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COASTAL EROSION: THE FUTURE OF SANDY BEACHES

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ABSTRACT

The coastal zone is a constantly changing area and is one of the most vulnerable one because of climate crisis. In addition to the high concentration of population in coastal areas, there is also high activity in sectors such as tourism, trade and work. Increasing storms and Sea Level Rise (SLR) are likely to cause future flooding in coastal areas, bringing about significant changes in these ecosystems. The threats posed by coastal erosion are very significant, as more than 100 million people live within one meter of mean sea level, meaning that in the coming decades they will have to deal with issues of immigration, finance, social and environmental issues. This paper is an attempt to highlight the magnitude of the problem of coastal erosion, while at the same time a typical case of a coastal zone in the center of the Aegean (Greece) is examined through interpretation of collected data, mapping of the area and geospatial analysis. The results present both its future development based on different climate change scenarios, and based on different scenarios of anthropogenic activities and interventions. At the same time, methods of natural self-protection of the coastal zone against coastal erosion and sea level rise are discussed.

KEYWORDS: Coastal erosion; Sea level rise; Climate risk; Coastal Vulnerability; Coastal protection

1. INTRODUCTION

Coastal erosion takes place when beach sediments are decreasing, following the retreat of the coast and the reduction of the total coastal zone (N Evelpidou, 2020; UNISDR, 2017). Based on the sediment budget theory, coastal erosion can occur when the quantity of incoming sediment is less than the quantity of sediment lost in a certain coastal cell (Kamphuis, 2010). The most important reason why this phenomenon is accelerating is because of the global warming, which increases the global (eustatic) sea level, causing rising

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seas and wave action, tides and currents to interfere with the coastal environment (Ariffin et al., 2019; Fan et al., 2019; Hinkel & Nicholls, 2010; King, Conley, Masselink, Leonardi, & Mccarroll, 2019; Saengsupavanich, 2020; SELAMAT, 2019; Zhang, Douglas, & Leatherman, 2004). Storm and tide surges, wave setup and Sea Level Rise (SLR) are assessed to be responsible for future flooding in coastal areas by 2100, with percentages of 63%, 5% and 32% respectively (Louisor et al., 2022). Extreme sea level (ESL) events associated with disastrous flooding will become common by 2100 under all emission scenarios (Oppenheimer & Glavovic, 2019), while Mean Sea Level (MSL) rise will be the primary driver of upcoming extreme changes in sea levels and coastal flood risk (Cannaby et al., 2016; Howard, Palmer, & Bricheno, 2019; Vousdoukas et al., 2018).

Increasing storms and SLR tend to cause in the future chronic flooding in inland areas, bringing major changes to these ecosystems (Luisa Martínez, Mendoza-González, Silva-Casarín, & Mendoza-Baldwin, 2014; Mo, Kearney, & Turner, 2020; Timmerman, Haasnoot, Middelkoop, Bouma, & McEvoy, 2021). The threats created by coastal erosion are of high relevance, as more than 100 million people live within one meter of the mean sea level, meaning that in the coming decades they will have to face real estate, migration, economic, social and environmental issues (Zhang et al., 2004). Coastal nations and low-lying coasts are the most vulnerable recipients to coastal erosion risk, while in general social-ecological systems and associated communities, low-lying coastal cities, islands, deltas, and the Arctic in particular will experience major threats (Oppenheimer & Glavovic, 2019). But in general, the coastal communities that need protection are Shanghai, Lagos, New York City, cities, towns and villages from the Arctic to southeast Asia, southern Africa, Central and South America, Europe, and Australasia, and coastal communities on islands from the Caribbean to the Pacific, Africa, India and south China Sea (C, 2021).

It's necessary to understand that erosion becomes a hazard when society doesn't adapt to its consequences on people. As an example, many human settlements are set on areas prone to coastal erosion, while at the same time it is estimated that around 70% of the global coasts are eroding (Bird, 1985; UNISDR, 2017). In the highly populated mega-deltas of Asia, the regulation of the rivers, alongside the rest of the negative natural and human contributions that are also mentioned above, cause a significant coastal sediment reduction and threat to hundreds of millions of people (UNISDR, 2017).

The observed coastal erosion through the last decades till today, reveal 2 types, the rapid case of tsunamis and storm surges and the slow one of SLR (UNISDR, 2017). For example, Australia is experiencing a large number of damaging storms, with a peak, the 1974 sequence (Callaghan, 2008). India and Thailand on the other hand are suffering from tsunamis, like the one of 2004 (Provinces et al., 2007; Thom, 2021). In Happisburgh (United Kingdom), countries of the Pacific and the coastline of Tongatapu (Tonga) SLR has already started filling and eroding the coastal zones (UNISDR, 2017).

