PERSPECTIVES ON SOME CONTEMPORARY GEOSCIENCE CHALLENGES IN INDIA

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PRELUDE

The major challenges in geoscience focus on understanding Earth's natural processes to address critical societal issues. These issues include managing limited natural resources, adapting to climate change, and mitigating natural hazards. Tackling these challenges requires collaboration across multiple disciplines and the integration of large, complex datasets. The United Nations Sustainable Development Goals (SDGs) and the global initiative to promote sustainability through science have encouraged scientists to reassess how they can effectively tackle urgent global and societal challenges. Geosciences are linked to most of the 17 SDGs, both directly and indirectly. It is essential to recognize global issues within local contexts, such as the impacts of climate change, water resource management, the need for sustainable energy sources, and the responsible use of vast ocean resources. In addition, advanced scientific research drives the development of innovative technologies that can provide solutions to contemporary problems.

In this context, the office bearers and members of the Federation of Indian Geoscientists and Allied Technologists (FIGA) engage in discussions regarding various global geoscience issues pertinent to India. They underscore the necessity of producing high-quality scientific research, which encompasses testing hypotheses, documenting new data, and employing contemporary techniques such as artificial intelligence and machine learning for data analysis and interpretation. Furthermore, it is essential to strengthen the workforce to effectively address challenges associated with energy, water resources, climate change, and the sustainable utilization of ocean resources.

India has committed to achieving net-zero carbon emissions, recognizing that fossil fuels are likely to continue to play a significant role in the energy mix. Consequently, it is imperative to explore viable options for clean energy sources, which include solar energy, all forms of hydrogen, wind energy, ocean currents or tidal waves, geothermal energy, hydroelectric power, biofuels, and fossil fuels such as gas hydrates. To reach India's net-zero objective, the following strategies are proposed: i) gasification of available coal and oil resources, alongside the discovery of new fuel gases, to facilitate a gradual transition to a low-carbon energy supply; ii) fostering innovation to ensure a secure supply of renewable and green energy resources; and iii) integrating Carbon Capture, Utilization, and Sequestration (CCUS) into existing fossil fuel utilization frameworks.

The strategic importance of critical and energy minerals is paramount in meeting net-zero targets and advancing the energy transition. The Ministry of Mines has identified 30 critical minerals, including lithium, cobalt, nickel, rare earth elements, graphite, copper, molybdenum, tungsten, and vanadium. Presently, India's domestic production of most critical minerals remains limited. It is recommended that planned exploration, economic extraction, and responsible utilization require a comprehensive integration of geosciences, chemical engineering, materials science, environmental management, and strategic policy formulation. Mere exploration is insufficient; the entire value chain—from midstream processing and refining to the application of relevant scientific disciplines—must be developed through collaboration among academic institutions, research organizations, and industry partners.

India exhibits considerable geological potential; however, there is a pressing need to bridge the gap between resource identification and industrial application. Geoscientific data, encompassing information related to the earth, oceans, climate, and the environment, constitutes one of the largest volumes of data generated globally, with continuous growth necessitating advancements in analysis, processing, and interpretation technologies. High-performance computing systems, artificial intelligence, and quantum algorithms will enhance data-driven forecasting and predictive models essential for knowledge generation and societal advancements.

India encounters a complex interplay of hydrological, environmental, and socio-economic challenges that significantly impact water resource development and management, as well as the stability of the hydrological cycle. Unresolved issues such as the interactions between groundwater and surface water, extreme weather events, and the deterioration of water quality are particularly pertinent within the Indian context. To ensure sustainable and equitable water availability for both current and future generations, it is imperative to strengthen data systems, integrate scientific findings with policy frameworks, and foster cooperation among stakeholders.

The effects of climate change exert an indirect influence on terrestrial water cycles, manifesting through increasingly intense storms. Disasters, including droughts, floods, aridification, wildfires, and pollution, result in loss of life, injuries, economic damages, and forced migration, leading to socio-economic and environmental setbacks. Implementing nature-based solutions, such as reforestation, terracing, and the construction of local dams, combined with the utilization of climate action data, can effectively mitigate the impacts of climate change and address meteorological hazards.

It is essential to initiate a comprehensive country-level systematic subsurface imaging program that employs multiple sensors to analyze a range of depths, from shallow to deep. Shallow imaging, which extends from several tens of meters to a few kilometers, will facilitate the identification of water and mineral resources. In contrast, deep imaging will contribute to a greater understanding of seismic and geological processes occurring deep within the Earth. By elucidating the relationship between deep structural features and their influence on shallower geological characteristics, as well as their evolution over time and across different spatial contexts, this program will enhance resource identification and improve predictive modeling capabilities.

The oceans are crucial to the Earth's life-support system, yet a significant portion of the deep ocean remains unexplored and inadequately understood. Oceans play a vital role in providing food, regulating climate, producing half of the oxygen we consume, serving as the largest carbon sink, and offering non-living resources for energy. Furthermore, they facilitate maritime transport and are essential for national security, while providing protection for coastal regions against storms, erosion, and other marine hazards. The Government of India's Deep Ocean Mission is a noteworthy initiative that encompasses these critical elements. It represents a coordinated national effort, incorporating international partnerships aimed at securing maritime domains and sustainably utilizing ocean resources for economic advancement.

India's progressive policies and strategic initiatives necessitate the development of a resilient, future-ready geoscience ecosystem, highlighting the importance of strengthening skilled human resources as a foundational element for achieving long-term national benefits

V.M. Tiwari & P Rajendra Prasad

ENERGY SECURITY AND ROLE OF AI-AIDED GEOSCIENCES

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Energy Security

Energy is the prime engine for any country's socio-economic growth and strategic advancement. The world's vast energy requirements are mostly met by fossil fuels (coal, oil, and natural gas), the burning of which has been attributed to global warming and climate change. The coal produces maximum amount of CO_2 followed by oil with the least amount by natural gas. A lot of efforts is thus being made to find out alternate(s) to fossil fuels as a remedial measure to combat carbon footprint and control further warming. The UN has set the target of carbon neutrality by 2050, net zero carbon emission by 2070, and taming further rise in temperature by 2^o C. However, no breakthrough has taken place in the renewable/green energy sectors: solar, wind, ocean current or tidal wave, geothermal, hydrogen, hydro, bio-fuels, plastic to aviation fuels or agricultural waste to ethanol, EVs or batteries on wheels. Though there lies a tremendous scope for developing innovative approaches from non-fossil fuels, 80% of global energy requirement is met by fossil fuels till date. The International Energy Agency (2021) has predicted that fossil fuels will remain as the main energy driver. Consequently, we need to foster low-carbon energy supply and strengthen the gas-based technology to meet cleaner energy necessity (SDG-7) and make much less impact to climate variability (SDG-13). These can be achieved through (i) gasification of available coals and oils, and discovery of new fuel gas for gradual transition to a low-carbon energy supply, and (ii) ingenuity for secured supply of tenable renewable/green energy resources. If we have depend on fossil fuels, we need to strengthen our research on Carbon Capture, Utilisation and Sequestration (CCUS) experiments by (a) efficiently arresting carbon from the static (power plants, industry processes and households), and dynamic (transportation) sources followed by (b) proficiently converting them into usable products such as methanol and its derivatives or carbonates, or by (c) transporting them for enhanced oil recovery, exploitation of gas-hydrates through molecular substitution, and geological sequestration. For capturing carbon, innovative approach based on absorption, adsorption, chemical looping, membrane gas separation or gas hydration is to be developed. The CO_2 can be sequestered by injecting them into porous rocks (sandstone, shale, dolomite) kilometres beneath the surface and overlain by impermeable and non-porous rocks that prevent their migrating upward. Sub-volcanic sediments, depleted oil/gas fields, deep coal seams, saline formations, submarine sediments are suitable reservoirs for CO_2 geological sequestration. As per the IPCC report, the reason for restricting global average warming by 2°C is that this may lead to sea level rise and hence submergence of many low lying lands and important cities (particularly in the coastal regions) and relocation of a few hundred million people worldwide. Besides, if the temperature rises beyond, it will severely affect the health security - heat-related deaths, infection with vector-borne diseases such as malaria and dengue fever etc., and development of nutrition problem.

