DOI: https://doi.org/10.53256/COSE_240102

Integrating open-access data for beach monitoring and countermeasure planning: a case study of the southeastern Adriatic

Ružica Rumenović, Morena Galešić Divić, Toni Kekez, and Veljko Srzić
University of Split, Faculty of Civil Engineering, Architecture and Geodesy, Split, Croatia
rrumenovic@gradst.hr

ABSTRACT: In tourism-driven coastal regions, beaches provide substantial economic and ecological value but are increasingly threatened by erosion and flooding, which jeopardise their long-term sustainability. To address these challenges, data-driven monitoring and countermeasure planning are essential, particularly in areas where continuous in situ monitoring infrastructure is limited. This study, conducted within the ClimBeach project (Interreg VI-A IPA CBC Croatia–Bosnia and Herzegovina–Montenegro), investigates how publicly accessible datasets can support coastal monitoring strategies and inform the selection of appropriate countermeasures across twelve pilot sites in Croatia, Bosnia and Herzegovina, and Montenegro.

Spatially distributed meteorological data (Visual Crossing), oceanographic products (Copernicus Marine Environment Monitoring Service), and historical shoreline changes derived from Google Earth satellite imagery are analysed to assess their suitability and reliability for monitoring beach evolution. These datasets provide insights into climatic influences, erosion-prone periods, wave climate variability, and site-specific vulnerability. Such information enables the development of adaptive monitoring schedules and supports the selection of hard, soft, hybrid, or management-based countermeasures.

By linking historical data trends with targeted interventions, this study proposes a cost-effective framework for beach monitoring and coastal resilience planning in the southeastern Adriatic. The findings contribute to the development of scalable coastal adaptation strategies that balance data accessibility, intervention feasibility, and resource efficiency in vulnerable coastal areas.

1 INTRODUCTION

Beaches constitute essential economic, ecological, and social resources, particularly in regions that rely heavily on tourism and fishing. They provide a wide range of benefits, including recreational opportunities, habitat provision, and contributions to community identity (Dixon et al., 2012). However, these valuable coastal systems are increasingly threatened by challenges such as shoreline erosion, sea-level rise, and the growing frequency and intensity of extreme weather events associated with climate change (Bonaldo et al., 2020). The need for adaptive and proactive coastal protection measures is therefore urgent, especially in regions where systematic, long-term monitoring and data collection remain limited (Ewing, 2015).

The eastern Adriatic coastline, extending along Croatia, Bosnia and Herzegovina, and Montenegro, exemplifies the demand for effective and evidence-based coastal management strategies. This region is subject to a complex interplay of processes, including dynamic sediment transport, human-induced alterations to natural sediment supply, and increasing coastal development, all of which drive rapid and site-specific shoreline changes. These dynamics underscore the importance of continuous and structured monitoring to detect trends and support timely management interventions (Pikelj et al., 2017). While several studies have examined coastal erosion in the northern Adriatic in the context of climate change (Torresan et al., 2019; Gallina et al., 2019), the southern and eastern Adriatic remain comparatively underrepresented in site-specific research. Nevertheless, recent studies have begun to address these gaps through shoreline monitoring initiatives (Miličević et al., 2022) and evaluations of beach nourishment practices (Bogovac et al., 2023a).

To build on these efforts and extend practical methodologies to under-monitored coastal areas, the ClimBeach project was initiated within the Interreg VI-A IPA CBC framework (University of Split, n.d.). The project aims to enhance coastal resilience through cost-effective monitoring approaches and targeted intervention planning across twelve pilot beaches in the three participating countries. This paper investigates how publicly available datasets—including meteorological records, wave and sea-level reanalysis products, and remote sensing imagery—can be integrated to support data-informed decision-making in beach management. In line with recent studies applying Copernicus Marine Environment Monitoring Service (CMEMS) data for wave modelling along the Croatian coast (Bujak et al., 2023), the present approach combines these data sources through a structured analytical framework designed to:

- characterise local environmental forcing and beach typologies;
- guide the placement and scheduling of in situ monitoring campaigns; and
- support the selection of appropriate countermeasures to mitigate erosion and flooding risks.

A beach classification scheme is introduced, drawing on established coastal morphology frameworks and refined through a comparative analysis of relevant literature and site-specific characteristics (Mangor et al., 2017). This classification links geomorphological features with wave exposure, sediment availability, and anthropogenic influence, based on a systematic assessment of open-access datasets encompassing meteorological, oceanographic, and shoreline change parameters.

The methodology section outlines the steps undertaken to conduct a comprehensive literature review, identify and select suitable open-access datasets, perform site-specific data analyses, and design a practical monitoring plan aligned with forthcoming procurement activities. The results section then presents a beach typology tailored to the twelve pilot sites, identifies suitable countermeasures, and describes the development of an adaptive monitoring plan. Finally, the paper discusses current limitations, including gaps in site-specific data availability, and highlights how these constraints inform priorities for future monitoring efforts and targeted coastal protection measures.

2 METHODOLOGY

This section describes the literature review, pilot sites, datasets, and analytical framework employed to support beach monitoring and countermeasure planning in the southeastern Adriatic.

2.1 Literature review

To ensure that the proposed approach is grounded in robust evidence and established practice, a comprehensive literature review was conducted as an integral component of the study methodology. The review pursued two primary objectives:

1. to evaluate the extent to which existing scientific literature reflects the coastal conditions characteristic of the eastern Adriatic; and
2. to compile a broad range of previously implemented countermeasures from other regions that may be suitable for local adaptation.

The review process combined systematic searches of major scientific journals and bibliographic databases with targeted screening of relevant project reports and coastal management guidelines. Search terms included combinations of *coastal erosion*, *beach stabilisation*, *nourishment*, *shoreline monitoring*, *hybrid countermeasures*, *Adriatic Sea*, and *under-monitored coasts*.

In total, 73 sources were systematically analysed, comprising peer-reviewed journal articles, specialised monographs, and applied technical reports. Although only a limited subset of these studies directly addresses the southern and eastern Adriatic, comparable case studies from the northern Adriatic, other Mediterranean regions, Japan, and Northern Europe provide valuable and well-documented examples. The reviewed literature encompasses both conventional hard engineering solutions and emerging nature-based or hybrid approaches, offering practical insights that inform site-specific planning for the twelve pilot beaches.

