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Vulnerability of Small Rivers Coastal Part Due to Floods: The Case Study of Lesvos North—West Coast †

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Abstract: This study presents the development of a vulnerability assessment methodology combining both hydraulic and oceanographic values to evaluate the fragility of the island's coast, subject to floods. The study area covers the coastal part Petra - Molyvos in North-West Lesvos Island, Greece. Petra stream drains a catchment area of 8.06 km^2. The flooded sections of the river's coastal part are analyzed by the HEC-RAS model, while the coastal vulnerability index (CVI) was calculated by the InVEST model. The scenario of habitats' role in beach protection showed 53% of coastal protection and the CVI moderate exposure to sandy beaches. A change in the geomorphology of the estuary was observed during the summer period, due to the river sediment dredging and small delta reclamation processes.

Keywords: HEC-RAS; coastal vulnerability model; erosion; Lesvos

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1. Introduction

Beaches are critical components of the coastal zone; coastal services contribute around 43% of the total benefits provided by human well-being [1,2]. Beaches provide cultural and ecosystem services, such as food, flood protection, natural environmental conservation, and recreation activities [2,3]. With the increases in multiple human activities, the bio-geological resources are being exploited, polluted, and exposed to stressful uses and pressures, increasing the coastal vulnerability. As a result, coastal erosion is threatening tourist zones and services.

Coastal erosion constitutes a contemporary environmental problem and the projections of coastal retreat under climate change and vulnerability highlight the threat to sustainable growth in the Aegean archipelagos [4,5]. The threat of coastal retreat increases as the rivers' dammed sediments are arrested in the reservoirs, which has an indirect impact on water storage due to the transportation of sediments by the surface water flow. For example, flash floods can be perceived negatively as they cause (i) damage to farms, and infrastructures, (ii) bank erosion, (iii) and the transport of sediment and coarse material [6,7]. As a large problem that puts the achievement of multiple sustainable development goals of the United Nations at risk, this should be managed through an integrated approach, considering the possibility of sustainable growth [3].

At the same time, the hydrological regimes of Intermittent Rivers and Ephemeral Streams are characterized by flow cessation and dry events at certain periods of the year [6], and ephemeral streams exhibit certain conditions during the hydro-geomorphological processes of runoff generation. Ephemeral streams are more frequent globally, and more than 50% of the river network is intermittent [8]. The Mediterranean strip is the most affected area in general, but in terms of specific regions or areas within countries, different percentages of the river network are affected. Specifically, in France, only 20% of the river network is affected, while in Sardinia and Sicily, 90% of the river network is affected. Additionally, in the southeast of Spain, more than 70% of the fluvial systems are ephemeral streams [9]. The flowing phase enhances sediment transport, while the non-flowing and dry phases facilitate river access and sand and gravel extraction [5].

This paper combines the main results with an analysis of floods after flushy rain episodes and the coastal erosion vulnerability of the sandy and rocky beaches. The aim is to discuss how ephemeral streams could behave to water and sediment balance in a touristic beach, under human and natural pressures. Vulnerability calculation was done using InVEST Coastal Vulnerability index, combining oceanographic and ecological parameters, while HEC-RAS was used to calculate the critical cross-sections in the Petra River.

2. Materials and Methods

2.1. Study Area

The study area covered the coastal part from Petra to Molyvos in west–north Lesvos Island, Greece (Figure 1). The area is characterized by a typical Mediterranean climate with warm and dry summers and cold and wet winters. The mean annual precipitation is 545 mm, and the mean temperature is 17.39 °C. During the winter, the precipitation records showed January, February, and December as the wet months. The main wind directions are north–northeastern, with a maximum intensity of from 4 to 5 bft and 5 to 6 bft. A Petra stream of 1.75 km in length drains a catchment area of 7.97 km^2, with a mean width of 6.15 m, a mean slope of 1.03%, and a mean depth of 1.63 m, and flows into the Aegean Sea.