The primary energy resources in the current global scenario are Oil – 33.1%, Coal – 27%, Natural Gas – 24.2%, Hydroelectricity – 6%, Renewables – 5%, Nuclear – 4.3%. India has a rich history of hydrocarbon exploration, beginning with the discovery of the Digboi oilfield in Assam in 1889, one of the earliest producing oilfields in Asia. Out of 26 Indian sedimentary basins covering 3.14 million km^2 total area including shallow-water (up to 400m isobath) and deep-water (from 400m Isobath to the outer limit of EEZ), prospect-wise we have 7 Category-I basins that have reserves and are already producing; 5 category-II basins that have contingent resources and are pending for commercial production) and 14 Category-III basins that have prospective resources and wait for discovery (https://www.ndrdgh.gov.in). The Category-I basins are Krishna-Godavari (KG), Mumbai Offshore, Assam Shelf, Rajasthan (Barmer, Jaisalmer and Bikaner-Nagaur sub-basins) Cauvery, Assam-Arakan Fold belt and Cambay basins. The Category-II basins are Saurashtra, Kutch, Vindhyan, Mahanadi and Andaman basins. The Category-III basins are Kerala-Konkan (KK), Bengal-Purnea, Ganga-Punjab, Pranhita-Godavari (PG), Satpura-South Rewa-Damodar, Himalayan Foreland, Chhattisgarh, Narmada, Spiti-Zanskar, Deccan-Syneclise, Cuddapah, Karewa, Bhima-Kaladgi and Bastar basins.

India produces less than $1/4^{th}$ of her energy requirement, and no major oil/gas fields has been discovered during the last many decades, and indigenous hydrocarbon production has plateaued in recent decades with crude oil import dependency now exceeding 85%. As the era of finding oil/gas at ease is almost over, we require to venture into the category-II and –III basins, particularly in the difficult terrains such as fold thrust belts or foreland of the Himalaya, sub-volcanic regions in central-western Indian onland and offshore, deep and ultra-deep waters for the exploration of conventional oil/gas. On the other hand, submarine gas-hydrates, shale gas/oil, coal bed methane are considered major unconventional energy resources of India. In this context, structural and stratigraphic analysis of the subsurface geologic environment using both conventional and advanced interpretation techniques is crucial and should be executed with great detail for understanding the reservoir heterogeneity, fluid migration, and permeability pathways - certain key parameters for optimizing hydrocarbon recovery and managing mature reservoirs. The Science-Technology-Innovation interface is need of the hour to tap these resources in an economically affordable and environmentally-safe manner.

Gas-hydrates, consisting of methane gas (99.9%) and water, are envisaged as major cleanest hydrocarbon energy resources. The methane stored within gas-hydrates along the Indian margin has been prognosticated to be more than 1500 times of country's present natural gas reserve (Sain and Gupta, 2012). The extraction of gas-hydrates can sustain India's crushing energy demand for several centuries. Therefore, it makes sense for the investment to the development and production of gas-hydrates because of their high market prospects to (i) make India energy self-reliant, (ii) reduce direct dependency on coal and oil, (iii) meet UN's sustainable development goals, and (iv) get rid of recent threat of elevated tariff imposed by the US. Several institutes/organizations under the umbrella of Indian National Gas-hydrates Program have generated plethora of information with regard to the delineation and assessment of gas-hydrates along with the derivation of critical parameters and understanding the petroleum system and dissociation kinetics. These are necessary for the development of geology-specific production technology. India must collaborate with countries like Japan, US, and China, which have made major strides for successful test production of gas-hydrates and environment related research into their respective countries for strengthening the research and development in India.

In parallel, geothermal energy has emerged as a promising but underdeveloped component of India's renewable energy portfolio. Derived from the Earth's internal heat, geothermal resources are closely linked to the country's tectonic and geological diversity. More than 300 geothermal hot spring systems have been identified and thus are grouped into seven major geothermal provinces: Himalaya, Sohana (Haryana), Cambay, Son–Narmada–Tapi, Godavari, Mahanadi, and West Coast provinces (GSI, 2022). High-temperature systems in the Puga Valley and Chhumathang (Ladakh), Manikaran (Himachal Pradesh), and Tattapani (Chhattisgarh) exhibit significant potential for both direct-use applications and binary-cycle power generation. Given their dependence on subsurface heterogeneity and tectonic settings, the geothermal systems share strong parallels with hydrocarbon reservoirs. Their evolution and provenance must be explored in detail for identifying zones of enhanced fluid circulation and heat extraction potential.

India is endowed with varied geographical landscapes covering lofty Himalaya in the north and a long coastline along the eastern and western margins with abundance of wind and sunshine, a mix of coal-bearing and gas-rich sedimentary basins, geothermal provinces, marine gas-hydrates, agriculture-dominated rural environment, industry-based urban ecosystem, variable climate like tropical in south to temperate in north to alpine in the Himalaya, monsoon rains on most parts of India in summer, sustained snowfall in extended winter over the elevated Himalaya. Thus, availability of different kinds of energy resources and varying necessity in different region offer an encouraging scenario for the development of hybrid technologies by combining two or more different types of energy resources such as solar and/or wind with geothermal or ocean energy as a plausible solution to climate change mitigation. There lies a tremendous scope for the development of mixed energy production by coupling gas-hydrates with the ocean currents or tidal waves or wind energy.

Role of AI-aided Geosciences

Human brain is capable for qualitative analysis and pattern recognition, but often gets exhausted to offer correct answers to quantitative questions and confused to deal with multiple data sets with variable formats. Whereas, a machine, if properly trained by a human being, can do such jobs with greater accuracy, even if the data volume is huge and problem is complex. This has prompted to develop AI-enabled approaches by fusing human intelligence with the machine intelligence that can process not only a large volume of data and but can solve complicated issues at much ease. Platform such as *AI-aided Geosciences* plays a pivotal role for solving the complex problems of interdisciplinary Earth System Sciences, which has demonstrated how machine learning and geospatial analytics can bridge the gap between **structural geology, reservoir engineering, and energy transition planning.** The adoption of AI/ML tools can enable geoscientists to process large and multi-dimensional datasets more effectively and derive actionable interpretations that are not so easy to achieve through conventional methods alone. The sustainable, resilient, efficient discovery and management of energy resources are increasingly getting reliant on advanced AI/ML-centric geoscientific techniques.

The AI-aided geosciences using physics-inspired ML and modern networks including CNN, GNN, PNN, Transformer, U-Net, GAN, etc. have transformed the subsurface image enhancement and automatic interpretation across the conventional and renewable energy domains. Data-driven algorithms, based on supervised and unsupervised learnings, have led to reliable detection of subsurface geologic structures and stratigraphic features, reservoir characterization, lithofacies prediction, and even delineation of subtle geologic patterns that are often overlooked in traditional workflows. Thus, AI/ML approaches offer rapid, objective, and scalable insights across large datasets. A transformative development has been the rise of Physics-Informed Neural Network (PINN), which can incorporate fundamental governing equations such as stress–strain relation, Darcy's flow or Fourier's heat conduction directly into the learning framework. Unlike conventional AI models that rely solely on data, the PINN blend data-driven learning with first-principle physics empowers consistent predictions even if the data are sparse and noisy. Employment of PINNplays a revolutionary role in subsurface exploration, risk assessment, and operational optimisation for conventional, unconventional and renewable energy resources, and carbon storage projects. Data assimilation frameworks using Bayesian or Kalman filter can integrate real-time or chronological observations with simulated estimates to continuously update the Earth models by including new measurements / parameters. Therefore, the ML architectures can incorporate domain-specific constraints by regularising physical properties like porosity, anisotropy, seismic velocity and correcting solutions for authenticity of geological features like faults and fractures. The probabilistic ML provides estimate of uncertainties that are required for decision-making.

Geosciences have seen rapid advancement through the integration of a variety of erudite AI models, each contributing uniquely to the challenges for the image enhancement and effective interpretation of Geoscientific data. The employment of convolutional neural network (CNN) is fundamental in extracting spatial patterns from regular grid datasets like seismic cubes, denoising seismic volumes and delineating features like faults, horizons, facies, etc. Addition of 3D U-Net structures, residual connections and attention layers has further elevated the ability to model both local and contextual geological structures. The Graph neural network (GNN) addresses the complexity of data structured as nodes and edges, which make them ideal for modelling spatial relationship in sensor networks, fracture connectivity and reservoir architecture. The Probabilistic neural network (PNN) focuses on classifying seismic events or lithology by estimating probability densities and offers quick training, which makes them robust to handle imbalanced data distribution. The Transformers learning algorithms with their self-attention mechanisms allow modelling of long-range dependencies in both temporal and spatial data. Recently, researches have demonstrated pre-trained transformer, based on large language models (LLM), computer vision (CV), and multi-modal data integration, for fault prediction from seismic data. The Generative adversarial network (GAN) has transformed synthetic data to address sample scarcity by producing realistic seismic traces, reconstructing missing information, and augmenting rare facies, while providing valuable calibration tools for simulating extreme or underrepresented events. The Auto-encoders and their variants allow compact encoding and denoising of geological attributes, underpinning unsupervised data compression, anomaly detection or clustering of multi-attribute seismic patterns. The U-Net architectures through the integration of residual and attention modules have demonstrated the performance in segmentation of faults, stratigraphic boundaries and facies for both 2D and 3D seismic data. Thus, the neural network architectures have empowered geoscientists to analyse, model, and interpret automatically (Sain and Kumar, 2022) or predict subsurface features or properties with accuracy, which are useful for data-driven decision for exploration and resource management.