2.2 *Case study sites*

Twelve pilot beaches were selected across Croatia, Bosnia and Herzegovina, and Montenegro within the framework of the ClimBeach project (Fig. 1). The selected sites represent a broad range of geomorphological settings, wave exposure conditions, and levels of anthropogenic pressure. The pilot sites are as follows:

- **PS1:** Janska Bay, Dubrovnik–Neretva County, Croatia
- **PS2:** Doli Bay, Dubrovnik–Neretva County, Croatia
- **PS3:** Vučine Beach, Pelješac, Croatia
- **PS4:** Trstenica Beach, Orebić, Pelješac, Croatia
- **PS5:** Druga Strana Beach, Neum, Bosnia and Herzegovina

- **PS6:** Meredek Beach, Neum, Bosnia and Herzegovina
- **PS7:** Plavi Horizonti Beach, Montenegro
- **PS8:** Jaz Beach, Budva, Montenegro
- **PS9:** Ričardova Glava Beach, Budva, Montenegro
- **PS10:** Pizana Beach, Budva, Montenegro
- **PS11:** Utjeha Beach, Montenegro
- **PS12:** Veliki Pijesak Beach, Dobra Voda, Montenegro

The site selection aimed to capture variability in sediment characteristics (sandy, gravel, and mixed beaches), degrees of urbanisation, and exposure to dominant wave directions, primarily bora and sirocco. This diversity supported the classification of the beaches into low-, moderate-, and high-energy categories, which in turn informed monitoring priorities and countermeasure planning.

Figure 1. Case study sites (Source: Google Earth).

The Croatian sites include both open-coast and sheltered environments. Trstenica (PS4) and Vučine (PS3), in particular, are characterised by increasing urban pressure and limited natural sediment supply. Neum, the only coastal town in Bosnia and Herzegovina, features two pilot sites with contrasting orientations and wave energy regimes. The Montenegrin beaches exhibit a wide range of conditions, from relatively natural and morphodynamically active settings such as Veliki Pijesak (PS12) to highly urbanised beach segments, including Ričardova Glava (PS9).

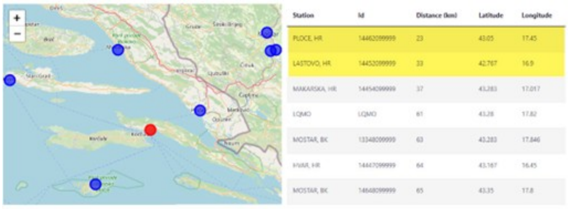
2.3 *Data sources and processing*

This section summarises the publicly available datasets and data processing steps used to characterise environmental conditions and support monitoring and planning activities across the twelve pilot beaches. The datasets were selected based on their availability, spatial and temporal resolution, and relevance to key coastal forcing parameters, including wind, waves, sea level, sediment transport, and shoreline evolution. Trstenica Beach (PS4) (Fig. 18), located in Orebić on the Pelješac Peninsula, is used as a representative case study to illustrate the data processing and interpretation workflows applied throughout the study.

2.3.1 *Meteorological and climatological data*

Historical meteorological parameters, including air temperature, precipitation, and wind, were obtained from Visual Crossing, a platform that processes and harmonises data from multiple reputable sources and integrates observations from various local meteorological stations, thereby providing reliable and consistent reconstructions of past climate conditions (Visual Crossing, 2020). The combination of global and local datasets ensures both accuracy and completeness in historical and forecast weather records.

As no dedicated meteorological station is located at Trstenica Beach, precipitation data were retrieved from Visual Crossing using interpolated datasets for Orebić (42.9747° N, 17.1841° E), the nearest available reference location, based on observations from surrounding stations in Ploče and Lastovo. To minimise topographic bias, orographic filtering was applied by excluding stations situated at elevations exceeding 100 m within a 50 km radius (Peña Quiñones et al., 2019), as illustrated in Figure 3.



Station	Id	Distance (km)	Latitude	Longitude
PLOCE, HR	14462099999	23	43.05	17.45
LASTOVO, HR	14452099999	33	42.767	16.9
MAKARSKA, HR	14454099999	37	43.283	17.017
LQMO	LQMO	61	43.28	17.82
MOSTAR, BK	13348099999	63	43.283	17.846
HVAR, HR	14447099999	64	43.167	16.45
MOSTAR, BK	14648099999	65	43.35	17.8

Figure 2. Location and meteorological station map for Orebić (42.9747° N, 17.1841° E) (source: Visual Crossing).

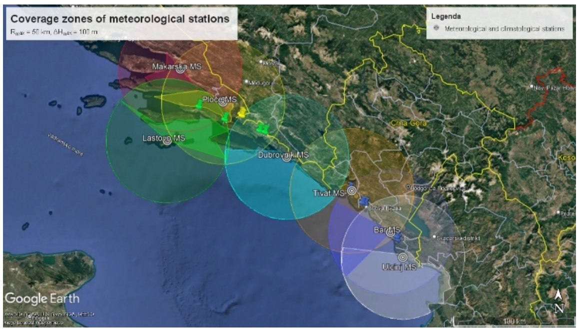


Figure 3. Meteorological station influence areas (source: Google Earth).

Visual summaries were generated to evaluate climatic conditions at Trstenica Beach for the period from 1 January 1992 to 1 January 2025, using interpolated Visual Crossing datasets as the primary data source (Figs. 2 and 3). All visualisations were produced using MATLAB® software (version R2024b). Figure 4 presents the total annual precipitation, which exhibits pronounced interannual variability, with elevated values during the period 2010–2015 and a potential slight decline in more recent years.