The significance of the upcoming economic consequences of coastal erosion have already been examined. In British rivers and coasts it is estimated that around $236 billion worth of assets are at risk from flooding and erosion, while in the following years, till 2100, this number is likely to increase, due to changes in society and climate (Thorne, Evans, & Penning-rowsell, 2007). In Australia, in 2008 it was calculated that $28-43 billion worth of residential buildings would be at risk with a 1.1 m SLR, meaning that around 157,000-247,000 settlements are being threatened (Unit & Division, 2013). In the Changjiang delta, the area where Shanghai is located, coastal erosion has been observed, due to cultivation and hill farming alongside the Changjiang River, causing land shortage, which means no space for further industrial and urban development in the biggest and most advanced socio-economically city of China (Chen & Zong, 1998; Higgitt & Lu, 1996; Lu & Higgitt, 1998).

In the U.S. it's estimated that the households prone to storm surges and coastal flooding were around 6.5 million in 2018, with a coastline length threatened by erosion at nearly 6,000 km (Botts, 2011; Hatzikyriakou & Lin, 2018). The significance of the vulnerability of many U.S. coastal communities was highlighted in 2012, when Hurricane Sandy destroyed over 650,000 structures and will continue to be visible as the effects of climate change and SLR are expected to impact many coasts and cause a critical concern (Blake et al., 2013; Botts, 2011; Lin, Kopp, Horton, & Donnelly, 2016). The New York metropolitan area is facing dangers too, as 2,400 km of shoreline will be dealing with erosion due to SLR in the coming years. A very upsetting prediction is that the return period of the 100-yr storm floods could be decreased to 19–68 years by the 2050s, and 4–60 years by the 2080s (Gornitz, Couch, & Hartig, 2002). Also, the southern coasts of Long Island have already seen the impacts, with most of the coastline being already eroded, but nothing like the salt marsh islands in Jamaica Bay, which a percentage of 50% of them being disappeared since 1900 (Gornitz et al., 2002; Leatherman S.P., 1985).

Some countries and islands have already started buying land from other nations, due to the threat of disappearing and submerging. The first one to act was the Maldives in 2009, that tried to purchase areas from

India and Sri Lanka. In 2014, the same tactic followed the people of Kiribati, a group of islands in the Pacific Ocean, as President Anote Tong issued a purchase of 20 sq km on Vanua Levu, one of the Fiji Islands (Cauchi, Correa-Velez, & Bambrick, 2019).

The present work is an attempt to highlight the magnitude of the problem of coastal erosion and a case study is presented, as a typical example of a coastal zone, with high touristic development, in the center of the Aegean Sea (Greece) and with morphological and anthropogenic characteristics that make it particularly vulnerable to coastal erosion. Literature, empirical and field research's data have been gathered, analyzed and interpreted to establish its vulnerability to different sea-level change scenarios according to the IPCC 2019 and its possible evolution based on anthropogenic pressures, while methods of natural self-protection of the coastal zone from coastal erosion and sea-level rise are discussed.

2. WHY COASTAL ZONE IS SO IMPORTANT?

The coastal zone consists one of the central pillars for sustaining life on Earth, not only as an ecosystem where biodiversity flourish, but also as the most favored area for the development and necessities of human civilization (Hausmann, 2001). In addition to the high concentration of population in coastal areas, there is also high activity in sectors such as tourism, trade, and labor, leading to richer coastal economies when compared to the inland ones (Jouffray, Blasiak, Norström, Österblom, & Nyström, 2020; Sachs, Mellinger, & Gallup, 2001; Zacharias, 2014).

During the 20th century, coastal zones have seen real changes with the increasing population and urbanization of 1990. Back then, 23% of the world, around 1.2 billion people, lived within a 100 km distance and 100 m elevation of the coast at densities about three times higher than the global average (Small & Nicholls, 2003). According to (Nations., 2017; VIM-TEC, 2019), by the Co-Chairs of the Executive Committee of the Warsaw International Mechanism and the United Nations respectively, it's estimated that globally the area within 100 km of the coastline is inhabited by about 40% of the global population (more than 2.4 billion people). But even coastal regions located less than 10 m above mean sea level are considered to host more than 600 million people (Around 10% of the global population) and 65% of the world's largest and numerous smaller cities (Durand et al., 2022). Citizens of coastal communities used to be around 37% of the world in total in 2017, meaning that today this number is even exceeded (Nations., 2017). Coastal areas seem to cover only a small part of Earth's total land and ocean area, 4% and 11% respectively, but the number of citizens they contain is more than 1/3 of the world and twice denser populated than inland areas (Barbier, 2012; Board, 2005; Milon & Alvarez, 1997). A similar pattern is seen in the U.S. too, as 40% of the total population of 2018 lived on the coast (NOAA, 2013). It's interesting to notice that even in the country level, coastal population is of high importance, as nations with the majority of their citizens concentrated farther than 100 km from the sea show 0.6 % slower economic growth (Hausmann, 2001).

Any level of Sea Level Rise (SLR) will impact the coastal population, with the solution of displacement and migration as the most probable one (Hauer, Evans, & Mishra, 2016; Hauer et al., 2020; Nicholls et al., 2011). So, if there are no counteractions, we are expecting the relocation of up to 1 billion citizens, the number projected to be even surpassed regarding the coastal habitants till the end of the century (Neumann, Vafeidis, Zimmermann, & Nicholls, 2015).