Large-scale analytics depend on up-to-date hardware and software capable of handling massive geoscientific datasets. Modern security and risk management demand AI-enabled monitoring of critical energy assets such as pipelines, wells and storage sites to detect leakages, theft and environmental threats. Additionally, the workforce development is equally vital; the policy should encourage interdisciplinary education blending geoscience foundations with data science, deep learning and ethical AI ideologies.

A few other key applications of AI/ML in Geosciences include monitoring and early warnings of different kinds of geological hazards like floods, landslides, earthquakes and tsunamis, cyclones, glacial/snow avalanche and glacial lakes outburst floods.

CRITICAL AND ENERGY MINERALS

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Scope

The twenty-first century is witnessing a profound transition in material metabolism for civilizational sustenance. The ever-growing demand for decarbonisation, electrification and digitalisation and its tempo have necessitated greater access to specific minerals (categorized as 'critical minerals') such as lithium, cobalt, nickel, graphite, manganese, rare earth elements (REEs), copper, uranium and thorium for seamless functioning of modern society. The criticality of a mineral is dynamic and a function of supply risk, economic indispensability and global politics. Minerals that are essential for key technologies for economic development and national security but possess poor concentration or vulnerable supply chains are designated as critical. Uranium, thorium, which directly fuels power generation and lithium, nickel, cobalt, copper, REEs, tellurium and gallium are energy minerals and constitute a subcategory of critical minerals. Together, they form the backbone of the evolving global energy and modern technology landscape and are vital to global transition to a low-carbon-emission economy and renewable energy technologies for meeting the 'Net Zero' commitments. These minerals are not rare in absolute abundance, but their economically recoverable concentrations occur only within specific lithological, structural and geochemical environments. Understanding those geological controls is therefore a prerequisite for any effective strategy for resource assessment and policy formulation.

The global demand for critical minerals is expected to increase 3- to 7-fold by 2040 (International Energy Agency, 2024). However, the global supply chains of critical minerals, by virtue of geological concentration and processing monopoly, are remarkably asymmetric. For instances, more than two-thirds of cobalt mining occurs in Central Africa; China continues to dominate rare-earth refining and magnet fabrication; and Australia, Chile and Argentina collectively control over 80% of lithium extraction. Such global asymmetry in supply chains has transformed mineral supply into a strategic instrument for foreign policy in geopolitics. Recent export restrictions on gallium, germanium and graphite (3Gs) exemplify leveraging mineral resources for influencing technological and defence sector deals worldwide.

Consequently, major economies have adopted national and multi-lateral strategic initiatives. Australia, Canada and Japan have launched partnership frameworks emphasizing resilient supply chains and ESG (Environmental, Social, Governance) compliance. The European Union's Critical Raw Materials Act (2024) has renewed targets for domestic extraction (10%), processing (40%) and recycling (25%) of critical minerals by 2030. Concurrently, the USGS has issued a draft "2025 List of Critical Minerals" comprising 54 mineral commodities including copper, potash, silicon and zirconium.

While the demand for electric vehicles and renewable-energy storage devices is likely to surge within a decade, the discovery-to-production gestation period for a new deposit is typically 12–15 years. This temporal mismatch generates a chronic supply gap and economic volatility. Moreover, technological lock-ins, such as cobalt-rich cathodes and REE-based permanent magnets, limited substitution (alternative) flexibility, reinforces dependence on a restricted suite of minerals.

The evolving global dynamics for emission-free energy transition have given rise to three intertwined issues that define the contemporary mineral economics. This first is the disparity between the accelerating magnitude of demand and the paucity as well as latency of supply. Even as the production of key minerals such as lithium and cobalt are projected to double, the downstream stages like processing, extracting, refining, alloying and component fabrication remain hindered by protracted gestation periods and technological bottlenecks. The second issue arises from geopolitical chokepoints. The capacity of large-scale processing and refining of critical minerals being limited to only a few nations, the global supply chain is highly susceptible to disruptions arising from export controls, policy shifts and regional instabilities. The third and perhaps the most paradoxical, is the sustainability dilemma. While these minerals form the backbone of the clean energy transition, their extraction and processing leave significant environmental footprints through intensive water consumption, tailings and chemical waste generation. Collectively, these issues highlight the urgent need for a more diversified, transparent and environmentally responsible approach for managing the global critical mineral supply chains.

The Indian Context

Driven by rapid industrialization, national electric mobility mission and ambitious plan for expansion of renewable energy capacity to 500 GW by 2030, India has recognized critical minerals as a strategic priority. The Ministry of Mines in 2023 published a list of 30 critical minerals, including lithium, cobalt, nickel, REE, graphite, copper, molybdenum, tungsten and vanadium. Nevertheless, dependence on imported strategic minerals poses significant challenges to the nation's energy security and industrial competitiveness. Recognizing this India has taken several policy steps.

At this backdrop, India's geological heritage and diversity is well suited to play a pivotal role. Atomic Minerals Directorate for Exploration and Research (AMD) is carrying out exploration and augmentation of minerals of rare earth group elements along the coastal / inland / riverine placer sands as well as in hard-rock terranes in several potential geological domains of the country. As on date, AMD has estimated 4,33,800 tonnes of in-situ uranium oxide in parts of Andhra Pradesh, Jharkhand and Rajasthan and approximately 7.23 million tonne (Mt) in-situ Rare Earth Elements Oxide (REO) contained in 13.15 Mt monazite [a mineral of Thorium (~10% ThO_2) and Rare Earths (~55% REO)], along with 761.97 Mt of titanium bearing minerals (ilmenite, rutile, leucoxene) and 38 Mt of zirconium bearing minerals occurring in the coastal beach, Teri / red sands and inland alluvium in parts of Andhra Pradesh, Odisha, Tamil Nadu, Kerala, West Bengal, Jharkhand, Gujarat and Maharashtra. Besides, 1.29 Mt in-situ REO resources have been established in hard-rocks in parts of Gujarat and Rajasthan. Further, AMD has established ~1,800 t of lithium oxide resources in G-2 category in the pegmatites of Marlagalla, Mandya district, Karnataka.

According to the National Mineral Inventory (NMI) compiled by the Indian Bureau of Mines as on 1 April 2020, India possesses substantial reserves of several key critical minerals. The country holds 21.16 Mt of graphite, 31.12 Mt of rock phosphate. Additionally, India has 8.94 Mt of tungsten ore and 2.46 Mt of vanadium ore, while Nickel resources of 189 Mt are concentrated in the ultramafic belts of Odisha, Jharkhand and Nagaland. Cobalt resources remain limited with ~45 Mt of ore.

To harness these resources effectively, the Government of India launched the National Critical Minerals Mission (NCMM) in January 2025, with a total expenditure of Rs. 16,300 crore for 2024-25 to 2030-31, to ensure a long-term, sustainable supply of critical minerals and to strengthen domestic value chains from exploration to recycling. Under its aegis, the Geological Survey of India (GSI) has significantly expanded its efforts, undertaking 195 exploration projects in 2024-25 and 230 projects in 2025-26 targeting lithium, REEs, tungsten, graphite, vanadium and other strategic minerals.

Recognising that India remains import-dependent, for several high-demand minerals, the Government has adopted a comprehensive policy framework combining legislative, fiscal and diplomatic interventions. Amendments to the MMDR Act, 1957 and related rules have simplified licensing and accelerated block auctions. Import duties on several critical minerals and their scrap were removed in Union Budgets 2024–25 and 2025–26 to ensure supply diversification and cost efficiency. Furthermore, the government has prioritised overseas mineral acquisition through Khanij Bidesh India Limited (KABIL), a joint venture between NALCO, HCL and MECL, which signed an Exploration and Development Agreement with Argentina's state-owned enterprise CAMYEN for five lithium brine blocks covering 15,703 hectares in Catamarca Province. India has also positioned itself in global mineral alliances through platforms such as the Minerals Security Partnership (MSP), Indo-Pacific Economic Framework (IPEF), India-UK Technology and Security Initiative (TSI) and the Quadrilateral Security Dialogue (QUAD), reflecting its commitment to responsible sourcing and resilient supply chains. Further, the National Geoscience Data Repository (NGDR) portal has been created to provide seamless access to India's geoscientific and mineral exploration data, enabling transparency, informed decision-making and greater private sector participation in the country's mineral exploration activities.

