying bed. The only exception is bio septic tanks and their variants which aim to decompose organic waste, including faecal waste, locally and convert it into manure (**Figure 2 refers**).

Figure 2. Typical wastewater treatment flowchart of processes involved



Source. NITI Aayog

Treatment is conducted in stages with the primary stage being a physical process. This stage involves the physical removal of effluents via screening, grit, or sedimentation. This is followed by a secondary stage in which the sludge undergoes aerobic or anaerobic digestion by microbes with the difference being that in the aerobic system, oxygen containing air is pumped to biologically oxidize the waste. Various methods can be used to achieve the outcomes of these stages. Some of the methods include moving bed biofilm reactor (MBBR), sequencing batch reactor (SBR), up flow anaerobic sludge blanket (UASB) to name a few. The tertiary stage involves chemical and/or membrane technologies to remove phosphorus, heavy metals, and other effluents which can't be removed by previous methods. After this stage, the water still needs to be disinfected, which can be done via chlorination.

Newer methods based on electrochemical oxidation and photo-electrochemical oxidation are non-biological methods to achieve the objectives of the secondary step.

While the above process is required for safe drinking water, for other uses like flushing, gardening, or any other non-consumption use, water can be treated with alternative methods. Phytoremediation is one such method which can be used on grey water or in some cases on black water. It is based on the property of certain plants and their soil ecosystems to either absorb toxic metals within their body and concentrate them or decompose organic effluents via the microbiome around their roots. Recalcitrant pollutants, including organic ones can be removed from the soil and water (in the case of wetlands and on riparian buffers). Significant progress has been observed in the treatment of the Ganga River water in India using water hyacinths and certain algal species. Biochar, which is a charcoal generated from biomass, has also been suggested to have water purification capabilities.

Adaptation Strategies

Strategies for the reduction of marine water pollution require a holistic approach including community involvement, international cooperation, policy enforcement, and technological innovation. There is a need for tighter regulations on industrial discharges and agricultural practices to control chemical and nutrient pollution. Sustainable agricultural practices prevent nutrients from water bodies from running off to cause eutrophication. Included among such practices are organic farming, among others, and trying to minimise the use of chemical fertilizers. Response technologies for oil spills, safety regulations for marine transportation, offshore drilling, and the prevention of oil spills form an important part with all these initiatives. Initiatives such as The Ocean Cleanup are being initiated, as are advances in wastewater treatment to improve the removal and capture of pollutants before they reach the marine ecosystems.

Effective adaptation strategies include enhancing monitoring systems to track pollution trends and HAB occurrences using advanced nuclear and isotopic techniques. These methods allow for the precise identification of pollutant sources and temporal patterns enabling targeted interventions. Ecosystem-based approaches such as restoring mangroves, coral reefs, and seagrass beds, offer "soft protection" by improving water quality and reducing exposure to contaminants. Additionally, public health measures like early warning systems for HABs, seafood safety protocols, and community education campaigns can minimise health impacts. Infrastructure adaptations such as flood-proofing buildings and raising structures in vulnerable areas further reduce exposure risks. Collaborative efforts between governments, research institutions, and international organisations are essential to implementing these strategies effectively. By integrating scientific advancements with local actions, coastal zones can build resilience against marine pollution-related health outbreaks while promoting sustainable development.

Future Directions and Research Priorities

Future directions must emphasise interdisciplinary collaboration, equitable governance, and innovative technological solutions. Emerging tools such as remote sensing and artificial intelligence can enhance real-time monitoring of pollutants like plastics, nutrient runoff, and oil spills, enabling rapid responses to contamination events. Research must address knowledge gaps in the cumulative effects of multiple stressors — such as ocean acidification, warming, and pollutant interactions — on marine ecosystems and human health, particularly in developing nations where coastal populations are projected to double in the upcoming years. Transdisciplinary approaches that integrate local ecological knowledge with scientific data are critical, as highlighted by disparities in priorities among scientists, policy-makers, and coastal communities. For instance, while scientists prioritise ocean acidification studies, resource dependent groups could advocate for inclusion of traditional practices in governance frameworks. Ecological restoration including mangrove reforestation and coral reef rehabilitation remains a key strategy to buffer pollution impacts while enhancing biodiversity and coastal resilience. Concurrently, socioeconomic research must evaluate how pollution disproportionately affects marginalised communities, informing policies that balance environmental justice with economic development. Policy innovation should focus on source reduction through stricter regulations on industrial discharge and agricultural runoff, coupled with incentives for circular economies to minimise waste.

International cooperation is essential to address transboundary pollution particularly in shared fisheries and migratory species habitats. Public engagement campaigns, aligned with the UN Ocean Decade's goals, can bridge awareness gaps and foster community-led conservation initiatives. Prioritising these interconnected strategies — grounded in equity, technological advancement, and ecosystem-based management — will be vital to achieving Sustainable Development Goal 14 and safeguarding coastal livelihoods in a rapidly changing climate.

Conclusion

Coastal water pollution has emerged as a severe threat to both marine ecosystems and human health with plastics, fertilizers, chemicals, and oil spills significantly disrupting the balance of ocean biodiversity. This pollution not only endangers marine life through entanglement and ingestion but also introduces harmful chemicals like persistent organic pollutants (POPs) and heavy metals into the food chain posing risks to vulnerable populations including children and pregnant women. Given the vital role oceans play in sustaining human life, economic security, and global biodiversity, immediate and comprehensive action is essential. Tackling ocean pollution requires a multifaceted approach and technological innovations such as improved recycling, biodegradable materials, and advanced waste treatment systems. International cooperation, strict regulations, and increased public awareness are equally critical to reducing pollutant inflows. Community participation in conservation efforts is vital for creating a shared sense of responsibility to protect our oceans.

To achieve long-term sustainability, it is crucial that we intensify efforts to manage ocean ecosystems holistically. Through coordinated global action, we can ensure that oceans continue to thrive for future generations, safeguarding both marine and human health. The future of a healthy marine environment depends on the choices we make today to reduce pollution and foster responsible stewardship.

05 July 2025

Acknowledgement

This paper was originally published in the edited volume 'Health and Climate Change: Promoting Health and Wellbeing', edited by Dr Saroj Pachauri and Dr Ash Pachauri, and released by the Protect Our Planet (POP) Academy, New York, in 2025.

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Resource Mining and Offshore Environmental Impact Assessments in India

Mr Soham Agarwal

On 28 November 2024, India's Central Government — more specifically the Ministry of Mines — launched the first tranche of thirteen offshore blocks for auction.[1] Three of these blocks are for 'construction sand' off the coast of Kerala, three for lime mud off the coast of Gujarat, and seven for polymetallic nodules and crusts off Great Nicobar Island.[2] These thirteen form part of a group of thirty-five blocks already handed over by the Geological Survey of India (GSI) for auction with another twenty-four (24) in the pipeline.[3] The news of this auction however, sparked a wave of protests amongst the fishing community in Kerala as the proposed mine sites for construction sand have been identified in *"Kollam Parappu"* also known as *Quilon Bank* which is claimed to be "one of the richest fishing zones on the southwest coast".[4] Due to its attractiveness as a major fishing ground, *Kollam Parappu* attracts fishermen from across the community including mechanised trawlers, mesh gill net boats, and fishing trollers.[5] Hence, the fishing community believes that commercial scale mining operations in the proximity of *Kollam Parappu* will irreversibly damage the local ecosystem and severely affect the available fish stock. This may lead to an adverse impact not only on the livelihoods of the fishing community but may also have an impact on the food security of coastal States. Kerala's opposition — expressed through a state assembly resolution — began the amendments made to the Offshore Areas Mineral (Development and Regulation) Act, 2002 itself, which enabled private participation in seabed mineral exploration within India's maritime zones.[6]

More specifically, the whole issue revolves around the conduct — or lack thereof — of an impartial and credible impact study of such activity on the marine environment

— an "Environmental Impact assessment" (EIA)[7] and has once again brought into the limelight, both the urgency and the complexities of marine spatial planning (MSP) as a subset of India's Ocean Governance policy and its implementation. The primary opposition stems from the Government of India not conducting an impact study before the notice of invitation was issued. A question was raised in the Rajya Sabha asking whether the Ministry of Environment, Forest and Climate Change (MoEFCC) had given any environmental clearances for deep sea mining off Kerala and whether the Central Geological Programming Board — an inter-ministerial body to coordinate mining activities in the country[8] — had submitted any study report documenting the environmental impact from this activity.[9] Vide a written response, the Minister of State in the MoEFCC, Shri Kirti Vardhan Singh stated, (1) that the Coastal Regulation Zone established under the CRZ Notifications 2011 and 2019 prohibited mining activity up to 12 nautical miles from the Low Tide Line i.e., within India's territorial sea; (2) that the provisions of the EIA Notification 2006, as per the Minister, applied up to the seaward limit of the territorial sea, under which no proposal has either been received or granted; (3) the offshore blocks to be auctioned were located beyond the territorial sea, and (4) the ministry had not received any study report from the CGPB regarding environmental impact concerns. The implication that may be drawn from this response is that because offshore mineral mining is proposed to be conducted beyond the territorial sea, it does not fall within the purview of the Environment Impact Assessment (EIA) Notification 2006 (as amended).

However, the Ministry of Mines, too, in response to this controversy, made public statements stating that the project "*will begin only after releasing a full EIA and conducting transparent, inclusive consultations with affected communities*".[10] This EIA, as per the official, will be in the public domain and will be conducted under the "Offshore Areas Mineral Conservation and Development Rules, 2024". Additionally, the official also indicated the inclusion within the production plan, a detailed environmental management plan describing essential baseline environmental data, a final impact assessment report — one that would outline mitigation strategies.[11] While there is some indication of such measures actually being planned, when and by whom this activity is to be conducted remains less clear and hence controversial. The local fishermen and the members of parliament (MPs) from Kerala have demanded that an *"independent EIA"* be conducted before the auction and grant of license to any operator.[12] While the Central Government has opined that the auction is a preliminary procedure and that the EIA will, indeed, be a part of the "production plan" submitted by the holder(s) of operating rights and that this would require government approval before the actual mining begins.[13] Against this convoluted and emotionally charged backdrop, this paper aims to shed light on offshore EIAs and, more specifically, their regulatory structures in India, with particular focus on offshore mineral mining. The paper also advocates a more holistic approach to environmental planning by adopting the concept of "Strategic Environment Assessments" (SEA), especially in the context of India's transition to a *'blue'* economy, which requires the balancing of competing interests of different sectors occupying the same ocean space, and ensuring sustainability in the entire set of processes.

Environmental Impact Assessments

As per the "Environmental Impact Assessment Guidelines for Ports and Harbours" prepared by the National Institute of Ocean Technology (an autonomous institution under the Ministry of Earth Sciences), an EIA is the "*process of examining the environmental, social and health effects of a proposed development"*.[14] The EIA, therefore, seeks to determine the *"environmental compatibility of a project"* by identifying the impacts, costs, potential management and, monitoring and mitigation measures.[15] A crucial aspect of the EIA is the collection of baseline environmental data, which forms the basis upon which any impact can be studied. Further, conceptually, there are predominantly four types of EIA, viz., strategic environmental assessments, regional EIA, sectoral EIA, and project-level EIA, each successively reducing in scope.[16]

A strategic environmental assessment (SEA) is a systematic analysis of the environmental effects of development plans beyond the project level when major alternatives are still open.[17] At the other end of the spectrum are project-level EIAs which consider, largely in isolation, the impact of a particular project upon the environment. Given that there are these multiple types of EIAs, which one to choose is a policy decision — albeit one of great consequence.

EIA in India

In India, the EIA process has been institutionalised and streamlined for the obtaining of an environmental clearance from the Central or State government, through the "EIA Notification of 2006" under the "Environment Protection Act 1986". The EIA Notification identifies four stages, viz., (1) "screening" (which addresses the question of whether the project requires the preparation of an EIA at all), (2) "scoping" (determination of the terms of reference for the preparation of an EIA and the ensuing Environment Management Report), (3) "public consultation" (where concerns of affected persons and other stakeholders are sought and noted), and (4) appraisal (scrutiny by a specially constituted "Expert Appraisal Committee" for the report). The EIA is considered to be a *process* that is required to be integrated into the entire lifecycle of the project rather than being viewed as a distinct stage or activity.[18] In fact, environmental considerations play a crucial role while assessing the feasibility of a project — especially in jurisdictions in which indicators of significant resultant harm to the environment may force the operator to abandon the project altogether.[19] Hence, early integration of assessing and planning for environmental-impacts not only promotes efficiency but also ensures that sustainability is treated as a core value with which the project is approached.

The application of this framework to offshore activities is demonstrated in the context of the exploration and exploitation of hydrocarbons i.e., oil and natural gas. Recently, in 2020, the MoEFCC shifted projects for offshore oil and gas ***exploration*** to Category B2 projects while retaining the ***production*** of oil and gas as a Category A project.[20] The implication of this move is that *exploration* activities no longer require an EIA to be conducted nor are the conduct of public hearings mandatory, and a mere environmental clearance from the concerned state would suffice.[21] *"Exploration Operations"*, as defined by the Director General Hydrocarbons (DGH) is the search for petroleum in the contract area using, *inter alia*, aerial-, geophysical-, and seismic surveys, etc., including structural test-drilling and the drilling of exploration wells.[22] Given that "exploratory drilling" is a temporary and short-duration activity when compared to "production drilling" (which spans significant periods of time),[23] this move is intended to promote the exploration and discovery of oil and gas wells by easing the number of regulatory compliances and clearances required. This need stems from the recognition that the high costs and delays that would accrue were a detailed EIA to mandatorily be conducted even before the preliminary estimates of any commercial quantity of the product are established, is likely to deter investments into exploration activities. Moreover, exploration is an activity which is conducted right after project discovery and before any pre-feasibility studies.[24] Pre-feasibility studies, on the other hand, constitute the first stage at which a more detailed assessment of environmental impacts is required. In fact, more often than not, the proponents of a given project must apply for an environment clearance along with a pre-feasibility study, which includes the anticipated impacts on the environment from subsequent project operations.[25] It is for this very purpose that in the case of hydrocarbons, the terms of reference stipulate that a "Final EIA Report" is submitted by the project proponent or by an established and reputed consultant engaged by the project proponent.[26]

For offshore mineral mining however, the source-legislation for EIAs differs. The process for applying for approvals is governed by the "Offshore Area Minerals (Development and Regulation Act) 2002" (as amended) and its various rules. A significant amendment to the 2002 Act has been the grant of a "Composite License", which functions as an exploration-cum-production license to ease regulatory compliances and make things easier and more attractive for private investors. This regime enables an entity to bid for a composite license which if granted, will enable the bidder to enter into an "Exploration License Deed of Composite License" with the Central government and submit an "Exploration Plan" under "Rule 6 Offshore Areas (Mineral Conservation and Development Rules 2024)". This "Exploration Plan", however, does not require any declaration of assessed environmental impacts during the *exploration* phase.

Rather, the requirement to undertake an environmental assessment forms an eventual part of the exploration process. The bidder has the obligation to complete a detailed exploration (G1 level of exploration) and prepare a detailed feasibility study report (Rule 22 of the Offshore Areas Mineral (Auction) Rules, 2024) as part of the composite license. The stages of exploration and feasibility studies have been elaborated under the "Offshore Areas (Existence of Mineral Resources) Rules

2024". Four stages have been identified for the exploration of any mineral deposit viz. "Reconnaissance Survey" (G4), "Preliminary Exploration" (G3), "General Exploration" (G2), and "Detailed Exploration" (G1) (Schedule I- Part I Existence of Mineral Rules). Each successive phase involves greater detail in estimating the quantity and grade of the mineral deposit with greater level of confidence.

This detail is a product of the methods by which profiling and sample collection is conducted. While a G3-level of exploration requires the collection of core samples, it is only at a G2-level that deeper coring/drilling is required. Part III Schedule I of the "Existence of Mineral Rules" further specify that for construction grade silica sand (the mineral resource in *Kollam*), it is at the G2-stage of exploration that a preliminary environmental impact assessment needs to be conducted. Further, at the G2-stage of exploration, the licensee is also required to collect information about the marine environmental setting, which includes data on currents, waves, noise levels, water quality, suspended and dissolved solids, etc. All this information will feed into the environmental impact assessment. Additionally, the feasibility study (also a part of the obligations of the licensee), requires a detailed techno-economic and socio-environmental evaluation of the mineral deposit. Therefore, environmental considerations *will* be addressed as part of the exploration process.

Currently, the auction blocks at *Kollam* are already at the G3-level of exploration conducted by the Geological Survey of India, Mangalore.[27] Therefore, any licensee will, as part of their exploration, have to collect baseline data and conduct an EIA. While gauging environmental impacts, indeed, are envisaged by the government, concerns amongst the fishing community persist over what us perceived to be the complete removal of any pre-clearance process or assessment for exploration activities. The lack of a public consultation process and the non-accounting of the impact of increased vessel traffic, sonar, magnetic, and seismic interference, and even minor drilling on fish stocks, fuels such speculation and seriously erodes public trust. This is also at variance from the process established for hydrocarbon exploration, which at the very least is still a B2 category project that requires environmental clearance even if without an impact assessment. A detailed assessment would be required to assess whether this difference in hydrocarbon- and mineral exploration is due to a variance in the methods by which hydrocarbon and mineral exploration is conducted.

Once exploration activities are completed, a production plan, which requires an environmental management plan, needs to be approved before any production activities may begin (Rule 15 Mineral Conservation and Development Rules 2024). Therefore, there clearly is a pre-clearance process for *production* activities.

However, two major challenges differentiate land-based EIAs from offshore ones. The first, is the fact that the marine environment is extremely dynamic, with inherent feedback loops that have the ability to amplify or diminish the impact of any anthropogenic activity.[28] Not only does this significantly complicate the process of conducting the EIA, but the complexity is also compounded by the fact that the marine environment is still poorly understood relative to the environment on land. Moreover, the existence of ocean currents and the singularity of the world ocean does not necessarily limit the impact of any activity within the confines of a particular region. Therefore, far greater precaution and diligence needs to be exercised for the conduct of offshore EIAs. This will also be in line with the precautionary principle under international law — issues of precautionary spotting notwithstanding — which require States to take precautionary measures for environmentally sensitive activities even if there is scientific uncertainty as to the true nature of impact.[29] It is in this context that the conduct of an offshore EIA by the project proponent may become problematic. Even though the project proponent will probably understand the mechanics of the underwater environment to some limited degree — a prerequisite to be able to undertake any activity — this limited understanding does not ensure a full appreciation of the impact that such activity may have on the marine environment. The second — and related —issue is the ability to effectively monitor the impact of such activity. The opacity of the marine environment makes it difficult to ensure accurate monitoring. Further, the monitoring and enforcement mechanism in the regulatory structure is limited. As per the "Mineral Conservation and Development Rules", Rule 39 incorporates the precautionary approach but places the burden on the operator. Monitoring will be done through a self-assessment report to be submitted by the operator to the Indian Bureau of Mines as per a specified format. While the format may prevent the manipulation of the impact data, clarifying the process by which the Indian Bureau of Mines or even the CGPB will verify the self-assessment report may help remove misperceptions and assuage concerns. Moreover, capacity development and capability enhancement has been envisaged through the establishment of an "Offshore Areas Mineral Trust" that will undertake, *inter alia*, research for mitigation measures and provide relief should a disaster occur.

Additionally, the ocean environment enables the operation of multiple sectors within the same space. This forms the core issue in the Quilon Bank issue as well. Rather than being motivated by any intrinsic desire to protect the ocean and its biodiversity, the fishermen's protest focuses solely upon the perceived loss of livelihood. In fact, mechanised trawlers have often themselves been cited as a significant risk to the oceans and its biodiversity. Therefore, another core challenge here is the management of competing resources and industries along with their environmental considerations.

A solution to this challenge is undertaking comprehensive "Marine Spatial Planning" (MSP) within India's maritime zones — a process that has also been included in India's "Draft Blue Economy Policy". Along with MSP, it is important to move from a project-based EIA approach to a SEA one for the marine environment. Extension of EIA principles to the higher levels of decision-making across sectors and line ministries is important to ensure that the cumulative impact of multiple sectors and projects in relatively close proximity can be holistically understood and addressed. Discrete projects, each taken in isolation, may trigger unforeseen consequences. While these, taken individually may not be excessively alarming, when taken in aggregate, they may well generate very significant and well-founded concern.[30]

Conclusion

Addressing the needs of a growing population seeking a better standard of living — at least as per the current consumerist metrics of growth — requires greater availability of resources. The oceans are an attractive and tempting reservoir of many of these resources. However, the marine environment is extremely complex, diverse, and many of its resources are to be found in close proximity to one another. This often leads to multiple potential users competing with one another, often at a great cost to the ocean and to the nation itself. While the current regime in place in India to address the potential impacts of offshore mining does plan for environmental contingencies, the lack of a public discourse prior to the auction of licenses, the availability of global literature documenting the deleterious impact of offshore mining on marine ecosystems, the lack of any public studies on the specific impacts of mining in the identified blocks, and the lack of clarity on the monitoring capacity and mechanism, conspire to denude public trust. It is, therefore, very important that India moves from a project-based EIA approach to a Strategic Environment Assessment within the context of a Marine Spatial Plan to truly enable a comprehensive "blueing" of the Indian economy and to cease obsessively confusing the "blue economy" with an "ocean economy".

09 August 2025

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Fortifying India's Critical Seabed Infra

Underwater Infrastructure – Cables and Pipelines

Mr Soham Agarwal and Vice Admiral Pradeep Chauhan (Retd)

The security and resilience of underwater infrastructure has been receiving increasing academic and policy attention especially within Europe considering the spate of infrastructure damage incidents in the past two years, some of which have had significant consequences.[1] India, too, is seized of the importance of underwater infrastructure, especially submarine telecommunication cables. The Telecom Regulatory Authority of India — the primary permitting/licensing agency in India — has released recommendations on the licensing framework and regulatory mechanism for submarine cable landing in India.[2] However, these recommendations approach the subject from a regulatory point of view rather than ensuring its security and resilience. Therefore, this paper seeks to address that gap with a special focus on the industry players and national institutions involved. It utilises and builds upon research and writings already conducted by the authors.[3]

The paper first presents a baseline brief of a typical subsea cable system. It goes on to provide inventory of the underwater infrastructure connecting India or Indian assets, with particular focus on the carrying capacity of such infrastructure. Such an inventory is important to understand the contribution of that system, whether it be cables or energy pipelines, to the Indian data network or energy ecosystem, respectively, as it is an important criterion to understand the criticality of the infrastructure system. Since underwater infrastructure systems comprise discrete systems, each with differing contributions, an analysis of specific infrastructures becomes important. Next, the study summarises the various vulnerabilities to the infrastructure system, incorporating physical vulnerabilities, as also cyber and legal ones, going on to supply-chain vulnerabilities and the potential actors from which threats to those vulnerabilities emanate. Finally, the report explores enabling mechanisms for protection of the cable systems that form part of critical underwater infrastructure.

The objective of this paper is to understand, within the Indian context but with particular reference to India-Europe connectivity, the threats and vulnerabilities to undersea infrastructure, and to identify measures that need to be taken to enhance their resilience and security.

Overview

In contemporary times, undersea infrastructure is rapidly growing, largely in conformity with what Dr Christian Bueger of the University of Copenhagen describes as "*The Blue Acceleration and the Age of Infrastructure*"[4] — a discernible mega-trend in the global security construct. Today, the seabed hosts a wide range of critical infrastructure, incorporating undersea telecommunication cables, energy pipelines carrying, *inter alia*, oil, gas, green hydrogen, etc., power cables, and a bewildering array of offshore installations for resource extraction. Within this paradigm, the demand-for and reliance-upon data has increased manifold and is likely to demonstrate exponential growth. As technology drives artificial intelligence and is, in turn, driven by it, humankind will need to have significantly increase its access to supercomputing facilities. This access will principally be through undersea data cables. Global undersea cable networks may be expected undergo massive expansion in order to support contemporary and future economies and societies. It is very likely that even within the plethora of types and forms of such infrastructure, undersea communication cables and energy pipelines will be the most critical and, paradoxically, also the most vulnerable. The spread of undersea cables already transcends national boundaries. So do their associated vulnerabilities. For instance, disruptions to the cable network in India may have an impact on the cable network in Europe and *vice versa*. Given the centrality that communication (data) cables and energy pipelines already enjoy, these are the two forms of undersea infrastructure that this document seeks to address. Infrastructure associated with underwater power transmission and resource extraction is planned to be addressed in subsequent studies.

As has already been mentioned, a corollary of our increased reliance on undersea infrastructure is the creation of a vulnerability point for the good functioning of nation-States. Coupled with an environment of heightened geopolitical contestation for greater access and control of resources, and diminishing mutual trust, this vulnerability becomes an attractive pressure-point for adversary States and non-State actors to exploit, in times of peace, tension, and conflict. Hence, the question of protection of such infrastructure acquires great significance and is rightfully receiving increased attention in defence and policy circles. This is a challenge that is not restricted to theory alone but is manifesting itself in the real world, too, with significant geopolitical ramifications. The Nord Stream pipeline disruptions in 2022,[5] the Baltic connector pipeline and cable damages in the Baltic Sea in 2023, and most recently, the disruptions of the C-Lion 1 underwater cable between Finland and Germany in 2024,[6] paint a worrisome picture. The damage to the Baltic connector involved the *New New Polar Bear*, a Hong Kong flagged Chinese container vessel, which dragged its 6,000 kg anchor on the seabed for some 180 kilometres (purportedly unrealised to its master, deck officers or crew!) and ended-up rupturing this 77-kilometre-long natural-gas pipeline running on the seabed of the Baltic Sea and connecting Estonia to Finland and Sweden. Interestingly, all three countries are now NATO members, with Sweden having signed the instrument of accession on 07 March 2024. It is also important to bear in mind that two undersea telecommunication-cum-data cables (EE-S1 between Estonia and Sweden[7] and a twin-redundancy undersea cable between Estonia and Finland, owned by Finnish telecommunication company "Elisa"[8]) were also broken by the *New New Polar Bear*.[9] In an uncanny repetition a year later, on 17 and 18 November 2024, another Chinese-flagged ship, this time the bulk carrier *Yi Peng 3*, was responsible for the rupturing of two undersea cables — one linking Sweden to Lithuania, and the other linking Finland to Germany (the "C-Lion 1" cable). Once again, the vessel dragged its anchor for some 180 kilometres, and once again, incredibly, the master, officers, and crew claimed that they remained unaware that they were, indeed, dragging their anchor despite the vessel proceeding at cruising speed.

In November of 2022, for instance, the SEA-ME-WE 5 (South East Asia-Middle East-Western Europe undersea cable system No 5) was severed in Egypt, disrupting internet-based services in several countries including Indonesia, Djibouti, Eritrea, Pakistan, and Yemen. Then, closer home, on 20 April 2024, the same undersea cable suffered another rupture, this time in the Strait of Malacca — "*Because of this, all traffic between Singapore and SEA-ME-WE 5's landing station in Kuakata, Bangladesh, is down. The damage means that Bangladesh has lost 1.7 TBps of international capacity"*.[10]

On 02 February 2023, and then six days later, on 08 February 2023, Taiwan's two undersea cables connecting the main island of Taiwan to its outlying island of Matsu were severed. According to Taiwan's National Communications Commission (NCC), the first one was suspected to have been cut by a Chinese fishing vessel some 50 kilometres (27 nautical miles [nm]) out at sea, while the second one was by a Chinese cargo ship.[11]

In February of 2024, three undersea cables in the Red Sea were severely damaged. In October of 2024, a report from network service provider RETN said the *"cable cuts impacted up to 70 per cent of Europe–Asia data traffic — far greater than the 25 per cent previously estimated"*.[12] Whether the damage to these cables was caused deliberately or not remains unclear, but several reports indicate that the cause of the ruptures could have been the dragging of the anchor of the cargo ship, the *Rubymar*, after it had been seriously damaged by missiles fired by Houthi rebels and abandoned. Whatever the cause, the AAE-1, Seacom/TGN, and Europe India Gateway (EIG) undersea cables were all impacted.[13]

Unsurprisingly, smaller and less economically developed countries are less likely to be supported by a wider range of data transport routes, making them particularly vulnerable to largescale disruption. As Tony O'Sullivan, CEO of the UK-headquartered RETN (one of the biggest data communications networks in the world and a principal provider of Eurasian undersea cable connectivity[14]) has stated:

> *"We are at a pivotal moment in network connectivity, and to be fully transparent, the industry is not equipped to meet current demands…With geopolitical events, natural disasters, cable cuts, design flaws, cybersecurity attacks and a shortage of new cables, we're really not too far away from entire countries becoming digitally inaccessible when the one or two cables that connect them go down"*.[15]

The truth of this apprehension of *"entire countries becoming digitally inaccessible"* has been in stark evidence in the case of Tonga. In 2019, Tonga spent more than a week cut adrift from the web, when its sole international undersea cable (TIC [Tonga International Cable]) was damaged, reportedly by a ship's anchor. After that outage, it signed a 15-year deal for satellite connectivity, but prohibitive costs limit the use of satellites across the archipelago for most people apart from government, a handful of senior officials, and some critical businesses.[16] Then, in 2022, a tsunami resulting from the undersea volcanic eruption of the *Hunga Tonga–Hunga Ha'apai* volcano, located some 65 km north of Tonga, damaged the TIC undersea cable once again, cutting the island-nation off for as long as a month!