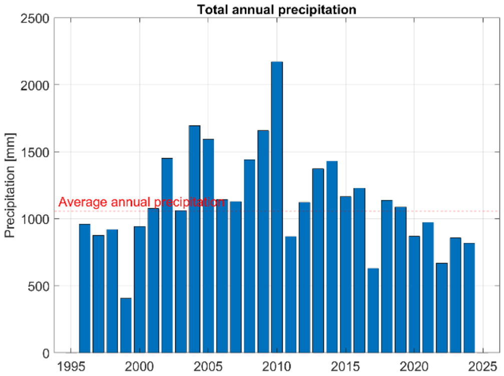


Figure 4. Total annual precipitation for the period 1995–2025 at Orebić (42.9747° N, 17.1841° E).

The temperature time series (Figure 5) confirms a typical Mediterranean climate, characterised by warm summers (July–August) and mild winters, with a clear and consistent seasonal pattern.

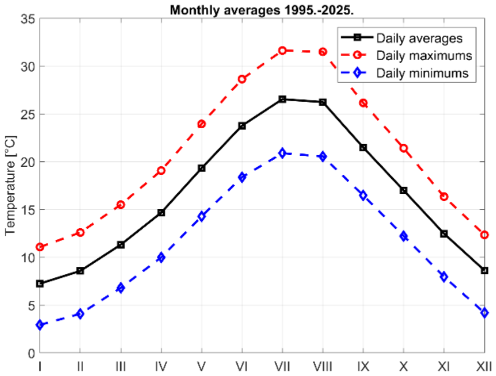


Figure 5. Average air temperature for the period 1996–2025 at Orebić (42.9747° N, 17.1841° E).

At Trstenica Beach, dominant southern (Ostro) and south-eastern winds (Scirocco, SE and SSE) play a significant role in sediment transport, driving erosion and shoreline reshaping through high-energy cross-shore and longshore processes (Aron, 2015). In contrast, Maestral and Bora winds have a comparatively limited influence on coastal morphodynamics at the site (Figure 6).

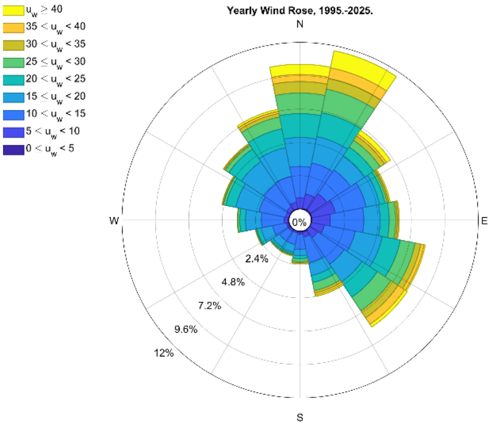
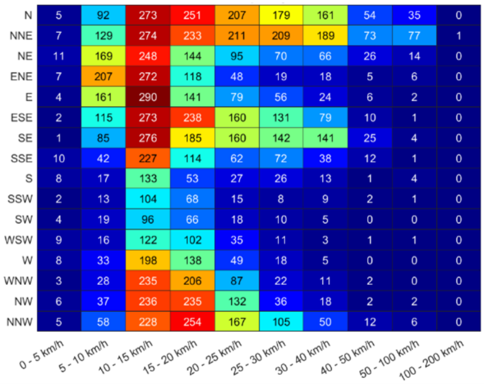


Figure 6. Annual wind rose for the period 1995–2025 at Orebić (42.9747° N, 17.1841° E)



	0 - 5 km/h	5 - 10 km/h	10 - 15 km/h	15 - 20 km/h	20 - 25 km/h	25 - 30 km/h	30 - 40 km/h	40 - 50 km/h	50 - 100 km/h	100 - 200 km/h
N	5	92	273	251	207	179	161	54	35	0
NNE	7	129	274	233	211	209	189	73	77	1
NE	11	169	248	144	95	70	66	26	14	0
ENE	7	207	272	118	48	19	18	5	6	0
E	4	161	290	141	79	56	24	6	2	0
ESE	2	115	273	238	160	131	79	10	1	0
SE	1	85	276	185	160	142	141	25	4	0
SSE	10	42	227	114	62	72	38	12	1	0
S	8	17	133	53	27	26	13	1	4	0
SSW	2	13	104	68	15	8	9	2	1	0
SW	4	19	96	66	18	10	5	0	0	0
WSW	9	16	122	102	35	11	3	1	1	0
W	8	33	198	138	49	18	5	0	0	0
WNW	3	28	235	206	87	22	11	2	0	0
NW	6	37	236	235	132	36	18	2	2	0
NNW	5	58	228	254	167	105	50	12	6	0

Figure 7. Wind frequency heatmap for the period 1995–2025 at Orebić (42.9747° N, 17.1841° E)

The wind frequency heatmap (Figure 7) indicates that moderate wind speeds (10–25 km h^{-1}) occur most frequently from the NE, E, and NNW sectors. Strong winds exceeding 40 km h^{-1} are comparatively rare but are nonetheless present in the long-term record.

2.3.2 *Oceanographic data*

Two distinct datasets from the CMEMS were employed:

- Wave data were obtained from the CMCC *MEDSEA_MULTIYEAR_WAV_006_012* reanalysis product based on the MEDWAM3I model (Korres et al., 2021). This high-resolution multi-year dataset covers the period from 1 January 1985 to 31 May 2023 and was extracted at the representative offshore location 42.5625° N, 17.8334° E for Trstenica Beach (indicated by the yellow marker in Fig. 1). The dataset provides hourly spectral wave parameters, including significant wave height (H_{m0}), mean wave period (T_{m02}), and mean wave direction. Wave components are classified into locally generated wind waves and primary and secondary swell components, enabling assessment of coastal exposure and dominant energy regimes. The reanalysis incorporates satellite-derived significant wave height data through assimilation from CERSAT–IFREMER and the Copernicus Marine WAVE TAC.

The wave rose shown in Fig. 8 indicates that waves predominantly approach from the west (W) and south-southeast (SE), with SE waves exhibiting higher energy levels.

