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Implementing an efficient beach erosion monitoring system for coastal management in Croatia

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ABSTRACT

This paper proposes a coastal erosion monitoring system for beach erosion management, which we demonstrate on natural and artificial pocket gravel beaches in Croatia. The approach uses low-cost Structure-from-Motion (SfM) photogrammetric imaging and multi-view stereo (MVS) to produce high-resolution 3D beach models for detecting morphological changes and erosion occurrence. Coastal state indicators, such as the shoreline position and subaerial beach volume, are derived from the 3D models and used to quantify changes between surveys. The method is illustrated through two case studies and, to our knowledge, these are the first repetitive measurements taken on the Croatian eastern Adriatic Coast (CEAC). In case of the natural Brseč beach, beach rotation was found to be a response to natural forcing from waves of various incident directions. For the artificial Dugi Rat beach, which loses sediment every winter and is subsequently re-nourished every spring, monitoring showed that beach nourishment is of limited durability. Both case studies showed that the SfM-MVS technique is suitable for the rapid and frequent acquisition of 3D survey data, from which quantitative coastal indicators can be derived to inform future coastal management interventions. Significantly, this low-cost data acquisition has a great potential for regular beach management survey.

The introduction of beach monitoring in Croatia is timely because emerging Integrated Coastal Zone Management (ICZM) practices will require data-based approaches. Moreover, rare natural pocket beaches and the ever-increasing number of artificial beaches are extremely vulnerable to natural and man-made changes. Adaptive beach management, based on systematic monitoring data, should be included in the ICZM, and we detail how SfM-MVS-based monitoring can be used at different levels of the ICZM. Implementing robust ICZM monitoring will require broad considerations and consultation with all stakeholders, so we propose that SfM-MVS beach surveys should be initially integrated into the existing monitoring practices for CEAC sea water bathing quality. Extension of the existing database with rapidly-gathered low-cost 3D beach survey data, from a number of targeted beaches, could be used to provide a crucial baseline for the ICZM and strategic coastal monitoring of the CEAC.

1. Introduction

Globally, coastlines are under pressure and, in Europe, 20% are affected by erosion (EUROSION study, European Commission, 2004). Within this, the Croatian eastern Adriatic coast (CEAC, extending over 6000 km along the eastern Adriatic Sea between Slovenia and Montenegro, Fig. 1) is exposed to multiple natural and man-made pressures affecting its stability. However, the CEAC is a key area for a growing tourist market; consequently, to deliver sustainable coastal development that ensures economic activities and preserves natural beach environments, Croatian coastal management should include an evidence-based understanding of natural processes such as erosion. Here, for the first time, we apply a photo-based beach monitoring technique to deliver sequential 3D models that are suitable for informing future coastal management decision-making.

The CEAC is highly valued for its biodiversity and has an attractive rocky karst landscape that has been used intensely by humans for centuries. Both biodiversity and landscape can be impacted by the currently growing tourist demand for beach capacity, which has driven the building of artificial beaches and the enlargement of many natural beaches by nourishment, frequently carried out without suitable environmental impact studies or appropriate post-nourishment

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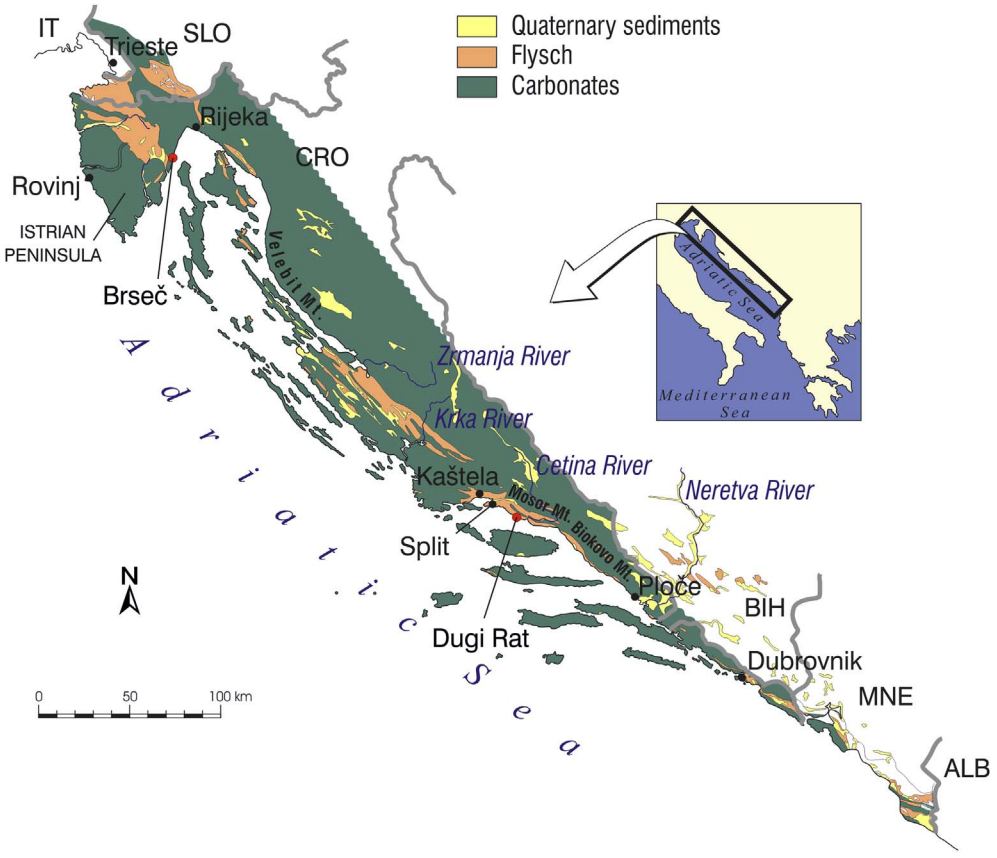

