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Modeling of Climate Change Effects on Coastal Erosion

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ABSTRACT: In the present work a Boussinesq type hydrodynamic and morphodynamic model is applied to simulate cross-shore coastal erosion during a storm surge event under extreme wave conditions. Non linear wave transformation in the surf and swash zone is computed by a non-linear breaking wave model based on the higher order Boussinesq equations for breaking and non breaking waves. The new transport rate formula (involving unsteady aspects of the sand transport phenomenon) is adopted for estimating the sheet flow sediment transport rates, as well as the bed load and suspended load over ripples. Suspended sediment transport rate is incorporated by solving the depth-integrated transport equation for suspended sediment. The model is applied to determine extreme beach erosion and coastal flooding due to storms in Eressos beach (Lesbos island, Greece). Extreme values of wave height and period as well as sea level rise are estimated using extreme value theory techniques. Marginal Extreme Generalized Value (GEV) distributions are first fitted to wave height and storm surge extremes. The dependence structure between wave height and storm surge extremes is modeled using a distribution from the family of Multivariate Extreme Value distributions (MVE), namely the simple bivariate logistic distribution function.

Keywords: Coastal erosion, Climate change, Coastal flooding, Nearshore numerical models, Extreme value theory.

1 INTRODUCTION

During the recent decades there is a growing scientific interest in the development of reliable scenarios (future projections) for the changes of the climate characteristics. Potential changes, both to atmospheric circulation and several meteorological parameters would have significant impacts on local communities, on the environment and ecosystems as they may adversely affect vital economic sectors such as agriculture and tourism.

The climate change is expressed on the open sea and the coastal zone through a number of impacts, such as: sea level rise, increase of the frequency of extreme wind events, change of the annual winds frequency, more frequent storm surge events, higher waves, changes of the dominant wave direction, stronger currents on the coastal zone etc. The above impacts, mainly due to a new sea level design and higher waves attack, induce morphodynamic responses such as beach and dune erosion, inundation on low-lying areas leading to increased flooding risk of the coastal zone.

Callaghan et al. (2008) performed a statistical simulation of extreme values of the wave climate in selected areas of the Australian coast using techniques of the univariate Extreme Value Theory. They developed a framework for determining coastal erosion hazard on sandy coastlines. This framework quantitatively reproduces the extreme beach erosion volumes obtained from field measurements at selected coastal areas. However the developed framework is based on the simple beach erosion model of Kriebel & Dean (1993). The structural function used to estimate the quantity of beach erosion is based on the equilibrium profile concept, which is a quite simplified approach (excluding longshore bar formation). On the other hand, the response of a coastal area to future storm events can be evaluated by means of an advanced hydro-morphodynamic model such as the one developed by Karambas and Koutitas (2002) and Karambas (2012). The model is based on the Boussinesq equations for nonlinear wave propagation in the near shore area and can be used to estimate coastal erosion as well as flooding due to wave setup/runup caused by extreme marine events.

In the present work a Boussinesq type hydrodynamics and morphodynamics model is applied to simulate cross-shore coastal erosion during a storm surge event under extreme wave conditions. The model is applied to determine extreme beach erosion and coastal erosion hazard due to storms in Eressos beach (Lesbos island, Greece). Extreme values of wave height and period as well as sea level rise are estimated using extreme value theory techniques.

2 HYDRODYNAMIC AND SEDIMENT TRANSPORT MODEL

Near-shore wave propagation and coastal hydrodynamics are simulated by a Boussinesq nonlinear wave model described in Karambas and Koutitas (2002) and Karambas et al. (2012).

