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Protection and Management of the Annunziata River Mouth Area (Italy)

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ABSTRACT: A better understanding and prediction of the dynamic processes that govern the coastal zone is the topic of the current paper; in particular, a deep investigation of the coastal processes that affect the shoreline dynamic and flood inundation risk is carried out at the Annunziata river mouth area (Italy). The Annunziata River is situated in the Northern part of Reggio Calabria city; it is, at the same time, a source of danger and an important environmental and hydrological resource for Reggio Calabria, since on the right side there is the city port and on the left side there is the public beach. The protection and management of coastal areas should be supported by a deep knowledge of the interaction between water motion and seabed topography, which affects the natural response of coastal systems to changes in external conditions and to human interferences. This work tries to analyze the coastal morphology through the use of some recent models based on spectral theory.

KEYWORDS: coastal protection and management, run-up, longshore sediment transport

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Introduction

Coastal morphology refers to the study of adaptation of the coastline, driven by wave-, current- and wind-induced sediment transport. Coastal morphological models are indispensable and powerful tools that allow us to set up a reliable protection and management plan for coastal areas.

Morphological models are based on various sub-models related to each of the physical phenomena involved in the dynamics of the coast such as storms, waves, longshore sediment transport (LST), set-up, run-up, shoreline evolution and wave structure interaction.

LST is the natural movement of sand along coasts, and it is connected to the wave-induced current and to the energy dissipation caused by breaking waves in the surf zone.[1] This energy is partially converted into potential energy as run-up, often expressed in terms of a vertical excursion upon the mean water level. The physical description and quantification of these phenomena are frequently carried out by means of numerical models.[3]

A sea storm is defined as a sequence of sea states in which the significant wave height H_s exceeds a given threshold. Predicting and defining sea storms[4,5] plays an important role in the study of coastal morphology. This is also important for wave modeling, since a reliable model for a storm approximation gives us an opportunity to predict extreme waves.[6]

The mutual interaction of these phenomena could cause advancement or retreat of the shoreline. Retreat is not desirable, especially where there are human settlements or transport infrastructures. Shoreline retreat is a natural process which is often accelerated by human activities,[7] which through the construction of coastal structures affect the natural evolution of the shoreline.[8,9] In these cases it is important to maintain a deep knowledge and investigation of the interaction between wave and structure[10–12] in order to avoid failure of the intervention.[13,14]

Run-up Estimation

Waves approaching the coasts dissipate most of their energy by breaking across the surf zone. However, a part of this energy is partially converted into potential energy as run-up on the foreshore of the beach.[4,5]

Wave run-up (defined as the time-varying location of the shoreward edge of water in front of a beach) is often expressed in terms of a vertical excursion consisting of 2 components: a super elevation of the mean water level (MWL), called as wave set-up, and fluctuations about that mean, called as swash.[2] Recent studies demonstrate that the value of the set-up is strongly influenced by the wave obliquity.[15] The set-up value is inversely proportional to the dominant direction of the wave group; consequently, a correct estimation of the directional spreading is necessary to obtain a correct evaluation of the set-up.[16]

The exact evaluation of the run-up and set-up and an understanding of the elements on which they depend are 2 fundamental aspects of the estimation of coastal risks, and of the planning and management of shore protection plans. Indeed, they are the main causes of erosion of beaches and coastal dunes,[17–19] as well as flooding of coastal areas.

Barbaro et al[20] described a probabilistic approach for estimating run-up levels. It is based on the equivalent triangular storm (ETS) model proposed by Boccotti[18] and it has been applied in conjunction with the empirical relation proposed by Stockdon et al.[2]

The probabilistic approach has been applied to estimate the return period of a storm in which run-up exceeds a fixed threshold. Further, the mean persistence of run-up above a fixed threshold has been calculated. This analysis has shown that characteristics of the waves and of the beach under examination are needed for a probabilistic estimation of the run-up.

