Remote Sensing Data Analytics for Sustainable Coastal Monitoring in the Asia-Pacific

Case Studies of Malaysian Peninsula Coastal Regions

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Abstract

Coastal regions across the Asia-Pacific are increasingly exposed to sea-level rise, erosion, and rapid urbanization, heightening the need for scalable and data-driven monitoring frameworks. This article explores how remote sensing data analytics and deep learning techniques, such as U-Net, DeepLabV3+, and hybrid convolutional models, can enhance sustainable coastal observation and management. By integrating multispectral satellite imagery (e.g., Landsat and Sentinel series) within geospatial and machine learning environments, automated shoreline mapping and multi-decadal change detection can be achieved with high precision. Case studies from Malaysia's Peninsular coast demonstrate how combining AI-based segmentation with the Digital Shoreline Analysis System (DSAS) provides actionable insights into erosion, accretion, and human impacts. The study underscores how AI-powered satellite informatics can support coastal resilience, adaptive management, and sustainable resource governance across the Asia-Pacific region.

Introduction

The coastal areas of the Asia-Pacific are some of the most dynamic and vulnerable natural environments in the world, experiencing unprecedented threats in the form of a climate-induced sea-level rise (Noor et al., 2022), intensified tropical cyclones (Kopf et al., 2025), and human-induced pressures related to intensive urban and economic development (Arbinolo et al., 2021). According to the Intergovernmental Panel on Climate Change (IPCC), the rate of mean sea level rise has been increasing globally. It has deep consequences on coastal cities and ecosystems that are at a low altitude (IPCC, 2021). Countries in the Southeast, such as Malaysia, Indonesia, Thailand, and the Philippines, face a compounded risk, such as coastal erosion, saltwater intrusion, loss of protective mangroves, and damage to critical infrastructure (Hens et al., 2018). Although useful, traditional in-situ methods of monitoring prove to be spatially sparse, expensive to maintain, and have limits on the ability to capture the large-scale changes and long-term variations that take place over long coastlines (Garcia-Soto et al., 2021; Kennedy, 2013). This data gap inhibits the capacity of policymakers and planners to make sound decisions towards sustainable coastal management. As a result, an urgent requirement exists regarding alternative, consistent, and comprehensive monitoring systems.

Satellite remote sensing has transformed the field of environmental monitoring through the provision of synoptic, multi-temporal, and freely available data at different spatial and temporal resolutions (Amitrano et al., 2021). Mission archives such as Landsat (since 1972) and Copernicus Sentinel (since 2014) provide decades of imagery, which allows examining traditional shoreline transformation. Nevertheless, manual extraction of shorelines out of such large data is meticulous and subjective. The paradigm shift has been initiated by the incorporation of advanced data analytics, especially deep learning (DL). U-Net and DeepLabV3+ are convolutional neural networks capable of processing the accurate segmentation of coastline on complex satellite images, which allow much better efficiency and accuracy than manually tackling the problem (Khurram et al., 2025).

Coastal challenges in the Asia-Pacific

A digital horizon: coastal resilience at the crossroads

The Asia-Pacific coastal areas are leading the frontier of global environmental change with mounting challenges of climate-induced sea-level rise, storm intensity, and unsustainable coastal development. According to the state of the climate in the South-West Pacific 2023 report by the WMO (World Meteorological Organization), from January 1993 to May 2023, the global mean sea-level rise (GMSL) was approximately 3.4 mm ± 0.3 mm/per year. This is increased by land subsidence of major deltas in the Mekong (Viet Nam), Irrawaddy (Myanmar), and Chao Phraya (Thailand) due to compaction of the river sediment and groundwater extraction (Becker et al., 2024). The combination of sea-level rise and land subsidence enhances the relative sea-level rise at the site, which in turn aggravates the rate of coastal flooding, erosion, and saltwater intrusion (Restrepo-Angel et al., 2021).

Recent assessments have estimated that coastal flooding is already inflicting approximately US$26.8 billion of loss every year in Asia and the Pacific, which is expected to increase to USD144-198 billion by 2050 unless there is significant adaptation (Monioudi et al., 2025). In urban deltas (like those in Bangladesh, Viet Nam, and Indonesia) where the sea-level rise is coupled with subsidence, tens of millions of the population are at a high risk of displacement (IPCC, 2022) (Figure 1). Human-driven subsidence, in addition to sediment starvation and coastal erosion, has raised the risk of relative sea-level rise significantly and led to the loss of vast territories over the past few decades in the Mekong Delta alone (Baldan et al., 2025).

