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Resource Estimation, Economic Viability, and Sustainable Mining of Subsurface Heavy Minerals using ArcGIS Raster Techniques: A Case Study from near-Shelf Region off Bavanapadu Coastal Sector, Andhra Pradesh, India

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Abstract

The Bavanapadu-Nuvvalarevu coastal sector in Andhra Pradesh, India, hosts substantial subsurface heavy mineral (HM) resources, presenting significant economic potential. This study employs ArcGIS raster techniques to estimate Total Heavy Mineral (THM) and Total Economic Heavy Mineral (TEHM) resources in a 39 square kilometers area, integrating geospatial analysis with field data from core sediment samples. The findings reveal a total of 2.681953 million tons of THM, including 2.434422 million tons of TEHM, with the highest concentration observed in the top 1-meter sea bed sediment layer (1.605286 million tons). Ilmenite, garnet, and sillimanite dominate the mineral assemblage, accompanied by smaller quantities of zircon, monazite, and rutile, offering an estimated revenue potential of $634 to $851 million USD. The application of ArcGIS methodologies, particularly inverse distance weighting (IDW) interpolation, enabled precise mapping of HM distribution, despite challenges such as wide sample spacing and shallow core penetration. While the study highlights the economic and industrial significance of the Bavanapadu sector, it also underscores environmental concerns, including habitat disruption and sediment degradation, associated with mining. Sustainable practices, such as advanced separation technologies, site rehabilitation, and comprehensive environmental impact assessments (EIAs), are essential to mitigate ecological impacts. This research demonstrates the efficacy of GIS-based techniques in resource estimation and sustainable mining, offering a replicable framework for coastal and offshore mineral resource management globally. The findings provide critical insights into balancing economic growth with environmental preservation, setting a benchmark for responsible heavy mineral extraction in dynamic coastal environments.

1. Introduction

Coastal ecosystems, some of the most biodiverse, and economically vital areas on the planet, are under increasing pressure from the demand for mineral resources. The extraction of heavy minerals from coastal sand-particularly along the Bavanapadu sector in Andhra Pradesh, India-has grown exponentially in response to the expanding global need for materials such as ilmenite, rutile, zircon, and garnet. These minerals are integral to industries ranging from aerospace to ceramics, making them invaluable to modern economies [1] [2]. However, the promise of economic prosperity from these mineral deposits is countered by the environmental risks that coastal and offshore mining poses. From habitat destruction to water quality degradation, the impact on fragile marine ecosystems is significant [3]. The challenge lies not only in the extraction of these resources but also in finding a balance between

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economic development and environmental conservation.

As shown in Figure 1, the geological features of coastal to continental shelf zones play a key role in the formation and accumulation of placer deposits. These deposits, often found near coastlines or in shallow waters, result from natural processes that concentrate valuable minerals in specific locations, making them highly accessible for extraction [4] [5]. Figure 2 further highlights the distribution of placer minerals along the continental shelf, visually depicting how these mineral accumulations occur in proximity to shorelines, in zones, where sediment transport and deposition facilitate the concentration of heavy minerals [6].

The Indian peninsula is endowed with numerous deposits of heavy minerals including monazite, garnet, ilmenite, zircon, and rutile, which are predominantly concentrated in coastal regions, with some exceptions of placer deposits found inland [7]. It's worth noting that only about one-third of India's coastal areas have been thoroughly explored for placer deposits Mohan and Rajamanickam [8]. Notable heavy mineral deposits coastal states in India [9]. Extensive studies on placer deposits have been conducted by various researchers [10,11,12,13,14,15,16,17,18], covering both the eastern and western coastlines of India.

Total Heavy Mineral (THM) refers to the overall concentration of heavy minerals in a deposit, while Total Economic Heavy Mineral (TEHM) represents the minerals that are economically viable for extraction viz garnet, sillimanite, ilmenite, rutile, and zircon. In this work, the total resources for Total Heavy Mineral (THM) and Total Economic Heavy Mineral (TEHM) have been calculated. To avoid repetition, we will use the abbreviations THM and TEHM throughout the text. heavy mineral placer deposits are widely distributed along the coasts of India, particularly in the inner and mid-shelf regions off Odisha, Andhra Pradesh, Kerala-Tamil Nadu, and Maharashtra. These areas have been identified by various government agencies as containing TEHM content ranging from 3% to 24% by weight. significant quantities of heavy mineral-bearing sands have been observed in the Bavanapadu sector, located off the coast of Andhra Pradesh. The sands host a diverse assemblage of economically valuable heavy minerals such as ilmenite, sillimanite, garnet, zircon, monazite, and rutile, alongside non-economic minerals like pyroxene and amphibole. The distribution and concentration of these minerals vary across different regions, influenced by hinterland geology and the hydrodynamic conditions of the depositional environment. The Bavanapadu coastal sector, with its rich deposits of THM and TEHM, represents a critical area for sustainable mining efforts in India [7].

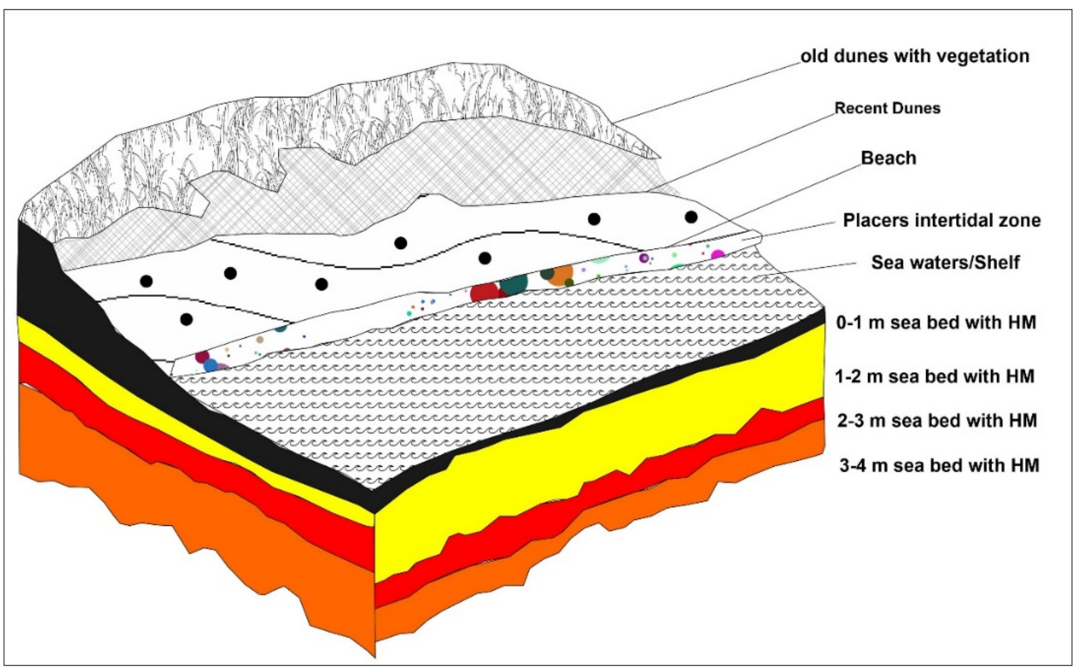

Figure 1. Generalized coastal to continental shelf and placer minerals, We can visually depict the geological features and the accumulation of placer deposits, which often form near coastlines or in shallow waters.