The return period of a run-up level that is higher than a fixed threshold is:

$$R\left(R_{u2\%} > X\right) = \left[\sum_{i=1}^{N} \frac{1}{R\left(H_s > h; \theta_i - \Delta\theta/2 < \theta < \theta_i + \Delta\theta/2\right)}\right]^{-1} \quad (1)$$

where $R_{u2\%}$ is the run-up value and $R\,(H_s > h;\ \theta_i - \Delta\theta/2 < \theta < \theta_i + \Delta\theta/2)$ is the return period of a sea storm in which the significant wave height H_s exceeds a fixed threshold h and the dominant direction θ ranges from $\theta_i - \Delta\theta/2$ to $\theta_i + \Delta\theta/2$, which are explicitly calculated by the ETS model and it is given by the equation[21]:

$$R\left(H_s > h; \theta_i - \Delta\theta/2 < \theta < \theta_i + \Delta\theta/2\right) = \frac{\bar{b}\left(h; \theta_i - \Delta\theta/2 < \theta < \theta_i + \Delta\theta/2\right)}{\exp\left[-\left(\frac{h}{w_\alpha}\right)^u\right]\left[1 + u\left(\frac{h}{w_\alpha}\right)^u\right] - \exp\left[-\left(\frac{h}{w_\beta}\right)^u\right]\left[1 + u\left(\frac{h}{w_\beta}\right)^u\right]} \quad (2)$$

where u, w_α and w_β are parameters that depend on the location under examination and $b\,(h;\ \theta_i - \Delta\theta/2 < \theta < \theta_i + \Delta\theta/2)$ is a base-significant wave height regression of the sea states where the direction ranges from $\theta_i - \Delta\theta/2$ to $\theta_i + \Delta\theta/2$.[21]

Longshore Sediment Transport

Consider a sand strip of unit length extending from the breaking depth d_b to the shoreline, exposed to the excitation induced by the surrounding wave field. Then, define μ the friction coefficient between the moving sand layer and the beach, γ_s, the specific weight of the sand, γ_a, the specific weight of the water, and the porosity, p. In this context, the longshore transport rate, Q_s, can be estimated by the equation[22]:

$$Q_s = \frac{R_{xy}}{\mu\left(\gamma_s - \gamma_a\right)\left(1 - p\right)} K \sqrt{g d_b} \quad (3)$$

where R_{xy} is the radiation stress tensor, g is the acceleration due to the gravity and K is an empirical coefficient. Equation (3) can be related to the spectral characteristics of the sea waves by relying on the sea state theory. Indeed, under the assumption of small beach slope and of straight and parallel bathymetric lines, Barbaro et al[23] have found that:

$$R_{xy} = \frac{1}{32} \rho g\, H_{sb}^2\, \delta\left(d_b, \theta_0\right) \quad (4)$$

in which ρ is the water density, H_{sb} is the significant wave height at the breaking depth and $\delta(d, \theta_0)$ is a function of the directional spectrum $S(w, \theta)$ (w being a non-dimensional frequency, θ a wave direction, k the wave number and d the water depth) with dominant direction θ_0 as given by the equation:

$$\delta\left(d, \theta_0\right) = \frac{\int_0^\infty \int_{\theta_0 - \pi/2}^{\theta_0 + \pi/2} S\left(w, \theta\right)\left[1 + \frac{2kd}{\sin h\left(2kd\right)}\right] \sin\theta \cos\theta \, d\theta \, dw}{\int_0^\infty \int_{\theta_0 - \pi/2}^{\theta_0 + \pi/2} S\left(w, \theta\right) d\theta \, dw} \quad (5)$$

By manipulating equations 3 and 4 by Barbaro et al[23] we obtain:

$$Q_s = K\,\varepsilon \quad (6)$$

where:

$$\varepsilon = \frac{\delta\left(d_b, \theta_0\right)}{32\,\mu\left(\frac{\gamma_s}{\gamma_a} - 1\right)\left(1 - p\right)} H_{sb}^2 \sqrt{g d_b} \quad (7)$$

