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Black Sea beaches vulnerability to sea level rise

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ABSTRACT

Integrated Coastal Zone Management (ICZM) aims to promote sustainable management of coastal zones based on ecosystem and holistic management approaches. In this context, policies have to consider the complex interactions that influence the fragile equilibrium of coastal ecosystems. Beaches represent both valuable and vulnerable natural resources because of the various ecosystem services they provide and their sensitivity to climate change and sea level rise.

We present the first comprehensive digital record of all Black Sea beaches and provide a rapid assessment of their erosion risk under different scenarios of sea level rise. Through the digitisation of freely available remote-sensed images on the web, we provide broad information on the spatial characteristics and other attributes of all Black Sea beaches (e.g. photo-based visual estimation of the sediment type, presence of coastal defences, urban development). These data have been assembled and stored in full Spatial Data Infrastructure (SDI) – allowing spatial queries, visualisation and data sharing – and are therefore particularly interesting to feed/supply web-GIS portals (coastal atlases) for visualisation purpose, spatial queries or spatial indicators calculations.

The resulting Black Sea beaches database contains 1228 beaches, with a total coastline length of 2042 km with an area of 224 km^2. The majority of the Black Sea beaches have been found to have small widths (61% have maximum widths less than 50 m), whereas 47% of all beaches presented coastal defence schemes, suggesting an already serious beach erosion problem.

The erosion risk of the Black Sea beaches was assessed through the comparison of their maximum widths with estimations of the sea level rise-induced retreat by an ensemble of six 1-D analytical and numerical morphodynamic models. Following more than 17,000 experiments using different combinations of wave conditions, beach sediment textures and slopes and 11 scenarios of sea level rise (up to 2 m), the means (best fits) of the lowest and highest projections by the model ensemble were estimated; these were then compared to the maximum widths of the Black Sea beaches. The analysis showed that sea level rise will

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have highly significant impacts on the Black Sea beaches, as for a 0.5 m sea level rise 56% of all beaches are projected to retreat by 50% of their maximum width. For a 0.82 m sea level rise (the high IPCC estimate for the period 2081–2100) about 41% are projected to retreat by their entire maximum width, whereas for 1 m sea level rise about 51% of all Black Sea beaches are projected to retreat by (drowned or shifted landward by) their entire maximum width, if the high mean of the model ensemble projections is used.

Results substantiate the risk of beach erosion as a major environmental problem along the Black Sea coast, which therefore needs to be taken into account in any future coastal management plans, as a matter of urgency. As these scenarios consider only sea level rise, they are considered to be conservative. Although the present results cannot replace detailed studies, the database and projections may assist Black Sea coastal managers and policy makers to rapidly identify beaches with increased risk of erosion, valuate accordingly coastal assets and infrastructure, estimate beach capacity for touristic development purposes, and rapidly assess direct and indirect costs and benefits of beach protection options. They also provide the necessary inputs to advance discussions relevant to the Black Sea ICZM.

1. Introduction

Erosion appears to be a major problem for the Black Sea coast (e.g. Kuleli et al., 2011; Stanica et al., 2011). Beaches, i.e. the low-lying coasts built on unconsolidated sediments, are amongst its most threatened coastal environments, with their erosion driven by: mean Sea Level Rise (SLR) (Shuisky, 2000); extreme storm events (e.g. Trifonova et al., 2012); diminishing sediment supply from the heavily managed rivers (e.g. Stanica et al., 2007); coastal development and poorly designed hydrotechnical and coastal protection schemes (e.g. Kokpinar et al., 2007; Romanescu, 2013); and river, coastal and near-shore sediment mining (e.g. Maktav et al., 2002).

Beaches are vital coastal ecosystems and ecological habitats (e.g. Dugan et al., 2013). They are the first line of defence against sea flooding of indispensable back-barrier coastal habitats (Rego and Li, 2010) and very valuable economic assets and infrastructure (e.g. Kontogianni et al., 2013). At the same time, beaches are vulnerable to erosion and inundation (IPCC SREX, 2012). Two main erosion types contribute to the total risk: long-term, irreversible landward migration and/or drowning of the beaches due to mean 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 (IPCC SREX, 2012, List et al., 2006). The projected SLR and potential increases in the destructiveness of extreme events, as well as intensifying coastal development, threaten to exacerbate the already significant erosion, with severe impacts on coastal populations, infrastructure, assets and ecosystem services (e.g. McGranahan et al., 2007; Peduzzi et al., 2013).