Why is underwater infrastructure becoming an increasingly attractive target in a heightened geopolitical scenario? In addition to the reliance of States on underwater infrastructure, a significant additional advantage is the difficulty of attribution of the act of damaging underwater infrastructure. It is difficult to identify not only the actor or the person/vessel that has caused damage to the cable but also the intention of the actor. It is often difficult to distinguish whether the damage was intentional or due to bad seamanship/seafaring practices. This makes such activities low cost, maintains deniability, ensures minimal escalation, has an asymmetric impact, and has an underdeveloped legal system in place to guide responses.[17] While vessel tracking and identification systems such as the Automatic Identification System (AIS) does help correlate the time of damage with vessel positions (at least in the case of underwater communication cables), it is challenging to understand whether the damage was intentional or not. In the case of the Taiwan-Matsu island undersea cable rupture, as also in in the Baltic Sea incidents, investigation agencies were able to use AIS data to clearly correlate the position and routes of the Chinese ships involved and match them with the time of the undersea pipeline/ cable damage.[18] Thereafter, however, the authorities had to undertake an analysis based on circumstantial evidence of the condition of the anchor, the prevailing weather conditions, and even the nationality of the captain and crew, in order to determine whether the act was intentional and perpetrated with malicious motive.[19] All of this has implications for not only insurance purposes but also to identify patterns of potential actors.

The implication of this trend, as highlighted by Dr Bueger, is that maritime security strategies need to evolve to incorporate the underwater domain, because infrastructure — especially that which is underwater — is becoming so fundamental that we need to re-orient our security thinking towards their protection and this is a key part of the new global common security agenda.[20] Moreover, it is being increasingly realised that, *"advancements in fibreoptic technologies mean that subsea cables hold potential as undersea sensors that can detect tsunamis, earthquakes, marine life and, critically, naval vessels… the emergence of distributed acoustic sensing, or DAS, which is an innovative technique that relies on fibreoptics to detect pressure waves emanating from acoustics of seismic activity"*.[21] What makes DAS technology different to current oceanic sensing is that it does not rely on discrete acoustic or seismic sensors placed along the seabed. Instead, it can potentially cover far greater distances by leveraging unused fibres (also known as "dark fibres") in existing commercial subsea cables. In short, commercial undersea cables can and are being weaponised and can now be used to track both surface and subsurface targets.

It is for all these reasons that underwater infrastructure has acquired greater focus both for offensive and defensive action. This is particularly true of Europe, with France promulgating — in the public domain — its strategy for "Seabed Warfare", which predominantly focuses on preserving its underwater infrastructure especially, submarine communication cables.[22] The seabed and its infrastructure clearly have acknowledged strategic connotations.

Dr Bueger emphasises that maritime security strategies need to evolve to incorporate the underwater domain, because infrastructure — especially that which is underwater — is becoming so fundamental that we need to re-orient our security thinking towards their protection and this is a key part of the new global common security agenda.[23] Such infrastructure — and consequently the ocean itself — needs to be viewed as a new addition to the global commons — a *"common infrastructure of mankind"* — which needs to be protected.[24]

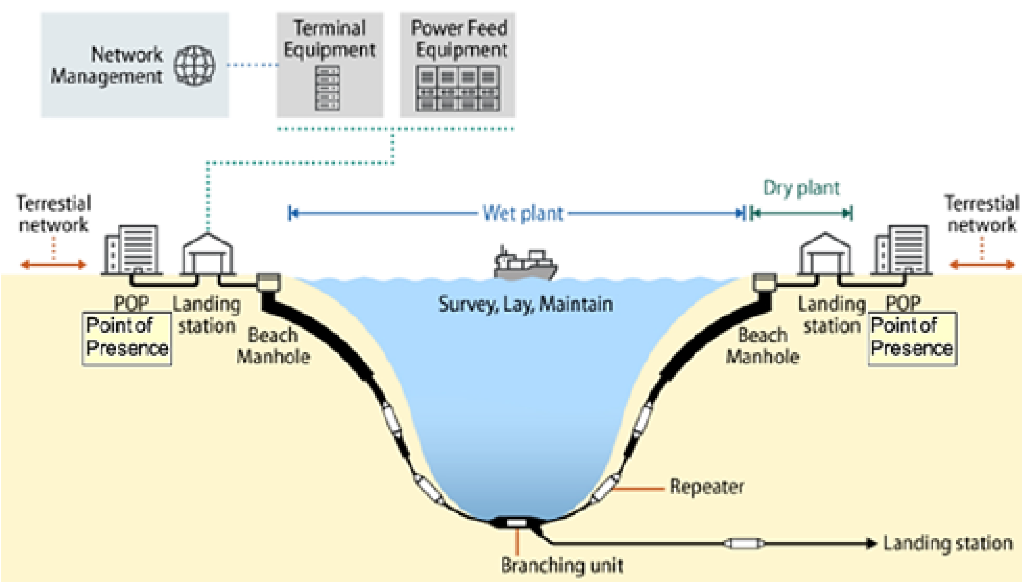
Undersea Telecommunication Cables

Undersea telecommunication cables are at the heart of international data connectivity and, consequently, of the modern-day internet as we know it. Fibre-optic cables — over five hundred of them globally — laid on the seabed carry more than 95 per cent of all global data traffic, a percentage that will only increase over time given the growth in the global demand for data capacity.[25] This is because cables still remain the fastest, cheapest, and most reliable way to transmit data over large distances, not least due to the sheer capacity of the data that can be transmitted per second. Despite their importance, however, undersea cables suffer from an 'invisibility' problem due to their location underwater wherein they receive little attention from policymakers and the public at large until they fail.[26]

The System and Its Layers

Figure 1 refers to a typical undersea cable system comprises a "wet plant" and a "dry plant".[27] The "wet plant" is that component of the cable system that lies underwater and includes the fibre-optic cable itself, the repeaters on the cable (which boost the signal to enable it to cover long distances), and often (but not always) a "branching unit" to some other direction, location, or destination. The "dry plant" of the cable includes the beach manhole (the point at which the cable makes landfall), and the cable landing station, which houses the submarine line terminal equipment (these

Figure 1. Underwater Communication Cable System



Source. Congressional Research Service, Undersea Telecommunication Cables: Technology equipment receive signals from the undersea optic-fibre cable and transmit them farther inland to terrestrial networks for transmission to the end-user),[28] and the power-feed equipment (which provides continuous electric supply to power the repeaters).[29] A single cable system can land at multiple points across the globe, each with its own "dry plant". A good example is the SEA-ME-WE 3 cable system (now retired), which incorporated as many as 39 cable landing stations in 33 countries across four continents.[30] This implies that envisaging the physical protection of underwater infrastructure is not limited to the subsea segment but must also include onshore components, which are equally critical.

Apart from the wet plant and dry plant, a cable system may also be considered to comprise three layers, viz., a 'physical' layer, a 'logical' layer, and a 'data' layer.[31] This corresponds to the broad characterisations of cyberspace. The physical layer consists of the hardware components of the cable as described above. The logical layer provides for the management of data transmission and ensures the routeing of data to its destination, and is done through a 'network management system' (NMS).[32] The NMS provides centralised, network-based control over the physical layer of the system, and allows the operators to remotely monitor and control the different components of the cable system, which includes not only the data transmission management but the power feed equipment as well.[33] An NMS, itself, has two components, an 'element management system' (EMS) housed at each landing station, and a 'unified management system' at what is called a "network operation centre' (NOC).[34] Multiple management systems are then connected to one another using a wireless access network (WAN).[35] Modern cable systems are equipped with 'reconfigurable optical add/drop multiplexing' technology, which allows for greater flexibility in the management of the data network and traffic, as specific wavelength bands can be activated to accommodate additional surges in traffic.[36] The 'information' layer can be envisaged as the data packets traversing through the cable system.

Undersea Cable Systems in India

Table 1. Submarine Communication Cables in India

Ser	Name of Undersea Cable System *(India-Europe Cables are shown in* **Bold Face***)*	Consortium Members (Indian and European)*[37]	Cable landing Stations (India and Europe)[38]	Design Carrying Capacity (TBps)	Activated/Lit Capacity[39] (2021) (TBps)
1.	**2Africa** (To Be Operationalised)	Orange Vodafone	Mumbai, India Marseille, France Tympaki, Greece Genoa, Italy Carcavelos, Portugal Barcelona, Spain Canary Islands, Spain	180.00	N/A
2.	**Asia Africa Europe-1**	Reliance Jio Infocomm, India OTEGLOBE, Greece Retelit, Italy	Mumbai, India Marseille, France Chania, Greece Bari, Italy	100.00[43]	5.75/7.11
3.	Bay of Bengal Gateway	Reliance Jio Infocomm, Vodafone	Chennai, India Mumbai, India	55	15.90/23.8
4.	Bharat Lanka Cable System	BSNL	Tuticorin	0.96	0.03/0.04
5.	Chennai-Andaman Nicobar Islands	BSNL	Chennai A&N Islands	0.4[44]	Data not available
6.	**Europe India Gateway**	Altice Portugal Gibtelecom Vodafone Bharati Airtel BSNL	Gibraltar Mumbai Sesimbra, Portugal	24.3	3.76/6.40
7.	FALCON	Global Cloud Xchange	Mumbai Trivandrum		4.20/4.27
8.	**FLAG Europe-Asia**	Global Cloud Xchange	Mumbai Palermo, Italy Estepona, Spain	19.2[48]	0.023/0.05
9.	**Gulf Bridge International System / MENA** (Terrestrial Connectivity to Europe through Iraq and Turkey)[49]	Gulf Bridge International Bharati Airtel[50]	Mumbai	5.12[51]	0.098/0.26
10.	MENA (Middle East-North Africa)	Telecom Egypt	Mazara del Vallo, Italy	24[52]	2.67/2.70
11.	i2i Cable Network	Bharati Airtel	Chennai	160[53]	22.76/27.23

Ser	Name of Undersea Cable System *(India-Europe Cables are shown in* **Bold Face***)*	Consortium Members (Indian and European)*[37]	Cable landing Stations (India and Europe)[38]	Design Carrying Capacity (TBps)	Activated/Lit Capacity[39] (2021) (TBps)
12.	ICE IV		Chennai Kochi	TBC	N/A
13.	**IMEWE (India-Middle East-Western Europe)**	Bharati Airtel Orange Tata Communications Sparkle (Telecom Italia)	Marseille Catania, Italy	36.6[54]	4.68/13.8
14.	India Asia Xpress (To be operationalised)	Reliance Jio Infocomm China Mobile (Other Partners TBC)	Chennai Mumbai	200[55] (estimated)	N/A
15.	**India Europe Xpress (To be operationalised)**	Reliance Jio Infocomm China Mobile (Other Partners TBC)	Mumbai Marseille, France Timpaki, Greece Savona, Italy	200 (estimated)	N/A
16.	Kochi-Lakshadweep Islands	BSNL	Kochi Lakshadweep Islands	0.10[59]	Data not available
17.	MIST (To be operationalised)	Orient Link	Chennai Mumbai	216[60]	N/A
18.	**Blue-Raman** (To be Operationalised)	Sify Technologies (CLS Owner)	Genoa, Italy Golfo Aranci, Italy Palermo, Italy Rome, Italy Marseille, France Chania, Greece Mumbai	16 fibre pairs each with 25TBps[61]	N/A
19.	**SAFE/WACS**	BICS KPN Orange Sparkle Telefonica OPT Tata Communications	Kochi	14.5[62]	0.034/0.48
20.	SEACOM/Tata TGN-Eurasia	Tata Communications	Mumbai	12	4.47/4.62
21.	**SeaMeWe-3**	Tata Communications A1 Telekom Austria Altice Portugal BICS British Telecom Cyta Deutsche Telekom	Kochi Mumbai Norden, Germany Ostend, Belgium Penmarch, France Chania, Greece Mazara del Vallo, Italy Sesimbra, Portugal	4.6[63]	0.056/0.68

Ser	Name of Undersea Cable System *(India-Europe Cables are shown in* **Bold Face***)*	Consortium Members (Indian and European)*[37]	Cable landing Stations (India and Europe)[38]	Design Carrying Capacity (TBps)	Activated/Lit Capacity[39] (2021) (TBps)
		KPN OTEGLOBE Orange Orange Polska Sparkle			
22.	**SeaMeWe-4**	Tata Communications Bharati Airtel Orange Sparkle Telecom Italia	Marseille, France Palermo, Italy Mumbai Chennai	122[67]	4.55/17.5
23.	**SeaMeWe-6** (To be operationalised)	Bharati Airtel Orange	Marseille, France Mumbai Chennai	130[68]	N/A
24.	Tata TGN-Tata Indicom	Tata Communications	Chennai		14.52/14.6

Source. Compiled by Authors from various sources

Notes:

(1) * Other international telecom partners may be a part of the consortium, but only Indian and European partners identified.

(2) **Design Capacity.** This is the maximum capacity that the cable can carry if all the equipment is installed at the dry plant.[69] In reality, due to cost considerations, submarine cable owners and operators rarely install all the available equipment. Such equipment is installed once there is sufficient demand for the additional cable capacity. In addition to the cost, there is also a time penalty in to be paid for upgrading the equipment at the dry plant ends of the cable system.

(3) **Lit Capacity.** The current capacity of the cable, based on existing installed equipment, is referred to as 'lit capacity'. It is the amount of data that can currently flow over the cable.[70] This capacity can be achieved in a near real-time basis by using multiplexing technologies to increase the amount of data flowing over the cable. Lit capacity is approximately 20 per cent of the designed capacity of any cable, leaving significant buffers for potential upgrades.[71]

(4) **Activated Capacity.** This is the capacity actively being used. Some amount of spare capacity is kept between 'activated' and 'lit' capacity to ensure management of any surge in data demand which may arise *inter alia* due to from faults in other cables.

India recognises the importance of taking all three capacity-metrics into account when identifying cables that may be more vulnerable to disruption than others. In a recent report, the Telecom Regulatory Authority of India has identified that as of 2022, the total LIT capacity of submarine cables landing in India was 138.6 TBps out of which 111.1 TBps was activated.[72] (While the data of activated/lit capacity used in **Table 1** may not be the latest figures, it is nevertheless useful to identify the contribution of particular cables to the overall capacity of the system). This means that 80.16 per cent of all of India's lit capacity has already been activated. Therefore, available redundancies in the entire system have decreased and are decreasing at an increasing rate. The percentage of LIT capacity activated from 2016 to 2022, for instance, has increased at an average of 10 percentage points from each preceding year.[73] Moreover, India's international bandwidth demand is expected to grow at a CAGR of 38 per cent from 2021 to 2028, which can potentially create significant shortages in available capacity.[74]

However, new projects slated to become operational soon, will bring significant design capacity into the system. While such projects introduce redundancies, they may, of course, also become more attractive targets especially if significant capacity is activated.

Significance to Europe of India's Undersea Cables

India's connectivity is also of interest to Europe due to India's geography and position in the Indian Ocean. India forms a natural landing point for submarine cable projects connecting the global East to West, on both strategic and commercial grounds.[75] In addition to the cables being important for data exchanges between Europe and India, landing points in India offer redundancy paths for the data interchanges to connect Europe beyond India in case of direct route failure. Currently, eight (8) cable networks directly connect India and Europe, with a cumulative designed capacity of nearly 350 TBps, and with an activated and Lit capacity of 21.6 TBps and 50 TBps, respectively.[76] In addition, four (4) cables projects, with over 500 TBps designed capacity, are being planned and are soon to be operationalised. It may be concluded that there is very significant data connectivity between India and Europe.

While there is only one direct route between Germany and India, digital integration within Europe makes Germany, too, an interested party in ensuring the protection of undersea cables between India and Europe, even if they land mostly in France and Italy. This gives rise to common challenges, threats and vulnerabilities, therefore giving rise to a common interest in ensuring their security and resilience. It needs to be borne in mind that severe degradation of a country's communications can take place without any disruptions being located close to the country's territory.[77] Hence India-Europe connectivity is particularly vulnerable given the number of chokepoints and geopolitical turmoil in the path of these cables.

Addressing the overarching vulnerabilities of undersea cable systems may be usefully conceptualised under two broad heads, namely, "resilience" and "security". The key difference between them is that resilience is the built-in mechanism of the system to ensure functionality through system design, operations, and restoration after disruptions, while security refers to the proactive protection to the system from hostile actors.

Resilience

Conceptualising the cable system in different layers provides an overview of the vulnerabilities of each layer of the cable system which, while not compartmentalised, do have distinct features. A manifestation of the vulnerability of any one layer can compromise the entire system and, therefore, protective measures adopted need to ensure that they are holistic in their approach. Moreover, these vulnerabilities may be targeted either individually or in conjunction. Due to the cable system comprising both physical and cyber components, submarine cable systems are also vulnerable to 'combination' or 'hybrid' events. As opposed to "security", the resilience of an undersea cable system involves its ability to address principally "natural" threats. Natural threats manifest themselves in damage to cable systems from natural disasters such as earthquakes, volcanic eruptions, tropical cyclones, coastal erosion, and coastal flooding.[78] Concern over the deleterious impacts of such phenomena effects is even more keenly felt by island nations which have low redundancies and are often located on tectonically active margins, and subject to cyclones, tsunamis, and fluvial sediment discharges.[79] These need not only be Small Island Development States (SIDS). Nations such as Japan — that are situated on active tectonic plate boundaries — are equally concerned with disruptions due to natural disasters as are their smaller island-counterparts. As has already been mentioned, damage to the sole submarine cable to Tonga in 2022 from an underwater volcano eruption, and to the Mariana Islands in 2015 by Typhoon *Chan-Hom*, severely limited their connectivity.[80] New Delhi must not be underestimate such threats either, given that India's two major island chains, the Andaman & Nicobar Islands, and the Lakshadweep Islands, too, are each connected to the mainland by a lone cable system.

The resilience of the "wet plant" is catered-to by deploying specially designed and manufactured fibreoptic cables, which utilise a suitable network topology. Typically, this is a "trunk and branch" (also known as a "tree-topology"), although "point-to-point typology is also encountered quite frequently".[81]

Further enhancement in terms of resilience is achieved by addressing the "data layer" of the system, typically by using a one or another form of multiplexing technology, which allows for a multiplicity of digital and analogue signals to be carried from a given source to one more destination without needing a dedicated connection between each device pair, although multiplexing does, of course, still require shared media. Since undersea cable networks employ laser systems to send light signals over fibreoptic cables, these networks tend to use wavelength-division multiplexing (WDM), in which *"multiple communications channels are consolidated and then transmitted on light waves with different wavelengths. WDM variations include coarse WDM and dense WDM (DWDM), which put fewer or more channels of information, respectively, on the medium at the same time"*.[82]

Security

"Security" in respect of an undersea cable system seeks to principally address risks and threats emanating from human and State-based malevolence. However, building and enhancing resilience — especially by way of creating multiple alternatives for the flow of data from its sources to its points of destination certainly mitigates "security" risks as well.

For instance, in the year 2012, a study was undertaken at the US Naval War College utilising an 'attacker-defender' model along with network modelling to understand the resilience in the network connecting Europe to India.[83] In this model, the attacker sought to inflict the maximum possible damage to the system overall and while the operator (the defender) seeks sought to ensure the maximum flow of data at any given point of time. This enabled an understanding of the ability of the network to absorb shocks to the system. The study utilised a 'gravity model' to understand the flow of data between India and Europe and concluded that when operating at lit capacity, five interdictions to the cables would isolate India from Europe and the optimal attack locations were almost always between Europe and Africa, in the Mediterranean.[84]

At designed capacity, due to additional redundancy in the system, the network was more "resilient" to initial disruptions (up to three), in a scenario of greater number or simultaneous disruptions, isolation of India from Europe would occur at five or more interdictions. This is because initially, additional spare capacity existed to enable the rerouting of data via other cables. Increases in demand for data will reduce the available spare capacity and hence, the "resilience" of the cable system — both as an enhancer of "security" as well as to cater for "natural" risks and threats — is also dependent upon how quickly service-providers can scale-up the available capacity on individual cables.

As a case in point, interdictions — howsoever caused — to CLS in France (specifically in Marseille) and Egypt will very likely isolate India from the internet altogether. This is because these two landing points are critical nodes where a majority of the cables connecting India and Europe either originate or transit through. Multiple interdictions have a greater disruptive impact as the number of alternative routes through which data may transit reduces.

Therefore, while adding additional capacity to the network does make it more resilient, it is also important as a "security" measure to maximise route- and landing station diversity so as to ensure that the system is more adaptive to shocks to the system. While the new planned connectivity projects between India and Europe will add significant capacity to the cable network, almost all these cable systems — barring the 2Africa cable — follow the same route through the Mediterranean due to the geography of the region. Going through Suez is the shortest route to Europe and affords multiple landing points in countries like Italy and Greece. Hence, even with additional capacity, the resilience of the network may not improve if there are simultaneous anthropogenic interdictions to the large-capacity cables. Hence, the security of cables in the Mediterranean and Red Sea is an important component. It is useful then, to understand the threats that these cable systems may face.

As highlighted previously, the underwater communication cable system may be conceptualised having layers viz. physical, logical, and information, with each layer having its own set of vulnerabilities and threats. Each will be considered in turn.

Physical Layer

Security of the physical layer, comprising the dry and wet plant of the cable system, i.e., the hardware components of the cable system, is a function of addressing threats from anthropogenic sources. The disruptions themselves may 'accidental', 'purportedly accidental', or 'overtly intentional'. There are three primary sources of accidental and 'purportedly accidental cable damage: ship anchoring activities, fishing (especially bottom trawling), and dredging. Security-enhancement measures against such threats, especially in shallow waters, include armouring the cable and burying it into the seabed. While this may be effective in mitigating the risk from fishing, dredging activities still pose major concerns. Further, burying is not always possible on a rocky seabed or one with rocky mounts. Here, the possibility of the cable being snagged by fishing gear rises significantly. Moreover, attempts by a vessel to locate and/or recover lost fishing gear or anchoring gear (such as chain cables or anchor themselves) using grapnels or lightweight kedge anchors, significantly risks such gear 'hooking' the cable.[85] In addition to bottom trawling, in deeper water, static fishing gear, involving lobster-pots that are weighted by heavy, grapnel-shaped multi-fluked anchors are used which may damage such cables underwater.[86]

Competing uses of the seabed and offshore activities such as oil and gas development, the setting-up and maintenance of infrastructure for offshore wind energy and other ocean-mechanical and ocean-thermal renewable-energy resources, exploration and operations related to seabed mining, etc., pose significant risks to underwater infrastructure.

As already mentioned, another major risk to undersea cable systems is a lack of route diversity.[87] The topography of the seabed, cost for protection of the marine environment, and the availability of landing infrastructure cause cables to bunch-up. It is interesting to note that cable routes often follow international shipping lanes and share much of the choke points for international shipping lanes. The core choke point for India-Europe connectivity remains the bunching of the cables in the Red Sea and their passage through the Strait of Bab el Mandeb, and the terrestrial route through Egypt.[88] Therefore, not only is the lack of route diversity a concern at shore, but also at sea and in foreign jurisdictions.

It is important to identify the causes and occurrence of accidental and purportedly accidental anthropogenic harm, as this remains the predominant cause of damage to submarine cables. In 2023, the Telecom Regulatory Authority of India estimated that nearly 63 per cent of all cable damages occur either due to fishing or anchoring in shallow waters (characterised as depths less than 1,000 metres).[89] This fact makes some scholars and practitioners opine that building resilience of the cable system is more important than expending resources on security scenarios involving intentional damage by malevolent State actors, State-sponsored non-State ones, and, of course, malevolent non-State ones as well.

Indeed, intentional damage of cable systems is a growing concern. Insofar as the physical layer is concerned, the three components comprising any undersea cable system, namely, the "wet plant", i.e., the cable itself, the "dry plant", i.e., the cable landing station (CLS) and the beach manhole (from where the optic fibre runs terrestrially to the CLS), and the repair infrastructure associated with the cable system (including cable repair vessels, cable equipment manufacturing units, and cable-equipment storage depots), all constitute likely targets that consequently need security. It is particularly important to bear in mind that the destruction of repair capabilities, when coordinated with destruction of the cable itself, will significantly hamper the ability of the State to recover its communications network.

Cable damage can occur both in shallow waters (depths lesser than 200 metres) or in deep waters (depths greater than 200 metres). Viewed from the lens of an aggressor, both shallow and deep waters bring their own set of challenges. On the one hand, cables laid in shallow waters are likely to be easier targets as the location of these cables are marked on navigational charts in order to prevent damage from inadvertent fishing and shipping activities.[90] Interestingly, the C-Lion 1 and BCS cables were damaged at depths of 46 metres and 175 metres respectively.[91] On the other hand, while physically accessing these cables may well be easier, the fact that undersea cables laid in shallow waters are often sheathed in armoured sleeves and/or buried within trenches dug into the seabed makes it more difficult to physically damage them. Of course, cable burial is feasible only if permitted by suitable seabed and sediment conditions along the laying route.[92] Therefore, States whose seabed conditions do not permit cables to be buried in shallow waters, would have to contend with substantial and substantive security vulnerabilities. In deep waters, cables are generally not marked on navigational charts — and are consequently harder to locate. On the other hand, they are seldom buried or armoured. Thus, while they are harder to reach for aggressors and hence harder to target, they are also easier to damage once accessed and, by corollary, harder to repair in case of damage. Therefore, damaging cables in deep waters has a greater and more enduring impact.

CLS are attractive targets as they constitute nodes where multiple cable landing stations congregate and any disruptions to which may have a serious impact. However, being shore-based assets, accessing CLS is much more difficult for adversaries. Damages to cable landing stations are more likely to be discreet, 'insider jobs', given that access into A CLS is extremely restricted. Moreover, their locations are not readily available in the public domain.

Cable repair infrastructure, especially cable repair vessels can be subject to attack either in port or at sea. This is especially true while they are stationery or undertaking cable repair. While an explicit kinetic attack may escalate matters, "accidental" collisions at sea may fall below the threshold of escalation and lie within the "grey zone".

The means of attack can vary in sophistication from using 'cutting devices' such as anchors and dredgers from aboard civil and merchant vessels to utilising underwater improvised explosive devices (IEDs) and subsurface craft to identify and disrupt the cables.[93] In the cases of Baltic connector and C-Lion 1, a relatively simple anchor-drag was sufficient to disrupt the cable. This highlights the asymmetry involved in targeting underwater infrastructure and the host of actors that may potentially undertake such activity. Ordinarily the length of a merchant ship's anchor cable will be such as to allow anchoring in depths of around 275 to 300 metres.[94] A disproportionately long anchor chain-cable on merchant ship that is found to have dragged its anchor and ruptured or damaged an undersea cable or pipeline would be a strong suspicion-indicator that would be difficult to explain away, its protestations of innocence notwithstanding. Therefore, anchor damage would generally not occur in water depths exceeding 300 metres.

It is also possible for divers and unmanned and/or autonomous underwater vessels to be utilised to undertake targeted cutting of an identified infrastructure system. In the case of Nord Stream pipelines, explosions had occurred on the pipeline that caused the disruption. These explosives would have to be discreetly placed on the pipeline. This would require specialist divers and submersibles to undertake. Therefore, the means utilised for disruption are dependent upon whether specific cables or pipelines are to be disrupted. Anchor damage can be undertaken in deeper waters, but it is going to be more challenging to locate the specific cable without precise coordinates. Nord Stream pipelines were placed at a depth of between 80 and 110 metres, which would have allowed for divers to undertake such a mission.[95] However, submersibles are required to reach deeper depths for specific cable targeting. NATO, for instance, assesses that Moscow has two primary means by which it could directly threaten trans-Atlantic undersea cables: submarines and surface vessels that can deploy autonomous or manned submersibles. An oft -quoted example of the former is the *Losharik* spy submarine, which — before a tragic fire in 2019 decommissioned it — is believed to have had the deep-sea capability necessary to map or destroy undersea cables. Although the *Losharik* is still being repaired, the Russian Navy is believed to have other such submarines and is developing unmanned undersea drones, such as the nuclear-powered *Poseidon*. As for surface ships, the most famous is the *Yantar*, which is ostensibly a research vessel but is understood to act as a spy ship that could deploy underwater submersibles to attack and destroy sections of cables.[96] This is not, of course, to say that Western powers do not have similar capacities and capabilities. They certainly do. For instance, *"the USS Jimmy Carter is currently the US Navy's principal seabed warfare submarine, specially fitted for covert spy missions deep beneath the waves… Plans are underway to build a follow-on* *special spy submarine using the newer Virginia Class hull"*.[97] This is, at the moment, understood to be a single "Mod VA SSW" (Modified Virginia, Subsea and Seabed Warfare) version of the *Virginia* Class submarine.

As already mentioned, the potential actors involved in such activity could be State actors or non-State ones. In times outside of armed conflict, the commonest variety might well be State-sponsored malevolent non-State actors. An example of the latter is the use by Hamas of uncrewed autonomous underwater vehicles to attack Israeli undersea infrastructure.[98] State-sponsored non-State actors can accomplish State-objectives while maintaining deniability by the sponsoring State. Further, since Article 113-115 of the United Nations Convention of the Law of the Sea 1982 (UNCLOS) gives jurisdiction for damage to cables in the High Seas to the Flag-State of the vessel that has caused the damage, co-operation from the Flag-State becomes an important prerequisite in any effective investigation. This cooperation is unlikely to be genuine and forthcoming if State agencies can themselves be linked to the operation.

Where State actors are concerned, it is important to reiterate that undersea cable systems are vulnerable to disruption not only during times of peace but also in times of conflict. A relatively early example is the Spanish-American War of 1892, where submarine telegraph cables were targeted in order to isolate Cuba from Spain.[99] The First and Second World Wars, too, saw cable cutting operations with decisive consequences. The impact was demonstrated by the interception of the Zimmerman Telegram when Germany was compelled to use a telegraph system controlled by Britain after their own telegraph cables were disrupted by British action.[100] State actors tend to undertake such activity overtly only during times of armed conflict.

Recently, however, NATO has indicated that Russian interest-in and activity-near critical European communications infrastructure is concerning even if done for purposes of strategic signalling and as a demonstration of capability.[101] While Russia has been utilising hard military assets, China's approach has been more subtle and is, arguably, of even greater concern. Beijing's approach is designed to enable China to become the major supplier for cable components/services and route more traffic through Chinese territory.[102] This is deeply worrying due to the data security elements involved in securing cable systems which shall be discussed subsequently.