Despite these advancements, India's domestic production of most critical minerals remains minimal. While global REO production in 2024 was ~45,000 tonnes (in mineral concentrate) in the U.S. alone (a fraction of global production), India's REE output remained confined to production of small volumes (by IREL (India) Ltd. and allied agencies) with limited separation and magnet manufacturing. As on date, India relies heavily on imports for magnets, specialty alloys and battery precursors.

India's critical mineral ambitions are riddled with multiples challenges: (a) limited risk-capital for greenfield exploration and slower pace of resource conversion; (b) inadequate pilot-scale metallurgical infrastructure for extraction and refining; (c) decoupling between exploration agencies and downstream users; (d) nascent recycling and circular-economy practices; (e) environmental and socio-economic constraints. Bridging these gaps requires simultaneous advancement of geosciences knowledgebase, development of domestic processing technology and proactive role of environmental and regulatory agencies. Thus, India today stands at the crossroads of significant natural endowment and emerging policy momentum, yet substantial gaps persist in value-chain integration, timeliness and sustainability.

Pathways for Mitigation and Sustainable Development

India's energy transition requires nurturing a holistic critical mineral ecosystem spanning exploration, processing, recycling and innovation. As India defines its strategic roadmap, it must ensure a coherent transition from subsurface scientific exploration to the development of sovereign technological capabilities. Exploration systems should evolve into dynamic, adaptive and data-driven robust frameworks. A new exploration paradigm for mineral discovery must combine aerial hyperspectral surveys, geophysical inversions, isotopic fingerprinting and machine-learning-based prospectivity analysis, crosslinking them with geochemical and structural databases. Multi-parametric datasets, when assimilated into 3-D geological models, should enable prediction of concealed ore systems at depth. Simultaneously, geological data infrastructures like Bhukosh and NGDR must be upgraded into real-time, interoperable platforms to facilitate ease of data access, encourage collaborative innovation and reduce asymmetric risk.

At this juncture, India on the ground needs dedicated exploration corridors or cluster zones, where infrastructure – roads, power, tailings facilities, water supply – is pre-provisioned. This will instil greater confidence among investor consortia to participate in such emerging exploration corridors and enable them to focus is strictly on geology and metallurgy instead of wasting energy for addressing logistic issues. This will reduce upfront cost, gestation period and accelerate project viability.

However, geology alone is not sufficient. India must build midstream processing and refining capabilities. Pilot plants for solvent-extraction, ion-exchange, molten-salt separation, hydrometallurgy and magnet fabrication should be developed through multi-institution consortia involving IITs, CSIR, BARC and industry partners. A seamless collaboration between academia and industry should be established to operate pilot plants using Indian ores, thereby validating process robustness within indigenous matrices and enabling subsequent industrial-scale deployment. Efforts should aim for energy-efficiency, closed-loop reagent usage, minimal waste and low carbon footprint. Complementing this effort is the imperative of adopting a circular economy. India must catalyse an ecosystem for recycling spent lithium-ion batteries, end-of-life electronics and rare-earth-magnet wastes. Well-designed collection networks, rigorous safety protocols and high-precision recovery technologies (pyro-hydrometallurgical hybrids, selective leaching, membrane separation) can convert waste into strategic feedstock. The recycled volumes offer both cost and supply security advantages, especially during external disruptions.

Financially, the Government may plan for a catalytic fund or financing mechanism that would absorb early-stage risk via convertible equity, guarantees, or provide first-loss support for exploration and first-of-kind processing units. This instrument must be tied to performance metrics – yield, energy intensity, and recycling share – so that private capital is drawn only when projects show credible scale-up pathways. Diplomatic and global partnerships are equally vital. India must negotiate for bilateral and multilateral mineral-development pacts that offer technical capacity, infrastructure co-investment and joint technology development opportunity in exchange for secure supply access. Membership in global frameworks like the Minerals Security Partnership provides not just access but governance norms, intelligence sharing and buffer alliances.

However, no mineral policy succeeds without environmental and social legitimacy. From project outset, baseline hydrology, biosphere mapping, community engagement, compensation and restoration must be integral – not an afterthought. In ecologically sensitive or tribal regions, the framework of social geology (the interface between geology and human systems) must be integrated. Poor ESG compliance risks litigation, project delays and reputational harm.

India's priorities in the critical minerals sector should evolve with changing technological and market dynamics. A robust, continuously evolving and data-driven forecasting framework must underpin strategic decision-making. Demand modelling for EV batteries, hydrogen electrolysers, grid-scale storage, nuclear power, defence electronics and renewable infrastructures should guide priority elements (e.g., Nd, Dy, Li, Ni), exploration focus and downstream incentive design.

Crucially, India must leverage the synergy between critical minerals and nuclear industry. Monazite-rich coastal sands contain REEs and thorium. Development efforts should focus on metallurgical circuits that can efficiently separate light REEs and concurrently concentrate actinides. Therefore, the geological, metallurgical and regulatory systems for REE extraction ought to be intimately linked with strategies for thorium fuel cycles and uranium exploration. This integrated approach safeguards India's crustal assets from being marginalized by policy inertia or technological limitations, instead aligning them within a unified framework of resource development.

Conclusion

Critical and energy minerals are the material-substratum for the contemporary energy transition towards Net Zero carbon emission. Their planned exploration, economic extraction and responsible utilisation demand an intricate synthesis of geosciences, chemical engineering, material sciences, environmental management and strategic policies. For India, endowed with a vast mosaic of heterogeneous geological domains, securing critical and energy minerals is both an economic and strategic imperative. The task ahead is not merely to locate deposits but to construct a scientific value chain – from understanding crustal processes to component fabrication – that is resilient, transparent and sustainable.

The country possesses significant geological potential but must bridge the gap between resource identification and industrial utilization through policy coherence, investment support, technological innovation and responsible mining practices. By involving advanced geoscientific methodologies, nurturing indigenous processing technologies and forging cooperative international partnerships, India can evolve from a passive consumer to an efficient architect of the global critical-mineral landscape. The challenge is profound, but so is the opportunity: to align the deep time of geology with the urgent need of civilizational sustenance.

CRITICAL ISSUES AND EMERGING CHALLENGES IN MANAGEMENT OF INDIA'S WATER RESOURCES

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Scope

Occupying 2.4% of the global land area, India houses nearly 17% of the world's population. Its varied geohydrological environment includes the Himalayas, the Indo-Gangetic-Brahmaputra plains, and extensive coastlines. The climate ranges from tropical in the south to temperate in the north, with annual precipitation of around 4,000 billion cubic meters. The Indian Summer Monsoon accounts for 70–80% of this rainfall, with significant regional variability. India relies on both surface water and groundwater for its resources. Major rivers are fed by Himalayan glaciers, while aquifers are recharged by rainfall. The 2020 assessment indicated that the total annual groundwater recharge is about 436 billion cubic meters, with 67% coming from rainfall. Extractable groundwater resources are around 398 billion cubic meters, with annual extraction at approximately 245 billion cubic meters, predominantly for irrigation. Population growth, rapid urbanization, industrial expansion, and changing agricultural practices have created significant stress on water resources in India, compounded by erratic monsoons, climate variability, and geological disparities. These situations, along with complex hydrological, environmental conditions, significantly challenge water resource management in India. These challenges can be addressed through integrating scientific insights with policy, technology, and community participation. Key issues identified by the global scientific community, such as groundwater-surface water interactions, extreme events, and water quality deterioration, remain relevant in India.

Major Challenges

Monsoon Dynamics and Climate Variability

The Indian Summer Monsoon (ISM) is central to the country's hydrology. Driven by the seasonal migration of the Intertropical Convergence Zone, it governs precipitation and water availability across most of the subcontinent. However, the predictability of monsoon rainfall remains limited due to complex ocean–atmosphere–land interactions and intraseasonal oscillations. Teleconnections with global phenomena such as the El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) further modulate rainfall variability. In recent decades, anthropogenic influences, greenhouse gases and aerosols have added new dimensions of uncertainty, contributing to the observed regional disparities in rainfall patterns and their extremities.

