Application of Remote Sensing in Coastal Geomorphology: A Case Study of Zoraće Velo, Hvar Island, Central Adriatic

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Abstract: In this study we analyse coastal landforms in Velo Zoraće Bay on the island of Hvar, the cliff, the beach and the drainage basin behind the beach. This study examines their evolution over the past 200 years, as well as recent seasonal changes. The oldest period was analysed using the Franciscan Cadastre from 1834, the second using Croatian State Geodetic Administration aerial images from the 1950s, and the most recent period was studied using unmanned aerial vehicle (UAV) and Global navigation satellite system (GNSS) in the field. The collected data was processed using the Agisoft software. High-resolution models (orthomosaic – 1cm, Digital Elevation Model (DEM), and Digital Surface Model (DSM) – 3cm were created, and their horizontal and vertical accuracy was determined using Ground Control Points (GCPs). All analyses were done in ArcGIS Pro software.

Particular attention is paid to the cliff formed in Paleogene flysch. As flysch is a soft rock, it is prone to denudation. According to the obtained data, the cliff has eroded an average of 16 m over the last 200 years, i.e., the annual retreat of the cliff is 9.3 cm, which roughly corresponds to the recent seasonal changes observed in the field from spring 2021 and autumn 2022. Extreme denudation was observed, up to 0.5 m in places, which could be associated with intense rainfall events. These events led to the formation of gullies and to the activation of slope processes on the cliff face. During the same period, the beach shoreline moved landward for 17 m, while the beach area reduced by approximately 30%.

Keywords: beach; cliff; flysch; erosion; UAV.

1 Introduction

Coastal zones are dynamic and complex environments characterized by constant changes. Natural processes, combined with anthropogenic pressures, play crucial roles in the evolution of these areas, influencing particularly coastal geomorphological features such as beaches and cliffs. Coastal erosion, one of the dominant processes, leads to significant land loss and changes in coastal morphology, including cliff retreat and beach reduction in beach surface areas (Davison-Arnott et al. 2019). Although beach erosion is a major issue in coastal zones, erosion also significantly impacts cliffs, deltas, and coastal swamps (Bird 2008). Furthermore, recent climate changes affect coastal areas through sea level rise and intense rainfalls, increasing vulnerability of coastal zones (Brunel and Sabatier 2007, Faivre et al. 2011, Luiendijk et al. 2018). Therefore, the research of coastal zones is becoming more common today, particularly in the framework of coastal management (Alexandrakis and Poulos 2014). Remote sensing and technological advancements made research in coastal geomorphology easier and precise, utilizing numerous tools (Miccadei et al. 2019, Casella et al. 2020, Mićunović et al. 2021, Marco-Pereto et al. 2024).

This paper focuses on the coastal landforms in Velo Zoraće Bay on the island of Hvar and examines their evolution over the past 200 years. Particular emphasis is placed on the recent seasonal changes observed in the last few years. The study area includes a cliff formed in Paleogene flysch, a type of soft sedimentary rock that is particularly vulnerable to denudation processes, as well as the beach, which is also subject to significant erosion. By employing a combination of archival data, aerial imagery, and modern remote sensing methods, this research aims to provide a comprehensive analysis of the coastal dynamics in Zoraće Velo Bay.

2 Materials and methods

2.1 Study area

Zoraće Velo Bay is located eastern of the town of Hvar (Figure 1), on the southern side of the island. Geologically, the entire bay lies at the contact point between Paleogene flysch and Lower Cretaceous limestones (Figure 1) what allowed the formation of particular geomorphological properties of the bay with a beach and a cliff.

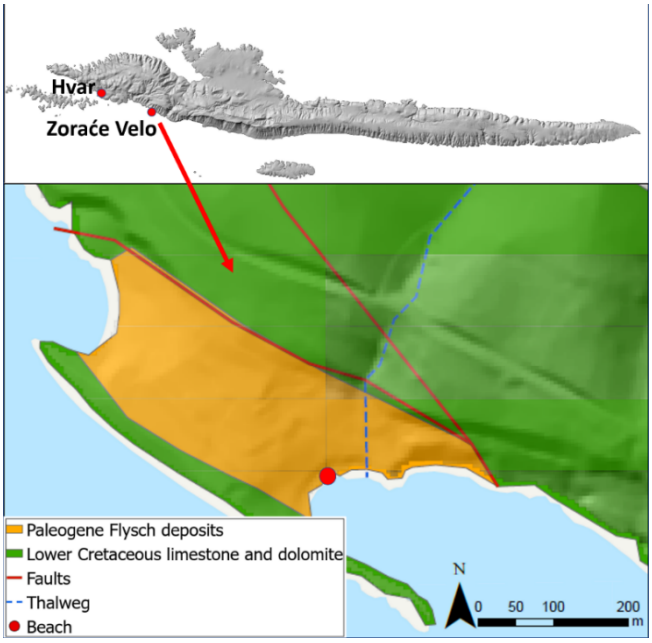

Figure 1. Geological map of Zoraće Velo Bay (Marinčić and Majcen 1976).

