Mapping coastal erosion using UAVs, GNSS, and GIS: the case of Rio Greece

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ABSTRACT

Coastal zones are defined as the areas of interface between land and sea, hosting 41% of the world's population. These areas are exposed to various risks cause by either natural processes or anthropogenic activities (i.e. erosion, heat waves, sea level changes, etc.). Nowadays coastal monitoring can be performed with different remote sensing data such as satellite, airborne or Unmanned Aerial Vehicle (UAV) images, exhibiting enormous possibilities for observation. However, in emergencies the prompt and accurate mapping and assessment of structural damage are of utmost importance for effective post-disaster response. In light of this, UAVs display exceptional capabilities in post-disaster mapping since they provide almost near real time data with high spatial resolution and low operational costs, they have a flexible survey planning, as well as they are able to collect data in hazardous environments. Moreover, it is noteworthy that it usually takes less than 45 minutes to one hour in the research area to receive the necessary information, while the generated processing products (i.e. orthophotos and Digital Surface Models) can be made available within 24 hours to the local authorities or stakeholders. In this framework, the current research focuses on the utilization of UAVs along with GNSS measurements to create high-resolution and high-precision maps of the damaged areas after the occurrence of weather extremes. The coastline of Rion in Western Greece was selected as case study. Specifically, the specific area has been affected by recurrent storms causing severe damages to the coastline since 2017. Hence, repeated UAV campaigns following the same photogrammetric grid were carried out in 2016, 2017, 2018, 2021 and 2024. UAV data were processed using SfM (Structure-from-Motion) photogrammetry resulted in the generation of multitemporal orpthophotos and DSMs. These products were compared in GIS environment. Meteorological data from the three nearest station we also integrated in the analysis of the results.

Keywords: UAV, GNSS, GIS, coastline, erosion, mapping, monitoring, weather extremes

1. INTRODUCTION

The land-sea interface area is perceived as a coastal zone in general terms. According to another definition, areas with low relief (i.e. located less than 10 m above sea level) are characterized as coastal areas, as they define the transition zone between land and sea and they establish dynamic natural environments [1]. Since the 1950s, coastal areas have been steadily increasing in population [2]. Although, the extent of the coastal area covers only 2% of the global land area, more than 10% of the world's human population lives along such a region. This is a generalized global trend. However, the concentration of the world's population in coastal areas increases the pressure on the environment and coastal ecosystems. In fact, studies indicate that by 2050, 70% of the world's population will live in urban areas and agglomerations [3]. The coastal areas are of utmost importance for human, flora and fauna ecosystems while they are increasingly vulnerable to many hazards caused by: coastal flooding, strong winds and waves, short- and long-term coastal erosion, storms and sea level rise [4]. In addition to all these natural processes, there are also human activities that can cause erosion or accretion, such as the construction of dams and reservoirs, seabed dredging, mining, and water and sand extraction [5]. Among the others possible hazards, erosion is classified as one of the more serious in coastal areas. Coastal erosion is a process that degrades coastal environment and it mainly occurs due to natural factors (e.g., related to climate change) and overcrowding (e.g., urbanization and massive tourism) [6]. Until a few years ago, climate change impact could be considered as a slow process, while the intense human presence contributed to the rapid and violent change of the coasts. Nowadays, coastal areas are at risk due to rising sea levels and increased weather extremes

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associated with climate change. In this framework, ensuring the stability of these areas becomes a high priority whilst accurate monitoring plays an important role in determining the amount of damage from flooding and erosion [7].

Over time, coastal monitoring methodologies have adopted to the technological developments. Hence, coastal monitoring methods involving conventional techniques such as classical topographic survey using total station or GNSS, beach profile analysis and tidal analysis, besides being expensive and labor intensive, they are considered outdated. On the contrary, remote sensing constitutes an effective approach for coastal mapping, monitoring and management. Satellite imagery is an ideal solution for the observation of large areas due to its extended coverage capability. However, the use of satellite imagery is quite challenging as the spatial resolution of the freely available data is very low or higher quality in terms of resolution satellite imagery is quite expensive.

Unmanned Aerial Vehicle imagery and Structure from Motion (SfM) photogrammetry constitute the more innovative approach of remote sensing. Thanks to their characteristics, UAV photogrammetry is defined as the most practical and cost-effective method that is increasingly used in various research fields. The main advantages of UAVs are: the low purchase and operational costs; the possibility to quickly plan and prepare flight campaigns in the field; the fact that most UAVs transmit images in real time, which allows the performance of the same flight in case of failure or error; and the low safety risks [8].

The use of UAV imagery has been demonstrated in many studies for coastal monitoring [9], [10], [11], [12], [13], [14], [15], [16], [17], [18] or damage assessment after a storm [19]. The complexity of the coastal environment requires the synergy of multidisciplinary methodologies in order to depict with high accuracy the onshore and the offshore environment. In recent studies UAVs [20], [21], [22], Unmanned Surface Vehicles (USVs) [23], [24], [25], or combination of both has been proposed and successfully applied [4], [26] to investigate different phenomena in shallow-water environments.