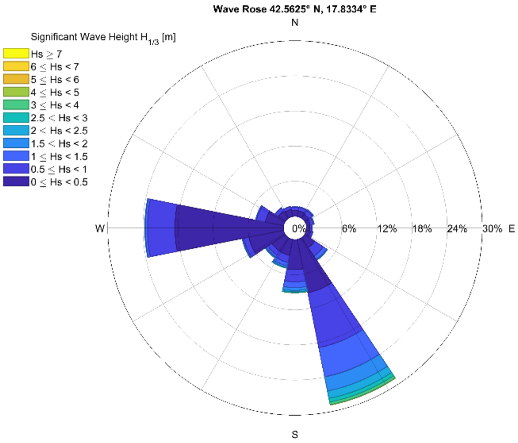


Figure 8. Wave rose for the period 1 January 1985–31 May 2023 at the representative location 42.5625° N, 17.8334° E.

Most wave conditions are characterised by significant wave heights below 2 m, with only occasional occurrences of larger events. Waves approaching from the SE sector display higher wave heights, typically in the range of 3–4 m, as indicated by the green and yellow sectors in Fig. 8. These higher-energy waves are likely associated with Sirocco winds acting over a long fetch. In contrast, waves from the W sector are more frequent but generally lower in energy, implying different sediment transport mechanisms and morphodynamic responses. The maximum significant wave height recorded in the dataset reached 6.86 m.

The scatter plot of significant wave height versus wave period (Fig. 9) reveals a clear relationship in which increasing wave heights correspond to longer wave periods. Smaller waves ($H_{m0} < 1.5$ m) typically exhibit periods of 3–6 s, characteristic of locally generated wind waves. Moderate waves ($H_{m0} = 1.5$–3 m) are associated with periods of approximately 6–10 s, indicating a mixture of wind waves and developing swell. Larger wave events ($H_{m0} > 3$ m) frequently display periods exceeding 10–15 s, suggesting the presence of well-developed swell generated by distant storm systems. This distribution highlights the coexistence of short-period local wind waves and long-period swell, governed by wind strength, storm activity, and broader regional oceanographic conditions.

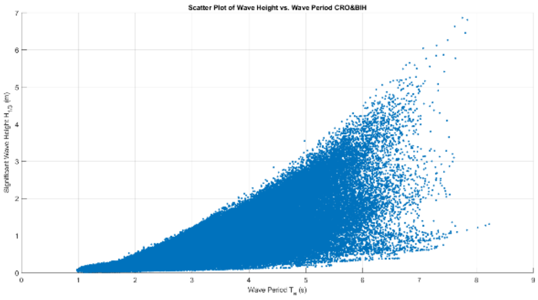


Figure 9. Scatter plot of significant wave height versus wave period for the period 1 January 2024–31 January 2025.

- Sea-level data were retrieved from the CMEMS *MEDSEA_ANALYSISFORECAST_PHY_006_013* product (Clementi et al., 2021), which provides sea surface height (zos) at 15-minute temporal resolution. To assess the reliability of the modelled sea-level data, CMEMS outputs were compared with long-term in situ measurements from the "sobr" tide gauge station (42.792° N, 17.620° E). Observed sea-level data were obtained from the European Marine Observation and Data Network (EMODnet) and are available at a 1-minute temporal resolution (Institute of Oceanography and Fisheries). These measurements are referenced to the local Mean Lower Low Water (MLLW) datum.

Comparison of the CMEMS modelled sea surface heights with the observed tide gauge records shows strong agreement in temporal variability. As the CMEMS data are referenced to a geoid while the tide gauge measurements are referenced to MLLW, a vertical offset was applied to enable direct comparison. This offset, equal to 0.35 m, was calculated as the mean difference between the two datasets over the overlapping period from 1 January 2024 to 31 January 2025 using hourly averaged values.

After applying the vertical correction, the adjusted time series exhibited high consistency, with a root mean square error (RMSE) of 0.079 m, a mean bias of 0.059 m, and a Pearson correlation coefficient (r) of 0.91 (Fig. 10). These results confirm that, once datum differences are accounted for, the CMEMS product provides a reliable representation of local sea-level variability and is suitable for coastal applications requiring absolute sea-level information. The use of co-located tide gauge data for vertical calibration further ensures that reference levels accurately reflect local conditions, thereby increasing confidence in the model's coastal performance.

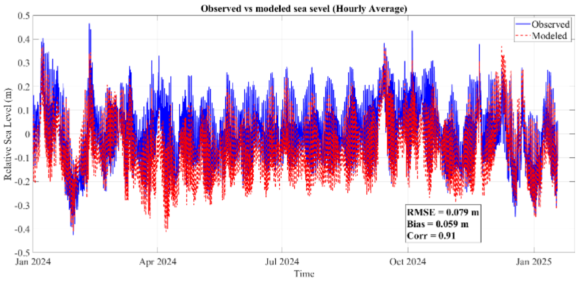


Figure 10. Comparison between observed and modelled sea level (hourly averages) for the period 1 January 2024–31 January 2025.

2.3.3 *Shoreline and morphological change*

Historical beach morphology was assessed using Google Earth satellite imagery covering the period from 2009 to 2024 (Figure 11).

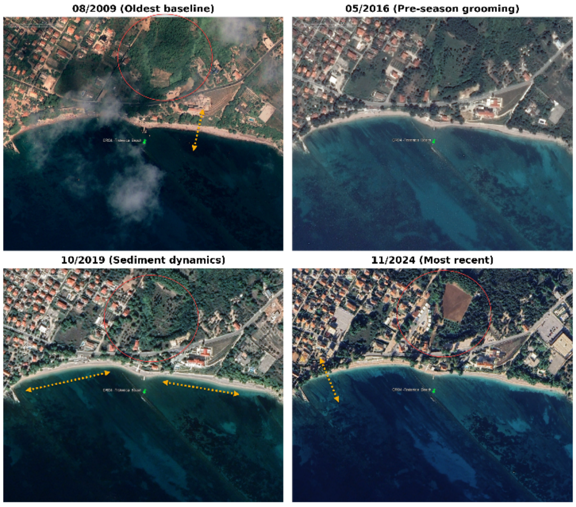


Figure 11. Satellite imagery of Trstenica Beach at selected time points (2009, 2016, 2019, and 2024).

