ANALIZA ANTROPOGENOG UTJECAJA NA MORFOLOŠKE PROMJENE ŽALA U PODGORI (SREDNJI JADRAN, HRVATSKA)

ANALYSIS OF ANTHROPOGENIC IMPACT ON MORPHOLOGICAL CHANGES OF BEACHES IN PODGORA (CENTRAL ADRIATIC, CROATIA)

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Obalna područja podložna su intenzivnim geomorfološkim promjenama. Žala su jedan od najranjivijih obalnih oblika. S obzirom na sve jači pritisak turizma i urbanizacije, stabilnost žala često je narušena antropogenim intervencijama, uključujući nadohranu sedimenta i izgradnju obalnih struktura. Ovaj rad analizira dugoročne morfološke promjene (posljednje 72 godine) triju žala na području Podgore (Minerva, Plišivac i Frara) radi kvantificiranja utjecaja ljudskih aktivnosti na dinamiku obalne crte i površine žala. U radu je provedena analiza arhivskih aerofotogrametrijskih i satelitskih snimaka (1951.–2023.) te snimaka prikupljenih bespilotnom letjelicom (2022. i 2023.). Snimke su obrađene i analizirane u ArcGIS Pro softveru. Rezultati pokazuju da su antropogeno preoblikovana žala (Minerva i Plišivac) podložna znatnim oscilacijama površine i pomacima obalne crte, dok prirodno žalo Frara bilježi znatno stabilniju morfodinamiku. Plišivac i Minerva proširena su nasipavanjem, pri čemu su periodični zahvati povećali površinu za oko 1500 m², odnosno 3000 m², zahtijevajući kontinuirano održavanje zbog značajnih erozijskih procesa. Analiza pokazuje da antropogeni zahvati mogu imati suprotan učinak od planiranog, povećavajući nestabilnost sedimenta i potrebu za učestalim sanacijama. Da bi se smanjila potreba za ponavljanim intervencijama i osiguralo dugoročno očuvanje žala, održivo upravljanje obalnim područjima trebalo bi uzeti u obzir detaljne geomorfološke analize.

Ključne riječi: geomorfologija; daljinska istraživanja; GIS, Makarska rivijera; turizam; obale

Coastal areas are subject to strong geomorphological changes, making beaches among the most vulnerable coastal landforms. Due to increasing pressure from tourism and urbanisation, the stability of beaches is often affected by anthropogenic interventions including sediment nourishment and the construction of coastal structures. This paper analyses the long-term morphological changes (over the last 72 years) on three beaches in the Podgora area: Minerva, Plišivac, and Frara, with the aim of quantifying the impact of anthropogenic activities on shoreline dynamics and beach area. The methods used include the analysis of archival aerial photographs and satellite images (1951–2023), as well as drone images from 2022 and 2023. The images were processed and analysed using ArcGIS Pro software. The results show that the anthropogenically reshaped beaches (Minerva and Plišivac) are prone to significant surface fluctuations and shoreline shifts, while the natural Frara beach has more stable morphodynamics. Plišivac and Minerva expanded through nourishment interventions, which periodically increased their surface area by about 1,500 m² and 3,000 m², respectively, but at the same time required continuous maintenance due to pronounced erosion processes. The analysis reveals that anthropogenic interventions can have counterproductive effects by increasing sediment instability and the need for frequent care. Sustainable coastal management should consider detailed geomorphological analyses to reduce the need for repeated interventions and ensure the long-term preservation of beaches.

Keywords: geomorphology; remote sensing; GIS; Makarska riviera; tourism; coasts

UVOD

Zbog prirodnih procesa i rastućih socio-ekonomskih pritisaka, obalna područja su složeni geomorfološki sustavi podložni intenzivnim promjenama. Danas više od 50 % svjetskog stanovništva živi u blizini obale, računajući pojas od ~100 km od obalne crte (Grobbe, 2023; Toure i sur., 2019), što uzrokuje pritisak na obalne ekosustave i prirodne resurse. Jedan od najranjivijih geomorfoloških oblika obalnih područja su žala. Žala su dinamični oblici na kontaktu kopna i mora, čija stabilnost ovisi o složenim interakcijama prirodnih i antropogenih procesa. Prve procjene istraživanja iz 1980-ih tvrde da su erozije žala na globalnoj razini oko 70 % (Bird, 1985). Novija istraživanja procjenjuju da su ti postoci ipak bitno niži, oko 24 % (Luijendijk i sur., 2018). Bozzeda i sur. (2023) ističu da je 20 % žala na globalnoj razini izloženo ekstremnoj eroziji. Vousdoukas i sur. (2020) upozoravaju na to da su pješčana žala pod najvećom prijetnjom jer je više od 50 % pješčanih žala u svijetu pod utjecajem erozijskih procesa. Iako se procjene razlikuju, opći trend upućuje na značajan gubitak sedimenta i destabilizaciju obalnih sustava, što predstavlja ozbiljan problem za priobalna područja diljem svijeta.

Slični trendovi erozije zabilježeni su i na području istočne obale Jadrana (Faivre & Mićunović, 2017; Mićunović & Faivre, 2024b; Rajčić i sur., 2010). Žala formirana u karbonatnim stijenama uglavnom su raštrkana, mala, uska i šljunkovita, dok su obale izgrađene u flišnim sedimentnim stijenama prepoznatljive po duljim pješčanim i šljunkovitim žalima. Iako ukupna duljina žala duž istočne obale Jadrana ne prelazi 5 % (Pikelj & Juračić, 2013), ona imaju ključnu ulogu u turizmu i zahtijevaju sustavnu zaštitu i održivo upravljanje. Kako bi se povećala njihova površina za rekreacijske aktivnosti, često se provodi nadohrana i nasipavanje (npr. Općina Podgora, 2007; 2011; 2014). Takve intervencije mogu uzrokovati značajne geomorfološke posljedice, ubrzanu eroziju i redistribuciju nanesenog materijala (Carter & Oxford, 1993). Na intenzitet erozijskih procesa utječu mnogobrojni čimbenici kao što je relativna promjena morske razine

INTRODUCTION

Coastal areas represent complex geomorphological systems that are subject to intense changes due to natural processes and increasing socio-economic pressure. Today, more than 50 % of the world's population lives near the coast, i.e., within a radius of about 100 km from the coast (Grobbe, 2023; Toure et al., 2019), which puts pressure on coastal ecosystems and natural resources. One of the most vulnerable coastal landforms are beaches. They are dynamic features at the interface between land and sea, whose stability depends on complex interactions between natural and anthropogenic processes. Research from the 1980s provided the first global estimates of beach erosion, with the assumption that around 70 % of beaches are affected (Bird, 1985). However, in more recent studies significantly lower values, around 24%, are assumed (Luijendijk et al., 2018). Bozzeda et al. (2023) emphasise that 20% of the world's beaches are exposed to severe erosion. Vousdoukas et al. (2020) warn that sandy beaches are the most threatened, with more than 50 % of the world's sandy beaches affected by erosion processes. Although estimates vary, the overall trend indicates a significant loss of sediment and destabilisation of coastal systems, which is a serious problem for coastal areas worldwide.

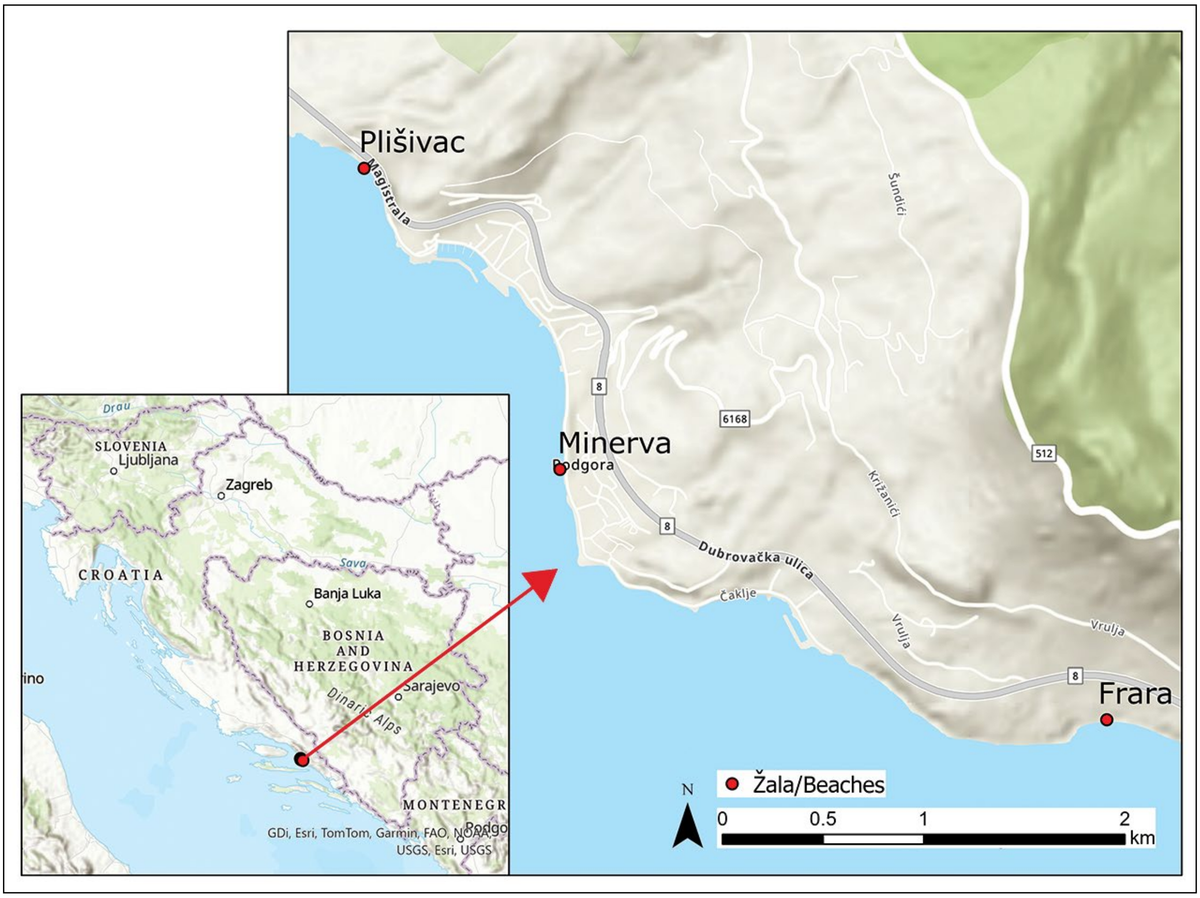
Similar erosion trends were also observed along the eastern Adriatic coast (Faivre & Mićunović, 2017; Mićunović & Faivre, 2024b; Rajčić et al., 2010). Beaches formed in carbonate rocks are generally scattered, small, narrow, and gravelly, while coastlines formed in flysch sedimentary rocks are characterised by longer sandy and gravelly beaches. Although the total length of beaches along the eastern Adriatic coast does not exceed 5 % (Pikelj & Juračić, 2013), they play a key role in tourism and require systematic protection and sustainable management. In order to increase their surface area for recreational use, nourishment and artificial fillings are often implemented (e.g., Municipality of Podgora, 2007, 2011, 2014). However, such interventions can cause significant geomorphological consequences, including accelerated erosion and redistribution of deposited material (Carter & Oxford, 1993). The intensity of erosion processes is influenced by various factors such as the relative sea-level change (Faivre et al., 2021, 2023), sediment composition and grain size, coastal mor-

(Faivre i sur., 2021; 2023), sastav i veličina sedimenta, morfološke karakteristike obale, energija valova, dominantni smjerovi vjetrova te utjecaj plime i oseke (Anthony, 2015). Neprimjereno nasipavanje sedimenta, odlaganje neprikladnog materijala na žalima i u njihovoj neposrednoj blizini, izgradnja obalnih konstrukcija i širenje turističkih kapaciteta dovode do značajnih promjena u transportu i akumulaciji sedimenta. Zbog toga pojedini segmenti žala mogu doživjeti progradaciju, dok su drugi izloženi intenzivnoj eroziji (Rajčić i sur., 2010).

Kako bi se ublažili negativni učinci erozije, primjenjuju se različite inženjerske metode zaštite obale poput izgradnje molova, pera, zaštitnih zidova i drugih stabilizacijskih struktura. Takvi zahvati često dovode do nenamjernih posljedica, poput poremećaja u transportu sedimenta i povećane erozije susjednih područja. Stoga je za učinkovito upravljanje žalima ključna precizna analiza promjena položaja obalne crte dugoročnim monitoringom (Addo, 2014). Sustavno praćenje

phology, wave energy, prevailing wind directions, and tidal effects (Anthony, 2015). Inappropriate sediment infilling, the deposition of unsuitable material on and near beaches, the construction of coastal structures, and the expansion of tourism infrastructure lead to significant changes in sediment transport and accumulation. As a result, some segments of the beach may undergo progradation, while others are subject to severe erosion (Rajčić et al., 2010).

To mitigate the negative effects of erosion, various methods of coastal protection are generally used, such as the construction of groynes, jetties, seawalls, and other stabilisation structures. However, such interventions often lead to unintended consequences, such as disruption of sediment transport and increased erosion in adjacent areas. Therefore, effective beach management requires accurate analysis of shoreline changes through long-term monitoring (Addo, 2014). Systematic beach monitoring is carried out through a combination of topographic field surveys (Cook, 2017), analysing satellite and aerial imagery and geoinformation methods. Long-term



Slika 1. *Područje istraživanja s označenim žalima*
Figure 1 *Study area with beaches locations*
Izvor / Source: *ESRI (2025) / Google Earth Pro (2025)*

žala provodi se kombinacijom terenskih mjerenja topografije (Cook, 2017), analize satelitskih i aerofotogrametrijskih snimaka te geoinformacijskih metoda. Dugoročne kvantitativne analize morfoloških promjena omogućuju preciznije projiciranje budućih trendova i razvoj strategija za održivo upravljanje obalnim područjima (Asokan & Anitha, 2019).

U ovom radu analiziraju se morfološke promjene žala Minerve, Plišivca i Frare (Sl. 1.), smještenih na području općine Podgora, koja je dio Makarske rivijere, jednog od turistički najznačajnijih obalnih područja u Hrvatskoj. Razvoj turizma, koji je započeo u drugoj polovici 20. stoljeća, doveo je do ubrzane litoralizacije, što značajno utječe na morfološka obilježja žala. S obzirom na te procese, cilj rada je kvantificirati morfološke promjene žala u posljednjih 70-ak godina metodama daljinskih istraživanja. U tu se svrhu analiziraju satelitske i aerofotogrametrijske snimke i podaci prikupljeni bespilotnim letjelicama (UAV). Osim kvantifikacije promjena, cilj ovoga istraživanja je usporedba morfodinamike antropogeno izmijenjenih žala u odnosu na prirodna žala te mogućnost identifikacije antropogenih zahvata metodama daljinskih istraživanja radi boljeg razumijevanja mehanizma promjena i osiguranja smjernica za upravljanje obalnim područjima u budućnosti.

PRIRODNO-GEOGRAFSKA OBILJEŽJA

Općina Podgora smještena je u Srednjoj Dalmaciji i najveća je općina Makarskog primorja površine od približno 77,45 km². Administrativno je čine naselja Podgora, Drašnice, Gornje Igrane, Igrane i Živogošće. Područje općine karakterizira spoj planinskog masiva Biokova i mora, a geomorfološki pripada Podbiokovlju. Geološku građu Podgore čine karbonatne stijene jurske i kredne starosti. Najstariji izdanci, iz jure, nalaze se na višim predjelima Podgore i Igrana. Riječ je o slabo uslojenim vapnencima s lećama breča te uslojenim do gromadastim vapnencima s lećama dolomita i breča (Marinčić i sur., 1977). Donjokredne naslage sastoje se od vapnenaca i breča te se nalaze na kopnenom rubu općine prema unutrašnjosti, dok

quantitative analyses of morphological changes enable more accurate predictions of future trends and the development of strategies for sustainable coastal management (Asokan & Anitha, 2019).