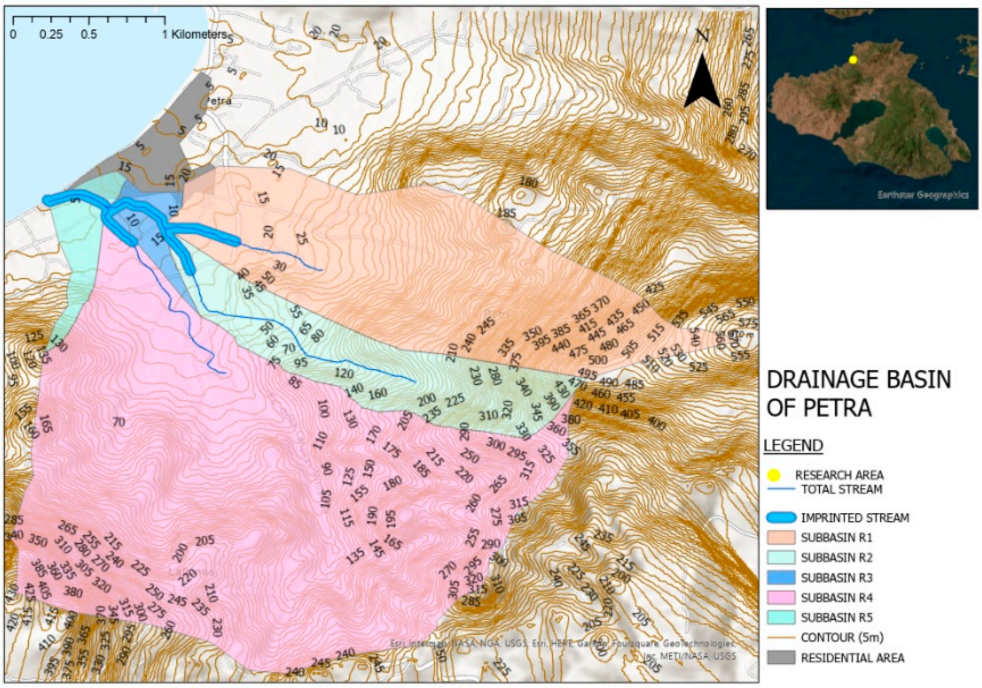


Figure 1. Petra catchment: The basin was divided into 5 subbasins to analyze the mainstream Petra River.

2.2. Coastal Vulnerability Models

The InVEST Coastal Vulnerability model is widely still used to assess coastal erosion, and can provide a framework for regional coastal zone protection and future development planning. To estimate erosion from coastal hazards for people throughout the Petra–Molyvos coastline, we mapped and valued the changes in ecosystems, which could help to convert in the flow, obtaining many different benefits [4]. The model builds on previous, similar indices that account for bio-geophysical components to compare their exposure to erosion and flooding in severe weather [5]. The InVEST CV model produces a qualitative index of coastal exposure to erosion, as well as summaries of human population density in proximity to the coastline. The exposure of erosion in the study area is defined by calculating the coastal vulnerability index (CVI), which ranks sites from lowest exposure (rank = 1) to highest risk of erosion (rank = 5) and inundation using the following variables: habitat type, the local bathymetry and topography, the relative wind and wave force associated with storms, and the population density (Equation (1)).

$$CVI = (R_{Habitats} R_{Shorline\ Type} R_{Relief} R_{Waves} R_{Surge})^{1/5} \quad (1)$$

2.3. HEC-RAS Model

The software (version 6.3.1) Engineers River Analysis System (HEC-RAS) developed by the Hydrologic Engineering Center allows for users to model rivers flowing through open natural channels and is used to compute water surface profiles [10]. The HEC-RAS system can simulate one-dimensional, steady-flow, water-surface profile computations and uses geometric and hydraulic computation routines. The river geometries, such as centerlines, bank lines, flow paths, and cross-sectional lines, are the major parameters processed in HEC-RAS to generate flood-prone areas [10].