Purely non-State actors such as violent extremists and terrorist organisations would most likely seek to inflict damage to the communications architecture of a State for the high visibility it would provide them. Fortunately, such a scenario has not unfolded till date but that does not mean that it will not. In the case of the Red Sea cable cuts, speculations that this was done by the Houthis were sparked by the sharing of a picture of the cables in the Red Sea.[103] However, the Houthis denied any responsibility and several analysts discount a "Houthi hand" given that the telecommunications industry is a source of revenue for the Houthis themselves.[104] Moreover, it is unlikely to be an attractive choice for non-State actors to pursue given that in order to be effective, terrorist activities need to instil fear amongst the mass populace. Since, as has been stated earlier, underwater infrastructure suffers from a problem of invisibility, terrorist groups may not achieve their goals by targeting underwater infrastructure. Moreover, they themselves rely on undersea internet-based communication for their own messaging and the dissemination of their propaganda.

From the foregoing arguments, it is clear that there is a relationship between the specific target, the depth at which that target is to be disrupted, and the means adopted for such disruption. While damage caused by a dragged anchor is a relatively low-cost endeavour that may be taken by a wide variety of actors, the level of sophistication and technology required for missions to physically damage, destroy or disrupt cables laid in deep water is likely to be possessed only by State actors.

Logical Layer

Vulnerabilities of the logical layer are seldom "natural" and almost always involve malicious human intent. These vulnerabilities stem from integrated Network Management Systems (NMS). The NMS is usually situated in a Network Operations Centre at a Cable Landing Station (CLS) and utilises Reconfigurable Optical Add/Drop Multiplexing technology that allows for greater flexibility in the management of the data network and traffic, especially between the main cable and branching units.[105] Hence an operator who gains access to the NMS may activate or block specific wavelengths which, with malicious intent, could completely disrupt the flow of data to a particular branching unit, disrupting the entire flow of data to a particular country connected via that branching unit.[106] In addition to fibreoptic connections, the NMS has the capability to monitor and control the power feeder equipment and the fibre testing equipment. Thus, unauthorised access may lead to disconnecting of the power supply to the repeaters or preventing the system from displaying fault notifications and making it more difficult to identify fault locations.[107]

NMS service providers do incorporate cyber-security mechanisms such as installing firewalls and creating secure networks running on a different protocol, which they hope will make them secure from unauthorised access.[108] However, this is not necessarily standard industry practice. A surprisingly large number of NMS service-providers use commercial operating systems such as Windows/Linux, and TCP/IP to connect to the network operation centre.[109] The several vulnerabilities of these systems are well understood and there is a high probability of their being successfully exploited. A lack of minimum standards, private industry ownership — with cost-effectiveness as its primary objective — may increase the likelihood of the adoption of weak security systems for this form of critical infrastructure, especially in developing nations.

As recently as 2022, a cyberattack on the network of an undersea cable operator was thwarted by the US Department of Homeland Security Investigations.[110] It was reported to have been from an international hacking group, the intentions of which remain unclear. Tracking the attackers was done by placing 'honeypots' on discord channels on the dark web. These attackers were based overseas and help from multiple agencies of different States was required to make arrests. Cyber-attacks are more plausible from non-State actors, especially for ransom. Given the criticality of the network and downtime costs involved, service providers would be more likely to yield in successful breach scenarios.

Information Layer

The security of the information flowing over these cables is also important. Data security vulnerabilities exist at two points — at the logical layer through the NMS, or through the physical layer either on the cable itself or at the Cable Landing Station. While tapping an optic fibre cable underwater is an complex undertaking, the physical layer is vulnerable to the inclusion of remote surveillance equipment by the cable manufacturer.[111] The US is particularly sensitive to this issue and has been pushing for ensuring that security risks from high-risk suppliers of undersea equipment are aggressively managed.[112] The US has utilised diplomatic tools to ensure that American cable manufacturers win major consortium contracts to manufacture and lay cables instead of Chinese cable-manufacturers, including for those cables that do not necessarily land either in the US or China. For instance, the US State Department ensured that *SubCom* wins the contract for the SEA-ME-WE 6 Cable connecting Singapore to France, by offering training grants to consortium telcos and threatening to impose sanctions on cable system operations.[113] China, similarly, has delayed granting a license to Japanese manufacturer NEC for laying a cable to pass through the South China Sea and land in Hong Kong and mainland China.

Beyond 'backdoors' in the cables themselves, the CLS presents another point at which data security may be compromised. Most jurisdictions have legal provisions that enable them to lawfully control access to data flowing through cable landing stations within their jurisdiction. This vulnerability was exposed to the world by the UK Government Communications Headquarters in respect of Operation TEMPURA, which involved mass surveillance by interception of data at cable landing stations in the UK, all of which was duly authorised under the 2000 Regulation of Investigatory Powers Act.[114] Such laws are also prevalent in China. The National Intelligence Law of the PRC requires Chinese citizens and organisations to cooperate with state intelligence work.[115] No definition of the terms, "cooperation" and "intelligence work", has been presented and could compel Chinese companies to give access to State authorities of the data flowing through Chinese cable landing stations, which may be China-bound or merely transiting China. In the US, a contractual mechanism is utilised wherein a Network Security Agreement is executed enabling US government agencies to seek access to data flowing through these networks by establishing a corporate cell within telcos, consisting of American nationals with government clearances, to facilitate surveillance consent.[116]

The United States has since officially established a "Committee for the Assessment of Foreign Participation in the United States Telecommunications Services Sector" to advise the Federal Communications Commission (FCC) on "public interest reviews" of foreign participation in the telecommunication sector.[117] All international telecommunication services, including permissions to land and operate international undersea cables within US territory, fall within the scope of the Committee's review.[118] For connections landing in the US, any applications involving 10 per cent or greater direct or indirect ownership, the Committee may advise the FCC to either accept, reject, or grant contingent approval to the application. The Committee seeks information on call-data information-storage practices, security practices, and persons who may have access to the network and data.[119] In this manner, the US has, for instance, blocked cable projects seeking to connect the US to Hong Kong out of data security concerns.[120]

India, too, has established a 'Trusted Telecom Portal' in line with the approved National Security Directive on the Telecommunication Sector in 2021.[121] A non-India-registered Original Equipment Manufacturer (OEM) may be included in the list of 'Trusted Products' from 'Trusted Sources', but only on application by a telecom provider or an India-registered subsidiary and after prior approval from the National Cyber Security Coordinator.[122] It is only products from these trusted sources that may be connected to the network, thereby ensuring that any compromised hardware is precluded.

This also points to the geopolitical contestations in controlling global communications by controlling the manufacturing and supply of cable equipment. The US House of Representatives has passed the "Undersea Cable Control Bill" to *"require the development of a strategy to eliminate the availability to foreign adversaries of goods and technologies capable of supporting undersea cables, and for other purposes"*.[123] It statutorily mandates the President of the United States to identify:[124]

1. Goods and technology capable of supporting construction, maintenance, or operation of undersea cable project,

2. Unilateral and multilateral export controls and licensing policy for such goods and technology

   i. Existing share of global market of US and allies

ii. Existing market share of adversaries

iii. Seek unified export controls and licensing polices to eliminate the availability of such goods and technology to foreign adversaries.

Therefore, understanding the supply chains of undersea cable equipment is extremely important to develop indigenous capability in these goods and technology given the geopolitical contestations surrounding them.

This study should also be undertaken by India and Germany to enable them to become bigger players in the cable equipment manufacturing ecosystem. This would also give them a greater leverage to set the global agenda on this issue. This would stand true both at the International Cable Protection Committee (largely an industry body) and at the newly launched International Advisory Body for Submarine Cable Resilience.[125] Being a player rather than merely a valued customer will allow greater traction at these international advisory bodies.

Protection

The protection of undersea cable systems is complicated by a number of historical (legacy) factors, to which must be added contemporary corporate functional, financial, and legal practices. By and large, the world over, undersea communication cables are primarily commercial enterprises undertaken by private entities on a "for-profit" basis. Currently, the four largest suppliers of undersea cables are Alcatel Submarine Networks (France), SubCom (United States), NEC (Japan), and Huawei Marine Networks (China). While network operators have traditionally been the main investors in undersea cables, content providers (Google, Amazon, Microsoft, Facebook) are also expanding their investments in this sector to ensure the interconnection of their data centres.[126]

Moreover, it is commonplace for different segments of the cable system to be owned by different private entities.[127] For instance, it is entirely possible that a particular private entity owns the cable landing station onshore but a different entity owns the optic fibre cable being connected to the cable landing station, while a third entity owns the capacity over the cable.[128] All this has a bearing on the provision of security to undersea cables, since the responsibility to ensure the security of the inherently interconnected cable system is quite diffused, involving multiple players. The problem is exacerbated if a 'consortium ownership' model exists, wherein a group of international telecom service providers jointly fund, build, operate, and own the cable system.[129] Depending upon the decisions made by consortium members, local regulations, and component suppliers, the NMS and NOC may deploy some sort of firewall architecture that may be less secure at certain nodes than at others. It is entirely possible for certain telecom providers to adhere to the bare minimum cybersecurity standards prevalent in their respective countries, and for these standards to be unexacting or insufficient or to become so with the gallop of technology over time.

Additionally, due to the predominantly private ownership of submarine telecom operations, another potential issue is the division of the responsibility of protection between the State and industry. While private players do factor in 'resilience' within the cable system, they usually do not operate within a 'security' scenario or factor the latter into their planning.

This stems from the fact that after the Cold War period, underwater infrastructure did not have to operate in the sort of heightened geopolitical environment that now prevails. Hence, private players have neither planned for nor have the capability to manage such threats, especially if these threats materialise through malicious intent. Therefore, these private ownership models notwithstanding, a considerable degree of responsibility falls upon the State to ensure both resilience and security of the cable system with particular emphasis on the latter.

Thus, the very nature of the bulk of the world's cable systems necessitates a collaborative and coordinated effort in order to secure these networks from damage. Such collaboration and coordination need to be undertaken not only between States but also between a given State and a host of private entities, as also amongst the private entities themselves.

At the supra-governmental level, the UN, acting through its principal technical body for telecommunication, namely, the International Telecommunications Union (ITU) has, as recently as 13 December of this year (2024) "created a new body to boost protection for submarine cables, aiming to help shore them up against damage and accelerate repairs"[130]

Other mechanisms under which such collaboration and coordination may be wrought are discussed in the succeeding paragraphs. The inclusion of redundancy in the network by laying more cables is often considered as a good way to enhance resilience. While that is indeed effective, it will go only so far in the case of simultaneous or multiple interdictions against undersea cables or cable landing stations. Moreover, barring a few strategic initiatives such as in the Pacific,[131] most new cable projects are driven predominantly by purely commercial interests. Hence, additional redundant capacity will only be supplied if there is corresponding demand for it. Consequently, additional measures need to be undertaken beyond introducing redundant capacity. Protective mechanisms may be undertaken in five broad areas, viz., acquisition of repair capacities and capabilities, technological measures, legal measures, operational preparedness, and international collaboration.

Acquisition of Repair Capacity and Capability

Prompt repair of cable faults is an effective method of enhancing the resilience of underwater communication cables. Faster repair equates to shorter downtimes, irrespective of the initial cause of disruption. Since there is no Indian-owned, Indian-flagged, or Indian-stationed repair vessel, Indian operators rely on traditional 'Club' agreements, and 'Private Maintenance' agreements.[132] This former involves a consortium where the participating cable owners agree to common conditions and prices for repairs, while the latter involves a bilateral agreement between the cable operator and the repair service provider. Since traditional club agreements correspond to geographical areas, India is within the "Southeast Asia and Indian Ocean Cable Maintenance Agreement" (SEAICOMA), which is primarily serviced by Global Marine Systems Ltd (a UK-registered entity) and "ASEAN Cableship Pte Ltd" (a Singapore registered entity).[133] Private maintenance contracts are generally executed with "E-marine", a UAE-based entity. The average response times for SEAICOMA in Indian waters is four-to-five months, and for E-marine it is three-to-five months.[134] This delay can be attributed to permission-related challenges; import and export clearance procedures; naval, customs, and crew clearance; and the transit time between the vessel's location, the cable storage depot, and the repair site.[135] Even more vulnerable are shallow water repairs — undertaken at a depth of less than 15 metres through local contractors — which may take as long as a year, as the cable vessel, jointing kits, and skilled personnel, are not available in India.[136] This vulnerability is enhanced during times of armed conflict due to reliance on foreign players for cable repair. Lack of willingness to operate in conflict zones, higher insurance premiums, clearance for foreign crew and vessels, and applicability of *force majeure* clauses make commercial contracts unreliable.[137] The industry, too, is suffering from a shortage of repair vessels, an ageing fleet, and a lack of skilled crew.[138]

Similarly, Germany too does not have a submarine communication cable repair vessel of its own. While France and the UK — both NATO allies, along with Germany — do have significant cable repair capacity and capability (ASN/Alcatel and Orange Marine are French companies, and Global Marine is British), any conflict in Europe is likely to stretch resources thin. Therefore, it is imperative that indigenous cable repair capacities and capabilities are developed. This can be by way of building cable repair vessels *ab initio* or retrofitting offshore support vessels (OSVs) for cable repair. This practice is common in industry and is being exploited by China to swiftly acquire cable repair vessels.[139] New vessels may cost around US$ 120 million to build, with a three-year build cycle, while retrofitting may be done (depending on the cost of the OSV) for approximately US$ 60 million within a year after acquisition. Therefore, there is not only a monetary but also a time advantage to this approach. The availability of such OSVs however, is often a challenge and frequently coincides with 'booms and busts' in the oil markets, as currently, the offshore oil and gas industry is the biggest users of OSVs for maintenance operations.

Repair capacities and capabilities are not, however, limited merely to the vessel alone but also include the jointing equipment, the storage depots, and the skilled crew to undertake the repair operations. These are all integral components of the repair process and their availability, too, needs to be secured.

Technological Measures

As has been mentioned earlier, technology such as Distributed Acoustic Sensors (DAS) allows for continuous, real-time monitoring along the length of the fibre optic cable by detecting acoustic vibrations along the submarine cables.[140] Any acoustic signature generated near the cable will be picked up and can alert network operators of any potential risk. However, DAS on a single cable may indicate the presence of a potential threat but only two or more DAS-enabled cables in proximity to each other will be able to triangulate the position of the acoustic signature. Therefore, DAS may only be effective when multiple cable providers opt to enable DAS on their cables. DAS-enabled cables may be effective when used along with AIS monitoring data. DAS data can then be correlated with AIS data to spot specific threats potentially in near real-time basis and prevent the damage of multiple cables. Even in the absence of AIS data (in the case of grey shipping or dark shipping), DAS cables can provide alerts for potential damage. However, DAS presents two major challenges. First, the fitting of acoustic sensors may alter the regulatory and permitting process for these cables. The inclusion of detection technology in the territorial sea of coastal States may create additional issues especially when it involves private players including foreign participants. The second challenge is the necessity of supporting technological and operational measures. DAS by itself just picks up acoustic signals. Technical capability to analyse this data, integration with other Maritime Situational Awareness (MSA) software/programs, and support of operational at-sea assets is also necessary for DAS to be effective. While current MSA software do display cable positions on their maps, fault notification integration is not carried out nor are submarine cables the focus of such endeavours. MSA operators may flag suspicious movement along cables, but this requires operational assets to enforce.

Technological measures are also necessary to ensure the logical and data security of the system. Since the network is interconnected, it is important that minimum standards for equipment, software, and best network-security practices are adopted. Some level of harmonisation should be achieved to ensure that breaches in one part of the system do not affect the others. Moreover, periodic review mechanisms should be established to ensure that security practices are evolving along with advances in offensive cyber capabilities. It is ideal if such conditions are established by laws or regulations as a pre-requisite to connecting the cable to the local network.

Operational Measures

Infrastructure protection is an important aspect of maritime security operations and thus, security agencies will play a crucial (even if secondary) role for underwater infrastructure protection. France has adopted a Seabed Warfare Strategy wherein it seeks to "*equip the French military with the ability to reach depths of 6,000 meters, or nearly 20,000 feet…as this makes it possible to cover 97 per cent of the seabed and effectively protect our interests, including submarine cables."*[141] Putting their policy into action the French have leased deep-sea assets such as Autonomous Underwater Vehicles and Remotely Operated Vehicles from the private sector and tested them in a seabed warfare operation Op CALLIOPE, to evaluate their capabilities, and include them within their undersea warfare CONOPS.[142] In fact, the French Navy has included a 'Seabed Warfare Serial' in its bilateral exercise with the Italian Navy.[143] The Royal Navy, too, has inducted *RFA Proteus* — also a former offshore support vessel — which is now a multi-role ocean surveillance ship (MROSS) capable of launching and retrieving submersibles for the defence of defence assets, into the Royal Fleet Auxiliary as a *"seabed warfare ship"*.[144] It may be seen that States are, indeed, expending resources in developing dedicated assets for the protection of critical offshore infrastructure. However, given the vast area of coverage for cables, it remains to be seen whether platform-based surveillance of undersea infrastructure is an effective method for protection of undersea infrastructure. Moreover, given that much of the damage can happen at significant distances from the coastal State, platform-based surveillance may not achieve the desired results. However, given that there are depth challenges to underwater infrastructure damage, platform-based surveillance may well be effective to cover shallow areas close to the cable landing sites. The possibility of identifying particular cables with high carrying-capacity to be specifically safeguarded in shallow depths may also be explored as they may maintain network resilience even if other cables are damaged.

It is also important that such operational measures are not undertaken in isolation but in collaboration with other international partners. The mandate of existing security structures, such as the Combined Maritime Forces (CMF) based in Bahrain, should certainly be expanded to include critical maritime undersea infrastructure. Alternatively, new EU-India led security structures specifically tailored for the protection of critical undersea infrastructure, based out of India, France, and perhaps Egypt, could be considered.

Within this context, information-sharing is, of course, extremely important. Therefore, development of a common information-sharing platform, a common language, and protocols to coordinate operations would be more efficient and effective.

Legal Measures

The law can play an important role in the protection of undersea infrastructure (especially that pertaining to undersea cable systems) by creating institutions, empowering agencies, creating offences, and establishing procedure for a legal finish in domestic jurisdictions. The nature of underwater infrastructure is such that it transcends areas of national jurisdiction. Therefore, both national and international law play an important role in the protection of underwater infrastructure. UNCLOS is the most widely ratified international treaty that concerns itself with the protection of underwater infrastructure. Article 21 UNCLOS permits coastal States to adopt laws and regulations that may alter the innocent passage regime on grounds of protection of cables and pipelines. However, the situation in the exclusive economic zone and continental shelf with respect to protection has not been specified. While Article 79 UNCLOS deals with the subject of submarine cables and pipelines on the continental shelf it does not specify measures a State can take for their protection given the special nature of the Exclusive Economic Zone and Continental Shelf. In this regard, Article 59 UNCLOS, has a 'residual powers' clause which allows for conflicts of jurisdiction within the exclusive economic zone to be resolved "*taking into account the respective importance of the interests involved to the parties as well as international community as a whole*". Given the importance of cables to the international community and especially the coastal State, it is likely that exercise of jurisdiction for the protection of infrastructure would not be contested. With respect to the high seas, as highlighted earlier, Articles 113 to 115 give jurisdiction to the Flag State of a national of the vessel/person who damages an undersea cable. In all three instances, however, national legislation is necessary to exercise the jurisdiction conferred under international law. Such exercise of jurisdiction has not been undertaken by most nations. Therefore, the creation of national legislation is important.

National legislation can also be used to confer jurisdiction where there is a gap in international law. International law permits the extra-territorial application of national law with well-defined principles. Two of these — the protective principle and universality principle — may be useful in this context.[145] The protective principle permits a State to exercise prescriptive jurisdiction (jurisdiction to prescribe laws) when its "vital interests" are threatened. The term "vital interests" is not exhaustive, and this principle has been utilised by the US to grant itself jurisdiction to prosecute against narcotics trafficking in the high seas.[146] Hence, based on this principle, States can confer jurisdiction to themselves to take action. India has adopted this in its Telecommunications Act of 2023, where the act extends to *"any offence committed or contravention made outside India by any person, as provided in this Act"* (s2(ii) of the Act). Damaging critical telecommunication infrastructure has been declared to be a punishable offence under this Act. Hence, criminal jurisdiction has been extended to acts and persons outside India. This potentially allows India to take action if its infrastructure has been damaged.

Conferring universal jurisdiction for the offence of damaging underwater infrastructure on States through an international treaty may also be an effective way to overcome legal challenges that may arise in enforcing claims against vessels that damage cables. Currently, the nation that has suffered the loss due to the cable disruption has to request cooperation from the Flag State for collection of evidence. However, it may be easier for States to board, arrest, and prosecute if damaging underwater infrastructure has universal jurisdiction. Precedence does exist in this regard as Article 10 of Convention for the Protection of Submarine Telegraph Cables 1884 as warships of the High Contracting Parties, if they have reason to believe that a vessel other than a warship may have damaged underwater cables, may demand from the captain or master the production of the official documents proving the nationality of the said vessel. It is not inconceivable as piracy too was accorded universal jurisdiction essentially for 'sea-policing' reasons, as acts on the high seas did not otherwise have any legal sanction.

Institutions

The nature of submarine communication cables is such that it straddles the domain of maritime and cyber security. As such there are multiple institutions — often working in silos — which are responsible for such infrastructure. In addition to the private sector, the 'line ministry' involved in India with respect to communication cables is the Department of Telecommunications (DoT) within the Ministry of Communications. Under the Department of Telecommunications, the Telecommunications Consultants of India Ltd (A Public Sector Undertaking) is responsible for providing telecom expertise to the DoT and other developing countries around the world.[147] The Indian Navy and the Indian Coast Guard, both of which function under the Ministry of Defence, are responsible for maritime security and providing defence clearances to cable projects. Cyber security in India is under the mandate of the Ministry of Electronics, and Information Technology (more specifically the Indian Computer Emergency Response Team (CERT-In), as well as the National Security Council Secretariat of India. Other bodies, such as the National Technical Research Organisation, and the DoT, are also responsible for cyber security in the country. The National Security Council Secretariat is responsible for inter-agency coordination activities, which is necessary especially given the cross-domain nature of these cables.

Indo-German Cooperation

All the above areas serve as an opportunity for Indo-German and Indo-EU collaboration. With respect to repair capacities, since Indian and German industry has not entered this market, strategic partnerships could and should be leveraged to establish joint ventures to procure and retrofit cable repair vessels either in India or Germany. Examples of such successful collaboration are the major telecom companies (predominantly public) of ASEAN Member States forming the ASEAN Cableship Pte Ltd, which now services SEAICOMA.[148] In addition to repair capacity, repair capabilities too may be developed in a collaborative manner by jointly establishing training centres in India and Germany. This will assist in plugging a significant gap currently plaguing the repair industry. Consultations with the Indo-German

Chamber of Commerce in Delhi can be a great starting point to identify the market opportunities and players to progress this forward.

Internationally, the newly established International Advisory Body for Submarine Cable Resilience is a great forum to discuss opportunities of enhancing protection for underwater cables under international law. Further, mechanisms of improving information-sharing and conducting combined critical infrastructure operations may be discussed at the Indo-German or India-EU level.

Underwater Oil and Gas Pipelines

Underwater oil and gas pipelines are often clubbed with underwater communication and power cables when it comes to its regulations and protection. There are, however, two significant differences between underwater oil and gas pipelines and underwater fibreoptic cables.

The first, is the level of interconnection between the different oil and gas pipelines in service. While oil and gas pipelines may be interconnected, this is done by design for specific purposes such as route diversification, enhanced safety and continuity of pipeline operation, and customer supply.[149] Therefore, any transfer of supply from one pipeline to the other is possible only if a prior interconnection has been built into the design. This is quite unlike optic fibre cables, where traffic may be routed onto other cables even if not part of the design of the cable, simply by executing transfer protocols with the other cable provider. The implication is that the resilience of underwater oil and gas pipelines is inherently lower to shocks to the network because of the nature of transmission. This makes the protection of particular pipelines very important.

The second is the environmental consequences that may ensue if pipelines are damaged. Leaking oil and/or gas can have significant environmental consequences and damage biodiversity and fish stocks, which may have cascading effects upon livelihoods and food security, especially if the damage has occurred in the proximity of the coastal State. Hence, ensuring prompt action to identify damage and shut off supply is extremely important. Increasingly, with the advancement of "Internet of Things" (IoT) technology, sensors are placed along pipeline and connected to a server, which allows for remote monitoring of the pipeline.[150]

Underwater Oil and Gas Pipelines in India

India's underwater oil and gas pipeline network is predominantly national in nature, designed to transport oil and gas produced in offshore fields within its continental shelf. Two international oil and gas pipelines between India and West Asia had been planned but are yet to take off. These are the Middle East-India Deepwater Pipeline (MEIDP) between Iran and India (failed to take off due to sanctions); and the recently proposed UAE-Gujarat gas pipeline.[151] A summary of Indian pipelines is given in **Table 2.**

Table 2: Oil and Gas Pipelines in India

Ser	Pipeline	Distance and Depth	Owner	Carrying Capacity
1.	Panna Subsea Pipeline (Oil)	Distance: 75 km, Depth: 65 metres[152]	ONGC	9,600 barrels of oil/ day[153]
2.	Mumbai High – Uran (Oil and Gas)	Distance: 204 km, Depth: 72 metres[154]	ONGC	16.63 MMT[155] and 12.25 MMSCM/ day of gas[156]
3.	Heera – Uran (Oil and Gas)	Distance: 81 km, Depth: 54 metres[157]	ONGC	11.50 MMT/ 26" diameter for Gas[158]
4.	Bombay-Uran Trunk 30" Pipeline	Distance: 203 km	ONGC	18 MMT/ 26" diameter for Gas[159]
5.	Vashishta & S1 Subsea Pipelines (Natural Gas) (Krishna – Godavari Basin)	Distance: 35.7 km & 4.4 km	ONGC	4.55 MMSCMD of gas[160]

Source: Compiled by authors from "Indian Petroleum & Natural Gas Statistics 2021-22", Ministry of Petroleum and Natural Gas, Government of India,

Conclusion

Since Soil and gas pipelines in India are in close proximity to the Indian coast, protecting them from threats may be easier than protecting India's underwater fibre optic cables. However, since the oil and gas pipelines predominantly service the

Western and Eastern Offshore blocks, protection of these pipelines is tied to the larger protection of these offshore blocks. The predominant threat to underwater oil and gas pipelines are similar to those for underwater communication cables. This may be seen in Europe, where pipelines have been damaged along with communication cables, as in the Baltic Sea. Rather, pipelines have predominantly physical risks to the pipeline infrastructure with remote networks used mostly for monitoring of the pipeline. It may, therefore, be reasonably concluded that both, threats and protective mechanisms, in respect of undersea pipelines are similar, if not identical, to those undertaken for optic fibre cables.

14 December 2024

Acknowledgment

This paper is the result of a study conducted by the National Maritime Foundation, for the Konrad Adenauer Stiftung (KAS) utilising desk-based research as the primary form of gathering and analysing information. This includes grey literature comprising policy documents, industry reports, and research papers authored by experts in academia and think tanks. Some part of the information provided in the paper has been garnered from conversations and interviews conducted by the authors with experts and industry practitioners, including those affiliated with the International Cable Protection Committee.

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Developing A 'Disaster-Resilience Framework' For Critical Undersea Communication Cable Infrastructure

Mr Soham Agarwal and Commodore Debesh Lahiri (Retd)

The vagaries of climatic conditions and increased occurrence of natural hazards have brought into focus the importance of ensuring resilient societies. Since infrastructure has become a key component to the proper functioning of modern societies, inherent within the concept of resilient societies is resilient infrastructure. This becomes more significant in the context of 'critical' infrastructure. Underpinning global communications, undersea communication cable systems have garnered much attention globally, most recently in the context of ensuring greater 'resilience' and security.[1]

Realising the importance of telecommunications infrastructure, especially for facilitating interactions between first responders and disaster management agencies during disaster-response and recovery, the Department of Telecommunications, Government of India, in conjunction with the Coalition for Disaster Resilient Infrastructure (CDRI), launched a report assessing the disaster risk and resilience of India's telecommunications sector ("DoT-CDRI Telecom Assessment").[2] Undersea cables and fibre-optic cable landing stations have been identified in this report to be a part of the *"national backbone (core) network"* which provides *"first mile connectivity"* within the national telecommunications network.[3] Further, submarine cables and cable landing stations have been identified as the *"weakest elements"* of the telecommunications network, particularly vulnerable to coastal erosion, floods, cyclones, and earthquakes.[4] Therefore, ensuring the resilience of the first mile connectivity is critical in ensuring the resilience of the telecom network as a whole.

Consequently, this paper seeks to develop a framework within which disaster-resilience of undersea communication cable infrastructure can be systematically assessed and addressed. While the previous paper by the authors identifies the disaster, i.e., the potential natural hazards that may threaten the functioning of the cable landing infrastructure, this paper seeks to understand how *'resilience'* of cable landing infrastructure may be assessed and consequently enhanced. It begins by offering an understanding of the term resilience, especially in the context of submarine cable landing infrastructure. It then identifies frameworks developed to assess and apply these concepts and finally develops a more detailed and specific framework for cable landing infrastructure.