This study analyses the morphological changes of three beaches: Minerva, Plišivac, and Frara (Fig. 1) in the municipality of Podgora, which is part of Makarska Riviera, one of the most important tourist coastal areas in Croatia. The development of tourism, which began in the second half of the 20th century, has led to accelerated littoralisation, which has significantly affected the morphological characteristics of the beaches. Considering these processes, the aim of this study is to quantify the morphological changes of beaches over the last 70 years using remote sensing methods. For this purpose, satellite and aerial images as well as, data collected by unmanned aerial vehicles (UAVs) are used. In addition, in order to quantify changes, this research also aims to compare morphodynamics of anthropogenically modified beaches with those of natural beaches. Furthermore, we aim to assess the potential of remote sensing methods in detecting anthropogenic interventions in order to better understand the mechanisms of change and provide guidance for future coastal management.

PHYSICAL-GEOGRAPHICAL CHARACTERISTICS

The municipality of Podgora is located in central Dalmatia and is the largest municipality along the coastal area of Makarska with an extent of approximately 77.45 km². Administratively, it comprises the settlements of Podgora, Drašnice, Gornje Igrane, Igrane, and Živogošće. The area is characterised by the intersection of Biokovo mountain and the sea, and geomorphologically belongs to Podbiokovlje region. The geological structure of Podgora consists mainly of carbonate rocks from the Jurassic and Cretaceous periods. The oldest outcrops dating back to the Jurassic are located in the higher parts of Podgora and Igrane. These include weakly bedded limestones with lenses of breccia, and bedded to massive limestones with lenses of dolomite and breccia (Marinčić et al., 1977). The Lower Cretaceous deposits consist of limestone and breccias and are located along the inland border of the municisu gornjokredne naslage predstavljene vapnencima s lećama breča (Marinčić i sur., 1977). Na obalnom dijelu općine, na donjim padinama Biokova, prisutne su eocenske klastične naslage fliša (Marinčić i sur., 1977). Kvartarne naslage rastresitog materijala javljaju se na južnim padinama Biokova, osobito na zapadnoj granici općine (Magaš i sur., 1979).

Područje Makarskog primorja, uključujući općinu Podgora, obilježava visok stupanj tektonske poremećenosti. To je posljedica kompleksnih geoloških zbivanja, a time i periodičnih pojava potresa (Faivre & Butorac, 2018; Herak i sur., 1996). Prema Mercallijevoj ljestvici, to područje pripada potresnoj zoni VII. stupnja i više, što upućuje na učestale i potencijalno razorne potrese (Herak i sur., 1996).

Općina Podgora geomorfološki je definirana hrptom Biokova i Rilića, njihovim južnim padinama te obalnim pojasom. Najviše nadmorske visine, koje prelaze 1200 m, nalaze se na hrptu Biokova, dok su najniže vrijednosti zabilježene u uskom obalnom pojasu. Reljef područja karakterizira velik nagib padina, pri čemu najveći udio površine ima nagibe veće od 12°. Područje između Podgore i Drašnica obilježeno je izrazito strmim reljefom, s nagibima većim od 55°. Blagi nagibi javljaju se uz obalu te na zaravnjenim dijelovima hrpta Biokova. Cijelim područjem dominira umjereno do izrazito raščlanjen reljef, uz pretežnu južnu, jugoistočnu i jugozapadnu orijentaciju padina.

Područje se nalazi u tektonski aktivnoj zoni te je podložno različitim geomorfološkim procesima, osobito padinskim procesima (Herak & Herak, 2012) tipičnim za područje Južnog Jadrana (Faivre i sur., 2021). Veliki nagibi padina pogoduju intenzivnim gravitacijskim procesima, pri čemu su urušavanja česta pojava duž Jadranske magistrale (Telbisz i sur., 2009). Na području istraživanja mnogo je jaruga, koje su većim dijelom godine suhe, no povremeno se aktiviraju bujični vodotoci zbog obilnih i intenzivnih oborina. Ti tokovi uzrokuju spiranje i jaruženje, a na svojem ušću u more najčešće oblikuju aluvijalne plavine. Njihova akumulacija ovisi o bujičnim procesima na padinama Biokova, pri čemu su žala glavni oblik akumulacijskih obala (Faivre i sur., 2011; Faivre & Mićunović, 2017).

pality, while the Upper Cretaceous deposits consist of limestone with lenses of breccias (Marinčić et al., 1977). In the coastal area of the municipality, on the lower slopes of Biokovo, there are flysch deposits from the Eocene (Marinčić et al., 1977). Quaternary deposits of loose material occur on the southern slopes of Biokovo, especially along the western municipality border (Magaš et al., 1979).

The coastal region of Makarska, including the municipality of Podgora, is a tectonically active area with periodic occurrence of earthquakes (Faivre & Butorac, 2018; Herak et al., 1996). According to the Mercalli scale, that area belongs to seismic zone VII and above, which indicates frequent and potentially destructive earthquakes (Herak et al., 1996).

The municipality of Podgora is geomorphologically defined with the ridges of Biokovo and Rilić, including their southern slopes and the coast. The highest elevations, which exceed 1200 meters, are found on Biokovo ridge, while the lowest are found in the narrow coastal zone. The relief of the area is characterised by steep slopes, with the majority of inclinations over 12°. The area between Podgora and Drašnice is characterised by extremely steep terrain with slopes of over 55°. Gentle slopes can be found along the coastline and on the flatter parts of the Biokovo ridge. The entire region is dominated by a moderately to strongly rugged relief with predominantly southern, south-eastern and south-western slope orientations.

The area is located in a tectonically active zone and is therefore susceptible to various geomorphological processes, especially slope processes (Herak & Herak, 2012), which are typical of the southern Adriatic region (Faivre et al., 2021). The steep slopes favour intense gravitational processes, and rockfalls which are a common phenomenon along the motorway Jadranska magistrala (Telbisz et al., 2009). There are numerous gullies in the study area, which are dry most of the year, but can be activated during heavy rainfalls. These streams cause washouts and gulling and often form alluvial fans at their mouths. Their accumulation depends on torrential processes on the slopes of Biokovo, with beaches being the primary form of accumulative coasts (Faivre et al., 2011; Faivre & Mićunović, 2017).

The municipality of Podgora is located in a Mediterranean climate zone with hot, dry summers and

Općina Podgora nalazi se u području sredozemne klime s vrućim i suhim ljetima te blagim i kišovitim zimama (Csa prema Köppenovoj klasifikaciji) (Šegota & Filipčić, 2003). Na klimu značajan utjecaj imaju blizina mora i Biokovo, koje uzrokuje razlike u temperaturi i količini oborina između priobalnog i unutrašnjeg dijela. Prema podacima obližnje meteorološke postaje Makarske, na području istraživanja prosječna godišnja temperatura zraka iznosi oko 16 °C. Srpanj je najtopliji mjesec (26,4 °C), a siječanj najhladniji (9,2 °C). Količina oborina neravnomjerno je raspoređena tijekom godine, s maksimumom u studenom (149,4 mm) i minimumom u srpnju (31,8 mm), što potvrđuje sezonski karakter padalina. Dugoročna analiza pokazuje trend porasta temperature zraka i promjenjivu dinamiku oborina, što upućuje na učestalije klimatske ekstreme.

Oblikovanje žala u velikoj je mjeri uvjetovano valovima i morskim strujama. S obzirom na prosječnu amplitudu morskih mijena od ±25 cm (mareograf Split; Faivre & Butorac, 2018), ova obala pripada mikroplimnim obalama, što znači da plima i oseka nemaju značajan utjecaj na morfološke promjene obale. Glavni čimbenici u dinamici valova su smjer i brzina vjetra. Prema podacima Državnog hidrometeorološkog zavoda (DHMZ) za meteorološku postaju Makarska, u razdoblju od 1981. do 2022. godine dominiraju južni vjetrovi, posebno jugo (SE), široko-oštro (SSE) i jugo levante (ESE), s najvećom učestalosti. Međutim, najjači vjetar u ovom području je bura (NE), koja zahvaljujući „speed-up" efektu na padinama Biokova može dosegnuti brzine do 32,7 m/s (12 bofora), što spada u kategoriju orkanskih vjetrova. S druge strane, jugo, iako učestali vjetar, ne postiže maksimalne brzine kao na otvorenom moru zbog reljefnog ograničenja, utjecaja otoka Hvara i Brača (Lepri, 2023; Vukičević, 1991).

Valovi uzrokovani jugom obično su viši od onih uzrokovanih burom zato što jugo puše duže i ravnomjernije. Najčešće su jugoistočnog smjera i dominantni su u zimskim i jesenskim mjesecima kada su valovi najveći. Ljeti su češći vjetrovi iz sjeverozapadnog smjera, poput maestrala, koji stvara umjerene valove. Ti valovi, iako manji, zbog svoje učestalosti značajno utječu na prijenos sedimenta i oblikovanje obale. Valovi

mild, rainy winters (Csa according to the Köppen classification) (Šegota & Filipčić, 2003). The area's climate is significantly influenced by the proximity of the sea and the mountain range Biokovo, which leads to temperature and precipitation fluctuations between the coastal and inland areas. According to the nearby meteorological station in Makarska, the average annual air temperature in the study area is around 16 °C, with July being the warmest month (26.4 °C) and January the coldest (9.2 °C). Precipitation is unevenly distributed throughout the year, with a maximum in November (149.4 mm) and a minimum in July (31.8 mm), which confirms the seasonal nature of precipitation. Long-term analyses show a trend towards rising air temperatures and variable precipitation dynamics, which indicates more frequent climate extremes.

The formation of beaches is largely influenced by waves and sea currents. With an average tidal amplitude of ±25 cm (Split tide gauge; Faivre & Butorac, 2018), this coast is classified as microtidal, which means that the tides do not have a significant influence on the morphological changes of the beach. The most important factors for wave dynamics are wind direction and speed. According to data from the Croatian Meteorological and Hydrological Service (DHMZ) for Makarska meteorological station, southerly winds prevailed in the period from 1981 to 2022 in particular scirocco (SE) and scirocco levante (SEE), which occur most frequently. However, the strongest wind in this area is the bora (NE), which can reach speeds of up to 32.7 m/s (12 on the Beaufort scale) due to the acceleration effect on the slopes of Biokovo and thus falls into the category of gale-force winds. On the other hand, the sirocco, although frequent, does not reach the maximum speeds as on the open sea due to the topographical conditions and the influence of the islands of Hvar and Brač (Lepri, 2023; Vukićević, 1991).

The waves generated by the sirocco are usually higher than those caused by bora, as sirocco tends to blow longer and more consistently. These winds usually come from a south-east direction and are predominant in the autumn and winter months, when the wave heights are at their highest. In summer, north-westerly winds, such as the mistral, are more frequent and generate moderate waves. Although these waves are smaller, their frequency significant-se mogu podijeliti na valove lijepog vremena i valove olujnog vremena (Rajčić i sur., 2010). Valovi lijepog vremena, npr. uzrokovani uglavnom maestralom, potiču akumulaciju sedimenta, dok olujni valovi, osobito oni izazvani jugom, imaju snažan erozijski učinak (Tišljar, 2004). Olujni valovi svojim povratnim strujama odnose sediment s obale prema dubljim dijelovima mora, što može rezultirati gubitkom materijala sa žala. Na području Srednjeg Jadrana gotovo 70 % značajnih visina valova (Hs) manje je od jednog metra, a prosječna značajna visina vala iznosi Hsavg = 0,87 m. Najvjerojatnije stanje mora ima značajnu visinu vala između 0,5 i 1 m i valni period između 3 i 4 sekunde, dok je najviša zabilježena značajna visina vala Hsmax = 6,05 m, izmjerena 8. prosinca 1992. (Farkaš i sur., 2016).

ly affects sediment transport and coastal modelling. Waves can be categorised as fair-weather waves and storm waves (Rajčić et al., 2010). Fair-weather waves, which are typically generated by the mistral, promote sediment accumulation, while storm waves, especially those generated by the scirocco have a strong erosive effect (Tišljar, 2004). Storm waves carry sediment away from the coast to deeper sea areas through their backwash currents, which can lead to a loss of material on the beach. In the central Adriatic, almost 70 % of significant wave heights (Hs) are less than one metre, with an average significant wave height of Hs_avg = 0.87 m. The most probable swell has a significant wave height between 0.5 and 1 m and a wave period between 3 and 4 seconds, while the highest recorded significant wave height was Hs_max = 6.05 m, measured on 8 December 1992 (Farkas et al., 2016).

METODE I MATERIJALI

Morfološke promjene žala analizirane su metodama daljinskih istraživanja i terenskog rada za približno sedamdeset godina, odnosno od 1951. do 2024. godine. Za to su korištene arhivske aerofotogrametrijske snimke Državne geodetske upra-

MATERIALS AND METHODS

Morphological changes of the beaches were analysed using remote sensing methods and fieldwork over a period of around 70 years, from 1951 to 2024. For this purpose, archival aerial photographs from the State Geodetic Administration, satellite

Slika 2. *Žalo Minerva prikazano na različitim kartografskim podlogama: a) Aviosnimka iz 2023. godine; b) Satelitska snimka iz 2023. godine, c) Ortomozaik (UAV) iz 2023. godine*

Figure 2 *Minerva beach on different cartographic bases: a) Aerial image from 2023; b) Satellite image from 2023; c) Orthomosaic (UAV) from 2023*

Izvor / Source: *Državna geodetska uprava (2025); Google Earth Pro (2025) / State Geodetic Administration (2025), Google Earth Pro (2025)* ve, satelitske snimke aplikacije Google Earth Pro te ortomozaici izrađeni iz snimaka prikupljenih bespilotnom letjelicom (Sl. 2.). Analiza je provedena na odabranim žalima, ravnomjerno raspoređenih u naselju Podgora: Plišivac (sjeverni dio), Minerva (središnji dio) i Frara (južni dio) (Sl. 1.). Od 1951. do 2024. godine vremenska rezolucija se povećava, a za pojedine godine korišteno je i nekoliko snimaka unutar jedne godine, npr. za 2005., 2018. i 2019. godinu (Tab. 1.).

Prikupljanje kartografskih podloga

Za potrebe analize korištene su snimke Državne geodetske uprave, uključujući arhivske aerofotogrametrijske snimke i digitalne ortofoto snimke (DOF) u razdoblju od 1951. do 2021. godine (Tab. 1.). Snimke do 1972. godine su pankromatske, crno-bijele, različitog prostornog obuhvata i s određenim oštećenjima koja mogu utjecati na njihovu prostornu rezoluciju. Dostavljene su u TIFF formatu, s prostornom rezolucijom od 0,5 m i definiranim koordinatnim sustavom HTRS96/TM. Snimke od 2005. godine dostupne su u RGB formatu (u boji), također različitog prostornog obuhvata. Zbog toga je bilo potrebno njihovo georeferenciranje i definiranje HTRS96/TM projekcije. Kako bi se osigurala konzistentnost i preciznija usporedba podataka, sve snimke svedene su na prostornu rezoluciju od 0,5 m s pomoću alata *resample*. Digitalni ortofoto podaci (DOF) za razdoblje od 2011. do 2021. godine analizirani su putem WMS servisa u softveru ArcGIS Pro.

Snimke su georeferencirane s pomoću alata *Georeference – Add control points* u ArcGIS Pro softveru. S obzirom na to da je fokus istraživanja žalo, koje predstavlja relativno malo područje u odnosu na cijelu snimku, definirano je između 5 i 10 fiksnih točaka na području žala (objekti, ulice ili geomorfološki markeri) na temelju kojih su snimke preklopljene. Alatom *Swipe* procijenjeno je da su se snimke na području žala vrlo precizno poklopile te da je pogreška zanemariva s obzirom na ciljeve istraživanja.