Extreme Events: Floods and Droughts

India experiences increasing frequency and intensity of extreme rainfall events, leading to recurrent floods and prolonged droughts. While the number of rainy days has marginally declined in many regions, rainfall intensity has increased, resulting in high uneven distribution. Large-scale climatic oscillations such as ENSO strongly influence drought occurrence. About 40% of El Niño events have historically coincided with major droughts in India. Conversely, extreme floods are becoming more common due to rapid urbanization, encroachment of floodplains and inadequate drainage infrastructure. Managing these extremes requires improved hydro-meteorological observation networks, coupled models and integrated risk-reduction strategies.

Environmental Flows and River Health

Over the past six decades, extensive dam construction and flow diversions have altered the hydrological regimes and the drainage networks of Indian rivers. While these interventions have enhanced irrigation and hydropower capacity, they also disrupted natural flow patterns, sediment transport and aquatic ecosystems. Many rivers, such as the Krishna and Godavari, have changed from perennial to ephemeral seasonal systems, severely degrading riverine and riparian practices. Maintaining environmental flows (E-flows) is now recognized as essential for river rejuvenation and ecological balance. However, standardized methodologies for E-flow assessment and implementation remain limited in India, necessitating scientific and policy interventions.

Groundwater Stress and Quality Degradation

Groundwater is India's lifeline, supporting over 60% of irrigation and 85% of rural drinking water needs. Yet, over-extraction has caused alarming declines in water tables, especially in north western, western and peninsular regions. The problem is aggravated by the country's geological heterogeneity—nearly three-fourths of the area underlain by hard rock aquifers with limited storage and low transmissivity. Mapping, monitoring and sustainable management of aquifers thus remain major scientific and regulatory challenges.

Water quality deterioration from industrial effluents, agricultural runoff and geogenic contaminants (such as fluoride, arsenic and iron) compounds the problem. The growing presence of micro and nano plastics, pharmaceuticals and other emerging pollutants in aquifers underscores the need for advanced monitoring and treatment technologies.

Inadequate information of aquifer systems

India's aquifer systems are divided into 14 primary classifications, with alluvial aquifers making up the largest segment, accounting for approximately 31% of the country's total area. Other significant aquifer types include basalt, sandstone, and banded gneissic complex aquifers, which are categorized as hard-rock aquifers and collectively represent about 65% of peninsular India. The available maps of these aquifer systems are insufficient, leading to a considerable information gap due to the diverse geohydrological conditions and logistical challenges. The geological composition of an aquifer is crucial in determining groundwater recharge rates, pollution risks, and the volume of water that can be sustainably extracted and used. Therefore, detailed mapping of aquifer systems is essential for effective water management.

Coastal Aquifers, Submarine Groundwater Discharge and Seawater Intrusion

India's long coastline is increasingly affected by over-extraction of groundwater, leading to seawater intrusion and irreversible damage to coastal aquifers. In several areas, groundwater levels have fallen below mean sea level, allowing saline water to encroach inland. At the same time, Submarine Groundwater Discharge (SGD)—the movement of freshwater from land to sea through the seabed—plays an important but poorly quantified role in coastal hydrology. Understanding and managing SGD processes are crucial for maintaining coastal water balance and ecosystem health.

Data Inadequacy and Knowledge Gaps

Despite a wide network of hydrometeorological stations, river gauging stations, groundwater monitoring systems, data gaps remain a major constraint. The spatial and temporal resolution of rainfall, streamflow, groundwater and water-quality observations are insufficient to capture India's diverse hydrological conditions. Limited data sharing among institutions further hampers integrated assessment and model development. This warrants enhanced observation systems, open data policies and the adoption of modern techniques such as remote sensing, GIS and numerical modelling.

Governance and Policy Constraints

Water is a state subject under India's Constitution, leading to fragmented governance and inconsistent management practices. Inter-state river disputes, overlapping institutional mandates and lack of coordination among departments hinder effective policy implementation. While the central government facilitates inter-state water sharing through tribunals and promotes programs like Jal Jeevan Mission and Atal Bhujal Yojana, coherent governance frameworks integrating surface and groundwater, quantity and quality and supply and demand management remain limited.

The government's emphasis on "Har Ghar Jal" (safe drinking water for all) and wastewater recycling marks important progress, but achieving easy access requires stronger institutional linkages, capacity building and technology adoption.

The Drinking Water Challenge

Responding to a Supreme Court directive, the Department of Science and Technology (DST) initiated a national mission to develop safe, affordable drinking water technologies. Expert committees identified key challenges, including contamination by fluoride, arsenic, iron, nitrate and microbial pathogens. DST's initiatives have emphasized decentralized water treatment systems, cost-effective purification technologies and wastewater recycling for secondary and tertiary use. These efforts aim to close the loop between water supply, reuse and environmental sustainability.

Surface Water Concerns

Most Indian rivers are under dual stress, declining flow and deteriorating quality. Prolonged dry spells, erratic monsoons, intensive irrigation and rampant pollution have transformed many perennial rivers into ephemeral seasonal streams. Excessive fertilizer and pesticide use, inadequate wastewater treatment and cultural practices such as immersion of idols contribute to the poor water quality. Effective river basin management, incorporating pollution control, watershed restoration and community participation, is critical for sustainable recovery of surface water systems.

Opportunities and the Way Forward

Recognizing that challenges are an inherent aspect of this sector, India possesses the resilience to enhance water security through scientific innovation, policy reforms, and participatory management. Based on the numerous workshops, seminars, and consultative meetings, primary challenges and strategies identified are as follows:

1. Reviving Traditional Wisdom
2. Development and Adaptation of Innovative Technologies
3. Detailed Aquifer Mapping
4. Strengthening Monitoring and Data Systems
5. Development of India-Centric Coupled Hydrological Models
6. Integrated Water Resources Management
7. Capacity Building and Governance Reforms

Furthermore, following the initiatives undertaken by the International Association for Hydrological Sciences (IAHS) and the dedicated efforts of the global hydrological community to identify twenty-three Unsolved Problems in Hydrology, a series of scientific questions has emerged that can appropriately address the challenges faced by the Indian water sector:

1. How do surface and groundwater interact under varying geomorphic, climatic, and land-use conditions?
2. What scientific basis provides the most accurate representation of groundwater assessment across heterogeneous aquifer systems?
3. In what ways do environmental flows, dams, and climate change transform perennial rivers into ephemeral ones?
4. What mechanisms govern the occurrence and distribution of extreme rainfall and prolonged droughts?
5. How can we quantify submarine groundwater discharge and its ecological impacts?
6. What are the sources, behavior, and fate of emerging contaminants and microplastics in groundwater?
7. How can predictive hydrological models be refined to reduce uncertainty and enhance reliability?
8. What trade-offs exist between developmental needs and the restoration of natural fluvial systems?

CLIMATE CHANGE AND METEOROLOGICAL HAZARDS

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Climate in the recent decade remained discussed from impact point of view. Changing climate and global warming is intensifying meteorological hazards. Extreme weather events have increased and become intense and devastating. Increased global temperatures due to human activities have worked as catalyst in disrupting natural weather patterns. Though there is natural climate hazards which always existed, but climate change added and increased the vulnerability of the entire population.

Hazards

There are layers on debate and scrutiny in how and why climate change drives meteorological hazards. Increased higher temperatures leading to heatwaves become common. It poses risks of health and more impact on ill and elderly and chronic ill populations intense. It acts as an health hazard leading to even deaths in the impact region. Apart from health, it dries the vertical atmosphere and contribute to enhances drought and wild fires. Increased electricity demand for increased supply for cooling is another destructive factor. Warmer atmosphere leads to holding more moisture, thus leading to extreme rainfall events during monsoons. Combined with warmer oceans, higher number of cyclonic storms, tropical storms, hurricane, etc. will occur, thus causing to massive destructions to the habitat, livelihood. These hazards cascade into flash flooding due to higher rainfall due to higher moisture in vertical atmosphere. This situation lead to more flooding and in case it occurs over the mountains and/or coastal zones in add to landslide and/or storm surges. Communities thus living over these regions are more at risks. On the contrary some of the regions are facing increasing and longer dry seasons and hence frequent droughts. Later stresses wate availability/ agriculture and crop threat, wildfires, etc. This imbalances the water management of the region as well. Climate change in a way making a ground for conjugate and compound risks. Most of these events are cascading in nature and interact in complex and non-linear manner. Sometimes it is difficult to manage and forecast the events. In most of the cases impacts lead to loss of lives and properties. Increasing minimum temperatures lead to reduced cold days, frost days and cold waves across nearly all land areas (very likely) will impact cold related morbidity and mortality; crop damages; vector control disease and impact on reduced electricity.

