PRIORITIZATION OF BEACH VULNERABILITY TO SEA LEVEL RISE: THE CASE OF SANTORINI, GREECE

Monioudi I.N.*, Markozanes F., Velegrakis A.F., Chatzipavlis A.E., Ćulibrk A., Kontopyrakis K.E.

Department of Marine Sciences, School of Environment, University of the Aegean, University Hill, 81100, Mytilene, Greece

Abstract

An indicator-based framework was developed to rank beaches, at an island scale, according to their socio-economic significance and vulnerability to sea level rise. The purpose of the analysis is to prioritize/select beaches for detailed assessment of beach erosion risks and design of requisite adaptation measures. The framework was employed for the case study of Santorini Island. Beach erosion risk due to mean and extreme sea level rise under Climate Variability and Change (CV&C) was assessed using cross-shore morphodynamic model ensembles and information (geo-spatial and socioeconomic parameters) that was recorded from readily available historical satellite imagery. Appropriate indicators which are relevant, representative, and measurable were selected and multicriteria approaches were used to optimize indicator weights and to rank the beaches according to their vulnerability to CV&C. This contribution addresses the need for a simple model for managers to employ when planning strategies for the management of touristic beaches under sea level rise.

Keywords: *beach erosion, climate variability and change, morphodynamic models, multi-criteria methods, coastal management*

*Corresponding author: Isavela N. Monioudi (imonioudi@marine.aegean.gr)

1. Introduction

Beach erosion, which is projected to greatly increase under CV&C, poses significant threat to island beaches, as they have limited dimensions and sediment supply (Monioudi *et al.* 2017) and in many cases, constitute major tourism destinations (e.g., Uyarra *et al.* 2005). As a consequence, beach carrying capacity and beach suitability as environments of leisure, might be significantly reduced, resulting to significant international travel expenditure loss and affecting local and national economies (e.g., Scott *et al.* 2012). In addition, the magnitude of the problem and the potential costs of the requisite adaptation measures (e.g., Narayan *et al.* 2016), require response prioritization according to carefully selected criteria which will enable the efficient allocation of the limited, in most cases, human and financial resources. The present work attempts to contribute to the discussion by developing a prioritization framework, which is applied to Santorini, one of the most touristic Greek islands.

2. Material and Methods

2.1 Beach erosion projections

The geo-spatial characteristics (i.e., max. width, area, sediment type), human development features (i.e., accessibility, density of backshore assets) and socio-economic parameters (e.g., beach development, carrying capacity, hotels/restaurants) of all Santorini beaches (30 were identified) were recorded. The spatial characteristics of these beaches were recorded on the basis of the images and other related optical information available in the Google Earth Pro application. The ‘dry’ (subaerial) parts of these beaches were digitized as polygons bounded on their landward side by either natural boundaries (vegetated dunes and/or cliffs) or permanent artificial structures (e.g., coastal embankments, seawalls, roads, and buildings) and on their seaward side by the shoreline. From these polygons, identification of spatial characteristics of the beaches i.e., beach maximum width (BMW), length and area were estimated. Historical changes (Figure 1a) were also studied through the historical imagery available in the Google Earth Pro application. Constraints in the approach can stem from the accuracy/resolution of the (not properly georectified) images and the varying hydrodynamic conditions during the image collection that can affect shoreline delimitation. These may introduce uncertainties which, however, cannot be avoided in regional studies.

Beach retreats under CV&C were projected using 1-D (cross-shore) morphodynamic model ensembles, following the methodology described in Monioudi *et al.* (2017). Specifically, beach retreat (erosion) was assessed with regard to; (a) relative sea level rise (RSLR) and high tide and (b) 1-100 year Extreme Sea Level (ESL, i.e. storm-induced water levels superimposed on RSLR and high tide), projected for the years 2050 and 2100 under the IPCC RCP8.5 scenario. Projections of the RSLR, tide and ESL$_{100}$ specifically for the island of

Santorini were abstracted from the JRC (Joint Research Centre) database (https://data.jrc.ec.europa.eu/collection/liscoast) (Vousdoukas *et al.* 2017). Given the large scale of the application (Island scale), the input data of the models could not be based on in situ measurements. Therefore, the models were set up using a plausible range of environmental conditions (i.e., combinations of different beach slopes, wave conditions and sediment size).

