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FORMATION ZONES D'EROSION

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Contents

1 Overview

1.1 Background and Introduction

Sustainable management of the coastal zone is a dynamic process, which should (a) consider both the fragility of coastal ecosystems and landscapes and the diversity of the activities/uses of the coastal zone; and (b) create appropriate 'checks and balances' for the interrelated social, economic and environmental components of development, using an integrated approach. This implies that sustainable management of the coastal zone should address the implications of development and conflicting uses on the physical environment as well as the impacts of environmental change on human activities and assets. Therefore, coastal zone development should (i) plan rationally for coastal zone activities; (ii) utilise the ecosystem approach in coastal planning and (iii) formulate land use strategies, plans and programmes that cover urban development and other socio-economic activities in the coastal zone. In addition, planning decisions should be made on the basis of assessments of the various risks to both human activities/infrastructure and the environment. In this context, assessing the risk of increasing coastal erosion that may severely impact the carrying capacity of the coastal zone should become a prerequisite for coastal zone management plans (e.g. Rochette and Bille, 2010).

Coastal erosion appears to be a major environmental problem for the Mediterranean coastal zone and the manner in which we will address it will define the future resilience and sustainability of the coastal zone. This has been recognized by the Mediterranean community, leading to the development and adoption of relevant regulatory instruments (see Annex I). For instance, the Integrated Coastal Zone Management (ICZM) Protocol to the Barcelona Convention identifies coastal erosion as a critical problem for the Mediterranean and prescribes that ('… *with a view to preventing and mitigating the negative impact of coastal erosion more effectively, [the Parties] undertake to adopt the necessary measures to maintain or restore the natural capacity of the coast to adapt to changes, including those caused by the rise in sea levels…'* (Art. 23, BC ICZM Protocol, 2008).

Beaches (i.e. the low-lying coasts built on unconsolidated sediments) are amongst the most erosion-sensitive constituents of the coastal system, accounting for most of the observed coastal erosion at a global scale (IPCC SREX, 2012). At the same time, beaches are very critical components of the coastal system. Beaches are not only important ecological habitats in their own right (e.g. Defeo and McLachlan, 2013), but they also front/protect from sea inundation/flooding (a) very significant transitional coastal habitats (e.g. wetlands and lagoons) which are protected by international conventions and EU Legislation (see Section 1.2); and (b) very valuable economic assets/infrastructure (e.g. urban, industrial and touristic developments, coastal roads, railways and airports) (e.g. Kontogianni et al., 2013). At the same time, as tourism has become almost synonymous with beach recreational activities (Phillips and Jones, 2006), beaches form extremely important economic resources. For example, tourism in the Mediterranean countries, which is mainly associated with beaches, is worth more than €100 billion per year with about 120 million foreign tourists visiting the Mediterranean coast.

Beach erosion can be differentiated into:

(i) long-term erosion, i.e. irreversible retreat of the shoreline position, due to mean sea level rise and/or negative coastal sedimentary budgets (e.g. Velegrakis et al., 2008) that force beach landward migration and/or drowning; and

(ii) short-term erosion, caused by storm waves/surges, which may or may not result in permanent shoreline retreats, but can nevertheless be devastating (e.g. Fritz et al., 2010).

In recent decades, the Mediterranean coast sediment balance has been increasingly negatively affected by river management practices, such as dam construction (Fig. 1.1). At the same time, projected mean sea level rise (e.g. IPCC, 2013; see also Section 5.1) will likely exacerbate the already significant beach erosion and severely impact coastal populations, activities, infrastructure and assets (e.g. Nicholls et al., 2007). In addition, storm waves/surges coupled with increasing mean sea levels (e.g. Marcos et al., 2011; IPCC SREX, 2012) will aggravate further the erosion risk, devastating beaches and coastal assets/infrastructure through coastal inundation and the spread of the wave energy onto previously dry land.

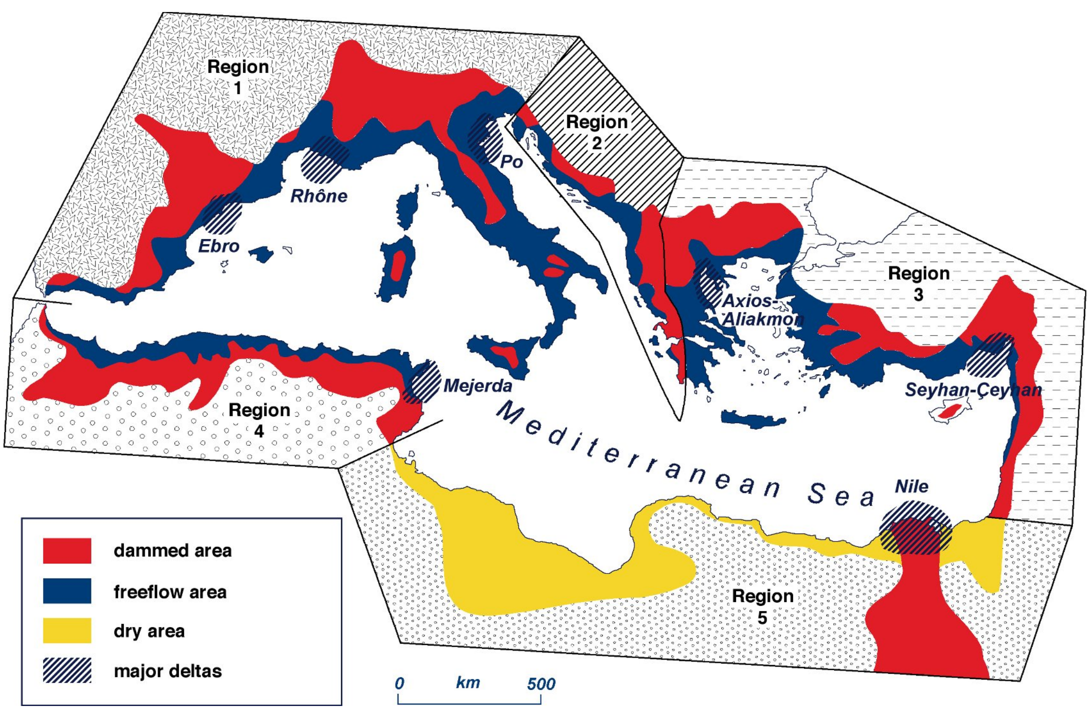

Fig. 1.1 Mediterranean coastal sediment supply has decreased from 1012 x 10^6 to 355 x10^6 tons/yr during the second half of the 20th century, due to dam sediment trapping. There are more than 3500 dams distributed over the Mediterranean drainage basin, 84% of which have been constructed after the 1950s (Poulos and Collins, 2002).

As the physical impacts of projected climatic changes on beaches are likely to increase, ever increasing coastal populations, activities and infrastructure will face growing exposure to coastal flooding, which might prove to be devastating for the economies of the Mediterranean coastal States. For example, coastal urban development will be severely affected by climate change-driven extremes (e.g. Maunsell, 2008; Lenton et al., 2009), the potential earnings from coastal tourism are likely to decrease significantly (e.g. Snoussi et al., 2008; Pacheco and Lewis-Cameron, 2010) and, most importantly, human lives will be at risk. Therefore, the development of management plans that increase the safety of coastal populations, infrastructure and assets and ensure the functionality/sustainability of beaches as environments of leisure is of paramount significance. Relevant management plans should be based upon coastal erosion/flood risk assessments that take into consideration climate change i.e. the long- and short-term sea level rise. Against this background, there is an urgent need to identify (and quantify, where possible) the extent of present and future beach erosion, in order to develop plans and tools to manage effectively the coastal zone.

1.2 The regulatory framework protecting the Mediterranean coastal zone

Coastal environmental regulation in the Mediterranean consists of several layers/levels i.e. international/regional, European and national. These include international Conventions (Annex I Table I.1), which regulate maritime zone delimitation, conservation, pollution prevention, preparedness and response, as well as liability and compensation in the case of marine pollution (mainly ship-source oil pollution, see also UNCTAD, 2012). At the regional level, the Barcelona Convention and its Protocols provide for the conservation of the Mediterranean coastal zone. Finally, as a number of the Mediterranean Coastal States are also EU Member States, several European environmental Directives are also particularly pertinent for the conservation of the Mediterranean coastal zone (Annex I, Table I.2).

Generally, the relevant legal instruments provide a wide-ranging regulatory framework for environmental protection and conservation across the Mediterranean coastal zone. However, there are challenges stemming from: (i) the non-ratification of important international legal instruments by several Mediterranean coastal States (Table I.1); and (ii) the uneven economic development of the Mediterranean coastal States which has certain repercussions in terms of the availability of economic resources and the capacity/expertise that is necessary for the effective national implementation of these legal instruments.

An extremely important regulatory instrument for the management of the Mediterranean coastal zone is the Integrated Coastal Zone Management Protocol to the Barcelona Convention (BC ICZM Protocol). Adopted in January 2008 by the Contracting Parties to the Barcelona Convention, the BC ICZM Protocol entered into force on the 24th March 2011. The BC ICZM Protocol, which has been also ratified by the EU, is the first international legal instrument aimed specifically at coastal zone management. Previously, coastal zones were regulated by international law in a fragmented way, with the few instruments aiming at transcending sectoral policies and guiding national systems towards integrated coastal management being confined to the realm of 'soft law' (Rochette and Bille, 2010). As Mediterranean coastal zones have been on an unsustainable development path for the last few decades, the application of this new legal tool is of vital importance for the future of the Mediterranean basin.

One of the most relevant (and controversial) provisions of the ICZM protocol relates to the establishment of so-called 'set-back zones' (Rochette et al., 2010). This is a management tool which is used increasingly in coastal policies as it meets many different policy objectives, such as biodiversity conservation, maintenance of ecosystem services and the protection of populations, infrastructure and assets against future risks of coastal erosion/inundation (see also Annex I, Table I.1). Article 8.2 of the ICZM Protocol, which prescribes the establishment of a 100 m setback zone in Mediterranean coastal areas[1], is a very significant provision, which demonstrates, amongst others, how international/regional law can affect national/local planning processes that are commonly the competence of national/local authorities. The provision has been the subject of intensive negotiations, as its implementation presents many challenges; it is, therefore, not surprising that the construction/building ban in the set back zone is subject to certain qualifications[2] (Rochette et al., 2010).

In practice, the implementation of Art. 8.2 requires projections of coastal and, particularly, of beach retreat/erosion under a changing and variable climate. Erosion (and its evolution) controls the location of the winter waterlines[3] from which the widths of the set back zones shall be measured. Therefore, in order to delimit the set back zones, it is necessary to forecast beach/shoreline retreats due to mean and storm surge sea level rise.

1.3 Projections of beach retreat/erosion

It should be noted that projections of beach retreat/erosion are carried out in the face of uncertainties regarding e.g. the future hydrodynamic forcing (sea level and wave dynamics) and the riverine and coastal sediment supply to the coast (which itself depends on precipitation dynamics, land use and river management, see Section 1.1). Moreover, the reliability of projections depends on the availability/accuracy of the model 'set up' information, such as the bathymetry/bed slope, the sediment texture and distribution and the presence of nearshore coastal works and/or ecosystems that can modify coastal

[1] According to the Article 8.2a the Parties to the ICZM Protocol '*shall establish in coastal zones, as from the highest winter waterline, a zone where construction is not allowed. Taking into account, inter alia, the areas directly and negatively affected by climate change and natural risks, this zone may not be less than 100 meters in width, subject to the provisions of subparagraph 8.2 (b) below. Stricter national measures determining this width shall continue to apply'.*

[2] According to the Article 8.2b, the Parties '*may adapt, in a manner consistent with the objectives and principles of this Protocol, the provisions mentioned above: 1) for projects of public interest; 2) in areas having particular geographical or other local constraints, especially related to population density or social needs, where individual housing, urbanisation or development are provided for by national legal instruments; (c) shall notify to the Organization their national legal instruments providing for the above adaptations'.*

[3] Winter waterlines are regarded as the reach of the highest annual waves; this is obviously controlled by the beach erosion/retreat which, in turn, is controlled by the sea level, the wave regime, the seabed slope and sediment size, as well as by the available sediment supply to balance offshore sediment losses and the human interventions (e.g. coastal works) in the coastal zone. Most of these controls are themselves dependent on the Climate Variability and Change.

hydrodynamics (e.g. Vousdoukas et al., 2012; Peduzzi et al., 2013). In the light of the above; the availability of such information is very significant for the reduction of uncertainties in the projections.

Beach retreat/erosion projections under variable/changing hydrodynamic forcing are carried out using models. These models can be either analytical or dynamic (numerical simulations) and can be classified according to their dimension as: (i) one dimensional (1-D) cross-shore models (e.g. Fig. 1.2); (ii) two dimensional cross-shore models (2-DV); (iii) two dimensional horizontal models (2-DH) (e.g. Fig. 1.3); (iv) pseudo-three dimensional models (Quasi-3-D models); and (v) three dimensional (3-D) models.

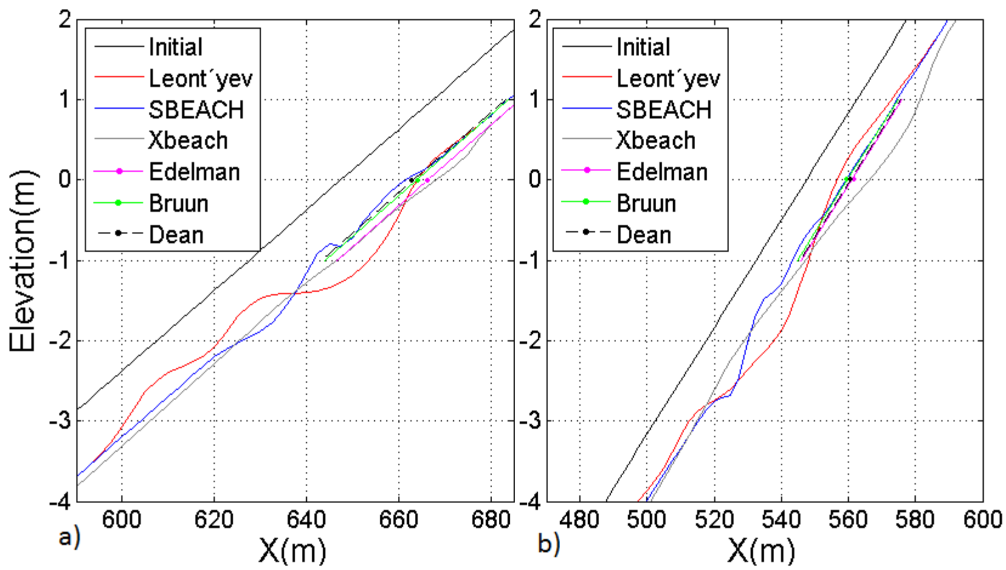

Fig. 1.2 Examples of the morphodynamic changes for the upper part of the beach (initial) cross-shore profile on the basis of 6 1-D cross-shore models for sea level rise of 0.82 m (IPCC, 2013). Input conditions: (a) offshore (at 20 m water depth) wave height H and period T, 2 m and 6 s, respectively, linear beach profile with 1/20 slope and median (d50) sediment grain size of 2 mm; (b) offshore (at 20 m water depth) wave height H and period T, 4 m and 8 s, respectively, linear profile with 1/15 slope and median (d50) sediment grain size of 5mm. In both cases, the origin of X axis is at 20 m water depth (Allenbach et al., 2014). For details of the models used see Sections 5 and 6).

The selection of the model to be used in an application depends mostly on: (a) the availability of good quality spatial information (e.g. beach morphology/bathymetry and the sediment size and its distribution); (b) good quality information on the forcing (waves and currents); (c) the availability of *in situ* information to calibrate/validate the models; and (d) most importantly, the expertise/experience of the available human resources.

The more elaborate 2-D and, particularly, the 3-D models are more sensitive to the accuracy of the model 'set-up' information and, more importantly, require particular expertise and large computational times (see e.g. Ramieri et al., 2011). Therefore, rapid assessments of beach reterat/erosion at various spatial scales (from local to basin scale) are commonly carried out by 1-D cross-shore models (Hinkel et al., 2009; Ranasinghe et al., 2013; Allenbach et al., 2014).

In the present demonstration workshop, beach retreats are projected through the use of a variety (both analytical and dynamic) of 1-D (cross-shore) morphodynamic models. These models can be used either individually, or in an ensemble, in a user-friendly mode (using Guide User Intrefaces - GUIs). Moreover, their use is characterised by some freedom in terms of the ‘set-up’ and forcing information; the user can choose to either use generalised (linear) information on bed slope and offshore wave conditions, or to enter more detailed information (if available) on cross-shore beach profiles and offshore wave conditions.