The danger of extreme weather also contributes to such risks. The Asia-Pacific region is one of the most affected areas in the world by tropical cyclones, and in warmer ocean environments, the storms are expected to get stronger and more precipitous (Chen et al., 2021). The most notable examples of such events include Typhoon Rai (2021) in the Philippines and Cyclone Mocha (2023) in the Bay of Bengal, which demonstrate the rising destructive power of tropical cyclones, especially when they are combined with high base-level sea levels and lead to compound coastal-flooding dangers (Bevacqua et al., 2020). Moderate storm surges can be devastating to coastal defences and drainage systems, coupled with heavy rainfall or even when coupled with a high tide. According to the Asia-Pacific Disaster Report 2023 (ESCAP, 2023), the vital factors contributing to overwhelming exposure to flood risk are climate extremes and a fast pace of coastal urbanisation. There is also a threat to coastal buffer ecosystems, like mangroves, although Southeast Asia is home to one of the highest mangrove forest proportions in the world. These mangrove ecosystems are disappearing at an incredibly fast pace due to the expansion of aquaculture, land reclamation, and pollution (Friess et al., 2019). In the Global Mangrove Watch data, an overall loss of about 5,245 km^2 of mangrove forests was experienced during 1996-2020, and hotspots of the loss were found in Southeast Asia (Indonesia, Malaysia, Myanmar) (Bunting et al., 2022). Confirmed by NOAA (National Oceanic & Atmospheric Administration) (2024), the current global coral bleaching (since the beginning of 2023) has already affected over 80 per cent of the world's coral reefs, greatly affecting their ability to provide natural protection of the coastline.

Most of the megacities in the region, including Jakarta, Manila, Bangkok and Ho Chi Minh City, which are built on reclaimed or submerged land behind crumbling flood-defences, are estimated to be chronically flooded in moderate emission scenarios (Ruan et al., 2024). Some areas of Jakarta, in particular, are sinking up to 3-10 cm per year, which is a more immediate risk than world-scale sea-level rise (Abidin et al., 2015). The process of urbanization and the increase of impervious surfaces decrease the infiltration and drainage capacity of the soil and increase flood peaks during monsoon rains (Yosua et al., 2024). Another hazard that is serious but less evident is saltwater intrusion. The impact of a rise in sea level, coupled with decreased upstream discharge and excessive groundwater extraction, allows

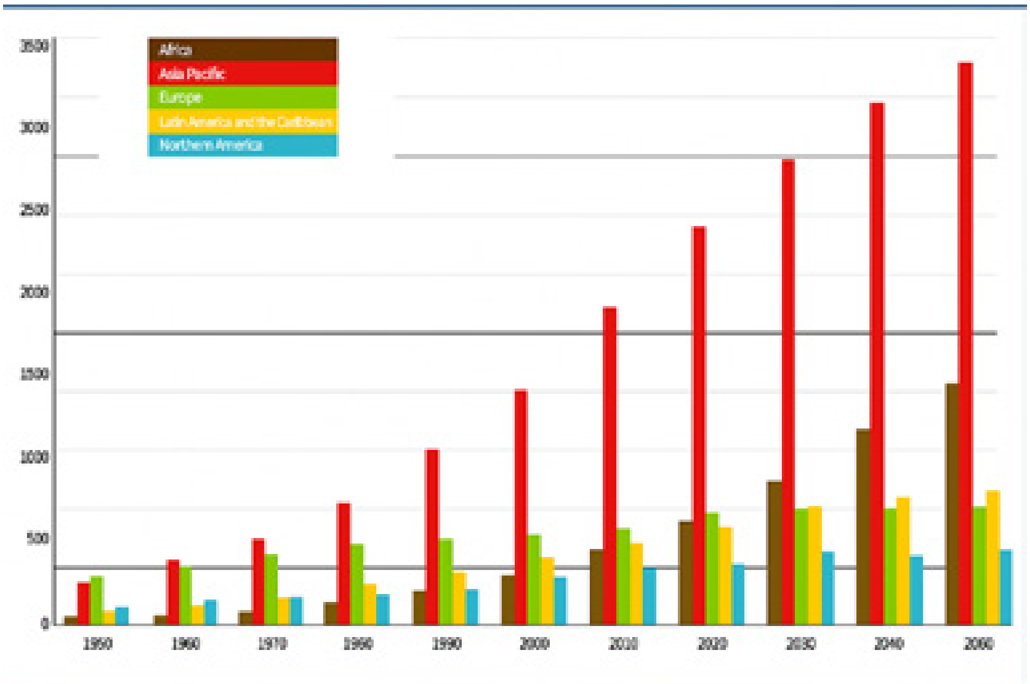

Figure 1. Projected population growth for the Asia-Pacific region from 1950 to 2050 (by Rollins, A. M. 2019).