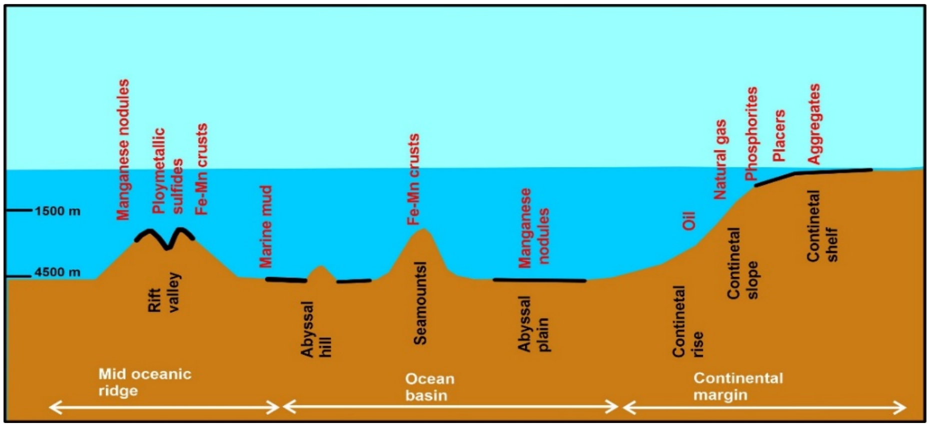

Figure 2. Continental shelf and placer minerals, depicting the geological features and the accumulation of placer deposits, which often form near coastlines or in shallow waters.

while the Bavanapadu sector has significant economic potential, traditional resource estimation methods like drilling and coring have limitations in mapping placer mineral deposits, particularly in dynamic coastal environments. Coastal zones and shelf zones are subject to frequent changes due to tidal shifts, storm surges, and sediment transport, making it difficult to accurately map the subsurface distribution of minerals using conventional techniques. As such, new approaches to resource estimation are needed-ones that account for these dynamic conditions and provide a more robust framework for assessing mineral reserves over large, often inaccessible areas. Geographic Information Systems (GIS), and specifically ArcGIS, have emerged as powerful tools in overcoming these challenges. By integrating spatial data from satellite imagery, remote sensing, and field surveys, GIS platforms allow for a more accurate and comprehensive estimation of heavy mineral resources across expansive coastal regions. This methodology not only improves the precision of resource mapping but also enhances the ability to predict the behavior of coastal sediments and mineral accumulations over time.

However, while GIS-based techniques have advanced the ability to map and estimate mineral resources, there remains a critical gap in the literature regarding their integration with sustainable mining practices. Despite the recognition of the need for environmentally responsible mining in coastal areas [19], there is limited research on how these technologies can be combined with environmental management strategies to ensure that mineral extraction is done in a way that minimizes harm to marine ecosystems. Mining in coastal regions presents unique challenges due to the fragile nature of these ecosystems, which support diverse species and provide essential services to local communities such as fisheries and tourism [20]. As such, there is an urgent need for studies that explore the synergy between advanced geospatial technologies, resource estimation, and sustainable mining practices in these sensitive areas.

This work seeks to fill this gap by utilizing ArcGIS to estimate the heavy mineral resources in the Bavanapadu sector, evaluate their economic potential, and propose a framework for sustainable mining that minimizes environmental impact. Specifically, The research aims to address the following questions: (1) How can GIS-based resource estimation techniques improve the accuracy and efficiency of mineral mapping in coastal regions like Bavanapadu-Nuvvalarevu sector? (2) What sustainable mining practices can be employed to balance economic growth with the protection of coastal ecosystems and the livelihoods of local communities? The findings of this study are expected to provide valuable insights into the responsible extraction of resources in the Bavanapadu-Nuvvalarevu sector, offering a model for other coastal and offshore mining operations worldwide. The findings are intended to guide future policy decisions and mining practices, ensuring that the exploitation of Bavanapadu's heavy minerals supports both economic prosperity and the preservation of its unique coastal ecosystem.

1.2. Studied location

The mineral exploration for placer minerals was conducted within the territorial waters off the Bavanapadu-Nuvvalarevu region, Andhra Pradesh, during cruise ST-282 aboard the research vessel Samudra Kaustubh. The survey covered an area of 39 square kilometers, situated off the Bavanapadu-

Nuvvalarevu coastline, defined by the coordinates shown in Figure 3. This region was selected for its significant geological potential, offering promising opportunities for placer mineral deposits along the coastal and continental shelf areas.

1.3. Hinterland geology

The hinterland forms a part of the Eastern Ghat Mobile (EGMB) belt comprising of high grade metamorphic rocks viz; Khondalite, Charnockite, pyroxenites, amphibolites, and migmatites with subordinate igneous and sedimentary terrains and acts as the chief source of detritus. The Khondalite group is represented by Khondalite (Quartz-felspar-garnet-sillimanite-graphite gneiss), calc granulite and quartzite which occur as impersistent bands within the Khondalite. The charnockite group consists of acid, intermediate and basic varieties. The migmatite group consists of various rock types including leptynite, porphyroblastic granitoid gneiss, garnet-biotite-hypersthene gneiss, quartzo-feldspathic mobilisates, and other associated hybrid rocks (Figure 4).

The near-shore coastal plains occupied by Tertiary and Quaternary sediments also might have supplied subordinate amounts of detritus. Two major Rivers viz.,Vamsadhara and Mahendratanaya, which lie in southern part of the studied area, and few minor streams drain through the rocks of Eastern Ghat Mobile Belt have contributed placer minerals to the offshore. The different geomorphic units present in the area are beaches, dunes, colluvial deposits, pediment, river terrace, channel bars, flood plains, coastal plains, aeolian plains, levees, pediplains, badlands moderately dissected hills and valleys and residual hills.