Satelitske snimke dostupne putem aplikacije Google Earth Pro obuhvaćaju razdoblje od ožujka 2005. do svibnja 2023. godine (Tab. 1.). Google Earth Pro omogućuje pregled snimaka srednje do

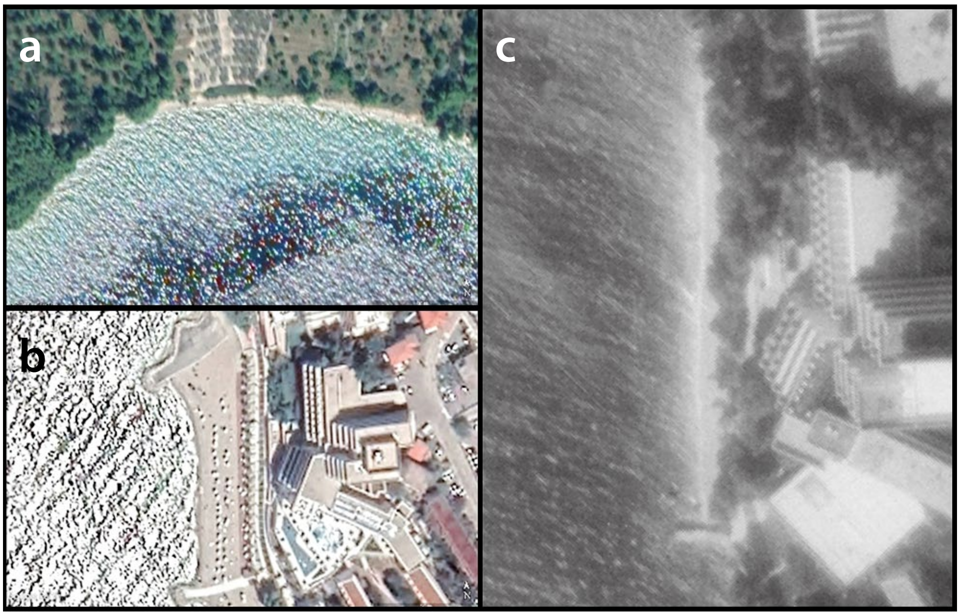
images from the Google Earth Pro application, and orthomosaics generated from drone images were used (Fig. 2). The analysis was carried out on selected beaches that are evenly distributed within the Podgora settlement area: Plišivac (northern part), Minerva (central part), and Frara (southern part) (Fig. 1). From 1951 to 2024, the temporal resolution of the available data increased, and for certain years — such as 2005, 2018, and 2019, several images from the same year were used (Tab. 1).

Collection of Cartographic Bases

For the purposes of this analysis, imagery from the State Geodetic Administration was used, including archival aerial photographs and digital orthophotos (DOP) covering the period from 1951 to 2021 (Tab. 1). The images up to 1972 are panchromatic, black and white images with varying spatial coverage and some damage that may affect their spatial resolution. They were provided in TIFF format with a spatial resolution of 0.5 m and in the HTRS96/TM coordinate system. The images from 2005 onwards are available in RGB format (colour), also with different spatial coverage, which required georeferencing and projection definition to HTRS96/TM. To ensure consistency and more accurate data comparison, all images were standardised to a spatial resolution of 0.5 m using the Resample tool. The digital orthophoto data (DOP) for the period from 2011 to 2021 were analysed using a WMS service in ArcGIS Pro software.

The images were georeferenced using the *Georeference – Add Control Points* tool in ArcGIS Pro. Since the focus of the research is on beaches, which represent a relatively small area compared to the overall image, between 5 and 10 fixed points were defined on the beach area (e.g., objects, roads or geomorphological markers), which were used to align the images. Using the Swipe tool, it was found that the images were very accurately aligned over the beach areas, with a negligible error in relation to the objectives of the study.

The satellite images available via the Google Earth Pro application cover the period from March 2005 to May 2023 (Tab. 1). Google Earth Pro allows viewing medium to high resolution imagery, importing and exporting spatial data, and measuring



Slika 3. *Satelitske /a) Frara i b) Minerva i avio c) Minerva/ snimke izuzete iz analize zbog lošije prostorne rezolucije*
Figure 3 *Satellite images (a – Frara and b – Minerva) and aerial image (c – Minerva) excluded from the analysis due to low spatial resolution*
Izvor / Source: *Državna geodetska uprava (2025) / State Geodetic Administration (2025)*

visoke prostorne rezolucije, uvoz i izvoz prostornih podataka te mjerenje linijskih i poligonskih oblika. Ovisno o mjerilu, upotrebljava različite izvore snimaka, uključujući Landsat, Sentinel, TerraMetrics, Airbus i Maxar Technologies (Google Earth Pro). Alat time-lapse omogućuje pregled snimaka od 1985. godine, no zbog niske rezolucije snimke

linear and polygonal features. Depending on the zoom level, it uses different image sources, including Landsat, Sentinel, TerraMetrics, Airbus, and Maxar Technologies (Google Earth Pro). The time-lapse tool allows you to view images back to 1985, but due to the low resolution, images prior to 2012 were not usable for the analysis (Fig. 3).

Tablica 1. *Vremenska rezolucija analiziranih snimaka*
Table 1 *Temporal resolution of the analyzed images*
Izvor / Source: *Državna geodetska uprava (2025); Google Earth Pro (2025) / Source: State Geodetic Administration (2025), Google Earth Pro (2025)*

Snimci Državne geodetske uprave / *State Geodetic Administration images*	**Satelitske snimke: Google Earth Pro / *Satellite images: Google Earth Pro***	**Terensko kartiranje (UAV i GNSS) / *Field mapping (UAV and GNSS)***
1951.	3. 3. 2005.	4/2022.
1960.	31. 8. 2012.	6/2023.
1966.	14. 3. 2014.	
1972.	5. 7. 2017.	
2005.	3. 1. 2018.	
2006.	28. 8. 2018.	
2011.	26. 9. 2018.	
2015.	18. 10. 2018.	
2017.	25. 7. 2019.	
2019.	29. 8. 2019.	
2021.	25. 8. 2020.	
	3. 9. 2021.	
	15. 8. 2022.	
	17. 5. 2023.	

do 2012. godine nisu bile uporabljive za analizu (Sl. 3.).

Treća skupina podataka odnosi se na snimke prikupljene bespilotnom letjelicom DJI Phantom 4 Pro v2.0, opremljenom RGB kamerom (FC6310, 20 MP). Terensko kartiranje i snimanje provedeni su na žalu Minervi u travnju 2022. i lipnju 2023. godine (Tab. 1.). Snimanje je obavljeno s visine od 30 metara, uz prednje preklapanje snimaka od 75 % te bočno preklapanje od 65 %, a tip misije bio je single-grid, čime je osigurana dovoljna preklopljenost snimaka za kvalitetnu fotogrametrijsku obradu i analizu žala. Za prikupljanje kontrolnih točaka korišten je Trimble Catalyst DA2 GNSS prijamnik s RTK (Real Time Kinematics) preciznošću. Tijekom snimanja, prijamnik je bio povezan s više od 30 satelita i na CROPOS (Hrvatski pozicijski sustav), osiguravajući visoku horizontalnu i vertikalnu preciznost podataka.

Obrada i analiza prikupljenih podataka

Prikupljene GNSS točke uređene su i filtrirane u ArcGIS Online, zatim su izvezene u CSV formatu i transformirane iz WGS_84 u HTRS_96_TM koordinatni sustav s pomoću geomatičkih metoda u programu t7D (softver Državne geodetske uprave). Snimke prikupljene bespilotnom letjelicom obrađene su fotogrametrijskim metodama u Agisoft Metashape Professional softveru s pomoću Structure from Motion (SfM) tehnike. Ta metoda omogućuje konstrukciju trodimenzionalnih modela iz dvodimenzionalnih preklapajućih snimaka (Westoby, 2012). Završni produkti uključuju ortomozaik prosječne rezolucije < 3 cm, digitalni model površina (DMP) prosječne rezolucije ~5 cm i gusti oblak točaka za dodatnu analizu reljefa. Fotogrametrija, iako vrlo učinkovita, najtočnije rezultate daje na terenima bez vegetacije jer se temelji na optičkim slikama.

Obalna crta žala definirana je kao granica između sedimentnog dijela žala i mora, a digitalizirana je ručnom vektorizacijom u ArcGIS Pro softveru pri standardiziranom mjerilu 1:1000 (Ciavola i sur., 2003). Na arhivskim pankromatskim aviosnimkama, obalna crta određena je po istom načelu, no zbog slabije rezolucije primijenjene su prilagodbe kontrasta, svjetlosti i saturacije boja radi poboljšanja

The third dataset comprises images acquired with a DJI Phantom 4 Pro v2.0 unmanned aerial vehicle (UAV) equipped with an RGB camera (FC6310, 20 MP). Field mapping and image acquisition were carried out on Minerva beach in April 2022 and June 2023 (Tab. 1). The flights were conducted at an altitude of 30 metres, with a frontal image overlap of 75 % and a lateral overlap of 65 %. To ensure sufficient image overlap for high-quality photogram- metric processing and beach analysis, a single-grid flight mission was used. A Trimble Catalyst DA2 GNSS receiver with RTK (Real-Time Kinematics) precision was used to acquire the ground control points. During the flights, the receiver was connected to more than 30 satellites and to CROPOS (Croatian Positioning System) to ensure high horizontal and vertical accuracy of the data.

Data processing and analysis

The collected GNSS points were processed and filtered in ArcGIS Online, then exported in CSV format and transformed from WGS_84 to HTRS_96_TM coordinate system using geomatics methods in t7D software (developed by the State Geodetic Administration). The images collected by the UAV were photogrammetrically processed using Agisoft Metashape Professional software with the Structure from Motion (SfM) technique. This method enables the construction of three-dimensional models from overlapping two-dimensional images (Westoby, 2012). The final products included an orthomosaic with an average resolution of <3 cm, a digital surface model (DSM) with an average resolution of ~5 cm, and a dense point cloud for additional terrain analyses. Although photogrammetry is very effective, it provides the most accurate results on vegetation-free terrain, as it is based on optical imagery.

The beach shoreline was defined as the boundary between beach sediments and the sea, and was manually digitised in ArcGIS Pro at a standardised scale of 1:1000 (Ciavola et al., 2003). The shoreline was determined in the same way on archived panchromatic aerial images. However, due to the lower resolution, adjustments were made to contrast, brightness, and colour saturation to improve the visibility of the boundary (Ewiak et al., 2016). The most accurately defined shoreline was obtained vidljivosti granica (Ewiak i sur., 2016). Najpreciznije definirana obalna crta dobivena je iz modela izrađenih UAV snimanjem. Iz digitalnog modela reljefa izvedene su sve točke rastera na visini 0 m, koje su zatim korištene za definiranje obalne crte, uz korekcije visinskih podataka dobivenih GNSS prijamnikom. Kopnene granice žala određene su na temelju morfologije žala, kontakta sedimenta žala i temeljne stijene, vegetacije ili rubova određenih građevinskih objekata i konstrukcija (kuće, zidovi i sl.) (Boak & Turner, 2005; Mićunović i sur., 2021).

Analiza površine i promjena obalne crte provedena je u ArcGIS Pro, pri čemu je uzeta u obzir izračunata pogreška digitalizacije (Mićunović i sur., 2021). RMSE pogreška iznosi 7,2 % za površine i 2,1 % za duljinu žala, dok postotno odstupanje za površinu žala varira od -2,3 % do 5,6 %, a za duljinu od -1 % do 2,7 % (Mićunović i sur., 2021). Digitalizacija linijskih oblika pokazuje manju pogrešku, dok je veća kod površinskih oblika, što ovisi o kvaliteti ulaznih podataka te o morfološkim karakteristikama žala i uvala. Pri interpretaciji rezultata navedene pogreške uzete su u obzir kako bi se osigurala što veća pouzdanost analize, dok su potencijalne nesigurnosti u usporedbi različitih tipova snimaka razmotrene procjenom kvalitete pojedinih izvora podataka.

Analiza pomaka obalne crte provedena je vektorskim polilinijama koje predstavljaju poziciju obalnih crta žala kroz vrijeme. Izrađeno je 16 transekata okomitih na obalu. Alatom „Intersect“ određene su točke presjeka transekata s obalnim crtama, a s pomoću „Calculate Geometry“ izračunate su X i Y koordinate u metričkom sustavu. Alat „Near“ korišten je za mjerenje udaljenosti između pozicija obalnih crta po transektima, čime su dobiveni podaci o pozitivnim i negativnim pomacima. Na temelju toga izračunati su pomaci koji su omogućili analizu vremenske dinamike obalne crte žala.

REZULTATI

Žalo Plišivac (antropogeno izmijenjeno žalo)

Žalo Plišivac nalazi se na sjevernom dijelu naselja Podgora, orijentirano u smjeru sjeverozapad–jugoistok (NW–SE) i oblikovano je ponajprije u

from the models derived from an UAV. From the digital elevation model, all grid points were extracted at an elevation of 0 m and used to define the shoreline, with corrections based on the elevation data obtained from the GNSS receiver. The landward boundaries of the beaches were determined based on beach morphology and the contact between beach sediment and bedrock, vegetation or the edges of built structures such as houses, walls, etc. (Boak & Turner, 2005; Mićunović et al., 2021).

The area and change analysis of the shoreline was carried out in ArcGIS Pro, taking into account the calculated digitisation error (Mićunović et al., 2021). The RMSE was 7.2 % for the area and 2.1 % for the beach length, while the percentage deviation for the beach area ranged from –2.3 % to 5.6 %, and for the beach length from –1 % to 2.7 % (Mićunović et al., 2021). The digitisation of linear features showed lower errors than surface features, which depends on the quality of the input data and the morphological characteristics of the beaches and bays. These errors were taken into account when interpreting the results to ensure maximum analytical reliability, while potential uncertainties when comparing different image types were taken into account by assessing the quality of each data source.

Shoreline displacement was analysed using vector polylines representing the position of the beach shoreline over time. Sixteen transects perpendicular to the coast were created. The *Intersect* tool was used to identify the intersections of the transects with the shorelines, and the *Calculate Geometry* tool was used to calculate the X and Y coordinates in the metric system. The *Near* tool was used to measure the distances between shoreline positions along the transects in order to obtain data on positive and negative shifts. On that basis, the displacements of the shoreline were calculated, which enabled the analysis of the beach shoreline change dynamics over time.

RESULTS

Plišivac beach (Anthropogenically modified beach)

Plišivac beach is located in the northern part of the settlement Podgora, oriented northwest–southeast (NW–SE) and formed mainly from alluvial material

Slika 4. *Lokacije istraživanja u Podgori: a) Žalo Plišivac prije provedbe antropogenih intervencija, označeno slovom A; b) Žalo Plišivac nakon antropogenih intervencija, podijeljeno na dva dijela, označena slovima B i C; c) žalo Minerva; d) žalo Frara*

Figure 4 *Study sites in Podgora: a) Plišivac beach before the anthropogenic interventions, marked as section A; b) Plišivac beach after the anthropogenic interventions, divided into two parts, marked as sections B and C; c) Minerva beach; d) Frara beach*

Izvor / Source: *Google Earth Pro (2025)*

aluvijalnom materijalu donesenom iz obližnjih jaruga (Sl. 4. a, b). Na temelju analize starijih i novijih snimaka uočene su značajne promjene u morfologiji žala, ponajprije zbog gradnje dvaju pera na sjevernom dijelu i uređenja rta na južnom dijelu žala 2018. godine. Novonastalo žalo poprimilo je oblik dvaju manjih (Tab. 2.; segmenti žala B i C, Sl. 4. b), međusobno odvojenih žala, međutim, pri izračunu površine žala i poziciji obalne crte uzeta su u obzir oba dijela, isključujući utjecaj pera, kako bi se dobila preciznija kronološka usporedba.