Understanding Resilience

Resilience, especially climate-resilience in the context of critical infrastructure has been referred to as "as "*the ability of a building, structure and its component parts to minimise loss of functionality and recovery time without being damaged to an extent that is disproportionate to the intensity of a number of current and scientifically predicted future extreme climatic conditions*".[5] This includes the ability of a system to (a) reduce the chances of a shock, (b) absorb the shock if it does occur, and (c) restore operations quickly after a shock.[6] Thus, in the case of critical infrastructure, climate-resilience is measured in terms of continued system performance in the face of disruptions caused due to climate hazards. Similar formulations of this concept have been made across available across open-domain literature and require systems to have the strength to (a) **anticipate** (and hence avoid) hazards, (b) **resist** (and hence absorb) the hazards, (c) **reconfigure** (and hence adapt) to the hazards, and (d) **restore** functioning after any disruptive event.[7] This has given rise to the *"R4 framework of resilience of critical infrastructure"*, which includes[8]:-

1. **Robustness**. *strength or ability of the infrastructure elements or systems to withstand a given level of stress without suffering from loss of function.* This is a characteristic of the engineering approach, i.e., hard protective structures that rely on the strength of individual elements of the system to withstand disruptive events.[9] Functionality is, therefore, ensured by the strength of

individual elements to remain unaffected. Robustness is often a function of the design of the infrastructure.

2. **Redundancy**. *existence of elements or systems that may be used as substitutes i.e., assuming functions in event of loss of functionality.* This includes measures such as spare capacity, multiple pathways, replaceable parts, and buffer stocks of requisite supplies.[10]

3. **Resourcefulness.** *capacity and capability of system operators to identify problems, establish priorities, and mobilise resources following an event.* This is the human resources component in the ensuring of resilience of the infrastructure system. Resourcefulness becomes particularly important in preparing for disruptive events, i.e., creating redundancies and when redundancies need to be manually activated during disruptive events.

4. **Rapidity.** *capacity to restore functionality in a timely manner in order to contain losses and avoid disruptions.* This introduces a temporal element to the matrix, requiring that functionality is not only restored but is done so in a "timely" manner. This component is particularly important with respect to 'critical' infrastructure, where longer downtimes have greater and wider consequences. It must, however, be noted that the rapidity in restoration of performance is invariably a function of the first three characteristics. A robust system is likely to endure less damage. Any damage that does occur could be absorbed by the redundancies within the system which can be activated by a trained and knowledgeable operator. Deficiencies in any of these components is likely to add to the restoration time of the system.

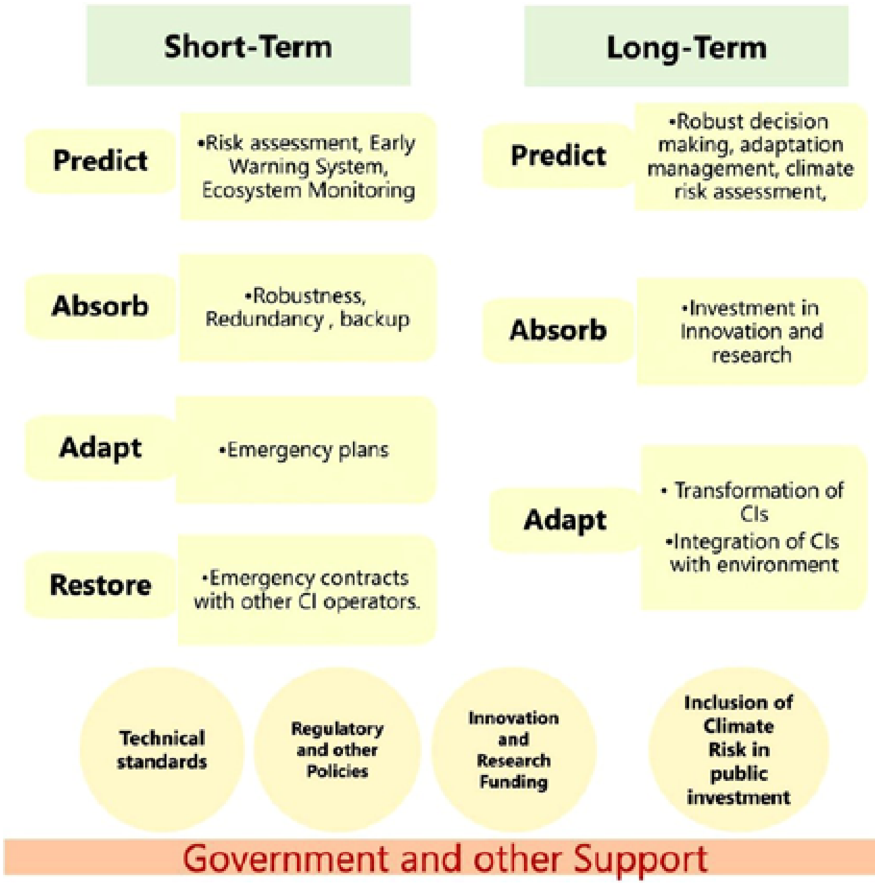
Therefore, ensuring resilience requires infrastructure system owners to ensure the product, the people, and the processes are geared towards resilience. Indeed, the concept of 'resilience' is unique mostly due to the inclusion of the latter two concepts. Not only must the physical structure of the infrastructure system be capable to withstand a hazardous event, but the system operators also must have the requisite knowledge and training to ensure that adaptive and restorative efforts are undertaken in a rapid manner. Thus, there is also a role of the requisite processes being in place (e.g., Standard Operating Procedures) that can guide operators in preparing-for and taking appropriate action.

The idea of resilience requires a different approach than does conventional risk management.[11] Conventional risk management techniques are predicated on the basis that hazards can be identified, estimated, and hence prevented. It undertakes an analysis either deterministically (consequence-analysis of specific hazards) or probabilistically (consequence-analysis of all hazards including probability of occurrence and severity) that may affect the system.[12] The concept of resilience, on the other hand, is more useful for a decision-making scenario characterised by deep uncertainty. Not only is the impact of climate change unpredictable, even more uncertain is the way this will evolve over a period of time. Different emission scenarios will significantly alter the frequency and intensity with which extreme weather events and natural hazards manifest themselves. Therefore, the temporal element, too becomes an important consideration.[13] Long-term impacts from climate change need to be factored into the resilience matrix, especially for the duration of the life cycle of the project. Therefore, it is important for cable-system owners to plan for both, short-term and long-term contingencies. Moreover, climate-resilience requires possessing the ability to withstand slow-onset events as well as unpredictable rapid-onset ones.[14] Therefore, a *"resilience framework'"* is probably the most appropriate one with which to approach the assessment of disaster-resilience undersea communication cable infrastructur.

Figure 1 breaks down the R4 framework into sub-processes that may contribute to each of the four prongs of the framework.[15] It also highlights that building critical infrastructure resilience is a multi-stakeholder process. In addition to the infrastructure operator, governmental and non-governmental organisations are critical to ensuring that the entire network remains resilient. This is because the ambit of infrastructure operators is limited to their particular asset or system, while governmental policies and standards can facilitate the implementation of standards / protocols / practices across systems.

Rather intuitively, all the four metrics of resilience requires advance planning to anticipate the threats and create the requisite physical and operational structures to enable the system to absorb and adapt the impact, as also to restore functionality in a

Figure 1. Risk Assessment and Resilience Framework for Critical Infrastructure



Source. Nikhil Kumar, et al., "A Novel Framework for Risk Assessment and Resilience of Critical Infrastructure Towards Climate Change

timely manner. This, therefore, requires an understanding of threats to the undersea cable communications system. These are encapsulated in the idea of "risk". Risk assessment, too, is identified in Figure 1 as the first step to building resilience.

It must be noted, however, that while this framework is generic and is potentially applicable across infrastructures, the DoT-CDRI Assessment Report developed a *"Disaster Risk and Resilience Assessment Framework" (DRRAF)* seemingly tailored to the telecommunication sector. While retaining both elements of risk and resilience, a structural difference in DRRAF is treating risk and resilience as two interactive yet distinct layers instead of integrating risk assessment as the first step in achieving resilience. On the other hand, a potential advantage of the DRRAF approach is the detail and structure it affords to the risk assessment process. Additionally, it may allow for the possibility to more easily adapt to changing circumstances. However, the core concept of risk and its primacy in the resilience process remains constant.

Disaster-Risk

The concept of "risk" is defined by the Intergovernmental Panel on Climate Change (IPCC) as the "***potential for adverse consequences** for human or ecological systems, recognising the diversity of values and objectives associated with such systems*".[16] Contextualised to natural hazards, "disaster-risk" is expressed as the *"likelihood of loss of life, injury or destruction and damage from a disaster in a given period of time"*.[17] Disaster-risk is a function of hazard, exposure, and vulnerability.[18]

Hazard. Likelihood and intensity of the potentially destructive natural phenomenon.[19] The nature and frequency of the hazard can give rise to an *'intensive'* risk (categorised by high-intensity, low-frequency events) and *'extensive'* risk (categorised by low-intensity, high-frequency events).[20] Identifying and tracking hazard occurrences and developments is the first step in understanding disaster-risk. Climate-change particularly affects this variable in the risk matrix by increasing the unpredictability, intensity, and frequency of weather-related phenomena.

Exposure. This denotes valuable places, assets, people, and infrastructure, which are exposed to the hazard.[21]

Vulnerability. This refers to the *'susceptibility'* of an individual, community, asset, or system to the impacts of the hazards.[22] In the context of assets and systems, the more susceptible to loss and damage a particular asset, the more vulnerable it is. Varying levels of vulnerabilities account for the differences with certain assets withstanding high intensity hazards while certain assets suffering severe losses from low-intensity events too.

Vulnerability vs Resilience. The concepts of vulnerability and resilience are interlinked, with literature painting a relationship between them that ranges from their being antonyms, to being subsets of one another, to being parts of an overlapping framework.[23] What is common in these frameworks is the treatment of each of the two concepts as distinct from the other. In essence, vulnerability refers to the existing weaknesses or limitations either in the design, location, materials, or operational processes of an infrastructural system. Inadequate design standards, poor construction quality, hazard-prone locations and lack of adequate funding mechanisms for repairs and maintenance will make assets more vulnerable. Naturally, these factors will affect the 'robustness' of the asset/infrastructure and have a bearing on its resilience, too. However, the concept of resilience is a more dynamic and proactive concept and seeks to focus upon processes that can enable resistance, continuity, and quick recovery. Resilience is, therefore, a more process-oriented approach.

Systemic Risks. Systemic risk, i.e., risk emanating from critical interdependencies not only within a system but also between systems and sectors, has evolved as a more dynamic approach to risk assessment and management.[24] Vulnerabilities within a particular system may have compounding or cascading effects across systems and even sectors. Therefore, an understanding of these interdependencies and associated cascading risks is extremely important for a holistic risk-assessment and effective resilience mechanisms.

Disaster-Resilience Framework of Submarine Cable Landing Infrastructure

Identifying key components and key assets constitute the first step in assessing vulnerability and potential resilience mechanisms. This paper is limited to offering an understanding of the vulnerability and resilience of shore-based landing infrastructure associated with submarine cable systems. Even within shore-based landing infrastructure, the focus of this paper is on the resilience of the physical infrastructure. It does not include within its scope the resilience of human, social, cultural, economic, political, and environmental components of submarine communication cable systems. There will be a profound economic, political, and social impact upon societies on the disruption of provision of internet services, which would clearly require an independent study.

Submarine Cable Landing Infrastructure may be divided into three main components:

1. **The Beach Manhole** (BMH). Since the BMH serves as the landing point of the cables, it often is the first point of vulnerability in the system especially from threats originating from the sea. Key parts of the beach manhole are:

    a. Internal Manhole

    b. Reinforced Concrete Structure providing manhole furniture. The purpose of this reinforced concrete housing is to enable access to the cable and manhole for repair and maintenance.

2. **The Cable Landing Station (CLS).** The CLS constitutes the most important component of the cable landing infrastructure. Functioning as the node of the entire system, the cable landing station is a critical component to the function of not only individual cables, but the entire cable system or even multiple cable systems. The primary key assets of a CLS are:[25]

    a. **Equipment Room.** The Equipment Room houses, *inter alia*, the Submarine Line Terminal Equipment, the Power Feed Equipment, and Optical Interconnectors, and is the most critical component of the CLS. Proper functioning of the Equipment Room is critical for the proper functioning of the CLS. Assets in the equipment room will be regarded as *"critical"* if gauged in terms of impact of damage, and cost/time taken for repairs.

    b. **Battery Room**. This room— usually situated adjacent to the equipment room—contains the batteries (both lithium-ion and lead-acid) that provide DC power to the assets in the Equipment Room.

    c. **Network Operations Centre**. Functioning as the coordination and management node of the CLS, the Network Operations Centre ensures operational control over the CLS and the cable system.

    d. **Power Room**. The Power Room in the CLS as the name suggest is the point where AC power is received within the CLS. It is the point at which the CLS is connected to the local electricity grid and power for the CLS, and its auxiliary equipment is received here.

e. **Back-Up Diesel Generators**. To mitigate against variable power supply, CLS have their own captive back-up diesel generators that can ensure continued electricity even if power is not available from the main grid.

3. **The Terrestrial Cables from the BMH to the CLS**. Frequently, CLS are not located right at the beach due to space availability and safety concerns. Therefore, buried cables connect the BMH to the CLS. Exposed cables on the surface and any competing civil works undertaken during disaster recovery operations are the primary vulnerabilities in this segment.

Table 1 creates a disaster-resilience framework by applying the "R4 framework" to the context of submarine cable landing infrastructure. Moreover, the framework also incorporates certain elements of the Design-Manage-Evolve paradigm developed within the Integrated Disaster Resilience Framework.[26] Since vulnerability assessment is critical to the *'Robustness'* function within the R4 mechanism, the table first identifies how certain factors affect the vulnerability of key components and assets. This falls within the *'Design'* paradigm of the framework as it identifies factors that need to be considered while planning and designing the cable landing infrastructure. The *'Robustness'* and *'Redundancy'* components are more effectively addressed within the design stage and have hence been included within that paradigm. *'Resourcefulness'* and *'Rapidity'* are attributes that can be better attained by the *'Operational and Governance'* mechanisms put in place both at the governmental/policy level and the operator's processes. Finally, interconnected sectors are identified to account for systemic risks.

Table 1: Resilience Framework for Cable Landing Infrastructure

Design			
Segment	**Factors affecting Vulnerability**	**Enhancing Robustness**	**Redundancy Measures**
Cable Landing Station (CLS) Building	Structural Stability of Building (1) Age of Building (2) Standards used	Structural Audit to be undertaken and weak sections to be reinforced Specific Indian Building Codes to be evolved for coastal and near-coastal critical infrastructure	Disaster Recovery CLS as part of single cable system. A disaster recovery CLS allows for the control of the entire operations of the cable system from an alternative CLS in the system.
	Distance from shore	Indirect Measure – a minimum distance, of 3 kms from the coastline needs to be specified for locating the CLS. This provides for sufficient protection from tsunami run-ups, and extreme wind speeds.	
	Relief/Mean elevation	Subject to economic and technical feasibility, the CLS should be located at a height above sea level factoring in the projected combination of storm surges, sea level rise and tsunami run-ups. Cyclone/ Tsunami barriers to be erected.	
Equipment Room	Location within CLS	Cement concrete room preferably on the first/ second floor, with all six sides isolated from direct impact of wind and rain	Developing interconnections with other landing stations for continued data transmission.
	Water Ingress Routes	Entry and exit of cables must be through cable glands and these glands must be sealed for waterproofness. Entry and Exit doors must be rubber-lined and have watertight integrity.	

		Flood sensors should be installed on the floor to detect any ingress of water.	
	Equipment Consoles	Equipment consoles should be clear of the floor and must be mounted on shock and vibration mounts. Cables inside the equipment room should be laid out — below the ceiling and above the equipment — on cable trays which must be supported on load hangars. Fire and smoke detection sensors must be installed with automatic fire fighting and suppression systems also installed.	
Power Supply to CLS	Primary Power Supply	Physical barriers or nature-based solutions like plantation of densely growing trees to reduce direct impact. Robustness of the primary power supply is integrated with the robustness of the power generation, distribution, and transmission sector marking a key example of systemic risks.	Liaise with electricity distribution company for an alternate power supply. Minimum two DG sets with both being independently capable of meeting the power requirements of the CLs and should have continuous duty rating. These DG sets should be connected to the power switchboard with provision for automatic/manual change-over. An alternate switchboard may be planned. Adequate stock of diesel to be maintained especially for CLS in island locations
	Back-Up Power Supply	Diesel Generator (DG) sets to be in a weatherproof enclosure, preferably on the first floor or minimum 10 feet above ground level.	
	Location of Switchboard, Power Receiver and Back-up Power Supply	Should be in a weatherproof enclosure, preferably on the first floor or minimum 10 feet above ground level.	

	Diesel Supply Availability	Supply should be in sealed oil drums and located in a weather-proof enclosure close to the DG sets with ease of supply from the drums to the ready-use tank of the DG sets with the help of gravity/manual pump/ aerodynamically operated/electric motor driven pump.	
Beach Manholes	Total Number	More than one BMH is usually a consequence of in-built redundancy within the system due to two pathways for the submarine cable	A cable splitter to be used to connect with minimum two BMHs.
		Cyclone/Tsunami barrier walls or retaining walls Nature-based solutions like plantation of mangroves etc.	
	Sediment Deposition	Cyclone/Tsunami barrier walls	
	Protective Measures	Sealed Manhole covers	
Terrestrial Component to CLS	Total Number	Minimum two independent cables	Each BMH should have two independent terrestrial cables each following a different path to the CLS
	Cable Burial Depth	Protective sheathing, conduits	
	Exposed Cables Damage due to physical impact (e, g., earth-moving equipment, road accidents etc.)	Protective sheathing, metal/cement concrete conduit	
	Competing Civil Works Earth-moving equipment, digging activities of other public/private agencies during disaster recovery operations	Easy availability of mapped locations of cables/pipes and other subterranean utilities to enable improved planning and coordination between public authorities/private agencies.	

		Improved planning between public authorities and private agencies with respect to digging permits	

Resourcefulness and Rapidity – Operations and Governance	
Availability of Personnel	While the CLS should be continually staffed by technically competent personnel. On receipt of Adverse Weather Event (AWE) warning, augmentation with suitably competent personnel should be done. Living accommodation for key personnel should be preferably arranged within the CLS premises or in close proximity.
Training of Personnel and Disaster Drills	Theoretical and practical training to be imparted to all personnel for operation and maintenance of CLS equipment in emergencies. Planned and surprise disaster drills should be practised in normal and off-working hours (preferably silent hours during the night)
Early Warning Systems	CLS should be directly informed about likely AWEs by the National/State Disaster Management authorities
Disaster SOPs	Standard Operating Procedures for AWE scenarios/contingencies should be written down, practised/exercised at regular intervals and the SOPs should be revised by incorporating solutions to observed shortcomings during the exercise
Inter-agency Co-ordination	Can be improved by regular periodic meetings, nominating suitably empowered single points-of-contacts and exchanging contact information including personal mobile numbers.
Policy Measures	A comprehensive single policy on BMHs, terrestrial cables and CLSs needs to be formulated including do's and don'ts with respect to location, routing, structural stability, physical safety etc.
Incident Reporting	Mandatory reporting of all AWEs by public and private operators in a standard format including the actions taken, shortfalls observed, and lessons learnt. These should be widely disseminated to all CLS operators.
Data Collection	Mandatory reporting of important data at regular periodic intervals in a prescribed format to a central data repository
Financial and Insurance Mechanisms	Allocated budget for undertaking periodic risk assessments and implementing resilience mechanisms for adaptive management. Innovative insurance mechanisms to be devised to cater for AWEs and their consequences.
Interconnected Sectors	
Power	AWEs are likely to severely degrade main power distribution and transmission systems, therefore local back-ups (DG sets, Battery storage systems etc.) should be catered for minimum continuous seven days operation
Transportation	Public transportation systems are likely to be severely affected in AWEs, hence transportation for key personnel to reach the CLS should be planned

Source. Compiled by Authors

The 'Resilience Framework' identifies individual components within each segment of the cables, identifies factors which affect their vulnerability, and how their robustness and redundancy may be enhanced using design considerations. Thereafter, measures to increase resourcefulness and rapidity through operations and management tools have also been identified.

Conclusion

The framework developed may be utilised to assess the resilience of brownfield or greenfield projects. The factors developed for each landing station is a culmination of the observations made by authors during their field visits to cable landing stations in India as part of their ongoing CDRI Fellowship Programme of 2024-25. The final application of this framework to cable landing stations in India, particularly those in Kochi, Chennai, Sri Vijaya Puram (erstwhile Port Blair), and Swaraj Dweep (erstwhile Havelock Island) of the Andaman & Nicobar Islands, will be presented in a subsequent paper.

25 July 2025

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Underwater Domain Awareness for and by Submarine Communication Cables

Mr Soham Agarwal

The announcement of the Autonomous Systems Industry Alliance (ASIA) under the US-India COMPACT (Catalysing Opportunities for Military Partnership, Accelerated Commerce & Technology) for the 21st Century signals the development of closer Indo-US defence industrial ties especially in the maritime domain.[1] Key identified technologies include the co-development of active towed array systems, unmanned surface vehicle systems, sonobuoys, and autonomous undersea vehicles, including wave gliders.[2] All this has been interpreted as a manifestation of greater Indo-US cooperation in enhancing underwater domain awareness (UDA), given the central role these technologies play in "sense-making" — particularly within the underwater environment. This is unsurprising as UDA has garnered much attention within Indian policy and defence circles. The Indian Navy, in particular, had made UDA one its key focus areas of the Indian Navy in 2020 itself.[3] In addition to these technologies, distributed acoustic sensing (DAS) through submarine communication cables has been gaining increased traction as a measure to not only protect this infrastructure system but also to contribute to enhancing UDA efforts in both civilian and military contexts. This paper seeks to contextualise this discussion of UDA to submarine communication cables.

The paper first outlines how the concept of UDA is expanding to include protection of critical underwater infrastructure. Thereafter, it discusses the concept of distributed fibre-optic sensing, more specifically DAS and its integration into underwater sensing networks. Finally, it discusses the technical, commercial, and regulatory challenges associated with this technology.

UDA for Critical Infrastructure Protection

Underwater Domain Awareness. UDA is the subsea component of maritime situational/ domain awareness (MSA/ MDA).[4] As per the International Maritime Organisation (IMO), MDA is the "*effective understanding of anything associated with the maritime domain that could impact security, safety, the economy or the marine environment*"[5], which has been contextualised in a war-fighting scenario by the Indian Navy to mean "*being cognisant of the position and intentions of all actors, whether own, hostile, or neutral, in all dimensions of a dynamic maritime environment, across the areas of interest.*"[6] This requires the ability to (i) collect, (ii) fuse, (iii) analyse, and (iv) share data of activities (which includes the position and intention of actors) and its analysis among relevant stakeholders.[7] It must be noted that given the vast expanse and depth of the world's oceans, attaining complete near real-time domain awareness is nearly impossible at will remain an aspirational goal. Therefore, what is sought to be achieved in more practical terms is underwater ***situational*** awareness which allows us to know and understand activities in an identified area of interest over a particular period of time. This requires sustained observation of the underwater environment, a comprehension of the situation obtaining within a given geography, and the projection of an anticipated future status.[8] The current lack of transparency of the underwater domain does not stem from a want of intent or effort but rather from the difficulties offered by the medium itself. The underwater domain is a highly hostile environment with significant challenges of high pressure, corrosion, varying temperature and salinity, lack of availability of power, and high signal-attenuation.[9] This limits the range and accuracy of data transmitted (usually via sound waves).[10] Technological advances seek to mitigate at least some of these challenges and in so doing, to improve range, data integrity, and a maximisation of the time that an asset can spend underwater, that too, at the lowest possible cost.

Application to Underwater Infrastructure. While this framework is predominantly applied to military contexts, there is wide civilian utilisation of this concept, too, especially for entities involved with the blue economy; environment protection and natural-disaster management; and research and development.[11] Even within the military context, UDA has focused primarily on submarine and anti-submarine warfare.[12] Technological development, operational plans, and policy focus, have all been geared towards detection and detection-avoidance in respect of submarines. However, the development-of and reliance-upon underwater infrastructure — such as submarine cables (for the power and communication) and energy pipelines — is rapidly growing in contemporary times, and with which grows the criticality and vulnerability of this infrastructure. There has been a considerable uptick in the disruptions of these cables — most notably in the Baltic Sea — which have had significant geopolitical ramifications.[13] Furthermore, the damage being caused by merchant vessels in circumstances evincing strong suspicions of intentional State-initiated damage, has added deliberate sabotage of cable infrastructure to the threat profile of these systems, which hitherto remained accidental in nature. In response, the North Atlantic Treaty Organisation (NATO) has launched Operation "VIGILANCE ACTIVITY BALTIC SENTRY", the aim of which is to "*improve situational awareness and deter hostile activities*".[14] This objective is sought to be achieved by deploying "*additional assets at sea…and below the surface of the sea*", supported by NATO's "Critical Undersea Infrastructure Network" and its "Maritime Centre for the Security of Critical Undersea Infrastructure".[15] Effort is also being devoted towards "*developing new technologies for surveillance and tracking of suspicious vessels and undersea monitoring*".[16] Information generated is sought to be actively exchanged, incidents tracked and assessed, and best practices shared. This points towards the integration of UDA for undersea infrastructure protection within broader MDA practices.

Current Approach. Although major Information Fusion Centres (IFC) — important players in global MDA efforts — such as IFC Singapore and India's IFC-Indian Ocean Region (IFC-IOR) display submarine communication cables on their maps, and document cable damage incidents, this is not a focus area for these centres.[17] Moreover, current monitoring mechanisms predominantly rely on Automatic Identification System (AIS) tracking of any suspicious behaviour of surface vessels. While the dragging of anchors by surface vessels has been the preferred *modus operandi* or at least the predominant cause of damage in recent incidents, surface-based tracking only enables *post-facto* correlation of vessel location and time of disruption. Therefore, it helps in establishing an audit trail, incorporating the identification of the vessel that has caused the damage but can seldom prevent that vessel from causing any further damage. While suspicious vessel-activity such as movement patterns across cables or the sudden slowing down of vessels may well be monitored, an obvious lacuna in the adoption of this approach is the possibility of the vessel(s) switching-off their AIS transmitters/ transponders or 'spoofing' vessel location.[18]

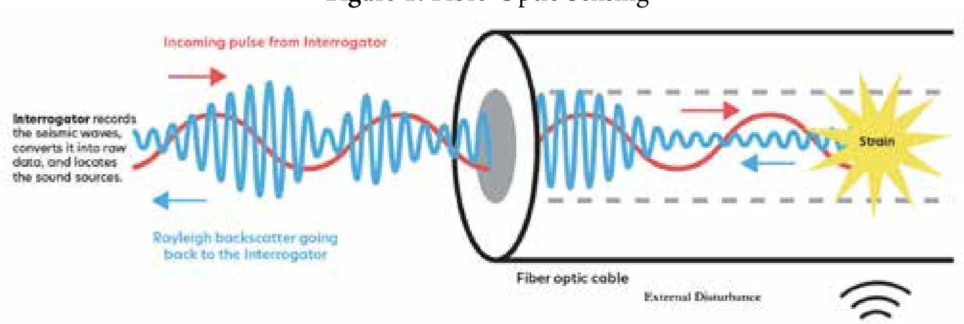
Establishing and maintaining the position and movement of surface vessels by tracking their underwater signatures offers a solution that could supplement or even replace AIS-based tracking. Towards this end, platform/asset-based surveillance is a measure that is already being adopted by States to protect such infrastructure. In this regard, uncrewed underwater vessels (UUVs) are an attractive choice. In addition to NATO's BALTIC SENTRY programme — which seeks to deploy subsea assets for monitoring and surveillance — the French Seabed Warfare Strategy, too, seeks to develop autonomous underwater vehicles (AUVs) that can dive to significant depths to monitor sensitive installations such as submarine cables.[19] The French strategy identifies technological developments such as magnetic detection (using optically-pumped magnetometers and colour centre detectors) and offer promising surveillance and tracking options.[20] In fact, cable route surveys undertaken during the project planning stage already utilise towed magnetometers to identify the existence of other cables/pipelines along the planned route.

However, a major drawback of platform-based surveillance relates to the limited area in which surveillance can be undertaken at a given time. Thus, while such endeavours may help for near-shore activity (this is, of course, significant, given that multiple cables tend to congregate at select landing points ashore), cable cuts may occur at significant distances along any stretch of the cable's lengthy traverse. Moreover, even though such surveillance may be useful against underwater vehicles or intelligence-based surveillance by "grey" hulls or "white" ones, damage caused by merchant vessels either intentionally or accidentally, cannot be addressed by surveillance platforms. Since the ordinary length of an anchor aboard a merchant ship is 275 m to 300 m, it is unlikely that cable damage from merchant vessels is going to occur in depths in excess of 300 m, not least because it would take away the deniability feature from accusations of intentional sabotage. The presence of these platforms may act as deterrence especially if coordinated in a manner that manages to cover significant parts of the areas of interest up to a depth of 300 m. While more feasible in smaller bodies of water such as the Baltic Sea, Red Sea, or Mediterranean Sea, the applicability of such approaches in the Arabian Sea or Bay of Bengal are much more complicated, not least due to the sheer size of such seas and bays. These efforts, therefore, need to be complemented with technologies that allow for underwater sensing to enable targeted pre-emptive action for protection.

Fibre Optic Sensing. Fibre-optic sensing, i.e., the utilisation of optical fibres as a sensor to measure physical or chemical quantities is manifesting itself in an increasing variety of applications,[21] many of which allows the optical fibre itself to measure vibrations, temperature, and strain.[22] "Fibre-optic sensing" works on the principle of "Coherent Optical Time Domain Reflectometry" (COTDR) by detecting modulations in the backscatter of a light pulse travelling through the fibre.[23] Light pulses are launched into 'dark fibres', i.e., those that are not being utilised for communications, from an interrogator (data acquisition and measurement device)[24] located at the Cable Landing Station ashore. This light pulse is scattered back to the origin due to the heterogeneities in the fibre. The backscattered light is varied by external influences. The phase-changes in the backscattered light are collected and analysed by the interrogator to detect and measure external influences at different points along the fibre.[25] **Figure 1** illustrates this mechanism.[26]

Sensors may be of two types, namely, "point sensors" or "distributed sensors". A distributed sensor is one wherein sensing can take place along the entire fibre, as

Figure 1. Fibre-Optic Sensing



Source. "Distributed Acoustic Sensing", EarthScope opposed to a point sensor, which can detect only at a single point.[27] Therefore, you can have a distributed temperature sensor (DTS) to detect temperature, distributed acoustic sensor (DAS) for vibrations, and a distributed strain sensor (DSS) for mechanical tension on the fibre. The current state of technology allows for a single fibre to measure for a single physical quantity at a time. Therefore, different fibres would need to be utilised for temperature, strain, and vibrations.