estuaries and aquifers to become more vulnerable to groundwater. This is already affecting the rice production in the Mekong Delta in Viet Nam (IPCC, 2022) and the water/ soil quality in coastal Bangladesh (Ashrafuzzaman et al., 2022). It is stated with high certainty in IPCC (2022) that in the continued warming of low-lying coastal areas like deltaic plains, there is a growing risk of salinization, especially when the elevation of the land is low and the sediment input is inadequate, which hinders adaptation. In spite of a great level of scientific development, there are still large gaps in data and monitoring. In most of the countries in the region, observation capabilities are still low with sparse networks of tidal gauges, intermittent subsidence surveillances, and limited to rough height measurements that limit accurate coastal risk evaluation (WMO, 2023). Additionally, it is mentioned in the Asia-Pacific Disaster Report, 2023 (ESCAP, 2023) that the elimination of data, model, and early warning systems gaps is necessary to make operational the anticipatory coastal planning.

The fragile pulse of the Malaysian peninsula

The east coast coastal belt, Kelantan-Terengganu-Pahang, is an ecological and economic hotspot of Peninsular Malaysia, as well as the southern belt of Johor. They support fisheries, tourism, agriculture, and biodiversity. Yet they are the locations of sea-level rise, mangrove loss, estuarine flooding, and saltwater intrusion. These problems do not spread in equal measure - neither do their solutions. What is required is a spatially intelligent, real-time way of diagnosing, identifying, and guiding interventions. This is where AI works with satellites.

The Asia-Pacific region is a considerable bearer of coastal hazards in climatic conditions. WMO reports that the rate of rise of sea levels along the coasts of the Pacific and Indian Ocean in Asia is currently higher than that of the world, posing a threat of coastal flooding (WMO, 2024). According to the State of the Climate in Asia 2023 report, the hydro-meteorological hazard events (mostly floods and storms) affected over 9 million people in 2023 (WMO, 2023). The spatial distribution of the patterns of coastal risk is different in the Malaysian Peninsula, as shown in Figure 2, which plots the National Coastal Vulnerability Index (NCVI). It reflects very-high vulnerability regions (in red) that are focused on the western shores of Selangor and Kedah, and the eastern shores of Kelantan and Terengganu, which proves the skewed distribution of exposure to erosion and flood hazards across the peninsula (Amiruddin, 2023).

The long coastline in the Peninsula, which borders the Strait of Malacca and the South China Sea, is very susceptible in Malaysia. Key challenges include:

- Erosion: Malaysia has a considerable portion of its coastline that has been identified as eroding and poses a danger to communities, agriculture, and tourism infrastructure.
- Sea-Level Rise: It is projected that it will increase further, and the threat of inundation and freshwater aquifers being contaminated with saltwater will persist.