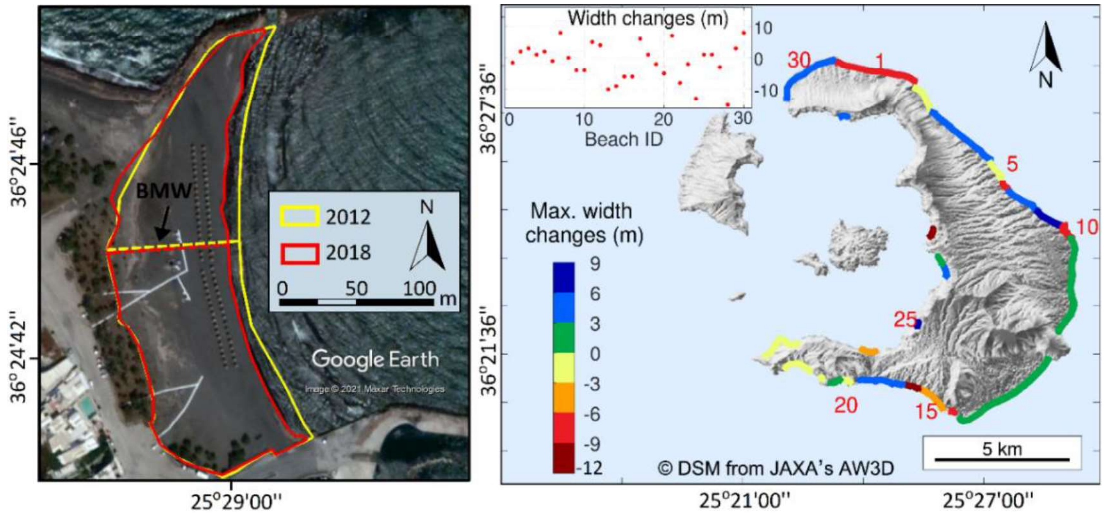

Figure 1. (a) Beach delimitation in the historical imagery (Monolithos beach (ID: 9) is used as an example); (b) historical changes in the recorded BMW. Changes shown are between the years 2012 and 2018.

2.2 Prioritization Framework Using a Multi-Criteria Approach

A prioritization framework was developed to rank beaches, at an island scale, based on their socio-economic importance and vulnerability to CV&C. The first step of the analysis concerned the selection of the most (i.e., the 10 highest ranking beaches) touristic and thus socio-economically important beaches (e.g., Andreadis *et al.* 2021). The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) multi-criteria method was used due to the large number (30) of alternatives (beaches); according to Zavadskas *et al.* (2016), this method is much less affected by the number of alternatives and criteria (indicators) compared to other available methods. The socio-economic indicators used for this step of the analysis are: (1) the touristic activity, based on the number of hotels and restaurants at and in the vicinity of the beach; (2) beach development/usage, based on the number of recorded umbrellas and sun beds during high season (summer) period; (3) beach "urbanization" which is the density (%) of the backshore infrastructure/assets found immediately (throughout the first line in the backshore zone) behind the beach in relation to the shoreline length; (4) beach accessibility, based on the state of the road (or the absence of, in the case of beaches that can only accessed through the sea) that leads to the beach and the distance from the main road network; (5) Blue Flag awards (in 2021), which are perceived as markers of beach quality by users (Tzoraki *et al.* 2018); (6) the beach area as an indicator of the beach carrying capacity (considering 10 m^2/per person); (7) the sediment type, which is used as an indicator of the beach recreational (hedonic) value, since users mostly prefer sandy beaches. The second step of the analysis involved the prioritization of the selected beaches in terms of their socio-economic significance and their erosion risk under CV&C, using a detailed pair-wise Analytical Hierarchy Process (AHP) multi-criteria approach. For this step, additional to the aforementioned (1-7) indicators, the following were used to describe the beach erosion risk under current (today) conditions: (8) the maximum beach width (BMW), which is a crucial spatial feature, as it does not only control the beach vulnerability to erosion but also the exposure of the backshore infrastructure/assets; (9) the historical trends of erosion/accretion, based on the maximum width changes. The sediment type (indicator 7) also affects the beach erosion potential, whereas the beach "urbanization" (indicator 3) increases the exposure/ impact potential from beach retreat. The AHP procedure was repeated to rank beach vulnerability under future (CV&C) conditions; in these cases, the "width reduction", expressed as a percentage of the current BMW, was used as an indicator instead of the BMW, whereas the "asset exposure" (i.e., whether or not the backshore infrastructure/assets will be impacted under a future ESL_{100}) was used instead of the "historical trends".