The utilisation of this technology for the protection of subsea communication cables is gaining traction. Cable manufacturing companies are actively promoting the utilisation of DAS technology on cables as part of an early-warning system to allow for preventive action against cable damage. Private enterprises seek to prevent damage against trawl activities, anchoring, and dredging activities.[28] As soon as a trawl or anchor begins to drag along the sea floor, acoustic waves generated from these impacts will strain the optic fibre. The interrogator will be able to localise the strain and indicate to the network operator the location of the disturbance. The network operator will then be able to correlate this information with AIS data to identify the vessel and arrive in a position where he/she can take preventive action.[29] Potential mechanisms could include sharing this information with relevant information fusion centres, port authorities, fishery organisations, and even defence forces, to intimate the vessel operator or mobilise assets in the vicinity in case of a severe threat. Importantly, the information about this threat would be received even if the vessel of concern is not transmitting on AIS.

UDA by Submarine Communication Cables

Environmental Monitoring. The applications of underwater fibre-optic sensing can extend even beyond the safety and security of the fibre-optic cable itself. Concerted efforts are being made to develop and integrate SMART cables, i.e., telecom cables installed or upgraded for "Scientific Monitoring and Reliable Telecommunications".[30] These include hazard-monitoring sensors that can read and record data relating to pressure, temperature, seismic activity, etc. While several models of sensor-instalment are available, they are usually installed in the repeaters of the optic fibre cable.[31] Therefore, in addition to providing telecom services, these cables can read physical values underwater and transmit them back to the landing station. The primary attractiveness of installing such sensors on these systems is that much of the cable infrastructure has already been laid and the cables merely need to be upgraded for sensing. Further, the operational cost of the cable system is covered by the revenue-generating telecom business. Given the cost and time efficiencies associated with utilising cables for creating a real-time ocean observation network, the International Telecommunication Union (ITU), the UNESCO-Intergovernmental Oceanographic Commission, and the World Meteorological Organisation, have jointly established a task force to develop standards and promote the adoption of these cables.[32] As such, even dedicated sensing cables are now actively being adopted by ocean scientific research bodies and authorities across the world, replacing buoys, gliders, and autonomous vehicles, for wider basin coverage at a fraction of the cost.[33]

This project focuses on a series of point sensors along the cable rather than distributed fibre-sensing described above. This may be because installing sensors on repeaters is more cost effective than utilising a dedicated dark fibre for sensing. Additionally, crosstalk between multi-parameter sensing and telecom data precludes a single fibre being used for both activities.[34] Fibre-optic sensing for ambient underwater environment sensing has obvious applications in navigation, earthquake/*tsunami* early-warning, and marine biological studies.[35] Of particular interest is the application of DAS for ship detection and communication between assets at sea and facilities ashore. Given the inherently dual-use application of underwater technologies, a military utilisation of such capability is very plausible. In fact, a deep-sea observation network has already been envisaged through the integration and networking of DAS, space, and surface assets.[36]

Vessel Identification. In 2021, a study utilised a 41.5 km long cable off France to detect a tanker first 5.8 km offshore in 85 m depth, and then 20 km offshore at 2,000 m depth.[37] While the signal-to-noise ratio was better at the shallower depth, low frequency signals below 50 Hz were detected even at 2,000 m. Research has further advanced and is currently focused upon target localisation (including range and bearing) of the vessel and classification (developing a means to identify the type of the vessel).[38] Efforts have also been made to improve localisation efforts, identify vessel velocity, improve the spatial resolution of detection, and compare the impact of varying 'field conditions' on collected data.[39] Additionally, investment in signal-processing technology, aided by the development of artificial intelligence/machine learning (AI/ML) and its training in the analysis of specific sound signatures can assist in identifying vessels of interest, in addition to improving the signal-to-noise ratio.

Not only is fibre-optic sensing technology improving, but advancements are also being made in fibre technology itself. Most notable is the emergence of multicore fibres — a first trial in respect of which was completed by NEC (Japan) in 2021 — which not only enables multiple signals to be transmitted through different cores of the same fibre but also enables multipurpose systems to run over a single fibre. Thus, communication, acoustic sensing, temperature sensing, and power over optic fibre, may well be simultaneously realised.[40] While not within the scope of this paper, multicore fibres are likely to revolutionise deep-sea observation systems and seabed warfare capabilities. It also makes it easier to realise a "pit stop" for AUVs to charge and upload their data simultaneously.

Communications. A major challenge in achieving UDA is the attenuation of signals underwater, severely limiting the range of communications. Communication with entities located ashore involves the surfacing of the vehicles at sea in order to create a satellite link or the use of surface buoys. However, high data-collection costs and sparse distribution of such nodes have prompted research in alternative shore-to-asset communication methods. DAS technology has been promising in facilitating near real-time acoustic communication. A recent experimental study managed to transmit acoustic communication packets at a range of 200-500 metres from the source, at a frequency up to 2 kHz.[41] This study also identified that time-gating at the interrogator could allow multiple platforms to transmit simultaneously enabling the creation of a more effective underwater network — without packet collision.[42] Researchers are also testing two-way communications using DAS technology. Bidirectional communication between a shore-station and an AUV has been demonstrated, with DAS enabling uplink communication between the AUV and the shore station, and with downlink communication between the shore station and the AUV occurring using a quantum magnetometer.[43] This creates a communication loop and extends the range and flexibility of AUVs.

Therefore, not only is fibre-optic sensing technology of value to the cable itself but also has a host of applications in achieving underwater domain (spatial) awareness.

Challenges

While the application of this technology is undeniably promising, there is no gainsaying that major challenges remain.

Nascent Technology. The technology currently is at a very nascent stage. While it demonstrates a great deal of promise, currently even state-of-the-art technology only enables cable monitoring up to a maximum of 100-150 km from the interrogator.[44] This coincides with the location of the first repeater. Research is also underway to develop optical repeaters that can manage DAS signals in addition to data signals. While "OptoDAS", which is a tool developed by "Alcatel Submarine Network", claims to detect gear (such as a ship's anchor) hitting the seabed from 2 km away, the location of the source would require triangulation, for which the cables in the vicinity, too, need to be DAS-enabled. The range *along* the cable across which the disturbance is felt is what the DAS interrogator would be able to depict. The advancements discussed above, where researchers have identified the range and bearing of the vessels, is through targeted beamforming to demonstrate this possibility.

UDA applications of DAS are at an even more nascent stage with issues of range and frequency persisting. Field trials in the open domain point to experiments done with objects in proximity to the interrogator and cable at a low frequency. Moreover, DAS is a passive sensor, which may limit its range and utilisation. In the Indian Ocean, an additional challenge is the high levels of medium- and low-frequency noise generated by merchant shipping activity.[45] Hence, there is still a long way to go for the technology to be mature enough to be adopted and deployed for UDA. However, this also presents an opportunity. There is a disconcerting lack of literature from Indian academia in this domain. A majority of the research available in the open domain is being conducted by Chinese or European universities, often involving significant grants from governments. Consequently, there needs to be investment in developing this technology further, especially given the potential and demonstrable benefits.

Privately-owned infrastructure. A major assumption while calculating the cost and time efficiencies of enabling DAS on submarine cables is the fact that the operators of these cables will permit such installation. Most global submarine communication-infrastructure is privately owned and, therefore, operator consent will be a critical aspect for the utilisation of this technology. Given the added challenges in other jurisdictions that these cable projects may face, many private operators may refuse consent. This would then require the placement of fresh cable projects for UDA purposes, which will negate the cost and efficiency that would accrue from using DAS. A State could, in theory, mandate that a fibre be given to the defence agencies, particularly the Navy, as a part of the ILD license issued to the telecom provider. Further, Section 21 of the Government of India's "Telecommunications Act, 2023", once notified, would give the Central government the power to notify the use of telecommunication equipment as necessary in the circumstances.[46] This, however, may prove counterproductive as it will probably hamper, if not prevent, the development of new cable projects and the establishment of data centres in India, as the two sectors are inherently linked.[47] Moreover, assuming that a private operator does consent to the installation of an interrogator, legal issues of data handling, data ownership, and data access will also arise. The ability to sell this data, manner of storage, and data sharing mechanisms between the enterprise and the State will have to identified and secured.

Militarisation of Private Infrastructure. The militarisation of private infrastructure can give rise to issues of souring business-State (B-to-G) relationships, increasing the difficulty in securing private sector collaboration — especially during conflict — and the utilisation of private infrastructure for deriving profit from conflict or to gain political favour in certain jurisdictions.[48] This is especially true for transnational infrastructure such as submarine cables.

Additionally, there is also the argument that enabling sensing on cables will make them more likely to be disrupted.[49] However, underwater infrastructure, especially submarine cables have been a target in times of conflict ever since the Spanish-American War of 1898 and leading up to the First and Second World Wars.[50] Therefore, utilising cables as sensors does not necessarily increase these chances. It is also feasible to argue that enabling DAS on cables may prevent their disruption even if intentionally targeted. This may even prevent such attacks as a proven intentional attack may exceed the threshold of conflict.

Regulatory Challenges. In addition to the rules related to data collection, processing, storage and distribution, DAS-enabled cables will require explicit coastal State approval before they can be installed. This will not only involve telecom regulatory authorities but even the defence forces of the State. Given consortium ownership structures, States may be even more apprehensive of permitting DAS enabled cables involving companies owned by potential adversary States. Further, even if one coastal State has given permission for DAS enabled cables, permits may well be required from others States through whose EEZ the cable may pass. They would be well within their right to regulate this activity as it may be classified as "marine scientific research" within the regulatory ambit United Nations Convention on the Law of the Sea 1982 (UNCLOS 1982). There are additional challenges from the perspective of the coastal State through whose EEZ such cable may pass but which may be unaware that such a cable is DAS-enabled. Each of these several facets requires a series of detailed research-studies by institutions — especially maritime-focused ones such as the NMF.

In sum, India must begin the process of creating/ developing and then adopting a regulatory framework for DAS-enabled cables, especially since the technology has become available and is actively being pursued by private entities. Even if it chooses to prohibit the connection of DAS-enabled cables to the Indian network, a formal policy needs to be enacted.

Recommendations and Conclusion

In essence, the application of DAS technology for the protection of submarine cables is being actively pursued by cable manufacturers and cable operators. This technology also has applications for enhancing underwater spatial awareness across civilian and military contexts. With respect to enhancing UDA for submarine cable protection, India needs to facilitate interactions between cable operators and the IFC-IOR, the Information Management and Analysis Centre (IMAC), and the Navy's Maritime Operations Centres (MOCs) to allow the near real-time sharing of fault and AIS data. IFC-IOR should also explore possible data-sharing agreements with potential DAS enabled cables in its area of interest and prepare protocols for preventing any activity which may damage cables in its area of interest.

Indian academia and maritime-focused policy-relevant think-tanks such as the NMF certainly need to lay greater focus upon developing underwater fibre optic sensing technology, which should be aided by the Indian State. Further, regulatory bodies in India need to develop a policy and eventually a regulatory framework for DAS enabled cables. Technology is leapfrogging in this space, and it is imperative that India keeps pace.

03 March 2025

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Disaster-Resilience of Undersea Communication Cable Systems in India

Mr Soham Agarwal and Commodore Debesh Lahiri (Retd)

The criticality of internet-based data is increasing in terms of penetration as well as volume and is no longer an urban phenomenon. As sectors such as agriculture (both land-based and fisheries), transport (road, air, and sea), healthcare, and rural development become ever more reliant upon timely information flowing over the internet, the demand for enhanced capacity and speed will drive an exponential increase in the number of undersea communication cables. For a country such as India, which is on the cusp of moving from a three trillion-dollar economy to a seven-trillion dollars one in less than a decade from now, the growth of submarine cables will be dramatic. Paradoxically, the degree of vulnerability of the country vis-à-vis this critical infrastructure will increase equally rapidly. While discussions on the threats-to and vulnerabilities-of the submarine communication infrastructure have gained traction, much of the it has centred around the anthropogenic factors of disruption.

Although anthropogenic factors such as anchoring and bottom trawling fishing, etc., account for a majority of cable disruptions, natural hazards — particularly climate change induced ones — are a growing concern. Hazard-related disruptions constitute nearly 20 per cent of reported disruptions to undersea cable infrastructure, and this percentage value is very likely to grow given the increasing frequency and intensity of natural hazards.[1] Further, given the concentration of cable systems at particular landing points, hazard-related disruptions can wipe out a larger number of cables in one go, thereby inflicting disproportionately high damage to the entire communication system.[2] In 2009 for instance, Typhoon Morakot broke nine cables off Taiwan by generating sediment-laden flows that damaged cables at depths of up to 4,000 metres and over 300 kilometres from the site of formation of the sediment flow.[3] Likewise, in 2011, a massive tsunami, which rocked north-eastern Japan, resulted in multiple submarine cable cuts and the isolation of the Kita Ibaraki and Ajigaura cable landing stations.[4] Such scenarios are hardly scarce and history is replete with examples of cable damage from natural hazards.[5] More recently, four major undersea cables serving Africa were damaged near the Ivory Coast and this was suspected to be due to seismic activity on the seabed. They took more than two months to be restored.[6] Island-States are particularly vulnerable to natural hazards as many of them are located on tectonically active margins that are subject to cyclones, earthquakes/tsunamis, and fluvial sediment discharge which often exacerbate matters.[7] This is compounded by the low redundancies within their communication networks, thereby increasing the vulnerability of these networks. For instance, the underwater volcanic eruption in Tonga in 2022[8] and the passing off Typhoon Chan-Hom through the Mariana Islands in 2015 completely severed — in both cases — a sole submarine cable connection, severely limiting connectivity.[9] Therefore, identifying the role of natural hazards in the matrix of submarine communication cable vulnerabilities, is not only important, but assumes crucial significance in the face of increasing frequency, intensity and duration of adverse weather events. This paper — written by the authors, who have been awarded the Coalition for Disaster Resilient Infrastructure (CDRI) Fellowship for 2024-25 for their project entitled "Enhancement of Disaster-resilience of Critical Infrastructure relevant to India's Undersea Communications Cables"— accordingly seeks to identify potential natural-hazard risks to submarine cable infrastructure in India, highlighting the imperative need for policy intervention *vis-à -vis* the planned/existing onshore cable landing infrastructure, and makes a compelling case for a contextualised disaster-risk assessment to be undertaken with respect to the cable landing stations in India.

Submarine Cable Infrastructure and their Hazard-Vulnerabilities

The submarine communication cable system comprises not only the optic-fibre cable (the "wet plant") but also a "dry plant" that includes the cable-landing station and the beach manhole.[10] Beach manholes are structures set into a beach, whereby the subsea cable is connected to a terrestrial fibre-optic cable to be carried into the cable landing station.[11] Hazard-related disruptions may occur either where the cable is submerged underwater or at the associated onshore infrastructure. Hence, the vulnerabilities may either exist onshore or offshore. In fact, both the continental shelf and the coast, which is where the cable landing stations are situated and where a majority of the cables congregate, have a higher incidence of natural hazards.[12] This notwithstanding, it is in waters deeper than 1,500 metres that nearly 30 per cent of faults are caused as a result of natural hazards.[13] This stems from the twin facts that in shallow depths, cables are armoured and are often buried beneath the seabed, thereby affording them some degree of protection from damage. On the contrary, the weight of the armour-sheath and the technical challenges of successfully burying cables in cases or conduits where the seabed is at a considerable depth from the sea surface, precludes such protective measures being adopted in deep waters.

Natural Hazards

Insofar as natural hazards are concerned, they may further be characterised as either instantaneous events — which are essentially one-off disruptions — or long-term hazards that manifest over large periods of time, such as sea-level rise.

Instantaneous Events. Instantaneous events occur as one-off events and have tremendous destructive force. Such events may occur either underwater or onshore, often with spillover effects from one onto the other. Underwater instantaneous events primarily damage the 'wet plant' of the cable system, i.e., the submarine cable itself. Damage could entail the exposure of previously buried cables, excessively burying cables beneath the mobilised sediment, or the cables suffering from abrasion or chafing.[14] On the other hand, onshore instantaneous events pose a greater hazard to onshore infrastructure such as the beach manholes and the cable landing stations. The following hazards are considered to be primary hazards:

1. **Submarine Landslides.** These are essentially downslope movements of sediment or rock when stresses acting downslope exceed the sediment strength on the slope.[15] They mobilise hundreds to thousands of cubic kilometres of

sediment volume and rock along slopes, and frequently occur in active river deltas, submarine canyons, volcanic islands, and on the open continental shelf.[16] Submarine landslides may be triggered by events such as earthquakes, volcanic eruptions, cyclones and major storms, rapid sediment-deposition by river floods, gas pressures, human activity, etc. They may even occur without instantaneous triggers due to factors such as weakening sediment strength and increasing stresses.[17] It is often the submarine landslide that is the primary cause of damage to underwater cables, and it is other factors such as earthquakes, cyclical wave action, etc., that are usually responsible for the occurrence of submarine landslides. The impact of submarine landslides on seabed infrastructure is so large and relatable that researchers have developed a methodology to study submarine landslides using historically available cable-break data.[18]

2. **Turbidity Currents.** Another form of sediment flow are turbidity currents. These involve the downslope transport of a dilute suspension of sediment grains, i.e., a mix of sediment and water, with speeds ranging from 28 metres per second at mid-slope to 6 metres per second in abyssal plains.[19] Turbidity currents may begin as submarine landslides and then transform into more fluid sediment flows after mixing with seawater capable of travelling much longer distances.[20] As a result, they can have a significantly larger impact on seabed infrastructure both at distance and at depth. In 2006, the Pingtung earthquake, whose epicentre lay offshore from southwest Taiwan, generated powerful turbidity currents that damaged fourteen cables at depths ranging from 612 metres to 3250 metres over a period of fourteen hours.[21] The formation of turbidity currents depends on factors similar to the formation of submarine landslides, with earthquakes, tropical cyclones, storm waves, cyclical wave action, and river sedimentation, being primary causes.[22] The velocity of the turbidity current depends upon the bathymetric slope across which it is moving and can have a significant destructive influence on cable systems.

3. **Earthquakes.** Earthquakes, as a natural hazard, threaten not only the submarine cable underwater infrastructure but also associated onshore

infrastructure. Much depends upon the position of the epicentre — focal point — of the earthquake. Earthquakes can give rise to submarine landslides and turbidity currents which, as highlighted above, have a significant impact on underwater cables, especially those unarmoured ones that are located at greater depths.[23] Earthquakes can also damage the beach manhole or cable landing station either from direct impact or from the creation of powerful tsunamis. History is replete with examples of extensive damage caused by earthquakes, from the 1929 Grand Banks earthquake, and the 2003 Boumerdès earthquake off Algeria, to the 2006 earthquake off Taiwan, which disrupted multiple cables at once.[24]

4. **Cyclones and Storm Surges.** Cyclones (also known as hurricanes and typhoons) are associated with extreme rainfall and high wind speeds. They have particularly adverse impacts upon coastal infrastructure associated with submarine communication cables. This manifests in the form of storm surges and high wind speeds. A storm surge is the abnormal rise of seawater level during a storm caused by powerful winds pushing water onshore.[25] The inundation caused by the storm surge can flood — and potentially damage — local infrastructure.[26] This was observed in Puerto Rico after Hurricane Maria (a Category 5 hurricane) flooded a cable landing station due to a storm surge of 1.8 to 2.7 metres. The cable network had to be powered down to prevent equipment damage.[27] This led to loss of connectivity not only in Puerto Rico but also in other South American States that relied on this cable landing station as a gateway for transit.[28] Since the beach manhole(s) and cable landing station(s) form a point of congregation for multiple cables, any significant damage to these will have a serious impact on the national and regional communication network than might be the case where damage occurs to individual cables.[29] The study, in fact, noted that "*storm surges are among the most costly and deadly natural hazards, and can episodically raise coastal water levels by up to 4 metres due to extra-tropical weather systems, and over 9 metres when caused by tropical systems*".[30] A substantial portion of critical infrastructure is susceptible to coastal flooding and climatic-prediction models indicate that this susceptibility is likely to increase.[31] The

study also noted that the "*effect of cyclones on shipping can also pose a risk to subsea cables. Roughly 13 percent to 40 per cent of ships that that attempt to "ride out" typhoons off major ports have been estimated to drag their anchors. As such they plough the seabed, endangering cables in the vessels' path. For example, in 1979, anchor dragging during Typhoon Hope damaged five subsea cables in Hong Kong Harbour*". In fact, storm surges and cyclones have impacts beyond just flooding, especially in the form of enhanced coastal erosion.

5. **Coastal Erosion.** Coastal erosion has an impact on shore-based infrastructure especially the beach manhole segment. This can erode the beach manhole cover and expose cables to wave action, the terrestrial portions of which may not be as resistant to seawater as their submerged counterparts.[32] Further, cable landing stations right on the shore could also face significant structural challenges in the face of a receding shoreline. In Argentina, due to the amount of erosion, a beach manhole had to be relocated farther inland and re-buried deeper in the beach to reduce chances of exposure.[33] Coastal erosion can occur up to several metres per year, with south Asia figuring as one of its hotspots.[34] Given the proximity of cable landing stations to the mean sea-level, roughly 37.6 per cent of cable landing stations were found to lie within ten metres of the present mean sea-level, and 4.9 per cent lie within two metres, with the majority of cable stations (80.6 per cent lying on slopes less than four degrees[35]— this threat acquires significant proportions.

Climate Change and Sea Level Rise. Climate change and sea level rise are not classified as instantaneous events as their effects are felt progressively over a period of time. The impact of climate change also manifests itself in the increasing intensity and frequency of current hazards.[36] Therefore, disaster-resilience needs to not only factor the occurrence of the hazards but also the manner in which it be impacted by climate change. Due to greater variations in sea level at times of tropical cyclones and storm surges, climate change and sea level rise will particularly affect onshore cable landing infrastructure. Similarly greater rates of coastal erosion occasioned by higher sea levels threaten the beach manhole cover. Climate change additionally affects and modifies human behaviour, since rising oceanic temperatures are affecting entire food chains from phytoplankton upwards, forcing their horizontal and vertical migration, thereby compelling humans to fish in deeper and more distant waters, where seabed cables lie unarmoured and are therefore more vulnerable.[37] Hence, each scenario of climate change variability will be associated with a corresponding risk, and an analysis factoring projected scenarios of climate change needs to be conducted.

A recent paper, entitled, *"Climate Change Hotspots and Implications for the Global Subsea Telecommunications Network"* has specifically identified and discussed natural hazards to the global telecommunications network with climate change having been factored. One of the key insights of the paper is that there is "*wide geographical variability in climate-driven changes…and it is essential to determine site-specific environmental conditions…*" to more accurately gauge and predict climate change-accentuated natural disaster risk.[38] Therefore, not only is it necessary to undertake a risk assessment of natural hazards adjusted for climate-change realities but to be truly effective this assessment must also factor site-specific conditions. This holds especially true for onshore cable landing infrastructure. It may be appreciated that the congregation of multiple cables presents a unique vulnerability that is compounded by the fact that the cable landing infrastructure has not received requisite focus vis-à-vis natural-disaster risks. This onshore segment, in fact, is particularly well suited for policy interventions involving national security and jurisdictional issues. Implementation of legal and policy tools for cable landing stations and beach manholes will accordingly be more effective and far reaching. National instruments allow for policy options such as mandating localised climate assessment as part of the planning and designing process. Therefore, such analyses must be conducted and policy response options developed.

Relevance to India

India currently has 17 international cable landing stations spread across five cities of the country, viz., Mumbai, Chennai, Kochi, Tuticorin, and Thiruvananthapuram.[39] Additionally, domestic submarine communication cables land in seven islands of Andaman and Nicobar chain, and eleven islands of the Lakshadweep chain.[40] It is pertinent to note that of the 17 cable landing stations in India, as many as eight are based in Mumbai and four are based in Chennai.[41] Consequently, any damage to cable landing infrastructure in these two cities may potentially affect the functioning of multiple cables simultaneously.

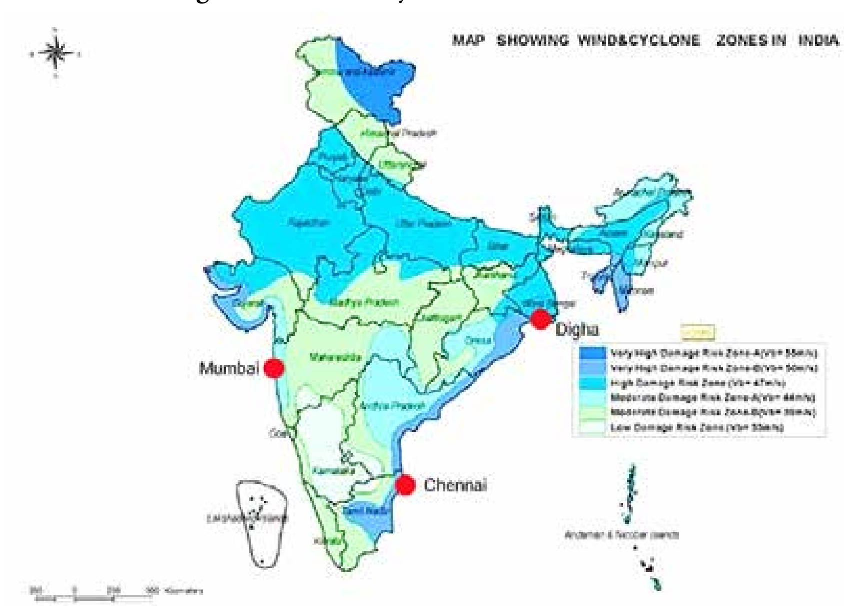
Further, recognising the importance of cable landing stations to India's push for a digitalised economy, the state of West Bengal has announced an "Internet Cable Landing Station Policy 2023" to bring ten cable landing stations to West Bengal by 2025 with Digha, in the district of Medinipur, being identified as a probable landing site.[42]

Resilience (of infrastructure) has been defined as the *"amount of change a system can undergo without changing state"* and vulnerability as "*the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes*".[43] Since, the amount of change a system can go through without it changing its state will determine its ability to cope with climate extremes, the concepts of resilience and vulnerability are clearly linked, and any assessment of the 'resilience' of infrastructure must begin by identifying the degree and extent of its 'vulnerability'.[44] Vulnerability, in turn, is a function of exposure, sensitivity, and adaptive capacity.[45] 'Exposure' as per the Fourth Intergovernmental Panel on Climate Change (IPCC) Assessment Report is "*the nature and degree to which a system is exposed to significant climatic variations"*[46] and hence, understanding the exposure of these cities to natural hazards becomes important as this will affect the exposure of the infrastructure located within these cities.[47] Since sensitivity, and adaptive capacity are functions of the infrastructural element, this analysis has been reserved for a future paper. As the exact locations of cable landing stations are usually not public information, hazard-wise susceptibility data for Mumbai, Chennai, Digha, West Bengal; and Andaman & Nicobar Islands(A&N) will be considered.

Tropical Cyclones. "A Vulnerability Atlas of India" (**Figure 1 refers**) has been prepared by the "Building Material Technology Promotion Council" (BMTPC) of the Ministry of Urban Development, which maps the vulnerability of districts of India vis-à-vis a variety of climate hazards.[48] Tropical cyclones are considered a multi-hazard weather system as they are often accompanied with strong wind speeds, high precipitation, coastal flooding, and storm surges.[49] An Indian Meteorological

Department (IMD) report has built on the BMTPC classification by undertaking a district-level analysis of these factors, assigned each of them a weighted value, and calculated a "proneness rating" ranging from very high (P1), high (P2), moderate (P3) and low (P4).[50] This data has been compiled for a period from 1891 to 2008 (**Table 1 refers**).

Figure 1: Wind & Cyclone Risk Zones in India



Source: National Disaster Management Authority

Table 1: Cyclone Proneness

District	Flood Zone	No. of Severe Cyclones	Total No. of Cyclones	Wind Speed (mps)*	PMSS (m)	PMP (cm)	Vulnerability	Proneness
Mumbai	Yes	01	1	44	5	95	High	P3
Chennai	Yes	0	0	50	3.5	52	Very High	P2
Digha	Yes	8	16	47-50	13	56	Very High	P1
A&N	Yes	2	2	44	N/A	N/A	High	P3
Legend: PMSS – Possible Maximum Storm Surge; PMP – Possible Maximum Precipitation. * 1 metre per second (mps) = 3.6 kilometres per hour = 1.944 knots								

Source: GS Mandal and M Mohapatra, "Cyclone Hazard Prone Districts of India: A Report"

Coastal Erosion. The "National Assessment of Shoreline Changes along the Indian Coast" — a study conducted by the "National Centre for Coastal Research" (NCCR) — indicates that 33.6 per cent of the Indian coast is undergoing erosion.[51] Of this, the shorelines in West Bengal and Tamil Nadu are eroding at a rate of 60.5 per cent and 42.2 per cent, respectively, over the period 1990-2018.[52] 25.5 per cent of the coastline of the state of Maharashtra, too, is suffering erosion.[53] The manner in which shorelines undergo change differs quite widely — even within the same state. The change need not necessarily be wrought by erosion. Accretion, or the seaward development of the shoreline is also a process that does occur. While a greater percentage of the coast of Tamil Nadu is undergoing erosion, the city of Chennai itself is undergoing high levels of accretion and is, in fact, classified as an accretion hot spot.[54] Even within Chennai, the coast near the Adyar River is stable or undergoing low levels of erosion, but the coast between the Adyar and the Coovum River — which corresponds to the area of Marina Beach — varies from "low erosion" to "high accretion".[55] Especially high levels of coastal accretion may also pose challenges to the beach manholes as it may render them more difficult to locate and access by maintenance teams. Further, additional build-up tends to create extra pressure on the beach manholes, weakening their structural integrity and thus necessitating more frequent repair and maintenance. This problem may be exacerbated if frequent repairs need to be carried out in Coastal Regulation Zones which would entail seeking of necessary permissions with the associated procedural requirements. In the above context, it is pertinent to note, that, not very far north of Marina Beach, the coast near Kattupalli is undergoing high levels of erosion.[56] Similarly, while the general coast along West Bengal suffers an alarming rate of erosion, the shoreline around Digha — where the new cable landing stations are proposed — experiences are both low levels of erosion as well as some accretion.[57] Therefore, when it comes to coastal erosion, the precise location of the beach manhole and cable landing station assumes great importance.