Impacts

Extremes lead to massive mobilization of the population and displacements. Forced displacements leaves behind the cattle, crop, etc. which remained unsettled and provide disproportionate low income populations and people in poverty. It might brought in the geopolitical transboundary nature of issues as well. Importantly, health impacts are on priority. Climate induced hazards have increased heat-related diseases. In addition vector borne diseases by mosquitoes; malnutrition by crop failures; breathing by fog/smog, etc. Climate change thus slows/disrupts cycle of the human systems and hence making health, crops and livestock more vulnerable. Overall these changes leads to impact the ecosystems, viz., ocean system, plant and animal species, man-animal conflict etc. Overall, socio-economic tolls is staggering and growing. These extremes are damaging the economy globally. Impact of extreme rain will lead to increased flood, landslide, avalanche, mudslide damage, soil erosion and thus stress govt exchequer further and further. Summer drying over will risk of drought (likely); crop yields; ground level water and thus impact the water management. Intense and increase tropical cyclone risk for lives, infection diseases epidemic, infrastructure damages, etc. In nutshell droughts and floods and associated teleconnection will impacts respective lengths, precipitation variabilities, extratropical-tropical storm interactions, coastal damages etc.

Limits and Thresholds

Containing global temperature by.5°C is one of the thresholds for avoiding the above catastrophic impacts. Policy planning and governance has to work on implementing these issues. In addition mitigation of climate change related hazard material need to be curbed and transformation to the renewable energy, viz. solar, wind, green energy is need to be implement. It will lead to reduce the greenhouse gas emissions. Further, adaptions to the resilient frameworks and early warnings strategies are needed to minimize the impacts. The global climate is changing, and will continue to change over coming decades and centuries. Climate trends are observed, and based on these fair future projections can be estimated for planning. These changes are not gradual and hence changes in climate variability and weather extremes, such as those listed above, are need to be monitored and assessed for disaster risk reduction. Thus, local and regional and local risk reduction strategies need to implemented and needs extra vigilant attention to minimise risk of natural disasters. At this juncture role of good and bad information at local to regional level becomes crucial for working on disaster risk reduction. Development networks and established linkages are feeder mechanisms for national meteorological services to address better hazard trends. However, Level of uncertainty need to be assessed for NOT to have general surprises. Disaster risk reduction and resilient development is needed for adapting possible increasing risks. It is important to face mounting vulnerability to natural hazards and hence help in risk reduction strategies.

Climate change is impacting terrestrial water cycles indirectly due to increase intense storms. In a way disaster like drought, floods, aridification, wildfires, pollution and floods, etc. lead to death, injury, loss of livelihoods and migration. Thus, leading socio-economic-environmental losses.

What we do

Solution of re-entering water in drought prone area can minimise it upto certain extent and provide cooling as well. Nature based solution if reforestation, terracing and locl dams is one of the solutions at local level. Climate action based on data integration with information can act as management handle. In present time early warning systems can provide a handle for at least flash floods. Minimising air Polluting is another task for limiting the associated health hazards. Farming communities adapting to the changing climate- water segmentation can hamper crop yield loss up to certain extend.

DEEP EARTH EXPLORATION AND GEOLOGICAL HAZARDS

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Scope

Understanding geological and tectonic processes of planet Earth and deciphering its subsurface structure helps in mitigating geological hazards and assessing the mineral wealth for it utilization for human growth and sustainable development. Over the past few years, significant progress has been made worldwide in utilizing new methods and tools to explore the subsurface Earth and understand the geological processes of the dynamic Earth. Although geoscience research in India is not progressing at the same pace, there have been a few remarkable efforts in recent years. The NASA-ISRO Synthetic Aperture Radar (NISAR) mission is the most notable effort from the Indian side. The NISAR products will help in continuous monitoring of earth processes, particularly the crustal deformation due to geological events. The initiative by the Survey of India of continuously operating reference station (CORS) GNSS network, in addition to the existing network in select regions, is another significant effort, involving the installation of more than 1,200 GNSS sites across Indian states. These two efforts are remarkable, as they will provide continuous monitoring of earth movements due to geological processes, thereby helping to understand the Earth's geological and hydrological processes and mitigate geological hazards by providing accurate information about the affected region in the event of any natural disaster.

Following the 2004 Sumatra-Andaman earthquake, the Government of India took a strong initiative to establish a tsunami warning centre, located at INCOIS, Hyderabad. Fortunately, since then, no large magnitude earthquake causing a large tsunami has occurred in the Bay of Bengal or Arabian sea. In view of the complexities in earthquake and tsunami generation, as seen in the past few years due to high quality data, we need to increase our research towards tsunami modelling, identifying the precise geometry of earthquake hosting faults under the sea, upscaling and adopting newer methods and datasets for tsunami monitoring. In this direction, we need to explore the utility of Distributed Acoustic Sensors (DAS) using fibre optic cables, which have been proven to be very effective in subsurface imaging and earthquake monitoring. It's worth mentioning that Japan has already laid several hundred km of DAS under the sea for earthquake and tsunami monitoring. Such efforts should also be made, not just in the submarine regions, but also on land, e.g., the Himalaya.

In view of the recent events of flood and debris flow due to intense rainfall, and landslides in the Himalayan region, we need to upscale our monitoring networks, identify regions of high risk in the wake of an increase in such events in the future due to climate change, and increase in vulnerability due to some poorly designed developmental activities. In most cases, the causative factors and affected regions are very localised, and the number of such vulnerable regions is enormous; thus, providing an early warning solution for individual regions is very challenging. However, efforts in this direction should be made in some selected regions, such as Joshimath. There has been some progress in landslide forecasting by the Geological Survey of India and NRSC; however, this needs to be further upgraded to be effectively utilized in operational forecasting. Most importantly, efforts should be made to identify vulnerable regions and rehabilitate the inhabitants, if any, to the nearby safer regions.

In the earthquake hazard, the focus of research has shifted from prediction to impact assessment and mitigation. This has led us to focus more on understanding the process and assessing the impact of seismic release during an earthquake. To mitigate the losses due to earthquakes, it is essential to understand the earthquake occurrence processes, factors that influence seismogenesis, understand the reasons for variability in earthquake size and location, the geometry of the faults that host these earthquakes and their influence on earthquake occurrence, thermal and rheological structure, strain budget in seismically active regions, and earthquake history. The Himalayan region is seismically the most active region in the Indian subcontinent. With the ongoing continuous accumulation of strain due to India-Eurasia collision and several Himalayan segments due for large magnitude earthquakes (notably the Kashmir region, Kumaun Garhwal Himalaya, western Arunachal Himalaya), it is important that seismological research should be intensified and emphasis should be given on identifying the potential regions of large damage during future earthquakes by developing damage scenarios due to large magnitude earthquakes with a view to identify regions of high risk and mitigation measures. Although the frequency of damaging earthquakes in the stable continental region of the Indian plate is less, the losses due to past earthquakes here are comparable to those in the Himalayan region, due to our limited understanding of seismogenesis, higher population density, poor awareness of safety, and inadequate construction practices. Thus, seismic hazard in the stable continental region of India, including the regions of paleostructures, cannot be ignored, despite the perception of low hazard as indicated in India's seismic zoning map. Such an understanding may lead to improvement of seismic hazard maps, construction of safer structures, retrofitting of existing structures and increasing public awareness. Finally, this will help in designing and upscaling the seismological, geodetic and other geophysical observational networks, and earthquake early warning systems.

Conclusion

We need to initiate a country level multi-sensor systematic subsurface imaging program that can help in shallow as well as deep imaging. Shallow imaging (a few tens of meters to a few kilometers) will aid in identifying water and mineral resources, whereas deep imaging will help in understanding the earthquake and geological processes deep within the Earth. It is necessary to determine how deeper processes and structures impact those at shallow depths. Also, understanding their evolution in time and space will help not only in identifying the mineral resources but also in making predictions. Such a program was conceived a few years ago, proposing a multi-sensor array that would sweep the entire country in a leapfrog manner, thereby minimizing the cost and involving more institutions.