3. Results

3.1 Beach erosion

The analysis of the historical imagery showed discernible decreases (erosion) of up to ~12 m in the beach maximum widths (BMWs) for 16 beaches and increases (accretion) of up to ~8 m for 14 beaches (Figure 1b), between the years 2012 and 2018. Concerning the future, due to the different conditions used in the model set ups, the ensembles produced a range of beach erosion projections. For each studied scenario, the 10th and 90th percentile of the projected range were estimated and compared with the maximum recorded beach width, resulting to the indicator "width reduction" (see section 2.2).

Table 1. The 10th and 90th percentile of beach retreat estimates by the model ensembles. Percentages of the beaches that will be retreated/inundated more than 50% of their current BMW and more than their current BMW. Numbers (N) and percentages of beaches where backshore infrastructure and assets are projected to be impacted are also shown.

Sea Level Rise (RCP8.5)			Retreat (R)/ Inundation(I) (m)		R/I to 50 % of max. width (%)	R/I to max. width (%)	Beaches with assets affected	
	Year	(m)					N	%
RSLR + tide	2050	0.30	10th	2.3	0	0	0	0
			90th	8.9	40	0	0	0
	2100	0.84	10th	8.3	23	0	0	0
			90th	24.9	83	67	12	40
ESL_{100}	2050	1.29	10th	15.4	70	20	5	17
			90th	47.8	100	83	17	57
	2100	1.88	10th	27.3	87	70	13	43
			90th	82.1	100	100	22	73

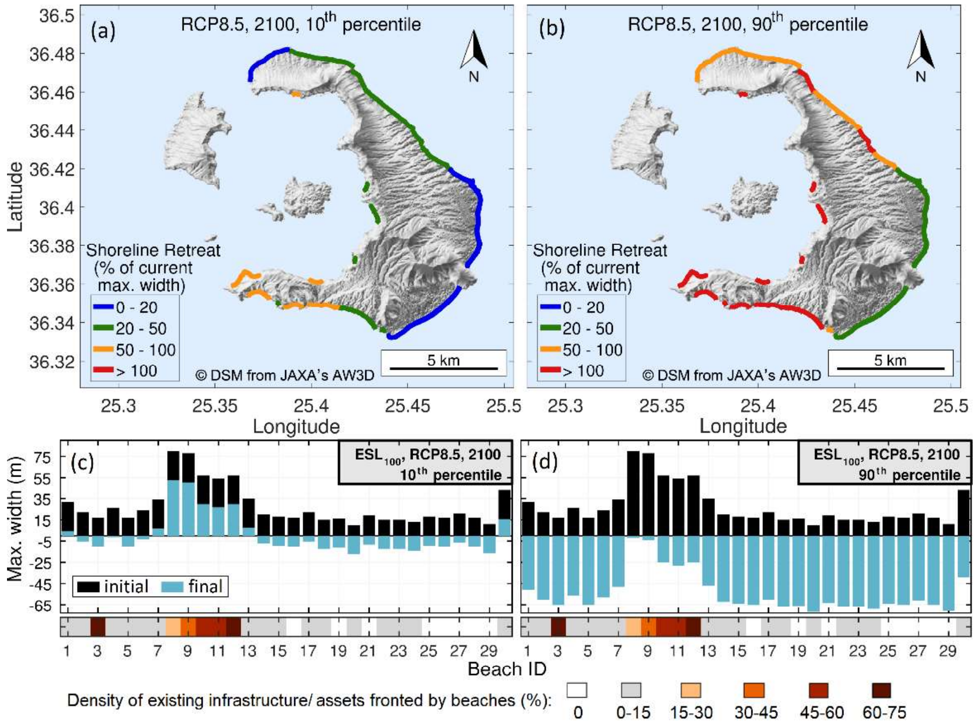

Figure 2. The percentages of the current BMWs of the 30 Santorini beaches projected to be eroded under RSLR and tide based on the (a) 10th and (b) 90th percentile of beach retreat estimates. In the lower panels, the (c) 10th and (d) 90th percentile of the shoreline retreat/inundation under an ESL_{100} are shown together with the recorded density of the backshore assets (as a percentage of the beach length). The current (initial) BMWs (black bars) are compared with those resulting from temporary inundation /retreat (blue bars); negative values indicate total beach inundation.