The current study focuses on the feasilbility of the combined use of a small commercial UAV, GNSS measurements and GIS software to map post-disaster coastal erosion in Rio, Western Greece. Over the last seven years, many storms occurred in the specific area causing severe damages to the coastline infrastructure. After every event, UAV imagery has been collected and processed using SfM photogrammetry to create accurate digital surface models and orthophotos of the area of interest. Furthermore, the outcomes were compared with meteorological parameters i.e. wind speed and wind direction to examine if there is correlation between erosion phenomena in such an area and specific weather phenomena.

2. AREA OF INTEREST & WEATHER EXTREMES

The northernmost suburb of Patras city, named Rion was selected as area of interest (Figure 1). The coastline of Rio covers an area of 4 kilometers in the Gulf of Patras, which is located in Western Greece between Central Greece and the Peloponnese and specifically between the two parts of the Rio-Antirrio Bridge. It is a relatively shallow sea basin that communicates to the west with the Ionian Sea by a 12-km-width channel and to the east with the Gulf of Corinth through the Rio-Antirio side, which is 2 km wide. The entire coastline along the Gulf of Patras has been facing erosion problems over the past few decades. Specifically, the erosional processes of the broader coastline have started about 50 years ago and it was mainly caused by human interventions such as the illegal sand and gravel in-stream extraction to provide materials to human constructions, the formation of new highways along the coastline and the extensive urbanization of the coastal zone. All these human activities provoked the significant reduction of materials transported from rivers to the sea, accelerating erosion rate. Moreover, other causes could be the intense sand extraction, poor planning and excesses of coastal structures (e.g. vertical walls next to the beach) leading to various phenomena such as: wave refraction / reflection, infrastructure construction on the coast (eg fishing havens - harbours, seaports) etc.

Over the last seven years the broader area is affected by weather extremes related to the climate change. As described in [19] when the wind speed range between 75–88 km/h or the value 9 in Baufort scale, the phenomenon is characterized as a strong /severe gale and a wave height of 7-10 meters hit the coast. If the wind speed is between 89–102 km/h or a value of 10 on the Baufort scale, the phenomenon is classified as a storm and the wave height can reach up to 12.5 meters. According to the data of the nearest meteorological stations (Patra, Rio) such extreme weather phenomena have occurred at least five times in the last seven years and more specifically in 2017, 2018, 2020, 2021 and 2024.

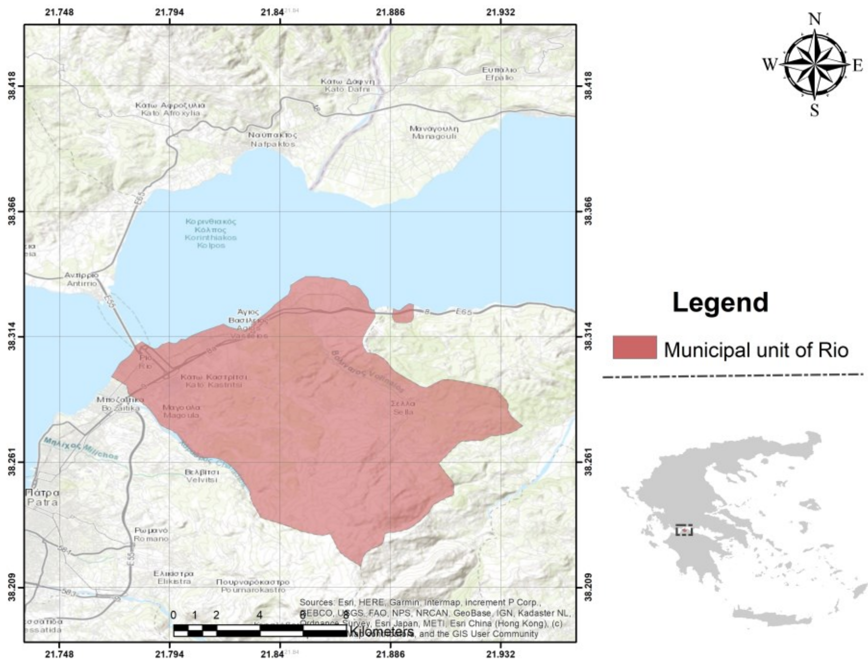

Figure 1. Location of the area of interest within Greece.

3. DATA COLLECTION AND PROCESSING METHODOLOGY

Two commercial quadcopters Phantom 4 (former) and Phantom 4 Pro have been used for coastal area mapping. As described in [18] during the summer of 2016 several UAV photogrammetric flights were performed and more that 2000 images were acquired along the Rio coastline. An orthophoto and a Digital Surface Model were created and used as basemap for the upcoming surveys. In addition, an orthophoto of the Greek Cadastral has been used as a basemap for the eastrn part of the coastline of Rio.