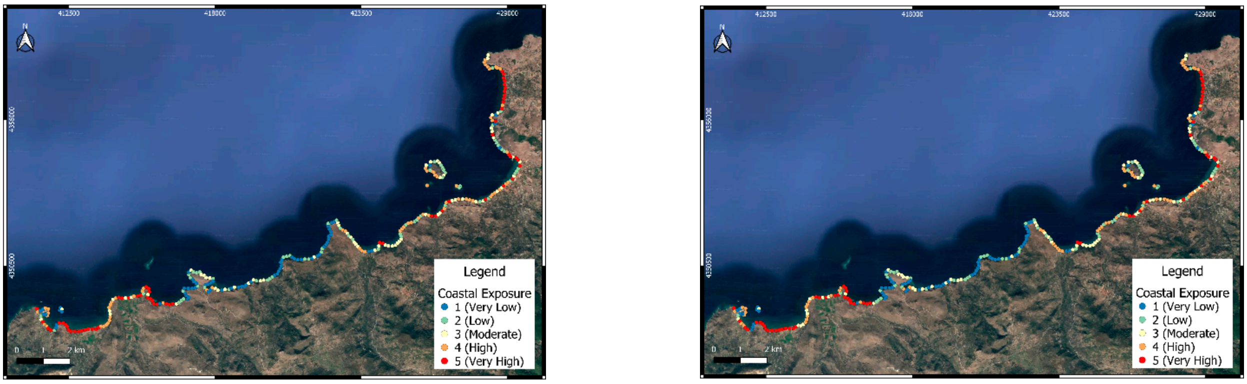
3. Results

The Aegean Archipelago climate, water masses' movement, and geomorphology have developed a strong ecological and human resilience to degradation. However, both environmental and anthropogenic changes are threatening the precarious balance between water resources and flood risk [7].

3.1. Coastal Vulnerability

Natural activities play a significant role in coastal vulnerability. The Aegean circulation ends with a northern flow in the eastern basin. The passage between Asia Minor, Chios, and Lesvos has more kinetic energy than the rest of the eastern basin (low kinetic energy) due to the 200 m isobath, which turns to the east. Additionally, the currents near Petra have low kinetic energy [11]. The complex physiography of the Aegean archipelago influences the wind, in addition to the wave climate. In general, wind and waves occur because of the short fetches and relatively mild duration [2]. The wind and waves on the Northern Aegean coastlines are mostly northern in direction, and as a result, they occur frequently on the Petra-Molyvos coastline. Although waves are generally more energetic in the winter season, even in the summer, energetic waves can be found the Aegean Sea and in Petra, which are mainly forced by the strong, dry N–NE 'etesian' winds [12,13].

The results of the InVEST Coastal Vulnerability model showed that the main exposed areas of erosion are sandy beaches. The two vulnerability scenarios—with habitats (Figure 2a) and without habitats (Figure 2b)—showed the importance of habitats in beach protection. A total of 13% of the coastal zone showed a high risk of erosion (rank = 4–5) and 21% of the coastal zone had moderate risk (rank = 3) for the scenario without habitats. The vulnerability scenario with habitats obtained a score of 53% for coastal protection, and the CV index showed moderate risk (rank = 2–3). Additionally, the results from the CV index showed low exposure (rank = 1–2) to rock beaches and high exposure (rank = 4–5) to sandy beaches (Figure 3).



(**a**) (**b**)

Figure 2. Map of Petra–Molyvos' exposure to erosion (**a**) with the habitats variable and (**b**) without the habitats variable.