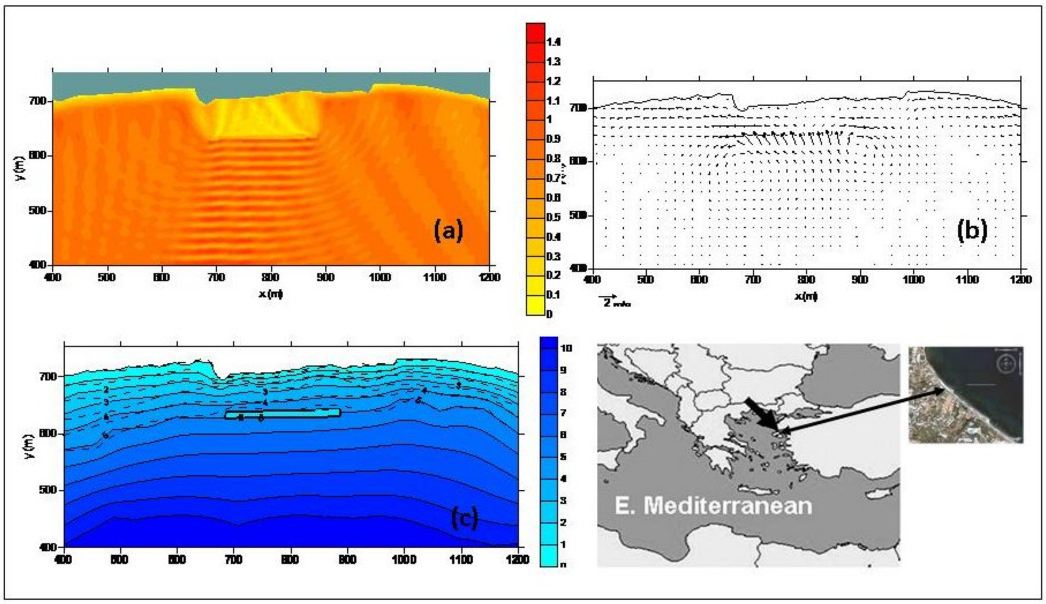

Fig. 1.3 Examples of a 2-DH morphodynamic model output from a Lesbos beach (East Aegean Sea, Greece).(a) Nearshore wave height (m) distribution in the presence of a breakwater. (b) Wave generated current. (c) Beach morphology evolution (solid line, initial bathymetry (isobaths); stippled line, final bathymetry (isobaths). Wave regime according to the ‘equivalent’ wave conditions (see Section 4.3), due to winds from N, NE, E and SE sectors) (Karambas et al., 2008).

1.4 Aims and content of the workshop

The main aim of the present demonstration workshop is to present a user friendly, integrated software toolbox that will allow an initial assessment of the beach retreat/erosion risk, and, thus, of the inshore displacement of the winter waterline under a changing and variable climate. The toolbox comprises a suite of components that can rapidly provide estimates of beach retreat under different long-term and short-term sea level rises and wave forcings. It is based on the use of different cross-shore analytical and numerical morphodynamic models of varied complexity, which can be used either individually or in combination (in an ensemble). The reason behind providing the opportunity to use the models in an ensemble, is that as different models have differential sensitivity to the controlling environmental factors, their common (ensemble) application may provide more tight predictions.

Initial beach morphology to set up the models can be either linear, or 'natural; in the former case beach profile is represented by a single bed slope (set by the user), whereas in the latter case actual beach profile data can be used being either a single observation or the 'mean' of a time series of beach profiles. Similarly, the models can be forced either by waves with user-set wave heights, periods and directions or by waves with characteristics estimated using wind records and wave hindcasting. A brief summary of the toolbox components is presented in Table 1.1.

Table 1.1 Summary of the components of the toolbox (presented as user-friendly Guide User Interfaces-GUIs). *For detailed information on the toolbox components, see the relevant Sections*

Component	Purpose	Input	Output
C1: Beach profile analysis (for details see Section 2)	To identify the 'mean' beach profile from a time-series of beach profiles, using Empirical Orthogonal Functions (EOFs).	Time series of beach profiles	'Mean' beach profile (the most significant spatial eigenvector (first spatial EOF Mode)
C2: Wind record analysis (for details see Section 3)	To identify the wind characteristics that can generate waves that may affect a beach (wind speed, frequency and duration) from the different (direction) sectors, on the basis of time series of wind records.	Time series of wind records (speed and direction)	Files of wind characteristics and windroses
C3: Wave estimation (for details see Section 4)	To estimate open sea wave conditions from wind characteristics (speed, frequency and duration) and the fetch (i.e. the maximum distance between two obstructions e.g. coasts, Islands) along which the wind can flow unhindered)	The output of C2 and the fetch (estimated using maps)	Open sea significant and equivalent* wave heights and periods
C4: Beach retreat assessment by analytical models (for details see Section 5)	To estimate beach retreat s under (long-term) sea level rise α using analytical models for linear (C4a) and 'natural' (C4b) profiles	C4a: wave characteristics (user-set or the output of C3); bed slope and sediment size C4b: wave characteristics (user-set or the output of C3); mean beach profile (output of C1) and sediment size	Beach retreat estimations either by individual models or by a several models (ensemble)
C5: Beach retreat assessment by numerical models (for details see Section 6)	To estimate beach retreat s under (short-term) sea level rise α using dynamic (numerical) models	C5a: wave characteristics (user-set or the output of C3); bed slope and sediment size C4b: wave characteristics (user-set or the output of C3); mean beach profile (output of C1) and sediment size	Beach retreat estimations either by individual models or by a several models (ensemble)

*a characteristic annual wave condition, estimated on the basis of the annual wind occurrence frequency, duration and speed for the different wind intensity and direction classes that affect the beach.

2 Cross-shore beach morphology- Analysis of beach profiles

2.1 Beach morphology

Beaches, i.e. the low-lying coasts built on unconsolidated sediments, are dynamic coastal sediment 'reservoirs', the sediments of which are distributed on both sides of the (moving) shoreline creating a sediment 'continuum' between the land and the sea. The onshore margins of the beach reservoir are natural and/or artificial features found behind the beach, such as vegetated dunes, coastal cliffs, coastal roads and/or building lines, whereas the offshore margin is formed by *the closure depth* (see below); sediments moved offshore of the *closure depth* are effectively lost from the beach sediment reservoir.

Beach morphology is characterised by a large spatial and temporal variability which is controlled by the coastal hydrodynamics forcing the disturbance, mobility/resuspension, transport and deposition of the sediments that build the beaches. The most characteristic beach morphological features are the berm, an onshore accumulation of beach sediments and the submarine bars and troughs (Fig. 2.1).

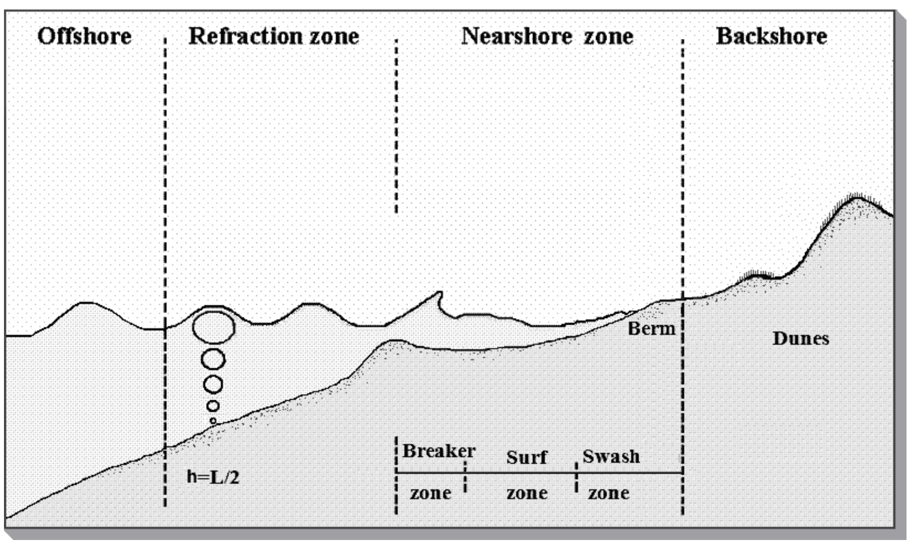

Fig. 2.1 The beach profile: Morphological features and wave zones (Open University, 1997).

Beaches are very dynamic. *Berms* are mostly built under low/moderate wave conditions, with their position and height (B_h) depending on the wave run up. Well-developed berms are mostly observed on beaches with relatively coarse grained sediments (pebbles, gravels and coarse sands) (Komar, 1998).

Sunamura (1989) suggested that berm heights B_h may be estimated using:

$$B_h = 0.125(H_b)^{5/8}(gT^2)^{3/8} \quad [2\text{-}1]$$

where H_b is the wave height at breaking and T the wave period (g the gravity acceleration 9.81 m/s^2).

The submarine *bars* (long-shore, oblique or crescentic) are built mostly during high wave conditions, during which sediments from the onshore beach are transported offshore; bars are usually paired with submarine troughs, i.e. channels of deeper water between the bars and the shoreline. Such cross-shore profile changes reflect the beach response to the high wave energy 'assault'; swallowing of the submarine beach due to bar formation results in higher dissipation of the impinging wave energy and, thus, in the protection of the beach from further erosion. Generally the position, size and water depth of the submarine bars and troughs depend on the height and position of the breaking waves. It has been found (Sunamura, 1989; Komar, 1998) that the distance *(lt)* of the deepest zone of the trough from the location of the wave breaking zone can be approximated by

$$l_t = L_0(10/s)(H_b/gT^2)^{4/3} \quad [2\text{-}2]$$

whereas the distance of the long-shore bar crest *(lc)* from the deepest zone of the trough by:

$$l_c = 0.18H_b(l_t/\mathrm{H}_b)^{3/2} \quad [2\text{-}3]$$

where L_0 the open sea wave length, H_b the wave height at breaking, T is the wave period and s the mean beach slope.

The cross-shore morphological changes of the submarine beach decrease in the offshore direction (Fig. 2.2). These changes seize to be apparent at a distance (and a corresponding water depth) from the shoreline called '*the closure depth*'; beyond this water depth there are no significant water depth changes due to beach sediment transport. Closure depth is considered to be the offshore margin of the beach sediment reservoir; sediments transported offshore of the closure depth can not return to the beach (Inman et al., 1993; Pilkey et al., 1993; Nicholls et al., 1998; Komar, 1998). If time series of cross-shore beach profiles are available, then the *closure depth* can be estimated on their collective plot as the area where the temporal morphological changes become insignificant (Lee and Birkemeier, 1993), i.e. smaller than the measurement error (Fig. 2.2).

In the absence of adequate temporal information (i.e. good quality time-series of beach profiles), the closure depth can be estimated by hydrodynamic Hallermeier (1981) has suggested that the closure depth (hc) can be approximated by:

$$h_c = 2.28H_{sx} - 68.5\frac{H_{sx}^2}{gT_{sx}^2} \quad [2\text{-}4]$$

where H_{sx} is the maximum inshore wave height with an annual occurrence of 12 hours and T_{sx} its period. As the H_{sx} and T_{sx} may not be always available, the closure depth (h_c) can be approximated also by:

$$h_c = 2\overline{H}_s - 11\sigma \qquad [2\text{-}5]$$

where $\overline{H}_s$ is the mean annual significant wave height (the mean height of the 1/3 of the higher annual waves) and σ its standard deviation. Also, by (Birkemeier, 1985):

$$h_c = 1.57 H_{sx} \qquad [2\text{-}6]$$

The closure depth is a very significant parameter for the design of e.g. beach replenishment schemes (Stive et al., 1991).

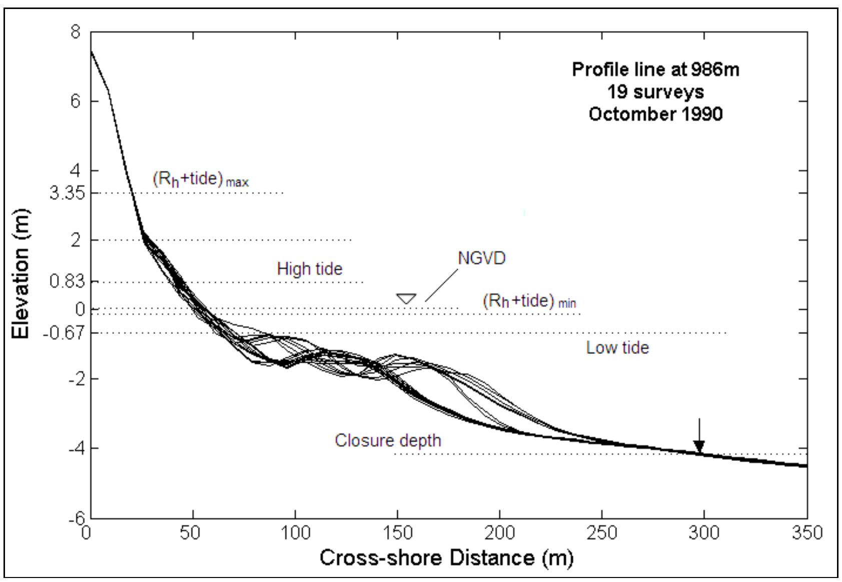

Fig. 2.2 Time series of cross-shore beach profiles (Experiment Delilah) from the US Army Corps of Engineering facility at Duck (Carolina, USA). The Low and High tide levels, the maximum ($(R_h$+tide$)_{max}$) and minimum ($(R_h$+tide$)_{min}$) wave run-ups and the National Geodetic Vertical Datum (NGVD) are shown. The position of the closure depths is marked by the black arrow.

2.2 Beach morphodynamics

Beach morphology is characterised by large variability at different spatial and temporal scales (Komar, 1998). Beach morphological changes can be divided on the basis of their spatio-temporal scales into (EUROSION, 2004):

- Changes of the general form of the coastline (scales of some km/decades), which may be related to significant changes in the beach sediment supply, the sea level and the wave climate.

- Seasonal changes that reflect the differential seasonal hydrodynamics and are mostly associated with sediment exchanges between the berm and submarine bars. In cross-shore beach profiles a ‘winter’ and a ‘summer’ beach profile can be identified (Fig. 2.3). The higher-steepness and more energetic winter waves erode the berms and transport their sediments to the submarine bars, whereas the summer waves tend to gradually transport submarine sediments to the onshore beach, re-building the berms.
- Morphological changes occurring in hours/days usually during extreme events. In such conditions, major morphological changes can take place along the full beach width (onshore and offshore) and sediment may even be transported beyond the *closure depth* being, therefore, lost from the beach sediment reservoir.

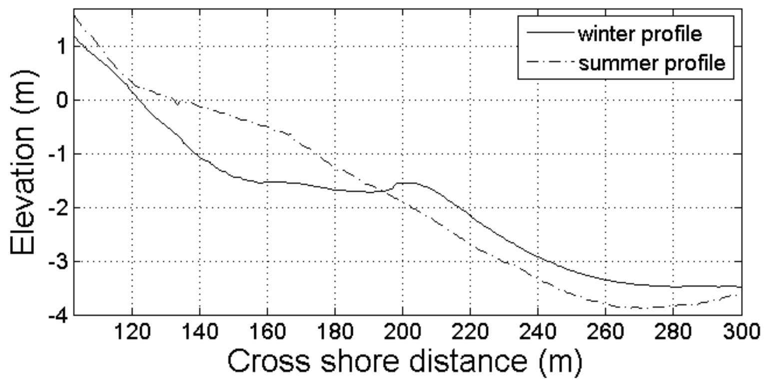

Fig. 2.3 Summer (28th July) and winter (16th December) beach profiles observed during the SandyDuck Experiment.

2.3 Analysis of beach profiles

Prevailing trends in the spatial and temporal variability of beach profiles can be identified using Empirical Orthogonal Function (EOF) analysis (Winant et al., 1975; Aubrey, 1979). The analysis aims to isolate the data spatial and temporal dependence, so that the information can be ‘summarised’ by a relatively small number of variables which, however, contain most of the original information. Advantages of the EOF method include (Aubrey and Emery, 1983): (i) the approach is objective; (ii) it provides objective ‘means’ of the classified variability trends and, .thus, constrains weak signals and/or noise’; (iii) makes easier the interpretation of the spatio-temporal variability; and (iv) provides non-correlated variability trends which are consistent in space and time χώρο.

In the present application, EOFs are used to analyse time series of cross-shore (1-D) beach profiles. The method analyses the beach profile evolution into major components, which simplifies the recognition of prevailing trends, as well as their interpretation. Previous research (e.g. Winant et al., 1975; Aubrey, 1979) has suggested that the 3 spatial eigenfunctions corresponding to the 3 highest eigenvalues can contain almost all the beach profile variability. It has been also found that the first spatial eigenfunction (e1) can describe the ‘mean’ beach profile during the monitoring time (the time series), the second (e2) may provide information on the preferred locations of the berms and submarine bars, whereas the third eigenfunction (e3) may be related to the low tide terrace. With regard to the 3 fisrt temporal eigenfucntions (which correspond to the 3 highest eigenvalues) Aubrey (1979) has suggested that: the first temporal eigenfunction (c1) can give information on the presence of general erosion/deposition trends of the beach profile; the second eigenfunction (c2) may be related to seasonal sediment transport processes; and the third temporal eigenfucntion (c3) may be associated with high morphological variability (see also Pena and Lanfredi, 1988).

In the present application the morphological information is provided as time series of cross-shore beach profiles, i.e. as time series of bed elevations records along a cross-shore line that originates at an established reference point. The elevations z recorded at different times n_t and at different positions n_x are given by:

$$z_{t_j,x_i}\text{ , where }(j=1,2,...,n_t, i=1,2,...,n_s) \qquad [2\text{-}7]$$

and, thus, the data can be arranged as a matrix:

$$\begin{matrix} t_1 \\ t_2 \\ ..... \\ t_{n_t} \end{matrix} \Rightarrow H_t = \begin{bmatrix} z_{t_1,x_1} & z_{t_1,x_2} & .... & z_{t_1,x_{n_s}} \\ z_{t_2,x_1} & z_{t_2,x_2} & .... & z_{t_2,x_{n_s}} \\ .... & .... & .... & .... \\ z_{t_{n_t},x_1} & z_{t_{n_t},x_2} & .... & z_{t_{n_t},x_{n_s}} \end{bmatrix} \qquad [2\text{-}8]$$

In this way, the beach profile data form an H_t ($n_t \times n_s$) matrix with elements $z(t_j, x_i)$, which has n_t rows and n_s columns. Using the matrix H_t, two square matrices can be generated:

$$A_t = \frac{1}{n_s n_t}(H_t^T H_t) \qquad [2\text{-}9]$$

$$B_t = \frac{1}{n_s n_t}(H_t H_t^T) \qquad [2\text{-}10]$$

where H^T is the transpose of *H.* Hence, matrix *A* has a dimension of $n_s \times n_s$, and matrix *B of* $n_t \times n_t$. Further, *A* and *B* matrices are Hermitian square matrices, i.e. they both possess sets of positive, real eigenvalues and eigenfunctions. For matrix *A, n* eigenvalues and eigenfunctions exist so that:

$$A_t e_i = \lambda_i e_i \qquad [2\text{-}11]$$

where e_i ($i = 1, 2, ..., n_s$) are spatially-related eigenfunctions.