After each weather extreme, photogrammetric flights were performed following the same grid. A typical example of a photogrammetric flight over the western coastline of Rio is presented in Figure 2. All the UAV missions were planned to have 90% overlap along the track (flight direction) and 75% across the track (sidelap). Each flight was performed at 90m above ground level resulting to a spatial resolution of 2.5cm/pixel.

To achieve the higher possible accuracy of the models many artificial targets, used as Ground Control Points (GCPs) were distributed over the broader area. The coordinates and height of each of these targets were measured using a high-precision geodetic GNSS receiver in order to ensure accurate positioning in Greece's Coordinate System (EGSA 1987, EPSG: 2100).

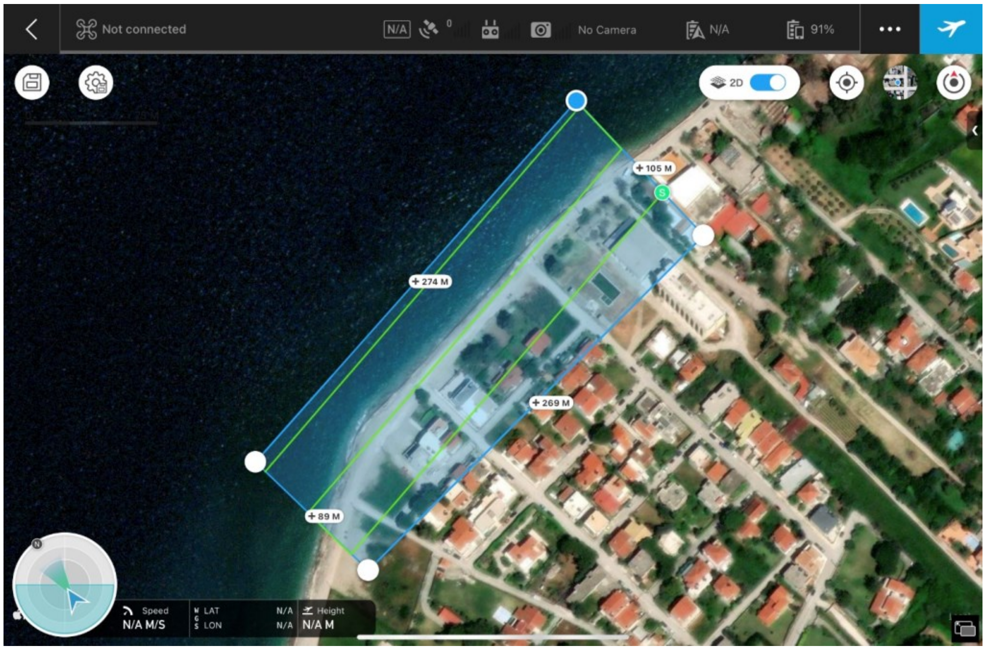

Figure 2. A typical example of the photogrammetric grid that was designed in order to cover the coastline.

4. POST-DISASTER MAPPING USING UAV AND GNSS

Multiple erosion events have been recorded during the last seven years along the coastline of Rio. The first event was occurred on November 2017 and the last one on January 2024. Specifically, a storm hit the coastline of Rio on the night of November 19, 2017. The wind speed exceeded the speed of 83.7 km/h in Patras and 91.7 km/h in Rio weather stations, respectively. As presented in Figure 3 severe damage was observed to the road network and to the western dock. Figures 4 and 5 display the orthophotos of the specific post-disaster mapping survey.

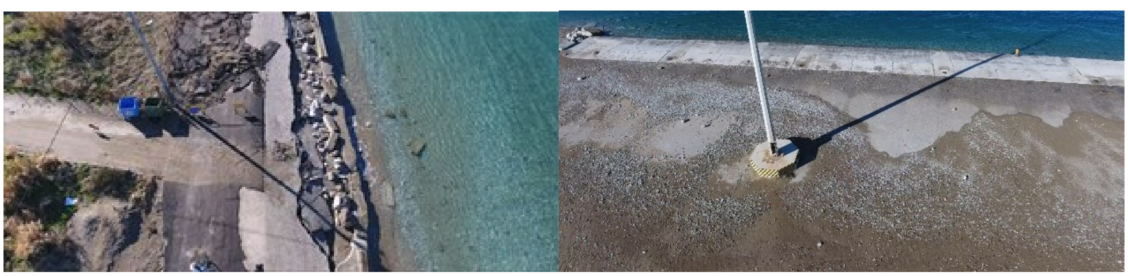

Figure 3. Damages occurred to the coastline during the November 2017 storm. Damages on the road network at the west coastline of Rio are displayed at the left, while damages at the dock are illustrated at the right.