The bed load transport (q_{sb}) (including sheet flow sediment transport rate and suspended load over ripples) is estimated with a quasi-steady, semi-empirical formulation, developed by Camenen, and Larson, (2007) for an oscillatory flow combined with a superimposed current:

$$\frac{q_{sb,wave}}{\sqrt{(s-1)gd_{50}{}^3}} = a_n\sqrt{\theta_{cw,net}}\,\theta_{cw,m}\exp\left(-b\frac{\theta_{cr}}{\theta_{cw}}\right) \qquad \frac{q_{sb,\text{current}}}{\sqrt{(s-1)gd_{50}{}^3}} = a_n\sqrt{\theta_c}\,\theta_{cw,m}\exp\left(-b\frac{\theta_{cr}}{\theta_{cw}}\right) \tag{1}$$

where s (= ρ_s/ρ) is the relative density between sediment (ρ_s) and water (ρ), g the acceleration due to gravity, d_{50} the median grain size, a_w, a_n and b are empirical coefficients (Camenen and Larson 2007), $\theta_{cw,m}$ and θ_{cw} the mean and maximum Shields parameters due to wave-current interaction, and θ_{cr} the critical Shields parameter for the inception of transport. The net Shields parameter $\theta_{cw,net}$ is given by:

$$\theta_{cw,net} = \left(1-a_{pl,b}\right)\theta_{cw,on} - \left(1+a_{pl,b}\right)\theta_{cw,off} \tag{2}$$

where $\theta_{cw,on}$ and $\theta_{cw,off}$ are the mean values of the instantaneous Shields parameter over the two half periods T_{wc} and T_{wt} ($T_w = T_{wc} + T_{wt}$, in which T_w is the wave period and $\alpha_{pl,b}$ a coefficient for the phase-lag effects (Camenen and Larson 2007).

The Shields parameter is defined by $\theta_{cw,j} = \frac{1}{2}f_{cw}U_{cw,j}^2/\left[(s-1)gd_{50}\right]$, with U_{cw} being the wave and current velocity, f_{cw} the friction coefficient taking into account wave and current interaction and the subscript j should be replaced either by *onshore* or *offshore.* For sediment transport estimation, we use the corrected near bottom U_{cw} (which incorporates the effects of undertow) instead of the instantaneous bottom velocity u_o.

Phase-lag effects in the sheet flow layer were included through a coefficient proposed by Camenen and Larson (2007)

In order to incorporate the suspended sediment transport rate, the depth-integrated transport equation for suspended sediment is solved. Here we adopt the transport equation proposed by Kobayashi and Tega (2002):

$$\frac{\partial(hC)}{\partial t} + \frac{\partial(hCU_s)}{\partial x} = S - w_s\,C \tag{3}$$

where C is the depth-averaged volumetric sediment concentration, U_s is the horizontal sediment velocity, S is the upward sediment suspension rate from the bottom and w_s is the sediment fall velocity. The horizontal sediment velocity U_s is assumed to be given by U_s=(U-w_s).

The suspension rate S per unit horizontal area is related to the wave energy dissipation (Kobayashi and Tega, 2002):

$$S = S_B + S_f; \qquad S_B = \frac{e_B D_B}{\rho g(s-1)h}; \qquad S_f = \frac{e_f D_f}{\rho g(s-1)h} \tag{4}$$

where D_B is the energy dissipation rate due to wave breaking, D_f is the energy dissipation rate due to bottom friction ($D_f = 0.5\,\rho\,\mathrm{f}\left|\boldsymbol{U}\right|^3$), e_B is the suspension efficiency for D_B and e_f is the suspension efficiency for D_f.

The suspended transport rate is estimated from:

$$q_s = hCU_s \tag{5}$$

The energy dissipation rate D_B in the swash zone is estimated from the wave model by adopting the mixing length hypothesis (Karambas, 2006).

The model had been validated against large scale experimental data for cross-shore profile evolution in Karambas and Koutitas (2002), Karambas (2006) and Karambas et al. (2012).

3 ANALYSIS OF EXTREME MARINE EVENTS

The univariate Extreme Value Theory (EVT) includes models for block maxima and exceedances over high thresholds (POT models). The first correspond to the family of GEV distributions (Generalized Extreme Value) including the Gumbel (Type I), the Fréchet (Type II) and the Weibull (Type III) distributions (Jenkinson, 1955). The cumulative distribution function of the GEV for $\xi \neq 0$ is given by the following formula (Coles, 2001):

$$G(x) = \exp[-\{1 + \xi \frac{(x-\mu)}{\sigma}\}^{-1/\xi}], \quad 1 + \xi \frac{(x-\mu)}{\sigma} > 0 \tag{6}$$

where μ, $\sigma > 0$ and ξ are the location, scale and shape parameters, respectively. The special case with $\xi = 0$ corresponds to the Gumbel distribution function. Hence, estimation uncertainty is not artificially reduced, because the selection of the most appropriate model is performed from the complete entity of extreme value distributions, without having a priori to specify the most suitable distribution function. The parameters of the GEV distribution function can be estimated by means of the Maximum Likelihood Estimation procedure (MLE).