Likewise, n_t eigenvalues and eigenfunctions can be defined for matrix *B*:

$$B_t c_j = \lambda c_j \qquad [2\text{-}12]$$

where c_j ($j = 1, 2, ..., n_t$) are temporally related eigenfunctions.

It can be proved that both matrices A and B have the same n ($n \leq n_s$ and $n \leq n_t$) non-zero eigenvalues (Landesman and Hestenes, 1992, p.219). Let e_k και c_k (k = 1, 2, ..., n) be the eigenfunctions of *A* and *B* associated with the non-zero eigenvalues, i.e. $e_k = [e_k(x_1), e_k(x_2), ..., e_k(x_{ns})]$ και $c_k = [c_k(t_1), c_k(t_2), ..., c_k(t_{nt})]$. In this case, the measured bed elevation at distance x_i and time t_j *can* can be written as a function of the ith component of e_k,, the jth component of c_k and the n non-zero eigenvalues:

$$Z(x_i, t_j) = \sum_{k=1}^{n} a_k e_k(i) c_k(j) \qquad [2\text{-}13]$$

where

$$a_k = \sqrt{\lambda_k n_t n_z} \qquad (k = 1,2,\ldots n) \qquad [2\text{-}14]$$

A necessary assumption in using the EOF analysis is that the data analysed have a common origin and spatial resolution. Therefore, the original irregularly-spaced bed elevation observations should be transformed through interpolation into a regular grid with a common origin.

In the case that there are time series of beach profiles from different locations of the same beach, the resulting 'mean' beach profiles (first spatial eigenfunctions) can be used in further analysis to provide a beach 'mean' spatial profile that contains most of the morphological variability of the study beach.

2.4 The beach profile Guide User Interface (GUI)

In order to provide a user-friendly tool, the estimations are carried out using a specifically designed Guide User Interface (GUI) (Fig. 2.4). For further information on its use, see the accompanying manual.

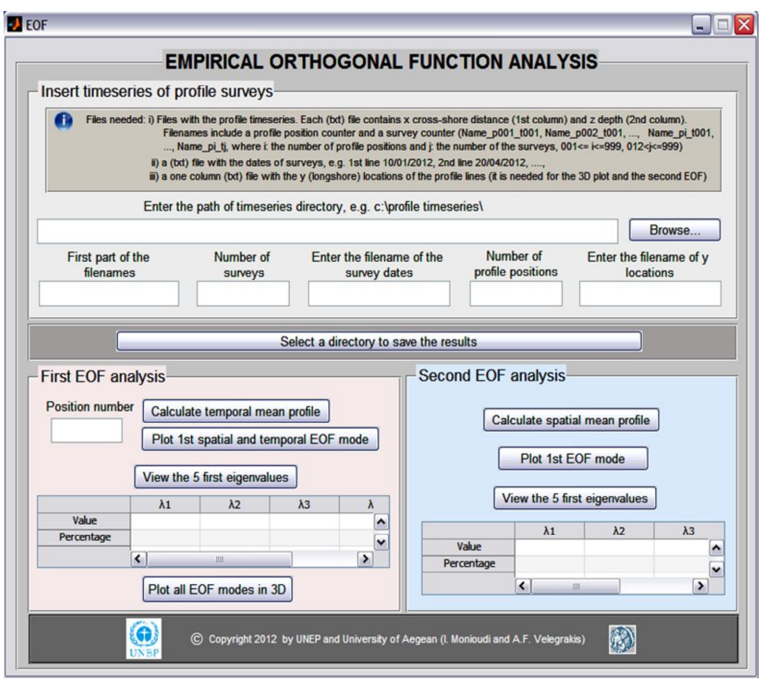

Fig. 2.4 The beach profile analysis GUI.

3 Wind time series analysis

3.1 Wind characteristics

The major wind characteristics are the direction and intensity (speed). Wind direction is related to the azimuth of the incoming wind, with the air flow considered to be linear and horizontal. Wind direction is measured in degrees in a clockwise fashion from the North (^{0}N). There are 8 major and 8 secondary wind directions (Fig. 3.1 and Table 3.1).

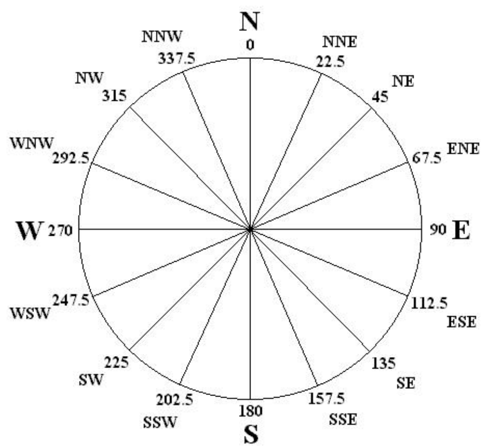

Fig 3.1 Major and secondary wind directions

The wind speed (i.e. the distance covered by the air mass in a time unit) depends on the height of the measurement. For oceanographic applications, the reference datum is set to be at 10 m above the sea level; therefore, if speed measurements have been obtained at a different height, these should be translated into speeds at the 10 m level (U10) through:

$$U_{10} = U_Z (10/z)^{1/7} \quad [3\text{-}1]$$

where U_z the wind speed at elevation z above the sea level and U_{10} the wind speed at an elevation of 10 m above the sea. Usual units of wind measurements are m/sec, km/h, miles/h (1609 m/h) and knots (1852 m/h); therefore, wind speeds of 1 m/s equal wind speeds of 3.6 km/h, 2.24 miles/hour and 1.94 knots.

Table 3.1 Major wind directions

Wind	Major Direction (^{0})	Wind sector (^{0})
North (N)	0	338-23
NorthEast (NE)	45	23-68
East (E)	90	68-113
SouthEast (SE)	135	113-158
South (S)	180	158-203
SouthWest (SW)	225	203-248
West (W)	270	248-293
NorthWest (NW)	315	293-338

A widely used measurement scale of wind speed is the Beaufort scale (Table 3.2). The units in the Beaufort scale can be translated into m/s using the empirical expression:

$$U_{(m/s)} = 0.836B^{3/2} \quad [3\text{-}2]$$

where $U_{(m/s)}$ is the wind speed in m/s and B the units of the Beaufort scale.

Table 3.2 Beaufort scale and its translation in other units according to the National Meteorological Service of Greece.

Wind Intensity (Beaufort Scale)		Wind speed			
B	Wind	m/s	km/h	knots	miles/h
0	Calm	0-0,2	< 1	< 1	<1
1	Light air	0.3-1.5	1-5	1-3	1-3
2	Light breeze	1.6-3.3	6-11	4-6	4-7
3	Gentle breeze	3.4-5.4	12-19	7-10	8-11
4	Moderate breeze	5.5-7.9	20-28	11-16	13-18
5	Fresh breeze	8.0-10.7	29-38	17-21	19-24
6	Strong breeze	10.8-13.8	39-49	22-27	25-31
7	Moderate gale	13.9-17.1	50-61	28-33	32-38
8	Fresh gale	17.2-20.7	62-74	34-40	39-46
9	Strong gale	20.8-24.4	75-88	41-47	47-54
10	Storm	24.5-28.4	89-102	48-55	55-63
11	Violent storm	28.5-32,6	103-117	56-63	64-74
12	Hurricane force	>= 32.7	>= 118	>= 64	>=75

A very significant graphical tool is the wind rose, which gives concise view of how wind speed and direction are typically distributed at a particular location. Using a polar coordinate system, the frequency of winds over a long time period is plotted by wind direction, with color bands showing wind ranges. The directions of the rose with the longest spoke show the wind direction with the greatest frequency (Fig. 3.2).

Wind data consist of observations of wind speed and direction obtained with a particular sampling frequency (usually half-hourly or hourly observations but, some times, more frequently), with the records containing information also on the date and time of observations. Data analysis is carried out in the following steps.

(1) Translation of speed measurements into m/s (if the speed measurements are taken in other units).

(2) Translation of speed measurements into U_{10} speeds (if speed measurements are obtained at different heights above sea level) using the Eq. [2-1].

(3) Estimation of the duration of winds with certain speeds and directions (from the time records).

(4) The following analysis may take place for each of the 8 major direction sectors:

- Isolation of the wind records from each sector;
- Separation of records according to speed;. and
- Classification of records with duration of e.g. longer than 3 hours into speed classes and estimation of the mean (and maximum) speeds, the wind duration as well as of the frequency of these events.

With regard to extreme events the criterion of Sanchez-Arcilla et al. (2008) can be used. According to this criterion, storm wave conditions can be generated by strong winds with minimum duration of 6 hours.

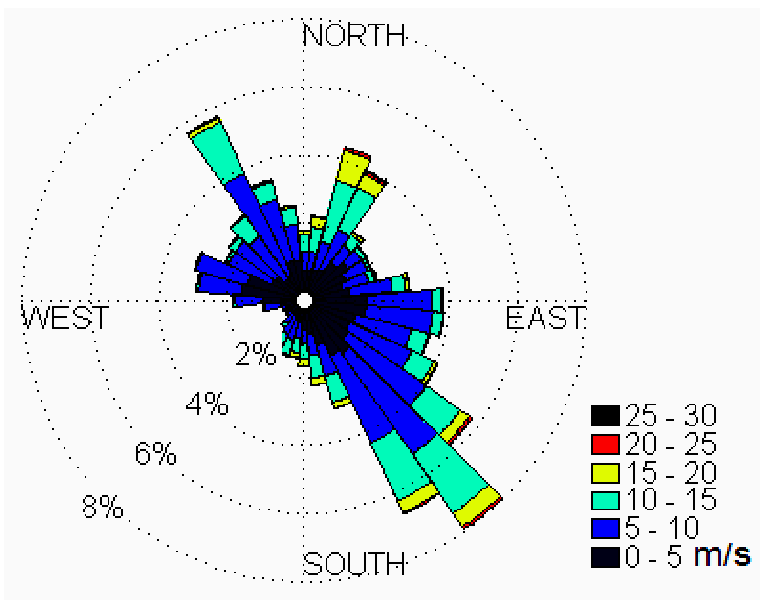

Fig. 3.2 Wind rose (data 2009-2011) from a meteorological station (University Station) at the island of Lesbos, E. Mediterranean, showing wind directions, speed ranges and frequency (in percentage of occurrence). The prevailing winds are from the SE, NW and NE

In addition to the above general analysis more specialised analysis can be undertaken which can provide information on e.g. the wind statistics (mean and maximum speeds, duration and frequency) that can affect a beach with a particular orientation.

3.2 The Wind Data Analysis GUI

In order to provide a user-friendly tool, the estimations are carried out using a specifically designed Guide User Interface (GUI) (Fig. 3.3). For further information on its use, see the accompanying manuals.

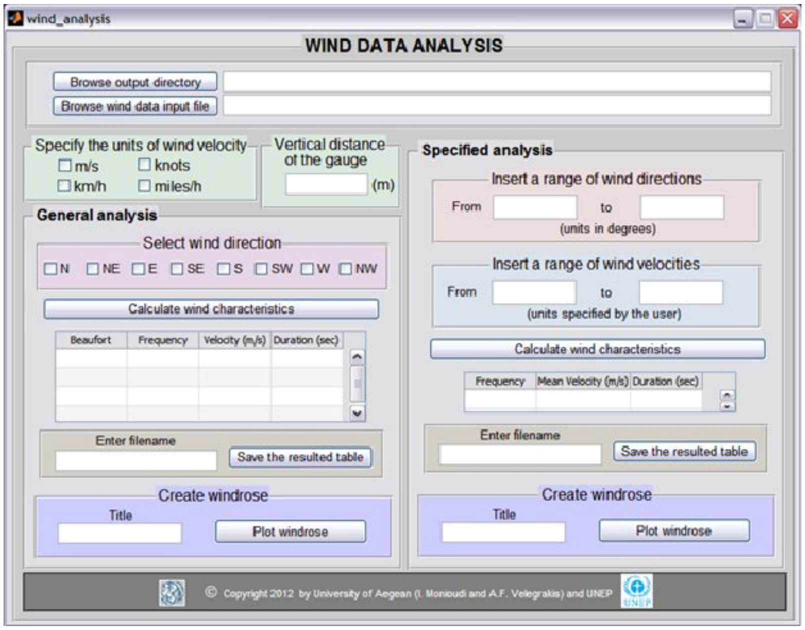

Fig. 3.3 The wind data analysis GUI.

4 Wave estimation from wind data

4.1 Wave characteristics

Progressive wind waves are characterised by certain basic parameters (Fig. 4.1): wave length *L* (in m), i.e. the distance from two consecutive crests; period *T* (in sec), i.e. the time needed for the wave to travel distance equal to the wavelength L; wave height *H* (in m), i.e. the vertical distance between the wave crest and the wave trough; and amplitude a, i.e. the half wave height (*H/2*) (in m). Another important factor affecting the manner that the wave energy influences the inshore waters/beach, is the water depth *h* (in m) which controls the wave dissipation and breaking.

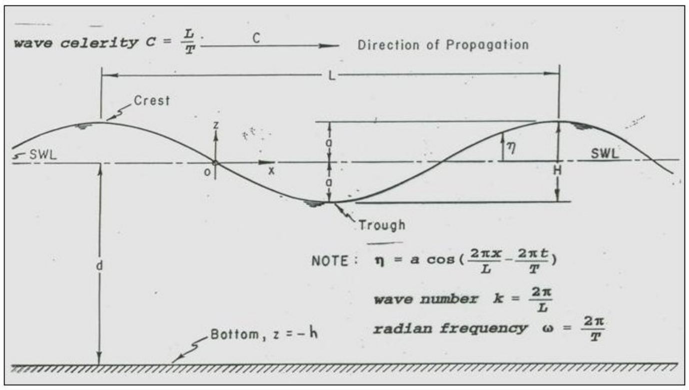

Fig. 4.1 Parameters of a progressive, monochromatic wave (after CEM, 2008). The solution for the elevation of the free water surface η in relation to the mean water level SWL, is according to the Airy wave theory.

In nature, the wave train is extremely rarely to be characterised by unique wave parameters (monochromatic wave), as it contains a combination of waves of different wavelengths, heights and periods (Fig. 4.2). Therefore, to describe/model the wave conditions, some simplifications of the polychromatic wave parameters may be necessary, which are provided by e.g. wave height statistics[4] and or spectral analysis of the wave time series (Fig. 4.2).

Waves in the open sea (i.e. over water depths larger than L/2) transfer energy and do not interact with the seabed; as they approach the beach, however, waves start 'feeling' the sea bed, losing energy due to bed friction and changing their direction of approach due to wave refraction. Finally, close to (and particularly inshore of) the wave breaking zone[5], the momentum field changes inducing the generation of flows/wave-generated currents (see

[4] Most important parameters of polychromatic waves include the significant wave height *Hs* i.e. the mean height of the 1/3 highest waves in a wave record and its corresponding wave period *Ts*, the maximum wave height *Hmax*, the *Hrms* and the peak wave period *Tp*.

[5] Generally occurring where the waves reach water depths *h* being about 1.2-1.3 times the wave height *H*.

Fig. 4.2(a)). Such wave generated currents may have very significant impacts on beach morphodynamics (Komar, 1998).

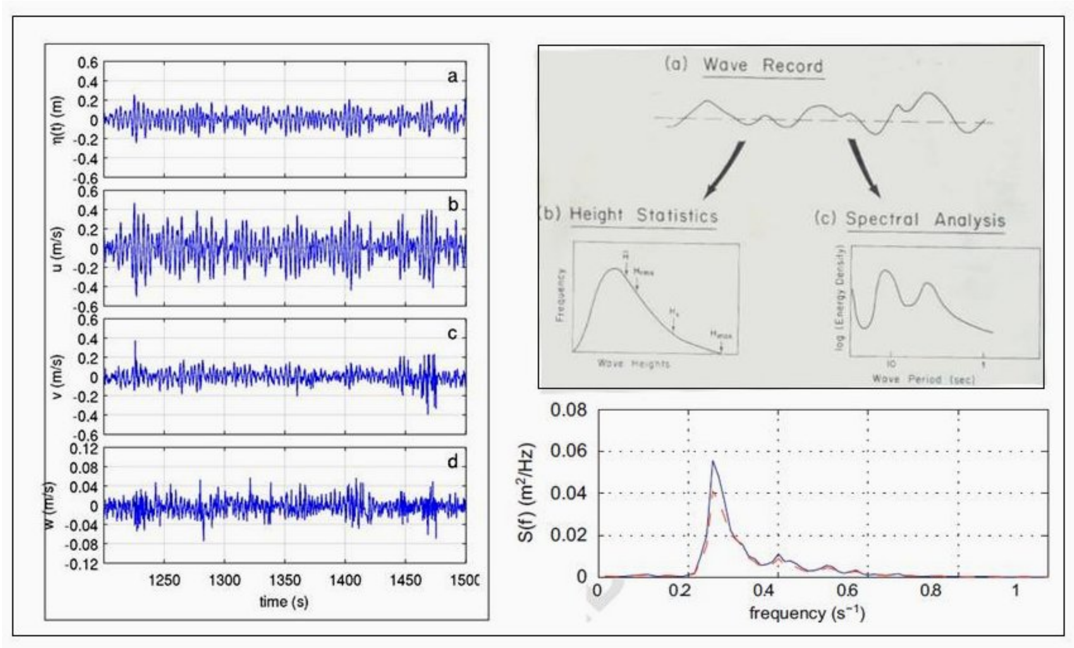

Fig. 4.2 (a) Example of synchronous high frequency beach wave (and corresponding current) measurements at about 1.2 m water depth (Vousdoukas et al., 2012). Key: η, water elevation and near-bed current velocity components, perpendicular to the coastline (u), parallel to the coastline (v) and along the vertical (w). (b) Translation of the wave record into wave height distribution and spectral density (Komar, 1998). (c) Wave spectra from two inshore hydrodynamic stations (blue line, offshore and red line, inshore) showing the polychromatic nature of waves and the dissipation of energy occurring between these two stations (Vousdoukas et al., 2012).