The beach is predominantly composed of fine-grained sediment (sand), but it also contains some coarser

sediment (gravel and pebbles), which have been brought in and accumulated from nearby gullies. The island has a Mediterranean climate, with typical maximum rainfall occurring in the winter months. Recently, climate change has manifested through more intense rainfall events, impacting coastal landforms, particularly beaches and cliffs (Faivre et al. 2011, Vlastelica et al. 2017).

2.2 Data acquisition and processing

This research is based on the analysis of beach and cliff evolution over the past 200 years, as well as on the seasonal changes in cliff morphology over the past few years.

The oldest period refers to the 1834 Franciscan Cadastre from the Austro-Hungarian Monarchy, where the beaches were mapped as separate parcels. The cadastral data were georeferenced, digitized, and analyzed using ArcGIS Pro software. The next period refers to the mid-20th century, utilizing black and white aerial images from the Croatian State Geodetic Administration, on which the beach and cliff were also digitized and analyzed. The recent period was analyzed using a UAV and the precise Trimble Catalyst DA2 RTK-GNSS. Field recording and data collection were conducted in March 2021 and November 2022 using a DJI Phantom 4 Pro v2.0 with an FC6310 RGB camera with a resolution of 20 megapixels. The flight was conducted at an altitude of 20–30 meters with 70–80% overlapping images. 10 Ground Control Points (GCPs) and 5 Ground Check Points were collected. The collected data were processed using Agisoft Metashape software. High-resolution models were obtained, including an orthomosaic with 1 cm resolution, and DEM and DSM with 3 cm resolution.

2.3 Geomorphological changes

Geomorphological changes on the beach and the cliff over the past 200 years were analyzed using ArcGIS Pro software. They were assessed by examining beach area changes and changes in beach shoreline positions. Digitized polygons and lines were compared and measured using the Near tool and Summary Statistics. For the recent period, the beach shoreline was automatically generated from the created DEM using raster data management tools, where pixels at 0 m elevation were defined. Changes in the cliff were analyzed by tracking shifts in the position of the cliff edge, focusing on the highest parts of the cliff. The digitized line was also analyzed using the Near tool and Summary Statistics. Recent seasonal changes in the cliff, observed during fieldwork, were analyzed using models generated in ArcGIS Pro software. These changes were examined using topographic profiles at six cross-sections, which revealed variations in material volume and the positions of the lowest and highest parts of the cliff. These profiles were analyzed using the Interpolate Shape and Profile tools according to the height of the generated DSM. Positional and digitizing errors were considered (Mićunović et al. 2021, Mićunović and Faivre 2024).

3 Results

The analysis of the collected data revealed significant changes in Zoraće Velo Bay over the past 200 years, as well as in the recent period. The largest recorded beach area was in 1834. According to the cadastral surveys the beach area was 1431.6 m^2. By the mid-20th century, the area had decreased to 1160.6 m^2 and today it is 976.4 m^2. These measurements indicate that the beach eroded by 18.9% from 1834 to the mid-20th century and by an additional 15.9% from the mid-20th century to the present day. Over the entire 200-year period, the beach has lost 31.8% of its surface area. A similar trend was observed in the shoreline retreat, which moved inland by 17.3 m over the past 200 years. In the first period, the shoreline retreated by 10.78 m, and in the second, it retreated by 9.61 m (Figure 2).

Significant changes have been also recorded on the cliff (Figure 2). Analysis of the data revealed a cliff retreat averaging 16 m over the past 200 years. In some places, the cliff has eroded by more than 20 m. The annual cliff retreat was calculated to be 9.6 cm/yr in the last ~200 years. There are no particular changes in the rates between the periods analyzed.

Short-term changes on the cliff were analyzed from spring 2021 to autumn 2022 (Figure 2 and Figure 3). Profiles from A to D relates to cliff segments with slope lower of 55°, while profiles E and F to slopes exceeding 55°.

Changes on cliff segments from A to D which have lower slopes, showed cliff retreat of 10-20 cm on average in a year and half. Profile B showed a retreat of over 0.5 m in the same period. During fieldwork, along the same coastal segment (the A-D coastal sector) slope processes were active. Their effects can be seen in the profiles (Figure 3) as eroded material accumulated at the base of the cliff.