Within a stationary context, the return level x_p corresponding to a return period of $1/p$, is the value that is expected to be exceeded at least once every $1/p$ years and can be assessed by inverting Equation (6) for a given exceedance probability, p (Coles, 2001):

$$x_p = \mu - \frac{\sigma}{\xi}[1 - \{-\log(1-p)\}^{-\xi}] \tag{7}$$

The variance of the return level estimates can be assessed using the delta method:

$$Var(x_p) \approx \nabla x_p{}^{\mathrm{T}} V \nabla x_p \tag{8}$$

where V is the variance-covariance matrix of the maximum likelihood estimators of the parameters μ, σ and ξ, while the delta function is also assessed at these estimates.

The family of GEV distributions is utilized in the present work to analyse extreme marine variables, constituting the sources of coastal erosion. The model of Equation (6) is first fitted to the annual maxima of significant wave height and storm surge data. The wave period is modelled by means of a conditional GEV distribution function with parameters depending on the significant wave height estimates. The parameters μ and σ of the fitted distribution are modelled using empirical regression functions (Repko et al. 2004):

$$\begin{aligned} g(H_s)_i &= aH_s + b \\ g(H_s)_i &= aH_s{}^2 + bH_s + c \\ g(H_s)_i &= aH_s{}^b \end{aligned} \tag{9}$$

where $g(H_s)_i$ correspond to the location (i=1) and scale (i=2) parameters and a, b, c are parameters to be estimated. The shape parameter, ξ, of the GEV, which determines the tail behaviour of the distribution, is considered constant.

The coastal hazards of flooding and erosion, as well as the failure of coastal structures are strongly associated with the wave conditions in the area of interest, as well as with sea water level. Extreme wave conditions in the deep water (to eliminate the effects of water depth on these conditions) are usually correlated with high water levels, due to the dependence of both mechanisms on local weather conditions. For this reason, it is recommended to estimate the joint probability distributions of extreme wave conditions with directions affecting the coastline and extreme storm surges. A simple bivariate model that is commonly adopted to model the dependent pair of extreme wave heights and storm surges is the bivariate logistic distribution function (Tawn, 1988):

$$G(x_1,x_2) = \exp[-(z_1^{1/r} + z_2^{1/r})^r] \tag{10}$$

where r is the dependence parameter ($0 < r < 1$). The variables X_1, X_2 correspond to pairs of significant wave height (x_1) and storm surge (x_2). Full dependence is achieved in the limit when the dependence parameter r tends to zero, while independence is obtained when r=1. The extreme values of X_1, X_2 variables follow the GEV distribution function (Equation (6)) and are transformed to marginal distributions of the form $G(x_i)=\exp(-z_i)$ i=1,2 resulting in (Stephenson and Tawn, 2004):

$$z_i = \{1+\xi_i \frac{(x-\mu_i)}{\sigma_i}\}_+^{-1/\xi_i} \tag{11}$$

where μ_i, σ_i, ξ_i are the parameters of the GEV distribution, estimated using the MLE procedure for the variables of significant wave height and storm surge.

4 ANALYSIS OF DATA

The marine data utilized in the present work correspond to significant wave height, wave period and storm surge simulations in the marine area of Eressos (Lesvos island, Greece). The wave data result from a wave prediction model formulated for the Greek Seas, based on the wave model SWAN (Ris et al. 1999, Booij et al. 1999). Storm surge data result from a two dimensional model of hydrodynamic circulation for the Greek Seas (Krestenitis et al. 2011). The wave and the storm surge data cover a period of 150 years (1950-2099). The atmospheric forcing of the models consists of wind (wind velocity and direction) and sea level pressure fields of the RCM (Regional Climate Model) model RegCM3 (Dickinson et al. 1989). The spatial resolution of the model is 10x10km. The future predictions of the model are based on the A1B SRES emissions scenario (Jacob et al. 2007).