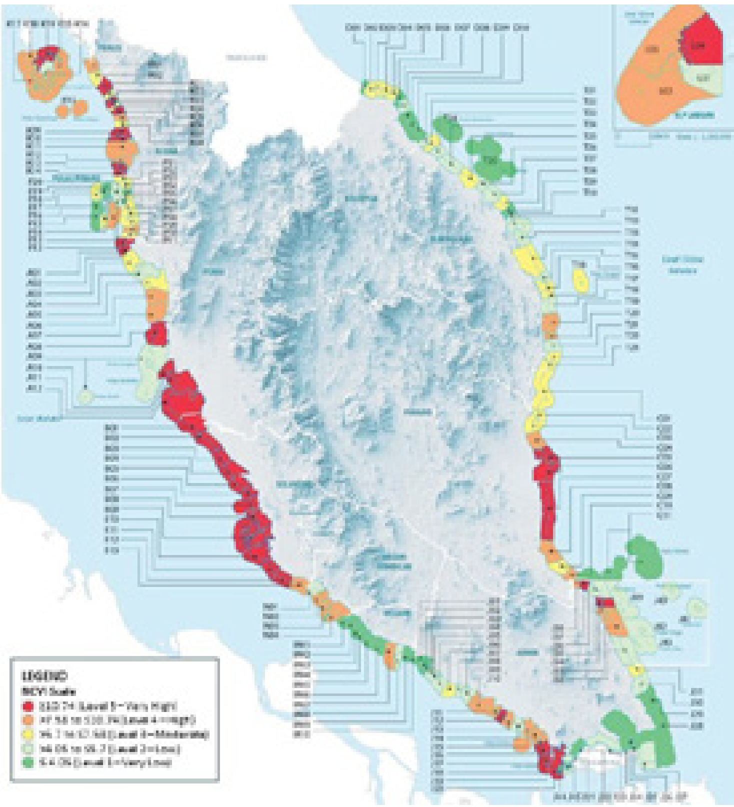

Figure 2. National Coastal Vulnerability Index (NCVI). Malaysia (by Amiruddin 2023).

- Land Use Change: Rapid urbanisation, agricultural and aquaculture deforestation, development of ports and other infrastructures have greatly changed the sediment transport regimes and decreased the natural coastal buffer, including mangroves (Billah et al., 2023).
- Extreme Events: Monsoon floods and tropical storms are likely to happen in the region and result in rapid and drastic changes in the coastal areas.

The accruing effects of these factors portray the urgency of high-resolution monitoring systems, frequent, and accurate monitoring systems to provide information on adaptation and mitigation plans.

Evolution of remote sensing in coastal monitoring

Historical context

Remote sensing as a science has transformed into a pillar of coastal science since the introduction of Landsat 1 in 1972, and it started as an experimental procedure. The earlier spectral algorithms, like the Normalized Difference Water Index (NDWI), were able to perform simple land-water mapping but failed in complicated settings that were hit by turbidity, vegetation, and shadowed buildings. As the fields of big data, machine learning, and deep learning, and cloud computing have advanced, the field has passed through another stage of multi-sensor integration, significantly enhancing the spatial accuracy and time continuity of monitoring the dynamics of the coasts.

Optical, radar, and altimetric sensors are currently integrated into an interoperable global system. Sentinel-2 is (10 and 20 m spatial resolution) multiple-spectral imagery of the shoreline and habitat, whereas SAR activities like Sentinel-1 and ALOS/PALSAR can also offer coverage at all times. The revolution of measurements of sea-level anomalies, tides, and land subsidence has been brought by altimetry missions (TOPEX/Poseidon, Jason series, Sentinel-6 Michael Freilich) and laser altimetry measurements by ICESat-2, playing an important role in flood-risk and coastal-planning research.

Recent research (ESA, European Space Agency, 2020) emphasizes the significance of harmonised, cross-sensory data that amalgamate optical reflectance, radar backscatter, and elevation data into single structures - transforming the disaggregate data into a coherent understanding of shoreline change, sediment transportation, and risk of inundation. The cloud-computing revolution by the use of Google Earth Engine and Copernicus Data Space Ecosystem can now process petabytes of imagery over the world in long-term and near-real-time. This combination of multi-sensor observation and cloud analytics has changed coastal monitoring into a planetary observatory, which observes the dynamic connection between land, sea, and society.

Deep learning implementation at shoreline analytics

Deep learning is a paradigm shift from rule-based to data-driven analysis. CNNs (Convolution Neural Network) are able to learn spatial hierarchies of features because they can be used to classify complex coastal scenes better than threshold-based algorithms. Zhao et al. (2022) and Khurram et al. (2025) showed that U-Net and DeepLabV3+ are more effective in accuracy and generalizability than traditional classification.

Core models

***U-Net*:** U-Net possesses a contracting-expanding architecture with skip connections that results in the high localization accuracy of the land-water interface.

DeepLabV3+: It uses atrous (dilated) convolution and spatial pyramid pooling, which allows it to capture multi-scale contextually relevant information; hence, it can work across varied coastal morphology.

Hybrid models: CNNs further improved by Conditional Random Fields (CRFs) or attention mechanisms yield more classification edges and less misclassification.