Under sea level rise of 0.30 m, projected for the year 2050 under RCP8.5, there could be some impacts on the basis of the high (90th percentile) projections of the morphodynamic modelling (Table 1). For the year 2100 under the same scenario, it appears that the selected beaches would be seriously affected due to the projected sea level rise (0.84 m); beach retreat is estimated between 8.3 m and 24.9 m and 67 % of the beaches might see their BMW reduced by up to 100 % (Table 1). Many of these beaches lack the accommodation space to retreat landwards and, thus, will suffer coastal squeeze without appropriate replenishment.

The 100-year ESL (ESL_{100}) in 2050 and 2100 will result in storm beach erosion of up to about 47.8 and 82.1 m, respectively under the RCP8.5 scenario. Substantial impacts are projected as early as 2050 and according to the most conservative projections, about 70 % of all beaches are projected to lose at least 50 % of their current maximum widths and 20 % to be completely eroded under the ESL_{100} (Table 1). In terms of asset exposure, at least 17 % of the beaches presently fronting assets are projected to be overwhelmed during the event. In 2100, impacts could be devastating. Under the RCP8.5 ESL_{100}, 70-100% of all beaches will be completely (at least temporarily) eroded (43–73% of the beaches fronting assets) under the low (10th percentile) and high (90th percentile) projections, respectively (Figure 2). These frontline backshore assets will sustain damages even in the case of a partial (or total) post-storm beach recovery as they are located within the beach erosion-recovery envelop.

3.2 Island Beach Prioritization

For the first stage of the analysis, in order to define the weights (or relative importance) of the indicators (1–7) adopted for the TOPSIS application, AHP was initially used to perform pairwise comparisons based on expert judgments and using a 1–9 scale (Saaty 2008). Adjustments were made to ensure the consistency of the derived pairwise matrix (Consistency Ratio, CR = 0). Following the identification of the possible pairs, suitable weights were assigned to each indicator/criterion using eigenvectors. The selected indicators are not all measured in the same units; thus, vector normalization was used to ensure uniformity and comparability. Then, the TOPSIS method was applied to estimate the preference scores (Figure 3b). The 10 selected beaches with the higher scores are depicted, in red, in Figure 3a and 3b.

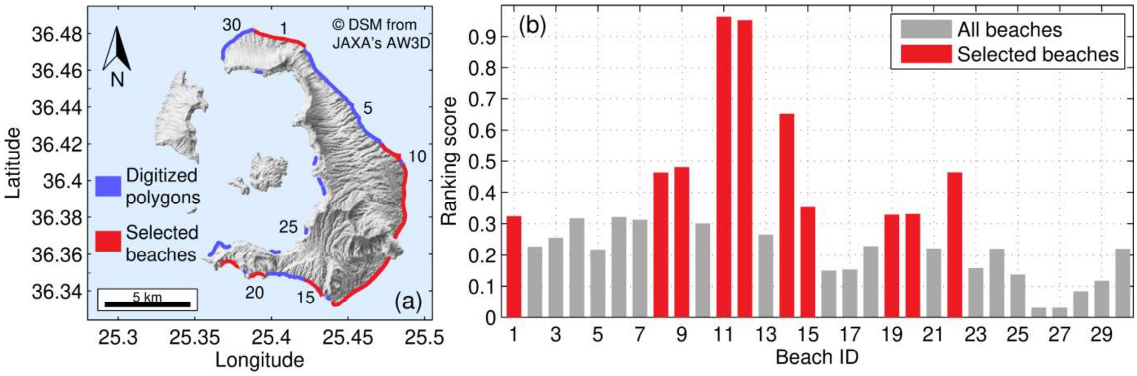

Figure 3. (a) Digitized polygons of Santorini beaches (clockwise beach numbering starting from the north) and selected beaches; (b) ranking scores of all 30 recorded beaches (TOPSIS method) according to their socio-economic significance; the 10 most highly ranked beaches are shown in the red color.

Regarding the second step of the analysis, the AHP multi-criteria approach was applied in order to rank the 10 selected beaches. The weights (or relative importance) of the indicators/criteria (1–9) were defined using the same procedure as in the previous stage. AHP was also used to perform pairwise comparisons among the alternatives (beaches) (matrix consistency was ensured) and then, using the eigenvector method, priority scales were defined for all alternatives and for each indicator/criterion. The final (global) preference score for each alternative (beach) was calculated using the Weighted Product Model (WPM). The whole procedure was repeated 5 times including the current status and the lowest (10th percentile) and highest (90th percentile) and retreat estimates under two IPCC scenarios (Table 2). Kamari beach, followed by Perissa and Vlychada beaches, consistently showed the highest scores, suggesting that these beaches are, the most socio-economically important and vulnerable to beach erosion under CV&C and, thus, should be of highest importance in the list for adaptation measures. It has to be mentioned that the above ranking, depends on the weights assigned to each indicator, which has been based on expert judgment; increasing the number of the interviewed experts will, in turn, adjust the scores.