SLR – both long- and short-term – threatens beaches with retreat. Since 1900, global mean sea level has risen by about 0.2 m; future mean SLR is, however, uncertain, with the latest IPCC report (IPCC, 2013) projecting for the period 2081–2100 a mean sea level of 0.26–0.82 m higher than that of the 1986–2005 period. Nevertheless, other recent studies that are based on alternative approaches forecast higher rises for the same period (e.g. Mori et al., 2013). Changes in the frequency and patterns of storm surges and waves will also cause, at least temporarily, significant beach erosion/inundation, particularly if such extremes couple with higher mean sea levels (Tsimplis and Shaw, 2010).

Coastal zone sustainability is dependent on the integrated management of the coastal ecosystems. It requires the collection/collation of varied environmental and socio-economic information, robust risk assessments and policies that can deal with the complex interactions between the natural and human components of the coastal zone. Beaches are both critical and sensitive constituents of the coastal system, and the manner with which we address their erosion problem will define the future resilience and sustainability of the coastal zone. This issue has been recognised by the international community, leading to the development of relevant international regulatory instruments. For example, the ICZM Protocol to the Barcelona Convention identifies coastal erosion as a critical problem for the Mediterranean and prescribes that ('...*in 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, ICZM Protocol, 2009). It is obvious that the design and implementation of such measures should be based on erosion risk assessments and management plans that reflect the spatial and temporal scope of their employment. Coastal management and regulation at the basin and regional scales should be based on assessments at similar scales, which require the collation and efficient sharing of relevant information and tools.

The Black Sea coastline is a densely populated and utilised region that requires integrated and sustainable management of its environment, development and resources (e.g. Tsereteli et al., 2011). Management of this zone should not only consider the present characteristics of its beaches, but also the potential risks associated with future climatic changes. However, to date, there is neither an accessible and integrated inventory of Black Sea beaches, nor an assessment of their erosion risk at basin scale.

This study is built around three main objectives. The first is to build a database of the present geo-spatial characteristics of the Black Sea beaches, based on examination of high resolution satellite images freely available on the web, and to distribute this information using the modern data-sharing solutions brought by Spatial Data Infrastructure (SDI) services. The second objective is to assess, at the basin-scale, the range of SLR-driven retreat of Black Sea beaches under different scenarios of sea level rise, using an ensemble of six coastal morphodynamic models. The last objective is to discuss the significance of generating and sharing basin-scale information on beach erosion, in order to support Black Sea ICZM policies.

2. Environmental setting

The Black Sea coastline has a total length of ~4400 km, fronting river catchments with a total area of about ~2.4 × 10^6 km^2, a mean elevation of ~400 m, an average slope of 4 degrees and a population of about 140 million (Ludwig et al., 2009). Its varied morphology comprises both low-relief coasts found mainly in the northwest and high relief coasts in the east and the south (Fig. 1). The Black Sea is located at the margins of the Tethys orogenic belts and comprises an older western and a younger eastern basin (e.g. Shillington et al., 2008). For extended periods during the Quaternary, it formed a lacustrine environment. The Late Pleistocene lacustrine conditions ended with the Holocene flooding over the shallow sill of the Bosphorus Strait (e.g. Esin et al., 2010), which was followed by a more gradual marine transgression (e.g. Erginal et al., 2013). The modern sedimentary environments of the basin comprise both wide and narrow continental shelves (Fig. 1), canyon-scarred continental slopes and deep sea fans (e.g. Lericolais et al., 2013).

The relative isolation and substantial freshwater inputs of the Black Sea have resulted in water column stratification (Ozsoy and Unluata, 1997), anoxia and methane-dominated deep sedimentary environments (e.g. Greinert et al., 2006). The dominant circulation feature of the basin is the cyclonic Rim Current (Staneva et al., 2001), which transports about 3–4 × 10^6 m^3 s^{-1} of water and sweeps the outer shelves of the basin with surface velocities of 0.4–1 m s^{-1}, being also active at the intermediate and deep water layers (Korotaev et al., 2006). Hydrodynamics vary in response to the large-scale climatic variability, such as the North Atlantic Oscillation-NAO and the East Atlantic/West Russia Oscillation (Capet et al., 2012) and possibly the Mediterranean Oscillation (Criado-Aldeanueva and Javier Soto-Navarro, 2013).