In general, around 30-50% of the world's tourism is taking place on the coastal zone (Ghosh, 2012), while in Small Island Development States, tourism accounts for over 25 per cent of Gross domestic producto (GDP) (Nations., 2017). As it's mentioned in (UNWTO, 2020), worldwide, 1 out of 2 tourists visit the coastal areas for tourism, as well as the total economic contribution of tourism in 2019 was 10.3% of the global GDP, creating 1/10 jobs. Also, coastal tourism is the largest sector across the Blue Economy in the European Union, in terms of global value added and employment (Commission, 2021). Following (Blue, 2016), the coastal areas of the Mediterranean attract around 15% of the global tourism.

Ports are the center of maritime trade, accumulating large shares of the world economy, as in 2020 the total volume of goods loaded worldwide was 10.6 billion metric tons (UNCTAD, 2021). Trade between nations consists 90% of shipping, while the ocean-based economy comes up to $3 trillion each year, about 5% of world's GDP (Nations., 2017). According to (NOAA, 2008), every year ships transport $1.5 trillion in and out of U.S. ports, supporting more than 13 million jobs. Across the Atlantic, it's estimated that, in 2020, 1,7 billion tons of goods were transported to/from main EU ports (SSS), while in the same year 3,273,103 tones were handled in the main EU ports (DSS), regarding Short and Deep-Sea Shipping respectively.

Coastal and marine processes offer services to our society that are highly valuable (Agency, 2015; Barbier, 2012). By a research that was made in 1997 (Costanza et al., 1997), the coastal and marine ecosystems (CMEs) used to represent the 68% of the total value of biosphere's ecosystem services, which was calculated to be $22.4 trillion, out of the maximum $54 trillion per year. This meant that the CMEs economy was even more important than the total global economy of the direct market, regarding its goods and services. An important fact that can highlight the importance of coastal zones, is that the total physical capital stock located in areas prone to coastal erosion was in 2006 calculated to be around $1.2 trillion, an amount so large, that could harm many coastal communities (Gopalakrishnan, Landry, Smith, & Whitehead, 2016). The number of jobs and production near the sea is extremely high, as for example worldwide 60 million people are employed in fishing and fish farming, which is the major source for food and income (Nations., 2017), and $164 billion are accumulated in exports (O, 2020). Fisheries and aquaculture contribute $100 billion per year and about 260 million jobs to the global economy, as well as coastal productivity supports 10-12% of the global population (Barua, Rahman, Barua, & Rahman, 2020). The annual coastal economy, regarding employment, ecosystem services provided by the ocean, and cultural services is estimated to be around $3-6 trillion/year (Nations., 2017). As for the U.S., the total stats of coastal economy, regarding all industries in 2021, consists of the establishments at 10,923,518, employment at 143,759,143, wages at $9,719,512,201,275, and the GDP at $22,996,086,000,000. Finally, it's calculated that annually coastal US counties produce $9.5 trillion in goods and services, employ 58.3 million people, and pay 3.8 trillion in wages (NOAA, 2013).

It's estimated that by 2041-2060, the population of low-elevation coastal areas will be more than 1000 million (Gómez-Villerías, 2022; IPCC, 2022). By the predictions introduced by Schwartz (Schwartz, 2005) and Vousdoukas (Vousdoukas, 2020), a 30 cm rise in the sea level would erode too many sandy beaches globally and could cause the disappearance of almost half of them by 2100 (Kettunen, Kirchholtes, Klok, Markandya, & Nunes, 2010) estimated that by 2050 $14 trillion worth of land-based services will be lost, which means that CMEs services will undergo a decrease of a similar magnitude. Blue Economy is expected to follow a growth at a faster rate than terrestrial activities for the next decades, about $3-5 trillion by 2030, according to OECD (OECD (Organisation for Economic Co-operation and Development), 2016). For example, across the Caribbean islands, with the CO2 emissions model of RCP 4.5, it's predicted that around 53% of sandy beaches will be lost and tourism revenue will decrease 38% by 2100 (Spencer, Strobl, & Campbell, 2022).

3. THE CRUCIAL ROLE OF HUMANS IN THE COASTAL ZONE

The factors that can cause shoreline retreat are divided into 2 categories, the natural and the human-induced (GILLIE, 1997). The most commons of the second ones are considered to be sand mining from riverbeds and beaches, construction of coastal structures (such as jet- ties, groins, seawalls, and breakwaters), reclamation of shorefront lands, and human-induced land subsidence (Hsu, Lin, & Tseng, 2007). In addition, increased human modification reduces the "naturalness" of coastal environments, exposing them to uncertain changes and dangers (Dahm, 2000). But it should be noted that the one with the greatest impact is the global climate change, an anthropogenic phenomenon that tends to alter the natural processes that sustain beaches and coasts (Doney et al., 2012; Harley et al., 2006; He & Silliman, 2019; Poloczanska et al., n.d.; Prasad & Kumar, 2014).