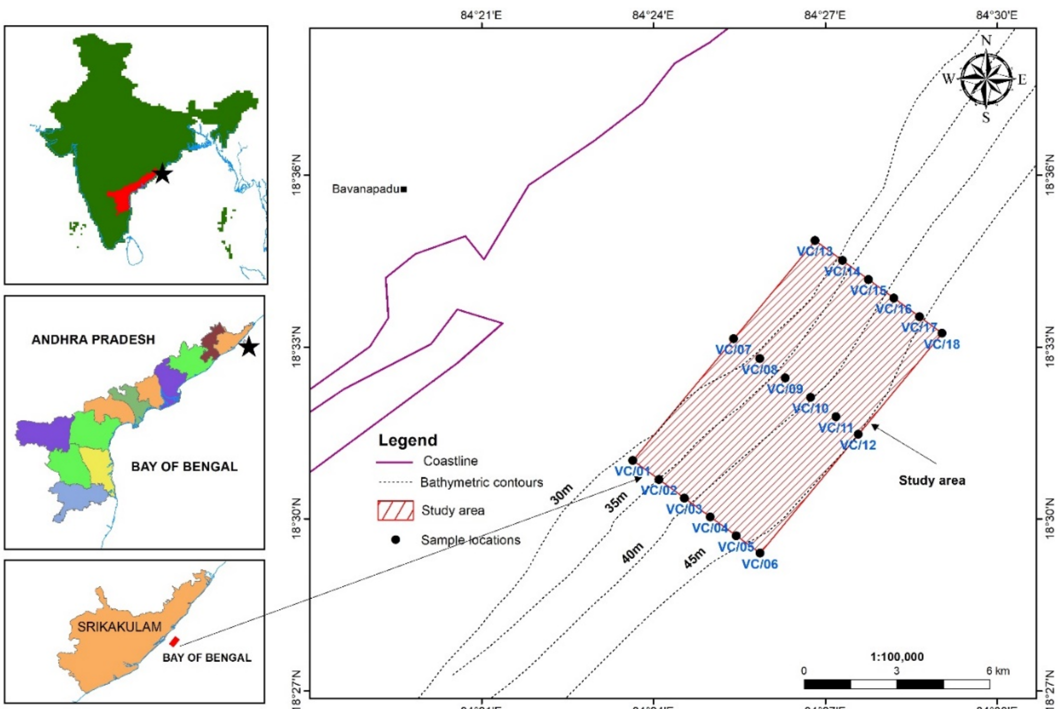

Figure 3. Location map of the study area and sample locations in the territorial waters off Bavanapadu, Andhra Pradesh, Bay of Bengal.

2. Methodology for Heavy Mineral Resource Calculation

Geostatistical models like kriging and inverse distance weighting integrate survey data to predict mineral distribution and economic viability. The interpretation of IDW is commonly used in resource estimation, particularly in mining. The magnitude of an estimate is significantly influenced by distance and weights, which change based on the distance between the estimation point and the target point [21]. Advancements in AI and machine learning further refine these estimations, enabling optimized extraction strategies, while minimizing environmental impact.

Given the presence of substantial heavy mineral concentrations in the top 1 meter of sediment in this region, it is crucial to assess the total heavy mineral resources in the studied area to evaluate the economic feasibility of potential offshore mining operations. Unlike terrestrial resource estimation, which typically relies on closely spaced sampling and deep drilling (up to 200 meters), marine resource calculation faces several challenges. These include wider sample spacing (≥ 1 km) and shallow core penetration depths, which are constrained by factors such as sea state, seabed morphology, and the availability of appropriate sampling facilities. Despite these limitations, the present study attempts to estimate the heavy mineral resources using ArcGIS-based raster techniques for the core samples collected from the studied area.

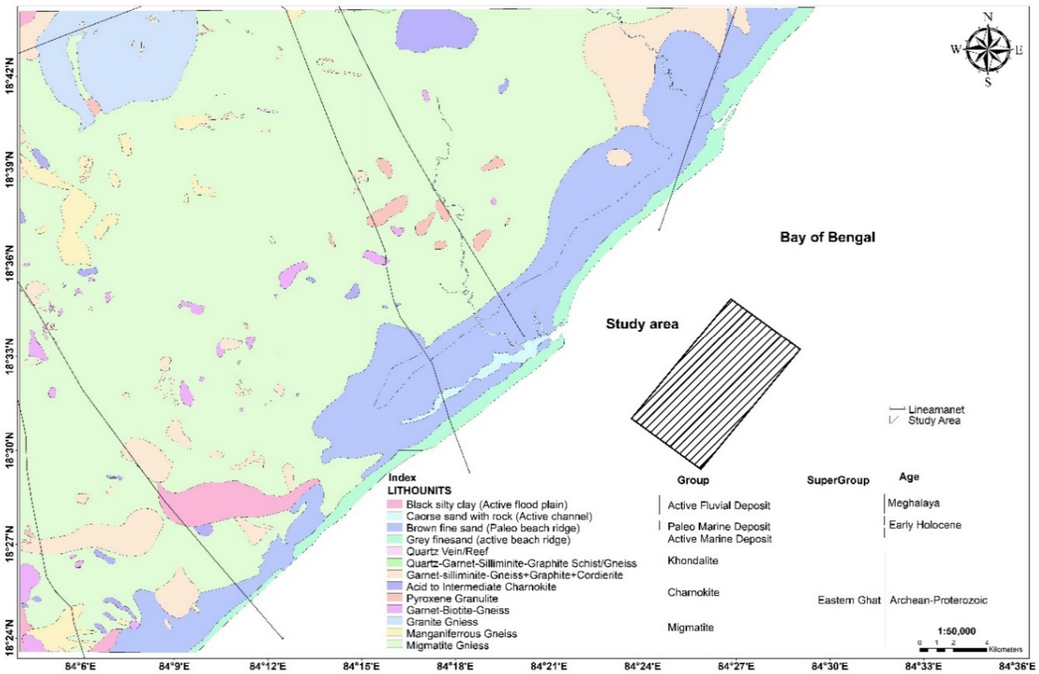

Figure 4. Hinterland geology of the studied area, off Bavanapadu-Nuvvalarevu, Andhra Pradesh, Bay of Bengal. Source: Bhukosh, GSI.

2.1. Data collection and preparation

The methodology for calculating heavy mineral resources in this study began with the exploration of heavy mineral placers by following a systematic approach to assess resource potential and heavy mineral composition. It begins with bathymetric surveys to map seabed topography, followed by geophysical techniques such as seismic and magnetic surveys to identify subsurface structures and sediment-hosted mineral deposits. Sediment sampling, primarily through vibro-coring, provides material for granulometric analysis, which helps determine grain size distribution and depositional environments. Heavy minerals are then separated by using density-based techniques like bromoform separation and examined through microscopic and SEM/EDX studies for detailed characterization. Geochemical analysis further assesses major, trace, and Rare Earth Element (REE) concentrations, offering valuable insights into mineral origin and economic viability. During the exploration, a total of 18 seabed sediment samples were collected using the vibro-coring facility aboard Samudra Kaustubh. The cores were collected across the entire area at one-kilometer intervals between each vibro core. Depending on the sediment type at each core collection site, some cores penetrated up to 4 meters, while others had shallower penetration. Therefore, resource calculations were conducted based on core samples corresponding to their respective penetration depths at each level (upto 4 meters). The samples were analyzed for their heavy mineral content, which included both economic and non-economic minerals. The distribution of these minerals across the studied area was then mapped using spatial interpolation methods in ArcGIS. Data preparation involved creating point shape-files of the sample locations, which were projected to the Universal Transverse Mercator (UTM) coordinate system to ensure geographic accuracy.