Case Study: multi-decadal shoreline change monitoring in Kelantan, Malaysia

Kelantan had the most active and erosive behavior along its coastline of the four eastern and southern states of Malaysia over the 34 years. The shoreline dataset derived by U-Net and processed with the help of DSAS displayed extensive and intense retreat and localized areas of accretion (Figure 3). The highest linear regression rate (LRR) of erosion was around -64.9 m/year around the Tumpat estuary near Kota Bharu, where erosion was sustained due to the interaction of monsoonal waves, strong littoral drift, and fluvial flooding (the most recent was the 2014 flood).

Though erosional trends prevailed, Kelantan did show some examples of high accretion rates, up to +47.6 m/year especially in areas of sheltered embayments and depositional conditions caused by large sediment loads in the Kelantan River system. The entire Net Shoreline Movement (NSM) ranged between approximately 1,885m (Movement landward) and +1,629m (Movement seaward) and indicated a great deal of variability along the coast. The shoreline moved by over 1.5-1.9 km in various transects, and this revealed both erosion and deposition of sediments (Figure 4). As shown in Table 1, key coastal parameters, satellite sensors, and deep-learning methods effective in the Asia–Pacific region is summarized.

The spatial analysis suggests hot spots of erosion occur at the mouths of the major rivers and bare coastal areas, and the accretion on the coast prevails in the sediment-laden or structurally protected sections. The results prove that the Kelantan shoreline is subject to the products of the interplay of high-energy monsoonal processes, riverine discharges of sediments, and episodic flooding, which makes it highly vulnerable to anthropogenic and climatic disturbances. In general, the deep learning-based DSAS system was able to adequately model these fine-scale transitions to offer a strong quantitative foundation to define essential erosion areas that

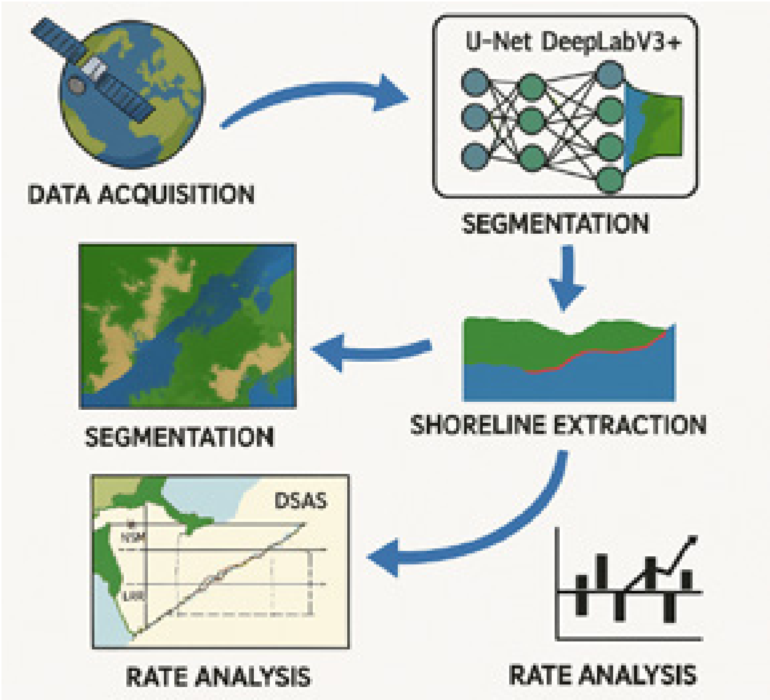

Figure 3. Schematic workflow of the application of remote sensing multi-decadal shoreline change monitoring in Kelantan, Malaysia.