Equation (6) renders an estimate of the LST rate given the spectral characteristics of the sea state and the sediment properties of the transported material. Further, it includes a coefficient, K, providing an empirical correction to the calculated LST[23]

$$K = 0.44 \ln\left(g T_p^2 / H_{sb}\right) \quad (8)$$

$$K = 10.13 \times 10^{-9} \ln (gT_p^{\,2}/H_{sb})^{11.1} \quad (9)$$

$$K = 11.40 \times 10^{-5} \exp[1.73 \ln (gT_p^{\,2}/H_{sb})] \quad (10)$$

$$K = 12.97 \times 10^{-5} (H_{sb}/L_{pb})^{-3.34} \quad (11)$$

$$K = 268.78 \exp[-83.1 (H_{sb}/L_{pb})] \quad (12)$$

where H_{sb} is the significant wave 8 at breaking, L_{pb} is the wave length at breaking and T_p the peak period.

The Site and the Input Data

The Annunziata River is situated in the Northern part of Reggio Calabria. Reggio Calabria a small city in the South of the Italian Peninsula (Fig. 1); its territory is characterized by a morphology that changes rapidly from mild near the coasts, to steep in the inland.

The head of the river is 1360 m above sea level, in the Aspromonte Mountains. The river arrives at the coastal plain after about 20 km, a great part of its course develops among the tablelands and versants and then it flows into the Strait of Messina Sea, near the Reggio Calabria Harbor. The particular configuration of the coast and the location of Sicily protect it from the severe Jonian and Tirrenian storms. In fact, only the waves, which come from a direction in the range of 240° N–345° N, affect the coast. In that range the fetches are quite limited; the longest is 10 km and it is in the direction of 240° N.

The Messina Strait is also characterized by the absence of wave data. Fortunately, in the port of Reggio Calabria, there is a wind measurement station. The river mouth is next to the city port and consequently the wind speed measured can be used for wave prediction. The time series reports the average wind speed and direction per hour measured at 4 m elevation for the last 4 years.

These equations govern the wave growth with fetch[24]:

$$U_{10} = U(z)\left(\frac{10}{z}\right)^{1/7} \quad (13)$$

$$U_A = U_{10}^{1.23} \quad (14)$$

$$\frac{gH_{s0}}{U_A^2} = 1.6\times 10^{-3}\left(\frac{gF}{U_A^2}\right)^{1/2} \quad (15)$$

$$\frac{gT_p}{U_A^2} = 2.857\times 10^{-1}\left(\frac{gF}{U_A^2}\right)^{1/3} \quad (16)$$

$$\frac{gt_m}{U_A^2} = 6.88\times 10^{1}\left(\frac{gF}{U_A^2}\right)^{2/3} \quad (17)$$

where U_{10} is the wind speed at 10 m elevation, $U(z)$ is the wind speed measured, U_A is the friction velocity, g is the gravity acceleration, F is the effective fetch, H_{s0} is the significant wave height in deep water, T_p is the peak period and t_m is the time required for waves crossing a fetch of length F under a wind of velocity U_A to become fetch-limited.

Figure 2 reports the wave height in deep water obtained from Equation (15) with its frequency of occurrence for each direction. The directions have been divided into 16 sectors of 22.5° width.

As consequence of the limited length of the fetches, small values are obtained for the significant wave height; in fact, the highest value of the significant wave height is 1.2 m. Equation (15) gives the significant wave height in deep water conditions as it is necessary to evaluate the wave height and

Figure 1. Investigated area.