2.2. Use of ArcGIS in resource assessment

To visualize the mineral distribution, spatial interpolation techniques using ArcGIS were applied. The Inverse Distance Weighting (IDW) method was used to generate resource maps, as it effectively estimates mineral concentrations in areas with wide sample spacing. The use of the IDW method allowed for a smooth interpolation of values between sampling points, producing a continuous spatial representation of heavy mineral concentrations. Inverse Distance Weighting (IDW) was chosen over Ordinary Kriging due to its ability to provide a straightforward and computationally efficient interpolation, particularly in cases where data points are irregularly spaced. Unlike Kriging, which requires a well-defined variogram model and assumes a certain level of spatial autocorrelation, IDW directly weights nearby points based on distance, making it more suitable for capturing localized variations in ore zones [22]. Map Algebra tools were then employed to calculate the tonnage of heavy minerals in each raster cell, taking into account the wet bulk density of the sediment.

2.3. Calculation of preliminary heavy mineral resources

THM resource at various depths within the studied area was calculated using ArcGIS (Version 10.8.1). The resource estimation process was carried out for each 1-meter-thick slice of sediment, with estimates made down to a depth of 4 meters below the seafloor. This approach ensures a layered understanding of heavy mineral distribution and resource availability within the sediment column. To calculate the resources of heavy minerals, point shape-files were prepared in ArcGIS based on the sample locations. Using the available data points, graphic buffer boundaries were created around each sampling point, with a radius of 500 meters, reflecting the 1-kilometer distance between each sample location. The buffer zones were also projected to the UTM coordinate system for consistency. For the estimation of heavy mineral concentrations, the Inverse Distance Weighted (IDW) interpolation method was employed to create a raster of heavy mineral percentages.

The calculation of heavy mineral tonnage was performed using ArcGIS's Map Algebra tool. Raster for HM tonnage is created by using the formula:

Tonnage = HM weight percentage raster/100 * cell size (sq.m.) * average thickness*1.8 (wet bulk density of the sediment).

where:

- Heavy mineral percentage raster represents the interpolated percentage of heavy minerals in the sediment,
- Cell size is 50 meters by 50 meters, resulting in an area of 2500 square meters per cell,
- Average thickness is the thickness of each sediment layer (1 meter),
- 1.8 is the wet bulk density of the sediment, measured in tonnes per cubic meter

Considering the sampling interval and to maintain uniformity, unit cell size each of 50 m x 50 m was selected for the area. Hence, the area of each unit cell is 2500 sq. m. Similarly, tonnage raster for non-magnetic Heavy Minerals was also created and their resource statistics viz; Total Resource, Minimum Tonnage, Maximum Tonnage, among the cells were obtained from the 'classification statistics Window'.

The same methodology has been followed for calculating the total sand resource estimation by considering the wet bulk density of the sediment is 1.5.

2.4. Sand resource calculation

In addition to calculating the total heavy mineral resources, the study also estimated the total sand resources within the studied area. This estimation followed a similar methodology, using a wet bulk density of 1.5 tonnes per cubic meter for the sediment. By considering the spatial distribution of sand in the studied area and applying the same raster calculation methods used for heavy minerals, the study provides a comprehensive assessment of both heavy mineral and sand resources. This information is crucial for determining the overall potential of the study area for mining and other extractive activities.

3. Results

3.1. Down core resources of sand, THM, and TEHM

The resource estimation for the Bavanapadu sector, covering approximately 39 square kilometers, reveals a significant concentration of THM and TEHM at various depths. Table 1 summarizes the estimated mineral resources across different depth intervals. Level wise resource polygons that were used to calculate resource of Sand, THM and TEHM shown in Figures 5-8.

Table 1. Resources of heavy minerals in million tonnes at different levels in the survey off Bavanapadu sector, Andhra Pradesh.

Range of level (m)	Area sq. km (including buffer area)	Total HM (million tons)	Total economic HM (million tons)	Total magnetic HM (million tons)	Total sand (million tons)
0.00-1.00m	18	1.605286	1.464713	0.75499	21.5499
1.00-2.00m	12	0.527832	0.451622	0.59243	9.947438
2.00-3.00m	6	0.320619	0.301537	0.012721	5.402361
3.00-4.00m	3	0.228216	0.21655	0.011175	0
Total (mt)	**39**	**2.681953**	**2.434422**	**1.371316**	**36.899699**

Depthwise distribution trends

- **0–1 m depth:** This layer contains the highest concentration of heavy minerals, with 1.605 million tons of THM and 1.464 million tons of TEHM, accounting for over half of the total economic mineral reserves.
- **1–2 m depth:** A moderate concentration of THM (0.528 million tons) and TEHM (0.452 million tons) is recorded, with a slight increase in magnetic heavy mineral content.
- **2–3 m depth:** Heavy mineral presence diminishes at this depth, with 0.321 million tons of THM and 0.302 million tons of TEHM.
- **3–4 m depth:** The lowest mineral concentrations are observed, indicating that economically viable mineral deposits are primarily within the upper 2 meters of sediment.

The findings suggest that the highest economic potential lies within the uppermost sediment layers, aligning with the depositional behavior of marine placer deposits. This distribution is consistent with previous studies that indicate wave action and sediment transport processes favor the enrichment of heavy minerals in shallow seabed layers.

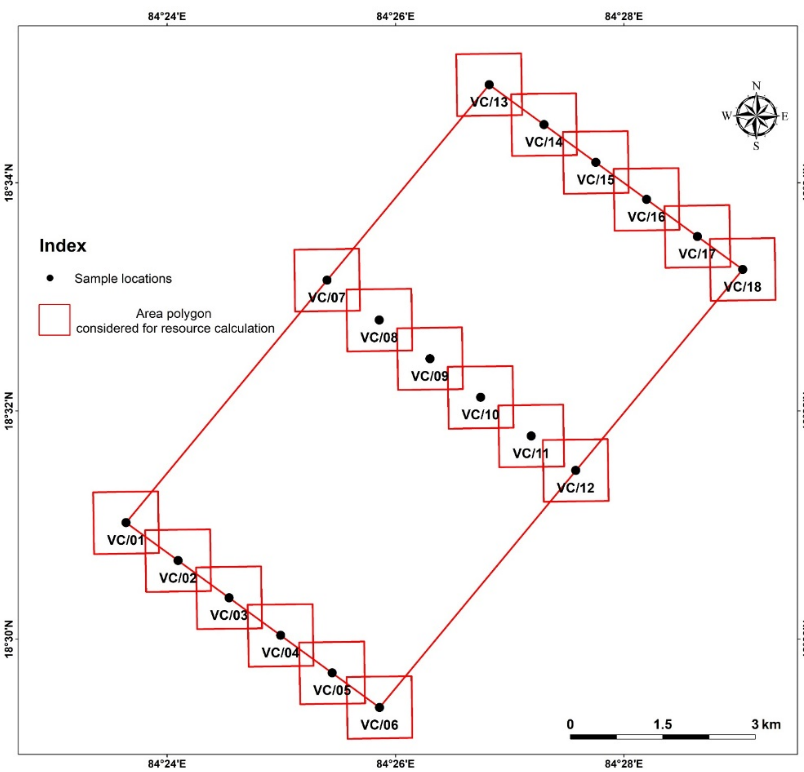

Figure 5. Resource polygon of Sand, THM and TEHM of samples (0.00 to 1.00m) collected off Bavanapadu, Andhra Pradesh, Bay of Bengal.