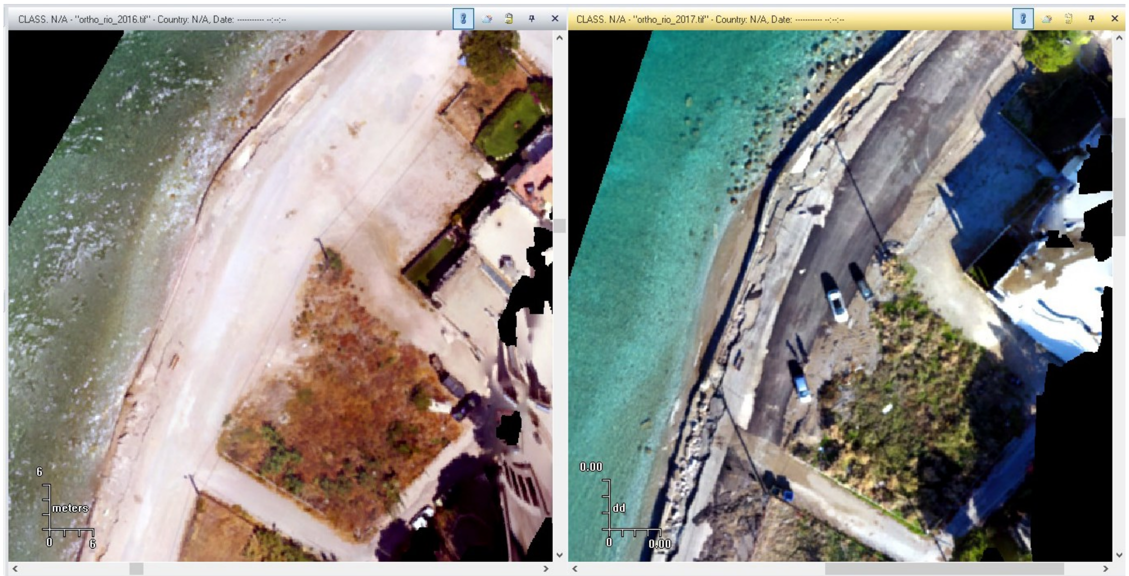

Figure 4. Damages on the road of the west coastline of Rio in November 2017. The orthophoto of the UAV flight campaign of 2016 is displayed at the left, while the respective orthophoto of the UAV flight campaign of 2017 is presented at the right.

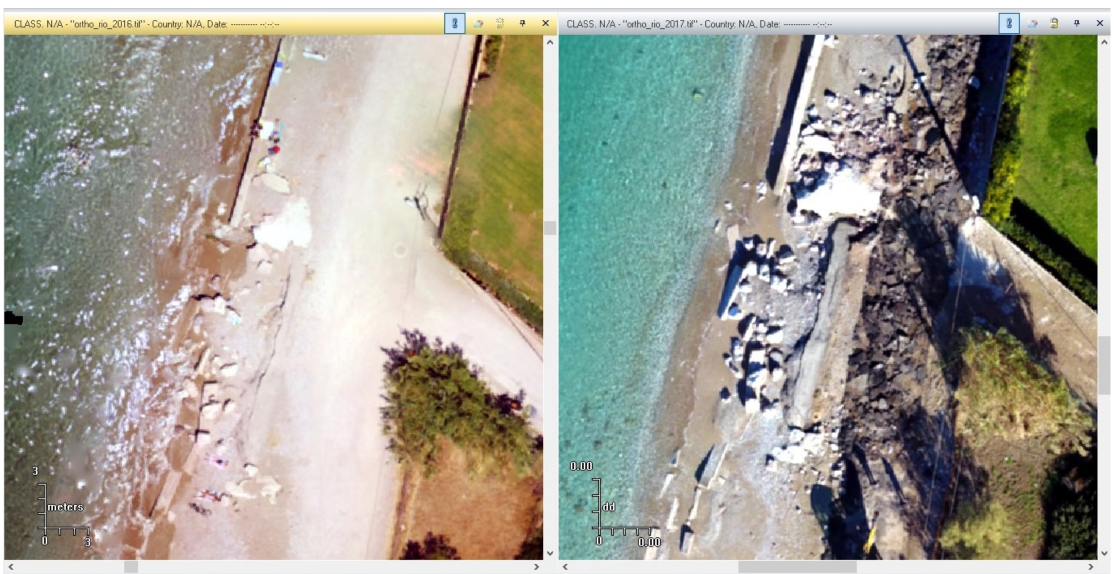

Figure 5. Damages on the road at the west coastline of Rio in November 2017. The orthophoto of the UAV flight campaign of 2016 is displayed at the left, while the respective orthophoto of the UAV flight campaign of 2017 is presented at the right.