Table 2. Ranking scores (AHP analysis) of the 10 selected beaches, regarding the beach vulnerability to CV&C. Results are for the current status and future projections under the RCP8.5 emission scenario for the years 2050 and 2100. For beach location see Figure 3a.

	Current	RCP 8.5, 2050		RCP 8.5, 2100	
		10th	90th	10th	90th
1. Baxedes	0.0644	0.0622	0.0726	0.0603	0.0658
8. Monolithos 1	0.0500	0.0551	0.0521	0.0524	0.0574
9. Monolithos 2	0.0739	0.0704	0.0666	0.0681	0.0738
11. Kamari	**0.2510**	**0.2527**	**0.2424**	**0.2455**	**0.2683**
12. Perissa	0.2323	0.2346	0.2251	0.2279	0.2472
14. Vlychada	0.0986	0.0871	0.1017	0.1033	0.0889
15. Eros	0.0662	0.0617	0.0713	0.0722	0.0612
19. Kokkini	0.0422	0.0407	0.0389	0.0395	0.0327
20. Kampia	0.0453	0.0519	0.0495	0.0501	0.0383
22. Mesa Pigadia	0.0761	0.0835	0.0798	0.0807	0.0663

4. Conclusions

The proposed framework can represent the status of island beaches, based on quantifiable geo-spatial and socio-economic characteristics and projections of beach erosion/retreat under different scenarios of mean and extreme sea level rise. It can provide coastal managers and policy makers, better insights on the challenges posed by beach erosion in island settings as well as with a framework for prioritization of adaptation responses and efficient resource allocation.

Acknowledgements

This research was supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the “2nd Call for H.F.R.I. Research Projects to support Post-Doctoral Researchers” (Project Number: 211).

References

Andreadis O., Chatzipavlis A., Hasiotis T., Monioudi I., Manoutsoglou E., Velegrakis A. (2021). Assessment of and Adaptation to Beach Erosion in Islands: An Integrated Approach. J. Mar. Sci. Eng. 9, 859.

Monioudi I.N., Velegrakis A.F., Chatzipavlis A.E., Rigos A., Karambas T., Vousdoukas M.I., Hasiotis T., Koukourouvli N., Peduzzi P., Manoutsoglou E., Poulos S.E., Collins M.B. (2017). Assessment of island beach erosion due to sea level rise: the case of the Aegean archipelago (Eastern Mediterranean). Nat. Hazards Earth Syst. Sci. 17, 449–466.

Narayan S., Beck M.W., Reguero B.G., Losada I.J., van Wesenbeeck B., Pontee N., Sanchirico J.N. Ingram J.C., Lange J.-M., Burks-Copes K.A. (2016). The Effectiveness, Costs and Coastal Protection Benefits of Natural and Nature-Based Defences. PLoS ONE 11(5), e0154735.

Saaty T.L. (2008). Relative measurement and its generalization in decision making why pairwise comparisons are central in mathematics for the measurement of intangible factors the analytic hierarchy/ network process. Rev. R. Acad. Cien. Serie A. Mat. 102, 251–318.

Scott D., Simpson M.C., Sim R. (2012). The vulnerability of Caribbean coastal tourism to scenarios of climate change related sea level rise. J. Sustain. Tour. 20, 883–898.

Tzoraki O., Monioudi I., Velegrakis A., Moutafis N., Pavlogeorgatos G., Kitsiou D. (2018). Resilience of touristic island beaches under sea level rise: A methodological framework. Coast. Manag 46, 78–102.

Uyarra M.C., Côté I.M., Gill J.A., Tinch R.R.T., Viner D., Watkinson A.R. (2005). Island-specific preferences of tourists for environmental features: implications of climate change for tourism-dependent states. Environ. Conserv. 32, 11–19.

Vousdoukas M.I., Mentaschi L., Voukouvalas E., Verlaan M., Feyen L. (2017). Extreme sea levels on the rise along Europe’s coasts. Earth’s Future 5(3), 304–323.

Zavadskas E.K., Mardani A., Turskis Z., Jusoh A., Nor K.MD. (2016). Development of TOPSIS Method to Solve Complicated Decision-Making Problems — An Overview on Developments from 2000 to 2015. Int. J. Inf. Technol. Decis. Making 15(03), 645-682.