Monitoring Dynamic Coastal Morphology Using Multi-Temporal Satellite Derived Bathymetry for Sustainable Marine Management: A Case Study of Adam's Bridge

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Coastal sustainability, marine habitats, and navigation are threatened by dynamic shifts in coastal morphology, making seabed monitoring essential for evidence-based management. Adam's Bridge, a shallow sandbank system connecting India and Sri Lanka, is highly suitable for investigating morphological change due to strong tidal currents and monsoon influences that frequently alter marine biodiversity and circulation patterns. This study applied a Satellite-Derived Bathymetry approach to monitor annual morphological changes in Adam's Bridge from 2019 to 2024. Because the area is extremely shallow and dynamic, obtaining in-situ depth measurements that correspond to satellite acquisition dates for continuous monitoring is difficult. Therefore, this study emphasized the use of space-borne bathymetric data sources for monitoring dynamic shallow-water environments. Sentinel-2 imagery and Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2) data were used for calibration and validation. Calibration and validation relied primarily on ICESat-2, demonstrating the potential of satellite-only datasets for bathymetric mapping in data-scarce regions. An empirical band-ratio technique was used to develop regression models and generate Digital Bathymetric Elevation Models (DBEMs) for bathymetric profile extraction. Image pre-processing substantially improved Sentinel-2 data quality. Successful sun-glint correction was confirmed by high correlations ($R^2 > 0.75$) between the NIR and visible bands, while land masking enabled accurate separation of terrestrial and aquatic regions. Refraction-corrected depths derived from raw ICESat-2 data provided reliable calibration and validation inputs for bathymetric modelling. Band-ratio regression models demonstrated strong performance for most study years, yielding R^2 values of 0.73 (2019), 0.70 (2020), 0.71 (2021), and 0.74 (2022). The 2024 model showed slightly reduced performance ($R^2 = 0.63$), potentially due to elevated turbidity or less favorable image acquisition conditions. Model standard errors ranged from 0.47–0.77 m. Validation of the 2022 Digital Bathymetric Elevation Model (DBEM) produced an RMSE of 0.89 m, achieving sub-meter vertical accuracy, with Total Horizontal Uncertainty (THU) and Total Vertical Uncertainty (TVU) estimated at 10 m and 0.89 m, respectively. Bathymetric profiles extracted from nine transects revealed pronounced spatiotemporal morphological variability across Adam's Bridge. Perpendicular transects indicated stronger cross-shore sediment migration relative to long-shore transport, while lateral transects identified oscillatory sandbank migration patterns. Interannual bathymetric profiles clearly captured alternating zones of sediment accretion and erosion, demonstrating the highly dynamic geomorphology of the region. Overall, this study demonstrates the feasibility of using satellite-only bathymetric approaches for morphological monitoring, providing a cost-effective solution for coastal management.

Keywords: *Adam's Bridge, Sentinel-2, ICESat-2, Morphological changes, Satellite-Derived Bathymetry (SDB)*