Changes in shoreline position were identified through manual interpretation of the imagery, revealing key morphological and environmental developments over time. The 2009 image was adopted as the baseline condition and shows extensive inland vegetation. A pre-season nourishment event carried out in 2016 resulted in a widened beach profile and lighter sediment colouration. By 2019, evidence of sediment redistribution is apparent, accompanied by localised beach narrowing. The 2024 image highlights inland urban expansion (indicated by red circles), which may influence surface runoff patterns and sediment dynamics. Yellow arrows denote the inferred directions of sediment movement. It should be noted that, due to the absence of time-of-day metadata in Google Earth imagery, no correction for tidal stage was applied. However, given that the maximum tidal amplitude in the study area is less than 25 cm (Šepić et al., 2022), this source of uncertainty is smaller than the spatial resolution of the imagery and is therefore not expected to significantly affect the identification of general shoreline change trends.

2.3.4 *Bathymetry*

Baseline bathymetric data were obtained from the European Marine Observation and Data Network (EMODnet), providing regional-scale seabed depth information across the Adriatic Sea (). To achieve higher spatial resolution in Croatian coastal waters, detailed cross-shore bathymetric profiles were additionally sourced from the VEPAR project (Hrvatske vode, 2022) (Figure 13). These bathymetric datasets support:

- analysis of wave dissipation patterns;
- identification of potential sediment traps and erosional hotspots; and
- informed placement of monitoring equipment in future field campaigns.

Together, the combined bathymetric datasets enhanced the resolution of coastal morphology assessments and contributed to refining the beach typology and monitoring strategies proposed in this study.

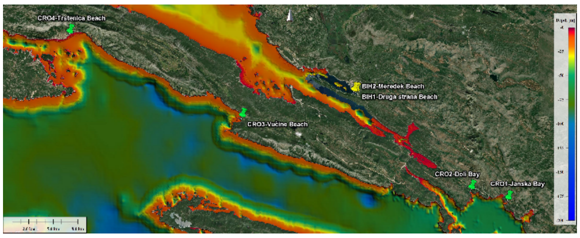


Figure 12. Regional bathymetric map showing seabed depth variations along the coastline.

Figure 13. Detailed bathymetric map of Trstenica Beach, showing isobaths representing depth contours in metres.

2.4 *Monitoring plan development*

The ClimBeach project aims to establish a cost-effective and scalable coastal monitoring plan for twelve pilot beaches across Croatia, Bosnia and Herzegovina, and Montenegro. Although full on-site implementation has not yet commenced, execution of the monitoring plan is underway through public procurement processes that have already been initiated. These processes include forthcoming photogrammetric surveys and sensor-based monitoring campaigns, which have been specified in accordance with the technical requirements, site-specific priorities, and monitoring frequencies defined within the proposed framework.

The monitoring plan was developed using a structured, data-informed methodology that integrates open-access datasets, insights derived from beach typology classification, and operational considerations shaped by available budgets and stakeholder input. Specifically, the monitoring framework was established by combining:

- publicly available datasets (as described in Section 2.3) to identify site-specific exposure conditions and data gaps;
- a typology-based classification of beaches (Section 2.2) to prioritise monitoring efforts;
- informal consultations with local experts and project stakeholders to assess site accessibility and practical relevance; and
- budgetary constraints and technical specifications defined by project partners, including predefined allowances for equipment types and monitoring campaigns.

Rather than adopting a uniform monitoring strategy across all sites, the proposed plan is designed to be adaptive, tailoring monitoring intensity and techniques to the specific characteristics, risks, and constraints of each pilot beach.

3 RESULTS AND DISCUSSION

Building on the structured methodology described in Section 2, this section presents the main outputs of the ClimBeach approach, namely: (i) a practical beach typology and classification of the pilot sites, (ii) indicative countermeasures, and (iii) a scalable monitoring plan incorporating risk mitigation measures. These results demonstrate how readily accessible, open-access, and low-cost datasets can be effectively used as a screening tool to support monitoring design and intervention planning in under-monitored coastal areas. The final subsection synthesises the key findings and discusses the current limitations of the proposed approach.

3.1 *Beach typology and classification criteria*

To structure the monitoring plan and guide countermeasure recommendations, the pilot beaches were classified into typological groups based on a synthesis of geomorphological literature, publicly available spatial datasets, and regional contextual knowledge. The principal classification parameters included:

- sediment type (sand, gravel, or mixed);
- wave exposure (low, moderate, or high, based on prevailing wind regimes and fetch length);
- degree of urbanisation or anthropogenic pressure (e.g. built surroundings, modified coastlines); and
- observed or reported erosion and flooding trends.

Although urbanisation and anthropogenic pressure were qualitatively assessed to inform the contextual understanding of each site, these factors were not used as primary axes in the final typological classification.

The qualitative typology was not derived from a single model but emerged from the comparative integration of multiple established frameworks (Mangor et al., 2017; Nordstrom, 2000), as described in Section 2.1. The resulting classification supports the design of site-specific monitoring protocols by prioritising higher-risk locations for more frequent or instrument-intensive observations. It also informs the selection of appropriate countermeasures, ensuring consistency between natural beach dynamics and proposed interventions.

Based on the defined parameters and a review of relevant literature, the following beach types are proposed:

- sediment-limited beaches;
- sediment-rich beaches;
- pocket beaches in confined settings;
- barrier islands and barrier spit beaches; and
- beaches in extreme environments (high-latitude or tropical).

Within this framework, the twelve pilot sites were assigned to the defined beach types based on the analysed literature and datasets (Section 2). Sediment-limited beaches include Janska Bay (PS1), Vučine Beach (PS3) (Figure 14), Meredek Beach (PS6) (Figure 15), Druga Strana Beach (PS5), Pizana Beach (PS10) (Trstenica Beach (PS4) (Figure 17), and Ričardova Glava Beach (PS9).

These sites are typically composed of coarse or mixed sediments with limited natural sediment replenishment and are often located adjacent to urbanised areas or hardened shorelines. They generally experience low to moderate wave exposure and are particularly susceptible to erosion. Consequently, they are potential candidates for protective measures such as seawalls, revetments, or localised beach nourishment.