The time series of marine variables resulting from wave prediction or hydrodynamic circulation models forced by RCM models are often subject to bias. Bias corresponds to the error component of the model that does not depend on time (Haerter et al. 2011). This component imposes the processing of the data, before using it to estimate the effects of climate change in any domain of application. In the present work, the wave data used for bias correction of the significant wave height cover a period of ten years (2001-2010). This data result from the wave model WAM forced by the non-hydrostatic meteorological model SKIRON with horizontal spatial resolution of 0.05x0.05 (Papadopoulos et al. 2002). To perform bias correction, the nonparametric quantile transform of Boé et al. (2007) is utilized in the present work.

Bias correction of the significant wave height data is followed by the splitting of the data in periods of 50 years, representing the periods of the present (1950-1999), the short-term (2000-2049) and the long-term future climate (2050-2099). The wave storm events directing to the coast of Eressos are then selected. These events are characterised by wave heights larger 1.5 m and duration more than 6 hours. The selection of wave storm events is followed by the selection of the annual maximum values of these events and the adjustment of the GEV distribution function to these values. The model is also fitted to the annual maxima of the storm surge data. Table 1 presents return level estimates (maximum likelihood estimates and associated 95% confidence intervals) of significant wave height and storm surge, resulting from applying univariate extreme value analysis, for return periods of 50, 100, 200 and 500 years for the three time periods considered in the present work.

From Table 1 it is evident that during the short-term future climate (2000-2049), there is a significant increase in the extremes of significant wave height and storm surge, compared to the respective estimates of the present climate (1950-1999) period. Similar conclusions are extracted for the wave period (not presented here for the sake of brevity). During the last future period (2050-2099), a decrease in the extremes of significant wave height and wave period are observed, compared to the estimates of the period 2000-2049, however these estimates are still increased compared to the present climate conditions.

Table 1. Univariate return level estimates of significant wave height.

T (years)	Return Levels (m)					
	1950-1999		2000-2049		2050-2099	
	H_s	SS	H_s	SS	H_s	SS
50	4.89	0.39	5.56	0.44	5.11	0.37 (0.35, 0.39)
	(4.55, 5.23)	(0.36, 0.41)	(4.90, 6.23)	(0.38, 0.49)	(4.67, 5.55)	
100	5.01	0.40	5.87	0.46	5.30	0.38 (0.36, 0.40)
	(4.59, 5.43)	(0.37, 0.42)	(5.00, 6.74)	(0.39, 0.53)	(4.76, 5.85)	
200	5.12	0.41	6.16	0.48	5.48	0.39 (0.36, 0.41)
	(4.61, 5.63)	(0.38, 0.44)	(5.05, 7.27)	(0.39, 0.58)	(4.81, 6.14)	
500	5.23	0.42	6.53	0.51	5.68	0.39 (0.36, 0.42)
	(4.61, 5.86)	(0.38, 0.45)	(5.06, 8.00)	(0.39, 0.64)	(4.85, 6.51)	