4.2 Wind wave generation

In the open sea, wind waves are considered to be generated in the stages, following the wind generation (Komar, 1998): (i) formation of capillary waves (with period $T < 1$ sec, H about 0.01-0.02 m) due, possibly, to the action of turbulent eddies within the air sea boundary layer; (ii) generation of larger waves (in terms of wavelength L, height H and period T) due to e.g. the differential air pressure and separation of flow; and (iii) transfer of energy from the shorter to longer waves due to offshore wave breaking.

Therefore, the wave conditions at the generation point ('*sea*') are *polychromatic*, with many different, in terms of length height and period, co-existing waves. As these waves travel away from the generation point are 'filtered'; long waves are both faster and less prone to dissipation than shorter waves and, thus, if there is enough wind energy transfer and adequate distance to the shoreline, the original polychromatic *sea* will be translated into a much more monochromatic *swell*.

4.3 Wave generation controls

Wind wave development depends on 3 parameters: the wind s*peed*, the wind *duration* and the *fetch*. The higher the wind intensity/speed, the higher the air-sea energy transfer. In wave hindcasting, the *controlled wind speed* U_A is used, which can be estimated from the wind speed at 10 m height above the sea surface U_{10} using the empirical expression:

$$U_A = 0.71(U_{10})^{1.23} \quad [4\text{-}1]$$

Generally, the air- sea energy transfer increases with the time of wind flow above the sea surface, i.e. the wind wave energy is controlled by the *wind duration* (t_D) . In addition, wind wave development depends on the fetch (*F*), i.e. the maximum distance between two obstructions (e.g. coasts. Islands) along which the wind can flow unhindered; small fetches do not allow for the development of large waves. The effective fetch at the location is estimated within a sector with a range ±45° relatively to the major direction (Fig. 4.3), using the following expression (Koutitas, 1994):

$$F_{eff} = \frac{\sum_i F_i \cdot (\cos a_i)^2}{\sum_i \cos a_i} \quad [4\text{-}2]$$

where *i* describes the radius direction even 5° on either side of the wind direction, F_i is the linear fetch of direction *i* and α_i is the angle of radius *i* with the wind direction. These lengths of these linear fetches can be estimated graphically from off and/or on-line charts.

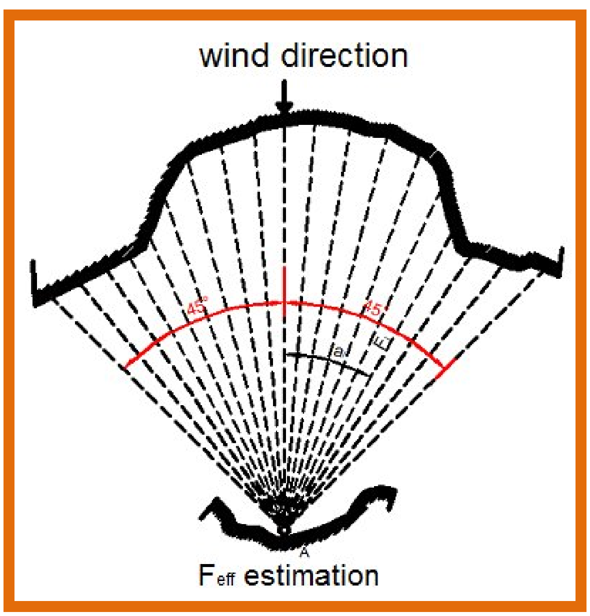

Fig. 4.3 Fetch estimation using the radii directions (every 5°) on either side of the wind direction (Koutitas, 1994).

An example

An example of effective fetch estimation for SE winds (135° N) for the Tsamakia beach (E. Lesbos, Greece) is given below (Fig. 4.4 and Table 4.1). The sector used has a range of 90-180° N; as however Tsamakia beach is protected from winds with orientations 155-180° N, the sector which has been used for the estimation of the effective fetch is the sector 90-150° N.

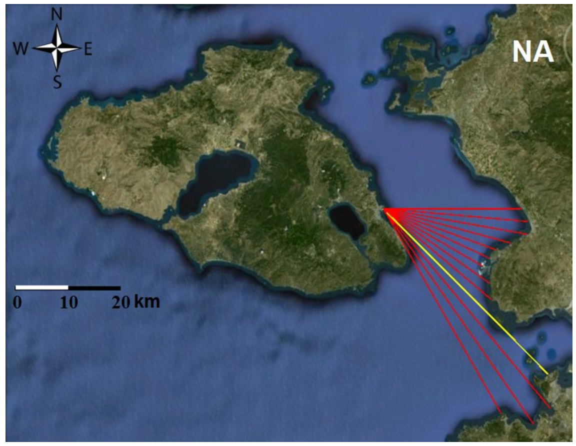

Fig. 4.4 Effective fetch of Tsamakia beach (E. Lesbos, Greece) for SE winds.

Table 4.1 Fetches of Tsamakia beach (E. Lesbos, Greece) for winds from the 90-150° N sector, on the basis of radius directions every 5°.

Radius	a_i	Direction	$\cos(a_i)$	$\cos^2(a_i)$	F_i [km]	$F_i*\cos^2(a_i)$ [km]
1	345	150	0.97	0.93	44.50	41.52
2	350	145	0.98	0.97	49.40	47.91
3	355	140	1.00	0.99	49.00	48.63
4	0	135	1.00	1.00	44.00	44.00
5	5	130	1.00	0.99	26.50	26.30
6	10	125	0.98	0.97	24.35	23.62
7	15	120	0.97	0.93	21.60	20.15
8	20	115	0.94	0.88	22.00	19.43
9	25	110	0.91	0.82	22.70	18.65
10	30	105	0.87	0.75	24.90	18.68
11	35	100	0.82	0.67	27.50	18.45
12	40	95	0.77	0.59	27.30	16.02
13	45	90	0.71	0.50	26.00	13.00
Sum	-	-	11.90	-	-	356.35

On the basis of the above data and Eq. [4-2], the effective fetch of beach F_{eff} has been estimated as about 30 km.

$$F_{eff} = \frac{\sum_i F_i \cdot (\cos a_i)^2}{\sum_i \cos a_i} = \frac{356.35}{11.9} = 29.95 km$$

Wave development conditions

Wave conditions can be differentiated on the basis of the above parameters (wind speed, duration and fetch) into:

- *Fully Developed Sea (FDS),*which is supplied with the full energy of a wind of particular speed; this condition does not depend any more on the wind duration t_D or the fetch F_{eff}, with the wave parameters being controlled only by the wind speed (U_A).
- *Fetch-Limited Sea development (FLDS),* which is characterised by a fetch F that is shorter than that required for the transfer of the maximum energy from a particular wind speed U_A; this condition does not depend on the wind duration t_D, with the wave parameters being controlled by the wind speed U_A and the effective fetch F_{eff}.
- *Duration-Limited Sea Development (DLSD, which* is associated with wind duration t_D that is shorter than that required for the transfer of the maximum energy from a particular wind speed U_A; this condition does not depend on the fetch, with the wave parameters being controlled by the wind speed U_A and the wind duration t_D.

4.4 Wave projections based on wind data

In the following section, some fundamentals of the wave projections on the basis of wind data (hindcasting) are detailed.

Wind generated waves in the open sea are *polychromatic*, i.e. the wave condition can be approximated by the synthesis of many *monochromatic* waves with different wave characteristics (lengths, heights and periods). In order to estimate this condition, the energy density spectrum i.e. the distribution of the energy density within the different frequencies (periods) (Fig. 4.2) can be employed.

It is assumed that the wave conditions under particular wind forcing and duration can be described by particular wave energy density spectra, such as: the *JONSWAP Spectrum,* which is based on extensive wind and wave records from the North Sea (NE Atlantic coast), and is better suited in cases where there are fetch limitations; and the *Pierson-Moskowitz (P-M) Spectrum,* which is better suited for fully developed seas, i.e. for wave conditions that do not depend any more on the wind duration t_D or the fetch F_{eff}.

The JONSWAP-Pierson-Moskowitz method

This method estimates the open sea significant wave height H_s and the wave period of maximum energy density T_P, on the basis of the controlled wind speed U_A., the effective fetch F_{eff}, and the wind duration t_D.

First, the validity of the expression [4-3] is examined:

$$\frac{gF}{U_A^2} \geq 22.8 \cdot 10^3 \qquad [4\text{-}3]$$

If the expression [4-3] holds, then the waves are fully developed and the expressions related to the *Pierson-Moskowitz spectrum* can be used:

$$\frac{gH_s}{U_A^2} = 0.243 \quad [4\text{-}4]$$

$$\frac{gT_p}{U_A} = 8.13 \quad [4\text{-}5]$$

where H_s the significant wave height και T_p the peak wave period.

If, however, the expression [4-3] does not hold, then the following expressions (*JONSWAP spectrum*) can be used (Hasselmann et al., 1976):

$$\frac{gH_s}{U_A^2} = 0.0016\left(\frac{gx}{U_A^2}\right)^{0.5} \quad [4\text{-}6]$$

$$\frac{gT_p}{U_A} = 0.286\left(\frac{gx}{U_A{}^2}\right)^{0.33} \quad [4\text{-}7]$$

In order to estimate the *x* in the expressions [4-6] and [4-7], the validity of the expression [4-8] is examined:

$$\frac{gt_D}{U_A} > 68.8\left(\frac{gF_{eff}}{U_A{}^2}\right)^{0.66} \quad [4\text{-}8]$$

where t_D is the wind duration.

If the expression [4-8] holds, then the fetch is constrained and x = F_{eff}. If, however, it does not, then the two terms of the expression [4-8] are considered equal, a new F_{eff} is estimated which can be used then as *x* in the expressions [4-6] και [4-7], from which the values of H_s και T_p can be estimated.

Finally, the wave period T_s which corresponds to the significant wave height H_s is estimated from the peak period T_p using:

$$T_s = 0.9T_p \quad [4\text{-}9]$$

Equivalent (effective) waves

It is reasonable to suggest that, normally, the (annual) morphodynamics of a particular beach is controlled by a characteristic annual wave condition the *equivalent/effective waves*. This condition can be estimated on the basis of the following approach.

On the basis of a annual wind record are estimated: the wind occurrence frequency, duration and speed for the different wind intensity classes (e.g. according to the Beaufort scale) and the directions that affect a particular beach. Using the *JONSWAP-Pierson-Moskowitz method, the wave heights* (H_i) and periods (T_i) of the different intensity classes are estimated. Then, the equivalent (effective) wave period T_e in the opens sea is estimated using:

$$T_e = \frac{\sum f_i T_i}{\sum f_i} \qquad [4\text{-}10]$$

where T_i, and f_i are the period and annual occurrence frequency, respectively, of each intensity class *i. The equivalent wave height* H_e is then estimated from the equivalent wave period T_e, on the basis of the expression (Borah και Balloffet, 1985):

$$H_e^2 T_e = \frac{\sum H_i^2 f_i T_i}{\sum f_i} \qquad [4\text{-}11]$$

where H_i, T_i, and f_i the wave heights, periods and occurrence frequency of waves that correspond to the different intensity classes.

An example

In the following section an estimation of the 'equivalent' waves is presented for the Tsamakia beach (E. Lesbos, Greece) using wind records from 2010 (Table 4.2). The characteristics of the 'equivalent' waves have been estimated using the JONSWAP method.

Table 4.2 *Characteristics of equivalent waves for Tsamakia beach, E. Lesbos. H_i, T_i, f_i the wave heights, periods and occurrence frequency of waves that correspond to the different intensity classes (in the Beaufort scale).*

Beaufort	H_i	T_i	F_i	T_i*F_i	$H_i^2*T_i*F_i$
1	-	-	0	-	-
2	-	-	0	-	-
3	0.27	2.74	1.14	3.124	0.228
4	0.48	3.41	1.1	3.751	0.864
5	0.74	3.93	1.75	6.878	3.7661
6	1.06	4.43	0.6	2.658	2.9865
7	1.36	4.82	0.23	1.109	2.0505
8	1.74	5.24	0.27	1.415	4.2835
9	2.12	5.59	0.11	0.615	2.7636
10	1.14	3.5	0.03	0.105	0.1365
Sum	-	-	5.23	19.653	17.079

The equivalent wave period is estimated as:

$$T_e = \frac{\sum f_i T_i}{\sum f_i} = \frac{19.65}{5.23} = 3.76 \text{ sec}$$

And the equivalent wave height as:

$$H_e^2 T_e = \frac{\sum H_i^2 f_i T_i}{\sum f_i} = \frac{17.08}{5.23} = 3.27 \rightarrow \quad H_e = \sqrt{3.27/3.76} = 0.93m$$

4.5 The wave estimation Guide User Interface (GUI)

In order to provide a user-friendly tool, the estimations are carried out using a specifically designed Guide User Interface (GUI) (Fig. 4.5). For further information on its use, see the accompanying manual.

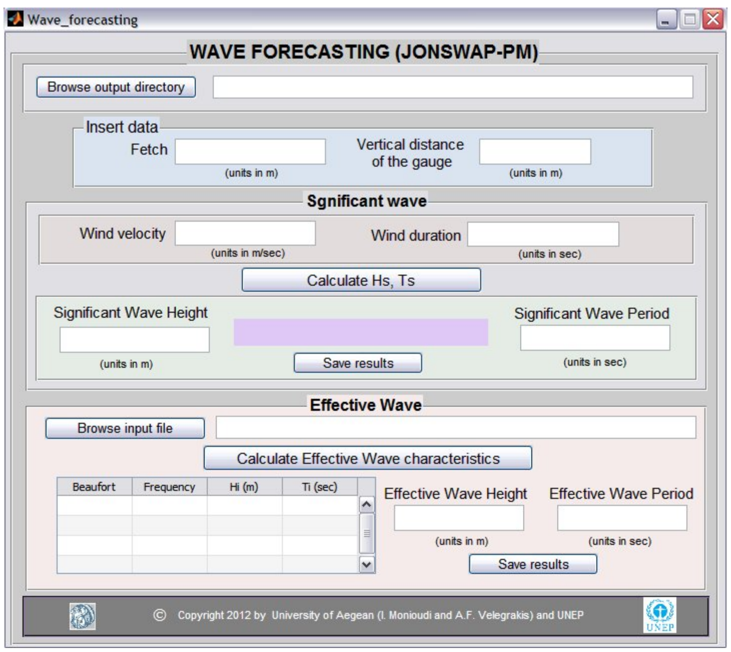

Fig. 4.5 The wave estimation GUI.

5 Analytical models of beach retreat under sea level changes

5.1 Beach retreat due to sea level rise

Beaches are under increasing erosion and/or inundation risk (IPCC SREX, 2012) that can be differentiated into: long-term, irreversible landward migration and/or drowning of the beaches due to mean sea level rise (SLR) or negative coastal sedimentary budgets (e.g. Velegrakis et al., 2008); and short-term erosion, caused by storm surges and waves, which even if they do not result in permanent shoreline retreats, can, nevertheless, be destructive (List et al., 2006). The projected sea level rise, potential increases in the destructiveness of extreme events and the increasing coastal development will exacerbate the already significant erosion, with severe impacts on coastal populations, infrastructure, assets and ecosystem services (e.g. Peduzzi et al., 2013).

Sea level rise, both long- and short-term, threatens beaches with retreat and/or drowning. Since 1900, global mean sea level has risen by about 0.2 m; future mean (long-term) SLR is, however, uncertain, with the latest IPCC report (IPCC, 2013) projecting for 2100 a mean sea level of 0.26 - 0.82 m higher than that of the period 1986-2005, with other recent studies (based on alternative approaches) forecasting even higher rises for the same period (e.g. Fig. 5-1). Global mean sea level rise is considered to be due to (a) ocean thermal expansion (OTE), i.e. ocean volume changes due to steric effects; (b) glacio-eustasy i.e. ocean mass increases from the melting of the Greenland and Antarctic ice sheets (GIS and AIS) and the glaciers and ice caps (GIC); (c) glacio-isostatic adjustment (GIA); and (d) changes in terrestrial water storage (e.g. Hanna et al., 2013).

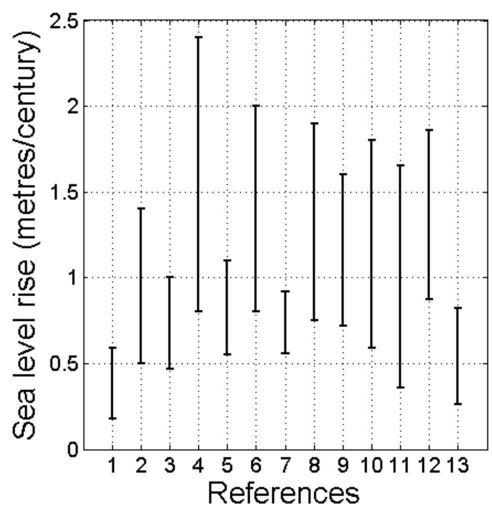

Fig. 5.1 Recent sea level rise projections for 2100 compared to that of IPCC (2007a). Key: 1, IPCC (2007a), 0.18-0.59 m; 2, Rahmstorf et al. (2007); 3, Horton et al. (2008); 4, Rohling et al. (2008); 5, Vellinga et al. (2008); 6, Pfeffer et al. (2008); 7, Kopp et al. (2009); 8, Vermeer and Rahmstorf (2009); 9, Grinsted et al. (2010); 10, Jevrejeva et al. (2010); 11, Jevrejeva et al. (2012); 12, Mori et al. (2013); and 13, IPCC (2013). The variability of the projections reflects differences in assumptions/approaches.