Figure 14. Vučine beach (PS3), sediment-limited beach (Source: Adriagate).

Figure 15. Meredek Beach (PS6), sheltered sediment-limited beach, (Source: Larissa)

Figure 16. Pizana Beach (PS10), sediment-limited beach (Source: BeachSearcher).

Figure 17. Trstenica beach (PS4), sediment-limited beach (Source: Adriagate).

Pocket beaches in confined settings include Doli Bay (PS2), Plavi Horizonti Beach (PS7) (Figure 18), and Utjeha Beach (PS11). These beaches are situated within sheltered embayments or enclosed coastal formations, often characterised by restricted sediment exchange and low wave exposure. As a result, they tend to maintain relative morphological stability unless affected by human activities or episodic storm events.

Figure 18. Plavi Horizonti Beach, pocket beach with moderate sediment availability (Source: Google Earth).

Sediment/rich beaches are represented by Jaz Beach (PS8) (Figure 19) and Veliki Pijesak Beach (PS12). These sites receive continuous or episodic sediment input through natural processes such as riverine supply or slope instability. They are typically influenced by moderate to high wave exposure and exhibit dynamic shoreline behaviour. In such environments, passive management strategies combined with continuous monitoring are generally preferred in order to preserve natural sediment transport processes.

Figure 19. Jaz Beach (PS8), Montenegro (Source: Guide to Europe).

The remaining typological groups—barrier islands and barrier spit beaches, and beaches in extreme environments—are included in the proposed classification framework to ensure completeness and applicability to future studies. However, none of the selected pilot sites fall within these categories.

To facilitate comparative interpretation, Figure 20 provides a simplified overview of the twelve pilot sites in terms of wave energy and sediment availability. This representation illustrates the relative positioning of the sites along these two primary axes and complements the descriptive typology presented above.

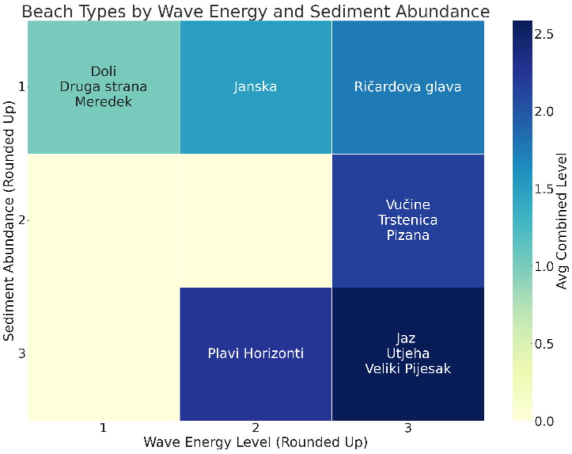


Figure 20 Beach types classified by wave energy and sediment abundance for the twelve pilot sites. Qualitative factors such as urbanisation and erosion trends, discussed in the text, are not included in this visualization.

Overall, this site-based classification enables the tailoring of monitoring intensity and countermeasure strategies to local conditions, thereby enhancing the effectiveness and long-term sustainability of the proposed interventions.

3.2 *Countermeasures categories*

To address beach erosion and coastal flooding, coastal protection strategies can be broadly grouped into four main categories: hard engineering, soft engineering, hybrid solutions, and management and policy-based approaches (Fig. 21).

Hard engineering measures, such as breakwaters and groynes, rely on engineered structures to provide immediate and often robust protection against wave action and sediment loss. Soft engineering measures, including beach nourishment and dune restoration, employ nature-based or nature-inspired solutions that aim to work with natural coastal processes and are generally more sustainable in the long term. Hybrid approaches combine elements of both hard and soft engineering to enhance resilience and adaptability under varying environmental conditions. In parallel, management- and policy-based strategies—such as Integrated Coastal Zone Management (ICZM) and ecosystem-based adaptation—seek to embed technical interventions within broader planning, governance, and decision-making frameworks.

These categories provide a structured reference for aligning the selection of future countermeasures with the typological vulnerabilities identified through the ClimBeach project, thereby supporting context-sensitive and sustainable coastal management.

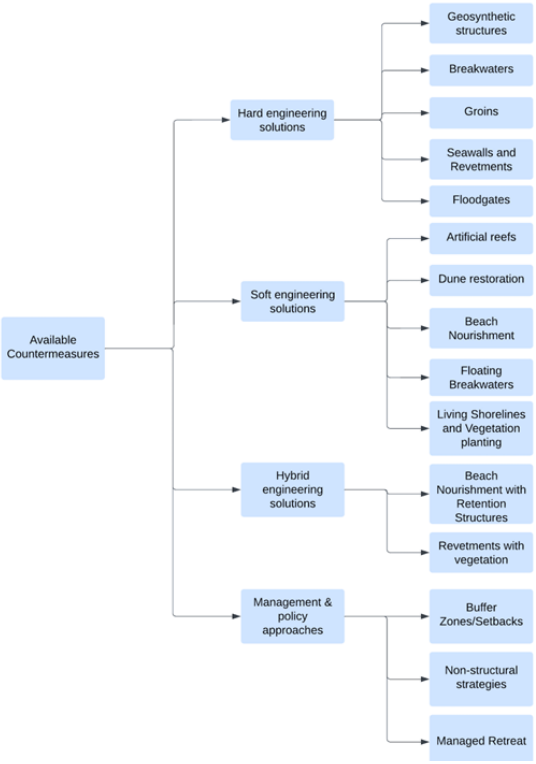


Figure 21 Available countermeasures (adapted from the ClimBeach Countermeasure Review Report, 2024)

3.3 *Monitoring framework and implementation plan*

The structured methodology described in Section 2.4 was applied to develop a scalable, multi-site monitoring framework tailored to typology-specific vulnerabilities and available resources. The framework identifies appropriate monitoring tools and observation strategies based on environmental forcing conditions, logistical feasibility, and cost efficiency.