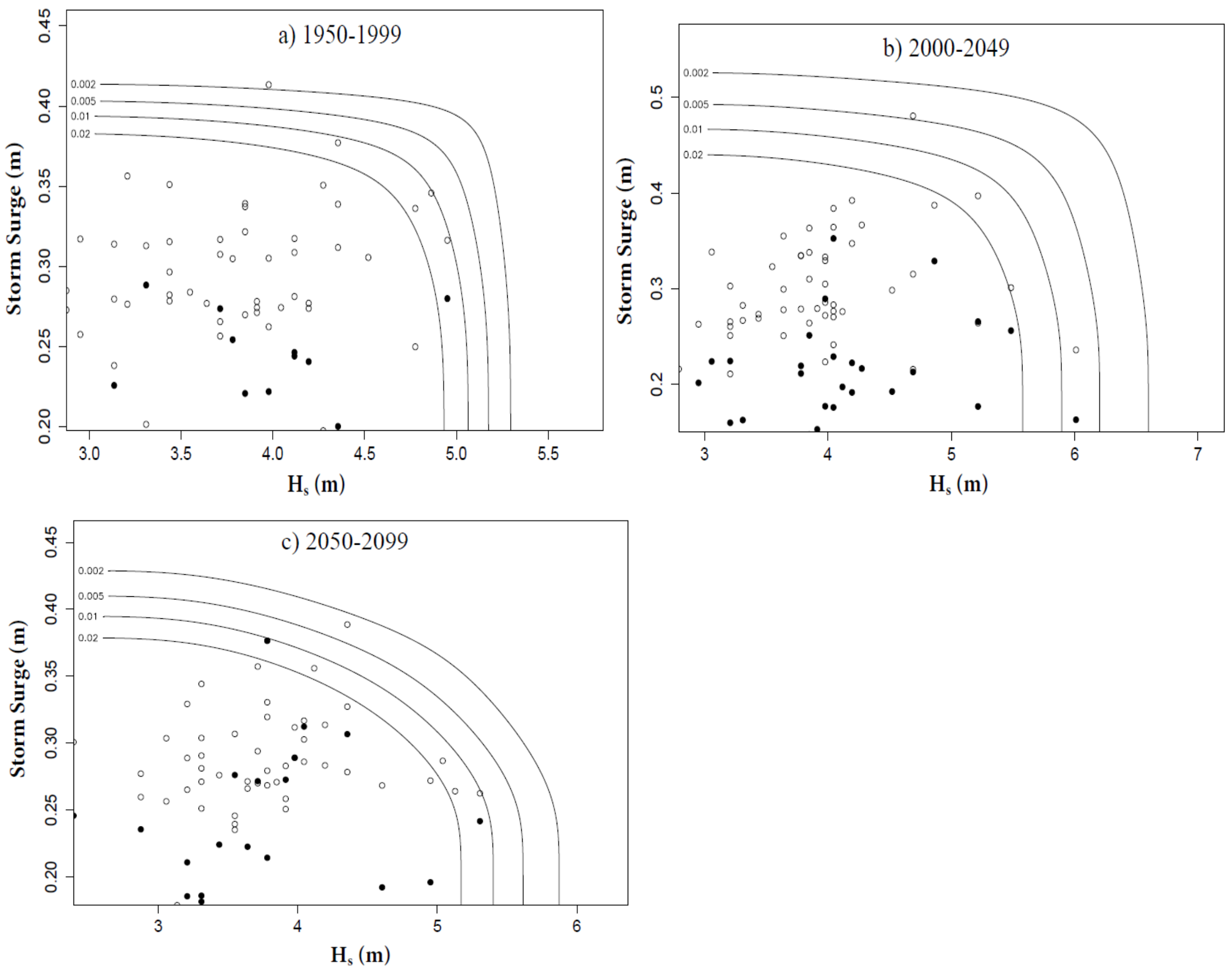

Figure 1. Joint estimates of significant wave height and storm surge for a) 1950-1999, b) 2000-2049 and c) 2050-2099.

Figure 1 presents the fitting of the bivariate logistic model (Equation (10)) to the annual maxima of significant wave height and storm surge for the three time periods considered (1950-1999, 2000-2049 and 2050-2099). The contours of equal probability of exceedance correspond to return periods of 50, 100, 200 and 500 years. The Figure also includes pairs of wave height and storm surge annual maxima, as well as pairs of annual maximum wave heights and concomitant storm surge values (black circles). For a given return period, the combination of marine variables corresponding to the most conservative response of the coast should be selected. Based on the combination selected, the respective wave period can be estimated using the conditional GEV distribution function described in Section 3.The parameters μ and σ of the conditional distribution are represented as exponential functions of the wave height estimates, because the AIC values (Hurvich and Tsai, 1989) for this combination (last combination in Equation (9)) resulted to be minimum.

