Innovation, Monitoring and Data-Driven Approaches for a Resilient Coastal Future

The second 2024 Volume of Coastal and Ocean Science and Engineering (COSE) brings together a diverse yet conceptually cohesive collection of five scientific contributions that examine the evolving relationship between coastal observation, modelling, prediction, and risk assessment. This issue reflects a discipline in transition: as climate-driven pressures intensify, coastal engineering is increasingly shaped by integrated, data-rich methodologies capable of translating physical complexity into actionable insight.

Across the contributions gathered in this Special Issue, there is a clear convergence of advanced monitoring platforms, multi-scale numerical methods, artificial intelligence, and refined statistical analyses. Together, these tools are reshaping how coastal scientists interpret structural vulnerability, predict hydrodynamic processes, and manage escalating climate risk. The studies share a common ambition: to develop coastal systems that are not only better understood and more predictable, but also more resilient and adaptively managed.

The articles in this volume span a broad range of themes—from hybrid visual–aerial monitoring of maritime infrastructure, to bottom-up climate stress-testing, to neural-network-based wave forecasting, to statistical detection of tide–surge interactions, and finally to multi-sensor remote sensing for infrastructure assessment. Taken together, they exemplify a contemporary coastal engineering paradigm rooted in high-resolution observation, data assimilation, and anticipatory risk governance.

1. Systematic Observation and Digital Monitoring of Maritime Infrastructure

The first contribution presents an extensive application of LNEC's OSOM+ methodology, a modernised evolution of Portugal's long-standing systematic monitoring programme for rubble-mound breakwaters and maritime structures. By integrating GPS-referenced visual inspections, high-resolution drone photogrammetry, and a sophisticated web-based GIS platform (ANOSOM-WEB), the methodology provides a comprehensive digital framework for tracking structural performance and diagnosing early-stage anomalies.

Using the West Breakwater at the Port of Sines as a case study, the authors demonstrate how multi-temporal photogrammetric products—orthomosaics, point clouds, digital surface models, and structural profiles—enable the detection of subtle armour-unit displacements and morphological adjustments. Crucially, OSOM+ transforms observational data into a decision-support system, allowing port authorities to schedule targeted maintenance based on quantitative assessments of structural evolution, risk condition, and spatially explicit diagnostics.

This work highlights a defining shift in contemporary coastal engineering practice: monitoring is no longer episodic, but continuous, spatially comprehensive, and digitally integrated—strengthening both operational preparedness and long-term resilience planning.

2. Bottom-Up Risk Assessment and Climate Stress-Testing for Future Flood Hazards

The second article offers a compelling comparison between top-down, scenario-driven climate assessments and bottom-up, vulnerability-focused frameworks, arguing for the complementary value of the latter under conditions of deep uncertainty. While top-down approaches ensure consistency with global climate projections, bottom-up methods excel at identifying local thresholds, adaptive capacities, and socio-environmental vulnerabilities that often determine real-world risk.

The authors show how participatory processes, fine-scale system mapping, and climate stress-testing can reveal critical tipping points—structural, social, or ecological—that remain invisible in scenario-based modelling alone. Their analysis reflects a broader conceptual shift: coastal risk assessment is evolving from a projection-centred exercise toward a resilience-oriented, locally grounded planning strategy.

In the context of accelerating sea-level rise and increasing storm impacts, this contribution underscores the need for hybrid frameworks that integrate climate science with site-specific knowledge and adaptive pathway planning, thereby fostering more flexible and robust adaptation strategies.

3. Artificial Intelligence for Nonlinear Wave Forecasting

The third contribution explores the growing interface between machine learning and phase-resolving wave modelling, demonstrating how neural networks can enhance the predictive skill of coastal wave forecasting systems. By training neural networks on hindcast datasets and high-fidelity nonlinear wave simulations, the authors successfully reconstruct complex wave dynamics, capturing short-term variability and nonlinear behaviour that are often underestimated by conventional approaches.