Sea Level Rise. Another aspect that will affect the availability of coastal space is the oft-discussed challenge of sea level rise, with India being no exception to the adverse impacts of this phenomenon. Sea-level rise figures, while not appearing to be overly alarming by themselves in the immediate term, are compounded by the annual flooding levels that the region routinely receives. Climate Central — a non-profit organisation that conducts research and reports on climate change and its effects on the lives of people — has developed a climate risk screening tool that identifies the extent of land projected to be below annual flood level by 2050. The following images depict the forecasted water levels at the sites of cable landing infrastructure because of the projected sea level rise and the annual floods based on a medium emission cut scenario factoring in a two degrees Centigrade increase in temperature. These images indicate that Mumbai and Digha are particularly vulnerable to a significant increase in water levels by 2050 (sea level rise combined with annual flood levels). In Chennai, and the Andaman and Nicobar Islands, specific cable landing locations will need to be identified in order to assess the risk as the effects at these places are not uniform. Is emphasised that particular focus needs to be given to this factor as cable projects are generally designed with a 25-year life cycle and, therefore, these sorts of adverse effects are expected to be experienced within the life span of one cable landing project, with 2024 as a base year (**Figures 2 to 5 refers**).

Multi-hazard Vulnerability. Obviously, it is important to not look at these hazards in isolation, as the effects over a geographic space are likely to be compounded over time. Hence an assessment of multi-hazard vulnerability is very important. The "Indian National Centre for Ocean Information Services" (INCOIS) has prepared a "Coastal Multi-Hazard Vulnerability Atlas" (**Figures 6 and 7 refers**) factoring sea-level change rate, shoreline change rate, high-resolution topography, and extreme water level.[58]

Dynamism of Climate Change

Recently, both Mumbai and Chennai have been bearing the brunt of more frequent and intense natural disasters. Mumbai is particularly vulnerable to flooding and storm surges that may be caused by tropical cyclones, whose frequency of occurrence and intensity are projected to increase with rising surface and upper ocean temperatures in the Arabian Sea.[59] Within the last five years alone, as many as three cyclones, namely, *Nisarga, Tauktae,* and *BiparjoyI*, have impacted Mumbai, a city often cited to be shielded from cyclones.[60] Additionally, the past decade has seen four years of notable flooding in the city.[61] Similarly Chennai is now routinely flooded during

Figure 2: Mumbai

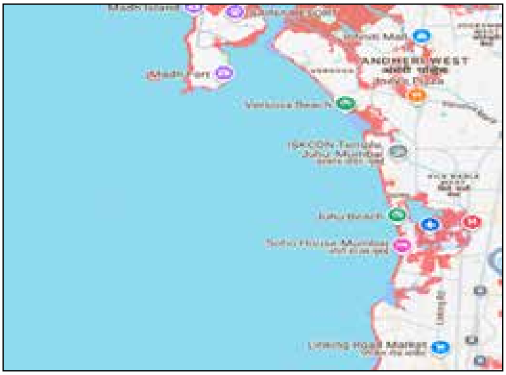


Figure 3: A&N

Figure 4: Chennai

Figure 5: Digha, WB

Source: "Land projected to be below annual flood level in 2050", Coastal Risk Screening Tool, Climate Central

Figure 6: Mumbai

Fig 7: Purba Medinipur, WB

Source: S Nayak et al., "Coastal Multi-Hazard Vulnerability Atlas", Indian National Centre for Ocean Information Services the period of November and December, having suffered fourteen cyclonic storms in the past 20 years.[62] Both these cities are particularly vulnerable to flooding and storm surges as their average elevation is less than 15 metres above sea level.[63] A large number of depressions are formed in the Bay of Bengal and hence the coastal districts of West Bengal and Tamil Nadu are in the "high" to "very high" risk of cyclonic storms intensity category.[64] Therefore, not only do existing cable landing stations need to be upgraded for climate resilience but new cable projects must factor climate change risks and impacts in the design and planning stages of each such project especially when incentivised through State policy.

Conclusion

Growing demand for stable and persistent data connectivity is driving the rapid growth of cable infrastructure. While undersea cable infrastructure is designed for a life of 20 to 30 years, the timelines in respect of climate change vary significantly. Moreover, neither the occurrence nor the effects of natural disasters are uniform across the globe. This requires resilience to be a bespoke solution relevant to local vulnerabilities, rather than being a generic 'one-size-fits-all' one. Localised effects of climate disasters require to be factored into the design and building of cable infrastructure, especially the cable landing stations and beach manholes. The mapping of local vulnerabilities associated with cable landing infrastructure in India's coastal cities is critical to the development of policy solutions tailored to Indian conditions. While at a global level, research has been done to identify "climate-change hotspots" vis-à-vis cable landing infrastructure, such research is not available for Indian conditions. For instance, the "Recommendations on the Licensing Framework and Regulatory Mechanism for Submarine Cable Landing in India" released by the Telecom Regulatory Authority of India on 19 June 2023 merely makes a mention of the fact that the cable network may be damaged by natural disasters without any details being provided in respect of mitigating mechanisms.[65] Likewise, while the "Expert Appraisal Committee" recommendations for the Chennai-Andaman Nicobar Islands (CANI) Submarine Cable System under the Coastal Regulation Zone regulations recommends moving the beach manhole and cable landing station at the Chennai end some 10-12 metres landward in high erosion areas,[66] a similar specificity is lacking for the Andaman-Nicobar leg of the project. Thus, while there is an acknowledgment of the impact of natural hazards on cable systems, a more detailed analysis of the extent of such impacts is certainly required. In this context, it is a matter of some solace (and considerable anticipation) that the National Maritime Foundation, New Delhi, will be undertaking a research project under the Coalition for Disaster Resilient Infrastructure Fellowship 2024-25. Within this fellowship project a contextualised disaster-risk assessment will be undertaken for cable landing sites in India, and policy solutions will be recommended to increase the disaster-resilience of such cable landing infrastructure.

27 November 2024

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India's Global Reach: Securing Energy, Connectivity and Minerals

Oman's Integration into IMEC: Strategic Imperatives for Enhancement of the IMEC Eastern Corridor

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The India-Middle East-Europe Economic Corridor (IMEC [sometimes also abbreviated to IMEEC]) represents a transformative connectivity initiative that emerged from the G20 Summit in New Delhi on 09 September 2023. The Memorandum of Understanding (MoU) was signed between India, the United States, the United Arab Emirates, Saudi Arabia, France, Germany, Italy, and the European Union, establishing a framework for enhanced economic integration between Asia, Middle-East, and Europe.[1]

IMEC comprises two distinct corridors: (1) The Eastern Corridor connecting India to the Persian Gulf, and (2) the Northern Corridor linking the Persian Gulf to Europe.[2] The Eastern segment currently encompasses maritime connectivity from the ports of Jawaharlal Nehru, Kandla and Mundra in India to the ports of Fujairah, Jebel Ali, and Khalifa (all in the UAE), and the Saudi Arabian ports of Dammam and Ras Al Khair, followed by railway networks connecting the UAE to Saudi Arabia and further to Israel, ultimately reaching Europe through the Israeli port of Haifa.[3] This multimodal approach integrates railways, shipping networks, and supporting infrastructure for electricity cables, digital connectivity, and clean hydrogen pipelines.[4] With the participating countries having a combined GDP of about 47 trillion USD (in 2023), IMEC represents nearly half of the world's economic output.[5] The Eastern Corridor exhibits significant strategic vulnerabilities that underscore the need for alternative routing, probably through Oman. The planned route through the Strait of Hormuz, one of the world's most critical oil transit chokepoints, facilitates approximately 20 per cent of global flows of oil and natural gas.[6] This narrow strait, with a width of just 33 km (17.82 NM) between Iran and the Musandam Peninsula, represents a critical vulnerability in IMEC's operational framework.

Furthermore, the current reliance of the Eastern Corridor upon UAE and Saudi ports within the Persian Gulf creates exposure to the risk of regional conflicts. The planned infrastructure of the IMEC involves territories that are already witness to violent geopolitical tensions, including the Israel-Hamas conflict, which has repeatedly demonstrated its capacity to disrupt regional trade flows. The concentration of critical infrastructure nodes within a geographically constrained area amplifies systemic risks and reduces operational resilience.

The Strait of Hormuz Challenge

The Strait of Hormuz presents critical geopolitical risks for the IMEC implementation, primarily due to Iran's ability to disrupt maritime operations. Iran controls the northern shore of this narrow waterway, giving Tehran significant leverage over international trade flows. Recent escalations following US strikes on Iranian nuclear facilities have intensified threats emanating from Tehran, with Iran's parliament approving the closure of the Strait of Hormuz, although the final decision has been left to the Supreme National Security Council.[7] The Islamic Revolutionary Guard Corps (IRGC) maintains operational control over the Persian Gulf[8] and has demonstrated its ability and willingness to harass commercial shipping, as evidenced by tanker seizures and mining incidents over the past several years.

Geopolitical implications extend beyond immediate military threats. Iran's strategic use of the strait as a lever in international negotiations creates persistent uncertainty for commercial operators.[9] Insurance costs for vessels transiting the strait have already increased substantially, from 0.125 per cent of ship value per transit to 0.2 per cent, marking a 60 per cent jump in the war-risk insurance premiums for vessels, with some shipping companies contemplating alternative routes to avoid potential risks.[10] The prospect of sustained closure could trigger global energy crises and supply chain disruptions affecting Indo-Pacific economies that are heavily dependent on energy imports from the Persian Gulf. The strait's vulnerability directly threatens operational reliability and commercial viability. Any disruption of shipping through the strait would immediately affect flows of containerised cargo from India to the UAE, which is amongst India's top export partners in the world. The concentration of major UAE ports, including Jebel Ali and Abu Dhabi, within the Persian Gulf creates systemic exposure to Hormuz-related disruptions. Considering the geopolitical vulnerabilities in the Strait, exploring Oman's participation in IMEC presents an opportunity to bolster the project's sustainability and reduce exposure to potential disruptions in the future.

Prospects of Oman's Integration into IMEC

Oman's integration into the IMEC presents compelling prospects rooted in geography, diplomatic neutrality, and economic complementarity. The sultanate's strategic positioning along the Arabian Sea and the Indian Ocean, largely free from the geopolitical constraints of the Persian Gulf, offers IMEC critical advantages. As opposed to the current IMEC route's vulnerabilities arising from the Strait of Hormuz, Oman's ports at Salalah, Sohar, and Duqm provide direct access to the Arabian Sea.

Oman's traditional diplomatic approach, characterised by neutrality and balanced regional engagement, provides stability advantages for international infrastructure investments.[11] Unlike other Persian Gulf States that are more or less directly involved in regional conflicts, Oman's *"Third Way"* foreign policy offers a secure operating environment for multinational corridor operations.[12] This neutrality offers IMEC strategic insulation from regional tensions that have disrupted other corridor segments, particularly those involving Israel and Iranian-aligned actors.

Economic synergies aligning with IMEC's objectives, in line with *Oman Vision 2040*, include facilitating seamless trade routes, fostering global energy security, promoting sustainable economic growth, enhancing regional connectivity, and driving technological innovations.[13]

Building on Oman's strategic advantages and diplomatic neutrality, a closer examination of the Sultanate's port infrastructure and capacity is essential in determining the feasibility and potential impact of its participation in IMEC.

Oman's Port Infrastructure and Capacity

Oman's maritime infrastructure encompasses a strategically distributed network of ports along its extensive coastline, each offering distinct advantages for IMEC integration. The country's port system includes three major facilities— Salalah, Sohar, Duqm— which taken in aggregate, handle over 104 million tonnes of cargo annually (as of 2024) (Table 1 refers). Container throughput across all Omani ports reached approximately 4.2 million TEU in 2024, with the port of Salalah contributing 3.3 million TEU and Sohar processing 942,000 TEU.[14] This substantial capacity, combined with ongoing expansion programs, positions Oman's ports as viable alternatives to Persian Gulf facilities for IMEC operations.

Table 1. Information of Ports in Oman

Port	Primary Function	Total Berths	Total Quay Length (m)	Maximum Draft (m)	Container Capacity (TEU)	Container Throughput (TEU)	2024 Total Cargo (tonnes)	Key Expansion/ Developments
Salalah	Container trans-shipment hub	21	5,197	18	6.5 million	3.3 million (2024) 3.8 million (2023)	21.2 million (2024)	300 million USD expansion (completed 2024)
Sohar	Multi-purpose deep-water facility	21	6,270	25	1.5 million	942,051 (2024), 818,000 (2023)	75.2 million (2024)	Significant growth in breakbulk/ ro-ro
Duqm	Strategic Greenfield Port	3	2,200	19	3.5 million	16,000 (2023)	8.4 million (2024)	Exceptional 152% cargo increase (2024)

Source: Collated by the Author from different sources

Port Efficiency and Performance Metrics

Salalah Port's ranking as the world's second most efficient container port, according to the 2023 Container Port Performance Index (CPPI), establishes it as a globally competitive facility for IMEC integration.[15] With 164.72 index points and handling 1,146 vessel calls in 2023, Salalah achieved the top position in the West Central and South Asia region.[16] Salalah's consistent performance demonstrates operational excellence that rivals international benchmarks, ranking second only to Yangshan Port in China (177.9 index points, 3,509 vessel calls). Its expansion from 5 million TEU to 6.5 million TEU, through the completed upgrade that cost 300 million USD, represents an increase of 44 per cent in terms of capacity. General cargo throughput climbed to 22.6 million tonnes in 2024, up from 20.6 million tonnes the previous year, driven primarily by limestone, gypsum, and dry bulk volumes. However, container volumes declined to 3.3 million TEU from 3.8 million TEU in 2023, attributable to the uncertainties of shipping through the Red Sea.[17] The port's efficiency stems from its strategic location, expanding connectivity, and world-class operations, all of which provide customers with significant competitive advantages in regional markets.[18] This performance directly supports IMEC objectives by ensuring rapid cargo processing capabilities essential for corridor operations.

Other Omani ports do not have quite the same comprehensive international efficiency ranking as does Salalah but, nevertheless, have impressive operational capabilities. Sohar Port, for instance, demonstrated exceptional growth, with breakbulk cargo achieving 77 per cent growth to reach 1.57 million tonnes in 2024. Likewise, overall cargo volumes reached 74.5 million tonnes (a 2.6 per cent decline from 2023 notwithstanding), container throughput jumped 15 per cent to 943,000 TEUs, while Ro-Ro traffic surged 25 per cent to 87,000 units, and ship-to-ship transfer activity increased 19 per cent to 3.3 million tonnes.[19] In similar fashion, the port of Duqm recorded an exceptional 152 per cent increase in cargo-handling, reflecting enhanced operational efficiencies and a rising demand for integrated port services.[20] The port's focus on breakbulk, project cargo, and dry bulk operations has creating globally recognised operational expertise for specialised handling requirements.[21]

Regional comparison reinforces Omani facilities competitive positioning within GCC markets. While UAE ports maintain larger absolute volumes, with Jebel Ali handling 14.5 million TEU and Khalifa Port processing 4.3 million TEU in 2022 (Khalifa Port ranked third globally in the 2022 CPPI, while Saudi Arabia's King Abdullah Port had topped the 2021 rankings), Omani ports nevertheless demonstrate superior efficiency metrics in several categories. Perhaps most important of all is the strategic positioning of Omani ports which, located as they are outside the Persian

Gulf provide increasingly valued security advantages as geopolitical tensions persist, potentially influencing commercial routing decisions favouring IMEC's resilience objectives.

Given the importance of Oman's ports in the IMEC, assessing the country's inland connectivity infrastructure will be crucial to identifying opportunities for optimisation and ensuring the smooth flow of goods and services.

Inland Connectivity Infrastructure Assessment

The 238 km Hafeet Rail, a USD 2.5 billion joint venture between Etihad Rail, Oman Rail, and the Mubadala Investment Company, provides the backbone for rail integration between the port of Sohar and the UAE National Rail Network.[22] Financial closure in October 2024 secured 1.5 billion USD in syndicated debt from Emirati, Omani and international banks, ensuring timely delivery. The engineering design specifies 60 bridges (some 34 m high) and 2.5 km of tunnels to negotiate complex topography while preserving operational efficiency.[23] The line supports high-capacity freight operations at 120 kmph one of the largest integrated diversified providers of rolling stock and infrastructure solutions and technologies for the global rail industry. with trainsets expected to haul over 15,000 tonnes, roughly 270 TEU per journey, directly aligning with IMEC's throughput requirements.[24]

Twelve planned stations will interlink five deep-water ports and associated industrial zones across both states, embedding maritime-rail multimodality at corridor scale.[25] Recent contract awards to Larsen & Toubro (L&T) and Power Construction Corporation of China *(abbreviated to "Power China"— a wholly state-owned Chinese enterprise)* for automated logistics complexes at Al Buraimi and Sohar, together with the supply of next-generation wagons by the CRRC Corporation Limited *(a Chinese state-owned rolling stock manufacturer)* and 27 heavy-haul locomotives from Progress Rail *(one of the largest integrated diversified providers of rolling stock and infrastructure solutions and technologies for the rail industry headquartered in the USA)*, underscore accelerated implementation and compliance with international heavy-axle standards.[26] The project's governance architecture aligns with Oman Vision 2040 and UAE Centennial 2071, while its Hormuz-independent routing directly advances IMEC's resilience objectives.

Oman's mature highway system sustains seamless port-to-border flows. The 725 km Rub al Khali (Empty Quarter) highway, opened in late 2021, furnishes a direct Saudi–Oman artery with border infrastructure capable of processing 966 freight trucks daily.[27] Within Oman, 16,000 km of paved roads including the eight-lane Al Batinah Expressway, linking Muscat to the Khatmat Malaha UAE crossing, provide express connectivity to the port of Sohar, enabling two-to-three-hour trucking to Abu Dhabi and Dubai under normal traffic.[28] The port of Salalah presently relies on the north–south coastal and desert corridors, whereby commercial vehicles cover the 1,022 km Salalah–Dubai route in approximately 16 hours, offering an operational interim alternative for time-critical cargo.[29]

The port of Duqm connects via the Muscat coastal highway and GCC road grid, requiring eight-to-ten-hour transits, yet delivering strategic diversification by situating cargo south of the Strait of Hormuz.[30] Omani authorities have floated tenders for 42 additional road projects including the dualisation of the Adam Thumrait artery to elevate capacity and safety along IMEC-relevant corridors.[31] Concurrent border modernisation introduces smart customs platforms and Global Navigation Satellite System (GNSS)-enabled tolling, reducing administrative dwell and distance-based user costs, thereby enhancing the competitiveness of road haulage within the emerging corridor architecture. Continuous deployment of Information Technology Systems (ITS) enables real-time traffic monitoring, while planned hydrogen-ready truck-refuelling corridors align with IMEC's decarbonisation mandate and Oman's Net-Zero 2050 infrastructure resilience strategy.[32]

Strategic Case for Oman's IMEC Integration

Oman's integration into the IMEC offers comprehensive solutions to the corridor's geopolitical vulnerabilities. This geographical positioning eliminates the chokepoint risk that the current IMEC routeing faces, providing resilient alternatives that are immune to Iranian interdiction.[33]

This risk-mitigation extends beyond operational concerns to encompass broader regional stability considerations. Oman's traditional neutrality and balanced diplomatic approach provide insulation from regional conflicts that could disrupt other Gulf-based infrastructure.[34] The Sultanate's successful maintenance of constructive relations with both Iran and Western powers creates a stable operating environment for international investments.[35] This diplomatic positioning becomes particularly valuable as regional tensions persist, with the Strait of Hormuz experiencing heightened threat levels and shipping disruptions.[36]

Diversification of critical infrastructure across multiple countries reduces systemic risk exposure inherent in concentrated facility networks. Incorporating Omani alternatives provides redundancy that enhances overall network resilience and maintains operational continuity during crisis periods. Integration significantly enhances connectivity by providing access to previously underutilised geographical advantages and transportation networks. This geographical diversity enables optimised routing based on cargo characteristics and prevailing security conditions.

Connectivity benefits extend to terrestrial networks through the earlier-mentioned Hafeet Rail infrastructure linking Omani ports to the UAE National Rail Network.[37] This integration enables cargo arriving at Omani ports to access the entire GCC railway network without requiring additional maritime transfers. Strategic positioning relative to major trade routes enhances connectivity to broader international networks. Salalah's established role as a transshipment hub for the East African, and West Asian markets provides proven connectivity to global shipping networks.[38] The port's integration with major shipping alliances, including the Gemini network involving such global players as Maersk and Hapag-Lloyd, ensures compatibility with international logistics operations.[39]

The development of specialised economic zones around major ports creates comprehensive logistics ecosystems that enhance regional connectivity beyond simple cargo transfer functions. The integration of the Sohar Freezone with port operations provides value-added services including manufacturing, processing, and distribution capabilities.[40] Likewise, the Special Economic Zone at Duqm offers similar synergies with additional advantages from renewable energy integration and green hydrogen production.[41]

Digital connectivity enhancements support the modernisation of regional logistics networks aligned with IMEC's technological objectives. Oman's investments in digital infrastructure, including the National Port Community System and smart port technologies, create foundations for advanced connectivity features envisioned in IMEC planning.[42] These capacities support the corridor's objectives for secure, high-speed data transmission alongside physical cargo movements, positioning Oman as a critical node in the emerging digital trade infrastructure.[43]

Implementation Framework

Successful IMEC integration demands comprehensive infrastructure development across multiple domains to ensure seamless connectivity and operational efficiency. Port infrastructure standardisation requires implementing Salalah Port's world-class efficiency benchmarks across the other ports of Oman, with container handling equipment compatibility and common port management software enabling integrated logistics operations.

The Hafeet Rail project completion represents the most critical requirement, while reducing Abu Dhabi-Sohar journey time to 100 minutes.[44] Technical specifications must ensure compatibility with international freight standards, including gauge uniformity and operational protocols supporting cargo volumes.

Digital infrastructure requirements encompass blockchain-based cargo tracking systems providing transparency and security throughout supply chains. High-speed data connectivity supporting submarine cable infrastructure linking Omani ports to the broader network will optimise cargo throughput and operational efficiency. Supporting infrastructure includes warehousing facilities, inland logistics parks, and modernised customs infrastructure implementing single-window clearance systems to reduce administrative delays.

Considerations for India

The ports of Salalah, Sohar, and Duqm have become deeply integrated into China's Belt and Road Initiative (BRI), positioning the Sultanate as a crucial node in Beijing's Maritime Silk Road. The China-Oman Industrial Park at Duqm represents a flagship project of the BRI, with Chinese investments of the order of USD 10.7 billion, through a 50-year lease agreement.[45] Similarly, the port of Sohar has established a sister-port agreement with China's Shenzhen Port, facilitating enhanced connectivity within China's 21st-century Maritime Silk Route networks.[46]

However, India's concerns regarding BRI can be addressed through a constructive partnership approach that offers Oman viable economic alternatives while respecting its sovereignty and strategic autonomy. Rather than compelling Oman to withdraw from Chinese investments, India should leverage its historical maritime ties and complementary economic strengths to present attractive partnership opportunities. The India-Oman Comprehensive Economic Partnership Agreement (CEPA), is nearing finalisation and represents a transformative framework offering Oman access to 98 per cent of Indian products and significant service sector liberalisation.[47]

Likewise, the 2017 MoU between the Adani Group and Duqm Port has set an official framework for investment and cooperation demonstrates a constructive approach, with ongoing discussions for port development complementing the existing 1.2 billion USD Indo-Omani joint venture for the region's largest sebacic acid plant.[48] The third tranche of the Oman-India Joint Investment Fund, worth USD 300 million, channels investments into India's fastest-growing economic sectors while creating reciprocal opportunities for Omani diversification.[49] India's approach offers Oman genuine multi-alignment opportunities, reducing dependency on single-source investments while maintaining existing relationships and promoting balanced, sustainable development that enhances regional stability.

Conclusion

Oman's integration into the IMEC represents a strategic imperative that directly addresses the corridor's most critical vulnerabilities while unlocking transformative economic opportunities for regional connectivity. The confluence of geopolitical risks inherent in the current route's dependence on the Strait of Hormuz, combined with Oman's geographical advantages and diplomatic neutrality, creates compelling justification for immediate inclusion in the corridor framework.

The strategic case rests on three fundamental pillars: (1) risk mitigation through geographic diversification; (2) enhanced operational resilience via world-class port infrastructure; and (3) diplomatic stability through Oman's proven neutrality. Salalah Port's ranking as the world's second most efficient container facility, coupled with the Hafeet Rail project creating seamless multimodal connectivity, establishes the infrastructure foundation necessary for IMEC integration. The Sultanate's balanced approach to international partnerships, exemplified by its constructive engagement with both Chinese BRI investments and emerging Indian partnerships through the forthcoming CEPA, demonstrates sophisticated multi-alignment that enhances corridor objectives.

Implementation requires coordinated action across diplomatic, infrastructural, and commercial domains. The existing momentum from India-Oman bilateral initiatives, including the joint investment fund and ongoing port development agreements, provides established frameworks for expanded cooperation. Rather than viewing Chinese presence as an impediment, India's approach should leverage complementary strengths to offer Oman genuine alternatives that respect its sovereignty while advancing mutual strategic interests. The corridor's ultimate success depends on recognising that Oman's integration transforms IMEC from a geographically constrained initiative into a resilient, multi-route network capable of withstanding regional disruptions while maximising economic efficiency.

09 July 2025

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Japan's Energy Stakes in the Indian Ocean

Ms Aashima Kapoor

In examining the evolving trajectory of Japan's energy stakes in the Indian Ocean, this article seeks to address the seminal question of whether, in face of the gradual decline in Japan's oil imports and the corresponding rise of non-fossil fuel sources, Japan's maritime interest in the Indian Ocean will decrease and, if so, what impact this might have upon the formulation and execution India's own maritime geostrategies within this western segment of the Indo-Pacific.

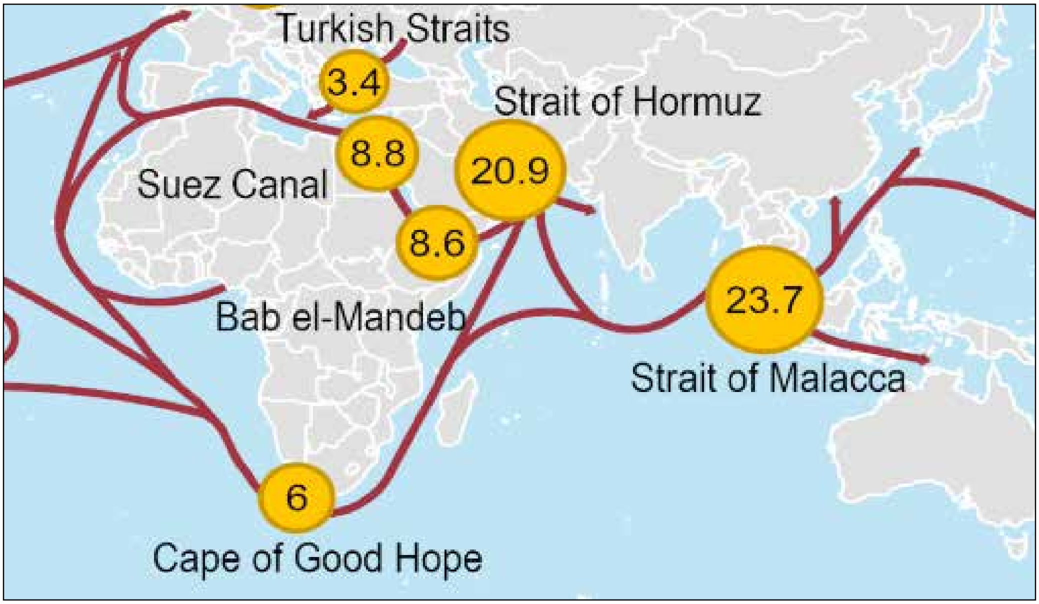
The attack on a Japanese-owned oil tanker, the *Kokuka Courageous,* in the Strait of Hormuz in June 2019 remains fresh in the minds of Japanese policymakers. As stated by Foreign Press Secretary Takeshi Osuga, "*Japan takes the attacks on the ship operated by a Japanese shipping company Kokuka Sangyo, near the Strait of Hormuz on June 13th seriously as a significant incident that threatens Japan's peace and prosperity. Japan firmly condemns such attacks, which threaten the safety of ships. Japan will continue to make efforts to gather information and secure the safety of navigation while closely coordinating with related countries.*"[1] However, this is not the first time Japan has prioritised the security of its energy supplies. The 1973 oil crisis, triggered by the Organisation of Arab Petroleum Exporting Countries (OAPEC) raising oil prices and restricting supply, significantly impacted Japan's oil imports, leading to an economic contraction and a shift toward energy policy diversification.[2] Later, the Great East Japan Earthquake of 2011 caused severe damage in the north-eastern coast of Japan area, with the massive tsunami it triggered leading to even greater devastation.[3] At the time, eleven reactors across four nuclear power plants in the region were operational, all of which shut down automatically when the earthquake struck. As a consequence of the disaster, thermal power generation increased, leading to a rise in Japan's dependence on fossil fuels by FY2019.[4] Yet, there is no gainsaying the fact that Japan has been seeking to reduce its dependence on oil imports that must traverse the Indian Ocean.