INDIA'S PRIORITY TO BOOST BLUE ECONOMY

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Scope

We live on a blue planet where oceans cover more than 70% of Earth's surface and underpin life and human economies. They provide food, help regulate global climate, generate a half of the oxygen we breathe, and serve as the world's largest carbon sink. Oceans also provide non-living resources such as energy, water and minerals, support tourism and recreation, facilitate maritime transport, and play a critical role in national security and coastal protection against storms, erosion, and other marine hazards. Despite their centrality to life on Earth, much of the deep ocean remains unexplored and poorly understood.

For India, the maritime domain represents a strategic and economic treasure. The country's exclusive economic zone (EEZ) exceeds 2 million km², and its coastline stretches over 11,000 km across nine coastal states and four union territories. India operates a dozan major ports and more than 200 minor and intermediate ports, and its waters sit on major international trade routes and in geopolitically significant regions. Approximately 95% of India's trade by volume (about 68% by value) moves by sea presenting huge potential for sustainable growth and security when managed responsibly.

Though Ocean offers opportunities, but it also faces major challenges. These include climatic stresses sealevel rise, ocean warming, marine heatwaves, coastal degradation, and threats to ecosystem and human health as well as nonclimatic stresses, such as marine pollution, overexploitation of living resources, and oil spills. Other important challenges are technological (mapping resources, harnessing and monitoring them), governance and policy, security, finance, and human capital.

The energy–water–food nexus must be a primary focus for future priorities. Alongside these, human health and the health of marine ecosystems demand attention, particularly as both will be affected by ongoing global warming. Global and regional strategies should prioritize how ocean resources can be sustainably harnessed to meet human needs while maintaining ecosystem resilience.

Living resources

Sustainable seafood production is central to food security. Key priorities include: (a) Promote sustainable deepsea and coastal fisheries, (b) Expand sustainable mariculture and local aquaculture to support smallscale and community aquaculture systems that are socially inclusive and ecologically sound, (c) Encourage farming of species suited to local conditions (finfish, shellfish, seaweeds) using best environmental practices. (d) Adopt and apply ecosystembased fishery management that considers trophic links, bycatch, and habitat needs, (e) Protect and restore key habitats—mangroves, seagrass beds, coral reefs—that support nursery functions and fisheries productivity, including enhancing biodiversity, (f) seaweed cultivation both on the coastal and deep waters, and (g) Restore and build "underwater forests".

To ensure long-term sustainability and economic viability of fisheries and mariculture, targeted technology and infrastructure investments are required—examples include fish-aggregation devices (FADs), selective fishing gear, robust cold-chain and postharvest management, and scalable mariculture systems. India should affirm its commitment to responsible stewardship of Southern Ocean resources, including krill and toothfish, by actively participating in and adhering to the decisions of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR).

Marine plants and animals are important sources of new medicines being developed to treat various diseases. India being a tropical country, endowed with great diversity of marine micro algal species, combined with optimal environmental conditions, provides great opportunities for commercial scale algal production which has applications in the food, nutritional, cosmetic, pharmaceutical and bio-fuel industry.

Non-living resources

Apart from living resources, the oceans offer substantial non-living resources and multiple forms of marine energy. These include solar energy (e.g., floating solar panels), osmotic power from salinity gradients, kinetic energy from currents and waves, offshore wind, and ocean thermal energy conversion (OTEC). The technologies for these resources are at different technology readiness levels (TRLs). It is imperative to develop a technology to harness these energy, including gas hydrates from the ocean. Also, it is imperative to estimate various energy resources along the Indian EEZ, especially state wise as well as season wise.

Another important ocean-derived resource is freshwater. Many desalination technologies exist, but the technique developed by the National Institute of Ocean Technology (NIOT) is distinctive: it exploits the thermal gradient between surface and subsurface waters to produce freshwater. The same plant can also produce energy and can pump nutrient-rich subsurface water to the surface. In tropical regions, where light is abundant, nutrient limitation is often a primary constraint on productivity; by bringing nutrients to the sunlit surface, such plants can boost primary productivity. Thus, a single plant can deliver water, energy, and food. It is essential to improve the efficiency and cost-effectiveness of this technology and to explore how it could be deployed on the mainland and shared with partner countries, especially small island developing states, strengthening India's role as a Global South leader.

The ocean is a major source of mineral resources both within inside and beyond national EEZ. India has secured exploration contracts with the International Seabed Authority (ISA) for polymetallic nodules in the Central Indian Ocean Basin and for polymetallic sulphides on the Southwest Indian Ridge and Carlsberg Ridge. Developing deepsea mineral resources responsibly requires integrated scientific research, advanced engineering, strict environmental safeguards and robust governance. India's ISA contracts provide an opportunity to lead in sustainable deepsea mining by investing in worldclass exploration technology, rigorous environmental science and internationally cooperative regulatory frameworks that prioritize the longterm health of the ocean. Policy enablers are needed to harness energy, water and minerals from the ocean: public–private- partnership (PPP) models, capital investment, sustained R&D, and infrastructure support.

Other marine Infrastructure

Marine transport and shipping are critical to India's economic development because the country sits astride busy international shipping routes. Meeting growing demand requires investment in financial, physical, natural, and human capital: deepening and modernizing berths to handle larger vessels, improving cargo- and car-handling facilities at existing ports, and designing optimal ship-routing systems. India can also harness coastal and marine tourism—marine heritage sites, island tourism, sailing, angling, diving, and snorkeling—by combining careful scientific planning with conservation of biodiversity and coastal ecosystems. Marine manufacturing and value-added ocean industries remain relatively untapped and include shipbuilding, marine biotechnology and pharmaceuticals, marine equipment and instruments, marine ICT, boat- and net-making, seafood processing, and aquaculture. To realize this "blue economy," India needs clearer regulations to improve ease of doing business and science, policies that attract private investment, and well-designed public–private partnerships targeted at sustainable marine development.

A multi-level, integrated and high-level institutional mechanism is essential for the formulation, implementation and monitoring of policies addressing the strategic challenges of maritime security. This mechanism should link national, regional and local authorities and enable coordinated decision-making across defence, fisheries, environment, shipping, earth sciences, tourism and other economic ministries. Equally important is sustained international cooperation: identify and engage partners who share strategic interests and capabilities to deepen maritime security collaboration, including cooperation in the blue economy.

Investment in technology is critical. We must prioritize research, development and deployment of technologies for sustainable ocean resource extraction, hazard mitigation and enhancement of ecosystem resilience. This includes advanced observational systems, autonomous platforms, sensors, data analytics and forecasting models. To deliver these innovations at scale, promote strong industry–institute–academia partnerships, support start-ups and incubators, and create mechanisms for rapid technology transfer and commercialization. Equally important are strengthened governance and legal frameworks, comprehensive marine spatial planning, and coordinated transboundary management.

Human capital is another pillar. Encourage and incentivize universities and engineering institutions to introduce and expand ocean-related courses and programmes. Support specialised institutions and centres of excellence that offer advanced studies in ocean governance, marine science and maritime technology, and provide scholarships, fellowships and vocational training to build a skilled workforce.

The Government of India’s Deep Ocean Mission is an important initiative that integrates many of these elements at a demonstration scale. It is vital to scale up such efforts with increased investment in observational infrastructure, systematic marine spatial planning along the coast, comprehensive mapping of ocean resources, and development of technologies for sustainable resource utilisation. With coordinated institutions, international partnerships, targeted R&D and strengthened human capacity, we can secure our maritime domain while harnessing the ocean sustainably for economic growth.

SOCIOECONOMIC IMPACTS OF GEOSCIENCES: POLICY INITIATIVES AND STRENGTHENING WORKFORCE

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Scope

Climate change is one of the major challenges that we are facing today, resulting in unusual rise in temperatures, extreme weather, sea-level rise, melting glaciers and soil erosion. This along with accelerating resource depletion and increasing natural hazards is affecting our vital ecosystems, thereby not only jeopardizing our food and energy supplies, but also the global habitability. Sundarbans mangrove forests, located between India and Bangladesh is one such area which is facing the threat of retreat due to climate change [1]. Simultaneously, the overexploitation of finite resources like oil, gas, and groundwater is increasing vulnerabilities globally. Further, the demand for critical minerals is exponentially increasing due to clean energy transitions and increase in digital transformations. As per the estimates given by the International Energy Agency (IEA), the lithium demand could increase eightfold, while other key minerals, like nickel, cobalt and rare earth elements (REEs), may double by 2040 [2]. The escalating disasters like floods, cyclones and environmental degradation also disproportionately impact vulnerable populations. As per literature, pollution due to PM. caused 8.1 million premature deaths in 2021 [3] and methane super-emissions from landfills [4], led to the global GDP losses reaching 2–5% annually [5, 6]. In this context, geosciences with advanced tools, such as remote sensing, Earth system modeling, and geophysical surveys support informed resource management, and also helps to address climate adaptation, hazard mitigation, and environmental restoration, thereby securing a sustainable and resilient future through linking scientific insight with policy.