The selected monitoring instruments and techniques include:

- Acoustic Wave and Current Profilers (AWACs) for high-resolution measurements of wave and current dynamics at high-energy beaches;
- drone-based photogrammetry to monitor shoreline position and beach volume, applicable to both aerial surveys and nearshore morphological assessments; and
- meteorological stations to improve the spatial resolution and accuracy of climate forcing data in under-monitored regions.

The placement of meteorological stations was guided by an analysis of station influence zones using topographic information from Google Earth and meteorological coverage from the Visual Crossing dataset (Figure 3). Particular attention was paid to areas where existing station coverage is limited due to elevation effects or remoteness. The Pelješac Peninsula, and Trstenica Beach in particular, was identified as a priority location for the installation of a new meteorological station owing to its exposure to prevailing wind regimes and the lack of nearby low-elevation data sources. Similarly, in Montenegro, sparse coverage in mountainous and coastal fringe areas informed the proposed deployment strategy.

Monitoring intervals were defined as either seasonal or event-driven, allowing intensified observation following major storm events or periods of rapid morphological change. Public procurement procedures for several monitoring components, including photogrammetric surveys and the installation of two meteorological stations, have already commenced and are expected to support implementation within the current project year.

A tentative deployment schedule has also been developed for AWAC instruments across pilot sites in Croatia, Bosnia and Herzegovina, and Montenegro. These deployments are staggered by location, duration, and energy exposure, with instruments rotated among sites based on historical wave exposure and monitoring priority. Aerial and photogrammetric surveys are planned at four to six epochs per site, adjusted to site-specific sediment dynamics and visibility constraints. Together, these measures ensure that data collection captures key events and periods of heightened morphodynamic activity.

3.4 *Risk mitigation strategy*

Recognising the operational challenges associated with coastal monitoring in dynamic and often harsh environments, a layered risk mitigation strategy was developed to ensure continuity of operations, data reliability, and efficient use of resources.

- Sensor reliability: Instruments such as Acoustic Wave and Current Profilers (AWACs) and meteorological stations may malfunction or sustain damage during severe weather events. To mitigate this risk, regular inspection and maintenance schedules are предусмотрен, and spare components are planned. In the event of sensor failure, data gaps may be addressed through interpolation or supplemented using open-access datasets, including products from the Copernicus Marine Environment Monitoring Service (CMEMS) and EMODnet.
- Extreme weather and data gaps: Severe storm conditions may prevent scheduled

data acquisition. In such cases, numerical model outputs and satellite-based observations—such as those from the Moderate Resolution Imaging Spectroradiometer (MODIS) and Sentinel-3 missions—are proposed to reconstruct missing measurements.

- Deployment limitations: Delays in instrument deployment due to restricted site access or limited technical support will be mitigated through flexible deployment windows and coordination with other project activities to optimise fieldwork efficiency.
- Survey contingencies: Financial constraints or adverse environmental conditions affecting planned surveys will be addressed through the use of alternative data sources, including satellite-derived bathymetry (SDB), Sentinel-2 imagery, and Unmanned Aerial Vehicle (UAV)-based surveys. Additional technical or logistical support may be sought through institutional collaborations where necessary.

Through this flexible and anticipatory approach, the monitoring programme aims to maintain the integrity, continuity, and scientific value of the collected data under a wide range of external constraints.

3.5 *Indicative countermeasure planning*

Beaches characterised by high wave exposure and limited sediment availability—such as steep pocket beaches or highly urbanised coastal stretches—may benefit from hybrid or soft engineering solutions, including beach nourishment, vegetative buffers, or submerged structures designed to attenuate wave energy. In contrast, sites with moderate exposure and sufficient sediment supply may be adequately managed through periodic monitoring combined with adaptive maintenance strategies.

The proposed recommendations are indicative and will be further refined based on the outcomes of forthcoming monitoring campaigns and subsequent numerical and physical modelling efforts. Integrating real-time observations with historical data trends is expected to improve the assessment of feasibility and prioritisation of site-specific coastal protection strategies, ensuring that implemented interventions are aligned with both prevailing environmental conditions and available financial and technical resources

3.6 *Discussion*

Open-access and low-cost datasets, when combined with relatively simple analytical methods, can effectively support beach classification and preliminary countermeasure planning in under-monitored coastal regions. Nevertheless, several limitations affect the precision and reliability of the resulting assessments.

First, shoreline mapping based on Google Earth satellite imagery introduces inherent uncertainty, as sea level, tidal stage, and wave conditions at the time of image acquisition are generally unknown. These factors can lead to apparent shifts in shoreline position, particularly on narrow or steep beaches.

Second, reanalysis products from the Copernicus Marine Service are well suited to capturing regional wave and sea-level trends but often lack sufficient nearshore resolution to fully resolve local wave energy gradients and site-specific exposure conditions.

Third, meteorological data derived from national weather stations may not adequately represent local forcing, especially in areas where topographic sheltering or coastal orientation significantly modifies wind and storm exposure.

Although the developed beach typology and indicative countermeasure framework provide a valuable baseline for planning, they require refinement through in situ shoreline monitoring, higher-resolution numerical modelling, and site-specific measurements to ensure effective and reliable local implementation.

4 CONCLUSIONS AND FUTURE WORK

This study demonstrates how open-access and low-cost datasets can be used to support practical coastal monitoring and protection planning in data-scarce regions. By linking wave exposure, sediment availability, and coastal morphology, a beach typology was developed to guide site-specific monitoring priorities and indicative countermeasure selection across twelve pilot beaches in the southeastern Adriatic.

The proposed methodology was primarily applied as a screening tool to structure monitoring plans and prioritise intervention needs under limited financial and technical resources. Clear spatial patterns emerged: sediment-limited and urbanised sites, such as Trstenica and Ričardova Glava, exhibit higher susceptibility to erosion and flooding, whereas sediment-rich and morphodynamically active beaches, such as Jaz and Veliki Pijesak, demonstrate greater natural resilience.

These findings directly support the development of *BeachCloud*, the ClimBeach project's open-access decision-support platform for adaptive coastal management. BeachCloud will integrate the typological framework with site-specific monitoring data, numerical and physical modelling outputs, and practical guidance to assist local authorities in planning resilient and cost-effective coastal protection measures.