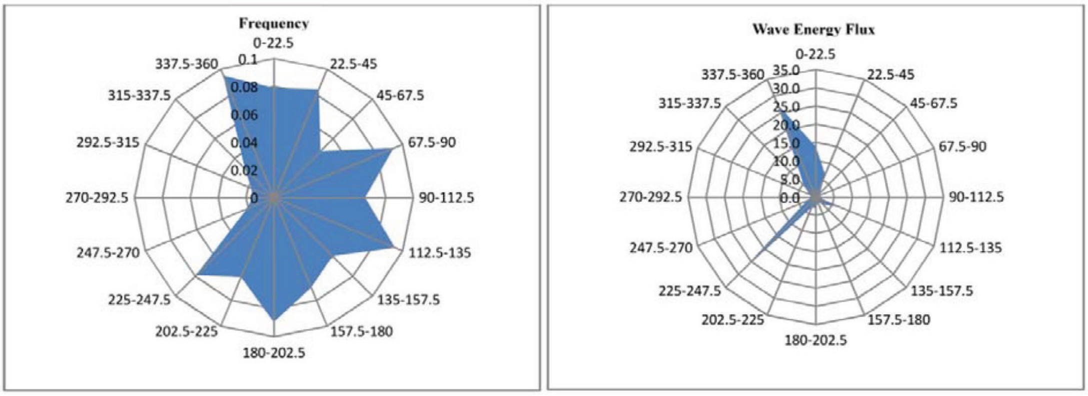

Figure 2. Frequency of occurrence of the significant wave height and wave energy flux (N/s) for each origin direction.

direction at the breaking point. If the contour lines are straight and parallel, a solution for the shoaling is given by the following equation:

$$\frac{H_s}{H_{s_0}} = \frac{\int_0^{\infty}\int_0^{2\pi} S(w,\theta)\, d\theta\, dw \rightarrow \frac{d}{L} \text{ fixed}}{\int_0^{\infty}\int_0^{2\pi} S(w,\theta)\, d\theta\, dw \rightarrow \frac{d}{L_{p_0}} = \infty} \tag{18}$$

where H_s is the significant wave height in shallow water, $S(w, \theta)$ is the directional spectrum, d is the water depth, L_{p0} is the wave length in deep water and L is the wave length in shallow water. This solution is suitable for 3D wind-generated waves and could be accepted in the case of a large-scale management plan, or could be selected by the rater when the goal is not to design an intervention but to decide where to place it.

Wave height is limited by both depth and steepness. For a given water depth and wave period, there is a maximum height limit above, which the wave becomes unstable and breaks. This upper limit of wave height, called breaking wave height, is in deep water a function of the wave steepness; in shallow water it is a function both of steepness and depth. Kamphuis[25] proposed the following breaking criteria for random wind waves:

$$\frac{H_{sb}}{d_b} = 0.56 \exp(3.5\lambda) \tag{19}$$

$$H_{sb} = 0.095 \exp(4\lambda) L_{p_b} \tan h\left(\frac{2\pi d_b}{L_{p_b}}\right) \tag{20}$$

where λ is the beach slope. Criteria (19) and (20) pertain to a plunging breaker and to a spilling breaker type, respectively.

Results and Discussion

The coast was divided in 3 sectors (Fig. 3). The direction of the simplified shorelines are as follows:

Figure 3. Sketch of the coast used in the simulation, and direction of the net longshore sediment transport.

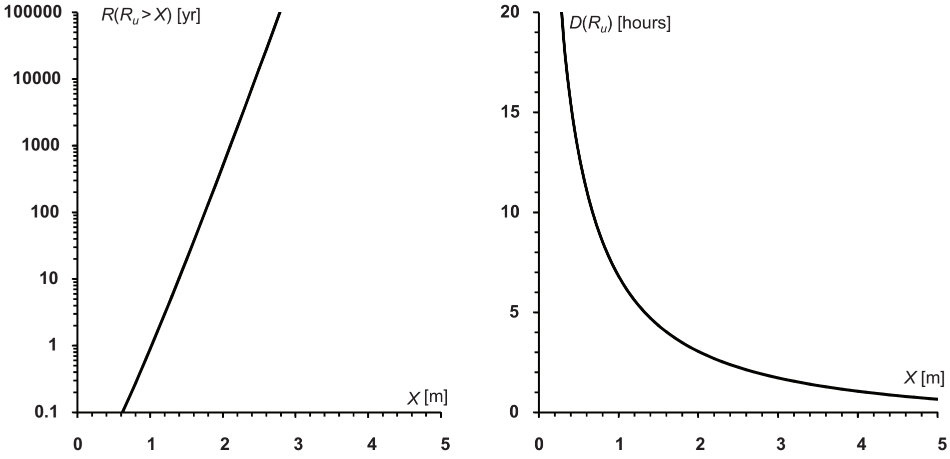

Figure 4. Run-up and its duration versus the return period calculated in the sector 1.