The basin precipitation has been estimated at 120–300 km^3 a^{-1} (Jaoshvili, 2002). Evidence of increasing occurrence of extreme events in some regions has been presented

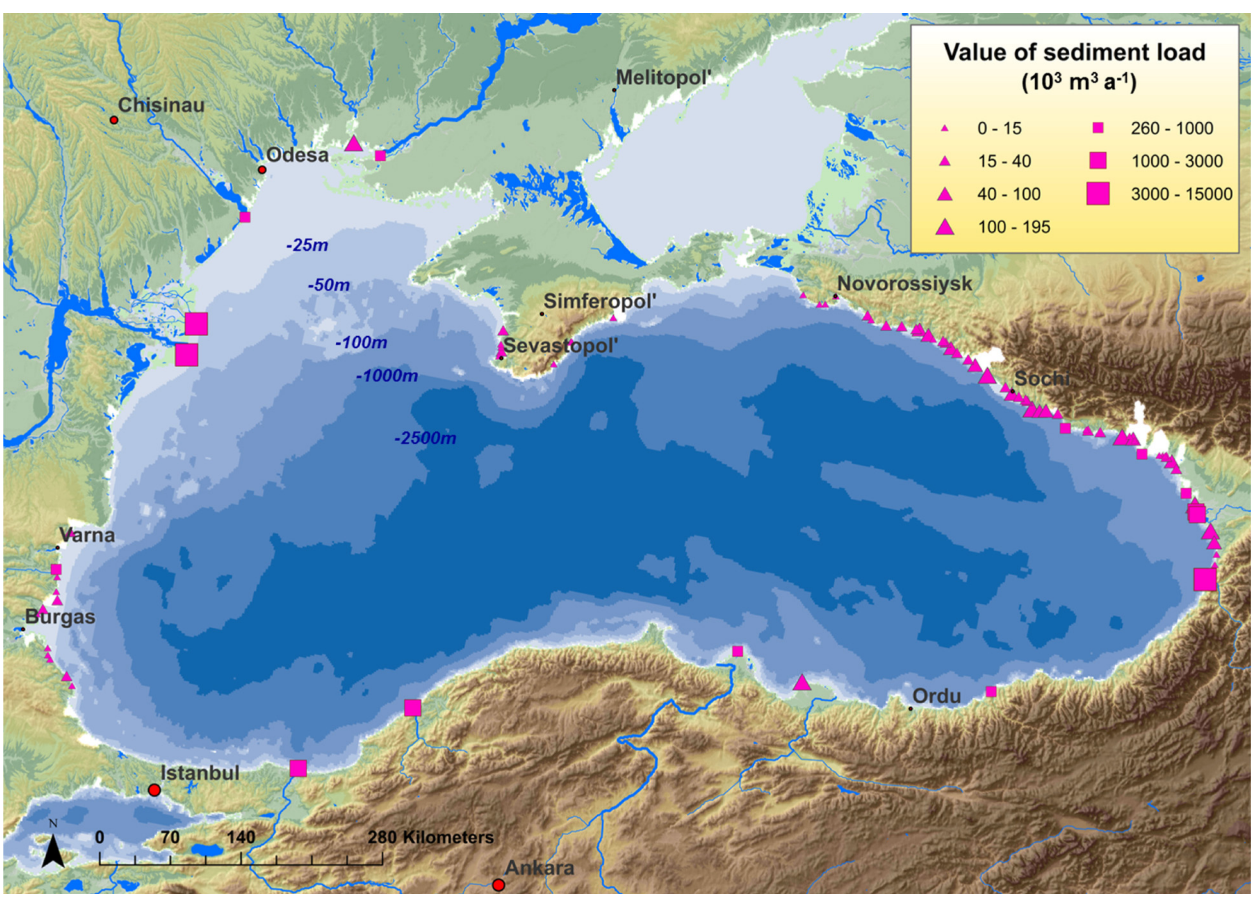

Fig. 1 – Physiography and annual river sediment supply to the Black Sea coast.
Source: Data from Beek et al. (2012), Jaoshvili (2002) and Mikhailov and Mikhailova (2008).

(Croitoru et al., 2013). The precipitation–evaporation budget is positive in the south/southeast and negative in the north (Stanev et al., 2004), with the basin-wide budget being negative. However, due to the high river inputs (350–470 $km^3 a^{-1}$, see Beek et al. (2012) and Mikhailov and Mikhailova (2008), the Black Sea has a positive freshwater balance, exporting mesohaline water through the Bosphorus Strait (Ludwig et al., 2009).