The study highlights several key advances:

- integration of artificial intelligence with deterministic hydrodynamic models;
- improved representation of nonlinear processes such as wave–wave interactions;
- enhanced forecasting at temporal scales relevant to harbour agitation, overtopping, and near-shore operations.

The resulting hybrid modelling framework illustrates how machine learning can augment—rather than replace—physics-based simulation. Together, these approaches offer strong potential for real-time forecasting systems capable of supporting coastal safety protocols and port operations under increasingly volatile meteorological conditions.

4. Detecting Tide–Surge Interaction in the Adriatic Sea

This study addresses a fundamental yet underexplored question for the Adriatic Sea: whether storm surges and astronomical tides interact statistically to influence extreme water levels. Applying three independent statistical frameworks—distributional analysis of extreme surges, timing relative to high tide, and correlation between skew surges and high tides—the authors analyse long-term tide-gauge records from the northern, middle, and southern Adriatic.

The results present a nuanced picture. While individual methods or locations exhibit weak indications of interaction, no consistent or robust evidence of tide–surge interaction emerges across all tests. This finding is particularly relevant in the context of the Adriatic’s microtidal regime, where storm surges dominate extreme sea-level events.

By clarifying the limited role of tide–surge interaction in this basin, the study supports simplified modelling approaches in which tidal and surge components can be treated as largely independent—improving hazard quantification and flood-risk assessment.

5. Multi-Sensor Remote Sensing for Coastal Structure Assessment

The final contribution introduces an advanced RTK-anchored, multi-sensor remote-sensing workflow that integrates UAV-SfM, handheld SfM, smartphone LiDAR (sLiDAR), and terrestrial laser scanning into a unified monitoring framework for rubble-mound breakwaters. Beyond methodological innovation, the study presents a fully reproducible uncertainty-quantification protocol, incorporating hybrid M3C2 analyses and LoD95 detection thresholds.

The authors demonstrate:

- how different sensing platforms complement each other in terms of coverage, resolution, and access to occluded or porous zones;
- how multi-sensor co-registration yields engineering-grade point clouds suitable for as-built verification;
- how formalised uncertainty propagation supports defensible change detection.

By lowering technical and financial barriers to high-resolution monitoring, this workflow offers substantial benefits for routine coastal infrastructure management, enabling more frequent, accurate, and comprehensive assessments under increasing climate-related pressures.

Collective Themes and Emerging Directions

Several unifying themes emerge across the five contributions:

1. *The rise of high-resolution, multi-source coastal observation*

Drone photogrammetry, remote sensing, and multi-sensor point clouds are redefining how coastal structures and processes are monitored.

2. *Integration of data-driven and physics-based modelling*

Neural networks, statistical methods, and hydrodynamic models are increasingly combined to address complex nonlinear phenomena.

3. *Emphasis on uncertainty, thresholds, and systemic vulnerability*

Both bottom-up stress-testing and multi-sensor workflows highlight the importance of understanding failure conditions and risk propagation.

4. *Need for flexible, adaptive risk-management strategies*

As sea levels rise and storms intensify, adaptation planning must be iterative, locally grounded, and scenario-rich.

5. *A shift toward predictive and near-real-time capability*

AI-enhanced forecasting, high-frequency monitoring, and digital diagnostic platforms point toward a dynamic future for coastal risk assessment.

Concluding Remarks

Volume II (2024) of COSE, a special issue, offers a comprehensive snapshot of innovation at the intersection of monitoring, modelling, and coastal risk analysis. It portrays a discipline in evolution—moving toward predictive, high-resolution, and system-aware methodologies that are essential for addressing the challenges posed by climate change.

By advancing digital observation, hybrid modelling, and participatory risk assessment, the contributions in this Special Issue collectively strengthen the scientific foundations needed to design, manage, and safeguard coastal systems worldwide.

This volume serves both as a reflection of current progress and as an invitation to future research, collaboration, and innovation in support of more resilient coasts and communities.

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