Indian Ocean: Global Energy Highway

The Indian Ocean (better thought-of as the western segment of the Indo-Pacific) has long been a crucial trade arena, serving as a vital link from the shores of eastern Africa to those of the Americas. It has facilitated global maritime trade, cultural exchanges, and enabled the movement of goods, people, and ideas across continents. The Indian Ocean (IO)— and the States that lie along its vast rim, as also those that are nestled as island States within this maritime expanse— is critical to global trade and economic prosperity. More than 75 per cent of the world's maritime trade moves along the busy international shipping lanes (ISLs) that crisscross this western segment of the Indo-Pacific.[5] Every year, over 145,000 ships navigate these waters, carrying 66 per cent of the world's oil, 33 per cent of global bulk cargo, and 50 per cent of global container shipments.[6] Insofar as energy-flows are concerned these are, for the most part, oriented along a west-to-east axis. In the west, the Red Sea and the Persian Gulf serve as particularly critical maritime corridors for this flow of energy, the vast bulk of which comprises crude oil. Prior to the shipping disruption caused by the Houthi attacks on international shipping, over 22,000 ships annually negotiated the narrow Strait of Bab-el-Mandeb, connecting the Red Sea to the Gulf of Aden and thence to the Arabian Sea. Notably, oil flows through both the Suez Canal (8.8 million barrels per day), and through the Bab-el-Mandeb Strait, accounting for approximately 8.6 million barrels per day of the world's seaborne oil as of 2023. Likewise, the Strait of Malacca remains one of the region's most significant chokepoints, with over 90,000 ships passing through it each year. In 2023, approximately 23.7 million barrels of total global seaborne oil transited each day through this vital passage, further accentuating the strategic importance of the Indian Ocean. **Figure 1** provides a graphical depiction of this flow of petroleum-based energy.

In 2023, oil-flows through the Strait of Hormuz averaged 20.9 million barrels per day (b/d), or the equivalent of about 20 per cent of global petroleum liquids

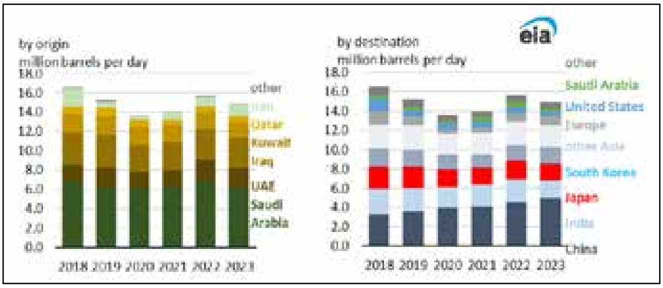
Figure 1. Daily (2023) Transit Volumes of Petroleum and Other Liquids through World Maritime Oil Chokepoints (Mn barrels/ day)



Source. US Energy Information Administration (EIA) analysis

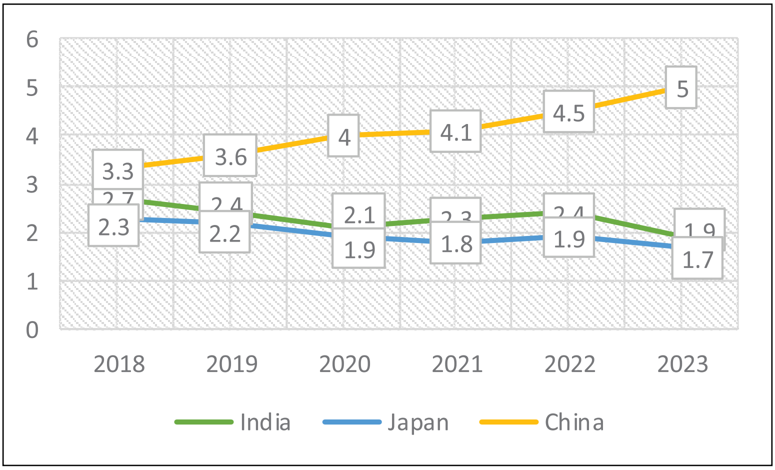
consumption.[7] According to the US Energy Agency (EIA), 83 million b/d of the crude oil and condensate that moved through the Strait of Hormuz went to Asian markets in 2023. **Figure 2** shows that China (5.0 million b/d), India (1.9 million b/d), Japan (1.7 million b/d), and South Korea (1.7 million b/d) were the major destinations for crude oil moving through the Strait of Hormuz, accounting for 69 million b/d of all Hormuz crude oil and condensate flows in 2023.[8] China is the highest among the four, followed by India, Japan, and South Korea. While this data is from 2023, **Figure 3** reflects a broader trend over the

Figure 2. Volume of crude oil and condensate transported through the Strait of Malacca



Source: US Energy Information Administration analysis based on Vortexa Tanker Tracking

Figure 3. Volume of Crude Oil Transported through the Strait of Hormuz by India, Japan, and China 2018-23 (million b/d)



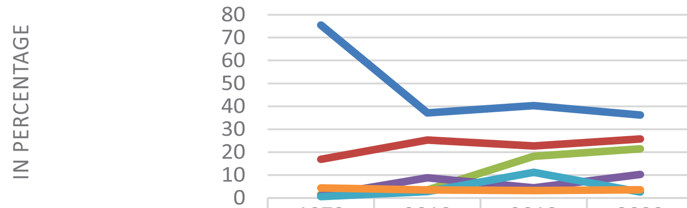
Source: US Energy Information Administration analysis based on Vortexa. (Graphics: Author)

past five years, during which Japan's oil flows have been steadily declining. Notably, China's imports have been consistently increasing, whereas India's have remained relatively stable.

These figures also show that China is steadily *deepening* its engagement with the Gulf region, particularly with the six member countries of the Gulf Cooperation Council (GCC) — Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the UAE. While the foundation of China's ties with these countries was built on oil and gas exports from these sources into China, Beijing's cooperation with the GCC has since expanded into a broad range of sectors, including infrastructure, finance, telecommunications, space exploration, renewable and nuclear energy, and even arms manufacturing. In contrast, Japan appears to be gradually scaling back its energy imports from the region. This shift may reflect growing concerns around energy security, as well as an attempt to reduce strategic vulnerabilities.

However, to better understand Japan's shift in fossil fuel imports, it is important to look at it through a broader lens. As seen in **Figure 4**, which traces the trend over the last five decades, Japan— being insufficient in natural resources— has long been considering ways to reduce its dependence on fossil fuel imports. This has translated

Figure 4. Trends in the mix of primary energy supply of Japan



	1973	2010	2019	2022
Oil	75.5	37.1	40.3	36.2
Coal	16.9	25.3	22.7	25.8
LNG	1.6	3.5	18.2	21.5
Renewable Energy	1	8.8	4.4	10.3
Nuclear Power	0.6	2.8	11.2	2.6
Hydro Electric	4.4	3.5	3.3	3.6

YEARS

Source: Ministry of Economy, Trade, and Economy, Japan (Graphics: Author)

into a steady transition towards non-fossil fuel sources, with a national target of achieving 59 per cent non-fossil fuel power generation by 2030.[9]

Japan is a country with a low energy self-sufficiency ratio — just 12.1 per cent in FY2019 — which is significantly lower than that of other OECD countries.[10] The main reason for this is that Japan is deficient in natural energy resources and depends heavily on imports, especially fossil fuels like oil. A large portion of Japan's oil imports come from West Asian countries such as Saudi Arabia, the UAE, Kuwait, and Qatar. Geography dictates the passage of these imports through the Indian Ocean. Within the West Asian subregion, two critical maritime chokepoints — the Strait of Hormuz and the Strait of Bab-el-Mandeb — serve as vital passages for a significant share of the world's oil trade, including that of Japan. The Strait of Hormuz connects the Persian Gulf to the Gulf of Oman, while the Strait of Bab-el-Mandeb links the Gulf of Aden to the Red Sea. These routes are essential for transporting oil to East Asia.

According to the Japan Maritime Public Relations Center (Shipping Now, 2019–2020), the most important sea routes used to import Japan's energy resources are the Indian Ocean route (which connects Japan via the East and South China Seas and the Strait of Malacca to the Indian subcontinent, West Asia, eastern Africa, and Europe), and the Pacific route (which connects Japan to North America, Australia, New Zealand, the Pacific Islands, and South America).[11] However, Japan has been quietly reducing its dependence on oil, particularly from the West Asian subregion — which also means that Japan may gradually reduce its strategic reliance on the Indian Ocean route. As Japan accelerates its domestic transition toward renewable energy, diversifies its energy suppliers beyond the West Asian region, and invests in cleaner technologies and LNG infrastructure closer to home, the rationale for maintaining an extensive maritime presence in the Indian Ocean purely for energy security could possibly diminish. This shift does not imply a withdrawal of Japan from the Indian Ocean but, rather, a recalibration of Japan's priorities, with security interests becoming increasingly multilateral and less tethered to traditional energy concerns.

Corresponding Rise of Non-Fossil Fuel Sources

Japan is actively increasing its use of renewable energy sources, including solar, wind, hydropower, geothermal, and biomass and, between 2019 and 2022, the share of renewable generation in Japan grew from 4.4 per cent to nearly 10 per cent. The country has set ambitious targets for reducing its reliance on fossil fuels and increasing the share of non-fossil fuel sources in its energy mix. The Japanese government aims to achieve 36-38 per cent renewable energy in its national power mix by 2030. As part of this broader vision, Japan is actively promoting a Green Transformation (GX) strategy— not only to fulfil its Paris Agreement commitments and enhance energy independence in developing countries, but also to support the international expansion of Japanese companies.[12] Under its Official Development Assistance (ODA), GX has been identified as a key priority, with public funding mechanisms such as those administered by JICA being mobilised to support this initiative.[13]

A central pillar of Japan's GX strategy is its international development vision, most notably the formation of the Asia Zero Emissions Community (AZEC). This regional platform aims to achieve decarbonisation while supporting the sustainable growth of fast-developing Asian economies. Currently, over 350 cooperation projects are underway between Japanese stakeholders and eleven AZEC partner countries — Australia, Brunei, Cambodia, Indonesia, Lao PDR, Malaysia, the Philippines, Singapore, Thailand, Viet Nam, and Japan itself.[14] These projects include innovative initiatives such as the construction of a green hydrogen plant in Malaysia and the production of sustainable aviation fuel from Indonesia's non-standard coconuts.

India, meanwhile, has demonstrated strong leadership of its own in its endeavours toward a global clean energy transition. With a target of achieving 500 GW of non-fossil fuel-based energy capacity by 2030, India is positioning itself as a frontrunner in the global green energy race. As a major economic power and a significant greenhouse gas emitter, India understands the critical need to balance climate responsibility with sustainable development. Notably, India has also been the largest recipient of Japanese ODA loans since 2003, underscoring the depth of economic cooperation between the two countries. However, despite these shared goals and a strong Indo-Pacific partnership, India is not currently a member of the AZEC framework. This reveals a significant gap in Japan's and India's climate and energy collaboration. Given their mutual ambitions for decarbonisation, regional stability, and economic leadership, this disconnect raises questions about missed opportunities for synergising their efforts. Strengthening cooperation in green energy, under initiatives such as the AZEC, could pave the way for a more comprehensive and aligned India-Japan partnership in the Indo-Pacific.

Conclusion

Japan's energy realignment is neither subtle nor incidental. While it continues to emphasise stability and security in the Indo-Pacific, its quiet disengagement from traditional energy corridors tells a different story— one of calculated withdrawal and strategic repositioning. Japan's energy policy is a careful balancing act that prioritises security, economic resilience, and long-term sustainability. While Tokyo reaffirms its commitment to stability in the Indo-Pacific, its quiet but deliberate shift away from traditional energy corridors suggests a strategic recalibration. This is not a hasty reaction to global disruptions but a well-calculated move to insulate itself from external vulnerabilities. Japan maintains oil reserves equivalent to approximately 230 days of domestic demand to safeguard its energy supply disruptions, while steadily diversifying its import sources.[15] Officially, it continues to build strong ties with West Asian oil-producing nations, yet the underlying reality is that Japan is working to reduce its exposure to a region that remains susceptible to instability.[16] The risks of price volatility and supply disruptions remain ever-present concerns, reinforcing the need for a more diversified energy portfolio. Japan's policies reflect this shift. By 2030, the share of coal in electricity generation is set to decline from 31 per cent to 19 per cent, while petroleum-based generation will shrink from four per cent to just two per cent.[17] The government's focus on expanding renewables, reviving nuclear energy, and investing in carbon capture and low-carbon hydrogen technologies demonstrates a broader commitment to energy independence and decarbonisation. Obviously, crude oil is not the only import that Japan is concerned about. There are other commodities as well and several of these demand Tokyo's continued focus upon the Indian Ocean. India itself plays an important role in sharpening this focus. For instance, over the past five years, India's exports to Japan have increased at an annualised rate of 0.046 per cent, from USD 5.61 bn in 2018 to USD 5.62 bn in 2023.[18] The main products that India exported to Japan were: (a) diamonds worth USD 380 million, (b) aluminium worth USD 366 mn, and (c) seafood (crustaceans) worth USD 281 million. For its part, Japan's exports to India in 2023 were worth USD 18.2 bn, with the main commodities being refined copper (worth USD 1.87 bn), precious metal compounds (worth USD 1.4 bn), and motor vehicles, parts and accessories (worth USD 862 million). It may be concluded that the IOR will continue to be central to Japan's economic and strategic interests, serving as a vital conduit not just for energy but also for food, technology inputs, and industrial resilience.

20 June 2025

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New Zealand's Critical Minerals Strategy 2025: Opportunities for India – New Zealand

Ms Kripa Anand

The growing global demand for critical minerals has made resource security a strategic priority for many nations. New Zealand's recently released critical minerals strategy outlines a long-term vision for developing its mineral sector to support economic growth and sustainable resource management. For India, securing a stable supply of critical minerals is essential for advancing its clean energy transition, high-tech manufacturing, and infrastructure development. This article analyses New Zealand's critical minerals strategy and explores the potential for India-New Zealand collaboration in the critical minerals sector, focusing on trade, investment, sustainable mining practices, and technological exchange.

A Minerals Strategy for New Zealand to 2040

In January of 2025, the Government of New Zealand launched a Minerals Strategy along with a Critical Minerals List, to chart a strategic roadmap for the country's minerals sector. The document, entitled *"A Minerals Strategy for New Zealand to 2040"*, was released by Resources Minister, Shane Jones, with the aim of doubling exports to USD 3 billion by 2035.[1] Mr Jones released the documents at OceanaGold's Waihi Operation in Hauraki, where gold has been mined since the 1800s, with OceanaGold having acquired the mine in 2015.[2] The document highlights the high dependence of New Zealand upon critical minerals, which form the backbone of technology, infrastructure, and industry, while emphasising the need for a cohesive strategy to guide New Zealand's mineral sector. It also states that the absence of a clear vision creates risks, including potential disruptions in the supply of essential minerals and missed economic opportunities for New Zealanders. The document underlines that a well-defined strategy is necessary to secure access to vital resources and seeks to ensure that mineral development aligns with both, national interests and global trends.

New Zealand's *"Minerals Strategy to 2040"* emphasises that by proactively shaping its mineral future, New Zealand can establish a framework that reflects domestic needs, considers international geopolitical factors, and integrates responsible mining practices. As of June 2023, the value of mineral exports by New Zealand was USD 1.46 billion, with 5,290 people employed in the sector and USD 21.6 million received in royalties.[3] The current strategy aims to increase exports to USD 3 bn in 2035 and to create 7,000 regional jobs. It lists three desired features — indicated as "outcomes" of New Zealand's critical minerals strategy: *Productive, Valued and Resilient.* The first focuses upon streamlining processes to increase efficiency in obtaining permits and attracting foreign and domestic investment in the critical minerals sector. The outcome in respect of *"Value"* aims to maximise the economic benefits derived from mineral resources, while *"Resilience"* seeks to ensure supply-chain stability and also that the country's minerals sector can withstand economic and environmental challenges.[4] The strategy also includes two guiding principles of *"Te Tiriti O Waitangi"* and of being *"Responsible"*.

"Te Tiriti O Waitangi" is a treaty that was signed in 1840 between the British Crown and Māori chiefs, establishing a relationship based on governance, the protection of Māori rights, and land.[5] The guiding principle of *"Te Tiriti o Waitangi'* embeds values of partnership, participation, and protection within the strategy. This approach ensures that the Māori have a meaningful role in decision-making, with their rights, interests, and self-determination over land and resources being properly recognised. By integrating *"Te Tiriti"* principles, the strategy seeks to foster equitable economic opportunities while safeguarding the Māori cultural heritage.

Alongside this, responsible mineral development is central to the strategy, emphasising environmental sustainability, ethical supply chains, worker safety, and community engagement. The approach prioritises minimising ecological impact, ensuring ethical sourcing, and promoting circular economy principles to reduce reliance on virgin mineral extraction. The document also underlines that high-value conservation areas, such as "Schedule 4 Land" under the "Crown Minerals Act 1991", will remain protected.[6] By balancing economic growth with environmental stewardship and social responsibility, the strategy aims to secure a sustainable, inclusive, and resilient minerals sector for New Zealand's future.

New Zealand's "Critical Minerals List" (**Table 1 refers**) comprises minerals that are both economically significant and vulnerable to supply disruptions, and play a crucial role in national security, technological advancement, and the transition to a low-emissions economy. These minerals are essential for international trade and supply-chain diversification, with their availability being impacted by domestic regulatory constraints, geopolitical factors, and global market dynamics. Industrial rock and building stone, aggregate, limestone, gravel, sand, and clay, are extracted in and around New Zealand.

Table 1. Commodities Included in New Zealand's Critical Minerals List

Sl. No	Mineral	Key uses	Produced in New Zealand?
1	Aggregate & Sand	Roading, construction	Yes
2	Aluminium	Packaging, automotive, aerospace, defence	Yes
3	Antimony	Defence, electric vehicles (EVs), medical	Potential
4	Arsenic	Treatment of wood, electronics (including semiconductors)	Yes
5	Beryllium	Aerospace, electronics (including semiconductors)	No
6	Bismuth	Electronics (data storage)	Potential
7	Boron	Permanent magnets, electronics, solar photovoltaic (PV) cells, fertiliser	No
8	Caesium	Cancer treatments, electronics, optics, aerospace, solar PV cells	Potential
9	Chromium	Stainless steel and other steel alloys	Potential
10	Cobalt	Battery and energy storage, steel alloys, fertiliser and livestock health	Potential
11	Copper	Power transmission, electronics, EVs, fertiliser and livestock health	Potential
12	Fluorspar	Aluminium production, insulating foams, refrigerants, steelmaking	No
13	Gallium	PV cells, electronics (including semiconductors)	No

Sl. No	Mineral	Key uses	Produced in New Zealand?
14	Germanium	Electronics (including semiconductors)	No
15	Gold	Jewellery, electronics, dentistry, aerospace	Yes
16	Graphite	Battery and energy storage applications	No
17	Indium	Electronics, solders, batteries, PV cells, bearings	No
18	Magnesium	Lightweight alloys, fertiliser and livestock health	Potential
19	Manganese	Steel and aluminium alloys, batteries, catalysts, glass, electronics, fertiliser, and livestock health	No
20	Metallurgical coal	Steelmaking, industrial processes	Yes
21	Molybdenum	Steel alloys and high temperature alloys, fertiliser and livestock health	No
22	Nickel	Stainless steel and other steel alloys, battery and energy storage	No
23	Niobium	High-temperature superalloys	No
24	Phosphate	Fertiliser, battery and energy storage applications	Potential
25	Platinum Group	Catalysts, hydrogen fuel cells, EVs, electronics, communications	Potential
26	Potash	Fertiliser	No
27	Rare Earth Elements	Permanent magnets, glass polishing, ceramics, metal alloys, LEDs, lasers	Yes
28	Rubidium	Medical, electronics	No
29	Selenium	PV cells, electronics, fertiliser and livestock health	No
30	Silicon	Glass, casting sand, nanomaterials, electronics	Yes
31	Strontium	Magnets, alloys, paints	No
32	Tellurium	PV cells, electronics	No
33	Titanium	Aerospace, medical	Yes
34	Tungsten	Tools for drilling, mining and cutting	Potential
35	Vanadium	Steel and titanium alloys, catalysts, magnets, coatings, battery and energy storage applications	Yes
36	Zinc	Anodising, corrosion protection, fertiliser and livestock health	No
37	Zirconium	Fuel cells, auto catalysts, bearings	Yes

Source. GlobalData, adapted from “A Critical Minerals List for New Zealand, January 2025”

New Zealand’s mining sector contributes significantly to its economy. In the year ending March 2024, the country’s mining industry contributed approximately 2.2 billion NZD to the national GDP.[7] Given that the total GDP for this period was about USD 262.92 billion, or roughly 420 billion NZD, the mining sector’s contribution equates to approximately 0.5 per cent of the total GDP. Resources such as coal, iron ore, gold, and silver are mined by the thousands of people directly employed in that industry. On the other hand, some see this as part of a broader government retreat from climate commitments, with experts suggesting New Zealand is easing green policies to boost the economy.

Gold and metallurgical coal are key additions to the critical minerals list. New Zealand has a rich gold mining history, dating back to the 1860s gold rush.[8] Despite producing less gold than Australia, New Zealand remains a key gold-mining nation in the Indo-Pacific, with the Macraes Mine leading output in 2023.[9] However, similar to coal, overall gold production has declined over the past decade. A range of factors is responsible for this decline.[10] The decrease in the production of gold is attributed to major resource depletion. After extensive mining since the 19th century gold rushes, accessible gold reserves have diminished, leading to reduced production. The COVID-19 pandemic also led to operational challenges and restrictions, leading to less profitable mining ventures, especially for smaller-scale gold operations that were once prevalent in the country.[11]

While coal is a key energy-source, much of it is exported, although exports have declined over the past seven years, with current production being significantly lower than that of a decade ago. Coal is found in regions of the country such as Waikato and Taranaki in North Island and the West Coast, Otago, and Southland in South Island, with the West Coast producing the most.[12] Organisations such as GNS Science have recommended excluding coal to align with Australia and the country's net-zero 2050 goal,[13] and New Zealand's commitment to reducing carbon emissions has, indeed, prompted a transition from coal to renewable energy sources, decreasing coal demand. Extant government policies include prohibiting new coal boilers in manufacturing and aiming to phase out existing ones by 2037, which have further reduced both production and consumption of coal.[14]

India's Critical Minerals Landscape

Against the foregoing background of New Zealand's critical minerals strategy, it is essential to examine India's critical minerals landscape, including its resource potential, growing demand, and strategic initiatives to secure supply chains. By identifying complementary strengths and resource needs, India and New Zealand can explore areas of collaboration to support mutual economic and strategic interests.

India's Ministry of Mines defines critical minerals as *"those minerals which are essential for economic development and national security, the lack of availability of these minerals or even concentration of existence, extraction or processing of these minerals in few geographical locations may lead to supply chain vulnerability and disruption*."[15]

In the fiscal year 2023-24, India's mining and quarrying sector contributed ₹5,25,881 crore (~ USD 63.5 billion USD), making up 1.5 per cent of India's GDP (estimated at USD 4.27 trillion).[16] Historically, the share of mining in India's GDP over the past decade has been 2.1–2.5 per cent but this has now declined slightly. In FY22, for instance, the sector contributed 2.3 per cent, down from 2.5 per cent in FY18.[17] Mining is a smaller part of India's GDP compared to that of other major mining economies. For example, in 2022, mining contributed 12 per cent to Australia's GDP and 7 per cent to South Africa's GDP.[18]

While the percentage share of mining in India's GDP has declined, its absolute value (₹5.26 lakh crore) has grown, largely due to the overall expansion of India's economy.[19] Thus, the value of mining within India's GDP increased from ₹76,877 crore (USD 9.25 billion USD) in Q3 FY23 to ₹82,680 crore (USD 9.95 billion USD) in Q3 of FY24. This suggests that while there is growth in the sector it is at a slower pace than the rest of the economy. In other words, India's mining sector is growing in absolute terms but declining in its relative contribution to the national GDP. Investments like JSW Group's steel plant in Andhra Pradesh indicate ongoing industrial reliance on mining.[20] It remains crucial for raw material supply but lacks the growth momentum seen in other mining-heavy economies. The sector almost certainly needs policy support, investment, and reforms, so as to boost its share in the national GDP and to match global benchmarks.

In 2023, the Ministry of Mines identified 30 critical minerals deemed essential for the nation's economic development and national security (**Table 2 refers**).

Table 2. Usage and Availability of Identified Critical Minerals

Sl. No	Critical Mineral	Major Applications	Availability in India
1	Antimony	Flame retardants, lead-acid batteries, lead alloys, plastics (catalysts and stabilizers), glass and ceramics	No proven reserves; inferred reserves in Lahul & Spiti, Himachal Pradesh. Obtained as a by-product in lead-zinc-silver smelting.
2	Beryllium	Computer, electronic, and optical products	Not available; entirely imported.
3	Bismuth	Pharmaceuticals, casting of iron	Not available; entirely imported.
4	Cadmium	Electrical equipment, chemical products, solar cells, electroplating	Recovered as a by-product of zinc smelting and refining.
5	Cobalt	EV batteries, aerospace, pigments and dyes	Not available; entirely imported.
6	Copper	Electrical wiring, solar panels, automotive industry	Domestic production meets only 4% of demand; significant imports required.
7	Gallium	Semiconductors, LEDs, thermometers, barometric sensors	Recovered as a by-product of alumina production (e.g., HINDALCO, NALCO).
8	Germanium	Optical fibres, satellites, solar cells, infrared night vision	Not available; entirely imported.
9	Graphite	Batteries, lubricants, fuel cells for EVs	9 million tonnes of reserves exist.
10	Hafnium	Superalloys, catalysts, semiconductors, nuclear reactors	Present in zirconium compounds; IREL and KMML produce zircon.
11	Indium	Electronics (laptops, LED monitors/TVs, smartphones)	Not available; entirely imported.
12	Lithium	EV batteries, rechargeable batteries, glassware, ceramics, lubricants	5.9 million tonnes inferred resources in Salal-Haimana, Jammu & Kashmir.
13	Molybdenum	Steel alloys, lubricants, medical applications	Mineable reserves available in Harur, Tamil Nadu.
14	Niobium	Jet engines, rockets, construction, superconducting magnets, MRI scanners	Not available; entirely imported.
15	Nickel	Stainless steel, solar panels, aerospace, EVs	Domestic production through Vedanta's NICOMET plant in Goa.
16	Platinum Group Elements (PGE)	Jewelry, medical devices, military electronics, LCDs, turbine blades	Found in Nilgiri, Boula-Nuasahi, Sukinda (Odisha), and Karnataka.
17	Phosphorus	Fertilisers, detergents, food additives, animal feed	Found in Rajasthan, Jharkhand, and Madhya Pradesh.
18	Potash	Fertilisers, explosives, road de-icing	Deposits in Rajasthan, Madhya Pradesh, and Uttar Pradesh.

Sl. No	Critical Mineral	Major Applications	Availability in India
19	Rare Earth Elements (REEs)	Permanent magnets, batteries, electronics, defence, aviation	India has 11.93 million tonnes of monazite-bearing beach sand reserves.
20	Rhenium	Superalloys, aerospace, petroleum catalysts	Not available; entirely imported.
21	Selenium	Pigments, photocells, solar cells, photocopiers, stainless steel	Not available; entirely imported.
22	Silicon	Semiconductors, electronics, transport equipment, paints	India produced 59,000 metric tonnes in 2022, ranking 12th globally.
23	Strontium	Aluminium alloys, pigments, glass, pyrotechnics	Not available; entirely imported.
24	Tantalum	Capacitors, superalloys, medical technology	Not available; entirely imported.
25	Tellurium	Solar power, thermoelectric devices, rubber vulcanizing	Not available; entirely imported.
26	Tin	Soldering, metal packaging, home decor	Produced in concentrates and metal form in Chhattisgarh.
27	Titanium	Paint pigments, aircraft, spacecraft, submarines, steel alloys	Found in Tamil Nadu, Andhra Pradesh, Odisha, Kerala, Gujarat, Maharashtra.
28	Tungsten	Hard materials, cutting tools, superalloys, oil drilling	Not available; entirely imported.
29	Vanadium	Steel alloys, military armour, superconducting magnets	24.63 million tonnes of vanadium ore reserves in India (as of 2015).
30	Zircon	Nuclear fuel rods, advanced ceramics, electronics	Found in beach sands of Kerala, Tamil Nadu, Andhra Pradesh, Odisha, Gujarat.