The Black Sea receives inputs from about 1000 rivers (e.g. UNECE, 2011). Most major rivers fluxes have decreased substantially during the past century, due to hydro-technical works and management. Presently, the river sediment supply from the 100 largest rivers to the Black Sea basin has been estimated as 35.5–41 $\times 10^6 m^3 a^{-1}$, with the medium- and coarse-grained, beach-forming sediments accounting for 9.1–10.6 $\times 10^6 m^3 a^{-1}$ i.e. only about 25% of the total (Algan, 2006; Mikhailov and Mikhailova, 2008). Considerable quantities of the river sediments are trapped in lagoons and limans and/or escape offshore (Panin and Jipa, 2002).

The micro-tidal coast (e.g. Korotaev et al., 2001) shows variable rates of mean SLR (Kubryakov and Stanichnyi, 2012), with an average over the basin of 2–2.7 mm a^{-1}, and relatively small (less than 1 m) seasonal and wind-driven sea level fluctuations (Gospodinova, 2004; Stanica et al., 2011; Tsimplis et al., 2004). Nevertheless, the Black sea coast faces energetic wind waves which, in some areas, may reach offshore significant wave heights exceeding 5 m (e.g. Akpınar and Kömürcü, 2012).

3. Methodology

3.1. *Beach characteristics/database*

A geo-spatial database of the Black Sea beaches has been assembled, using the images and available information within the Google Earth Pro application. In the compiled database, only open sea beaches have been considered. Beach area is defined as the low-lying sedimentary body that is bounded on its landward side by backshore natural morphological features (vegetated dunes and/or cliffs) or permanent artificial structures (e.g. coastal embankments, roads, railways and buildings) and on its seaward side by the median line between the 'dry' and 'wet' coastline shown on the imagery (Fig. 2). Beaches have been delimited in length by natural barriers, such as river mouths or rock