Figure 2. Aegean Sea, Lesbos Island and case study area.

5 APPLICATION TO ERESSOS BEACH (LESBOS ISLAND, GREECE)

The hydro-morhodynamic model of paragraph 2 is applied to determine extreme beach erosion and coastal flooding due to storms in Eressos beach (Figure 2). The extreme values of wave height and storm surge are taken from Table 1 for return level 50 and 100 years in the period 2000-2049 (H_s=5.56 m/SS=0.44 m and H_s=5.87 m/SS=0.46 m respectively). During that period significant increase of extreme wave height (of order of 14%) and storm surge is predicted (in comparison with the previous period (1950-1999). The wave period is modelled by means of a conditional GEV distribution function with parameters depending on the significant wave height estimates.

The initial cross-shore profile is adopted according to filed measurements at January 2011 by Coastal Morphodynamics team of Department of Marine Sciences of University of the Aegean. Two cross-shore profiles are considered, from which the one includes the presence of a sea wall, located 2.5 m inshore the shoreline.

The bed cross-shore evolution is presented in Figures 3 and 4. The beach retreat is predicted to be 11 m for 50 years return period. Wave run up above sea level rise due to storm surge is 1.3 m. For 100 years return period the beach retreat is 12 m and run up 1.35 m. Given the significant erosion of the last 20 years (of order of 30 m!) the above values are significant and explain the flooding of coastal area which occurs 1-2 times during the last winders. It is notice here that according to Karambas et al. (2008) the main reason of the significant erosion of the last 20 years occurred because of the increase of frequency of appearance of the S waves, that transport the sediment from the Eastern region of the coast to the Western region.

Additionally, in Figure 5, the bed morphology evolution in front of the sea wall is shown, for 50 years return period. The scour is predicted to be about 40-50 cm and explain the failure of the sea wall that happens several times last years.

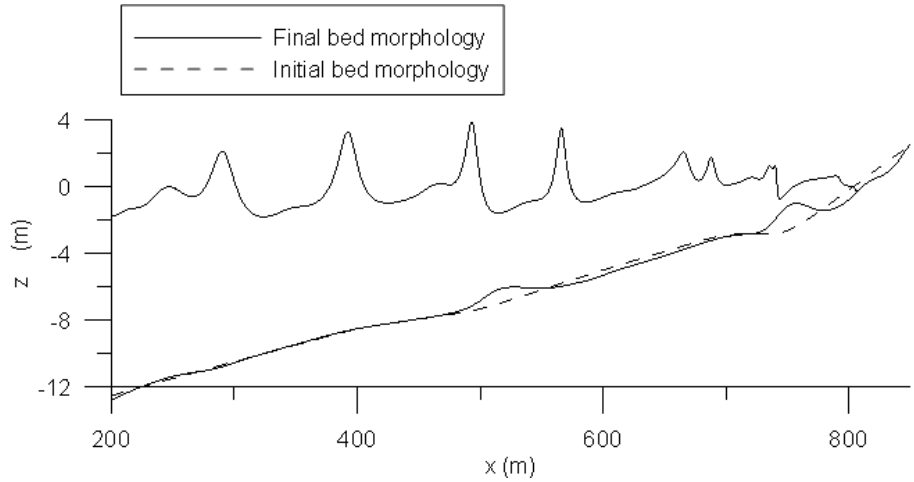

Figure 3. Bed morphology evolution under extreme wave height and storm surge values (50 years return period, H_s=5.56 m and SS=0.44 m).