Less than four months later, another extreme weather event occurred along the coastline of Rio. As it can be observed from Figure 6, the road network exhibited again severe damage. Similar phenomena were recorded in 2021, when the road network at both sides of the Rio Antirio Bridge was destroyed. Photos from the in-situ survey are presented in Figure 7. The entire road from the bridge to the Porto Rio hotel was heavily damaged (Figure 7). The destruction was detected and map through the performance of UAV flight campaigns over the area of interest (Figures 8 and 9). More recently, in January 2024 the erosion phenomena affected mainly the eastern coastline of the Rio destroying the road network in the area of Agios Vasilios (Figure 9).

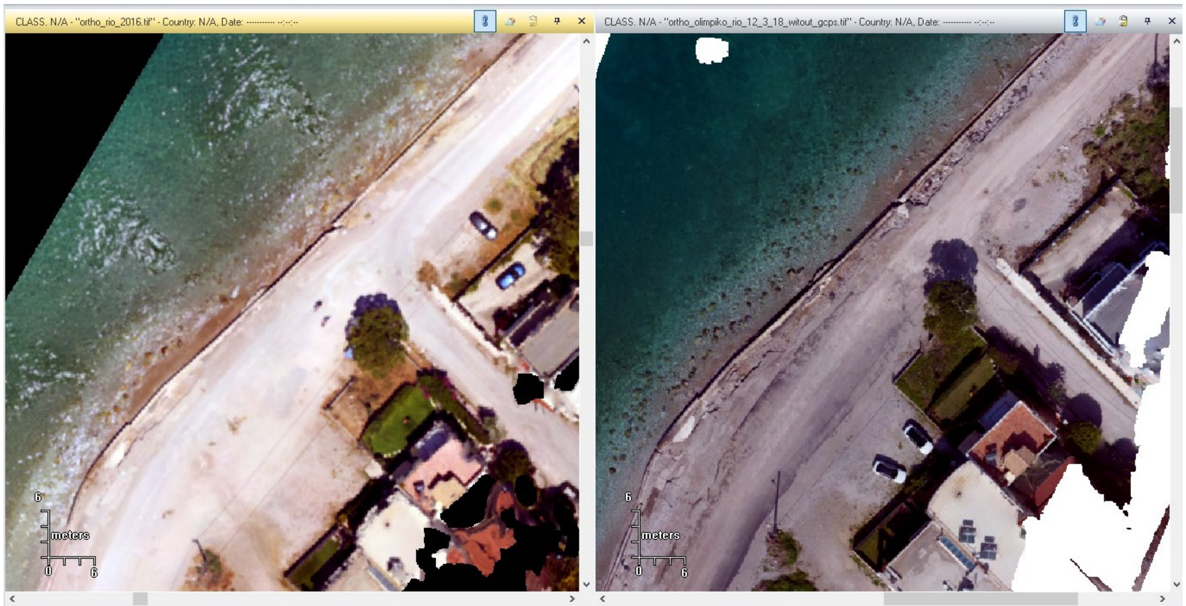

Figure 6. Damages on the road at the west coastline of Rio in March 2018. The orthophoto of the UAV flight campaign of 2016 is displayed at the left, while the respective orthophoto of the UAV flight campaign of 2018 is presented at the right.

Figure 7. Photos from the in-situ survey on the west coastline of Rio in November 2021. The left image is an east-viewing perspective, while the right image is a west-viewing photo.