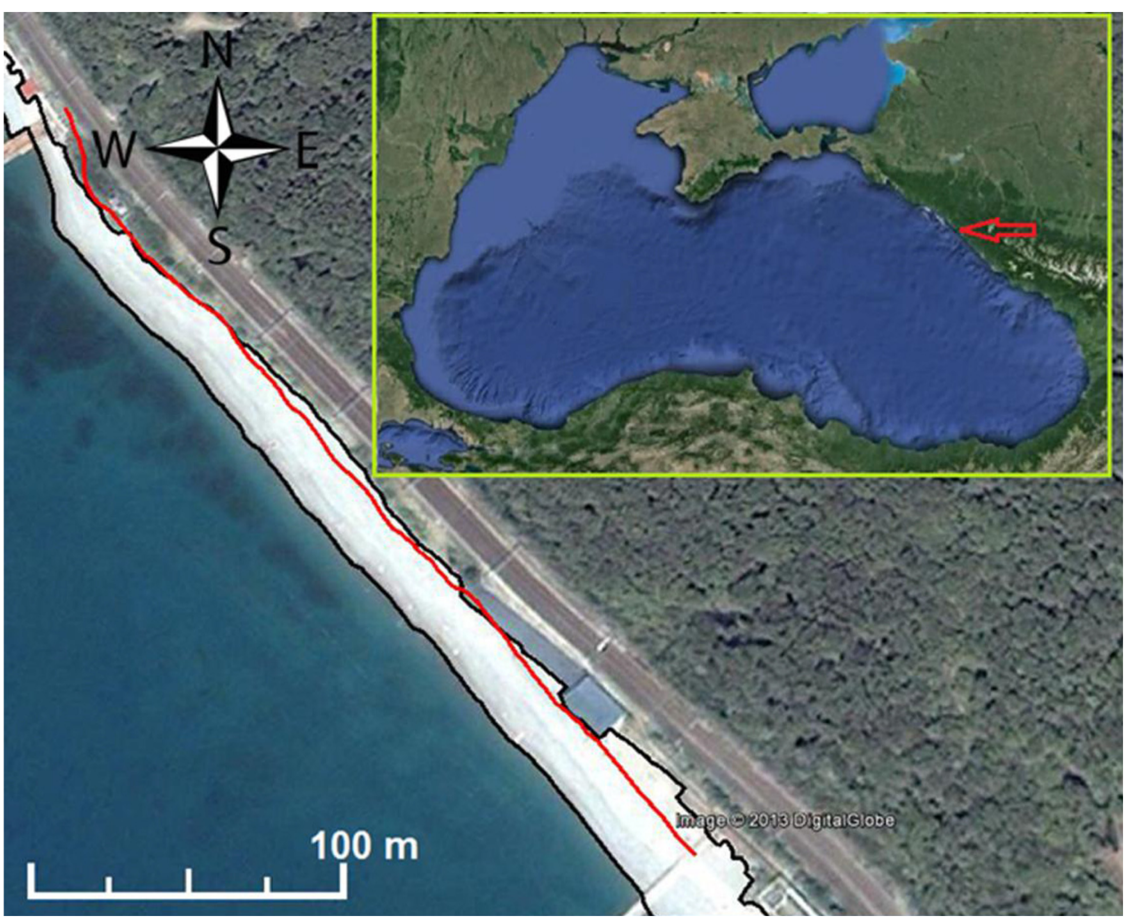

Fig. 2 – Beach delimitation and beach retreat predictions due to SLR at the Black Sea coast of Sochi (Russia). The black lines show how the beach area has been delimited, whereas the red line shows the maximum beach retreat projected by the model ensemble for 0.5 m SLR. It appears that under such conditions, the beach will be shifed backward/drowned, endangering also the main coastal transport network to Sochi. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

promontories, but not by artificial structures (groynes and seawalls).

To avoid inconsistency, digitisation has been carried out by a unique analyst who has followed consistently the above beach delimitation rules. Beaches have been digitised as polygons, using the available in the application tool and exported to a GIS for further analysis. A custom-made AML (ARC Macro Language, proprietary language for ArcInfo applications in ESRI software) script was then used to automatically estimate total beach length and area, extract beach orientation (in degrees) and, following the subdivisions of polygons in regular sections, beach width statistics (mean, minimum, maximum and standard deviation).

Uncertainties in the above approach stem from the facts that the available remote sensing images are not synoptic at the basin scale i.e. they have been collected in different years and seasons (within the period October 2000–January 2011). There are inherent uncertainties, particularly with regard to the synoptic widths of the basin's beaches, due to inter-annual and seasonal variability and the different tidal and wave run-up conditions during which these images have been collected (e.g. Vousdoukas et al., 2009). Therefore, although tidal effects can be regarded as small due to the microtidal regime of the Black Sea coast (tidal ranges less than 0.15–0.20 m, see e.g. Korotaev et al., 2001; Tsimplis et al., 2004), beach geo-spatial characteristics obtained on the basis of temporally varying remote sensing images may introduce uncertainty in their comparison. Nevertheless, such uncertainty cannot be avoided when working at the basin scale.

In addition to the spatial characteristics, other information has been recorded, including: the acquisition date of the imagery used; the presence of natural (e.g. river mouths, vegetated dunes, back-barrier lagoons and cliffs) and artificial (e.g. coastal protection schemes and backshore development) features; the presence of breaking waves at the image; and an assessment of the beach sediment texture (e.g. gravel, sand) on the basis of the available photos on the Google Earth application. All these have been codified and recorded in an attribute table that forms part of the database.

The complex and interdisciplinary nature of ICZM requires improved procedures on information, data and model exchange, as difficulties associated with data accessibility and compatibility are often encountered by scientists, researchers, decision-makers and the general public with negative effects on the efficient mining/exploitation of the available information (Bernard and Craglia, 2005; Vandenbroucke, 2010). Therefore, the concept behind the development/use of Spatial Data Infrastructures (SDIs) has been to collate information from many different sources and to share it with the widest possible group of potential users. SDIs were developed to facilitate and coordinate the sharing of geospatial data, encompassing data sources, systems, network linkages, standards and institutional issues, by providing a suite of services for data publishing, discovering, gathering and facilitating their integration (Nebert, 2005). An SDI fundamental quality must be its interoperability, i.e. the ability of different systems/components for effective information exchange (Open Geospatial Consortium, 2004). It offers the possibility to widely and effectively exchange institu data, to maximise their value and their reuse, but also promote the exchange of information with other interoperable systems. These interactions promote the creation of new knowledge, emerging from relationships that were not previously envisioned. A suite of standards to search, discover and access heterogeneous geospatial resources were developed by the Open Geospatial Consortium (OGC) (Giuliani and Gorgan, 2013; Giuliani et al., 2013). Resources can be visualised as maps through the Web Map Service (WMS) standard (Open Geospatial Consortium, 2006a,b), while vectors and raster data can be accessed via the Web Feature Service (WFS) (Open Geospatial Consortium, 2005) and the Web Coverage Service (WCS) (Open Geospatial Consortium, 2006a,b). Finally, processing algorithms can be shared through the Web Processing Service (WPS) (Open Geospatial Consortium, 2007a,b).