The "coastal squeeze" of the global population during the last century into the urbanized coastal megacities (cities with population that exceeds 8 million) is happening right now, as in 1950 there were only 2, Ney York and London, while today the number has soared to 16, Tokyo, Mumbai, Shanghai, Guangzhou, Shenzhen, Kolkata, Karachi, Manila, Osaka-Kobe, Jakarta, Buenos Aires, Rio de Janeiro, New York City, Los Angeles, Lagos and Istanbul (Pelling & Blackburn, 2014; Schlacher et al., 2007). So, hazards and vulnerability of coastal erosion in coastal megacities are products of the interplay between multiple forms of change (demographic, infrastructural, environmental, social, economic, etc.) (Blackburn, Pelling, & Marques, 2019).

The human systems that in general can interact with coastal erosion include the built environment (settlements, water, drainage, transportation infrastructure and networks), human activities (tourism, aquaculture, fisheries), and institutions that organize human activities (policies, laws, customs, norms, and culture) (Berkes and C. Folke, 1998). Basically, anything that humans do to change or impede the natural processes along the coast tends to have a negative impact on the coast. Throughout history, humans always interacted with the coast, at the past without awareness, till the present that even attempts to control erosion have resulted in worse effects (Davis, 2021).

Human constructions on the coast can cause amplified levels of erosion. For example, ports can alter the currents, waves, and water quality in a coastal area (Kudale, 2010; Tsinker, 2004), jetties expose the downdrift zone to erosion (Saengsupavanich, Yun, & Lee, 2022), seawalls and revetments can impact both harmful and positive depending on their position and the natural evolution of the beach (Weggel, 1988).

Another case is the decrease of fluvial supply by the creation of reservoirs for power production and irrigation purposes, the construction of river dams, the deepening of navigation channels, and the mining of river sand, as a side-effect of human interventions in the natural environment (Sharma, Vo, Meybeck, Green, & Syvitski, 2003). Breakwaters, dikes, walls, buttressing, etc., which have long been deployed to reinforce the coastline, not only disrupt sediment transportation behavior but also cause severe bottom abrasion and erosion. For that reason, researchers around the world (Nabi, De Vriend, Mosselman, Sloff, & Shimizu, 2013a, 2013b; Petropoulos, Evelpidou, Kapsimalis, Anagnostou, & Karkani, 2022; Petropoulos, Kapsimalis, Evelpidou, Karkani, & Giannikopoulou, 2022)develop numerical models in order to simulate the morphodynamic state of the coast. For example, the MIKE 21 Flow Model simulates the morphodynamic of an embayed beach with sediment transport and bed level changes due to currents or combined waves/currents, coupled with the HD, SW, ST, and Shoreline Morphology modules, considers the space and time period of the prevailing and extreme conditions of the phenomena of interest. Also, has the efficiency to study the wave transformation over different temporal and spatial scales; it also allows repeating running tests with different wave exposure forcing conditions along different values of parameters (Balas & Inan, 2002) in order to better understand the nearshore circulation. The numerical model estimates the coastal erosion processes and the natural variations in sand budgets and allows for an assessment of marine spatial planning and the study of the impact and effectiveness of shore interference works. The reliable key calibration parameters, such as sediment grading, grain diameter, manning, and bed thickness, were calculated and used in the MIKE 21 Coupled Model FM simulations (Petropoulos, Evelpidou, et al., 2022) in combination with bathymetry, sediment analysis, and substrate component data from the bay. The values of the main parameters used by the model were set based on the program manuals along with empirical validation through the repeated running of tests. The model was successfully applied and tested in a number of basic, idealized, realistic, and complicated situations from which the output results can be compared with analytical solutions or information from the literature (Bulhoes & Fernandez, 2011; Jose, Kobashi, & Stone, 2007)

Human intervention on waterways via dams, diversions, levees etc., accompanied by SLR and increased flooding, follows the loss of insane amounts of acres of estuary habitat every year. The coastal land loss due to the reduced supply of new sediment is the result that threatens on a social level entire communities and economically the local production and exchanges (Warrick et al., 2019).

Coastal Louisiana and the Mississippi River Delta is an example, as a football field's worth of land disappears every hour (Ortiz, Roy, & Edmonds, 2017). This effect is caused by man-made constructions, mostly levees, on the area, that were built to protect from flooding the cities, the infrastructure, and other economic resources, but turned out to be harmful in other ways. Since the 1930s, more than 5,000 square kilometers of land have disappeared, which means that the region is at high risk, while it represents a powerful economic output with the oil and gas, trade, and fishery industries (Blum & Roberts, 2009; Olson & Suski, 2021; Ortiz et al., 2017). The Nile Delta has experienced issues with erosion from human grounds, as from 1909 to 1971 the rates of sediment discharge were estimated at 42 m/year, following the construction of the Low Aswan Dam, but finally it turned out that the problem was boosted by the creation of the High Aswan Dam, increasing the erosion at 129 m/year (Stanley & Warne, 1993).