Analiza prikupljenih kartografskih podloga pokazuje značajne promjene u površini žala Plišivca tijekom promatranog razdoblja (Tab. 2.; sl. 4., 5. i 10.). Početna mjerenja iz 1951. godine prikazivala su površinu od približno 2470 m². Od 1951. do 1972. godine zabilježene su manje oscilacije površine. Prvi značajniji rast površina počinje 2005. godine, kada je površina narasla na gotovo 2900 m². Sljedeći rast javlja se 2014., a najveći 2020. godine, kada je po-

deposited from nearby gullies (Fig. 4a, b). Based on the analysis of older and more recent images, significant morphological changes were identified, mainly due to the construction of two groynes in the northern part of the beach and the modification of the headland in the southern part in 2018. The newly created beach has two smaller, separate segments (Table 2; beach segments B and C, Fig. 4b). However, for the calculation of the beach area and the position of the shoreline, both segments were taken into account, without the influence of the groynes, to allow a more accurate temporal comparison.

The analysis of the collected cartographic sources shows that the surface of Plišivac beach changed significantly over the observed period (Tab. 2; Figs. 4, 5, and 10). The first measurements from 1951 showed an area of about 2,470 m². From 1951 to 1972, only slight fluctuations in the surface area were observed. A notable increase in surface area began in 2005, when it grew to almost 2,900 m². A further increase occurred in 2014, with the largest increase occurring in 2020, when the beach

Tablica 2. *Površine žala Plišivca od 1951. do 2023. godine (Dijelovi žala Plišivca A, B i C prikazani su na Sl. 4.)*
Table 2 *Plišivac beach areas from 1951 to 2023 (Parts of Plišivac beach A, B and C are shown in Fig. 4.)*
Izvor / Source: *Državna geodetska uprava (2025), Google Earth Pro (2025) / State Geodetic Administration (2025), Google Earth Pro (2025)*

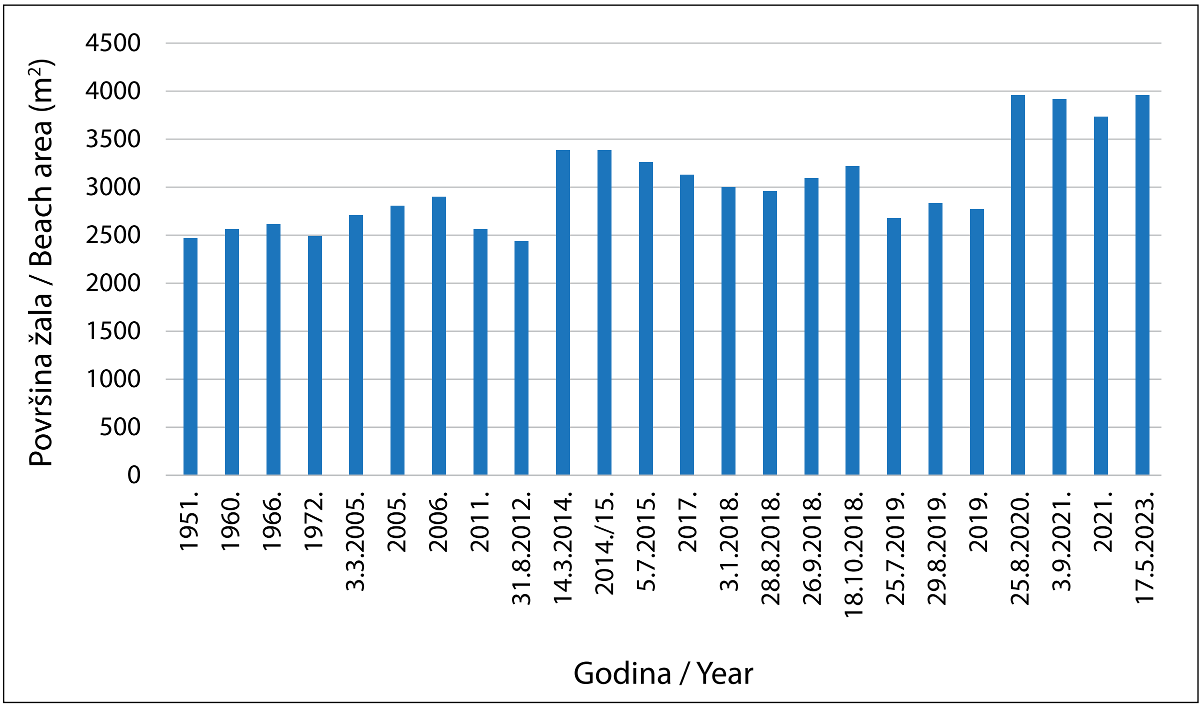
Godina snimanja / *Year of survey*	Izvor snimaka / *Source of images*	Žalo Plišivac / *Plišivac beach*			Ukupna površina (m²) / *Total area (m²)*
		A	B	C	
1951.	DGU	2471,22			2471,22
1960.	DGU	2567,78			2567,78
1966.	DGU	2613,35			2613,35
1972.	DGU	2491,93			2491,93
3. 3. 2005.	Google Earth Pro	2707,4			2707,74
2005.	DGU	2805,11			2805,11
2006.	DGU	2893,86			2893,86
2011.	DGU	2558,23			2558,23
31. 8. 2012.	Google Earth Pro	2434,54			2434,54
14. 3. 2014.	Google Earth Pro	3386,34			3386,34
2014./15.	DGU	3390,28			3390,28
5. 7. 2017.	Google Earth Pro	3259,43			3259,43
2017.	DGU	3118,4			3118,4
3. 1. 2018.	Google Earth Pro	3003,75			3003,75
28. 8. 2018.	Google Earth Pro		604,44	2335,25	2939,69
26. 9. 2018.	Google Earth Pro		631,96	2460,42	3092,38
18. 10. 2018.	Google Earth Pro		632,51	2587,89	3220,4
25. 7. 2019.	Google Earth Pro		597,71	2075,83	2673,53
29.8.2019.	Google Earth Pro		625,87	2207,58	2833,45
2019.	DGU		481,12	2282,1	2763,22
25. 8. 2020.	Google Earth Pro		834,73	3115,09	3949,82
3. 9. 2021.	Google Earth Pro		821,29	3083,32	3904,61
2021.	DGU		684,29	3055,66	3739,95
17. 5. 2023.	Google Earth Pro		819,76	3139,06	3958,83

vršina žala dostigla 3949,82 m², što je ukupni porast od više od 1270 m² u odnosu na početnu snimku. Satelitske snimke Google Eartha u odnosu na DGU imaju iste trendove, uz manje varijacije u pojedinim godinama. Rezultati pokazuju da je površina žala u početnim godinama stabilna, 2014. i 2020. godine dolazi do značajnih povećanja površine, a od 2021. do 2023. godine površina se ponovno stabilizira te iznosi oko 3900 m².

Uz zabilježeni rast površine, primijećeni su i periodi erozije žala (Sl. 5.). Primjerice, 2012. i 2019. godine žalo ima vrlo sličnu površinu početnoj površini iz 1951. godine, što spada u minimalne površine u promatranom razdoblju. Najveći pad zabilježen je 2019. godine kada je površina smanjena na 2673,53 m².

reached an area of 3,949.82 m². A total increase of more than 1,270 m² compared to the first image was obtained. The satellite images from Google Earth show the same general trends as those from the State Geodetic Administration (DGU), with only slight variations in certain years. For example, the results show that the beach area remained stable in the first few years, followed by a significant increase in 2014 and 2020. From 2021 to 2023, the area stabilised again at around 3,900 m².

In addition to the recorded increase in surface area, periods of erosion were also observed (Fig. 5). In 2012 and 2019, for example, the beach had a surface area similar to the initial value from 1951, which marked some of the lowest values in the observed period. The largest decrease occurred in 2019, when the surface area dropped to 2,673.53 m².



Slika 5. *Promjene površine žala Plišivca od 1951. do 2023. godine*
Figure 5 *Changes in the surface area of Plišivac beach from 1951 to 2023*

Žalo Minerva (antropogeno izmijenjeno žalo)

Žalo Minerva smješteno je južnije od žala Plišivca, u središnjem dijelu naselja Podgore, orijentirano u smjeru sjever–jug (N–S) (Sl. 4. c). Također je oblikovano ponajprije u aluvijalnom materijalu nanesenom iz obližnjih jaruga. Osim površine, na žalu Minervi detaljno su analizirane i promjene pozicije obalne crte u promatranom razdoblju. To žalo bilježi najveće morfološke promjene zbog intenzivnog turističkog razvoja naselja Podgore. Promjene su jasno vidljive na satelitskim snimkama Google Eartha, ortofoto snimkama Državne geodetske uprave (DGU) i snimkama prikupljenim bespilotnom letjelicom (UAV). Snimke UAV-a iz travnja 2022. godine korištene su kao referentna podloga za usporedbu izmjerenih položaja i duljina obalne crte, omogućujući precizniju analizu dinamike promjena.

Analiza snimaka, kao i na žalu Plišivcu, upućuje na značajne promjene u morfologiji žala Minerve tijekom promatranog razdoblja (Tab. 3.; Sl. 6.). Početna mjerenja iz 1951. godine pokazala su da je površina žala iznosila oko 452 m². Tijekom promatranog razdoblja zabilježene su tri faze značajnih povećanja površine žala: 1972., 2017. i 2020. godine. Površina žala

Minerva beach (anthropogenically modified beach)

Minerva beach is located south of Plišivac beach, in the central part of the settlement of Podgora, and is orientated north–south (N–S) (Fig. 4c). It is also formed primarily from alluvial material deposited from nearby gullies. In addition to the surface area, the changes in the shoreline position were also analysed in detail for Minerva Beach during the studied period. This beach underwent the greatest morphological changes due to the intensive development of tourism in Podgora. These changes are clearly visible on the satellite images from Google Earth, the orthophoto images from the State Geodetic Administration (DGU), and the UAV images. The UAV images from April 2022 were used as a reference base for comparison of measured coastline positions and lengths, which allows a more accurate analysis of the dynamics of change.

Similar to the case of Plišivac, the analysis shows significant morphological changes at Minerva beach (Tab. 3; Fig. 6). The first measurements from 1951 showed that the beach area was about 452 m². Three phases with a remarkable increase in area were recorded: 1972, 2017 and 2020. In 1972, the beach area reached 1,366 m², in 2017 it almost doubled to 2,598 m², and in 2020, it

Tablica 3. *Površine žala Minerve od 1951. do 2023. godine*
Table 3 *Surface areas of Minerva Beach from 1951 to 2023*
Izvor / Source: *Državna geodetska uprava (2025), Google Earth Pro (2025) / State Geodetic Administration (2025), Google Earth Pro (2025)*

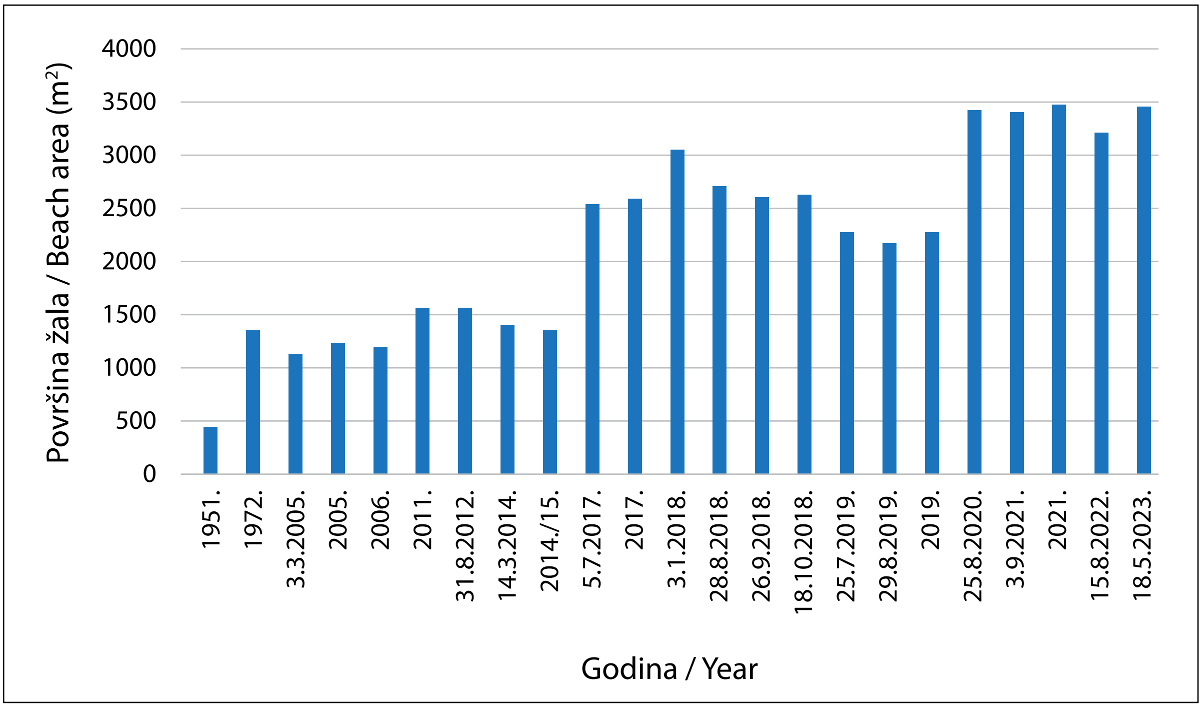
Godina snimanja / *Year of survey*	Izvor podataka / *Source of data*	Površina (m^2) / *Area (m^2)*
1951.	DGU	452,32
1972.	DGU	1365,74
3. 3. 2005.	Google Earth Pro	1136,16
2005.	DGU	1237,68
2006.	DGU	1216,91
2011.	DGU	1574,83
31. 8. 2012.	Google Earth Pro	1572,88
14. 3. 2014.	Google Earth Pro	1409,1
2014./2015.	DGU	1366,9
5. 7. 2017.	Google Earth Pro	2549,14
2017.	DGU	2598,48
3. 1. 2018.	Google Earth Pro	3047,13
28. 8. 2018.	Google Earth Pro	2707,98
26. 9. 2018.	Google Earth Pro	2611,97
18. 10. 2018.	Google Earth Pro	2630,66
25. 7. 2019.	Google Earth Pro	2276,55
29. 8. 2019.	Google Earth Pro	2177,68
2019.	DGU	2280,63
25. 8. 2020.	Google Earth Pro	3428,85
3. 9. 2021.	Google Earth Pro	3407,77
2021.	DGU	3483,92
4./2022.	UAV	3454,25
15. 8. 2022.	Google Earth Pro	3219,94
17. 5. 2023.	Google Earth Pro	3465,85

1972. godine je 1366 m^2, zatim se 2017. godine gotovo udvostručuje i iznosi 2598 m^2, a 2020. godine površina raste na 3428,85 m^2. Najviša izmjerena vrijednost dosegnuta je 2021. godine, s 3483,92 m^2. Tijekom promatranog razdoblja zabilježeni su i različiti periodi smanjenja površine žala. Prvo značajnije vidljivo je 2014./2015. godine, kada se površina žala smanjila na 1366,9 m^2. Također, značajno smanjenje uočeno je 2018. i 2019. godine, kada se površina smanjila na 2177,68 m^2.