Importantly, the ClimBeach project has already initiated activities to refine and expand the proposed screening framework. Public procurement, installation of in situ monitoring systems for shoreline position, waves, and sea level, and deployment of additional meteorological sensors are currently underway across the twelve pilot sites. These efforts will generate high-resolution datasets for validating observed shoreline trends and calibrating advanced numerical models, including planned XBeach simulations and selected physical modelling, to test and optimise proposed countermeasures under realistic forcing conditions.

In the longer term, the integration of UAV-based shoreline monitoring, community-based data collection, and the implementation and evaluation of nature-based and hybrid solutions will further strengthen adaptive coastal management. The structured approach presented in this study, together with the ongoing ClimBeach activities, aims to provide a replicable and transferable framework for enhancing beach resilience planning in under-monitored coastal regions facing increasing climate-driven risks.

ACKNOWLEDGEMENTS

This work was supported by the Interreg VI-A Croatia–Bosnia and Herzegovina–Montenegro 2021–2027 programme (Priority Axis: Green investment in environmental protection and efficient risk management) through the European Regional Development Fund, as part of the project *"Improving Coastal Areas' Resilience to Climate Change Impacts and Setting up Guidelines for Sustainable Beach Stabilisation and Management"* (ClimBeach).

REFERENCES

Adriagate (n.d.). *Trstenica Beach, Orebic, Croatia*. Available at: https://www.adriagate.com/Croatia-en/Trstenica-beach-Croatia

BeachSearcher (n.d.). *Pizana Beach, Budva, Montenegro*. https://beachsearcher.si/sl/beach/499201056/pizana-beach

Bonaldo, D., Bucchignani, E., Pomaro, A., Ricchi, A., Sclavo, M., & Carniel, S. (2020). Wind waves in the Adriatic Sea under a severe climate change scenario and implications for the coasts. *International Journal of Climatology*. https://doi.org/10.1002/joc.6524

Croatian Hydrographic Institute (HHI), 2019. *Tide tables - Adriatic Sea - East coast*.

Direct-Croatia.com. *Vučine Beach*. https://www.direct-croatia.com/apartments/vucine-beach-zuljana

Dixon, A., Oh, C., & Draper, J. (2012). Access to the beach. *Journal of Travel Research*, https://doi.org/10.1177/0047287512451136

ERA5-Assimilation module https://help.marine.copernicus.eu/en/articles/5327052-is-era5-data-used-in-copernicus-marine-products

European Marine Observation and Data Network (EMODnet)https://emodnet.ec.europa.eu/en/physics%23approach

Ewing, L. (2015). Resilience from coastal protection. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*. https://doi.org/10.1098/rsta.2014.0383

Gallina, V., Torresan, S., Zabeo, A., Rizzi, J., Carniel, S., Sclavo, M., & Critto, A. (2019). Assessment of climate change impacts in the North Adriatic coastal area. https://doi.org/10.3390/w11061300

Google Earth (2022). *Plavi Horizonti Beach, Montenegro – Historical Imagery*. https://earth.google.com

Guide to Europe (n.d.). *Jaz Beach, Montenegro*. Available at: https://guidetoeurope.com

H Miličević, D Carević, D Bujak (2022). Učinkovitost detekcije obalne linije pomoću video sustava: primjer plaže Ploče u Rijeci. *8. simpozij doktorskog studija građevinarstva*.

Korres, G., Ravdas, M., Denaxa, D., & Sotiropoulou, M. (2021). *CMCC/MEDSEA_MULTIYEAR_WAV_006_012_MEDWAM3I* https://doi.org/10.25423/cmcc/medsea_multiyear_wav_006_012

Larissa (2016). *Exploring Ravno, Neum & Beaches of Bosnia & Herzegovina (incl. Meredek Beach)*. https://fromlarissawithlove.com/2016/09/16/via-dinarica-exploring-ravno-neum-beaches-bosnia-herzegovina/

Mangor, K., Drønen, N.K., Kærgaard, K.H., Kristensen, S.E. (2017). *Shoreline management guidelines*. DHI ebooks.

Marinas.com, *Janska Marina, Janska, Croatia*. https://marinas.com/view/marina/g9c8jr1_Janska_Marina_Janska_Croatia

Mathworks Inc. (2024). *MATLAB, version R2024b*.

Nordstrom, K. F. (2000). Beaches and Dunes of Developed Coasts. Cambridge University Press. https://doi.org/10.1017/CBO9780511549519

Pikelj, K., Ružić, I., Ilić, S., James, M. R., Kordić, B. (2017). Implementing an efficient beach erosion monitoring system for coastal management in Croatia. *Ocean & Coastal Management*, 148, 243–256. https://doi.org/10.1016/j.ocecoaman.2017.11.019

Roland, A. (2015). *Analysis of the morphodynamics of Orebic and perspectives for the future coastal protection and coastal management*. https://doi.org/10.13140/RG.2.2.23175.75682

Sveučilište u Zagrebu, Građevinski fakultet (2022). *Studija upravljanja rizicima od poplava mora (VEPAR) – UPRIMO: Završno izvješće*, p. 30. Hrvatske vode.

Šepić, J., Pasarić, M., Međugorac, I.,Vilibić, I., Karlović, M., & Mlinar, M. (2022). Climatology and process-oriented analysis of the Adriatic sea level extremes. Progress in Oceanography, 209, 102908. https://doi.org/10.1016/j.pocean.2022.102908.T Bogovac, D Carević, D Bujak, V Novaković (2023). Analysis of beach nourishment and construction in Croatia. *Građevinar*.

Torresan, S., Gallina, V., Gualdi, S., Bellafiore, D., Umgiesser, G., Carniel, S., & Critto, A. (2019). Assessment of climate change impacts in the North Adriatic coastal area. https://doi.org/10.3390/w11061157

University of Split, Faculty of Civil Engineering,Architecture and Geodesy. Available at: https://gradst.unist.hr/eng/research/projects/interreg/climbeach

Visual Crossing (2020). *How We Process the NOAA Integrated Surface Database Historical Weather*.