It should be highlighted that beachrocks have also the potentiality to prevent coastal erosion, due to their ability to minimize the energy of the waves, acting like breakwaters (Khan & Kawasaki, 2015). As suggested by Danjo and Kawasaki (Danjo & Kawasaki, 2013), they can easily and eco-friendly (due to the dependence of local materials for the formation) be developed. In 2021 the first artificial beachrock was made in Greece (Polidorou, Saitis, & Evelpidou, 2021) and the public application of this protective technique is to be seen in the near future.

Coral reefs are fundamental ecosystems for the protection of coastal zones, as they prevent flood dangers through their hydrodynamics and morphological effects that break the waves approaching the beaches and reduce their energy (Escudero, Reguero, Mendoza, Secaira, & Silva, 2021; Monismith, Rogers, Koweek, & Dunbar, 2015; Storlazzi et al., 2019). The unfortunate fact is that coral reefs are being degraded while conservation and management activities remain largely inadequate (Luisa Martínez et al., 2014; Omori, 2011). For instance, in the Caribbean, around 50% of the hard coral cover on reefs has been destroyed in only 3 decades (TA, 2003).

Finally, fast ferries interact with the shorelines through the wake waves that they generate. Each one consists of a sequence of 10 low and long waves with a significant height below 1 m, which break as plunging breakers. The ways they can influence the coasts are by higher wave uprush than that produced by normal waves, by changing the coastal morphological processes in the area, eroding it and creating beach berms and by breaking unexpectedly and violently (Bilkovic & Davis, 2018; Zaggia et al., 2017).

4. CASE STUDY

As a case study we chose a coastal zone located in the center of the Aegean Sea (Greece, Mediterranean). It is a constantly developing tourist area, the characteristics of the coastal zone make it vulnerable while at the same time it has self-protection mechanisms. However, anthropogenic activities endanger these mechanisms. Naxos is the largest island in the Cyclades, with a coastline that reaches 148.00 km (Figure 1). The relief is mountainous, with a central mountain range that crosses the island from its north to the southern end. According to the latest census of 2011, its population is 1,793,000 inhabitants.

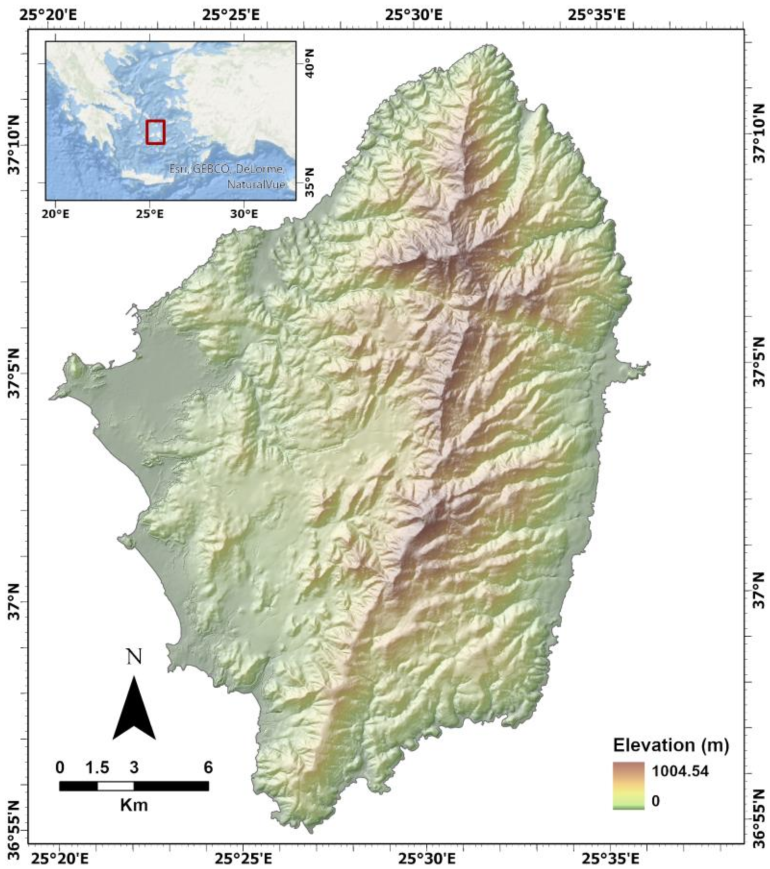

Figure 1. Naxos Island, located at the center of the Cyclades islands, Aegean Sea.

Erosional processes and tectonic forces are the major factors in the formation of the landscapes and landforms of the area. According to Evelpidou (N Evelpidou, 2001), the lithology of Naxos is consisted of various lithological formations with different resistance in erosion, which, in combination with the action of the hydrographic network and tectonics, has created the present morphology. The erosion in Naxos mainly occurs through runoff erosion, which, in combination with the transported material, pre-existing discontinuities get extended, creating a variety of geomorphological landscapes. One of the main processes sculpting the landscape of Cyclades and Naxos is the differential erosion, due to variations in vulnerability of the geological formations. Depositional processes have contributed to the present-day landscape at the western part of the island.