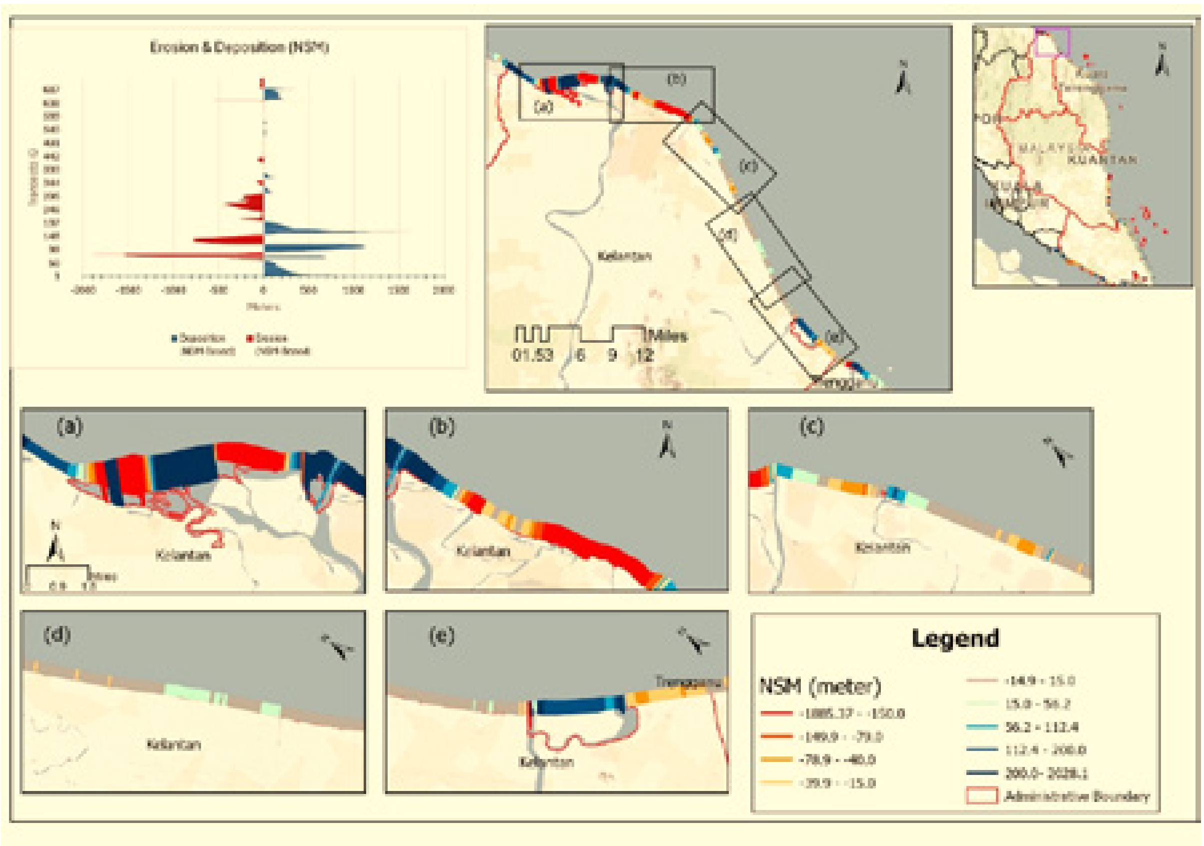

Figure 4. Spatial distribution of shoreline change analysis in Kelantan state: NSM results (1990 - 2024) (by Khurram et al. (2025)).

Table 1 summarizes key coastal-monitoring parameters, the satellite sensors commonly applied, and deep-learning approaches that have proven most effective in the Asia-Pacific context.

Monitoring Parameter	Satellite Sensors / Products	Data Analytics & Deep Learning Approaches
Shoreline Position & Change	Landsat 5-9, Sentinel-2, Sentinel-1	U-Net, DeepLabV3+ for segmentation; DSAS for change rate calculation
Coastal Erosion & Accretion	Multi-temporal composites from the above missions	CNN-based change detection; DSAS (EPR, Linear Regression Rate)
Land Use/Land Cover (LULC) Change	Landsat, Sentinel-2	Random Forest, Support Vector Machines (Ul Din and Mak, 2021); U-Net for semantic segmentation
Sea Level Rise & Inundation	Satellite Altimetry (TOPEX/Jason series, Sentinel-3, Sentinel-6)	Integration with Digital Elevation Models (DEMs); ML for flood risk modeling
Mangrove Forest Extent & Health	Sentinel-2 (Red Edge bands), Landsat	Spectral Indices (NDVI, EVI); CNN models for species classification and health assessment
Urban Sprawl & Impervious Surface	Landsat, Sentinel-2, Very High-Resolution (VHR) data (e.g., WorldView)	Spectral Unmixing; DeepLabV3+ for precise urban feature extraction

should be given priority when developing future coastal protection and adaptive management projects.

Coastal management and wider applications

Mapping risk and enhancing resilience

The use of AI-based geospatial analytics can reveal the interrelationship of coastal risks in terms of interrelating climatic, hydrological, and human components. The overall impact of the stresses of the environment is identified across the researched coasts, as processes of coastal erosion, habitat loss, flooding, and salinity intrusion are interdependent.