Regarding metadata documentation, data and services should be described according to the ISO standards 19115 (resource metadata), 19139 (metadata encoding) and 19119 (service metadata) of the International Organisation for Standardisation (ISO). The OGC Catalogue Service for the Web (CSW) specification (Open Geospatial Consortium, 2007a,b) complements the ISO standards, by defining an interoperable interface to publish, search and query metadata. Consequently, SDI interoperability not only facilitates a wide and effective data exchange/use between different institutions, but also provides for information exchange with other interoperable systems.

The Black Sea beaches database provides, for the first time, a complete record of the Black Sea beaches in a freely available and standardised format. It is available through the following links for:

Data visualisation with WMS: http://envirogrids.grid.unep.ch:8080/geoserver/eg_BSbeaches/BlackSea_beaches/ows?service=WMS&request=GetCapabilities

Data download with WFS: http://envirogrids.grid.unep.ch:8080/geoserver/eg_BSbeaches/BlackSea_beaches/ows?service=WFS&request=GetCapabilities

Metadata (ISO and CSW): http://envirogrids.grid.unep.ch:8080/geonetwork/srv/en/main.home?id=224

3.2. *Beach retreat predictions due to sea level rise*

Estimations of the SLR-induced retreat of the Black Sea beaches have been obtained through the application of an ensemble of six 1-D analytical and numerical models (Bruun, 1988; Dean, 1991; Edelman, 1972; Leont'yev, 1996; Roelvink et al., 2010) and SBEACH (Larson and Kraus, 1989). The Bruun (1988) model is a widely used (e.g. Hinkel et al., 2009) analytical model that estimates the long-term coastal retreat – referred hereafter as S – under a SLR α on the basis of the concept of equilibrium profile (Cooper and Pilkey, 2004; Zhang et al., 2004); its results are controlled by the height of the beach face and the distance between the coastline and the beach closure depth (Komar, 1998). Edelman's (1972) analytical model can deal also with temporally variable sea level changes, estimating beach retreat using the initial height of the beach face, the water depth at wave breaking and the surf zone width, whereas the Dean's (1991) analytical model estimates beach retreat on the basis of the water depth at wave breaking, the height of breaking waves and the surf zone width. The SBEACH model (Larson and Kraus, 1989) is a 'bottom-up' morphodynamic model, consisting of combined hydrodynamic and sediment transport modules and containing detailed descriptions of the wave transformation and sediment transport in the coastal zone; sediment transport is controlled by the wave energy flux and the beach slope, whereas the sediment continuity equation is addressed by a finite difference scheme and a 'stair–step' beach profile discretization. The numerical model based on the Leont'yev (1996) algorithms uses the energetics approach (Battjes and Janssen, 1978), with the wave energy balance in the cross-shore direction controlled by the wave propagation angle and the wave energy and its dissipation; sediment transport rates are estimated separately for the surf and swash zones. Finally, the XBeach model (Roelvink et al., 2010) is an open-source, widely used numerical model of the near-shore processes intended to estimate the effects of time-varying storm conditions (e.g. Roelvink et al., 2009; Vousdoukas et al., 2011); it contains a time-dependent wave action balance solver and allows for variation of the wave action over time and over the directional space. In the present contribution, all numerical models have been used in their 1-D modes.

Coastal erosion/retreat due to SLR is controlled by the wave energy, as this influences beach sediment transport, the distance of the wave breaking and the closure depth from the coastline and the width of the surf zone. In order to assess the range of coastal retreat at the basin scale, different combinations of wave conditions must be examined. Therefore, experiments were carried out using different plausible combinations of wave conditions i.e. waves with heights *H* of 0.5, 1, 1.5, 2, 3, 4, 5 and 6 m and with periods *T* from 3 to 12 s. Likewise, in order to address the beach sediment texture and slope variability along the basin's coastline, experiments were carried out for combinations of 7 different median (d50) grain sizes (d50 of 0.2, 0.33, 0.50, 0.80, 1, 2 and 5 mm), 5 different linear profile slopes (beach slopes of 1/10, 1/15, 1/20, 1/25 and 1/30) and 11 SLR scenarios (0.10, 0.15, 0.22, 0.30, 0.40, 0.50, 0.75, 1, 1.25, 1.50 and 2 m). It should be noted that the results of the analytical models (Bruun, 1988; Dean, 1991; Edelman, 1972) are independent of the beach sediment size.