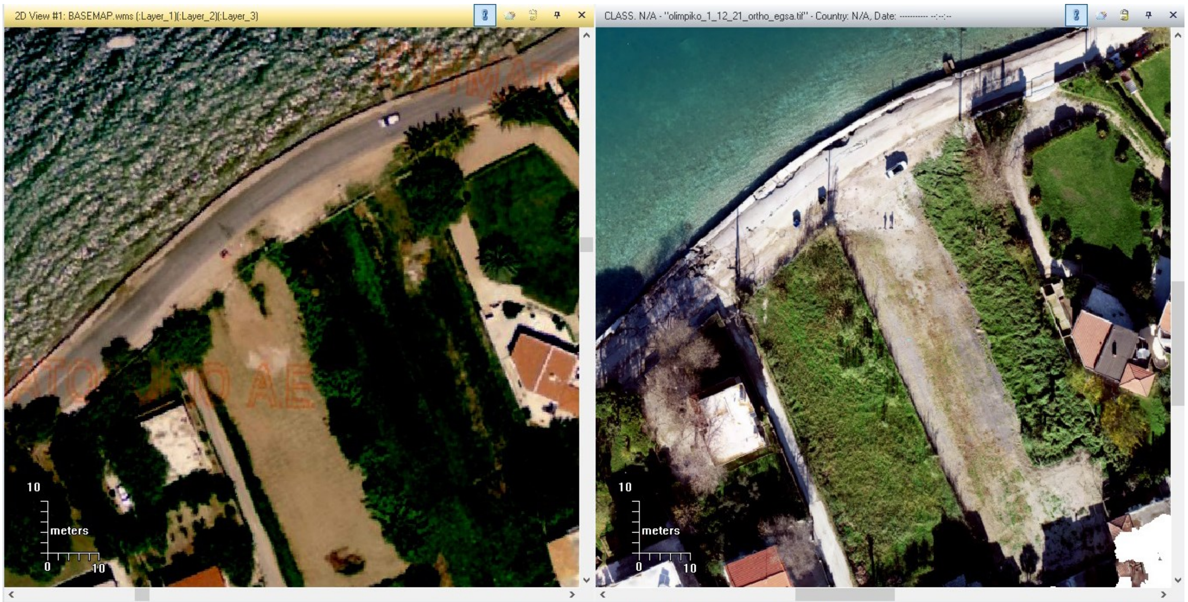

Figure 8. Damages on the road at the east coastline of Rio in November 2021.The orthophoto of the Greek Cadastral is displayed at the left, while the respective orthophoto of the UAV flight campaign of 2021 is presented at the right.

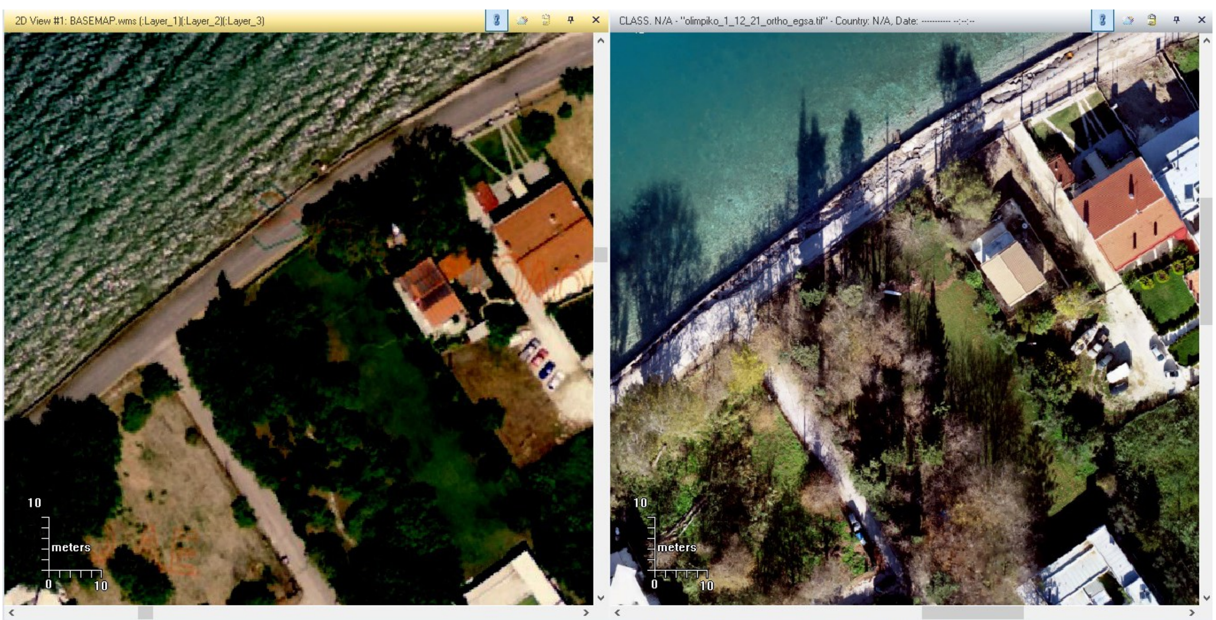

Figure 9. Damages on the road at the east coastline of Rio in November 2021. The orthophoto of the Greek Cadastral is displayed at the left, while the respective orthophoto of the UAV flight campaign of 2021 is presented at the right.