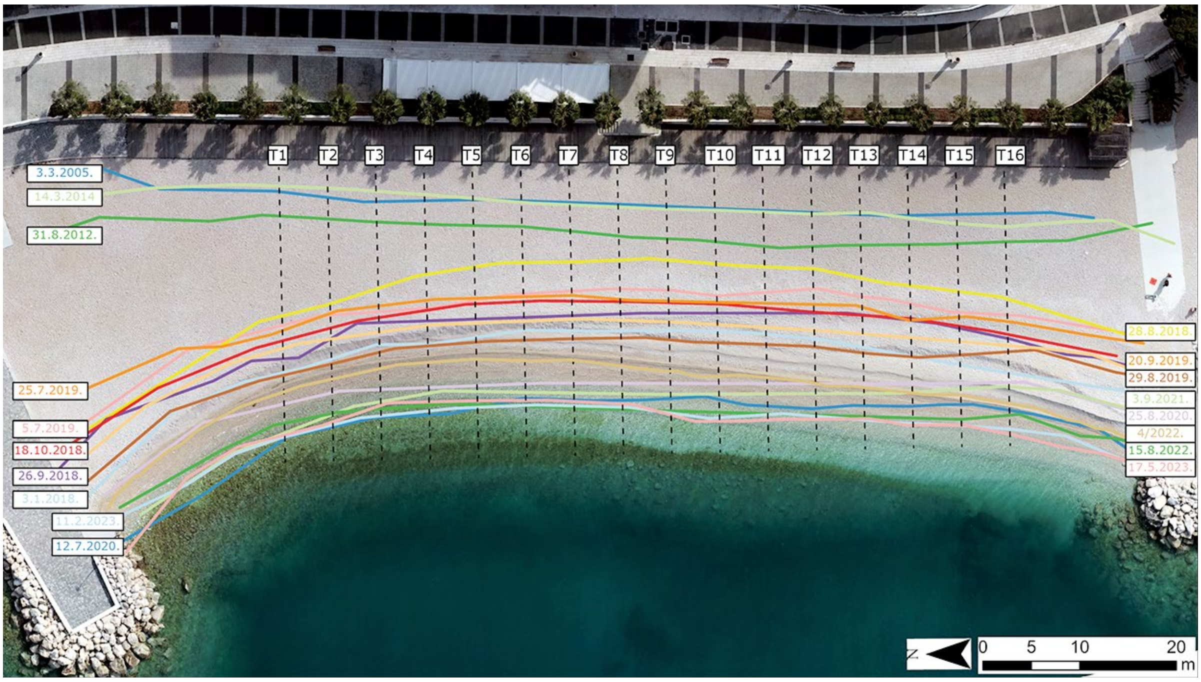
Na žalu Minervi analizirani su i pomaci obalne crte. Analiza je provedena na temelju sedamnaest različitih pozicija obalne crte u razdoblju od 2005. do 2023. godine (Sl. 7.). Podaci o poziciji obalne crte prikupljeni su Google Earth Pro aplikacijom kako bi se smanjila odstupanja među različitim kartografskim podlogama. Žalo je po-

grew further to 3,428.85 m^2. The highest value was recorded in 2021 with an area of 3,483.92 m^2. During the studied period, several phases of surface area reduction were also recorded. The first significant decrease occurred in 2014 and 2015, when the beach area fell to 1,366.9 m^2. Another notable reduction was observed in 2018 and 2019, when the area decreased to 2,177.68 m^2.

Shoreline shift was also analysed at Minerva beach. The analysis was based on 17 different shoreline positions recorded between 2005 and 2023 (Fig. 7). The shoreline data was collected using the Google Earth Pro application to minimise discrepancies between different cartographic sources. The beach was divided into 16 transects with a spacing of 5 metres, within which shoreline changes were analysed at different time intervals.



Slika 6. *Promjene površine žala Minerve od 1951. do 2023. godine*
Figure 6 *Changes in the area of Minerva beach from 1951 to 2023*



Slika 7. *Pozicije obalne crte žala Minerve od 2005. do 2023. godine*
Figure 7 *Shoreline positions of Minerva beach from 2005 to 2023*

dijeljeno na šesnaest transekata s razmakom od 5 m, unutar kojih su analizirane promjene položaja obalne crte u različitim intervalima. Najveći pomaci zabilježeni su na početnim i završnim transektima, koji predstavljaju rubne dijelove žala zbog njihove zakrivljenosti, dok su najmanji zabilježeni na središnjim transektima. Prosječne vrijednosti pomaka po transektima relativno su

The largest shifts were recorded the marginal transects representing the curved edges of the beach, while, as expected, the smallest changes were observed in the central transects. The average displacement values per transect are relatively similar and range around 1.35 metres. The overall analysis of the shoreline displacement shows that the shoreline moved seaward by an average of 22.09 m over the slične i kreću se oko 1,35 m. Analiza ukupnog pomaka obalne crte žala pokazuje da se crta tijekom osamnaest godina pomaknula prema moru za prosječno 22,09 m. Maksimalni pojedinačni pomaci obalne crte dostižu do 26,64 m (T1), dok su minimalni pojedinačni pomaci zabilježeni u središnjem dijelu (T7) i iznose 20,81 m, a njihov ukupan raspon 5,45 m.

Usporedbom prosječnih godišnjih pomaka obalne crte po godinama i transektima utvrđeno je da prosječni godišnji pomak iznosi 1,38 m. Iako prosječne vrijednosti upućuju na dominantnu progradaciju obalne crte, odnosno pomak prema moru, uočene su i značajnije epizode erozije. Primjerice, 2014. godine zabilježen je pomak od -3 m, 2018. godine čak -7 m, a 2019. godine -2 m. Standardna devijacija prosječnih pomaka obalne crte žala iznosi 4,14 m, što upućuje na varijabilnost položaja obalne crte tijekom analiziranog razdoblja. Visoka standardna devijacija u odnosu na prosječnu vrijednost (1,38 m) pokazuje da pomaci nisu bili vremenski ujednačeni, već su se izmjenjivale epizode nagle progradacije, odnosno erozije obalne crte. Takva morfodinamika upućuje na nestabilnost sustava, pri čemu su određena razdoblja i prostorne zone bile podložnije promjenama od drugih.

Žalo Frara (prirodno žalo)

Žalo Frara smješteno je na južnom dijelu naselja Podgore i orijentirano u smjeru istok–zapad (E-W) (Sl. 4. d). Oblikovano je u aluvijalnom materijalu nanesenom iz obližnjih jaruga te dijelom u sedimentu nastalom abrazijom klifa. Žalo je potpuno prirodno, bez značajnijih antropogenih utjecaja, a pristup mu je moguć isključivo morskim putem.

Za razliku od žala Plišivca i Minerve, analiza dostupnih snimaka upućuje na relativno stabilnu morfodinamiku žala Frare u razdoblju od 1951. do 2023. godine (Tab. 4., Sl. 8.). Početna površina žala 1951. godine iznosila je 883 m². Do kraja stoljeća zabilježen je postupni rast, s najvećim ukupnim povećanjem između 1972. i 1999. godine, kada je površina narasla za oko 200 m². Najveća površina zabilježena je 2005. godine, kada je dostigla približno 1270 m². Od tada su prisutne blage

18-year period. The maximum individual shoreline displacement reached up to 26.64 m (T1), while the smallest displacement was measured in the middle section (T7) and amounts to 20.81 m, with a total range of 5.45 m. A comparison of the average annual displacements of the shoreline by year and transect shows an average annual displacement of 1.38 metres. Although the average values indicate a predominant progradation of the shoreline, i.e., a seaward advance, some significant erosion episodes were also observed. For example, a retreat of -3 m was recorded in 2014, -7 m in 2018, and -2 m in 2019. The standard deviation of the average displacement of the shoreline was 4.14 m, which indicates the variability of the shoreline position in the analysed period. The high standard deviation compared to the average value (1.38 m) shows that the shifts were not uniform over time, but rather characterised by alternating episodes of sudden progradation and erosion. This type of morphodynamics indicates the instability of the system, with certain periods and spatial zones being more susceptible to change than others.

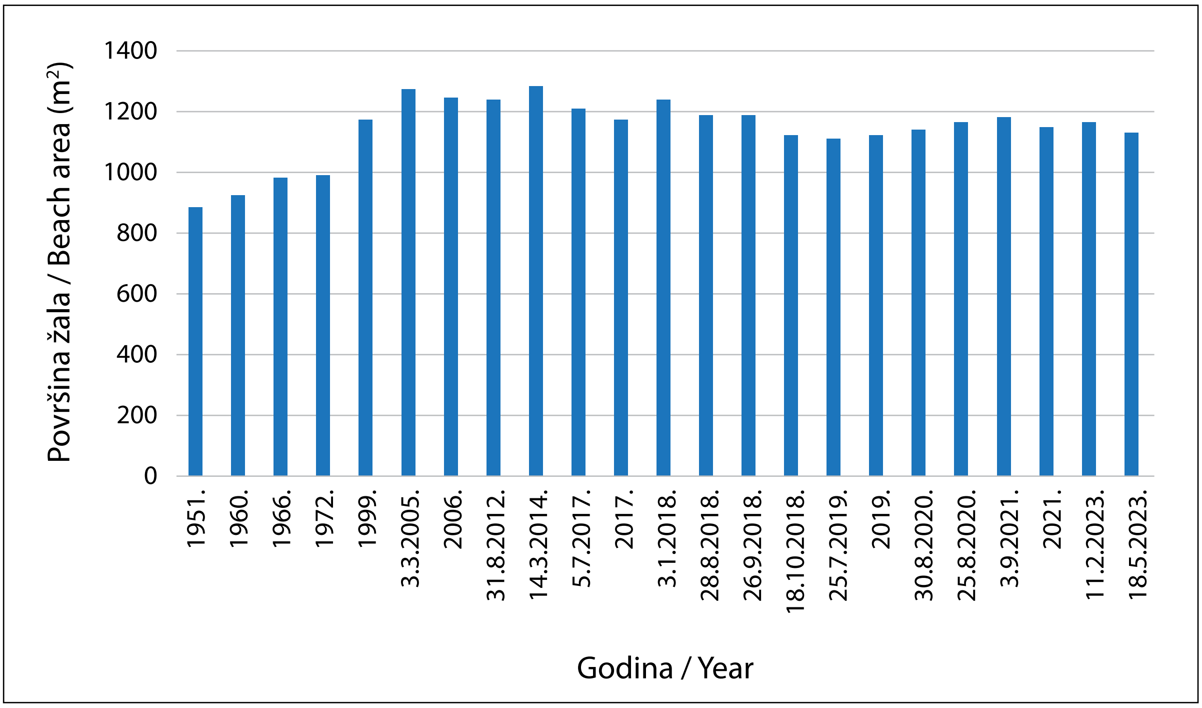
Frara beach (Natural beach)

The Frara beach is located in the southern part of the settlement of Podgora and is orientated east–west (E–W) (Fig. 4d). It consists of alluvial material transported from nearby gullies and partly of sediments formed by the erosion of cliffs. The beach is completely natural, with no significant anthropogenic impact, and is only accessible from the sea.

In contrast to the beaches of Plišivac and Minerva, the analysis of the available images shows relatively stable morphodynamics on Frara beach in the period from 1951 to 2023 (Tab. 4, Fig. 8). The area of the beach in 1951 was 883 m². There was a gradual increase until the end of the century, with the strongest growth occurring between 1972 and 1999, when the area increased by about 200 m². The largest area was recorded in 2005, when it reached around 1,270 m². Since then, only minor fluctuations have been observed. The analysis of the satellite images from Google Earth Pro in comparison with the data from the State Geodetic Administration (DGU) for the period from 2005 to 2023 confirms that the changes in surface area were less pronounced. Overall, the

Tablica 4. *Promjene površine žala Frare od 1951. do 2023. godine*
Table 4 *Changes in the surface area of Frara beach from 1951 to 2023*
Izvor / Source: *Državna geodetska uprava (2025), Google Earth Pro (2025) / State Geodetic Administration (2025), Google Earth Pro (2025)*

Godina snimanja / *Year of survey*	Izvor podataka / *Source of data*	Površina (m²) / *Area (m²)*
1951.	DGU	883,17
1960.	DGU	923,95
1966.	DGU	982,85
1972.	DGU	992,05
1999.	DGU	1175,55
3. 3. 2005.	Google Earth Pro	1272,63
2006.	DGU	1248,82
31. 8. 2012.	Google Earth Pro	1239,89
14. 3. 2014.	Google Earth Pro	1285,2
5. 7. 2017.	Google Earth Pro	1208,95
2017.	DGU	1175,42
3. 1. 2018.	Google Earth Pro	1240,71
28. 8. 2018.	Google Earth Pro	1189,21
26. 9. 2018.	Google Earth Pro	1196,51
18. 10. 2018.	Google Earth Pro	1122,89
25. 7. 2019.	Google Earth Pro	1113,59
2019.	DGU	1119,69
30. 3. 2020.	Google Earth Pro	1142,34
25. 8. 2020.	Google Earth Pro	1164,47
3. 9. 2021.	Google Earth Pro	1181,19
2021.	DGU	1147,95
11. 2. 2023.	Google Earth Pro	1163,61
17. 5. 2023.	Google Earth Pro	1132,22



Slika 8. *Promjene površine žala Frare od 1951. do 2023. godine*
Figure 8 *Changes in the surface area of Frara beach from 1951 to 2023*

oscilacije. Analiza satelitskih snimaka Google Earth Pro u odnosu na DGU za razdoblje od 2005. do 2023. godine potvrđuje da su promjene u površini bile manje izražene. Ukupno gledajući, promjene površine žala Frare tijekom analiziranog razdoblja bile su manje značajne u usporedbi s ostalim istraženim žalima.

RASPRAVA

Općenito gledano, analiza dugoročnih promjena morfologije žala na području Podgore jasno upućuje na značajan antropogeni utjecaj, koji se očituje urbanizacijom, razvojem turističke infrastrukture i različitim obalnim intervencijama, poput nasipavanja i izgradnje pera. Analiza arhivskih snimaka i dokumenata od 1951. do 2023. godine pokazuje početke modernizacije naselja, izgradnju hotela i apartmana (Sl. 10. b, e), širenje cestovne infrastrukture (Sl. 10. a, d) i urbanizaciju priobalnog prostora koji su utjecali i izravno i posredno na dinamiku žala.

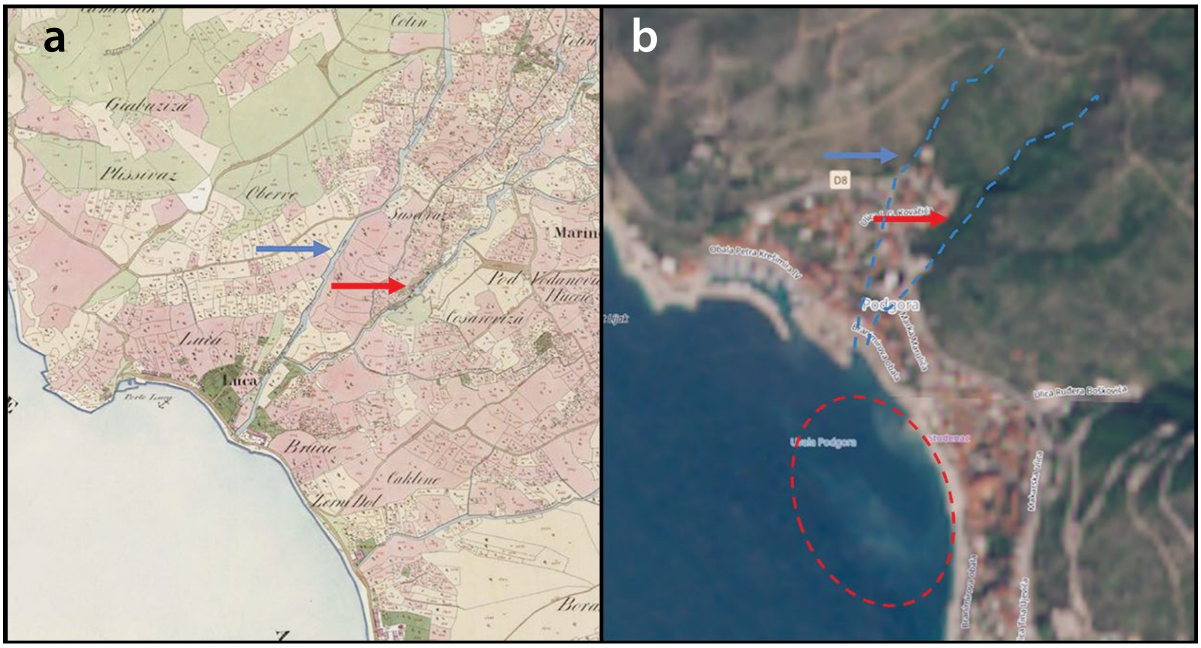
Žala kao geomorfološki sustavi pod utjecajem su marinskih procesa, ali i onih na kopnu. Tako usporedba Franciskanskog katastra s početka 19. stoljeća s aviosnimkama iz 1950-ih jasno pokazuje da su na istraživanom području vodotoci nekoć bili aktivni (vodotok ucrtan kao stalni vodotok – Torrente Suseovaz, Sl. 9.). Već na snimkama iz sredine 20. stoljeća vidljivo je da su vodotoci dijelom zatrpani ili preusmjereni zbog izgradnje prometnica i urbanizacije. Time je potpuno izmijenjeno prirodno otjecanje površinskih voda te je smanjen i prirodni donos sedimenta na žala. Danas, pod utjecajem sve češćih ekstremnih oborina (Gajić-Čapka & Cindrić, 2014), dolazi do njihove ponovne aktivacije, ali ovi procesi sad uzrokuju značajne štete na infrastrukturi i dovode do morfoloških promjena duž obale (Faivre i sur., 2011; Hooke, 2006). Posebno izražen primjer takvih procesa zabilježen je u listopadu 2024. godine, kada je zbog intenzivnih oborina od približno 140 l/m² u kratkom razdoblju došlo do naglog aktiviranja bujičnih vodotoka. Prema lokalnim medijima (Dalmacija danas, 2024), nastala je šteta od oko 6 milijuna eura, pri čemu su uništene ceste, objekti i

changes in the surface area of Frara beach during the period analysed were less significant compared to the other beaches subject of the study.