In the coastal zone, the most characteristic landforms (Figure 2) are owed to depositional processes with notable examples of coastal dunes, lagoons, tombolos, as well as beachrocks mainly located on the west coast while erosional processes have formed tafoni, marine notches (Niki Evelpidou & Pirazzoli, 2014), coastal cliffs (N Evelpidou, 2001; Niki Evelpidou et al., 2012; Niki Evelpidou, Pavlopoulos, Vassilopoulos, Triantaphyllou, et al., 2010)[1].

[1] *Additional information: https://arcg.is/1fqOyC and Evelpidou et al.* (Niki Evelpidou et al., 2022).

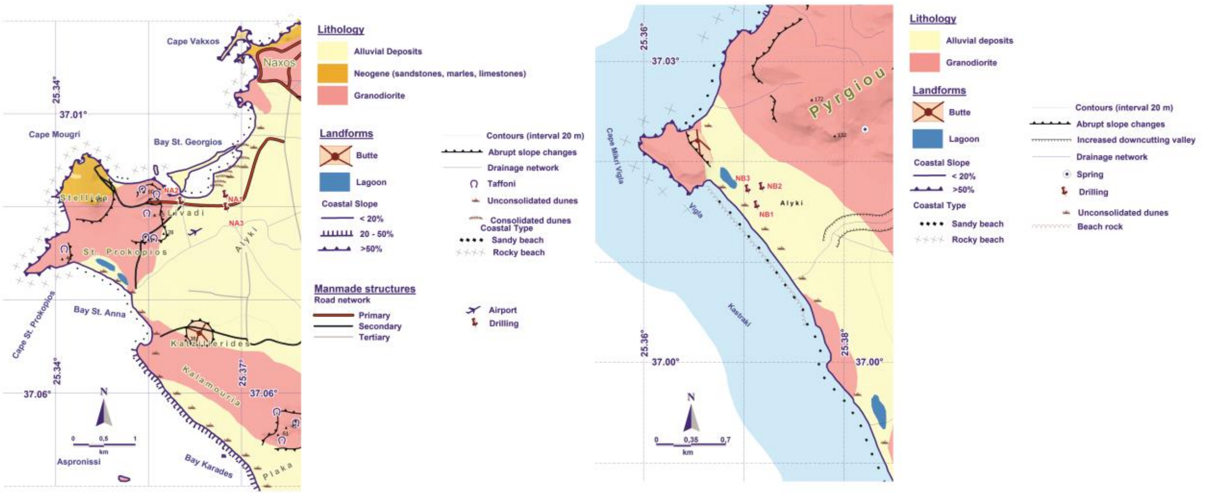

Figure 2. Geomorphological map of Agios Georgios (left) and Vigla (right) area (Niki Evelpidou et al., 2012).

5. MATTERIAL AND METHODS

The research that we conducted, in order to examine the vulnerability of the western coastal zone of Naxos Island (Cyclades, Aegean Sea, Greece) in coastal erosion, involved a series of methods of data integration, analysis and modelling. These methodologies included: (a) photointerpretation of aerial photographs from 1960 until today. The aerial photographs from 1960 and 1988 were obtained from the Hellenic Military Geographical Service, were photointerpreted through stereoscopic observation and were used for the documentation of coastal features; (b) mapping of the coastal zone and topographic sections using DGPS (Differential Global Positioning System). Specifically, a DGPS-GNSS Spectra SP60 was used for this purpose, which offers an accuracy of 5 cm; (c) GIS software, such as ArcGIS Pro version 2.6, ArcMap version 10.4, for the geospatial analysis. A classification of the coast of the western Naxos Island according to its vulnerability to an anticipated future sea-level rise, using the Coastal Vulnerability Index (CVI) and utilizing Geographic Information Systems (GIS) technology. The data were used for CVI collected during field work, from satellite images, historical maps and literature research.

CVI index relates in a semi-quantitative manner the following six physical variables, geomorphology, coastal slope, relative sea-level rise rate, shoreline erosion or accretion rate, mean tidal range and mean wave height, aiming to identify areas that are comparatively more vulnerable to sea level change (Figure 3).

Variables	Very Low 1	Low 2	Moderate 3	High 4	Very High 5
GEOMORPHOLOGY	Rocky cliffed coasts, Fjords	Medium cliffs, Indented coasts	Low cliffs, Glacial drift, Alluvial plains	Cobble Beaches, Estuary, Lagoon	Barrier beaches, Sand beaches, Salt marsh, Mud flats, Deltas, Mangrove, Coral reefs
SHORELINE EROSION/ACCRETION (m/yr)	> 2.0	1.0 - 2.0	-1.0 - 1.0	-2.0 - -1.0	< -2.0
COASTAL SLOPE (%)	>12	12 – 9	9 – 6	6 – 3	<3
RELATIVE SEA-LEVEL CHANGE (mm/yr)	< 1.8	1.8 - 2.5	2.5 - 3.0	3.0 - 3.4	> 3.4
MEAN WAVE HEIGHT (m)	< 0.55	0.55 - 0.85	0.85 - 1.05	1.05 - 1.25	> 1.25
MEAN TIDE RANGE (m)	> 6.0	4.0 - 6.0	2.0 - 4.0	1.0 - 2.0	< 1.0

Figure 3. CVI variables according to Pendleton et al. (2004).