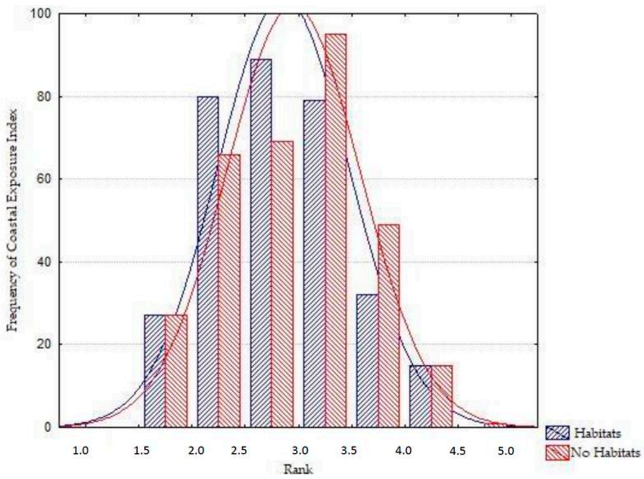


Figure 3. Histogram with a frequency of the occurrence of observed coastal vulnerability index values.

3.2. Hydraulic Study

The Froude value at the location R5 (Table 1) of the cross-section S2 is 0.15 and is characterized as subcritical. This cross-section is located 17 m upstream (Figure 4a,b) the mouth of the stream towards the sea. It presents the lowest velocity and energy line slope values in the branch (v = 0.57 m/s, slope = 0.0005 m/m), and the mean velocity of 1.33 m/s. The Froude value at the cross-section S18 location is 0.14 (Figure 4a,c) and is characterized as subcritical. The S18 has the smallest geometry in the branch. The velocity and slope values of the energy line are also small (v = 0.48 m/s, slope = 0.0005 m/m), and the branch average velocity is 1.10 m/s. The Froude value at the cross-section S26 location is 0.44 (Figure 4a,c) and is characterized as subcritical. The S26 geometry is the second smallest for the branch. The power line velocity and gradient values are low throughout the branch, with the cross-section values of v = 0.87 m/s, slope = 0.0059 m/m, and the branch average velocity is 0.90 m/s. Upstream of the cross-section, there is a hydraulic jump where the flow changes from supercritical to subcritical. The Froude value at the cross-section S32 location is 0.27 (Figure 4a,e), and the velocity and slope of the energy line are significantly lower than all other cross-sections (v = 0.66 m/s, slope = 0.001856 m/m). The wetted surface is the largest present in branch R1, while the branch average velocity is equal to 1.42 m/s. Finally, the Froude value at the cross-section S37 location is 0.43 (Figure 4a,f) and is characterized as subcritical. The velocity and slope of the energy line are the third smallest (v = 0.99 m/s, slope = 0.006421 m/m). The cross-section shows the second smallest geometry, and the branch average velocity is equal to 1.25 m/s. The simulation results show that, under flashy rain events, several cross-sections of the stream are overflooded.

Table 1. Stream of Petra's hydraulic characteristics.

Stream of Petra					
Reach	**Subbasin Area (km^2)**	**Subbasin Δη (m)**	**Reach Length (m)**	**Q (m^3/s)**	**Overflow Section**
R1	2.06	560	375	2.15	S32
R2	0.87	485	317	1.40	S37
R3	0.14	15	399	1.55	S26
R4	4.65	345	258	3.90	S18
R5	0.20	145	367	8.50	S2