DISCUSSION

In general, the analysis of the long-term morphological changes of the beaches in Podgora area clearly shows a significant anthropogenic influence, which manifests itself in urbanisation, the development of tourist infrastructure, and various coastal interventions such as beach nourishment and the construction of groynes. The analysis of archive images and documents from 1951 to 2023 shows the beginning of settlement modernisation, the construction of hotels and apartments (Fig. 10b, e), the expansion of road infrastructure (Fig. 10a, d), and the urbanisation of the coastal area, all of which have influenced beach dynamics both directly and indirectly.

Beaches as geomorphological systems are influenced not only by marine but also by terrestrial processes. A comparison of the Franciscan cadastre from the early 19th century with aerial photographs from the 1950s, for example, clearly shows that the watercourses in the study area were once active (the watercourse is marked as a permanent stream *Torrente Suseovaz*, Fig. 9). Even the photographs from the middle of the 20th century show that some watercourses were partially filled in or diverted due to the construction of roads and urban development. That completely changed the natural flow of surface water and reduced the natural supply of sediment to the beaches. Today, these watercourses are being reactivated under the influence of increasingly frequent extreme rainfall events (Gajić-Čapka & Cindrić, 2014), but the processes are now causing significant infrastructure damage and morphological changes along the coast (Faivre et al., 2011; Hooke, 2006). A particularly notable example of such a process was recorded in October 2024, when around 140 litres/m² of intense rainfall in a short period of time triggered a sudden activation of torrential streams. According to local media (Dalmacija Danas, 2024), the damage was estimated at around 6 million euros. Roads, buildings, and infrastructure were destroyed, and large amounts of sediment were transported into the sea. Analysis of a Sentinel-2 satellite image taken on



Slika 9. *a) Isječak Franciskanskog katastra, početak 19. stoljeća s naznačenim pozicijama vodotokova b) Prikaz područja općine Podgora s ucrtanim koritima vodotokova koji su reaktivirani 8. listopada 2024. i vidljivom akumulacijom sedimenata u moru na Sentinel-2 satelitskoj snimci*
Figure 9 *a) Extract from the Franciscan cadastre, early 19th century, showing the location of water-courses; b) Map of the area of the Podgora municipality with the channels of the water-courses reactivated on 8 October, 2024 and the visible sediment accumulation in the sea on a Sentinel-2 satellite image*
Izvor / Source: *Arcanum (2025), European Space Agency (2025)*

infrastruktura, dok su velike količine sedimenta transportirane u more. Analizom Sentinel-2 satelitske snimke snimljene 8. listopada 2024. jasno je vidljiva povećana koncentracija sedimenta u moru (Sl. 9. b). Taj primjer upućuje na negativan antropogeni utjecaj, pri čemu su infrastrukturne intervencije značajno izmijenile reljef i prirodne procese, povećavajući ekstremne poplavne događaje.

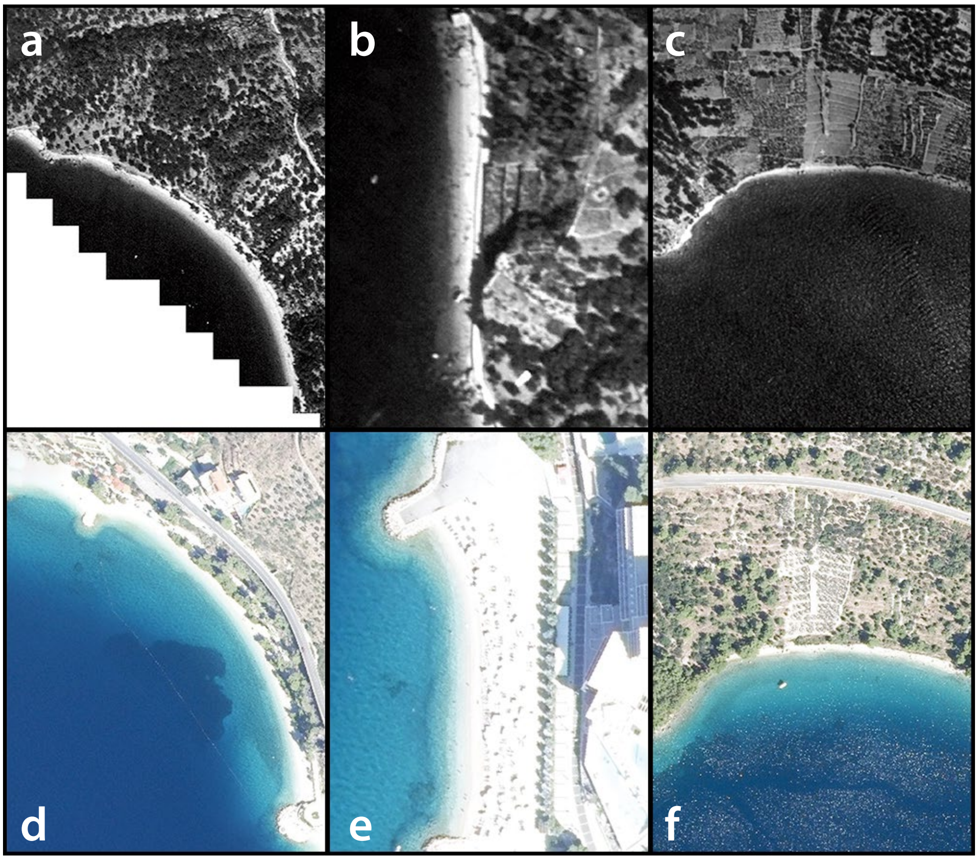
Analiza snimaka istraživanog područja omogućila je i analizu infrastrukturnih zahvata na istraživanom području. Na žalu Plišivcu dolazi do izgradnje pera uzastopno 2011., 2014. i 2018. godine, a 2011. na žalu Minervi. Uz gradnju pera na oba žala dolazi do nasipavanja koja su vidljiva u naglim promjenama površina, a koja su i zabilježena u Glasniku općine Podgore (2007; 2011; 2014; 2015; 2016; 2023) te Zapisniku o obavljenom kontrolnom inspekcijskom pregledu (2020).

Primjeri žala Plišivca i Minerve posebno ilustriraju intenzitet antropogenih utjecaja. Ti su lokaliteti doživjeli značajne promjene površine i pozicije obalne crte žala. Analiza satelitskih i aviosnimaka pokazala je da su oba žala proteklih sedam desetljeća

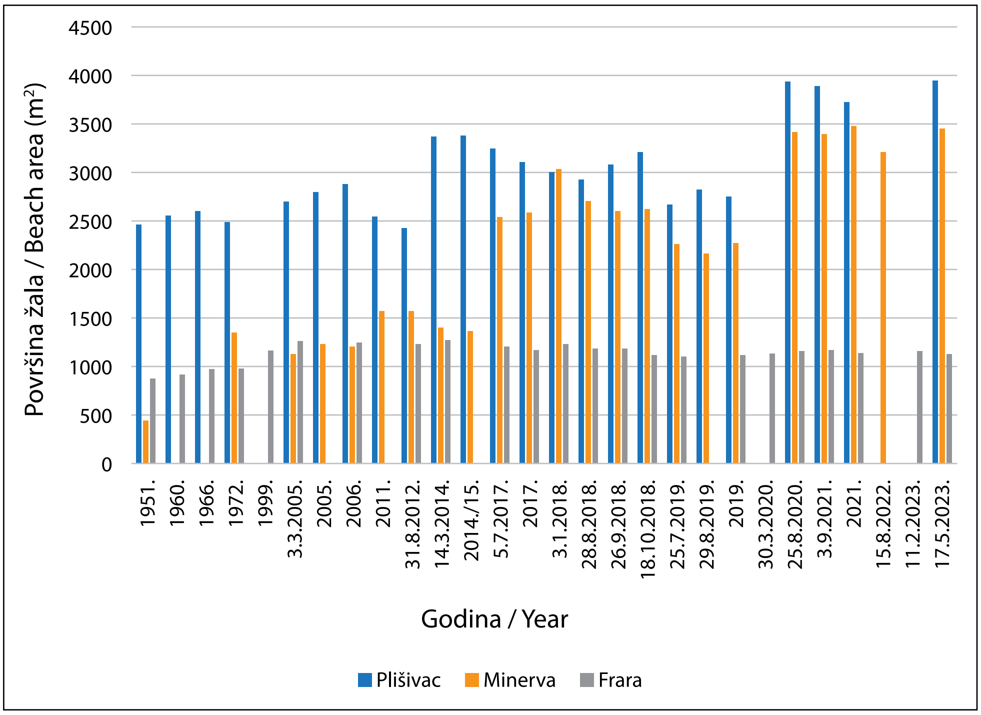
8 October, 2024 clearly shows an increased concentration of sediment in the sea (Fig. 9b). This example clearly illustrates the negative anthropogenic impacts where infrastructure interventions have significantly altered the terrain and natural processes, increasing the occurrence of extreme flood events.

The image analysis of the study area also made it possible to investigate specific infrastructural interventions. Groynes were successively built on Plišivac beach in 2011, 2014, and 2018, and on Minerva beach in 2011. In addition to groyne construction, beach nourishment was carried out on both beaches, resulting in sudden changes in surface area. These interventions are documented in the official bulletins of the Municipality of Podgora (2007, 2011, 2014, 2015, 2016, 2023) and in the Inspection Control Report (2020).

The examples of Plišivac and Minerva beaches illustrate the intensity of anthropogenic influences well. In these places, both the area and the position of the shoreline have changed considerably. Analyses of satellite and aerial images showed that both beaches have gone through different phases over the last seven decades. The earliest indirect anthropogenic changes, such as the construction of roads and



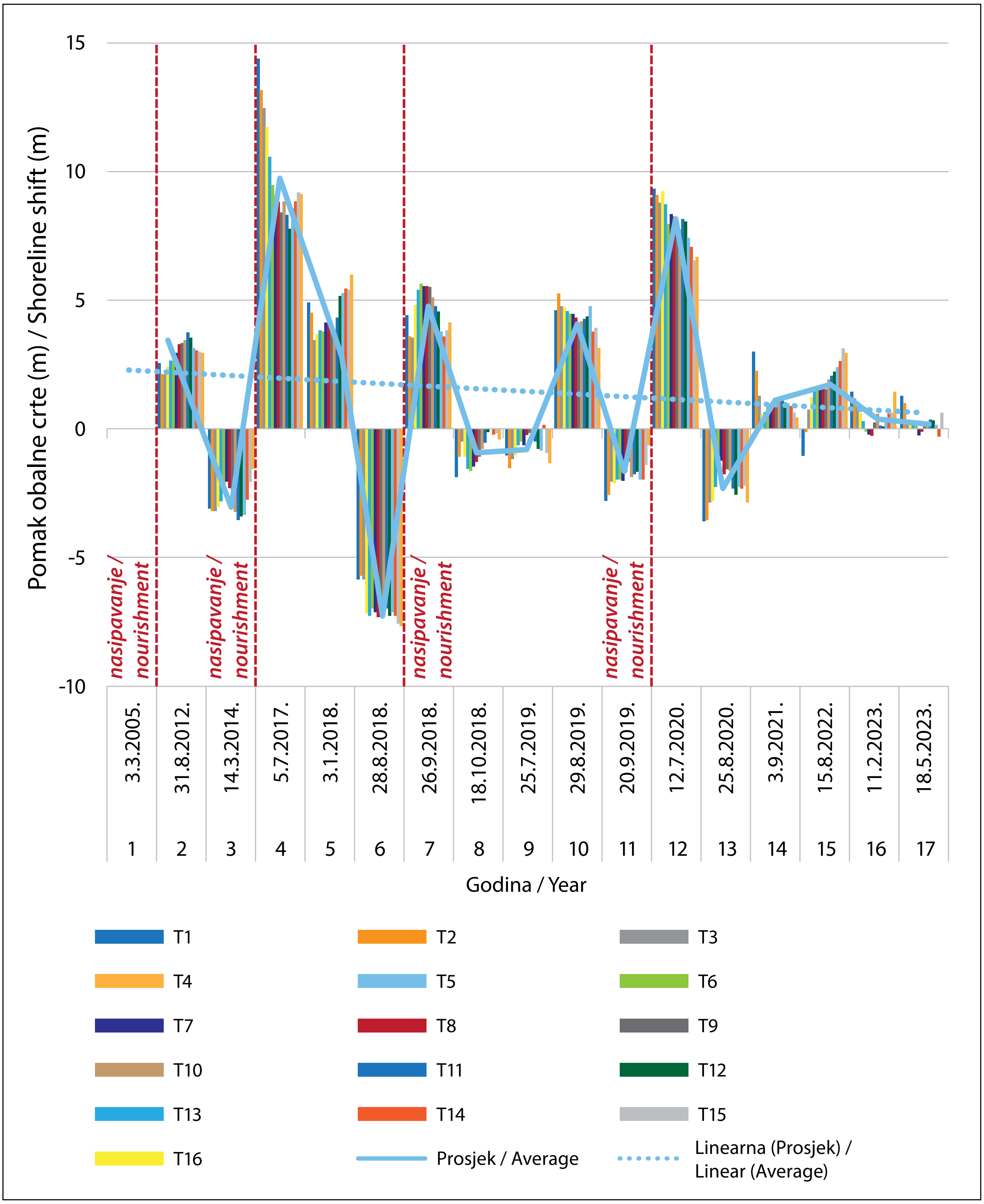
Slika 10. *Arhivske aerofotogrametrijske snimke žala iz 1951. godine: a) Plišivac, b) Minerva, c) Frara te iz 2023. godine: d) Plišivac, e) Minerva, f) Frara*
Figure 10 *Archival aerial photographs of beaches from 1951: (a) Plišivac, (b) Minerva, (c) Frara; and from 2023: (d) Plišivac, (e) Minerva, (f) Frara*
Izvor / Source: *Državna geodetska uprava (2025) / State Geodetic Administration (2025)*



Slika 11. *Izmjerene površine žala Plišivca, Minerve i Frare (snimke žala nisu dostupne za sva žala u svim godinama)*
Figure 11 *Measured surfaces of the beaches of Plišivac, Minerva, and Frara (images are not available for all beaches and all years)*

prolazila različite faze. Prve neizravne antropogene promjene poput gradnje cesta i kuća imale su manji utjecaj na obalu crtu, a najveće promjene javljaju se dohranjivanjem žala i infrastrukturnim zahvatima na žalima. Od 1951. do 2023. godine površina žala Plišivca povećala se za 1487 m², a žala Minerve za 3013 m². Međutim, zabilježene su potom i značaj-

houses, had relatively minor impact on the shoreline, while the largest changes were caused by beach nourishment and infrastructure interventions. Between 1951 and 2023, the area of Plišivac beach increased by 1,487 m², and that of Minerva beach by 3,013 m². However, significant erosion phases were also recorded, indicating an overall high level of morpho-



Slika 12. *Promjene pozicije obalne crte žala Minerve od 2005. do 2023. godine (T1–T15 definirani transekti duž kojih su provedena mjerenja, Sl. 7.)*
Figure 12 *Changes in the shoreline position of Minerva beach from 2005 to 2023 (T1–T15 are defined transects along which measurements were taken, see Fig. 7)*

ne erozijske faze koje upućuju na ukupnu značajnu morfodinamku navedenih žala (Sl. 11.).