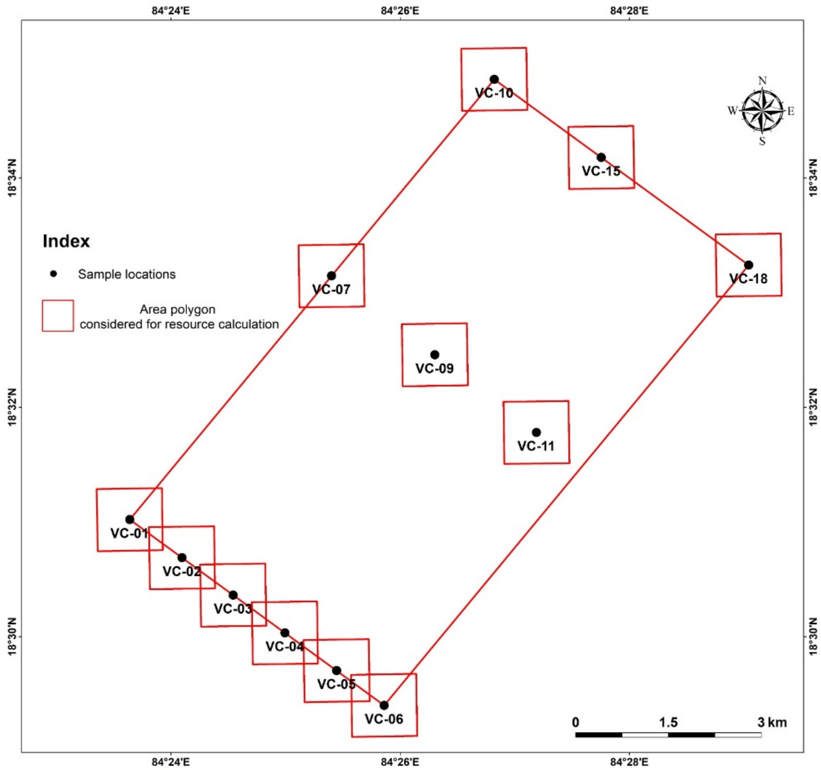

Figure 6. Resource polygon of sand, THM and TEHM of samples (1.00 to 2.00 m) collected off Bavanapadu, Andhra Pradesh, Bay of Bengal.

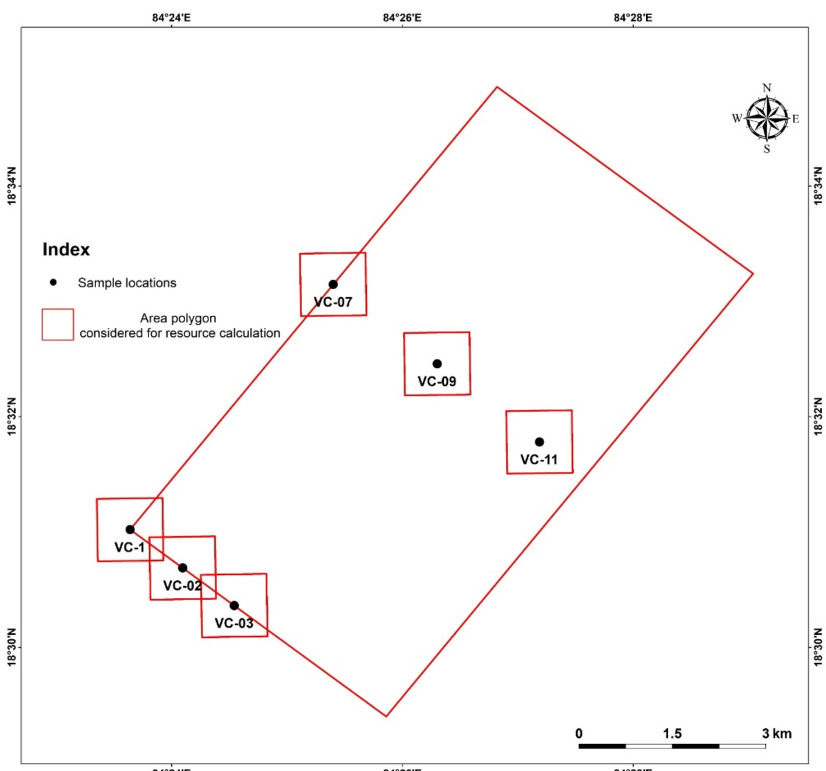

Figure 7. Resource polygon of Sand, THM and TEHM of samples (2.00 to 3.00 m) collected off Bavanapadu, Andhra Pradesh, Bay of Bengal.

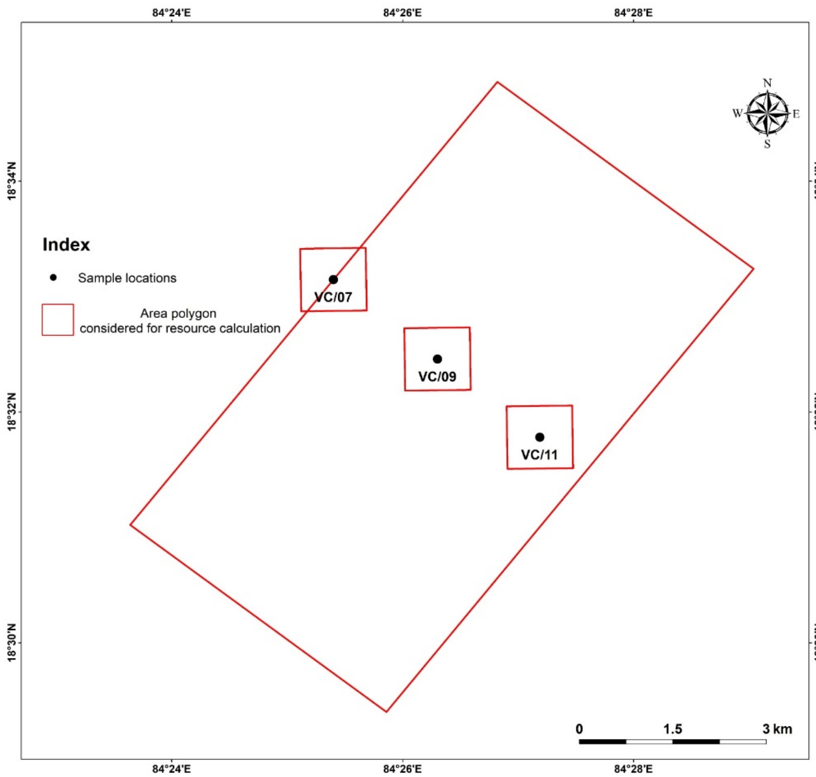

Figure 8. Resource polygon of Sand, THM and TEHM of samples (3.00 to 4.00 m) collected off Bavanapadu sector, Andhra Pradesh, Bay of Bengal.