Hotspots in erosion: For a long time, the shoreline has been steadily receding, in some cases several meters a year, in many vulnerable areas, which stresses the need to focus on specific adaptation and sediment management.

Degradation of the ecosystem: The reduction of the mangrove cover and fragmentation of the habitats highlight the necessity to adopt nature-based solutions where the restoration of the ecosystem must be incorporated as a component of climate protection.

Flood exposure: A Predictive model of floods assures that intact natural buffers can cut off the extent of inundation by half, supporting their usefulness in safeguarding livelihoods.

Salinity intrusion: The inland movement of saline intrusion into agricultural deltas is an indication of growing water and food security concerns rising sea levels.

Collectively, such insights can prove that AI-enabled remote sensing is superior to conventional monitoring it is a decision-support and early-warning system. This will help the nations to develop their robust and resilient coasts in the long term, as it will enable them to develop predictions and governance of the coasts.

From data to decisions: the governance edge

The AI-satellite framework has its value of transformation based on its policy translatability. Scientific knowledge is made into an action plan:

- Zoning and setback control based on real-time coastal-risk overlay based on AI classification and DSAS change indicators.
- Restoring mangrove corridors that give the greatest ecological and socio-economic benefits through rehabilitation (Alongi et al., 2023).
- Community dashboards: Community dashboards that combine IoT sensors for tides and Earth-observation data to keep people informed of floods;
- Evidence-based climate-adaptation policy, and use of infrastructure investment as spatially justified risks evaluation (ESCAP, 2024; WMO, 2025)

This is an adaptive, predictive, and participatory paradigm of digital environmental governance that fills the old dichotomy between information creation and operationalization of the decisions. Achieving this is possible by integrating machine intelligence into national coastal-management processes, where Malaysia is able to shift to engineering in a proactive mode, and resilience planning.

Building resilient shores: Malaysia's evolving coastal strategy

To institutionalize this data-driven resilience model, Malaysia should undertake these coordinated reforms:

1. **Establish a national coastal intelligence unit** that consolidates AI–remote sensing analytics within federal and state planning agencies, delivering dynamic dashboards for shoreline monitoring and zoning alerts (Khurram et al., 2025).
2. **Risk-informed development,** which entails, before issuing a permit to any coastal development, that all aquaculture, tourism, and infrastructure must take into account certified AI-generated erosion and flood overlays (ESCAP, 2024).
3. **Invest in nature-based infrastructure**, escalating mangrove restoration and seagrass restoration as cost-effective climate shields that stabilize sediments, reduce waves, and enhance carbon sequestration (Alongi, 2020; UNEP, 2024).
4. **Empower local data stewardship** coaching communities in the coastal areas in conducting citizen-science validation and in engaging local people in participatory mapping with access to open-source applications such as Google Earth and QGIS (Fraisl et al., 2022).
5. **Regionalize the framework across ASEAN,** expand the Malaysian AI-satellite model to the entire Southeast Asian coast, and help in developing common resilience principles and cross-border sediment-management plans (ADB, Asian Development Bank, 2024).

Coastal futures, digitally defended

In the Anthropocene, defending coasts is less about concrete and more about cognition. The integration of artificial, spatial, and ecological intelligence enables nations to anticipate, rather than merely react to, environmental transformation. Malaysia's leadership in operationalizing this AI–remote sensing model could redefine coastal management across the Asia-Pacific, where scientific foresight becomes the cornerstone of sustainability. The satellites are already in orbit; the algorithms, in code. What remains is the collective will to turn intelligence into action (Horton et al., 2020).

Conclusion

This study demonstrates that remote sensing data analytics offers an effective, scalable solution for sustainable coastal monitoring in the Asia-Pacific, as shown in the Malaysian Peninsula case studies. By integrating multi-temporal satellite imagery with deep learning techniques, accurate shoreline and land–water dynamics were mapped to reveal patterns of erosion and accretion. The approach enhances monitoring efficiency, supports climate-resilient coastal management, and aligns with global sustainability goals. Overall, remote sensing–based analytics provide a robust framework for data-driven decision-making toward protecting vulnerable coastal environments. Coastal agencies should integrate remote sensing–based monitoring into routine management frameworks, combine optical and radar data for improved accuracy, and develop open-access geospatial platforms to support community and policy-level decision-making for long-term coastal sustainability.

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