Source: Ministry of Mines, Critical Minerals for India, *"Report of the Committee on Identification of Critical Minerals"*, June 2023 (compiled by the author)

While the report, as shown in **Table 3** highlighted India's complete import dependency for ten critical minerals, it did not fully address a far more pressing concern — the extent and nature of dependence upon China. The extraction and processing of critical minerals are largely dominated by a few countries, and China is in the vanguard of these. As a consequence, China's dominance in critical minerals significantly impacts the supply chains of countries such as India — and New Zealand — which rely upon imports for these essential resources. India relies heavily on imports for critical minerals such as lithium, cobalt, and nickel, with demand expected to more than double by 2030. Of great concern in the present and foreseeable geopolitical milieu, is the fact that India's dependence upon imports for its needs of lithium and cobalt is predominantly upon China, which also commands more than 60 per cent of global lithium-ion battery production.[21]

Table 3. India's Net Import Reliance for Critical Minerals (2020)

Sl. No	Critical Mineral	Import Percentage	Major Sources of Import
1	Lithium	100%	Chile, Russia, China, Ireland, Belgium
2	Cobalt	100%	China, Belgium, the Netherlands, the US, and Japan
3	Nickel	100%	Sweden, China, Indonesia, Japan, and the Philippines
4	Vanadium	100%	Kuwait, Germany, South Africa, Brazil, and Thailand
5	Niobium	100%	Brazil, Australia, Canada, South Africa, and Indonesia
6	Germanium	100%	China, South Africa, Australia, France, and the US
7	Rhenium	100%	Russia, the UK, the Netherlands, South Africa, and China
8	Beryllium	100%	Russia, the UK, the Netherlands, South Africa, and China
9	Tantalum	100%	Australia, Indonesia, South Africa, Malaysia, and the US
10	Strontium	100%	China, the US, Russia, Estonia, and Slovenia
11	Zirconium (zircon)	80%	Australia, Indonesia, South Africa, Malaysia, and the US
12	Graphite(natural)	60%	China, Madagascar, Mozambique, Vietnam, and Tanzania
13	Manganese	50%	South Africa, Gabon, Australia, Brazil, and China
14	Chromium	2.50%	South Africa, Mozambique, Oman, Switzerland, and Turkey
15	Silicon	<1%	China, Malaysia, Norway, Bhutan, and the Netherlands

Source. Critical Minerals for India, Ministry of Mines

China has discovered 173 types of minerals, including 13 energy minerals, 59 metallic minerals, and 95 non-metallic minerals.[22] In 2020, China's cobalt-refining capacity was approximately 166,000 tonnes per year, with its refining facilities operating at about 60 per cent capacity.[23] Additionally, China accounts for more than a third of the world's copper and nickel processing. China's extensive control over critical minerals presents significant supply chain challenges for both, India and New Zealand, prompting these nations to seek alternative strategies to ensure resource security. It is obvious that Indo-Pacific nations need to maximise their domestic resources and engage in global supply chains through diverse international partnerships across the mining-, processing-, assembly-, and end-use industries.

While India is currently exploring trilateral cooperation with France and Japan, the India-New Zealand relationship also stands to gain from bilateral cooperation. At the 26th Conference of Parties (COP26) in Glasgow, Prime Minister Narendra Modi outlined India's climate action plan, known as the *Panchamrit* strategy, which includes the following five commitments:

1. **Non-Fossil Energy Capacity:** Achieve 500 gigawatts (GW) of non-fossil energy capacity by 2030.
2. **Renewable Energy Consumption:** Source 50 per cent of energy requirements from renewable sources by 2030.
3. **Emission Reduction:** Reduce total projected carbon emissions by one billion tonnes by 2030.
4. **Carbon Intensity Reduction:** Lower the carbon intensity of the economy by 45 per cent by 2030, relative to 2005 levels.
5. **Net-Zero Emissions:** Achieve net-zero emissions by 2070. [24]

These five commitments underscore India's dedication to transitioning to sustainable energy and addressing climate change challenges.

Recommendations

Given these commitments, India and New Zealand need to develop complimentary policies and regulatory frameworks for ethical and environmentally responsible mining. By fostering investment, trade, research, and security cooperation, such a dyadic partnership would enhance resource security and economic resilience in both nations. The following policy-relevant recommendations are offered for consideration by the Governments of both nations:

1. A key area of collaboration lies in investment and mineral exploration, where Indian mining firms such as Vedanta, Hindalco, NMDC, and ONGC can expand their operations by investing in exploration projects in New Zealand. At the same time, New Zealand-based companies like Bathurst Resources, Chatham Rock, and OceanaGold could partner with their Indian

counterparts for mineral extraction and processing, promoting joint ventures that encourage responsible resource utilisation. Additionally, India and New Zealand can establish pilot projects for sustainable extraction techniques, including bio-mining and deep-sea mineral exploration, contributing to the development of eco-friendly and efficient resource utilisation strategies.

2. In the domain of scientific research and technological exchange, joint research and development (R&D) efforts need to be focused upon advanced mineral processing and sustainable extraction technologies. Collaboration between the India's "National Institute of Oceanography" (NIO) and New Zealand's "National Institute of Water and Atmospheric Research Ltd" (NIWA) could lead to cooperative and collaborative deep-sea mining research in the South Pacific, ensuring that mineral exploration aligns with marine conservation priorities. Both nations can further advance low-carbon mineral processing technologies through partnerships between, say, the Indian Institutes of Technology (IITs) and New Zealand's University of Otago, thereby strengthening their commitment to sustainable industrial growth. Further, enhancing geospatial mapping for resource discovery by leveraging expertise from Geoscience Australia, the Geological Survey of India (GSI), GNS Science (New Zealand), and the New Zealand Institute for Minerals to Materials Research (NZIMMR) can facilitate more efficient mineral identification and extraction.

3. Trade and resource-collaboration form another cornerstone of this partnership. India, with its significant reserves of Rare Earth Elements (REEs), titanium, and zirconium, can play a crucial role in supplying minerals that New Zealand requires in greater quantities than those that it produces. Similarly, New Zealand can benefit from India's support in the export and refining of copper and manganese, minerals that are scarce in New Zealand but essential for industrial applications. Establishing long-term supply agreements between both countries can promote market stability, decrease reliance on external sources, and create a more resilient critical minerals supply chain.

4. A strategic partnership in clean-energy supply-chains can further enhance mutually beneficial collaboration between the two nations. Joint initiatives could focus upon the development of EV battery mineral supply-chains,

particularly in terms of the sourcing and processing of cobalt, graphite, and lithium. Partnerships between, say, India's "Tata Chemicals" or "JSW Energy" and New Zealand's "Meridian Energy" can strengthen the value chain for these essential minerals. Additionally, India's National Green Hydrogen Mission and New Zealand's expertise in renewable energy can facilitate joint R&D efforts on hydrogen storage materials, particularly utilising Nickel, and Platinum Group Elements (PGEs). These collaborations would contribute to advancing global clean energy goals while ensuring both nations benefit from secure and ethical mineral supply chains.

5. Beyond trade and research, maritime security and logistics infrastructure present further opportunities for cooperation. As both nations seek to enhance mineral shipments and supply chain security, strengthening Indo-Pacific naval coordination between the Indian Navy and the Royal New Zealand Navy (RNZN) can ensure the safe and efficient transportation of critical minerals. New Zealand's expertise in marine conservation and sustainable seabed mining regulations can be leveraged to promote ethical resource extraction while balancing economic and environmental priorities. Additionally, joint investments in port infrastructure, particularly in Indian ports such as Visakhapatnam and Kandla, and New Zealand's ports such as Auckland and Tauranga, can improve the efficiency of mineral trade logistics and exports.
6. To institutionalise these collaborative efforts, India and New Zealand should develop a Bilateral Critical Minerals Agreement under multilateral frameworks such as the Indo-Pacific Economic Framework for Prosperity (IPEF). Establishing a joint working group between India's Ministry of Mines and New Zealand's Ministry of Business, Innovation & Employment (MBIE) would facilitate government-level engagement, policy alignment, and investment promotion.

Conclusion

An India-New Zealand Critical Minerals Partnership has the potential to create a robust, mutually beneficial framework that strengthens resource security, technological innovation, and sustainable economic growth. By leveraging each country's strengths and utilising multilateral platforms, this collaboration can enhance supply chain resilience, support the global transition to a greener economy, and integrate responsible maritime exploration strategies. Through a combination of investment, trade agreements, research initiatives and security cooperation, India and New Zealand can establish a future-focused, critical minerals partnership that benefits both nations and the global economy.

09 March 2025

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Book Reviews

BOOK REVIEW

Building Industries at Sea: ‘Blue Growth’ And the New Maritime Economy

Kate Johnson, Gordon Dalton, and Ian Masters (Editors)
River Publishers, 2018, 516 pages
eISBN: 978-87-93609-25-9

Dr Gulshan Sharma

For thousands of years the oceans have been highly prized and have provided us with efficient transport and a plentiful supply of food. Consequently, global society is reluctant to change its set ways and is largely resistant to new ideas. As such, it is often the case that new ideas are not accepted — certainly not as quickly as their advocates would like. These sobering realisations notwithstanding, the editors of this book, Kate Johnson, Gordon Dalton, and Ian Masters hold that traditional uses of the sea can, indeed, coexist with novel technology. The purpose of this book is to undertake a detailed analysis of prospective maritime business sectors that would address both, “Blue Growth” and the “Blue Economy” and to highlight the regimes of maritime governance under which these sectors should operate.

The book is organised into four distinct parts: (1) “The Blue Growth Sectors”, (2) “The Blue Economy Sectors”, (3) “Planning by Sea Basin”, and (4) “Combining Uses”.

Part 1 highlights the promising opportunities for offshore aquaculture in Europe. Recent technological advancements, aimed at alleviating pressure on coastal areas that cannot support any further growth in production, are paving the way for significant fresh investment in this sector. The opening chapter of this part highlights that while offshore aquaculture is still in its early stages, there is significant interest from governments as well as industry to explore its potential. It emphasises the high market value of Atlantic Salmon, which is driving large companies to invest in offshore projects, while also bringing out the fact that shellfish and seaweed cultivation may better suit offshore conditions despite their current market limitations. The next chapter delves into the challenges within the discipline of blue biotechnology, emphasising the need for basic research due to the relatively nascent understanding of marine biodiversity. A primary concern is the sector's reliance on policy bodies for funding, often neglecting involvement from large companies that possess the necessary resources for successful implementation. Moving to Chapter Three, the discussion shifts to the offshore extraction of metals, wherein geopolitical factors and resource scarcity drive exploration efforts. While some researchers warn of impending shortages, others argue that current land-based reserves are sufficient for at least three decades. This chapter suggests that despite ample existing reserves, market perceptions often undervalue longevity in resource availability, leading to hesitancy in investment. The fourth chapter raises a critical question regarding the slow establishment of wave and tidal energy technologies as viable options for renewable energy. The delay stems from multiple factors, primarily investor scepticism due to the absence of fully operational commercial arrays. Although tidal energy shows promise in terms of its technical viability, wave energy has struggled due to technological uncertainties and the closure of recent projects. The closing chapter of this Part focuses upon the significance of offshore wind energy in the Atlantic and Baltic basins. These regions are expected to remain focal points for future development, although currently subsidised electricity prices may hinder competitiveness. In contrast, the Mediterranean and Caribbean basins face challenges in establishing commercial offshore wind markets due to limited projects and high electricity costs.

In Part Two, the authors shift their focus to more traditional maritime industries. The chapters in this part intricately weave the narrative of transition in the face of challenges such as climate change, overfishing, and regulatory frameworks. The opening chapter of this Part (Chapter 6 of the book) examines the global state of fisheries, noting that nearly all coastlines are fished to some extent and provide significant employment-opportunities for vulnerable communities. In Europe, small-scale fisheries have thrived by shifting their collective focus to species like crustaceans and molluscs, which have seen increases in stock, largely due to reduced finfish predation. The wild fish industry is under pressure, but it remains a resilient one and the cornerstone of the "blue" economy. The next chapter in this part discusses the future of the oil and gas (O&G) industry, projecting a decline in offshore activities as accessible reserves diminish. This shift pushes exploration into remote areas, making operations more expensive and potentially unfeasible. Although the Caribbean and Mediterranean basins hold substantial hydrocarbon deposits, many of them are outside EU waters, raising concerns about supply-limitations as North Sea reserves dwindle. The following two chapters explore the interconnected sectors of shipbuilding, maritime transportation, and coastal tourism. Chapter 8 of the book highlights how European shipbuilding, trying to cope with strong Asian competition, has embraced specialisation to produce high-value vessels, supporting Blue Growth initiatives through technological advancements. Chapter 9 emphasises the significance of coastal and maritime tourism, particularly cruise tourism, which contribute substantially to employment and revenue in Europe. However, this sector faces uncertainties such as fluctuating fuel prices and the adverse impacts of climate change.

Moving forward, the book progresses into more sophisticated realms, with Part Three concentrating upon "Planning by Sea Basin", while Part IV addresses "Combining Uses". The discussion on Multi Use Platforms (MUPs) and Multi Use of Space (MUS) is aimed at optimising oceanic resources (Chapters 10 to 13) while minimising conflicts among industries. The narrative promotes synergy across sectors, privileging collaboration (Chapter 14) over competition.

However, the book is not without its limitations. The authors acknowledge the absence of transformative technologies for the blue economy. The data is carefully curated to be relevant to Europe and this makes the reader question its global applicability. That said, it must be acknowledged that even while the focus remains predominantly on European sea basins, the authors have managed to successfully engage the audience in a dialogue about the ocean's universal importance. Their emphasis on maritime policy paves the way for discussions around ocean governance, although theirs is a narrative fraught with complexities that may deter some who seek answers rather than exploration.

This notwithstanding, this book is a must-read for environmentalists, policymakers, scientists, and, indeed, anyone interested in the exciting potential of the ocean economy. Readers are left inspired to undertake their own exploration of the vast uncharted possibilities that lie beneath the waves.

13 November 2024

About the Reviewer

Dr Gulshan Sharma is a Research Associate and an environmental scientist at the National Maritime Foundation (NMF). Her research encompasses maritime issues related to the Blue Economy and Climate Change and she specialises in climate change resilience, biodiversity conservation, and marine plastic pollution. With extensive experience in research and academia, she is dedicated to advancing sustainable practices in the marine environment. She may be reached at climatechange3.nmf@gmail.com.

BOOK REVIEW

How the World Ran Out of Everything: Inside The Global Supply Chain

Peter S Goodman
New York: Mariner Books, 2024. 416 Pages
ISBN 978-00-6325-792-4

Ms Sushmita Sihwag

The crisis of globalisation could aptly be called "*the crisis of our times"*. Bubbling with the global financial crisis of 2008, it evolved into simmering discontent among large sections of Western societies with the capitalist model that relocated manufacturing to developing countries with lower costs, such as China, and finally boiled over during the socio-economic upheaval triggered by the COVID-19 pandemic. The fissures of the current global economic system were laid bare to reveal an unsightly substratum masked by a thin veneer of efficiency and speed. Peter S Goodman's latest book, "*How the World Ran Out of Everything: Inside the Global Supply Chain*", examines the unravelling of the global supply chain during the pandemic and highlights how the fragility of those once-invisible links, that connect the world into a "*global village*" became apparent as they broke down, with each snapped link reflecting a critical failure in the hitherto seamlessly operating global economic system. Goodman, who is the Global Economics Correspondent for the *New York Times*, weaves a seamless narrative which unfolds in three parts: the workings of the global supply chain and China's emergence as the centre of global manufacturing, the inner workings of the critical industries within this supply chain, and the opportunity the pandemic crisis presents for reinventing it.

The first part of the book delves into the rationale behind the *en masse* relocation of American and European manufacturing to China, alongside the simultaneous shift to "*lean*" and "*just in time*" manufacturing strategies. Goodman attributes this shift to the ravenous desire of corporate executives to drive down manufacturing costs by exploiting cheap Chinese labour and the lax regulatory standards obtaining in China. This, combined with the blind application of efficiency measures such as "*lean*" manufacturing — a concept developed by a resource-constrained Toyota in post-World War II Japan to minimise inventory — across industries created the perfect recipe for significant supply chain disruptions when the pandemic struck. This book follows the story of Hagan Walker, an American business owner whose small company, Glo, relied upon Chinese factories for manufacturing its products. The narrative seamlessly switches between the personal and the political as Goodman intertwines personal stories, such as that of Walker, with incisive political and economic analyses, illustrating how historical trends contributed to the supply chain crisis faced by firms like Glo during the pandemic. He details a logistical nightmare where over fifty container vessels carrying cargo were stuck in a weeks-long disruption at the twin ports of Los Angeles and Long Beach in October 2021, waiting to unload cargo. Fundamental structural flaws in the design of the global supply chain, along with gross miscalculations by corporate executives and shipping carriers — anticipating reduced demand during the pandemic when in fact it surged as people stuck at home ordered more recreational goods — led to a dystopian scenario wherein nearly everything, from toilet paper to computer chips and shipping containers, seemed to be in short supply and prices skyrocketed as supply gradually dried up.

The subsequent section examines the ripple effects of the "*Great Supply Chain Disruption*" for other sectors of the American economy, such as agriculture. Goodman highlights the travails of California's almond industry which was unable to export its produce to the rest of the world due to soaring demand for factory goods and a consequent shortage of containers. Digging deeper, the author unearths the implementational limitations of the US government's policy responses to ameliorate the situation and tame inflation, including the Ocean Shipping Reform Act of June 2022, and critiques the ineffectual attempts to dictate terms to foreign shipping carriers. Shipping carriers, on the other hand, profited heavily off the engineered scarcity and were disinterested in unclogging supply chain bottlenecks to facilitate diversified exports. They readily found corporate executives willing to pay ten times the pre-Covid ocean freight charges for shipping cargo to the American West Coast. Decades of cost-cutting, including layoffs, exacerbated labour shortages across the supply chain — from factory workers to truckers and dockworkers. Goodman argues that the profit-driven nexus between large monopolistic corporations and shipping carriers, functioning essentially as a "*cartel*" with a chokehold on prices, was the primary cause of the trials and tribulations of millions of small and medium business owners and consumers during the pandemic.

Goodman then turns his analytical lens to the workings of the American railroads, concluding that "*precision scheduled railroading*" — which applied the "*just in time*" concept to rail freight — resulted in "*operational perils, [labour] shortages, malfunctioning equipment, and delays*". These issues arose from decades of budget cuts aimed at boosting shareholder dividends. The author argues that the supply chain was faultily designed, prioritising shareholder profits over the interests of smaller business owners, workers, and consumers, and sacrificed resilience on the altar of narrowly defined efficiency metrics. Shedding light on the tragic death of Tin Aye, a female immigrant from Myamnar working at a Colorado slaughterhouse owned by JBS Foods — the largest meat processing company in the world — the author reveals the dark underbelly of large corporations that wilfully compromised worker safety by operating their plants in a business-as-usual manner during the pandemic. Deplorably, they did so in the name of feeding the American populace in the midst of a raging pandemic, but in fact, sat on millions of pounds of meat to be shipped for higher prices to markets in Asia, and China in particular. In stark contrast, American consumers faced record-high beef prices, even as small ranchers across the US went out of business as large conglomerates like JBS squeezed them out of the value chain.

In the final section, Goodman explores alternatives to the current global supply chain model, advocating its restructuring to better serve the needs of consumers, workers, and smaller business owners, rather than just a handful of anointed corporate behemoths. He notes the growing interest of American firms in Mexico as a viable alternative manufacturing location due to its proximity, as also its existing road and rail linkages with the US, making it, in aggregate, a more resilient manufacturing base than China. At the same time, he acknowledges that a complete decoupling from Chinese manufacturing remains a distant pipe dream as the scale and breadth of the Asian giant's industrial capacity makes it nearly impossible to replace it as the world's factory floor in the near future. Goodman further examines various "*China Plus One*" strategies, including "*reshoring*" to the US and "*friendshoring*" to like-minded countries like Vietnam, although, of course, many of these are still dependent upon Chinese raw materials. This notwithstanding, he views the gradual shift towards diversification and the inclusion of resilience as a key component of the strategic calculus of American businesses as a positive development, which must be provided the requisite momentum even though the pandemic itself is now behind us.

In summary, *How the World Ran Out of Everything* is a timely and incisive work of investigative journalism that provides a much-needed fillip to the critical conversation on supply chain resilience as shortages wane and the global economy stabilises in the post-pandemic period. Goodman's compelling prose brings to the fore the poignant stories of ordinary Americans and the human costs of reducing the complex web of the global supply chain to myopic efficiency metrics, which have ironically led to far more pernicious structural inefficiencies and compromised long-term resilience. One of the notable achievements of the book is the "*personalisation*" of the scarcity crisis, which otherwise seemed, for most people, to have been desultorily unfolding in distant ports and viewed only on news channels. Through deft writing skills, the author manages to simplify complex economic concepts, such as "*just in time*" manufacturing and "*precision scheduled railroading*", making them accessible to a broad audience. However, the book could have been further enriched with the inclusion of historical data sets represented through graphs, maps, and flowcharts, which would have made it an indispensable scholarly resource. Further, the author could have undertaken a deeper exploration of India as an alternative manufacturing hub.

The book nevertheless offers valuable lessons for Indian policymakers, regulators, and captains of industry as the world's most populous country aims to bolster its own logistics sector and position itself as a viable "*Plus One*" to attract global manufacturers away from China. Despite India's own dependence upon China for raw materials, which Goodman highlights in the book, the country's size, untapped resources, and burgeoning demographic dividend, present significant potential to develop a competitive supply chain that could rival China's in the long term. To realise this potential, India must continue to invest in improving logistical efficiency, develop skilled labour, and address structural and regulatory inefficiencies that currently stymie the development of a large domestic industrial base. At the same time, it is crucial to learn from the American economic system's vulnerabilities and avoid being swayed by trendy economic concepts at the cost of ignoring their ground-level implications. An enduring lesson for Business and Management Schools across India, if not across the globe as a whole. The clinching argument, as the author suggests, is that it is vital to consider both efficiency and resilience while redesigning the global supply chain to withstand future pandemics and other potential shocks, including those emerging from climate change, geopolitical tensions, and the US-China trade rivalry, which already loom large on the horizon.

21 February 2025

About the Reviewer

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BOOK REVIEW

What The Wild Sea Can Be: The Future of the World's Oceans

Author: Helen Scales
Grove Press UK, 2024. 266 pages
ISBN: 978-I-8047I-051-7

Ms Kripa Anand

The book, What the Wild Sea Can Be, which has been longlisted for the 2024 Baillie Gifford Prize for non-fiction, has been authored by Dr Helen Scales, who is a marine biologist, writer, and broadcaster, and whose books have been adapted for stage and screen and translated into 15 languages. She writes regularly for the Guardian, teaches at Cambridge University and is a storytelling ambassador for the Save Our Seas Foundation. In this latest book, Dr Scales highlights the devastating effects of human actions on the world's oceans while celebrating the remarkable resilience of marine ecosystems in the face of these challenges. She explores ongoing efforts to safeguard the ocean, including the establishment of highly protected reserves, the restoration of seagrass meadows and giant kelp forests, and initiatives aimed at preserving coral reefs.

Dr Scales paints a beautiful picture of the ocean and the remarkable diversity of life it supports, along with an equally ugly picture of the devastation that humanity has inflicted upon the ocean. She uses the term "anthropocene" (a word that describes the current era in which humans have had a significant impact on the planet) almost as a pejorative but with quite some justification, given that over the past fifty years, the total mass of vertebrate life in the ocean has halved, with the oceans becoming more acidic and hotter than ever.

The book encompasses three themes: Ocean Conversion, Vanishing Glories, and Ocean Revival, explored across ten chapters. The theme of ocean conversion is discussed in the first two chapters, namely, "Ancient Seas" and "Remixing Seas". Dr Scales avers that the history of the ocean is important because it provides context for what is happening in contemporary times. In a prehuman world, the ocean was both, a "cradle of evolution and an arena for extinction". The Palaeozoic, Mesozoic, and Cenozoic eras each saw distinct life forms, but even dominant species, such as trilobites, a group of extinct marine arthropods, could not withstand changing conditions. While earlier oceans were shaped by geography, climate, and ecology, human intervention now drives changes, leading to a "remixing" of the seas.

There are numerous examples of humans, driven by economic greed, deliberately introducing invasive aquatic species, which have harmed the local environment. Dr Scales gives the example of lionfish, which were brought into captivity by aquarium keepers in the 20th century, to be bred as pets but were soon released in the Western Atlantic. Native species failed to recognise them as predators, allowing lionfish to thrive while reducing local fish populations by 65 per cent in places like New Providence Island. To control the population of lionfish, "diving derbies" are held where divers try to catch as many lionfish as possible. While lionfish are looked at as evil invaders, it is crucial to remember that these fish are a problem created by human actions.

In part two of the book, Vanishing Glories, the author delves into the coldest continent on Earth, Antarctica. Emperor penguins return there annually to complete a crucial life cycle stage, relying on windproof, waterproof feathers to endure extreme temperatures. However, as temperatures rise, sea ice is breaking during their chick-rearing period, causing many to drown before their feather coats fully develop. Without intervention, Emperor penguins could face extinction by the century's end. The fate of other krill-dependent species, such as Adelie and Chinstrap penguins, is also precarious. Meanwhile, factory ships from China and Norway harvest krill for salmon farms and pet food, further threatening the Antarctic food chain. Currently, only two marine reserves exist in the Southern Ocean to protect these critical ecosystems.

Chapter 4, Missing Angels, describes the decline of species such as the oceanic whitetip shark, once among the most abundant, large marine animals. By 2019, their population had fallen by 95 per cent, leading the International Union for Conservation of Nature (IUCN) to classify them as "Critically Endangered". More than one-third of all known sharks, skates, and rays now face extinction. Technological advancements in fishing—such as longline fishing, monofilament lines, and fossil-fuel-powered ships—have increased industrial fishing efficiency but at a devastating cost. In the US pelagic fleet, longlines extend up to 28 miles, with other fleets using even longer ones. These lines, primarily targeting marlin and tuna, also catch and kill sharks. With few fishing vessels having observers, most shark catches go unreported. When observers are present, they document shocking numbers; in 2018, a Spanish longliner near the Cape Verde Islands caught an average of 7.6 oceanic whitetips per line, with some lines catching as many as 54.

Sharks play a crucial role in marine ecosystems and their decline disrupts the marine balance, leading to unchecked populations of rays and smaller sharks. Even native species, such as rays, are increasingly labelled as invasive, leading to misguided culling efforts. Conservation efforts have made some progress. The "Convention on International Trade in Endangered Species" (CITES) regulates species at risk, listing sharks like the basking shark, whale shark, and the Great White shark. Over time, additional species, including manta rays and hammerhead sharks, have been added to its protected list. Dr Scales describes how sharks were historically viewed as dangerous due to films like Jaws but research has revealed their intelligence and their complex behaviour. Over the years, many shark sanctuaries have been established. However, unless longliner deaths are controlled, these sanctuaries offer little protection for highly migratory species.

Pollution is another major issue, particularly affecting marine mammals with high blubber content, such as orcas, seals, and polar bears. The ocean is contaminated with sewage, chemicals, oil spills, pesticides, mercury, and plastic. Lulu, an orca from Britain's west coast community, died after becoming entangled in fishing lines in 2016. A necropsy revealed that she had high levels of toxic polychlorinated biphenyls (PCBs), chemicals known to impair brain function, immunity, and fertility. The pollutants likely contributed to her inability to reproduce and her eventual entanglement.

The final section, Ocean Revival, focuses on restoration efforts. Dr Scales highlights the successful recovery of species like the Nassau grouper in the Cayman Islands and the northern elephant seal, which rebounded from near-extinction. Marine reserves such as Lamlash Bay in Scotland and areas in Aotearoa, New Zealand, have shown that sea life can thrive when given protection. Ecosystem recovery also boosts resilience to climate change. However, while conservationists fight for no-take zones, deep-sea mining is rapidly expanding. Mining companies are seeking polymetallic nodules from the Clarion-Clipperton Zone (CCZ), an area rich in biodiversity. Despite some areas being designated "no-mining" zones, these were chosen only after mining companies selected their preferred sites, minimising true protection.

In Chapter 10, the author explores potential future developments, such as floating ocean cities. Maldives is planning an ocean city in collaboration with former president Mohamed Nasheed and the Dutch architectural firm, Waterstudio, and this is expected to be operational by 2027. In the Pacific, Dutch entrepreneur Boyan Slat founded the "Ocean Cleanup", a nonprofit company aiming to remove plastic pollution from the Great Pacific Garbage Patch. However, ocean plastic removal is complex, as many marine fauna camouflage with their surroundings, risking accidental removal. The author stresses that grassroots action—limiting plastic production, industrial fishing, and deep-sea mining—is essential for lasting change.

Dr Scales underscores humanity's dependence on the ocean for clean air, rain, and a habitable environment. She highlights successful conservation campaigns, such as universities divesting from fossil fuel financing and European supermarkets pushing for improved Indian Ocean tuna fisheries. Public pressure has led to policy changes, such as France's ban on plastic-wrapped produce. A recent success story in

India saw a record-breaking mass nesting of 682,000 Olive Ridley turtles at Odisha's Rushikulya river mouth in February 2025, following conservation efforts.

While the book provides a holistic perspective in terms of ocean conservation, for readers looking for an action-oriented approach, it can sometimes feel less focused than might be desired. Dr Scales revisits themes and ideas multiple times, making parts of the book seem repetitive. While the book provides an in-depth understanding of the ocean's complexities and is a passionate call to arms, it would have benefited from a tighter structure and as such, might not be an ideal read for those looking for a more sharply-analytical narrative. Also, while this book encompasses all parts of the world, the focus remains primarily on the perspectives of the Global North. In future, Dr Scales would do well to consider incorporating the perspectives of the Global South, so as to offer a more balanced and nuanced view on the subject.

What the Wild Sea Can Be is, therefore, a deeply personal book as the author writes from her own experiences of studying the ocean and witnessing its changes. Through the use of anecdotes, Dr Scales effectively blends personal narrative, environmental insight, and scientific analysis, to paint a vivid picture of the wild, untamed waters that cover much of the face of the Earth. She portrays how deeply interconnected the world is, from sharks to sea stars, orcas, kelp forests and otters, all of which creatures play an indispensable role in maintaining a crucial balance through a complex interplay of natural cycles. What sets this book apart is Scales's skill in making intricate and sometimes unsettling topics understandable to a lay audience. What the Wild Sea Can Be is a compelling, and informative read that inspires action on ocean conservation. Written by a passionate expert, it is a must-read for those wanting to comprehend the deep significance of the world ocean.

24 March 2025

ENDNOTES

1. Hrusikesh Mohanty, "Olive Ridleys Set New Mass Nesting Record at Rushikulya", The Times of India, 22 February 2025. https://timesofindia.indiatimes.com/city/bhubaneswar/olive-ridleys-set-new-mass-nesting-record-at-rushikulya/articleshow/118485378.cms

About the Author

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