Short-term extreme sea levels are due to due to storm surges. Storm surges have durations of up to few days and are generated by atmospheric forcing, i.e. strong wind friction (Fig. 5.2) and/or differential atmospheric pressure; their height is controlled by the storm intensity and direction as well as the coastal geomorphology (Nielsen, 2009· Zhong et al., 2010).

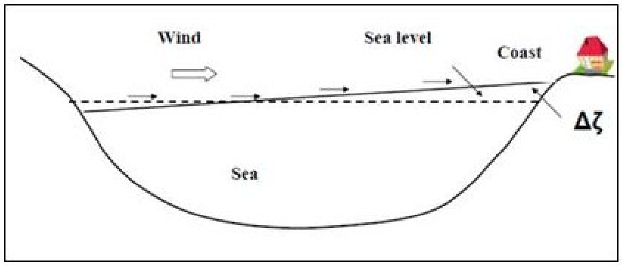

Fig. 5.2 Storm surge generation in a basin from strong winds (after Koutitas, 1994)

Storm surge levels are generally low in the Mediterranean Sea (Fig. 5.3); these rarely exceed 60 cm, with the exception of the head of the Adriatic Sea where extreme sea levels (tidal residuals) of up to 1.5-1.6 m have been observed (Tsimplis and Shaw, 2010). Potential changes in the frequency/patterns of storm surges/waves due to climate change will exacerbate beach retreats in the region, particularly if future extremes couple with higher mean sea levels

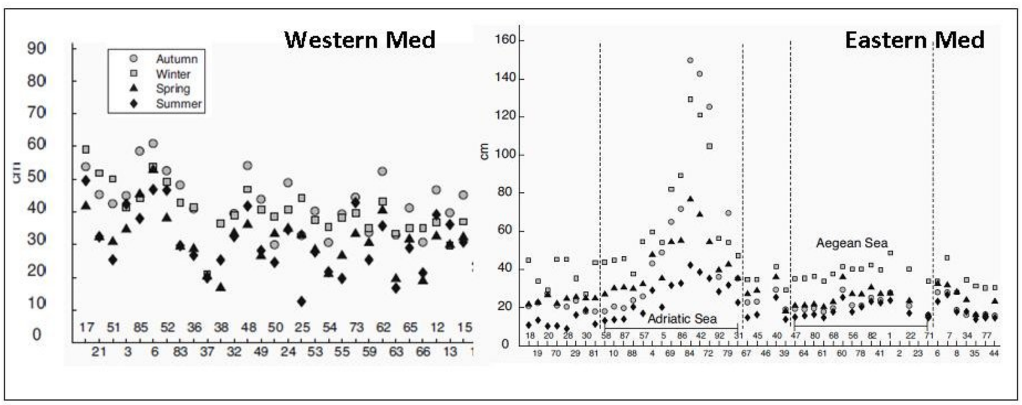

Fig. 5.3 Maximum seasonal extreme sea level values (tidal residuals) in the western and Eastern Mediterranean (Tsimplis and Shaw, 2010). For location of the stations, see the original publication.

Beaches respond to the sea level rise (both long- and short-term) with retreat (Fig. 5.4). The impacts of this retreat will depend on the 'degrees of freedom' of the beach. i.e. its capacity to 'roll over' unhindered by back-barrier constraints such the presence of natural (e.g. coastal cliffs) or artificial (seawalls, coastal roads, residential and/or touristic housing) features and the beach sediment budgets. In the case of back-barrier constraints and/or unfavourable sediment budgets, beaches may 'drown', with very significant impacts on the ecosystems and assets they front.

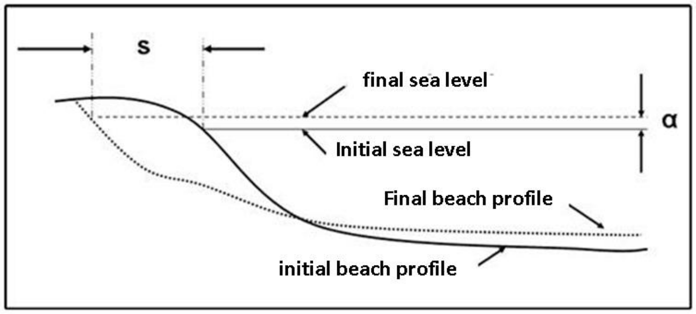

Fig. 5.4.Scetch showing the beach response to sea level rise. If the sea level rises by α, beach feace sediments are eroded and transported offshore to be deposited at the seabed, resulting to a shoreline retreat of s.

Several models have been developed for the prognosis of beach response to sea level changes. The scope of application of these morphodynamic models varies, depending amongst others on the time-frame of prognosis, the availability of data to set-up and force the model data and the expertise/experience of the user. With regards to the spatial scope of the models, these can be differentiated into 1-, 2- and 3-D models; their selection/use depends on the study aims, as well as on the availability of data to set-up/force the models, the expertise/experience of the user and the computation power.

In the present toolbox, 1-D (cross-shore) models are used, as they can be set-up/forced by a minimum amount of morphological, sedimentological and hydrodynamic) information, require much less experience/expertise that the 2- and certainly the 3-D models and are considered adequate for the purpose of a first assessment of the beach dynamics under sea level rise.

The models included into the toolbox can be differentiated into: (i) analytical models and (ii) process-response, dynamic models. Analytical models deal with the problem of beach retreat under sea level rise solving a one or a set of equations, without taking into account the dynamic nature of hydrodynamics and sediment dynamics. In contrast, process response models simulate the beach retreat using the coupling of hydrodynamic and sediment dynamic models; they estimate numerically sediment transport at the different sections and translate the spatial and temporal sediment transport differentials into beach morphological changes.

5.2. Analytical models

The toolbox includes the widely-used cross-shore analytical models of Bruun (1988), Edelman (1972) and Dean (1991).

The Bruun model

The Bruun (1988) model is a widely-used model, based on the concept of the beach equilibrium profile (e.g. Pilkey et al., 1993; Cooper and Pilkey, 2004; Zhang et al., 2004; and Ranasinghe et al., 2013). Its analytical expression is (Bruun, 1962;·1983; 1988):

$$s = \frac{l \cdot a}{h_c + B_h} \qquad [5\text{-}1]$$

where s is the beach retreat, l the cross-shore distance to the closure depth h_c (see Section 2.1), α the sea level rise and B_h the (first) berm height from the mean sea level (Fig. 5.5). .

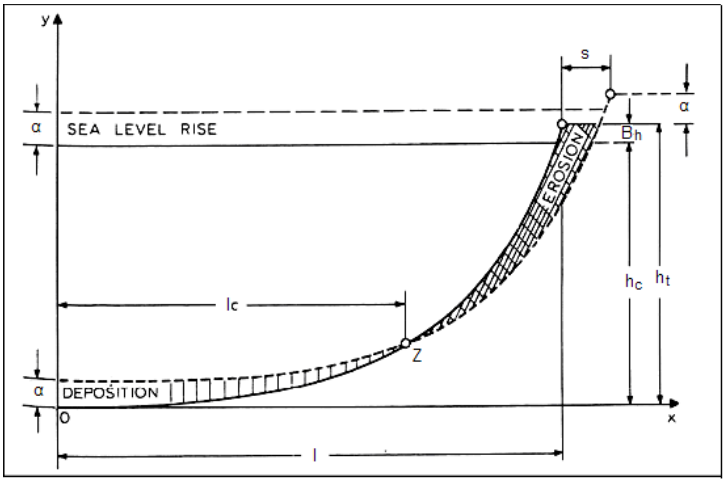

Fig. 5.5 Sketch showing the parameters of the Bruun model. The upper part of the beach is eroded due to sea level rise α with the sediment deposited at the lower (submarine) beach inside of the closure depth, resulting to beach retreat of s. Key: h_c, closure depth (Section 2.1); B_h, berm height, see Eq.[2-1]; and h_t= h_c+B_h,. (after Slott J., 2003).

The Edelman model

The Edelman (1972) model can deal with natural cross-shore profiles and with larger and temporally variable changes. According to this model, the cross-shore profile maintains its basic morphology under a rising sea level and its basic expression for the beach retreat *s* is:

$$\frac{ds}{dt} = \frac{d\alpha}{dt}\left[\frac{w_b}{h_b + B_h(t)}\right] \qquad [5\text{-}2]$$

Where s the beach retreat, α the sea level rise, $B_h(t)$ the instantaneous overall berm height above the sea level, and h_b και w_b το wave breaking depth and the surf zone width, respectively. After integration:

$$s(t) = w_b \ln\left[\frac{h_b + B_o}{h_b + B_o - \alpha(t)}\right] \quad [5\text{-}3]$$

where B_o the initial berm height.

The Dean model

The Dean (1991) model assigns a greater significance than the previous models on the wave energy. Beach retreat s due to sea level rise α is given by:

$$s = (a + 0.068H_b)\frac{w_b}{B_h + h_b} \quad [5\text{-}4]$$

where h_b the wave breaking depth, H_b the wave height at breaking, w_b the surf zone width and B_h the (first) berm height (above the mean sea level). The wave height at breaking H_b can be estimated on the basis of the CEM (2008) empirical expression:

$$\frac{H_b}{H_0} = 0.56\left(2\pi\frac{H_0}{gT^2}\right)^{-0.2} \quad [5\text{-}7]$$

where H_0 is the open sea wave height.

The depth at wave breaking h_b can be estimated by:

$$h_b = H_b/\gamma, \quad \text{όπου} \;\; \gamma = \xi^{0.17} + 0.08 \quad [5\text{-}8]$$

5.3 The analytical model GUIs

In order to provide a user-friendly tool, the estimations are carried out using a specifically designed Guide User Interfaces (GUIs) (Fig. 5.6). For further information on their use, see the accompanying manual.

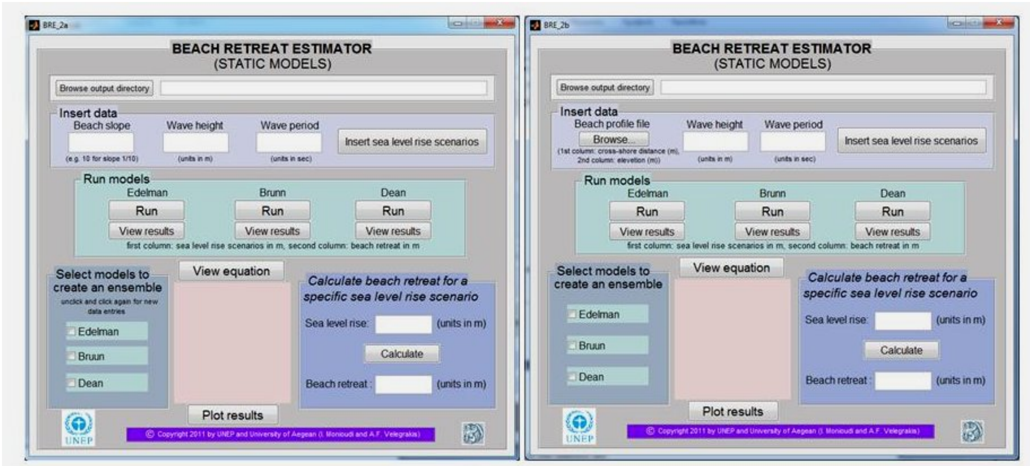

Fig 5.6 GUIs to estimate beach retreat under sea level rise using static (analytical) models in the case of (a) linear profiles and (b) natural profiles.

6 Numerical models of beach retreat under sea level rise

6.1 Introduction

These models consist of modules that estimate consecutively, for each time-step: (i) the coastal hydrodynamics on the basis of the bathymetry (in the case of 1-D cross-shore models, the cross-shore profile) and the offshore (open sea) wave conditions (ii) the sediment transport due to the coastal hydrodynamics (waves and wave-generated currents) and (iii) the coastal morphological changes (changes in the cross-shore profile) due to the hydrodynamically-induced, differential sediment transport. The process is repeated for the set duration time (*n* time steps) (Fig. 6.1), with the main initial set up conditions being the initial morphology (the cross-shore profile or its general slope), the sediment texture (e.g. the median sediment grain diameter D50), and the open sea wave conditions.

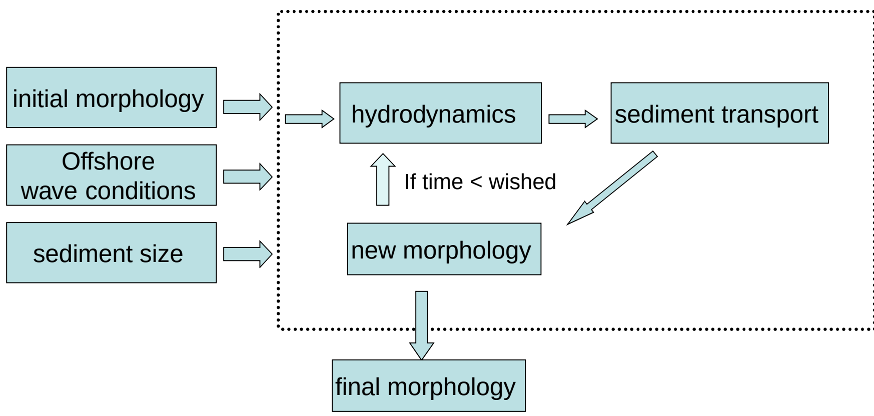

Fig. 6.1 Simplified flow diagram of a numerical morphodynamic model (beach profile evolution model).

The hydrodynamic module estimates the cross-shore evolution of the wave height and the near bed wave orbital velocities and the characteristics of the wave generated currents, using equations that describe the transformation of the shoaling waves; there are several approaches, as e.g. hydrodynamic modules that are based upon the energetics approach (see e.g. the Leont'yev model below). The sediment transport module uses the results of the hydrodynamic module as inputs and estimates the total (bedload and/or sheet flow and suspended sediment) transport for each spatial (discretisation) step of the profile. The sediment transport distribution along the cross-shore profile forms then the input to the morphological module, which uses the sediment transport differentials along the profile and the *sediment continuity equation* (see below) to estimate morphological changes for each time step[6]. The modified beach profile is then used as input for the hydrodynamic module in the next time-step the process is repeated till the end of the set duration time (*n* time steps).

Continuity Equation for sediments

In all sedimentary environments, if there is a difference between the sediment input and output through a control volume, then this should represent either bed deposition, or bed erosion (Fig. 6.2).

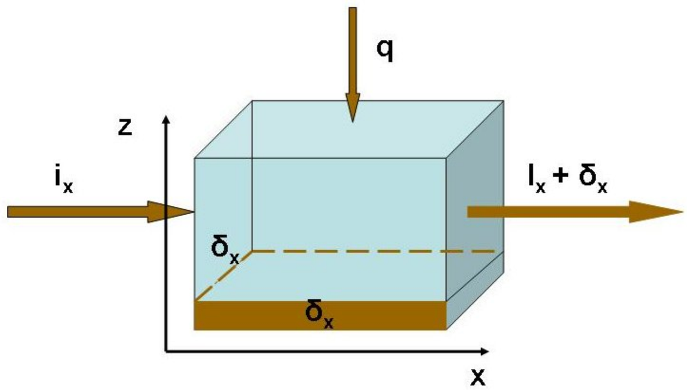

Fig. 6.2 Sketch showing the parameters of the continuity equation.

If i_x is the sediment input to the control volume, $i_x + \delta_x$ the sediment output and q the sediment that settles through the water column, then for time δ_t:

$$(i_x - i_x + \delta_x)\delta_x\delta_t + q\delta_x\delta_x\delta_t = \delta_z\delta_x\delta_x \quad [6\text{-}1]$$

Dividing by $\delta_x \delta_x \delta_t$:

$$(i_x - i_x + \delta_x)/\delta_x + q = \delta_z/\delta_t \quad [6\text{-}2]$$

And for $\delta_x \rightarrow 0$ and $\delta_t \rightarrow 0$:

$$-\partial i/\partial_x + q = \partial_z/\partial_t \quad [6\text{-}3]$$

This is the sediment continuity equation, which expresses the concept that sediment input-output differentials translate into changes in the bed elevation *z.*

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[6] Morphological modules commonly contain 'smoothing' terms, which account for the cases that the estimated morphological changes result in bed slopes above a threshold value; these terms ('avalanching terms') aim to account for the gravity impacts.

6.2 Short description of the used numerical models

The Sbeach model

The Sbeach model (Larson and Kraus, 1989), is a widely-used 'bottom-up' morphodynamic model, consisting of combined hydrodynamic, sediment transport and morphological development modules. The hydrodynamic module contains detailed descriptions of the coastal wave transformation (breaker decay model), with its basic expression being:

$$\frac{dE_F}{dx} = -\frac{k_w}{h}\left(E_F - E_{Fs}\right) \qquad [6\text{-}4]$$

where k_w an empirical wave decay coefficient, E_F the wave energy flux and E_{Fs} the 'stable' wave energy flux. The cross-shore coordinate x increases from the wave breaking point to the shoreline (CEM, 2008).