Posebno su izražene promjene na žalu Minervi, na kojem su antropogeni utjecaji prisutni od sredine 20. stoljeća. Prve snimke iz 1951. godine pokazuju da tada nije bilo građevina uz žalo, ali je kopnenu granicu činila ograda, što sugerira tada postojeću ljudsku intervenciju. Značajnije promjene započinju 1972. godine izgradnjom hotela Minerve, što je dovelo do nasipavanja dodatnih 900 m² i izgradnje betonskih struktura što se izravno reflektira u prvoj fazi povećanja površine (Sl. 6.). Daljnji infrastrukturni zahvati, uključujući šetnicu i hotelski kompleks, nastavili su oblikovati ovaj prostor do 2005. godine. Ključne promjene započele su 2011. godine izgradnjom sjevernog pera, što je dodatno povećalo površinu žala za 350 m², dok su južne betonske pregrade zamijenjene manjim perom. Te intervencije značajno su utjecale na dinamiku sedimenta i obalnu crtu (Sl. 12.). Nakon 2011. godine započinje trend erozije, pri čemu se površina žala postupno smanjivala, a obalna crta pomicala prema kopnu, što je dovelo do potrebe za sanacijom 2017. godine (Glasnik – službeno glasilo Općine Podgora, 2016). Tada je proveden značajan zahvat na žalu, koji je obuhvaćao nasipavanje 156 m obalne crte i proširenje žala za 1218 m², uz stabilizaciju materijala s pomoću pera na sjevernoj i južnoj strani (Informacija o procjeni utjecaja na okoliš, 2015). To nasipavanje jasno je vidljivo u naglom povećanju površine žala (faza 2, Sl. 6.). Nakon zahvata pojačava se erozija što potvrđuje i grafički prikaz (sl. 10. i 11.). Nakon 2017. evidentirano je novo nasipavanje u najmanje dvije faze i dodatno povećanje površine za 500 m² (Tab. 3.).

Posebno izražen bio je utjecaj juga u prosincu 2019. godine, kada je izgubljeno 870 m² površine, što je dovelo do hitnih sanacija i ponovnog nasipavanja (Zapisnik o obavljenom kontrolnom inspekcijskom pregledu, 2020). Do kolovoza 2020. godine provedena je još jedna intervencija, povećavši površinu žala za 1251 m² (faza 3, Sl. 6.). Potom analize ponovno pokazuju postupan gubitak sedimenta. Do 2023. godine smanjeni su opsezi nasipavanja. Iako je u razdoblju od 72 godine površina žala Minerve povećana za 3013 m², analiza pokazuje da je to rezultat međudjelovanja nepre-

dynamic activity on these beaches (Fig. 11).

Significant changes are particularly evident at Minerva beach, where anthropogenic influences have been present since the mid-20th century. The earliest images from 1951 show that there were no buildings near the beach at that time, but there is a fence marking the landward boundary which indicates that human intervention had already occurred. More significant changes began in 1972 with the construction of the Minerva Hotel, which led to the filling in of a further 900 m² and the building of concrete structures, which is directly reflected in the first phase of area increase (Fig. 6). Further infrastructural interventions, including a promenade and a hotel complex, characterised the area until 2005. The most significant changes began in 2011 with the construction of the northern groyne, which increased the beach area by a further 350 m², while the southern concrete barriers were replaced by a smaller groyne. These interventions significantly influenced the sediment dynamics and the position of the shoreline (Fig. 12). After 2011, an erosion trend began in which the beach area gradually decreased and the shoreline retreated landwards, necessitating remediation in 2017 (Official Gazette of the Municipality of Podgora, 2016). At that time, a major intervention was carried out on the beach, which included the nourishment of 156 metres of shoreline and an extension of 1,218 m², with the material stabilised by groynes at the northern and southern ends (Environmental Impact Assessment Report, 2015). This nourishment is clearly recognised by the sudden increase in the beach area (Phase 2, Fig. 6). After the intervention, the erosion intensified, as confirmed by the graphical representations (Fig. 10 and 11). After 2017, further nourishment was documented in at least two further phases, which led to an additional 500 m² increase in area (Tab. 3).

The impact of the scirocco (south-eastern wind) was particularly pronounced in December 2019, when 870 m² of beach area was lost, resulting in an emergency restoration and renewed nourishment (Inspection Control Report, 2020). In August 2020, a further intervention was carried out, which increased the beach area by 1,251 m² (Phase 3, Fig. 6). Subsequently, analyses again showed a gradual loss of sediment. By 2023, the extent of nourishment efforts decreased. Although the area of Minerva beach increased by 3,013 m² over the 72 years, the analysis kidnih antropogenih intervencija (nasipavanja) i potom faza erozije.

Očito je da su sanacijski zahvati postali redovita potreba, osobito nakon jakih nevremena. Tako je, primjerice, nakon elementarne nepogode u prosincu 2019. godine provedena hitna nadohrana materijala i stabilizacija pera, što je jasno vidljivo iz prikupljenih podataka i na žalu Plišivcu i na žalu Minervi. Budući da je prirodni (lokalni) sediment u ovom području ograničen zbog pro-

shows that this was the result of continuous anthropogenic interventions (nourishment), followed by phases of erosion.

It is obvious that restoration measures have become a regular necessity, especially after severe storms. For example, after a natural disaster in December 2019, emergency measures were carried out to replenish sediments and stabilise groynes, as clearly demonstrated by the data collected for Plišivac and Minerva beaches. As the availability of natural (local) sediment in this

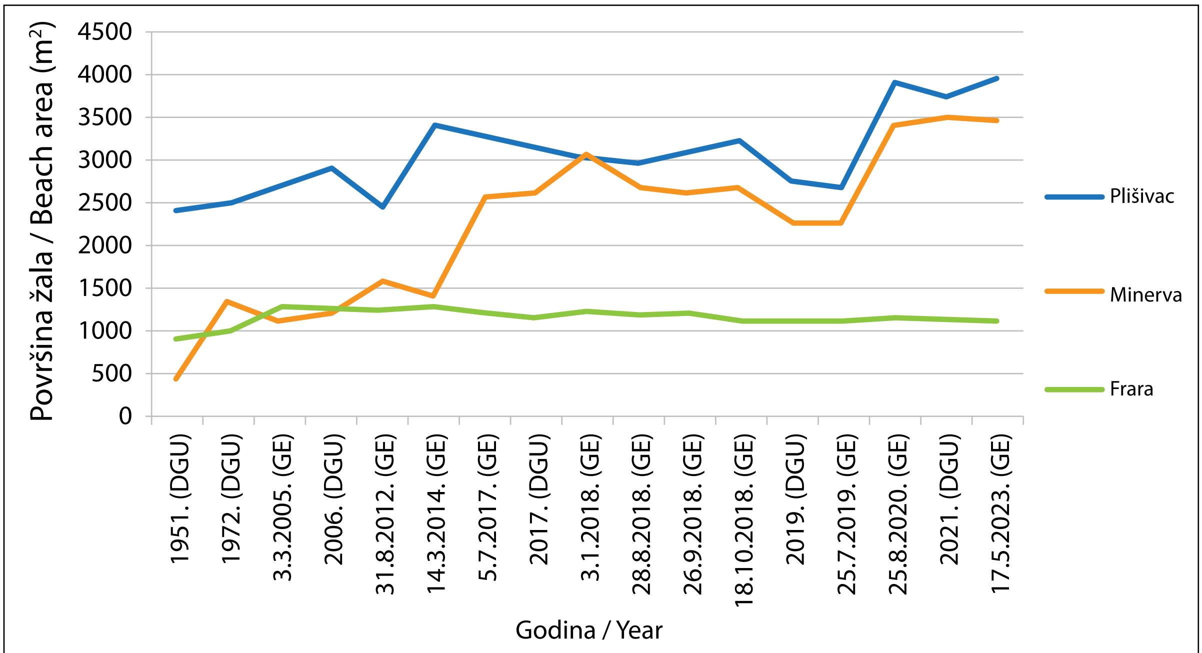
Slika 13. *Veličina i oblik dohranjenog sedimenta na žalu Minervi*
Figure 13 *Size and shape of the nourished sediment at Minerva beach*
Izvor / Source: *Snimio autor / Recorded by the author*

mjena zemljišnog pokrova u drenažnim bazenima te pojačanog antropogenog utjecaja na kopnenom dijelu kao kod npr. Pranzini (2013) i Mićunović i Faivre (2024a), dohrana se uglavnom oslanja na dohranjivanje alohtonog materijala (npr. Glasnik – službeno glasilo Općine Podgora, 2014; 2015). Terensko kartiranje pokazalo je da se nasuti sediment bitno razlikuje od prirodnog, varirajući u veličini i obliku (uglavnom ima oštriji, šiljast oblik), što može uzrokovati brži gubitak materijala (Sl. 13.). Sitniji sediment lako odnose valovi i morske struje, premještajući ga u dublje dijelove, čime se smanjuje učinkovitost nadohrane i ubrzava potreba za novim zahvatima (Blott & Pye, 2004; Tortora, 2020).

Izgradnja pera kao mjera zaštite sedimenta žala na nekim se lokacijama pokazala učinkovitom strategijom. S jedne strane može smanjiti gubitak sedimenta i stabilizirati žala (Geßner i sur., 2024), no s druge strane može poremetiti prirodni transport sedimenta, što dugoročno može negativno utjecati na morfologiju obale (Geßner i sur., 2024). Primjer žala Plišivca pokazuje da je nakon izgradnje pera 2011. godine došlo do smanjenja površine za 335 m², a do ponovnog povećanja površine došlo je kasnije nasipavanjem. Na žalu Minervi, iako su pera izgrađena kako bi se stabilizirao nasuti materijal, oscilacije u površini upućuju na stalnu potrebu za održavanjem i prilagođavanjem obalnih inter-

area is limited due to land cover changes within the drainage basins and increasing anthropogenic impacts on the terrestrial part of the system, as discussed in Pranzini (2013) and Mićunović and Faivre (2024a), nourishment generally relies on the use of allochthonous material (e.g., Official Gazette of the Municipality of Podgora, 2014; 2015). Field mapping has shown that the deposited sediment differs significantly from natural sediment and varies in size and shape (typically sharper and more angular), which can lead to more rapid loss of material (Fig. 13). Finer sediment is easily transported to deeper waters by waves and currents, reducing the effectiveness of nourishment and accelerating the need for new interventions (Blott & Pye, 2004; Tortora, 2020).

The construction of groynes as a sediment protection measure has proven to be an effective strategy at some sites. On the one hand, it can reduce sediment loss and stabilise beaches (Geßner et al., 2024), but on the other hand, it can disrupt natural sediment transport, which can have a negative impact on coastal morphology in the long term (Geßner et al., 2024). The example of Plišivac beach shows that the beach area was reduced by 335 m² after the construction of a groyne in 2011, with the surface area only increasing later as a result of the re-nourishment. Although groynes were built on Minerva beach to stabilise the deposited material, the fluctuations in the surface area indicate a constant need for maintenance



Slika 14. *Usporedba površina žala Plišivca, Minerve i Frare od 1951. do 2023. godine*
Figure 14 *Comparison of the surface areas of Plišivac, Minerva, and Frara beaches from 1951 to 2023*

vencija.

Usporedba s prirodno očuvanim žalom na istraživanom području, poput žala Frare, pokazuje da prirodni procesi omogućuju dugoročnu stabilnost sedimenta bez potrebe za antropogenim intervencijama. Promjene površine žala Plišivca i Minerve pokazuju korelaciju (r^2 = 0,7) tijekom cijelog promatranog razdoblja (72 godine), dok sva tri žala pokazuju slične trendove promjena površine prije 2015., dakle prije direktnih nasipavanja površina (Plišivac i Frara r^2 = 0,6 i Minerva i Frara r^2 = 0,7). Posredni utjecaji očito ne izazivaju toliku morfološku neravnotežu, dok izravni utjecaji izazivaju jake erozivne faze i destabilizaciju obalnih reljefnih oblika. To sugerira da ljudske aktivnosti, iako su načelno usmjerene na očuvanje i proširenje žala, često mogu imati suprotan učinak, dovodeći do povećane erozije i nestabilnosti nasutog materijala (Sl. 14.). Stoga se postavlja pitanje dugoročne održivosti takvih strategija upravljanja obalom i potrebe za preciznijim planiranjem kako bi se minimizirali negativni učinci na obale.

Na području istočne obale Jadrana dohranjivanje žala sve je učestalija praksa, ponajprije kao odgovor na prirodne erozijske procese i ljudske intervencije. Taj trend vidljiv je i u drugim dijelovima srednje Dalmacije, u kojima su istraživanja pokazala slične trendove. Pikelj i sur. (2015) analizirali su prirodno žalo Glavica i antropogeno žalo Dugi Rat nakon djelovanja bure i juga. Rezultati su pokazali da bura nema značajan utjecaj na morfologiju žala, što je u skladu s istraživanjem u Podgori. Međutim, jugo je uzrokovalo izražene promjene, pri čemu su na prirodnom žalu bile intenzivnije nego na antropogenom zbog izmijenjenog dužobalnog i poprečnog transporta sedimenta (Pikelj i sur., 2015). Ta razlika može se objasniti orijentacijom žala prema dominantnim vjetrovima – dok je Glavica izravno izložena jugu, Dugi Rat je djelomično zaštićen. Iako antropogene intervencije poput nasipavanja i izgradnje pera mogu privremeno stabilizirati sediment, dugoročno ne sprječavaju njegovu redistribuciju pod utjecajem valova. To potvrđuje i analiza žala Dugog Rata, gdje su između 2014. i 2019. godine provedena fotogrametrijska istraživanja (Šeparović Markota, 2019; Tominić, 2017). Učestale dohrane dovele su do vidljivih promjena površine,

and adjustment of coastal interventions.

A comparison with the naturally preserved beaches in the study area, such as Frara beach, shows that natural processes enable long-term sediment stability without the need for anthropogenic interventions. The surface changes at Plišivac and Minerva beaches show a correlation (r^2 = 0.7) over the entire observation period (72 years), while all three beaches before 2015, i.e., before the start of direct nourishment, showed similar trends, with correlations of r^2 = 0.6 be- tween Plišivac and Frara and r^2 = 0.7 between Minerva and Frara. Indirect impacts do not appear to cause significant morphological imbalance, while direct impacts lead to intense erosion phases and destabilisation of coastal landforms.

This suggests that while human activities generally aim to maintain and extend beaches, they often have the opposite effect, contributing to increased erosion and instability of the nourished material (Fig. 14). This raises concerns about the long-term sustainability of such coastal management strategies and highlights the need for more precise planning to minimise the negative impacts on the coasts. Along the eastern Adriatic coast, beach nourishment is becoming increasingly common, mainly in response to natural erosion processes and human intervention. This trend can also be observed in other parts of central Dalmatia, where studies have revealed similar patterns. Pikelj et al. (2015) analysed the natural beach Glavica and the anthropogenic beach Dugi Rat after exposure to the winds bora and sirocco. The results showed that bora had no significant impact on the beach morphology, which is consistent with the results from Podgora. However, the scirocco caused notable changes, with the impact on the natural beach being stronger than on the anthropogenic beach, which can be attributed to the altered longshore and cross-shore sediment transport (Pikelj et al., 2015). This difference can be explained by the orientation of the beaches in relation to the prevailing winds; Glavica is directly exposed to the sirocco, while Dugi Rat is partially sheltered.