Profiles E-F recorded changes in the upper part of the cliff, with a visible retreat of about 10 cm. Profile E, in particular, showed changes at the base of the cliff, where 0.5 meters of sediment had accumulated. Overall, the cliff retreated by an average of 10 cm across all profiles during the studied period.

4 Discussion

The changes on the Zoraće Velo beach are consistent with the erosion trend observed on the island of Hvar. The general reduction in beach area of about 30% is below the island average of 50% (Mićunović and Faivre 2024).

However, the shoreline retreat of ~17 meters is significant and the largest recorded on the island of Hvar (Mićunović and Faivre, 2024). Consequently, this fact points to a backward movement of the beach. This prompted a detailed investigation of the entire Zoraće Velo Bay to identify better geomorphological processes affecting changes of the beach. According to these results, one would expect a much greater reduction in beach area. However, this particular beach is bordered by a cliff formed in flysch. As flysch is an easily erodible sediment, the process of cliff retreat has enabled such significant shoreline shift.

This particular beach is one of the few formed in flysch on the island of Hvar. The unique bay, bordered by carbonate bedrock, allowed the preservation of flysch deposits. Obtained data shows that denudation affected the cliff and

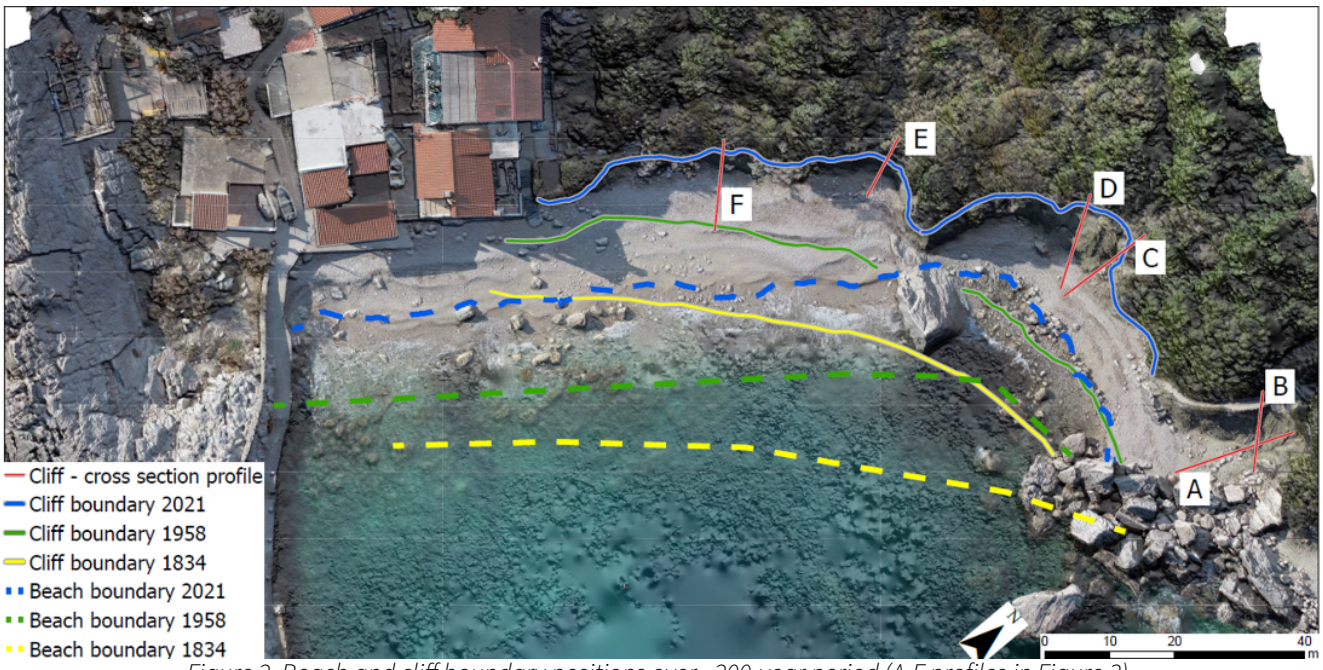

Figure 2. Beach and cliff boundary positions over ~200-year period (A-F profiles in Figure 3).