Sediment transport is controlled by the wave energy flux and the beach slope according to:

$$q = \mathrm{K}_s\left(D_e - D_{eq} + \frac{\varepsilon}{\mathrm{K}_s}\frac{dh}{dx}\right), \quad D_e > D_{eq} - \frac{\varepsilon}{\mathrm{K}_s}\frac{dh}{dx}$$

$$q = 0\,, \qquad D_e < D_{eq} - \frac{\varepsilon}{\mathrm{K}_s}\frac{dh}{dx} \qquad [6\text{-}5]$$

where K_s is an empirical transport rate coefficient, D is the wave energy dissipation per unit volume, D_{eq} is equilibrium energy dissipation per unit volume and ε is a transport rate coefficient for the slope-dependent term.

Finally, the beach morphological evolution module is based upon the sediment continuity equation (see above) and operates within a finite differences scheme and a 'stair – step' beach profile discretisation. The typical domain boundaries are set to the (onshore) maximum wave run up height R_h (estimated by empirical expressions, see Vousdoukas et al., 2009) and the (offshore) closure depth (estimated through a threshold in the offshore sediment transport).

The Leont'yev model

The numerical model based on the Leont'yev (1996; 1997) algorithms uses the energetics approach (Battjes and Janssen, 1978), with the wave energy balance in the cross-shore direction controlled by the wave angle φ, the group velocity c_g, the wave energy E_w and its dissipation due to breaking D_e:

$$\frac{\partial\left(\overline{E_w}\cdot c_g\cdot\cos\varphi\right)}{\partial x}=-D_e \qquad [6\text{-}6]$$

Sediment transport rates are predicted separately for the surf and swash zones. The transport rate q_W due to wave/current interaction is determined by:

$$q_W=\frac{\varepsilon_b}{2\tan\phi}f_W\rho\left(\overline{\tilde{u}^3}\cos\phi+3\overline{\tilde{u}^2}U_d\right)+\varepsilon_s\left(F+B\right)\left(\frac{W_s}{U_d}-\frac{\partial d}{\partial x}\right)^{-1} \qquad [6\text{-}7]$$

where f_W is the bed friction coefficient for wave orbital velocities u (Nielsen, 1992), U_d is the wave undertow velocity, W_s is the sediment fall velocity and ε_s is the efficiency factor of suspended load transport. F and B express wave power 'expenditure' due to bed friction F and excess turbulence at the bottom boundary layer (Roelvink and Stive, 1989). On the surf zone, run up sediment transport is estimated using Leont'yev (1996):

$$\hat{q}_R=c_1\rho\left(2gR\right)^{3/2}\left(\tan\beta_{eq}-\tan\beta\right) \qquad [6\text{-}8]$$

where c_1 a dimensionless proportionality coefficient and $\tan\beta_{eq}$ the equilibrium beach slope. For the swash zone, run up transport rate is given by:

$$q_R=\hat{q}_R\left(\frac{1-x/x_M}{1-x_R/x_M}\right)^{3/2} \quad x_R\le x\le x_M \qquad [6\text{-}9]$$

where x_R, x_M are the swash zone lower and upper limits, respectively. The wave run up-induced transport rate q_R decays from the swash zone towards the outer margin of the surf zone, is according to:

$$q_R=\hat{q}_R\exp\left(c_3\left(x-x_R\right)/H_o\right) \quad x\le x_R \qquad [6\text{-}10]$$

where H_o the offshore wave height and c_3 is set to be 0.2 - 0.3. Suspended and bedload transport rates are assumed to decay linearly to zero from the breaking point to the beach margins. Finally, beach profile evolution is assessed by solving the sediment continuity equation through a forward finite differences scheme.

6.3 The dynamic (numerical) model GUIs

In order to provide a user-friendly tool, the estimations are carried out using a specifically designed Guide User Interfaces (GUIs) (Fig. 6.3). For further information on their use, see the accompanying manual.

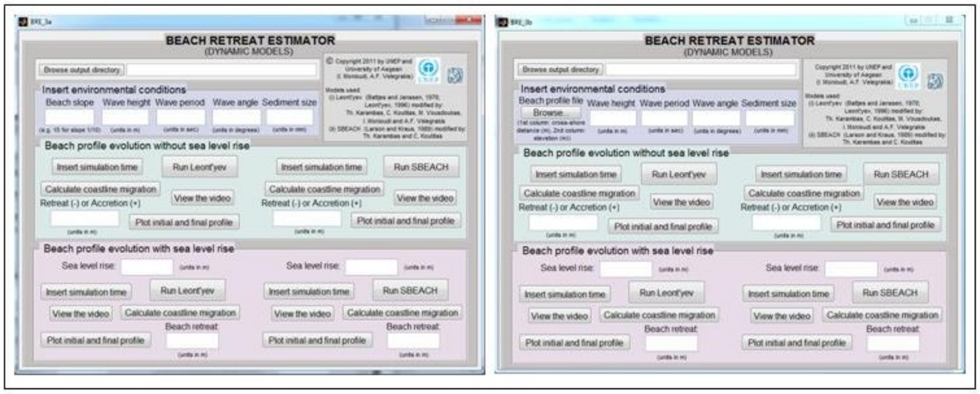

Fig 6.3 GUIs to estimate beach retreat under sea level rise using dynamic (numerical) models in the case of (a) linear profiles and (b) natural profiles.

7 Concluding remarks

The presented toolbox which ultimeately estimates sea level induced-changes in the dry beach width, is fast, easy, flexible and free to use, does not require particular expertise as other available tools (Ramieri et al., 2011) and enables rapid assessments of beach erosion at various spatial scales (from local to global). It provides for the application of different analytical/numerical cross-shore morphodynamic models either individually, or in an ensemble mode, that can supply predictions of ranges of beach retreats induced by sea lavel changes under varying geo-environmental conditions. The results could then be used to forecast beach exposure to sea level rise on the basis of the horizonantal beach spatial characteristics (e.g. dry beach width). Consequently, the methodology/tool is not limited by the resolution/accuracy of coastal DEMs (e.g. McLeod et al., 2010).

Nevertheless, there are also constraints. First, all predictions are based on the assumption that beaches comprise an inexhaustible sediment reservoir, with no lateral and/or offshore sediment losses (i.e. beyond the closure depth) (e.g. Vousdoukas et al., 2009a); cross-shore modeling obviously cannot resolve such issues, as detailed 2-D and/or 3-D morphodynamic modeling is required, based on detailed information on morphology, sedimentology and hydrodynamics and trained/validated by appropriate synoptic field observations. Secondly, in order to facilitate simplicity/utility the toolbox has been designed not to account for other erosion-controlling factors, such as geological controls, coastal sedimentary budgets, the presence of inlets and extreme event duration and sequencing (e.g. Revell et al., 2011; Corbella and Stretch. 2012; Ranasinghe et al., 2013), as well as the presence of artificial beach protection schemes and of protecting nearshore ecosystems (e.g. Peduzzi et al., 2013). Thirdly, the toolbox is designed to predict beach retreat and not inundation. Although wave run–up is dealt with in the numerical models of the ensemble, its effects are manifested in the results only if they induce sediment transport and morphological changes (see e.g. Leont'yev, 1996). Yet, wave run up-induced inundation that does not result in beach retreats may also be a significant management consideration (e.g. Jimenez et al., 2012).

Against this background, the results provided by the models may underestimate beach retreat/erosion and inundation exposure for individual beaches. However, as has been stated earlier, the aim of the presented toolbox is not to replace detailed beach modeling studies, but rather to provide a science-based, user-friendly facility for the rapid assessment of potential ranges of beach retreats mostly at large spatial scales and/or at areas with minimal environmental information. Detailed research is still essential in coastal areas, particularly if undertaken within the framework of a strategic approach, which certainly should involve comprehensive coastal monitoring (e.g. Nicholls et al., 2013).

Finally, the presented toolbox is not designed to account for interactions between human development and beach retreat/erosion (Bi et al., 2013). Humans play an increasingly important role in the evolution of beaches, by directly eliminating, trodding upon, reshaping and/or stabilizing them and/or by indirectly affecting them through large coastal development schemes that may change coastal sediment supply patterns (e.g. Nordstrom, 2013). Future coastal development will modify further the ‘naturally’-induced beach retreat/erosion; this, in turn, will affect the socio-economic components of the coastal system (e.g. Brad Murray et al., 2013), requiring beach risk establishment/allocation that will certainly result in disputes; thus, policy-makers need to consider in addition to the geophysical problem, future behaviours of key actors such as the legacy property right-holders, the insurance/finance sector and local governments (e.g. Gibbs et al., 2013).

References

Allenbach, K., Garonna, I., Herold, C., Monioudi, I., Giuliani, G., Lehmann, A.F. Velegrakis, 2014. A. Black Sea sandy coastline vulnerability to sea level rise. Special issue in Environmental Science and Policy (under review).

Aubrey, D. G., 1979. Seasonal patterns of onshore/offshore sediment movement. Journal of Geophysical Research 84, 6347-6354.

Aubrey, D. G., and Emery, K. O., 1983. Eigenanalysis of recent United States sea levels.

Battjes, J. A., and Janssen, J. P. F.., 1978. Energy loss and set-up due to breaking in random waves. 16th International Conference on Coastal Engineering, ASCE, Hamburg, pp. 569-587.

BC ICZM Protocol 2008; Barcelona Convention Integrated Coastal Zone Management 2008 Protocol http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:034:0019:0028:EN:PDF

Bi, X., Lu, Q., and Pan, X., 2013. Coastal use accelerated the regional sea-level rise. Ocean & Coastal Management 82, 1-6.

Birkemeier, W. A. 1985, Field Data on Seaward Limit of Profile Change, *Journal of the Waterways, Port Coastal and Ocean Engineering*, American Society of Civil Engineers 111(3), 598-602.

Borah D.K. and Balloffet A., 1985, Beach evolution caused by littoral drift barrier, *J. of Waterway, Port, Coastal and Ocean Eng.*, ASCE, 111(4), 645-660.

Brad Murray, A., Gopalakrishnan, S., McNamara, D.E., Smith M.D., 2013. Progress in coupling models of human and coastal landscape change. Computers and Geosciences, 53, Modeling for Environmental Change, 30–38.

Bruun, P., 1962, Sea level rise as a cause of shore erosion, *Journal of Waterway, Harbors Division. ASCE* 88, 117-130.

Bruun, P., 1983, Review of conditions for uses of the Bruun rule of erosion, *Coastal Engineering* 7(1), 77-89.

Bruun, P., 1988, The Bruun Rule of erosion by sea level rise: A discussion on large-scale two- and three-dimensional usages, *Journal of Coastal Research* 4(4):622-648.

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

CEM, 2008, Coastal Engineering Manual, US Army Corps of Engineers. EM 1110-2-1100.

Corbella, S. and Stretch D.D., 2012. Predicting coastal erosion trends using non-stationary statistics and process-based models. Coastal Engineering, 70, 40–49.

Cooper, J. A. G. and Pilkey, O.H., 2004. Sea-level rise and shoreline retreat: Time to abandon the Bruun Rule. Global and Planetary Change 43 (3-4), 157-171.

Dean, R. G., 1991, Equilibrium beach profiles: characteristics and applications, *J. Coastal Research* 7(1), 53– 84.

Defeo, O. and McLachlan, A., 2013. Global patterns in sandy beach macrofauna: Species richness, abundance, biomass and body size, Geomorphology,

Edelman, T., 1972, Dune erosion during storm conditions, in: *Proceedings of the 13th International Conference on Coastal Engineering* ASCE, pp. 1305-1312.

EEA, 2012. Climate change, impacts and vulnerability in Europe, 2012. An indicator-based report. European Environmental Agency (EEA), Copenhagen, 300 pp. (ISBN 978-92-9213-346-7) http://www.eea.europa.eu/publications/climate-impacts-and-vulnerability-2012.

EUROSION, 2004, Living with coastal erosion in Europe: Sediment and Space for Sustainability, in: *Coastal erosion – Evaluation of the need for action*, Directorate General Environment, European Commission.

Fritz HM et al. 2010. Cyclone Gonu storm surge in Oman Estuarine, Coastal and Shelf Science, 86,.102-106.

Grinsted A, Moore JC and Jervejeva S, 2010. Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD. Climate Dynamics 34, 461- 472.

Hanna E. et al., 2013. Ice sheet mass balance and climate change. Nature, 498, 51-59.

Hallermeier, R.J., 1981. A profile zonation for seasonal sand beaches from wave climate. *Coastal Engineering* 4, 253-277.

Hasselmann, K., Ross, D.B., Muller, P., Sell, W., 1976, A Parametric Wave Prediction Model, *Journal of Physical Oceanography* 6, pp. 200-228.

Hinkel, J., Nicholls, R. J., Vafeidis, A. T., Tol, R. S. J., and Avagianou, T., 2009. Assessing risk of and adaptation to sea-level rise in the European Union: An application of DIVA. Mitigation and Adaptation Strategies for Global Change 15(7), 703-719.

Horton R, Herweijer C, Rosenzweig C, Liu J, Gornitz V, and Ruane AC, 2008. Sea level rise projections for current generation CGCMs based on the semi-empirical method. Geophysical Research Letters 35 DOI: 10/1029/2007GL032486.

Inman, D. L., Hany, M., Elwany, S., and Jenkins, S. A., 1993, Shorerise and bar-berm profiles on ocean beaches. Journal of *Geophysical Research* 98(C10), 18,181-18,199.

IPCC, 2007a. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Solomon S, D Qin, M Manning, Z Chen, M Marquis, KB Averyt, M Tignor and HL Miller (eds)). Cambridge University Press, Cambridge, UK and New York, NY, USA, 996 pp.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Summary for Policymakers. http://www.climatechange2013.org/images/uploads/WGIAR5-SPM_Approved27Sep2013.pdf

IPCC SREX, 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change IPCC [Field CB, V Barros, TF Stocker, D Qin, DJ Dokken, KL Ebi, MD Mastrandrea, KJ Mach, GK Plattner, SK Allen, M Tignor, and PM Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

Jevrejeva S, Moore JC and Grinsted A, 2010. How will sea level respond to changes in natural and anthropogenic forcings by 2100? Geophysical Research Letters 37. DOI: 10.1029/2010GL042947.

Jevrejeva S, Moore JC and Grinsted A, 2012. *Se*a level projections to AD2500 with a new generation of climate change scenarios. Global and Planetary Change, 80-81, *14-20.* doi:10.1016/j.gloplacha.2011.09.006.

Jiménez, J.A., Bosom, E., Valdemoro, H.I., Guillén, J., 2012. Storm-induced damages along the Catalan coast (NW Mediterranean) during the period 1958–2008. Geomorphology, 143-144, 24-33.

Karambas, T., Velegrakis, A.F., Vousdoukas, M.I., Pantazis, A., Andreadis, O. and Meligonits, R., 2008. Design of artificial beaches and related offshore breakwaters along the eastern Coast of Lesvos, Greece. Technical Report DMS/UOAG/4/2008. 75 pp plus appendices (in Greek with Engllish abstract)

Komar, P. D., 1998, Beach Processes and Sedimentation, Prentice Hall, N.J., USA, pp. 544.

Kontogianni A., Tourkolias C.H., Damigos D. and Skourtos M., 2013. Assessing sea level rise costs and adaptation benefits under uncertainty in Greece. Environmental Science & Policy (in press).

Kopp R, Simons F, Mitrovica J, Maloof A and Oppenheimer M. 2009. Probabilistic assessment of sea level during the last interglacial stage. Nature 462, 863–867. (doi:10.1038/nature08686)

Koutitas, X.G., 1994. Introduction to coastal engineering and port works. Ziti Publication, Thessaloniki, Greece. (in Greek).

Landesman, E. M., and Hestenes, M. R., 1992, Linear Algebra for Mathematics, Science and Engineering, Prentice-Hall, Englewood Cliffs, New Jersey.

Larson, M., and Kraus, N. C., 1989, SBEACH: Numerical model for simulating storm-induced beach change; report 1: empirical foundation and model development. *Technical Report - US Army Coastal Engineering Research Center* 89-9.

Lee, G., and Birkemeier, W. A., 1993, Beach and nearshore survey data: 1985-1991, CERC Field Research Facility, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, pp. 26.

Lenton TM, A Footitt and A Dlugolecki, 2009. Major Tipping Points in the Earth’s Climate System and Consequences for the Insurance Sector. WWF, Gland, Switzerland and Allianz SE, Munich, Germany.

Leont'yev, I. O., 1996, Numerical modelling of beach erosion during storm event, *Coastal Engineering* 29(1-2), 187-200.

Leont'yev, I. O., 1997, Short-term shoreline changes due to cross-shore structures: a one-line numerical model, *Coastal Engineering* 31(1-4), 59-75.

List, J. H., Farris, A. S., Sullivan, C., 2006. Reversing storm hotspots on sandy beaches: Spatial and temporal characteristics. Marine Geology, 226, 261– 279..

Marcos M, Jordǚ G, Gomis D and Pιrez B, 2011. Changes in storm surges in southern Europe from a regional model under climate change scenarios. Global and Planetary Change, 77(3–4), 116–128. Doi:10.1016/j.gloplacha.2011.04.002.

Maunsell , 2008. Climate Change on Infrastructure in Australia and CGE Model Inputs Maunsell Australia Pty Ltd, in association with CSIRO. www.garnautreview.org.au.

Mori N, Shimura T, Yasuda T and Mase H, 2013. Multi-model climate projections of ocean surface variables under different climate scenarios—Future change of waves, sea level and wind. Ocean Engineering, http://dx.doi.org/10.1016/j.oceaneng.2013.02.016i

Nicholls, R. J., Birkemeier, W. A., and Lee, G.-h., 1998, Evaluation of depth of closure using data from Duck, NC, USA, *Marine Geology* 148(3-4), 179-201.

Nicholls RJ et al., 2007. Coastal systems and low-lying areas. In: Climate change 2007: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the AR4 of the IPCC [Parry M et al (eds.)]. Cambridge University Press, Cambridge, UK, 315-356.