Fig. 1. Simplified lithological map of the Eastern Adriatic coast with study sites locations (red dots) (modified after Pikelj and Juračić (2013) and Pikelj et al. (2013)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

maintenance. Under increased natural pressures such as sea-level rise (SLR) (Nicholls and Cazenave, 2010), enhanced storminess (Kaniewski et al., 2016), coastal inundation due to storm surges (Međugorac et al., 2015), and unusual waves such as meteotsunamis (Šepić et al., 2012), it is likely that the CEAC coastal and beach management issues will only deepen.

At the beginning of the 21st Century, coastal development in Croatia was affected by unplanned and expanding construction, most of which was inconsistent with natural and cultural heritage (Cimerman, 2004). Currently, this is changing; Croatia is a signatory to the Barcelona Convention on environmental conservation within the Mediterranean, which includes the Protocol on Integrated Coastal Zone Management (ICZM; European Commission, 2008). The ICZM was ratified by the Croatian Government in 2012, but implementation remains in its infancy, and there is a lack of coordination among governing bodies from local to national levels and across different agencies and ministries. The responsibilities of different authorities can be unclear and can overlap and, furthermore, there is a lack of public participation in decision-making, and of public awareness about the problems that the coastline is facing. Fundamentally, progress is hampered by the complexities of the existing legal system due to the numerous different relevant laws, multiple directives for law enforcement and strategic documents related to coastal management. An integral model of coastal zone management has yet to be established.

Likewise, there is no integrated system of beach management designed to evaluate beach environments from all aspects. Currently, Croatian beach management is the responsibility of local authorities (coastal municipalities and towns) and includes land and sea use, infrastructure development, cultural heritage preservation, allocation of concessions etc., as well as beach erosion issues. Management practices are guided by two main national documents: the Law of maritime domain and seaports (https://www.zakon.hr/download.htm?id=505) and the Regulation on Sea Bathing Water Quality (Official Gazette 73/08), with the latter shaped according to EU directive 2006/7/EC (OJEU, 2006). However, the related beach management strategies and directives are broad and services-oriented (Ministry of Tourism, 2013; PAP/RAC, 2010) and, critically, omit issues of coastal erosion. Tackling this gap, to enable appropriate adaptive policies to be developed and applied through estimating future beach changes, requires an understanding of coastal processes and their effects over local and regional scales. Beaches act as an energy buffer, contribute to coastal environmental diversity and provide recreational environments. Regardless of which of these form the primary role, a better understanding of beach origin and evolution is crucial for effective beach protection within coastal management strategies. Such an understanding is usually derived from extensive monitoring thus, as the first step in Croatia, it is essential to identify vulnerable coastal locations and to implement a suitable monitoring plan to acquire data over appropriate spatial and temporal scales.

Typically, beach monitoring comprises deriving high-resolution topographic digital elevation models (DEMs) using data from terrestrial and airborne laser scanners, multibeam sonars, differential global positioning system (dGPS), and total station surveys (Baptista et al., 2008; Casella et al., 2014; Pietro et al., 2008; White and Wang, 2003). Techniques such as satellite and video imaging can be used for detecting the shoreline position, with the latter also providing intertidal DEMs (Kroon et al., 2007). Most recently, the use of unmanned aerial vehicles (UAVs) has been explored (Brunier et al., 2016; Gonçalves and Henriques, 2015; Jaud et al., 2016). DEMs are then used to assess coastal processes and coastal morphology changes over various temporal and spatial scales (Li and King, 2007; White and Wang, 2003; Young and Ashford, 2006) and can be used to support coastal management (Davidson et al., 2007). However, for the CEAC, most satellite data have suboptimal temporal and spatial resolution, and airborne LIDAR could only be acquired occasionally due to the high cost involved, leading to inadequate temporal coverage. dGPS surveys are still