3.2. Preliminary Resources of individual economic heavy minerals

The frequency of different heavy mineral specimens in all the three coarser fractions +60, +120 & +230 of each sub sample has been quantified by counting the individual mineral grains. The total resources of individual economic heavy minerals at each level are calculated and presented in Figure 9.

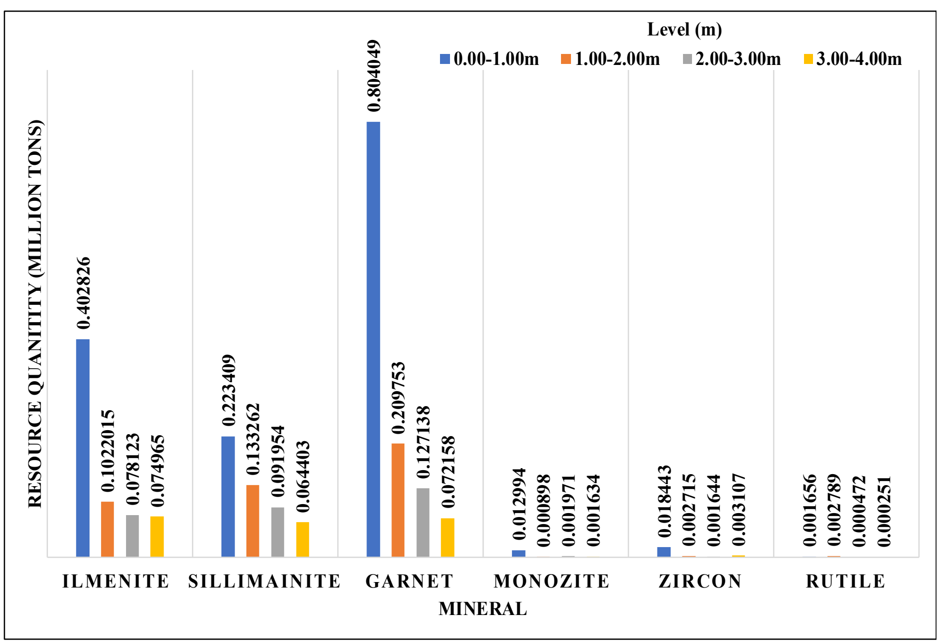

Figure 9. Resources of individual heavy minerals in million tons at different levels Bavanapadu, Andhra Pradesh, bay of Bengal.

3.3. Mining of heavy minerals

Heavy Minerals (HMs), classified as minerals with a specific gravity greater than 2.9 g/cm³, hold significant economic value due to their industrial applications. Heavy minerals (HMs) are a diverse group of minerals characterized by a specific gravity greater than 2.9 g/cm³, distinguishing them from lighter minerals found in sedimentary deposits (Table 2). Heavy Minerals (HMs) are used in many high-tech applications (e.g. nuclear reactors, photovoltaic cells, electronics, green, and nano- and space technology), and thus global demand is increasing day by day. The demand for these minerals has surged, driven by technological advancements and the growing use of materials like titanium and zirconium in high-tech industries [23]. As such, HMs are crucial to the global mineral supply chain, and their extraction is of critical importance to various industrial sectors. HM deposits can be mined by dredging (mining of material through suction or mechanical dredging from the bottom of a water body), dry mining (collection of material using front-end loaders or excavators), or hydraulic mining (with the aid of high-pressure jets). Major efforts have been made in the last two decades to develop mining methods for near-shore secondary HM deposits (e.g. monazite). Mining of placer deposits in lakes or coastal areas is done largely by dredges, with on-board storage of tailings after ore processing, and discharge of excess water and tailings back into the environment or in backfilling [24].

Table 2. Characteristic properties of heavy minerals (adapted from Fawzy et al., 2022, Journal of Physics: conference series).

Mineral	Specific Gravity (Sp. gr.)	Hardness	Color	Streak	Crystal system
Magnetite	5.19	5.5–6.5	Black	Black	Isometric
Ilmenite	4.79	5–6	Black to brown	Black	Hexagonal
Zircon	4.6	7.5	Colorless, brown, or green	Colorless	Tetragonal
Apatite	3.2	5	Green, brown	White	Hexagonal
Sphene	3.5	5–5.5	Yellow, brown	White	Monoclinic
Rutile	4.2	6–6.5	Reddish brown, black	Pale brown	Tetragonal
Garnet	3.5	6.5–7.5	Red, green, brown	White	Isometric
Pyroxene	3.5	5–6	Dark green, black	White to gray	Monoclinic
Amphibole	3.2	5–6	Dark green, black	White	Monoclinic
Epidote	3.4	6–7	Green	Grayish white	Monoclinic
Uranothorite	5.5	5.5	Brown to black	Light brown	Tetragonal
Monazite	5.26	5–5.5	Brown, yellow	White	Monoclinic
Xenotime	4.75	4.5	Yellowish-brown	White	Tetragonal
Fergusonite	5.7	5.5–6	Brown to black	Brown	Tetragonal
Khatyrkite	4.35	Unknown	Grayish	Unknown	Hexagonal
Gold	17	2.5–3	Yellow	Yellow	Isometric

3.4. Economic Viability, Revenue potential

The estimates for the TEHM resources in the Bavanapadu region, including ilmenite (0.658 million tons), sillimanite (0.513 million tons), and garnet (1.213 million tons), offer valuable insights into the area's economic viability. These numbers suggest that the Bavanapadu deposit has the potential to make a significant contribution to India’s heavy mineral resource base.

The offshore heavy mineral deposits at Bavanapadu represent a major economic opportunity, with a range of valuable minerals like ilmenite, rutile, zircon, monazite, garnet, and sillimanite. These minerals are vital for industries such as aerospace, ceramics, and electronics. Early estimates suggest the region could hold around 1.9 million tons of these minerals, positioning Bavanapadu as a potential mining hub that could serve both domestic and international markets. The global demand for heavy minerals is on the rise, and the current prices reflect their importance in various applications—ilmenite, for example, is priced between $350 and $480 per ton, rutile between $1,200 and $1,400 per ton, and zircon between $1,640 and $1,775 per ton. Monazite, a key source of rare earth elements, is even more valuable, ranging from $5,202 to $5,300 per ton. With Bavanapadu’s strategic location, the region is well-positioned to tap into export opportunities, particularly to markets in China, the United States, and other industrialized countries (Figure 10).