Nicholls, R.J., Townend, I.H., Bradbury, A.P., Ramsbottom, D., and Day, S.A, 2013. Planning for long-term coastal change: Experiences from England and Wales. Ocean Engineering, http://dx.doi.org/10.1016/j.oceaneng.2013.01.025i

Nielsen, P., 1992, Coastal Bottom Boundary Layers and Sediment Transport. Advanced Series on Ocean Engineering, 4. Word Scientific. 324 pp.

Nielsen, P., 2009, How storm size matters for surge height, *Coastal Engineering* 56, 1002-1004.

Nordstrom, K.F. 2013. Developed coasts. In Treatise on Geomorphology, Vol. 10, pages 392–416.

Pacheco B.G. and A. Lewis-Cameron, 2010. Weathering the storm – Crisis marketing for small island tourist destinations. Marketing Island Destinations, Concepts and Cases, 149-164.

Peduzzi, P., Velegrakis, A.F., Estrella, M. And Chatenoux, B. 2013. Integrating the role of ecosytems in disaster risk and vulnerability assessments: Lessons from the Risk and Vulnerability Assessment Methodology Development Project (RiVAMP) in Negril Jamaica. In FG Renaud et al., (eds), The role of Ecosystems in Disaster Risk Reduction, United Nations University Press (ISBN 978-9280812213), 109-139

Pena, H. G., and Lanfredi, N. W., 1988, Beach profile analysis by Empirical Orthogonal Functions, *Journal of Coastal Research* 4(3), 457-463.

Pfeffer W, Harper J and O’ Neel S, 2008. Kinematic constraints on glacier contributions to 21st century sea-level rise. Science 321, 1340–1343. (doi:10.1126/science.1159099).

Phillips, M.R. and A.L. Jones, 2006. Erosion and tourism infrastructure in the coastal zone: Problems, consequences and management. Tourism Management, 27, 517-524

Pilkey, O. H., Young, R. S., Riggs, S. R., Smith, A. W. S., Wu, H., and Pilkey, W. A., 1993. The concept of shoreface profile of equilibrium: A critical review. *Journal of Coastal Research* 9, 255-278.

Poulos S. E. and M. B. Collins, 2002. A quantitative evaluation of riverine-sediment fluxes to the Mediterranean Basin: Natural flows, coastal zone evolution and the role of dam construction.. In S.J. Jones and L.E. Frostick (eds.), Sediment flux to basins: Causes,controls and consequences. Geological Society of London Special Publication 191, Geological Society Publishing House: pp. 227–245.

Rahmstorf S, Cazenave A, Church JA, Hansen JE, Keeling RF, Parker DE, and RCJ Somerville, 2007. Recent climate observations compared to projections. Science 316, 709-709.

Ramieri E, Hartley A, Barbanti A, Duarte Santos F, Laihonen P, Marinova N, Santini M, 2011. Methods for assessing coastal vulnerability to climate change. ETC CCA Background Paper, Copenhagen (DK) 8-9 June 2011. European Topic Centre on Climate Change Impacts, Vulnerability and Adaptation European Environment Agency, 76pp. (http://www.oannes.org.pe/)

Ranasinghe R, Duong TM, Uhlenbrook S, Roelvink D, and Stive M, 2013. Climate-change impact assessment for inlet-interrupted coastlines. Nature Climate Change, DOI: 10.1038/NCLIMATE1664.

Revell, D.L., Battalio, R., Spear, B., Ruggiero, P., and Vandever J., 2011. A methodology for predicting future coastal hazards due to sea-level rise on the California Coast. Climatic Change, 109, S251-276.

Rochette J. and Billé R., 2010. Analysis of the Mediterranean ICZM Protocol: At the crossroads between the rationality of provisions and the logic of negotiations. Institute for Sustainable Development and International Relations (IDDRI). 26 pp

Rochette, J. du Puy-Montbrun, G., Wemaëre M.,and Billé, R., 2010. Coastal setback zones in the Mediterranean: A study on Article 8-2 of the Mediterranean ICZM Protocol Institute for Sustainable Development and International Relations (IDDRI) Analyses 05/2010. 24 pp. http://www.iddri.org/Publications/Coastal-setback-zones-in-the-Mediterranean-A-study-on-Article-8-2-of-the-Mediterranean-ICZM-Protocol

Rochette, J. and Billé, R., 2012. ICZM Protocols to Regional Seas Conventions: What? Why? How? Marine Policy 36, 977-984.

Rohling E, Grant K, Hemleben C, Siddall M, Hoogakker B, Bolshaw M and Kucera M, 2008. High rates of sea-level rise during the last interglacial period. *Nature Geosciences* 1, 38–42. (doi:10.1038/ngeo.2007.28)

Roelvink, J.A. and Stive, M.J.F., 1989, Bar-generating cross-shore flow mechanisms on a beach, Journal of Geophysical Research 94(C4), 4785– 4800.

Sanchez-Arcilla, A., Gomez-Aguar, J., Egozcue, J.J.,Ortego, M.I., Galiatsatou, P. and Prinos, P., 2008. Extremes from scarce data The role of Bayesian and scaling techniques in reducing uncertainty. *Journal of Hydraulic Research* 46(2), 224-234.

Snoussi M. et al., 2008. Vulnerability assessment of the impact of sea-level rise and flooding on the Moroccan coast: The case of the Mediterranean eastern zone. Estuarine, Coastal and Shelf Science, 77, 206-213

Stive, M. J. F., Nicholls, R. J., and DeVriend, H. J., 1991, Sea-level rise and shore nourishment: a discussion, *Coastal Engineering* 16, 147-163.

Sunamura, T., 1989, *In* Lakhan and Trenhail (Eds): Applications in Coastal modelling, Elsevier, Amsterdam, 159-213.

Tsimplis MN and Shaw A, 2010. Seasonal sea level extremes in the Mediterranean Sea and at the Atlantic European coasts. Natural Hazards and Earth System Sciences, 10, 1457–1475.

Tsimplis MN and Shaw A, 2010. Seasonal sea level extremes in the Mediterranean Sea and at the Atlantic European coasts. Natural Hazards and Earth System Sciences, 10, 1457–1475.

UNCTAD, 2012. Review of Maritime Transport 2012. Technical Report of United Nations Conference for Trade and Development, UNCTAD/RMT/2012. United Nations publication ISBN 978-92-1-112860-4, e-ISBN 978-92-1-055950-8. (http://unctad.org/en/PublicationsLibrary/rmt2012_en.pdf).

Vermeer M and Rahmstorf S 2009 Global sea level linked to global temperature. Proceedings of the National Aceademy of Sciences USA 106, 21527–21532. (doi:10.1073/pnas.0907765106). Vellinga P *et al*. 2008. Exploring high-end climate change scenarios for flood protection of the Netherlands. International Scientific Assessment for the Delta Committee. Scientific report WR-2009-05. KNMI, Alterra, The Netherlands. http://www.knmi.nl/bibliotheek/knmipubWR/WR2009-05.pdf.

Velegrakis, A.F., Vousdoukas, M., Andreadis, 0., Pasakalidou E., Adamakis, G. and Meligonitis, R. 2008. Impacts of dams on their downstream beaches: A case study from Eresos coastal basin, Island of Lesvos, Greece. *Marine Georesources and Geotechnology*, 26, 350–371.

Vousdoukas. M.I., Velegrakis, A.F, Dimou, K, Zervakis, V., Conley, D.C., 2009. Wave run-up observations in microtidal, sediment-starved beaches of the Eastern Mediterranean. Journal of Marine Systems, 78, 537-547.

Vousdoukas, M.I., A.F. Velegrakis, M. Paul, C. Dimitriadis, E. Makrykosta, D. Koutsoubas, 2012. Field observations and modeling of wave attenuation over colonized beachrocks.. *Continental Shelf Research*, 48, 100-109

Winant, C. D., Inman, D.L., and Nordstron, C.E., 1975. Description of Seasonal Beach Changes Using Empirical Eigenfunctions. Journal of *Geophysical Research* 80(15), 1979-1986.

Zhang, K., Douglas, B.C., and Leatherman, S.P., 2004, Global warming and coast erosion, Climate Change 64, 41-58.

Annex I Relevant Regulatory instruments.

In this Annex a brief summary of regulatory instruments relevant for the protection of the Mediterranean coastal zone is presented in Tables I. 1 and I.2.

Treaty	Objectives	Entry into force *	Mediterranean Contracting Parties*	Comments
UNCLOS 1982	Comprehensive global legal regime for the marine environment.	16/11/1994	All Med States except Israel, Libya, the Syrian Arab Republic, and Turkey	Establishes/delimits Maritime Zones); details rights and responsibilities of the Coastal State with regard to exploring, exploiting, conserving and managing the natural resources, the establishment of offshore installations and structures, marine scientific research and the environmental protection and preservation of marine environment; prescribes transboundary obligations; provides for a global framework to manage the seas and oceans and establishes guidelines and/or procedures for economic and commercial activities, scientific research and the settlement of disputes; and prescribes a general obligation to protect and preserve the marine environment. Contracting Parties shall: take measures to prevent, reduce and control all type of pollution of the marine environment, prevent accidents and deal with emergencies.
Bern 1979	Aims to conserve wild flora and fauna and their natural habitats and to promote European co-operation in that field	06/06/1982	Albania, Bosnia & Herzgovina, Croatia, Cyprus, France, Greece, Italy, Malta, Monaco, Montenegro, Morocco, Slovenia, Spain, Tunisia, Turkey, EU	Contracting Parties must act to: promote national policies for the conservation of wild flora and fauna (particularly those referred to in the Appendices I and II of the Convention), and their natural habitats; consider conservation of wild flora/fauna in their planning and development policies, and in their measures against pollution; promote relevant education; encourage and coordinate relevant research; co-operate to enhance the effectiveness of these measures through co-ordination of efforts to protect migratory species and the exchange of information and the sharing of experience and expertise. The
CBD 1992	Conservation of biological diversity; sustainable use of its components; and fair and equitable benefit sharing of genetic resources	29/12/1993	All Med Coastal States	Contracting Parties shall (amongst others): ensure that activities within their jurisdiction/control do not cause damage to the environment of other States; develop national conservation strategies, plans or programmes; identify/monitor components of biological diversity that are important for conservation; establish a system of protected areas; regulate/manage biological resources important for biodiversity conservation; promote environmentally sound and sustainable development; rehabilitate/restore degraded ecosystems; prevent the introduction of, control or eradicate alien species that threaten ecosystems, habitats or species; integrate considerations of biological resource conservation and sustainable use into national decision-making; establish/maintain programmes for relevant scientific and technical education and training; promote/encourage research contributing to conservation; introduce appropriate procedures requiring environmental impact assessment for proposed (coastal) projects.
Espoo Convention (UNECE) Espoo SEA Protocol 2003 (UNECE)	To assess environmental impacts in a transboundary context To assess early transboundary SEAs	10/09/1997 11/07/2010	Albania, Croatia, Cyprus, EU, France, Greece, Italy, Malta, Montenegro, Spain, Slovenia Albania, Croatia, EU, Montenegro, Slovenia, Spain	Sets out obligations for EIAs of certain activities at the planning stage; prescribes a general State Party obligation to notify/consult with other states on all major projects that can have significant adverse transboundary impacts; prescribes post-project monitoring requirements. The Sofia Amendment 2001 (not yet in force) allows non-UNECE States to join. Prescribes integration of EIAs into plans/programmes at the earliest stage; provides for Strategic Environmental Assessments-SEAs and for extensive public participation in the governmental decision-making in numerous development sectors.
Aarhus 1998 Convention	Establishes rights of the public (individuals and	30/10/2001	Albania, Bosnia & Herzegovina (B & H), Croatia,	Provides for: access to environmental information held by public authorities of the Contracting Parties; public participation in environmental decision-making; access to justice, i.e. “the right- to

	associations) with regard to the environment		Cyprus, EU, France, Greece, Italy, Malta, Montenegro, Slovenia, , Spain	review procedures and challenge decisions made without respecting the above rights or environmental law in general"
RAMSAR 1971 Convention	Framework for national action and international cooperation for the conservation and wise use of wetlands and their resources	21/12/1975 Paris Protocol 01/10/1986 Regina Amendment 01/05/1994	All Med states (336 sites) Only 10 Med States are Parties to both the Paris Protocol and the Regina Amendments	Contracting Parties shall: designate wetlands (riparian, coastal and marine with water depths > 6 m at low tide) on account of their international significance in terms of ecology, botany, zoology, limnology or hydrology for inclusion in a *List of Wetlands of International Importance*; formulate/implement wetland conservation planning; establish nature reserves in wetlands; encourage relevant research and information exchange; consult with each other about implementing obligations, especially in the case of shared wetlands
MARPOL 73/78 Convention (IMO)	To preserve the marine environment through the complete elimination of ship pollution (Annexes I & II are mandatory, Annexes III, IV, V & VI are optional)	Annexes I & II 02/10/1983; III, 01/071992; IV, 27/09/2003; V, 31/121988; VI, 19/05/2005	All Med States except Bosnia & Herzegovina (B & H) ** All except B & H Turkey ** All except B & H, Israel and Turkey ** All except B & H ** All except Albania, Algeria, B & H, Egypt, Israel, Lebanon, Libya, Monaco, Montenegro **	Regulates against accidental/routine ship pollution described in its 6 Annexes; prescribes strict controls on operational discharges in special areas; Annex I covers oil pollution, with its 1992 amendments makes double hulls mandatory for new oil tankers; Annex II details discharge criteria/measures for about 250 noxious liquid substances-no noxious residue discharges are permitted in Territorial Sea, but no provision for EEZ; Annex III contains general requirements for standards on packing, marking, labelling, documentation, stowage, quantity limitations, exceptions and notifications for harmful substances; Annex IV prohibits sewage discharge, except when the ship has an approved sewage treatment plant-not comminuted or disinfected sewage cannot be discharged in the Territorial Sea, but no such provision for the EEZ; Annex IV specifies distances from land and the manner in which ship garbage may be disposed of (complete ban for plastics)-since the beginning of 2013, all garbage discharge is prohibited, except if otherwise provided; Annex VI sets limits on SOx, NOx, particulate matter and ozone depleting substance emissions-since the beginning of 2013, mandatory technical/operational energy efficiency measures reducing the amount of ship greenhouse gas emissions have been included.
OPRC 1990 OPRC-HNS Protocol 2000	To facilitate international co-operation and mutual assistance in preparing for and responding to major oil pollution incidents Protocol on Preparedness, Response and Co-operation to Pollution Incidents by Hazardous and Noxious Substances	13/5/1995 14/7/2007	All Med states except Bosnia & Herzegovina, Cyprus, and Montenegro Egypt, France, Greece, Malta, Slovenia, Spain, Syrian Arab Republic and Turkey	Requires States to plan and prepare by developing national systems for pollution response, and by maintaining adequate capacity and resources to address oil pollution emergencies; OPRC-HNS Protocol 2000 extends the regulatory framework to address pollution incidents by Hazardous and Noxious Substances, i.e. chemicals. Contracting States are required to establish national systems for responding to oil (and HNS) pollution incidents, including designated national authorities and operational contact points and national contingency plans, which must be backstopped by minimum levels of response equipment, communication plans, regular training and exercises. The instruments also promote cooperation amongst Parties, through bilateral and multilateral agreements, to augment national level response capacity when needed. A mechanism is provided for Parties to request assistance from any other Party, when faced with a major incident.
CLC 1992, as amended in 2000 (IMO)	Governs shipowner liability for pollution and damage caused by persistent oils escaped or discharged from tankers	30/5/1996	All Med States except Bosnia & Herzegovina and Lybia (Lybia is Contracting State to the CLC 1969)	Mandatory liability of shipowner for oil pollution damage in Contracting States due to oil spill from tankers. Strict Liability (i.e. independent of fault), but is subject to limited exceptions and subject to a financial cap, dependent on ship-size, up to a maximum of 89,77 million SDR ***per incident; requires compulsory insurance for ships carrying more than 2000 tons of oil in bulk and provides for direct action against insurers. Applies only to "*persistent hydrocarbon mineral oil*" spills (cargo or