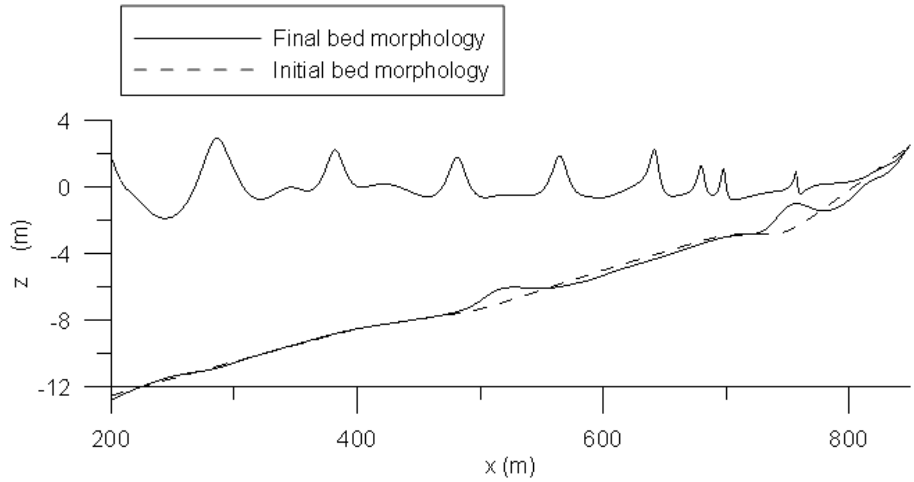

Figure 4. Bed morphology evolution under extreme wave height and storm surge values (100 years return period, H_s=5.87 m and SS=0.46 m).

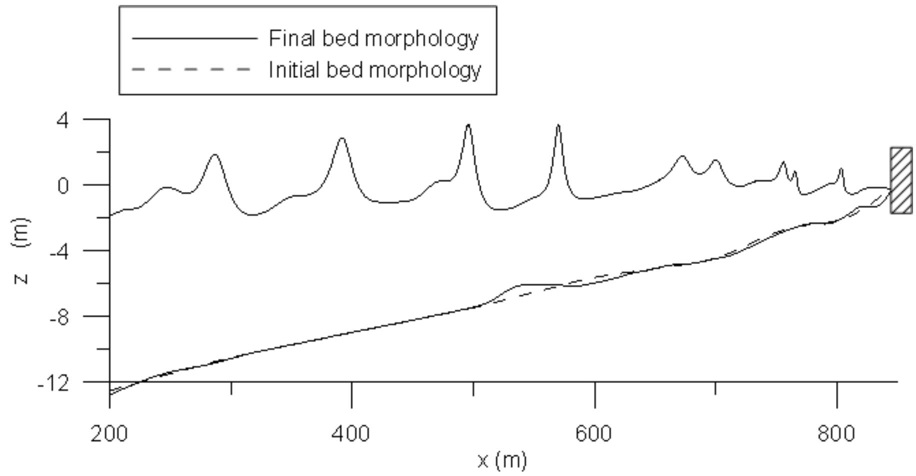

Figure 5. Bed morphology evolution and scour in front of the sea wall under extreme wave height and storm surge values (50 years return period, H_s=5.56 m and SS=0.44 m).

6 CONCLUSIONS

The extreme meteorological events (i.e. high waves and storm surge) lead to morphodynamic changes in the coastal zone, such as beach and dune erosion, inundation on low-lying areas leading to increased flooding risk of the coastal zone. Civil Engineers need the help of extreme value theory techniques and advanced mathematical models, in order to confront the above problems in coastal zone, by simulating the climate change impacts on coastal flooding and erosion.

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REFERENCES

Boé, J., Terray, L., Habets, F., Martin. E. (2007). Statistical and dynamical downscaling of the Seine basin climate for hydrometeorological studies, Int. J. Climatol., Vol. 27, pp. 1643-1655.

Booij, N., Ris, R. C., Holthuijsen, L.H. (1999). A Third-Generation Wave Model for Coastal Regions. 1. Model Description and Validation, J. Geophys. Res., Vol. 104, pp. 7649-7666.

Callaghan, D.P., Nielsen, P., Short, A. and Ranasinghe, R.. (2008). Statistical simulation of wave climate and extreme beach erosion, Coastal Engineering 55, 375-390.

Camenen, B., Larson, M. (2007). A unified sediment transport formulation for coastal inlet application. Technical Report, ERDC/CH: CR-07-1, US Army Corps of Engineers, Engineering Research and Development Center, Vicksburg, MS, USA, pp. 247.

Coles, S. (2001). An Introduction to Statistical Modelling of Extreme Values, Springer, London.