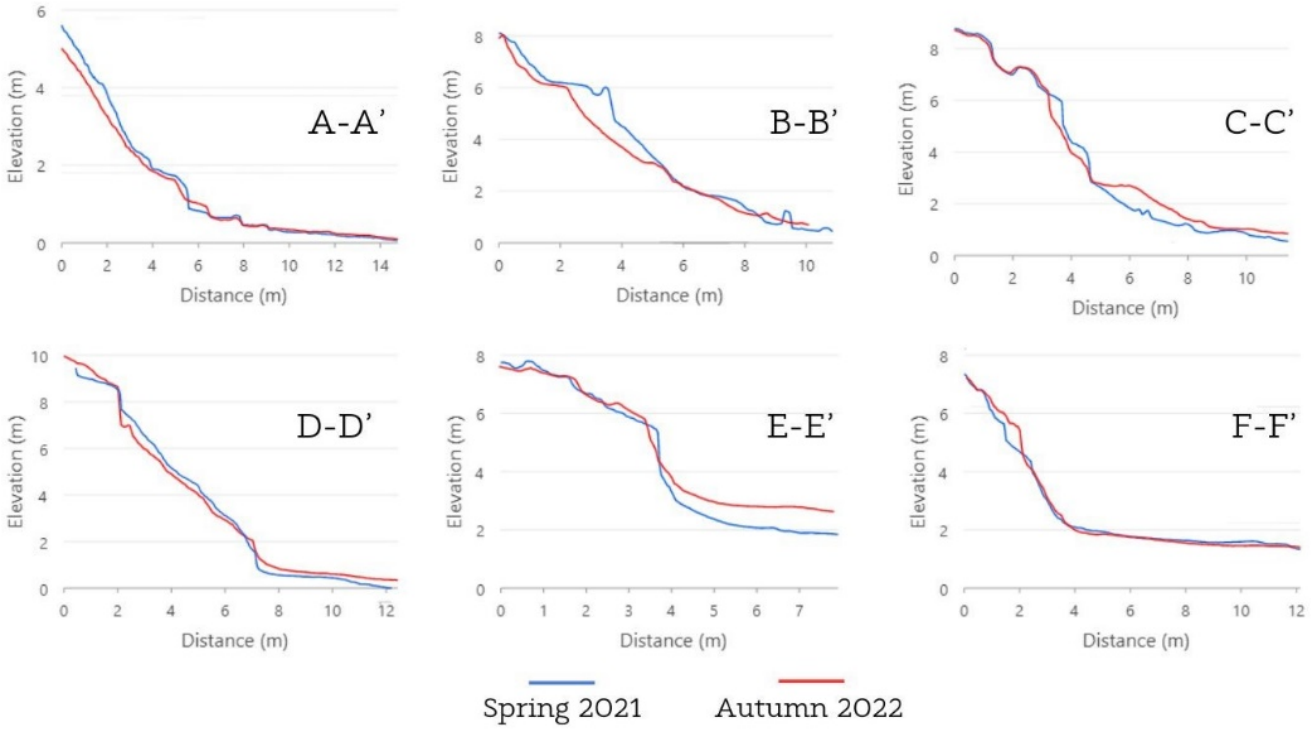

Figure 3. A-F cliff cross-section profile (marked in Figure 2).

caused cliff retreat of 16 meters on average over the past 200 years. However, there is some difference between the cliff segments. The cliffs (E-F) are partially covered by vegetation at their upper parts, which protects the sediment. On cliff segments with lower slope (profiles A-D) denudational processes have activated. Consequently, slope and denudational processes have contributed to the cliff retreat process in this area.

Similar studies conducted on the Slovenian coast suggest that slope processes, including landslides and collapses, act as accelerators of cliff retreats (Furlani et al. 2011, Šegina et al. 2012). Cliff retreat in flysch deposits was studied in the Split area. It was found to be of the order of 3–18 cm/year, with an average of 10 cm/year. Accordingly, this corresponds to our findings at Zoraće Velo cliff. In addition to abrasion caused by sea level rise in the larger studied area slope processes played an important role in cliff retreat, leading to considerable erosion in places (Vlastelica et al. 2017).

5 Conclusions

This research has shown significant geomorphological changes in Zoraće Velo Bay, including beach erosion, beach shoreline retreat, and cliff retreat. The shoreline retreat of 17 m is driven by erosion of easily erodible flysch sediments influenced by denudational, gully erosion, slope processes and sea-level rise. These changes align with general erosion trends in coastal environments. Remote

sensing methods, such as the analysis of archival materials combined with fieldwork, have proven to be very useful for these analyses. The generated high-resolution models enabled a detailed analysis of short-term changes on the cliff with centimeter-level precision.

This study has highlighted the importance of understanding geomorphological processes and demonstrated how remote sensing methods and the application of UAVs in coastal geomorphology can be useful, and provide accurate results for various research objectives with the aim of sustainable coastal management.

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