	Replaces the 1969 CLC, which is still in force but is more restrictive, and liability is limited to a maximum of 14 million SDR*** per incident			bunkers) from ships constructed/adapted for carriage of oil as cargo. Compensation is available – irrespective of where the incident itself occurred – for pollution damages in a Contracting State. Compensation is also available for preventive measures '*wherever taken*' after the incident to prevent/minimize pollution damage and further loss or damage caused by preventive measures. Compensation for environmental '*impairment*' other than loss of profit is limited to the costs of '*reasonable measures of reinstatement actually undertaken or to be undertaken*'. Contributions may be made to the cost of post-spill studies, including studies to establish the nature and extent of environmental damage caused by an oil spill and to determine whether or not reinstatement measures are necessary and feasible.
IOPC Fund Convention 1992, as amended in 2000 (IMO)	Establishes a regime for compensation, when CLC 1992 is inadequate.	30/5/1996	All Med States except Bosnia & Herzegovina, Egypt, Lebanon and Lybia Only Contracting States to the CLC 1992 may accede to the Convention	Establishes a Fund financed by contributions from oil receivers in Contracting States to provide a second compensation tier for oil pollution damage from tanker oil spills. Provides compensation when (a) no liability for pollution damage arises under the 1992 CLC; (b) the shipowner is financially incapable of meeting his obligations in full and his insurance can not satisfy such claims; or (c) the damage exceeds the amount of the shipowner's liability under the 1992 CLC. Compensation up to 203 million SDR***per incident (irrespective of ship-size). No compensation is available for oil pollution damage by warships or resulting from war, hostilities, civil war or insurrection.
Supplementary Fund Protocol 2003	Provides for additional compensation, when protection under the CLC 1992/IOPC Fund 1992 is inadequate.	3/3/2005	Croatia, France, Greece, Italy, Montenegro, Morocco, Slovenia, Spain and Turkey Only Parties to the IOPC Fund 1992 may accede to the Protocol	Establishes a Supplementary Fund financed by contributions from oil receivers in Contracting States to provide a third tier of compensation for oil pollution damage from tanker oil spills. Applies to established claims under the IOPC Fund only. Compensation is available up to an overall maximum of 750 million SDR*** per incident.
BUNKER 2001 Convention (IMO)	To ensure adequate, prompt, and effective compensation to persons who suffer damage caused by oil spills by fuel carried in ships' bunkers	21/11/2008	All Med States except Algeria, Bosnia & Herzegovina, Israel, Lebanon, Libya and Monaco	Covers loss/damages caused from the escape/discharge of bunker oil (except if covered by the CLC 1992 Convention-tankers); compensation for environmental impairment other than loss of profit shall be limited to costs of reasonable measures undertaken to reinstate the environment; prescribes covering of costs of preventive measures and of losses/damages caused by preventive measures; prescribes requirements for direct action, allowing compensation claims for pollution damage to be directly brought against insurers.
BARCELONA Convention (BC 1995)	Sets out the legal framework for regional/sub-regional agreements/cooperation for the protection of the marine and coastal environment of the Mediterranean Sea	09/07/ 2004	All Med states except Bosnia and Herzegovina (B & H) and Lebanon pending notification ***	Requires that the Contracting Parties shall take all appropriate measures (individually or jointly) in accordance with the provisions of the Convention and those of its Protocols to which they are a Party, to prevent, abate and combat pollution and to protect and enhance the marine environment of the Mediterranean Sea. Encourages Parties to: cooperate and share information; establish a continuous pollution monitoring system; cooperate in the fields of science and technology; work out appropriate procedures for pollution liability and compensation; draft procedures for monitoring the application of the Convention. Main 1995 amendments concern the: coastal application of the Convention; application of the precautionary principle; application of the "polluter pays" principle; promotion of impact assessments; protection/preservation of biological diversity; prevention of pollution from cross-border movement of dangerous waste; access to information and public participation

BC SPA & Biodiversity Protocol 1995	Establishment/protection through concrete measures of Special Protected Areas– SPAs and the Biological Diversity See also CBD 1992	12/12/1999	All Med States, except Bosnia & Herzegovina, Greece, Israel, and Libya***	The main tool for the *in situ* sustainable management of the Mediterranean coastal biodiversity envisages: creation, protection and management of SPAs; establishment of a list of SPAs of Mediterranean Importance (SPAMIs); and species protection and conservation. Deals with the: conservation of typical for the Mediterranean marine and coastal ecosystems; protection of endangered habitats, or habitats necessary for the survival, reproduction and restoration of threatened or endemic species; protection of sites of scientific, aesthetic, cultural or educational interest; development/implementation of appropriate conservation management plans; setting up/promoting SPAs; conservation of endangered species; and sustainable use of biological resources.
BC LBS Protocol 1996	Prevention of pollution from land-based sources and activities	11/05/2008	All Med states (and EU), except Algeria, Bosnia & Herzegovina, Egypt, Lebanon, and Libya. ***	Aims to: prevent, abate, combat and control pollution of the Mediterranean Sea caused by discharges from rivers, coastal establishments or outfalls, or emanating from any other land-based sources within the territories of State Parties; accelerate the development of short term and medium term regional action plans/programmes containing legally binding measures and timetables for their implementation
BC ICZM Protocol 2008	To promote Integrated Management of the Coastal Zone	24/03/2011	Albania, Croatia, France, Montenegro, Morocco, Slovenia, Spain, Syrian Arab Republic and EU ***	Aims to: facilitate sustainable development and use of natural resources through rational planning; ensure preservation of the integrity of coastal ecosystems; prevent and/or reduce the effects of natural hazards and climate change; achieve coherence between initiatives and public decisions; and ensure institutional coordination to facilitate comprehensive approaches. The parties shall: minimise use of natural resources and promote codes of good practice; ensure the preservation of coastal ecosystems; legislate, plan and manage in order to protect and conserve coastal habitats/species of high conservation value; ensure that fishing practices are sustainable and control inputs and wastes of aquaculture; encourage sustainable coastal tourism; undertake to adopt the necessary measures to prevent and mitigate coastal erosion; establish a zone where construction is not allowed (set-back' zone) in coastal zones; regulate sand extraction; create and/or strengthen existing appropriate monitoring mechanisms; and promote scientific and technical research, exchange of information and cooperation for the provision of scientific and technical assistance.
BC Prevention Emergency Protocol 2002	Co-operation in preventing ship pollution and, in cases of emergency, combating pollution	17/03/2004	All Med States (and EU), except Albania, Algeria, , Bosnia & Herzegovina, Egypt, Israel, Italy, Lebanon, Libya Tunisia **	Sets the co-operation principles to combat accidents or operational discharges of oil or other HNSs; covers prevention of, preparedness for and response to pollution from marine sources, without prejudice to the sovereignty/jurisdiction of other Parties or other States. The Parties shall: maintain and promote, either individually or through bilateral or multilateral cooperation, pertinent contingency plans; develop/apply relevant monitoring activities; disseminate to the other Parties information concerning the competent national organization/authorities and their preparedness and response regulations; coordinate their communication means in order to respond speedily and reliably; assess the nature, extent, direction, drift speed and possible consequences of the spillage and take every practicable measure to prevent, reduce and, to the fullest possible extent, eliminate its effects; assess the environmental risks of recognized maritime traffic routes.

*Table I.1 Significant International regulatory instruments for the protection of the Mediterranean coastal zone (the list is not exhaustive). *The date shown is the first date the Convention/Protocol entered into force, i.e. when the prescribed number of State ratifications was reached. For each Contracting Party, legislation enters into force upon ratification or accession. Contracting Parties as of November 2013. **Ratification status (18/11/2013) of the IMO Conventions according to http://www.imo.org/About/Conventions/StatusOfConventions/Pages/Default.aspx ***SDR is an international reserve asset (IMF, 1969) to supplement official reserves. It is fully convertible and its value is based on a basket of 4 key international currencies (end of November conversion rate 1 SDR ≈ $1.5). For conversion rates see http://www.imf.org/external/np/fin/data/rms_sdrv.aspx ****Status of Ratification of Barcelona Convention and its Protocols http://www.unepmap.org/index.php?module=content2&catid=001001004.*

Key: UNCLOS 1982, United Nations Convention for the Law of the Sea. Note that not all Mediterranean Coastal States are parties to the Part XI of the Convention and/or the Agreement for the implementation of the provisions of the Convention relating to the conservation and management of straddling fish stocks and highly migratory fish stocks; ratification (18/09/2013) http://www.un.org/depts/los/reference_files/status2010.pdf. Bern Convention 1979, Convention on the Conservation of European Wildlife and Natural Habitats http://conventions.coe.int/treaty/en/Treaties/Html/104.htm .

CBD 1992, Convention for the Biological Diversity http://www.cbd.int/intro/default.shtml ; Espoo Convention 1991, Convention on EIA in a Transboundary Context http://www.unece.org/fileadmin/DAM/env/eia/documents/legaltexts/conventiontextenglish.pdf; Espoo (Kiev, 2003) SEA Protocol, Espoo Protocol on SEA http://www.unece.org/fileadmin/DAM/env/eia/documents/legaltexts/protocolenglish.pdf. Aarhus 1998 Convention, Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters http://www.unece.org/fileadmin/DAM/env/pp/documents/cep43e.pdf. RAMSAR Convention (see also the EU Regulation 1367/2006), The Convention on Wetlands of International Importance http://www.ramsar.org/cda/en/ramsar-documents-texts-convention-on/main/ramsar/1-31-38%5E20671_4000_0. MARPOL 73/78, International Convention for the Prevention of Pollution From Ships 1973 (modified through the 1978 Protocol) http://www.imo.org/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx.

OPRC Convention 1990, International Convention on Oil Pollution Preparedness, Response and Co-operation, 1990; OPRC-HNS Protocol 2000, Protocol on Preparedness, Response and Co-operation to pollution incidents by Hazardous and Noxious Substances, http://www.imo.org/OurWork/Environment/PollutionResponse/Pages/Default.aspx. CLC 1992, International Convention on Civil Liability for Oil Pollution Damage, 1992. FUND Convention 1992, International Convention on the Establishment of an International Fund for Compensation for Oil Pollution Damage, 1992; Supplementary Fund Protocol 2003, http://www.iopcfunds.org/fileadmin/IOPC_Upload/Downloads/English/explanatorynote_e.pdf. BUNKER Convention, International Convention on Civil Liability for Bunker Oil Pollution Damage http://www.imo.org/About/Conventions/ListOfConventions/Pages/International-Convention-on-Civil-Liability-for-Bunker-Oil-Pollution-Damage-(BUNKER).aspx. Barcelona Convention (BC) Amended (1995), Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean http://195.97.36.231/dbases/webdocs/BCP/BC76_Eng.pdf , http://www.unep.ch/regionalseas/regions/med/t_barcel.htm. BC SPA & BD Protocol 1995, BC Special Protected Areas and Biodiversity Protocol, 1995 http://195.97.36.231/dbases/webdocs/BCP/ProtocolSPA95_eng.pdf. BC LBS Protocol 1996, Barcelona Convention Protocol 1996 Against Pollution from Land-Based Sources and Activities http://195.97.36.231/dbases/webdocs/BCP/ProtocolLBS80_eng.pdf, http://ec.europa.eu/world/agreements/downloadFile.do?fullText=yes&treatyTransId=13905. BC ICZM Protocol 2008; Barcelona Convention Integrated Coastal Zone Management 2008 Protocol http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:034:0019:0028:EN:PDF. BC Prevention Emergency Protocol 2002, Protocol concerning Cooperation in Preventing Pollution from Ships and, in cases of Emergency, Combating Pollution of the Mediterranean Sea http://195.97.36.231/dbases/webdocs/BCP/ProtocolEmergency02_eng.pdf.

Directive	Objective	Date*	Comments
Wild Bird Directive (79/409/EEC), amended by Directive 2009/147/EC	To create a comprehensive protection scheme for rare and/or vulnerable bird species through the designation of Special Protection Areas (SPAs).	15/02/2010	Plans/projects likely to have significant effects (either individually or in combination) on SPAs, shall be subject to assessment (see also Art. 7 of the Habitats Directive); regularly occurring migratory species should be protected; Member States shall encourage research required for the protection, management and use of the population of all bird species (Art. 1), with emphasis on Annex V subjects (Directive 2009/147/EC)
Habitats Directive (92/43/EEC) Several amendments in response to enlargement of the EU	To promote/ensure the preservation of biodiversity;.	06/1994	Requires cooperation for the maintenance/restoration to a favourable conservation status of certain rare, threatened, or typical natural habitats(SACs) and species; establishment of necessary conservation measures corresponding to the ecological requirements of natural habitats; to take steps to avoid deterioration in SAC habitats; plans/projects likely to have significant effects shall be subject to assessments (Art. 6)
Environmental Impact Assessment (EIA) Directive (85/337/EEC)	To ensure that environmental consequences of development projects are identified and assessed before authorisation	3/07/1988	Definition of projects subject to Environmental Impact Assessments (EIAs); definition of procedures/contents of EIAs; Annex I projects are subject to mandatory EIAs, whereas for Annex II projects Member States can determine the EIA scope ("screening"); envisages public participation in the authorisation procedure.
Amended Environmental Impact Assessment (EIAA) Directive (97/11/EC),	To widen the scope of EIA by increasing the number of types of projects covered, and the number of projects requiring mandatory EIA (Annex I); to introduce changes to align the EIA Directive with the ESPOO Convention	14/03/1999	Strengthening of the procedural base of the EIA Directive; provision for new screening arrangements and minimum information requirements for Annex II projects; Member States may determine projects requiring assessment on a case-by-case basis (Art. 4(2)). The EIAA Directive was further amended by Council Directive 2003/35/EC, to align provisions on public participation with the Aarhus Convention 1998 on public participation in decision-making and access to justice in environmental matters
Water Framework Directive (WFD) (2000/60/EC)	To establish a framework for action in water policy preventing further deterioration of aquatic ecosystems;	22/12/2003	To enhance protection/improvement of aquatic environment through specific measures; to phase out discharges, emissions and losses of priority substances; WFD applies inshore of a line set at a distance of one nautical mile from the UNCLOS 1982 baseline (Art. 2).
Strategic Environmental Assessment (SEA) Directive (2001/42/EC)	To contribute to the integration of environmental considerations into the preparation/adoption of plans/programmes; to ensure that environmental assessments are carried out for certain plans/programmes, likely to have significant effects	21/07/2004	Covers more activities, entire sectors, wider geographic areas and longer time periods than project EIAs; does not replace project EIAs, but streamlines incorporation of environmental concerns into decision-making; assesses combined impacts of multiple projects/activities; competent authorities should report on probable environmental effects, consult other environmental authorities and the public, and consider the findings when reaching a decision; Art. 3(8) includes an exemption in the case of plans/programmes the sole purpose of which is to serve civil emergency; monitoring allows for identification/remediation of unforeseen impacts; transboundary obligations.
Freedom to access to information Directive (2003/4/EC)	To impose a general duty on public authorities to make environmental information available upon request. Seeks to implement provisions by the relevant Aarhus Convention.	14/02 2005	Member States must provide relevant information on relevant legislation, policies, plans/programmes, monitoring data, environmental state reports, authorisations with significant environmental impacts and environmental impact studies and risk.
Flood Risk Directive (2007/60/EC)	To reduce and manage the risks that floods pose to human health, the environment, cultural heritage and economic activity.	26 /11/2007	imposes a general duty to Member States to assess flood risk of the water courses and coastlines, to map the flood extent, assets and humans at risk in these areas and to take adequate/coordinated measures to reduce risks; requires Member States to carry out preliminary assessments to identify river basins and coastal areas at risk by 2011, draw up comprehensive flood risk maps by 2013 and establish flood risk management plans (prevention, protection and preparedness) by 2015; prescribes that Member States shall take

			into consideration long term drivers (e.g. the climate change and land use practices) in the flood risk management; requires coordination with the WFD, coordination between States that share water courses and public participation procedures in the flood management plans; prescribes that all assessments, maps and plans to be made available to the public
The Marine Strategy Framework Directive-MSFD 2008 (2008/56/EC)	To develop strategies/take measures to achieve and maintain 'good environmental status' in the marine environment of EU Member State jurisdiction at the latest by 2020; (Art. 1)	15/07/2010	Establishes a science-based and participatory policy-making framework to maintain and restore to a 'good environmental status' the EU marine environment, using adaptive management that considers climate change, declining biodiversity, damage to habitats, eutrophication, and pollution; pollution must be phased out together with significant risks to and impacts on marine biodiversity and ecosystems, human health and the legitimate uses of the sea (Art. 1); strives to integrate the fragmented EU marine environment conservation framework; adopts an 'ecosystem approach' for the 3 EU 'Marine Regions' (the Mediterranean and Baltic Seas and the NE Atlantic) to reflect environmental particularities and promote specific solutions; adopts coordinated approaches according to which Regional/sub Regional Member States must cooperate to achieve coherence/coordination in assessing the environmental status, and the impacts of human activities (Art. 10), define qualitative descriptors/indicators, establish/implement monitoring programmes (Art 11), update targets and develop measures to achieve/maintain good environmental status (Art. 5) by set dates; imposes duties to Member States to ensure that all interested parties can participate and publish/make available strategy summaries (Art. 19); prescribes that transboundary impacts must be considered through relevant assessment/monitoring methodologies and measures and provides for involvement of all States bordering (and within) the catchment of a Marine Region or Sub-Region, regardless of EU membership.

Table I.2 European Legislation relevant to the protection/management of the coastal zone. *The date referred to in the text is either the date that the Directive entered into force or the latest transposition date into the national legislation of the EU Member States; the inconsistency arises due to the successive EU enlargement. ** Latest transposition date: 19/07/2015. EU legislation applies to the EU Mediterranean Coastal States: Cyprus, France Greece, Italy, Malta, Slovenia, Spain and Croatia.

Key: Wild Bird Directive, Directive on the conservation of wild birds (2009/147/EC) (http://eurex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32009L0147:EN:NOT). Habitats Directive, Directive on Conservation of Natural Habitats and of Wild Fauna and Flora (92/43/EEC) Consolidated version 2007, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:01992L0043-20070101:EN:NOT). See also , http://ec.europa.eu/environment/nature/natura2000/marine/index_en.htm). Environmental Impact Assessment (EIA) Directive, Directive on the Assessment of the effects of certain public and private projects on the environment (85/337/EEC) (last amended version http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:1985L0337:20090625:EN:PDF). Environmental Impact Assessment Amended Directive, Directive amending Directive 85/337/EEC on the assessment of the effects of certain public and private projects on the environment (97/11/EC) (http://ec.europa.eu/environment/eia/full-legal-text/9711.htm). The Strategic Environmental Assessment (SEA) Directive, Directive on the Assessment of the effects of certain plans and programmes on the environment (2001/42/EC) http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2001:197:0030:0037:EN:PDF). The Freedom to access to information Directive, Directive on Public access to environmental information repealing Council Directive 90/313/EEC (2003/4/EC) (http://eur

lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:041:0026:0032:EN:PDF). Water Framework (WFD) Directive, Directive establishing a Framework for Community action in the field of water policy (2000/60/EC) (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2000:327:0001:0001:EN:PDF).
The Flood Risk Directive, Directive 2007/60/EC on the assessment and management of flood risks (http://ec.europa.eu/environment/water/flood_risk/)

Marine Strategy Framework Directive (MSFD), Directive establishing a framework for community action in the field of marine environmental policy (2008/56/EC) (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:164:0019:0040:EN:PDF).