Harnessing Geosciences for Socioeconomic Growth and Climate Resilience

The geosciences use Earth system knowledge and transform them into practical solutions to advance sustainability and enhance resilience for mitigating increasing environmental and economic challenges. The geoscientific techniques such as geochemical surveys, mineralogical mapping, and geophysical prospecting are essential for locating and extracting critical minerals in resource management and energy security field. These minerals are crucial to clean energy technologies, including electric vehicle batteries, wind turbines, and solar panels. In the energy sector, the hydrocarbon exploration is conducted by seismic imaging, basin analysis, and reservoir modelling, whereas the geothermal studies and spatial resource mapping facilitate the expansion of renewable energy systems [7]. Geosciences are also vital for climate change adaptation and mitigation. Numerical weather prediction, satellite remote sensing, and high-performance computing enable accurate modeling of coupled atmosphere–land systems, supporting critical functions such as seasonal monsoon forecasting and early warnings for droughts, floods, and heatwaves [8]. These insights support informed decision-making across agriculture, public health, transportation, and energy sectors, reinforcing climate resilience.

Equally vital is the role of geosciences in disaster risk reduction and resilient infrastructure development amid increasing climate-induced and geophysical hazards like cyclones, extreme rainfall, landslides, earthquakes, and tsunamis. Tools including probabilistic seismic hazard assessments, flood modeling, and tsunami inundation mapping are key components of early-warning systems and risk-sensitive zoning, especially when integrated with satellite remote sensing and hydrometeorological data to enhance preparedness [9]. In urban planning and infrastructure, geotechnical assessments, utilizing borehole drilling, Cone Penetration Testing (CPT), and Ground-Penetrating Radar (GPR), inform the safe design and construction of buildings, transport networks, tunnels, and dams [10]. GIS-based land-use planning and Digital Elevation Models (DEMs) guide sustainable urban expansion and hazard-informed development [11]. Additionally, geosciences support circular economy objectives through environmentally responsible waste management, including landfill siting, groundwater protection, and pollution monitoring. These capabilities not only safeguard ecosystems and infrastructure but also strengthen financial resilience by improving risk modeling, insurance pricing, and catastrophe bond frameworks. In summary, geosciences serve as a vital link between science, innovation and policy, to integrate environmental knowledge in the sustainable and inclusive development of the society.

National and Global Policies Landscapes in Geoscience

Due to rising geopolitical tensions, sanctions, and supply chain vulnerabilities, individual regions face an urgent need to ensure their own resource security, thus positioning geosciences at the core of national and global strategies. Global initiatives such as the European Union's Critical Raw Materials Act (2024) [12] and the IEA's Strategy for Securing Reliable Critical Minerals Supply (2022) [13] highlights sustainable production, recycling, strategic stockpiling, and supply diversification of critical minerals. Similarly, the U.S.-led Minerals Security Partnership (2022) [14] promotes multinational collaboration for Environmental, Social, and Governance (ESG) compliant mineral supply chains. Parallelly, in the disaster risk management domain, the Group on Earth Observations (GEO) and the Disaster Risk Reduction Working Group (2022) [15] leverages the Earth observations for multi-hazard early-warning systems.

India reflects these global policies through a range of comprehensive missions aligning with the geosciences field, and led by various prominent ministries and departments, such as Ministry of Earth Sciences (MoES), Department of Science & Technology (DST), Ministry of Mines, Department of Space (DoS), Ministry of Power (MoP), Ministry of New and Renewable Energy (MNRE) etc. Paralleling the international efforts to diversify and secure mineral supplies, the National Mineral Exploration Policy (NMEP, 2016) and National Mineral Policy (NMP, 2019) promote private sector participation, transparent auction-based allocation, R&D, and ESG-compliant resource governance. The National Critical Mineral Mission (NCMM, 2025), supported by the AI/ML-enabled National Geoscience Data Repository (NGDR), targets exploration and processing of 30 critical minerals [16]. In the global blue economy initiatives, India's Deep Ocean Mission (DOM, 2021) advances sustainable deep-sea mining technologies, ocean energy harvesting, and climate advisory services [17]. India's National Green Hydrogen Mission (2023), aims to establish a green hydrogen hub by 2030 [18], supporting global clean energy transitions. The forthcoming Carbon Capture, Utilization, and Storage (CCUS) Mission, led by MoP, and backed by NITI Aayog and Prime Minister's Science, Technology, and Innovation Advisory Council (PM-STIAC), aims to develop a CO capture capacity to decarbonize heavy industries, mirroring international net-zero pathways through advanced geophysical modeling and safe sequestration [19]. Together, these integrated frameworks position India to meet its Net Zero 2070 goals while strengthening sustainable growth and resource security.

India's Mission Mausam (2024) aims to enhance Earth system observation and disaster resilience by integrating multi-domain geoscience with advanced modelling. This includes the Bharat Forecasting System (BharatFS) which is the world's highest-resolution climate model [17, 20]. These initiatives strengthen climate resilience and disaster preparedness in alignment with the global GEO framework and disaster risk reduction plans. ISRO's Earth observation satellites further enhance real-time early-warning systems, aiding in disaster resilience program. The National Geospatial Policy (NGP, 2022) establishes an open-access geospatial data framework with interoperable standards and a Digital Elevation Model by 2030, supporting risk-informed land-use and sustainable infrastructure development [21]. Complementing this, the upcoming National Geospatial Mission seeks to build foundational geospatial infrastructure and a centralized data repository to modernize land records, enhance urban planning, and support infrastructure design using satellite technology. These national policies, aligned with global initiatives, highlight India's commitment to addressing climate change, energy security, disaster mitigation, and sustainable development.

Workforce in Geosciences and Way Forward

India's forward-looking policies and strategic initiatives require a resilient and future-ready geoscience ecosystem, and significant progress are being made to strengthen this fundamental foundation. By enhancing implementation frameworks and optimizing key areas, these efforts are poised to unlock their full potential and drive long-term national benefits. However, to build on this momentum it is essential to ensure broader access to geospatial infrastructure and digital technologies, particularly in remote and underprivileged regions. Strengthening faculty capacity and embedding emerging tools such as GIS, AI/ML, and Earth system modeling into academic curricula will enhance institutional readiness and national capability [22].

As geosciences become increasingly data-driven and interdisciplinary, there is a growing need to modernize education and training frameworks to reflect evolving industry demands. This will be achieved through access to knowledge across disciplines. The One Nation One Subscription (ONOS) scheme [23] is a dedicated effort in this direction which ensures that access to global scientific knowledge is provided to all. The access to scholarly content is being provided to the students, faculty, and researchers across government-funded Higher Educational Institutes (HEIs) and R&D institutions, thereby strengthening India's research and innovation ecosystem.

Along with this, an integrated approach through collaboration between academia, research institutes, and industry is equally important to drive India's progress in this sector. To achieve this, there is a need to align academic programs with real-world applications, enhancing investments in research, and promoting global knowledge exchange through international collaborations through open-data platforms and joint research. In this context, India has launched several strategic initiatives that align with national priorities in science, technology, innovation and sustainable development. The Anusandhan National Research

Foundation (ANRF) [24] has been established to promote high-impact, multidisciplinary research through grants to research institutions, start-ups and industries engaged in cutting-edge research. Moreover, the recently launched Research, Development, and Innovation (RDI) Scheme [25], with a total outlay of 1 lakh crore, aims to provide long-term, low-interest loans to private sector for doing high-impact R&D. This scheme will promote the translation of fundamental research into deployable technologies. All these efforts are expected to enhance national R&D capacity, promote research equity, and advance technology readiness in several fields including key geoscience domains.

Furthermore, motivating increased participation of women and underrepresented communities will enrich the geosciences community and also promote inclusive growth. To achieve the climate goals and sustainable development targets several government-led initiatives, such as Industry-Academia partnerships, geoinformatics centers, and the Production-Linked Incentive (PLI) Scheme, are also helping in driving innovation in key areas, such as mineral exploration, renewable energy, carbon capture, and marine research. Accordingly, it is imperative to build a geoscience workforce that is well-trained and equipped to take on the emerging opportunities being rolled out. Overall, integrating geoscientific insights into policymaking can lead to greater evidence-based governance and long-term resilience against upcoming environmental challenges.

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