Table 3 summarizes the estimated revenue potential for each mineral, based on current market prices. For instance, ilmenite, with an estimated 658,116 tons, could generate between $230 and $315 million USD (₹1,900 to ₹2,606 crores INR), while zircon might generate between $42 and $45 million USD (₹350 to ₹379 crores INR). Overall, the total revenue potential from these resources ranges from $634 million to $851 million USD (₹5,232 to ₹7,024 crores INR).

THM resources are currently sufficient to meet global demand, except when disrupted by geopolitical conflicts or natural disasters. However, demand has risen in recent decades due to technological advancements and the transition from fossil fuels. Ensuring sustainable utilization, minimizing waste, and enhancing recycling are crucial to stabilizing prices, particularly for REE-bearing HMs. Despite challenges like the Covid-19 pandemic, the production of ilmenite, rutile, and zircon is projected to grow from 2020 to 2030, driven by expanding Chinese and Indian economies. To sustain future supply, systematic exploration of new HM deposits is imperative [23].

Table 3. Global market value of individual minerals in USD and INR

Mineral	Estimated tonnage	Market price (USD/tonne)	Revenue potential (Million USD)	Revenue potential in crores (INR)
Ilmenite	658,116	350 - 480	230-315	1900-2606
Rutile	5,168	1,200 - 1,400	6-7	51-59
Zircon	25,909	1,640 - 1,775	42-45	350-379
Monazite	17,497	5202 - 5300	91-92	750-765
Garnet	1,213,098	200 - 300	242-363	2001-3002
Sillimanite	5,13,028	Pricing varies		
Total	**1,919,788**	-	**634–851 million USD**	**5232–7024 Crores INR**

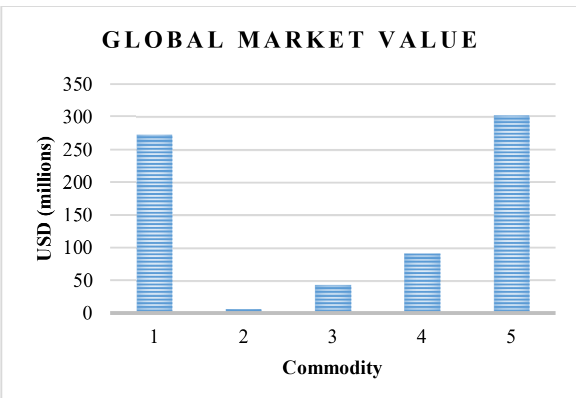

Figure 10. Global market value of individual minerals in USD.

4. Discussion

4.1. Economic potential of the Bavanapadu heavy mineral deposit

ArcGIS raster techniques were employed to estimate the mineral resources, providing an effective preliminary estimate despite logistical constraints. Limitations such as wide sample spacing and shallow core penetration may have affected the precision of the resource estimation. Similar challenges have been reported in marine resource estimation, where underwater conditions and uneven seabed morphology complicate resource quantification. The study's use of the Inverse Distance Weighted (IDW) interpolation method was key to producing tonnage rasters that presented a clearer spatial distribution of heavy mineral resources, despite these challenges.

The study's results show that the Bavanapadu sector in India contains substantial heavy mineral resources, with an estimated 2.681953 million tons of THM, which is promising for future mining development. These resources include both TEHM and magnetic heavy minerals, contributing significantly to India's heavy mineral industry. The presence of ilmenite, rutile, zircon, and monazite adds considerable value to the region, reinforcing its potential for industrial applications in aerospace, electronics, and construction industries. This aligns with previous studies on placer deposits along India's coastline, which demonstrate significant mineral concentrations in similar coastal regions.

The mineral assemblage in the Bavanapadu sector, composed of ilmenite, sillimanite, garnet, zircon, monazite, and rutile, confirms its economic relevance. These minerals are vital for various industrial applications such as titanium dioxide production (ilmenite and rutile) for the pigment industry, zircon for ceramics, and monazite as a source of rare earth elements. This highlights the importance of targeted extraction processes based on mineralogical composition for optimizing economic returns.

4.2. Depthwise distribution and concentration

The depth-wise analysis revealed that the majority of the heavy minerals are concentrated in the top 1 meter of sediment, with an estimated 1.605286 million tons of heavy minerals including 1.464713 million tons of TEHM. This result aligns with common trends observed in marine placer deposits, where wave action and coastal processes concentrate heavy minerals near the surface. The decrease in mineral concentration with depth is consistent with expectations for such deposits, emphasizing the importance of targeting shallow sediments for maximum recovery.

4.3. Challenges in marine resource extraction and sustainability

Most developing countries with HM resources have various challenges and limitations for production and processing [25]. Heavy minerals mining generally has a smaller environmental footprint than other mining methods, large-scale operations still pose significant environmental risks. Issues such as deforestation, habitat disruption, sedimentation, and water pollution can arise, especially with hydraulic mining techniques that may introduce harmful contaminants like mercury and cyanide. Moreover, the global supply of heavy minerals is limited, which raises concerns about resource depletion. This underscores the need for strict environmental regulations and responsible mining practices.

The challenges of marine resource extraction such as sampling difficulties and environmental concerns, must be addressed to ensure the long-term sustainability of the industry. while placer mining generally has a lower environmental footprint compared to primary deposits, it still presents challenges such as water contamination, habitat destruction, and erosion. Techniques like dredging, though effective for resource extraction, can lead to significant ecological disruption. Therefore, responsible mining practices such as minimizing water usage and improving waste management are essential for reducing the environmental impact. New models such as the semi-quantitative model [26], provide a more precise, comprehensive, and actionable approach to sustainability assessment, making them more suitable for evaluating sustainable development in THM mining.

4.4. Pathways to sustainable mining practices

Given that the highest mineral concentration is found within the top 1 meter, targeted mining strategies focusing on shallow dredging methods may optimize resource recovery, while minimizing environmental impact. Additionally, the estimated 36.9 million tons of sand resources highlight potential secondary economic benefits, particularly for construction and industrial applications. By integrating geospatial analysis with resource estimation, this study provides a robust framework for assessing offshore heavy mineral deposits, facilitating informed decision-making for future exploration and sustainable extraction.

Sustainable mining practices are essential to balancing economic potential with environmental responsibility. Key strategies include efficient mineral processing, reducing energy, and water consumption, and implementing effective site reclamation. These measures will help ensure the long-term viability of heavy mineral extraction in Bavanapadu, while minimizing environmental damage.

Reclamation and restoration efforts are crucial, especially in placer mining, where coastal ecosystems are highly sensitive. The use of sophisticated mining methods and tools can help minimize ecological disturbances [27].

Regulatory agencies actively monitor environmental impacts throughout the mining process. Strict environmental regulations and comprehensive management plans are essential to ensuring that economic benefits do not come at the cost of environmental degradation. With the rising demand for heavy minerals-especially for technology and renewable energy applications-ongoing research is needed to improve mining methods and sustainability. Substituting and recycling materials can also reduce the negative effects of mining and processing heavy minerals.