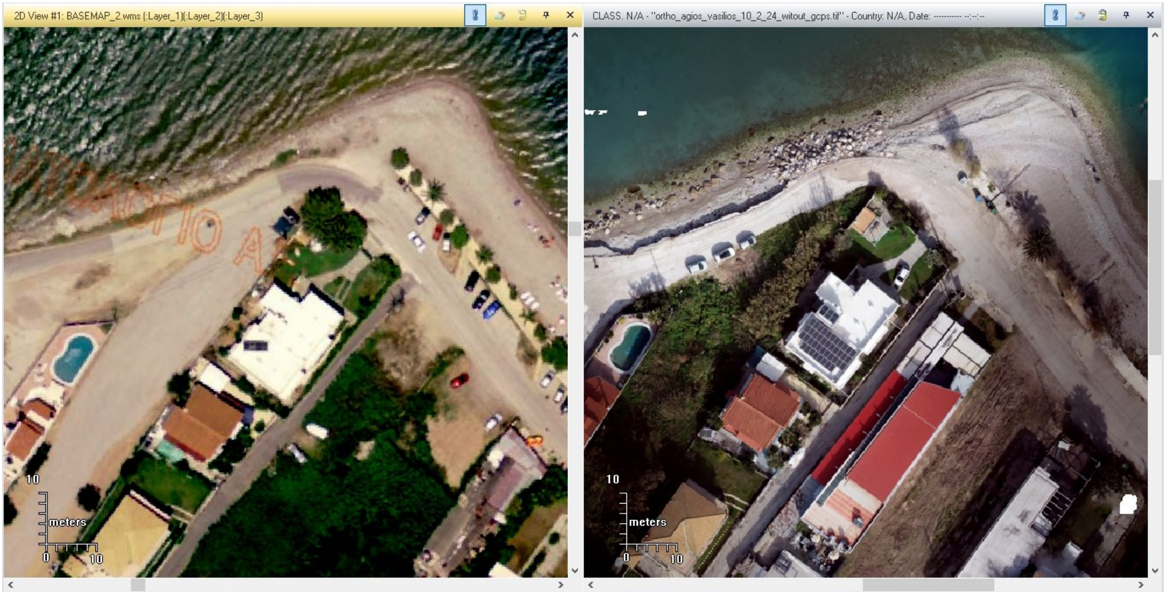

Figure 10. Damages on the road of Agios Vassilios at the east coastline of Rio in January 2024. The orthophoto of the Greek Cadastral is displayed at the left, while the respective orthophoto of the UAV flight campaign of 2024 is presented at the right.

5. METEOROLOGICAL DATA ANALYSIS

Meteorological data usually includes temperature, pressure, humidity, wind speed, wind speed high and wind direction, cloud cover, and precipitation amount. In general weather conditions affect almost all daily activities, such as social gathering, sports, leisure, holidays, etc. Extreme weather conditions may cause damages such as erosion, floods, landslides etc. In this framework, accurate weather measurements are essential to prevent or reduce the effects of unpredictable and undesirable situations.

The archive meteorological data of the two nearest stations to Rio (Rio station and Patras Station) were analysed to examine if there is a correlation between the weather conditions and the erosion phenomena. Figures 11-14 display the maximum daily wind speed of November 2017, March 2018, November 2021 and January 2024, respectively. As it can be observed from the diagrams all the erosion phenomena are correlated to very high wind speeds. In particular, in November 2017 (Figure 11) the wind speed overpasses 91km/h. In March 2018, the wind speed raises up to almost 100 km/h as presented in Figure 12, while in November 2021 the highest point is detected at almost 90km/h (Figure 13). During the latest erosional event in January 2024 the maximum wind speed was measured on January 6th at 85km/h.

To conclude, it is obvious that there is a strong correlation between the wind speed and the erosional phenomena in Rio coastline. In more detail, when the wind speed overpasses 85km/h or the value 9 in Beaufort scale, very high waves hit the coastline, provoking severe damage and erosion. At the same time, we also analyze the wind direction, and we identify that SW/NE wind strongly affect the specific area.

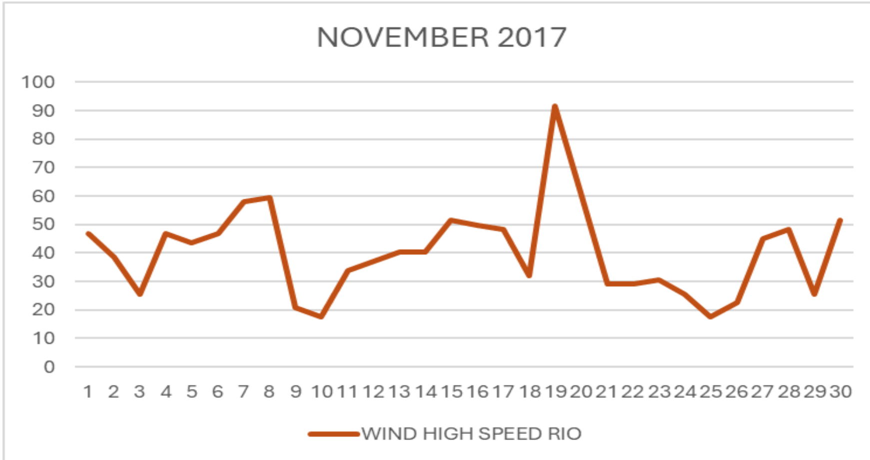

Figure 11. Wind Speed diagram of November 2017.