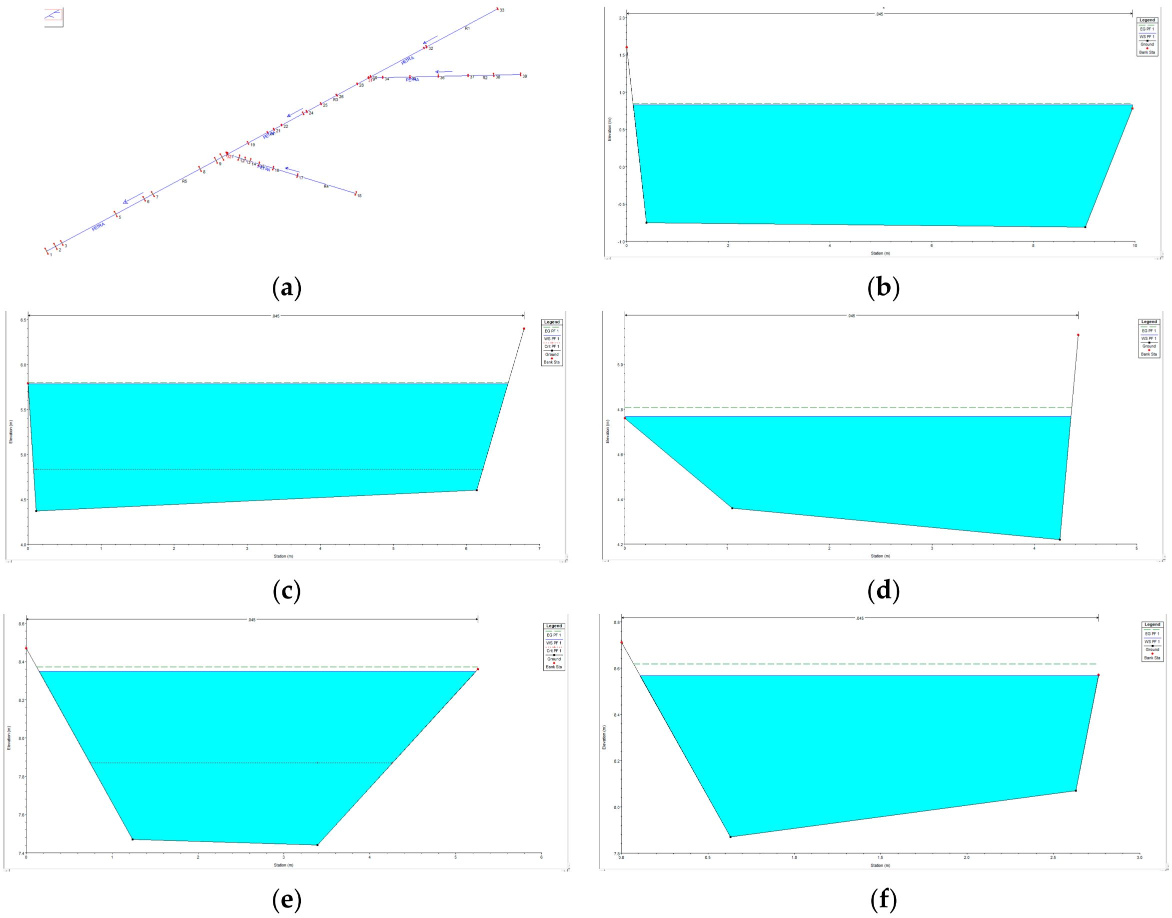


Figure 4. The critical cross-section and the stream plot: (**a**) the Petra stream (**b**) S2, (**c**) S18, (**d**) S26, (**e**) S32, and (**f**) S37.

4. Conclusions

The paper analyses the importance of rivers in the sediment transport balance in the coastal zone of Molyvos-Petra. It discusses the factors affecting coastal streams after flashy rain episodes and the vulnerability of the sandy and rocky beaches. Concluding, how ephemeral streams could behave to sediment balance in a touristic beach, under human and natural activities.

Multiple indicators are used to evaluate the vulnerability of each coastline. According to the results, the habitat is an important part of the coastal zone, and its influence on coastal exposure plays a significant role. All kinds of habitats, whether along the coastline or in the water, have protective effects on the coast [14]. Further, if the coastline is composed of many rocks, low in exposure and high in relief, it can reduce the erosion of waves on the coast. However, the coastline composed of sandy beaches, which are high in exposure and low in relief, has little effect on reducing the impact of wind and waves [14].

Moreover, the hydraulic analysis of the Petra River, during the rainy events showed low velocities in geometrically small cross-sections. People should pay more attention to some impacts, such as storm surges, floods, coastal erosion, and other natural disasters that endanger the economy, life, property safety, and the ecological environment around the coastal zone when people focus on the development of the coastal zone [14].

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