The variable of geomorphology expresses the relative erodibility of various coastal landforms and was derived from detailed field geomorphological mapping. Shoreline erosion or accretion rates were obtained from interpretation of field survey and topographic maps. The slope of the coastal zone was estimated using the Digital Elevation Model (DEM) of the area derived from topographic maps at the scale of 1:5,000. Bibliographic data were used for the mean tidal range, mean wave height and relative sea level change.

The shoreline of the study area was divided into sections, with a length of 20.0 m. The Coastal Vulnerability Index (CVI) was estimated for each section, as the square root of the values of the ranked variables divided by their total number involved.

6. RESULTS AND DISCUSSION

Numerous coastal and marine landforms attest to the late Holocene and present-day evolution of the region and relative sea level variations, providing evidence regarding the morphological layout of the coastline and the evolution of the coast. The western coastal zone of Naxos Island consists of a sandy beach, bordered by low lying sand dunes, lagoons and an alluvial plain, while the submarine area is distinguished by a sequence of beachrock slabs (Figure 2) (N Evelpidou, 2001; Niki Evelpidou, Pavlopoulos, Vassilopoulos, MariaTriantaphyllou, et al., 2010; Niki Evelpidou et al., 2012; Karkani et al., 2017). These systems are becoming increasingly vulnerable, due to natural processes such as wave energy, sea level rise, but also due to human interventions that have significantly eliminated sediment input to the coastal zone and the increasing touristic development, leading to their erosion and degradation.

According to CVI results (Figure 4), the most vulnerable coastal regions were found along the sandy coastal area, while the steep rocky coast areas are the least vulnerable sections. In many sites dune fields are developed across a nearly continuous 20-kilometer region, defining the back-shore border relative to the coastline. At the same time, lagoons extend behind the dunes, inland, below sea level. Sand dunes (Figure 5) are one of the island's most vulnerable and threatened ecosystems with average dimensions of 3–10 m in height and 30–150 m in width, with steep slopes on the windward and mostly the leeward side, while the greatest major coastal wave height along the N–NW direction is 5.6 m. Based on the distribution of dune fields, it would appear that the relief, the morphological characteristics of the region, and the sand source supply had the most significant influence in determining their placement. Another landform located in the western part of the island is the coastal cliffs, which occupy a total length of 27.31 km, followed by sandy and cobble beaches with a total length of 21.07 km.

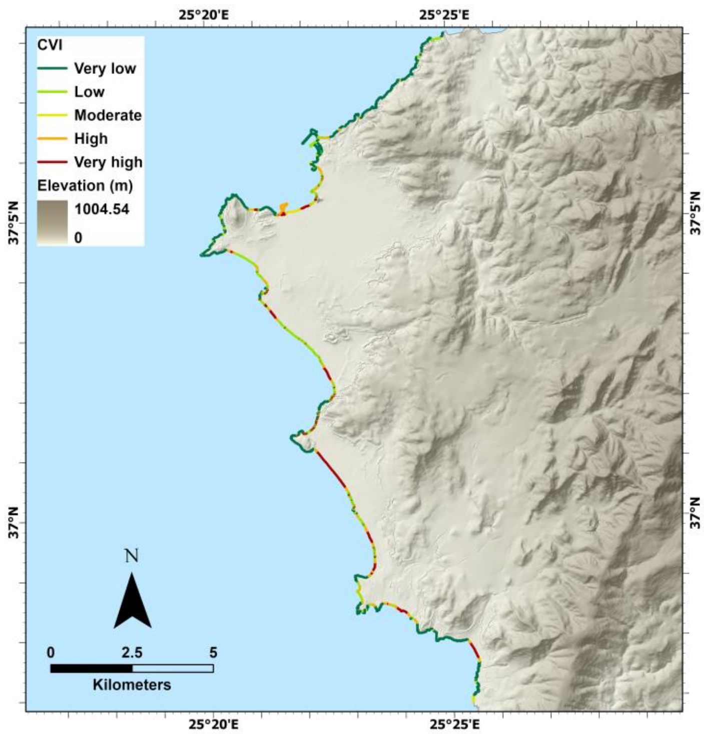

Figure 4. Coastal Vulnerability Index (CVI) map of the study area. The coastline is divided into five ranges (from very low to very high) (Tzouxanioti, 2021).

Figure 5. Dune fields of Plaka area, Naxos Island.