Experiments were carried out for all morphological, sedimentological and forcing combinations (about 17300 experiments), and the means (best fits) of the lowest and highest projections by all the 6 models of the ensemble were estimated. The approach has been simplified using a custom-made Graphical User Interface (GUI) tool (for details, see Chatenoux et al., 2012) that is also accessible on-line.[1]

The adopted approach for assessing the reduction of the beach widths under different forcings and sea level rises has been based on the following proposition. As different models have differential sensitivity to the controlling environmental factors, an ensemble approach may provide more reliable prediction ranges than the individual models. Although the scope of application of the 3 analytical models of the ensemble is primarily for long term SLR, whereas the 3 numerical models have been designed to project morphodynamic changes under short-term sea level changes, their use in an ensemble format can provide estimations of the ranges of beach retreat under both short and/or long term SLR. In our study, results from all models have equal weighing in the ensemble projected ranges of beach retreat. These ranges have been used to forecast maximum and minimum horizontal beach retreat under long- and short-term SLR.

[1] http://www.grid.unep.ch/index.php?option=com_content&view=article&id=47&Itemid=253&lang=en&project_id=204F6705.

4. Results

4.1. *Beach characteristics*

The database of the Black Sea beaches contains 1228 beaches, with a total shoreline length of 2042 km, which represents approximately half of the Black Sea coastline, and an area of 224 km^2. The majority of the Black Sea beaches have relatively small widths (61% of the beaches have maximum widths less than 50 m), with only 8% showing maximum widths in excess of 100 m (Fig. 3). Beach sediment texture has been found to be variable, with coarse and medium sediments observed in about 35% of the beaches. Turkey scores the longest shoreline with 672 kilometres principally composed of small beaches, 77% of the 679 recorded beaches have a shoreline smaller than 1 km. Bulgaria, Ukraine and Russia have about half beaches with a shoreline under 1 km, while less than a third are recorded in Georgia and Romania (Fig. 3).

The Black Sea beaches and surrounding environments have been summarised into 17 classes (such as vegetation and sand mixture, grass vegetation, shrub vegetation, tree vegetation, buildings, roads, walls, sea walls and revetments, dunes, dunes with vegetation, vegetation on steep slope), with about 12% fronting hilly landscapes or urbanised areas, 9% fronting vegetated areas and only 1% baked by dunes. However, a single beach may be ascribed to several classes, and 64% of the beaches have a composite denomination.

Results show that less than a third (32%) of the Black Sea beaches can be regarded as natural open sea beaches, with Georgia having the greatest proportion of such beaches. 47% of beaches were observed to be artificially protected by varying shore protection schemes, such as groynes, breakwaters, seawalls, revetments and training walls, whereas about 21% of the beaches were found to be protected by natural features (Fig. 3). However, the above distribution varies along the coastlines of the different Black Sea States. Russian beaches are the most protected by artificial structures (60%), followed by the Romanian (51%), Bulgarian (46%), Ukrainian (45%), Georgian (37%) and Turkish (32%) beaches. Beaches partially protected by coves are dominant in Bulgaria (35%) and Turkey (30%).

The fact the almost half (47%) of the Black Sea beaches are associated with artificial coastal protection schemes suggests that there is already a considerable beach erosion problem. Considering that the efficiency of these protection schemes is already in doubt in several areas (e.g. Kosyan and Yesin, 1997; Romanescu, 2013), beach erosion aggravation due to SLR is likely to exacerbate the already significant impacts on coastal ecosystems, communities and infrastructure (e.g. Gospodinova, 2004; Kuleli et al., 2011), particularly in the neighbourhood of inlets; in these areas, the increase in the accommodation space that will be induced by the SLR will reduce the river sediment supply to the open coast and thus,