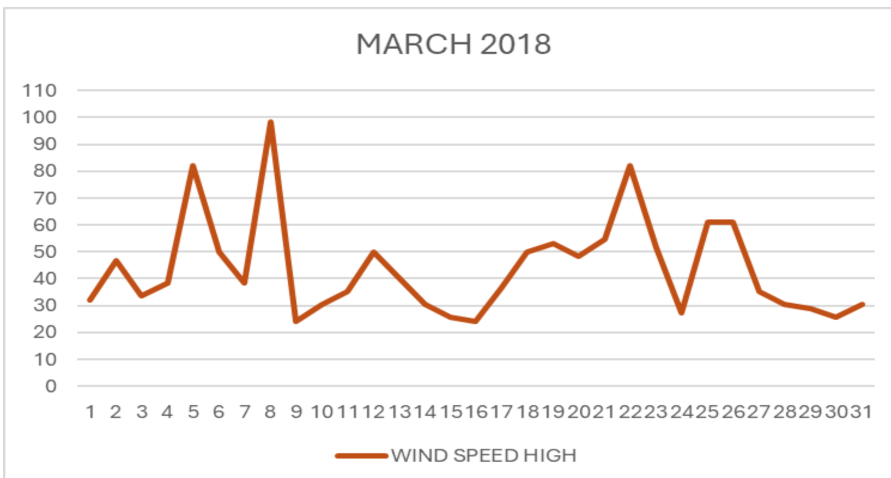

Figure 12. Wind Speed diagram of March 2018.

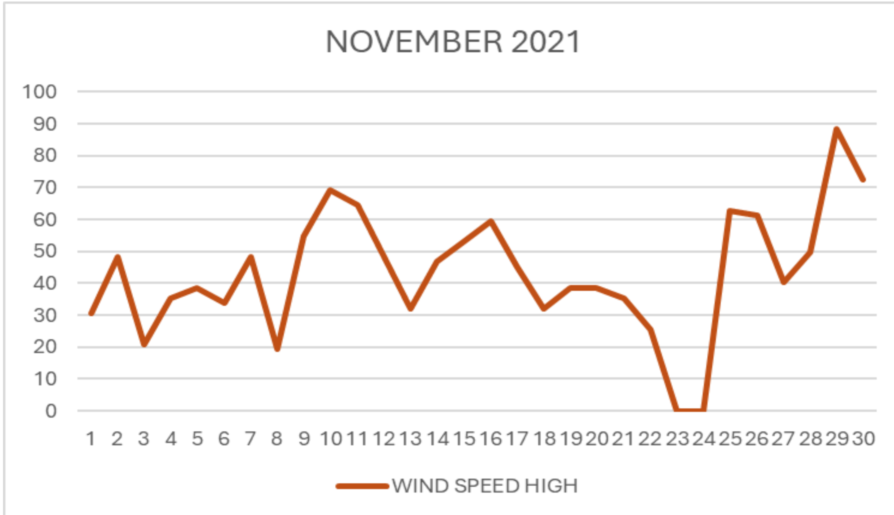

Figure 13. Wind Speed diagram of November 2021.

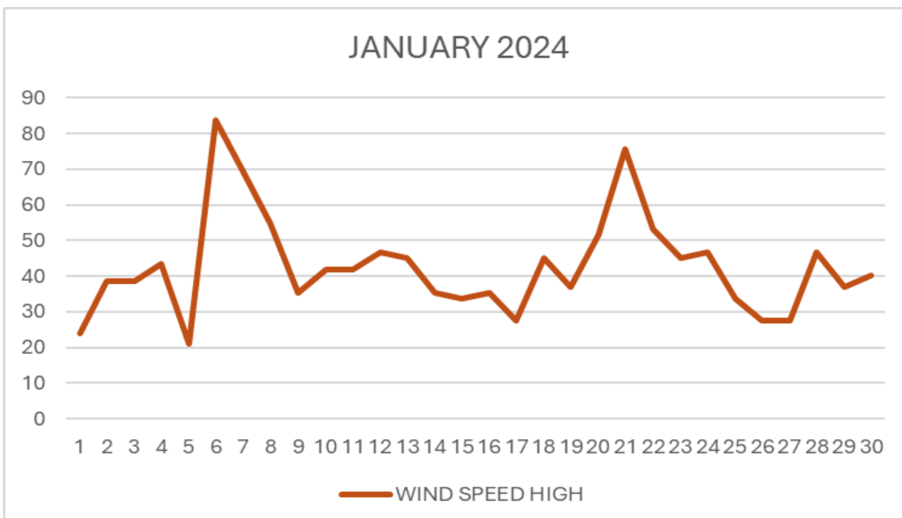

Figure 14. Wind Speed diagram of January 2024.

6. CONCLUSIONS

In the current study, UAV and GNSS data along with GIS methods were combined to map the post-disaster damages on the coastline of Rio. These erosional phenomena have been observed after weather extremes. The key-findings of the research are summarized in the following:

- UAV proved to be a valuable and accurate solution to map and monitor erosion as they are easily deployed in the field almost immediately after weather extremes.
- The analysis of the archived meteorological data proved that there is a strong correlation between the wind speed high, the wind direction and the occurrence of damages along the coastline of Rio.
- Common characteristics for all the erosional phenomena occurred in the area of interest are the following: a) a maximum daily wind speed of more than 85 km/h and b) a SW/NE wind direction.

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