Recent scientific interest in sustainable mining highlights the need for updated research methods, comprehensive approaches, and clear regulations to balance economic, social, and environmental factors [28]. Multi-Criteria Decision-Making (MCDM) techniques help mining operations make better decisions by evaluating multiple factors, minimizing risks, optimizing resources, and integrating economic, environmental, and social considerations [29].

Soil restoration and public health are crucial aspects of mining. Sustainable remediation can be achieved through focused research, cross-disciplinary collaboration, and strong policies [30]. Additionally, nature-based solutions such as phytoremediation play a vital role in reducing heavy metal contamination in mining areas [31].

Corporate Social Responsibility (CSR) in mining primarily affects social factors, but has a limited impact on economic and environmental aspects. Many mining companies struggle to meet their social and environmental obligations, deviating from Sustainable Development (SD) goals. Increasing pressure from stakeholders and regulators is pushing companies to adopt responsible policies that balance profitability with social and environmental responsibilities. Future mining business models should integrate IT, Research and Development (R&D), and proactive stakeholder engagement. Sustainability reporting and resource management also need improvement. Expanding global research on CSR's role in sustainable development and benefit-sharing strategies will be crucial for the industry's long-term success [32].

Environmental Literacy Training (ELT) plays a key role in fostering ecological awareness and ensuring long-term environmental responsibility in mining communities. By educating workers, companies, and local populations, ELT helps promote sustainable development and responsible mining practices [33].

5. Conclusions

This study provides a comprehensive assessment of sub-surface heavy mineral resources in the Bavanapadu-Nuvvalarevu coastal sector, Andhra Pradesh, using advanced geospatial techniques. The integration of ArcGIS raster techniques, particularly inverse distance weighting (IDW) and Map Algebra, proved effective for resource estimation and spatial mapping in a dynamic coastal environment. This methodology addresses challenges like wide sample spacing and shallow core penetration, offering a replicable framework for similar studies.

The Bavanapadu sector holds immense potential as a resource hub for heavy minerals, offering significant economic and industrial value. By adopting sustainable mining practices, integrating advanced technologies, and addressing ecological concerns, this region can serve as a model for responsible mineral extraction. The study's geospatial methodology provides a replicable framework for similar coastal resource assessments, supporting data-driven decision-making. Future research should focus on long-term environmental monitoring, policy-driven conservation strategies, and technological advancements to enhance extraction efficiency while minimizing ecological impact. A balanced approach will ensure that economic benefits align with environmental preservation and community well-being.

Recommendations

Enhancing resource estimation and monitoring

- Utilize advanced technologies such as machine learning, remote sensing, and geophysical surveys (e.g., seismic reflection and magnetometry) to improve the precision and reliability of resource estimation.
- Conduct regular reassessments of heavy mineral reserves to track resource depletion and adjust mining strategies accordingly.

1. Promoting sustainable mining practices

- Implement sustainable mining techniques including land rehabilitation, erosion control, and habitat restoration, to minimize environmental damage.
- Conduct thorough environmental impact assessments (EIAs) and establish stringent regulations to ensure mining activities align with environmental protection goals.
- Maximize the economic benefits of heavy mineral extraction by reinvesting revenues into local infrastructure, education, and environmental conservation initiatives.

Data availability: The datasets generated and/or analyzed during the current study are available upon request from the corresponding author.

Declarations: The authors declare that this research work is original and has not been published previously in any other journal.

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تخمین منابع، قابلیت اقتصادی و استخراج پایدار مواد معدنی سنگین زیرسطحی با استفاده از تکنیک‌های رستری ArcGIS: مطالعه موردی از منطقه نزدیک به فلات قاره در بخش ساحلی باواناپادو، آندرا پرادش، هند

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چکیده:

بخش ساحلی باواناپادو-نووالاروو در آندرا پرادش، هند، میزبان منابع معدنی سنگین زیرسطحی (HM) قابل توجهی است که پتانسیل اقتصادی قابل توجهی را نشان می‌دهد. این مطالعه با استفاده از تکنیک‌های رستری ArcGIS، کل منابع معدنی سنگین (THM) و کل منابع معدنی سنگین اقتصادی (TEHM) را در منطقه‌ای به مساحت ۳۹ کیلومتر مربع تخمین می‌زند و تجزیه و تحلیل‌های مکانی را با داده‌های میدانی از نمونه‌های رسوب مغزه ادغام می‌کند. یافته‌ها نشان می‌دهد که در مجموع ۲.۶۸۱۹۵۳ میلیون تن THM، از جمله ۲.۴۳۴۴۲۲ میلیون تن TEHM، وجود دارد که بیشترین غلظت آن در لایه رسوبی ۱ متری بالای بستر دریا (۱.۶۰۵۲۸۶ میلیون تن) مشاهده شده است. ایلمنیت، گارنت و سیلیمانیت در مجموعه مواد معدنی غالب هستند و مقادیر کمتری زیرکون، مونازیت و روتیل نیز در کنار آنها قرار دارند که پتانسیل درآمدی تخمینی ۶۳۴ تا ۸۵۱ میلیون دلار آمریکا را ارائه می‌دهند. کاربرد روش‌های ArcGIS، به ویژه درون‌یابی وزن‌دهی معکوس فاصله (IDW)، امکان نقشه‌برداری دقیق از توزیع HM را فراهم کرد، علیرغم چالش‌هایی مانند فاصله زیاد نمونه‌ها و نفوذ کم عمق مغزه. در حالی که این مطالعه اهمیت اقتصادی و صنعتی بخش باواناپادو را برجسته می‌کند، نگرانی‌های زیست‌محیطی، از جمله اختلال در زیستگاه‌ها و تخریب رسوبات مرتبط با معدن‌کاری را نیز برجسته می‌کند. شیوه‌های پایدار، مانند فناوری‌های پیشرفته جداسازی، احیای سایت و ارزیابی‌های جامع اثرات زیست‌محیطی (EIA)، برای کاهش اثرات زیست‌محیطی ضروری هستند. این تحقیق اثربخشی تکنیک‌های مبتنی بر GIS را در تخمین منابع و معدن‌کاری پایدار نشان می‌دهد و چارچوبی قابل تکرار برای مدیریت منابع معدنی ساحلی و فراساحلی در سطح جهان ارائه می‌دهد. این یافته‌ها بینش‌های مهمی در مورد ایجاد تعادل بین رشد اقتصادی و حفظ محیط زیست ارائه می‌دهند و معیاری را برای استخراج مسئولانه مواد معدنی سنگین در محیط‌های ساحلی پویا تعیین می‌کنند..

کلمات کلیدی: کانی‌های سنگین، تکنیک‌های رستری ArcGIS، تخمین منابع، توجیه اقتصادی، معدنکاری پایدار.