Dette H.H., Peters K. and Newe J. (1998). Large wave flume experiment '96/97.MAST III - SAFE Project, Report No. 825.

Dickinson, R., Errico, R., Giorgi, F., Bates, G. (1989). A regional climate model for the western United States, Clim. Chang., Vol. 15, No. 3, pp. 383-422.

Haerter, J.O., Hagemann, S., Moseley, C., Piani, C. (2011). Climate model bias correction and the role of timescales, Hydrol. Earth Syst. Sc., Vol. 15, pp. 1065-1079.

Hurvich, C.M., Tsai, C. (1989). Regression and time series model selection in small samples, Biometrika, Vol. 76, pp. 297-307.

Jacob, D., Barring, L., Christensen, O.B., Christensen, J.H., de Castro, M., Deque, M., Giorgi, F., Hagemann, S., Hirschi, M., Jones, R., Kjellstrom, E., Lenderink, G., Rockel, B., van Ulden, A.P., van den Hurk, B.J.J.M. (2007). An inter-comparison of regional climate models for Europe: model performance in present-day climate, Clim. Chang., Vol. 81, pp. 31-52.

Jenkinson, A.F. (1955). The frequency distribution of the annual maximum (or minimum) values of meteorological elements, Q. J. Roy. Meteor. Soc., Vol. 81, pp. 158-171.

Karambas, Th. V. and C. Koutitas. (2002). Surf and swash zone morphology evolution induced by nonlinear waves. J. Waterw. Port Coast. Ocean Eng., ASCE, 128(3), 102-113.

Karambas, Th. (2006). Prediction of sediment transport in the swash zone by using a nonlinear wave model. Cont. Shelf Res., 26, 599-609.

Karambas Th.V., Samaras, A. and Ch. Koutitas. (2012). Environmentally friendly shore protections methods: use of advanced numerical models in beach nourishment projects. Int. Conference Protection and Restoration of the Environment XI, Thessaloniki, 768-777.

Karambas Th. V. (2012). Design of detached breakwaters for coastal protection: development and application of an advanced numerical model. Proceedings of the 33rd International Conference on Coastal Engineering 2012,1(33), sediment.115. doi:10.9753/icce.v33.sediment.115

Karambas Th. V., O. Andreadis and A. Vekegrakis (2008). Erosion of Eressos beach: possible reasons and proposals for coastal protection . 4th National Conference on Management and Improvement of Coastal Zones, Mytilene, Greece, 457—476 (in Greek).

Kobayashi N., Tega Y. (2002). Sand suspension and transport on equilibrium beach, Journal of Waterway, Port, Coastal, and Ocean Engineering 128, no 6, 238-248.

Krestenitis, Y., Androulidakis, Y., Kontos, Y., Georgakopoulos, G. (2011). Coastal inundation in the north-eastern Mediterranean coastal zone due to storm surge events. J. Coastal Conserv., Vol. 15, 353-368.

Kriebel, D.L. and R. G. Dean. (1993). Convolution method for time-dependent beach-profile response. J. Waterw. Port Coast. Ocean Eng., ASCE, 119 (2), 204–226.

Papadopoulos, A., Katsafados, P., Kallos, G. (2002). Regional weather forecasting for marine application, GAOS, Vol. 8, No 2-3, pp. 219-237.

Stephenson, A.G. and Tawn, J.A. (2004), Exploiting occurrence times in likelihood inference for componentwise maxima, Biometrika, Vol. 92, No. 1, pp. 213–217.

Repko, A., P.H.A.J.M. Van Gelder, Voortman, H.G., Vrijling, J.K. (2004). Bivariate description of offshore wave conditions with physics-based extreme value statistics, Appl. Ocean Res., Vol. 26, pp. 162-170.

Ris, R. C., Holthuijsen, L. H., Booij, N. (1999). A Third-Generation Wave Model for Coastal Regions. 2. Verification, J. Geophys. Res., Vol. 104, pp. 7667-7681.

Tawn, J.A. (1988). Bivariate extreme value theory: model and estimation, Biometrika, Vol. 75, No 4, 397-415.