The coastal slope identifies the relative vulnerability and the potential rapidity of shoreline retreat. Coastal regions with low sloping should retreat faster than steeper ones. In particular, the western coast is of low vulnerability area due to the presence of steep rocky cliffs. In the figure 4 the low lying areas, with high and very highly vulnerable of the western coast are indicated. In addition, due to recent sea level measurements of 4.3 mm/yr, which is the mean eustatic global sea level rise rate according to the RCP 2.6 scenario (IPCC, 2019b, 2021), the understudy area is considered highly vulnerable. Shorelines change rates in western part of Naxos Island incorporate from accretion equal to +0.18 m/yr to retreat equal to -0.16 m/yr. In conclusion, 50.40 km of the study's area coastline, is relatively stable, while 1.28 km of the coastline is eroding (mainly in Agios Georgios area).

The analysis of historical aerial photos suggests that the most significant pressures on the coastal zone are the result of modern human interventions and the growth of tourism and residential facilities (Figure 6). In fact, the development of sand dunes in those areas has been influenced by human activity, particularly along the southern coast, where they have been replaced by dense urbanization, so exposing the region to extreme natural occurrences. Manmade pressures at the backside of sand dunes (e.g., parking areas, coastal roads) reduce their width and make them susceptible to erosion, in conjunction with the lack of clastic feeding from seasonal streams, rendering these circumstances irreversible.

Figure 6. Anthropogenic pressure and coastal squeeze especially during summer months endanger the existence of the sand dunes and this will result in the flooding of the coastal zone.

Sand dunes in these regions are vulnerable to substantial environmental pressures, both direct and indirect, caused primarily by human activity, exposing significant portions of coastal communities to the risk of seawater inundation. Specifically, the effects of uncontrolled tourism development (e.g., irregular road network and passages on the sand dunes, sand extractions and clearings), in combination with the reduced supply of material for the development of the sand dunes, results in their leveling and consequently in their destruction. Coastal retreat will result from the long-term loss of sand from the beach system, with the outgoing amount of sand being greater than the incoming amount.

7. SELF-PROTECTION MECHANISMS

Location and shape of dune fields make them significant variables in the coastal zone, particularly in the advance of seawater in the event of a sea-level rise due to global climate change. The sand dunes serve as a natural barrier that protects the interior from powerful natural occurrences, hence preventing the intrusion of water bodies. According to the conservative scenario of the IPCC (IPCC, 2019a, 2021) for the next 100 years, if sea level rises by only 0.5 m, the area of land that will be submerged by the sea will be limited due to the high altitudes and slopes of the sand dunes, which contribute to the area to prevent coastal flooding (Maroukian, Pavlopoulos, Gaki-Papanastasiou, & Zamani, 2001). Finally, sand dunes operate as water filters, increasing and preserving the quality of coastal water, while providing niches for highly specialized plants and animals, including countless rare and endangered species. Coastal wetland ecosystems are extremely significant and valued due to their high biodiversity and ecological services.

The combination of geological subsidence in the studied area (submerged beachrocks/notches) and the continuous global climate change, especially related to sea-level rise, poses a threat to a variety of coastal landforms as well as a number of touristic activities on the western coastlines of Naxos. In the absence of sand dunes, marine flooding will follow not only to the beach, but also to the lagoons and many acres of rural and residential land, resulting in significant environmental changes and economic losses due to the effects on local inhabitants and tourists in the area (Figure 7). In addition, sand dunes can also protect from coastal hazards, such as tsunamis, as they can partially absorb tsunami wave energy (Gogou et al., 2019), and in fact the dunes fields of Glyfada offer better protection in comparison to those of Agios Prokopios, as the former have been less impacted by anthropogenic pressures (Gogou et al., 2019).

At the same time, the presence of the underwater beachrocks along the shallow submarine area of the western coasts, which extend from many kilometers parallel to the present-day coastline, act as natural breakwaters, protecting the coastal zone from erosion (Figure 8) (Imran, Kimura, Nakashima, Evelpidou, & Kawasaki, 2019). Their existence and maintenance are crucial for the protection of the coastal zone. The possible loss of sand dunes is a threat to the wider areas, particularly low-lying coastal areas, from marine floods, resulting in the social, cultural, and economic degradation of the affected regions.

Figure 7. This is what will happen in the area of Agios Prokopios if the sand dunes are destroyed. Notice from the topographical section that the lagoon is – 0.1 meters below the present sea level and the dunes protect the area behind them from being flooded by the sea.

Figure 8. Beachrocks appears in the western part of Naxos Island, at Plaka beach.

8. CONCLUSION

The interaction of the coastal ecosystem alongside the human growth towards it, has been explained as the major case of the coastal erosion and its threats to the environment, economy, and local communities. As an example of the vulnerability of coastal zone the case of the west and south-western part of Naxos, is presented since this phenomenon is visible as human activities have forced the amplification of coastal retreat, mostly in sandy beaches, while sand dunes are being destroyed.

Apart from the natural causes of coastal erosion, focus must be given to the anthropogenic ones that either directly or indirectly boost the problems, as well as the actions that can be taken to protect from such issues. Minimizing the coastal squeeze and the threats of advancing coastal tourism, protecting the dune fields, and constructing man-made structures for the protection from flooding and wave erosion (such as beachrocks), are the main examples of solutions that need to be taken into action as fast as possible, so that the effects of climate change and SLR won't devour our lands.

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