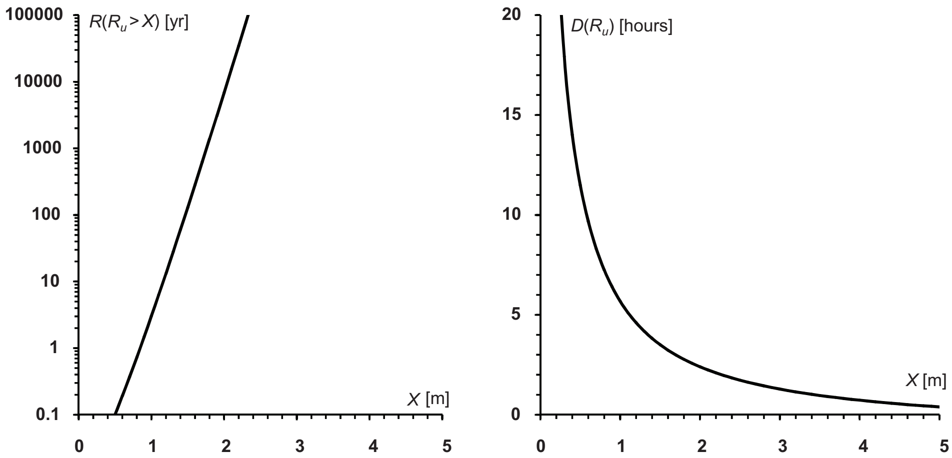

Figure 5. Run-up and its duration versus the return period calculated in the sector 2.

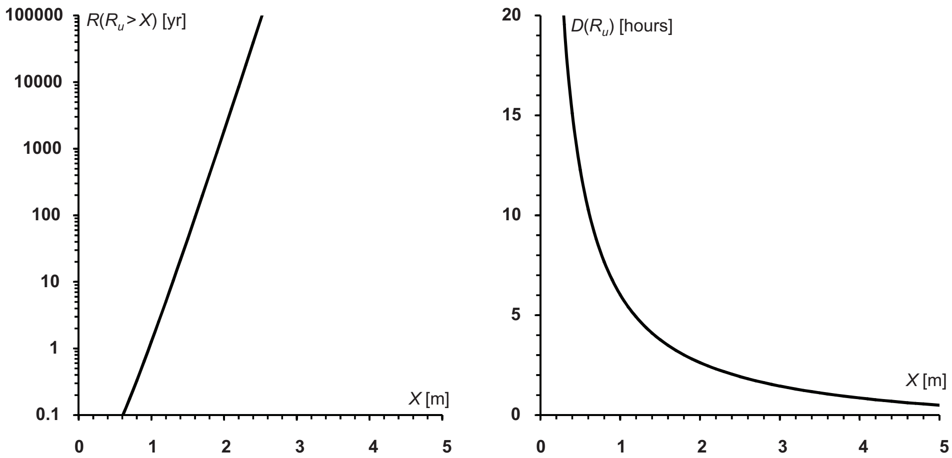

Figure 6. Run-up and its duration versus the return period calculated in the sector 3.

Table 1. Longshore sediment transport rate along the coast near the Annunziata river mouth.

Q_1	27610 m^3/year
Q_2	41687 m^3/year
Q_3	15161 m^3/year

$$Y_1 = 140°, Y_2 = 60°, Y_3 = 95°.$$

Under this schematization, a hypothesis can be adopted that considers the contour lines as straight and parallel.

As the total volume of transported sediments is due to the contribution of several sea states, the longshore sediment transport is calculated by weighting the contribution of each significant wave height, with respect to the frequencies. The results are reported below.

As we can see, the annual amount of energy associated with a sea state is influenced more by the fetches than by the frequency of the occurrence; in fact, for a direction between 0° and 225°, the energy is close to 0 but the frequency is not; this is due to the limited fetch corresponding to that direction.