Although anthropogenic interventions such as nourishment and the construction of groynes can temporarily stabilise the sediment, they do not prevent its long-term redistribution by wave action. This is confirmed by the analysis of Dugi Rat, where photogrammetric studies conducted between 2014 and 2019 (Šeparović Markota, 2019; Tominić, 2017) ali je nasuti materijal ubrzano redistribuiran. S obzirom na to da granulometrijska svojstva nasutog materijala utječu na njegovu otpornost na eroziju, može se pretpostaviti da su isti procesi prisutni i u Podgori, gdje se kontinuirano bilježe gubici sedimenta unatoč učestalim sanacijama.

Usporedba s drugim prirodnim i antropogenim žalima pokazuje slične obrasce. Pikelj i sur. (2017) analizirali su žalo Brseč, koje se razvija tijekom sezonskih promjena, ali dugoročno zadržava stabilnost zbog prirodnog transporta sedimenta. S druge strane, antropogeno modificirana žala, poput Dugog Rata, zahtijevaju stalne intervencije jer se sediment kontinuirano gubi.

Ti rezultati odražavaju i stanje u Podgori – dok su Plišivac i Minerva podložni kontinuiranim antropogenim intervencijama, žalo Frara, koje nije pod izravnim ljudskim utjecajem, pokazuje dugoročnu stabilnost. Jedan od ključnih čimbenika u redistribuciji sedimenta je dužobalni transport. Rajčić i sur. (2010) analizirali su njegov utjecaj na širem području Omiša, gdje su obalne konstrukcije značajno izmijenile prirodni režim sedimenta, naročito poslije juga. Slično tome, u Podgori je nakon juga 2019. godine na žalima Minervi i Plišivcu zabilježen znatan gubitak sedimenta, što je zahtijevalo dohranu. Međutim, iako se geomorfološka obilježja obale mogu razlikovati, trendovi redistribucije sedimenta nakon olujnih događaja pokazuju sličnosti između tih lokaliteta.

Slični trendovi zabilježeni su i na otoku Hvaru. Analiza promjena na žalima Mini i Zogonu na otoku Hvaru pokazuje da nadohrane često nemaju dugoročan učinak i zahtijevaju stalne intervencije kako bi se očuvala stabilnost dohranjenog materijala. Na žalu Mina, nakon nadohrane sedimenta 2021. godine i izgradnje pera, površina se inicijalno povećala za gotovo 300 %, no već u dvije godine smanjila se za 25 %, ukazujući na trend erozije (Mićunović, 2024). Na žalu Zogon, gdje je provedena nadohrana od 300 m³ sedimenta te izgradnja potpornog zida i terase na žalu također je primijećen naknadni trend erozije, a izgrađena infrastruktura nije izdržala pod utjecajem juga (Mićunović, 2024).

Slični trendovi uočeni su i u širem mediteranskom području. Primjerice, istraživanja južne

revealed frequent nourishment activities that led to visible changes in the surface, but added material was quickly redistributed. Since the granulometric properties of nourished material influence its resistance to erosion, it can be assumed that similar processes are taking place in Podgora, where continuous sediment loss has been recorded despite repeated maintenance measures.

A comparison with other natural and anthropogenic beaches shows similar patterns. Pikelj et al. (2017) analysed Brseč beach, which develops through seasonal changes but remains stable in the long term due to natural sediment transport. On the other hand, anthropogenically modified beaches, such as Dugi Rat, require constant intervention due to continuous sediment loss. These results also reflect the situation in Podgora: while Plišivac and Minerva are subject to constant anthropogenic intervention, Frara beach, which remains free of direct human influence, shows long-term stability. One of the key factors for the redistribution of sediments is longshore transport. Rajčić et al. (2010) analysed its effects in the wider Omiš area, where coastal structures significantly altered the natural sediment regime, especially after scirocco events. In Podgora, too, significant sediment loss occurred on the beaches of Minerva and Plišivac after the sirocco storm in 2019, which required nourishment. However, despite the differences in the geomorphological characteristics of the coast, the trends in sediment redistribution after storm events show similarities between these locations.

Similar trends were also observed on the island of Hvar. An analysis of the changes at Mina and Zogon beaches on Hvar shows that nourishments are often not effective in the long term and require constant intervention to maintain the stability of the deposited material. At Mina beach, the surface initially increased by almost 300 % after the placement of sediments and the construction of a groyne in 2021, but decreased by 25 % within just two years, indicating an erosion trend (Mićunović, 2024). At Zogon beach, where 300 m³ of sediment was added and a retaining wall and terrace were built, a similar erosion trend was observed after the intervention, and the built infrastructure did not withstand the impact of the scirocco (Mićunović, 2024).

Similar trends were also observed throughout the Mediterranean region. Studies in southern Spain, for

Španjolske pokazala su da su nakon olujnih događaja zabilježene promjene površine žala od ±20 % (Anfuso i sur., 2001). Usporedno, žalo Minerva izgubilo je do 30 % nasutog materijala, dok je na žalu Plišivcu zabilježen nešto manji gubitak od ±15 %. Učestalost i intenzitet promjena potvrđuju da su nasipi u urbaniziranim područjima skloniji eroziji, dok izoliranija žala, poput Frare, pokazuju veću dugoročnu stabilnost. Ti rezultati poklapaju se i s talijanskim primjerom – na žalu Ladispoli, gdje su nasipane velike količine sedimenta kako bi se proširilo žalo za 40 metara, obalna crta vratila se na početnu poziciju u samo nekoliko godina (Tortora, 2020). Taj primjer dodatno ističe ograničenja zaštitnih struktura poput pera, koje nisu spriječile redistribuciju sedimenta. Slični problemi uočeni su i na žalu u Nici na Azurnoj obali, gdje se od 1976. do 2014. godine nasulo oko 600 000 m³ sedimenta, no unatoč značajnim ulaganjima, erozija je i dalje kontinuirani problem (Cohen, 2014). Iako su na tom području izgrađena pera, pokazalo se da ona samo privremeno stabiliziraju sediment, dok se dugoročno sediment i dalje gubi u dublje dijelove mora zbog strmog nagiba dna i ograničenih prirodnih izvora sedimenta. Održavanje žala zahtijeva stalna i skupa nasipavanja, čime se postavlja pitanje dugoročne održivosti ovakvih zahvata. Usporedba tih primjera jasno pokazuje da nasipavanja i obalne konstrukcije mogu imati kratkoročnu stabilizacijsku funkciju, no u većini slučajeva ne predstavljaju trajno rješenje.

S obzirom na te trendove, jasno je da dohrana žala u Hrvatskoj, iako uobičajena praksa, često nije sustavno planirana i dugoročno učinkovita. Procjenjuje se da je u Hrvatskoj posljednjih pet godina na te mjere utrošeno približno 6,1 milijun eura (Bogovac i sur., 2021), no rezultati pokazuju da su dugoročne koristi ograničene. Od 2010. do 2020. godine Općina Podgora je, prema službenom glasniku i proračunskim izvještajima, uložila oko 700 000 € u održavanje žala u naselju, što iznosi prosječno 70 000 € godišnje. Takva značajna financijska izdvajanja upućuju na kontinuiranu potrebu za sanacijama i nasipavanjem, što potvrđuje da su antropogeni zahvati dugoročno neodrživi bez stalnih intervencija. Međutim, u razdoblju od 2021. do 2025. godine ta su ula-

example, have shown that storm events led to changes in the beach surface of up to ±20 % (Anfuso et al., 2001). In comparison, Minerva beach lost up to 30 % of the nourished material, while Plišivac beach suffered a slightly smaller loss of about ±15 %. The frequency and intensity of these changes confirms that nourished beaches in urban areas are more susceptible to erosion, while more isolated beaches such as Frara show greater long-term stability. These results are consistent with the example from Italy, at Ladispoli beach, where large amounts of sediment were added to lengthen the beach by 40 metres, the shoreline returned to its original position within a few years (Tortora, 2020). This case illustrates the limits of protective structures such as groynes, which could not prevent the redistribution of sediment.

Similar problems were observed on the beach of Nice on the Côte d'Azur, where around 600,000 m³ of sediment was deposited between 1976 and 2014. Despite significant investment, erosion remains a persistent problem (Cohen, 2014). Although groynes were constructed in this area, they only temporarily stabilised the sediment, while in the long-term sediment continued to be lost to deeper waters due to the steep underwater slope and limited natural sediment sources. The maintenance of beaches in such an environment requires continuous and costly renourishment measures, which raises concerns about the long-term sustainability of these measures. A comparison of these examples clearly shows that nourishment and coastal structures have a short-term stabilising function, in most cases they are not a permanent solution.

In view of these trends, it is clear that beach nourishment in Croatia, although a common practise, is often neither systematically planned nor effective in the long term. It is estimated that approximately € 6.1 million have been spent on such measures in Croatia in the last five years (Bogovac et al., 2021), but the results show that the long-term benefits are limited. From 2010 to 2020, the municipality of Podgora invested around €700,000 in beach maintenance within the settlement, an average of €70,000 annually, according to the Official Gazette and budget reports. These significant financial allocations indicate a continuous need for remediation and nourishment, confirming that the anthropogenic interventions are not sustainable in the long term without continuous efforts.

In the period 2021–2025, however, these investganja značajno smanjena na ukupno 88 000 €, odnosno prosječno 17 000 € godišnje, što može upućivati na smanjenje dostupnih sredstava ili prepoznavanje ograničene učinkovitosti dosadašnjih mjera. Takav trend dodatno naglašava potrebu za dugoročnijim i održivijim strategijama upravljanja žalima. Uz povećanu učestalost ekstremnih vremenskih uvjeta i relativnog porasta morske razine (Faivre i sur., 2023; 2024), potreba za dohranjivanjem će se povećavati, što upućuje na nužnost preciznijeg planiranja upravljanja obalnim područjima.

ZAKLJUČAK

U ovom radu analizirane su dugoročne morfološke promjene triju žala u Podgori – Minerve, Plišivca i Frare – radi kvantificiranja utjecaja antropogenih intervencija na dinamiku obalne crte i stabilnost sedimenta. Istraživanje je provedeno primjenom metoda daljinskih istraživanja, GIS analize i terenskih mjerenja, koristeći arhivske aerofotogrametrijske snimke, satelitske snimke i UAV podatke prikupljene od 1951. do 2023. godine, čime je omogućena detaljna usporedba promjena u prostornoj i vremenskoj dimenziji. Primijenjena metodologija pokazala se učinkovitom u detekciji promjena površine i pozicija obalne crte posljednjih 70-ak godina, ali i u praćenju značajnijih antropogenih intervencija na žalima. Također, omogućila je kvantifikaciju tih promjena i preciznu rekonstrukciju dinamike geomorfoloških procesa na žalima.

Usporedba dinamike promjena između antropogeno preoblikovanih žala (Plišivac i Minerva) i prirodnog žala (Frara) jasno pokazuje da antropogene intervencije do 2015. godine nisu imale znatno veći utjecaj na površine žala, dok su zahvati nakon 2015. bitno utjecali na obalnu morfologiju i nestabilnost sedimenta. Prirodni procesi na žalu Frari omogućuju relativnu stabilnost žala cijelo razdoblje, dok su dohranjivanja i zahvati na ostalim žalima doveli do periodičnih oscilacija površine, što je zahtijevalo kontinuirane mjere održavanja. Detaljna analiza prirodnih i antropogenih procesa dodatno potvrđuje da povećanje površine žala Medore i Plišivca te izgradnja pera

ments were significantly reduced to a total of €88,000 or an average of €17,000 per year. This could indicate a reduction in available funds or an increasing realisation of the limited effectiveness of previous measures. This trend emphasises the need for long-term and sustainable beach management strategies. With the increasing frequency of extreme weather events and relative sea level rise (Faivre et al., 2023; 2024), the need for re-nourishment will continue to increase, emphasising the urgency of more accu- rate coastal management planning.

CONCLUSIONS

In this study, the long-term morphological changes of three beaches in Podgora: Minerva, Plišivac, and Frara, were analysed in order to quantify the impact of anthropogenic interventions on shoreline dynamics and sediment stability. The research was conducted using remote sensing methods, GIS analyses, and field measurements, incorporating archival aerial images, satellite imagery, and UAV data from 1951 to 2023. This approach enabled a detailed compar- ison of spatial and temporal changes. The methodology used proved effective in detecting changes in beach surface and shoreline position over the last 70 years, as well as tracking major anthropogenic impacts on beaches. Furthermore, it enabled the quantification of these changes and the accurate reconstruction of the dynamics of geomorphological processes affecting the beaches.

The comparison of the dynamics of change between the anthropogenically modified beaches (Plišivac and Minerva) and the natural beach (Frara) clearly shows that the anthropogenic interventions before 2015 did not have a significantly greater impact on the beach area. However, the interventions after 2015 had a significant impact on the coastal morphology and the instability of the sediments. Natural processes enabled relative stability at Frara beach throughout the observation period, while nourishment and coastal works at the other two sites led to periodic surface fluctuations, that required continuous maintenance measures. A detailed analysis of natural and anthropogenic processes also confirms that increasing the surface area at Minerva and Plišivac beaches, and the construction of groynes for this purpose, are not u tu svrhu nisu dugoročno održive mjere. Stalni erozijski procesi na tim antropogeno preoblikovanim žalima upućuju na težnju geomorfoloških oblika da se prilagode prirodnim uvjetima i uspostave stabilnu ravnotežu. Stoga obalni sustav na ovom području prirodno pogoduje morfologiji duljih, ali užih žala, umjesto širokih i umjetno proširenih oblika koji su nestabilni i zahtijevaju konstantne intervencije.

Analiza dugoročnih promjena žala na području Podgore pokazuje da su antropogene intervencije, iako provedene radi stabilizacije i očuvanja turističkih kapaciteta, često imale neželjene posljedice u vidu povećane erozije i potrebe za čestim sanacijama. S druge strane, prirodna žala poput Frare pokazuju znatno stabilnija morfološka obilježja, što potvrđuje važnost očuvanja prirodnih obalnih procesa kao ključnog elementa održivog upravljanja obalom. Stoga bi buduće strategije upravljanja priobaljem trebale težiti ravnoteži između potreba turizma i očuvanja prirodnih resursa, pri čemu je nužno oslanjanje na geomorfološke analize kako bi se smanjila potreba za učestalim intervencijama i konstantno financijsko opterećenje povezano s održavanjem žala.

Doprinosi autora: M.M.: konceptualizacija, istraživanje, metodologija, softver, pisanje – priprema originalnog nacrta, pisanje – pregled i uređivanje.

L.V.: metodologija, pisanje – priprema originalnog nacrta, softver, vizualizacija, validacija. S.F.: konceptualizacija, metodologija, resursi, pisanje – pregled i uređivanje, prikupljanje sredstava.

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sustainable long-term solutions. The ongoing erosion processes observed on these anthropogenically modified beaches show the tendency of geomorphological forms to adapt to natural conditions and establish a stable equilibrium. This suggests that the coastal system in this area naturally favours the morphology of longer but narrower beaches, as opposed to wide, artificially expanded forms that are inherently unstable and require constant intervention.

The analysis of long-term changes to beaches in the Podgora region shows that anthropogenic interventions, although carried out with the intention of stabilising and maintaining tourist infrastructure, often led to unintended consequences, such as increased erosion and the frequent need for remediation measures. In contrast, natural beaches such as Frara have much more stable morphological characteristics, confirming the importance of preserving natural coastal processes as a key component of sustainable coastal management. Future coastal management strategies should therefore aim to strike a balance between the needs of tourism and the conservation of natural resources. They should be based on detailed geomorphological analyses in order to reduce the need for frequent interventions and the ongoing financial burden associated with beach maintenance.

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