Globally, the direction of the longshore sediment transport is from the North to the South (see Fig. 3) and the highest value is in sector 2. The decrease in the longshore sediment transport rate from sector 2 to sector 1 allowed for the formation of a stable beach in an area characterized by coastal erosion.

The run-up estimation has been carried out through Equation (1). In Figures 4 to 6, the run-up and its duration are reported versus the return period. In Table 2, the corresponding values are reported for the return periods of 10, 50, 100, and 1000 years. The relationship between run-up value and run-up persistence can be easily understood by looking at Figures 4, 5 and 6. As we can see, there is an inverse relationship between run-up value and run-up persistence. The highest value of run-up should be realized when the wave direction is orthogonal to the shoreline; therefore, the highest values are obtained for sectors 1 and 2, since shoreline directions are more exposed to waves arriving from the Northwest.

Conclusions

The current paper reports an investigation of the main coastal dynamic processes at the Annunziata river mouth. Since in the Messina Strait there are no gauges to measure wave climate, wind data were used. Wave growth with wind and fetch are described in Equations (13)–(17), and the results are reported in Figure 2. The wave transformation from deep to nearshore waters was made following the hypothesis that contour lines are straight and parallel, for which Equation (18) was used. Breaking conditions were obtained through the Equations (19) and (20). The coast near the river mouth was divided into 3 parts in order to satisfy the hypothesis that contour lines are straight and parallel. The sketch of the coasts and the directions of the annual sediment transport rate are reported in Figure 2. The longshore sediment transport rate was evaluated through Equation (6) and the run-up was estimated through Equation (1); the results are reported in Tables 1 and 2. The direction of the longshore sediment transport is reported in Figure 3, and a plot of the run-up and the relative duration are reported in Figures 4, 5 and 6.

List of Symbols

λ, Beach slope; $\bar{b}$, Base (duration) of Equivalent Triangular Storm; d, Water depth; d_b, Water depth at breaking; ρ, Water density; θ, Angle between wave direction and y axes; h, Significant wave eight threshold; g, Gravity acceleration; H_s, Significant wave height; H_{sb}, Significant wave height at breaking condition; μ, Friction coefficient; F, Fetch; Q_s, Longshore sediment transport value; L, Wave length; L_{pb}, Wave length at breaking; L_p, Wave length in deep water; P, Porosity; R_{xy}, Radiation stress; $R_{u2\%}$, Run-up; R, Return period; S, Directional spectrum; γ_s, Specific weight of sediment; γ_a, Specific weight of water; T_p, Peak period; U_{10}, Wind velocity at 10; U_A, Wind velocity on the ground; $U(Z)$, Wind velocity; u, Probability parameter for H_s; X, threshold; k, Wave number; w, Non-dimensional frequency; w_α, w_β, Directional probability parameter for H_s.

Author Contributions

CLS, GF and AC each made significant contributions to this research, and to the writing of the manuscript. All authors reviewed and approved of the final manuscript.

Table 2. Run-up and its duration calculated for the return periods of 10, 50, 100, 1000 years.

SECTOR	R = 10 Yr		R = 50 Yr		R = 100 Yr		R = 1000 Yr	
	R_U [m]	$D(R_U)$ [h]	R_U [m]	$D(R_U)$ [h]	R_U [m]	$D(R_U)$ [h]	R_U [m]	$D(R_U)$ [h]
1	1.40	4.9	1.62	4.0	1.79	3.5	2.12	3.0
2	1.12	5.1	1.38	3.9	1.48	3.4	1.79	2.9
3	1.28	4.5	1.50	3.9	1.60	3.5	1.94	2.9

DISCLOSURES AND ETHICS

As a requirement of publication the authors have provided signed confirmation of their compliance with ethical and legal obligations including but not limited to compliance with ICMJE authorship and competing interests guidelines, that the article is neither under consideration for publication nor published elsewhere, of their compliance with legal and ethical guidelines concerning human and animal research participants (if applicable), and that permission has been obtained for reproduction of any copyrighted material. This article was subject to blind, independent, expert peer review. The reviewers reported no competing interests.

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