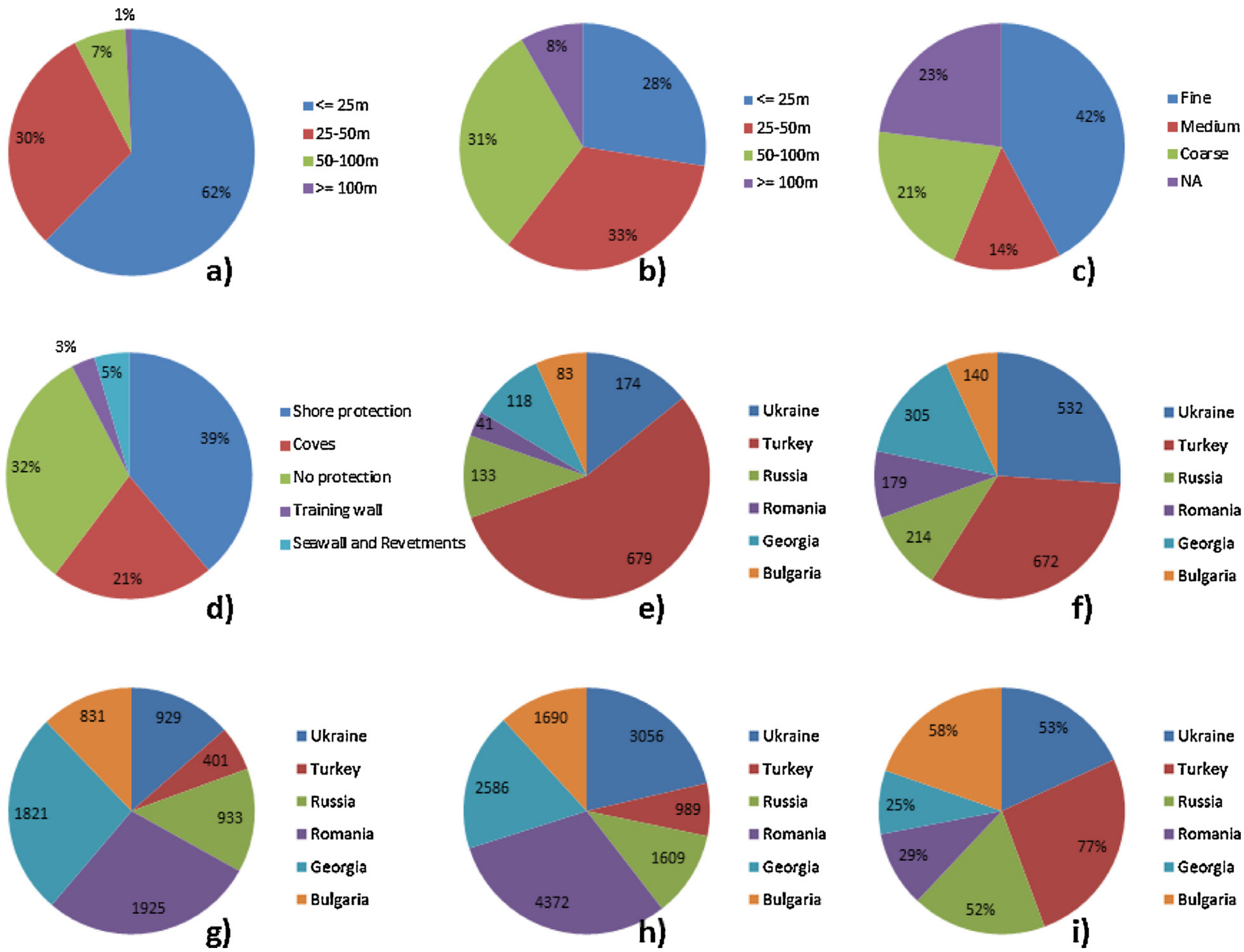

Fig. 3 – Characteristics of the Black Sea beaches (a) mean width; (b) maximum width; (c) beach sediment texture and (d) beach protection schemes (for the definition of terms refer to US Army Corps of Engineers, 1984 and www.coastalwiki.org). National beach statistics; (e) number of beach recorded, (f) total length shoreline in kilometres, (g) median length shoreline in metres, (h) mean length shoreline in metres, (i) percentage of beaches with a shoreline smaller than 1 km.

aggravate further the present beach erosion (Ranasinghe et al., 2013).

4.2. *Projections of beach retreat*

Modelling results show that SLR will result in coastal retreats that will be accompanied by significant morphological changes (Fig. 4), particularly close to the coastline. The different models' results varied for most tested conditions, showing also significant ranges, as expected by the varied morphological, hydrodynamic and sedimentological forcings used. Generally the six models showed differential sensitivity to forcing, which supports the value of an ensemble approach.

The Bruun (1988) model provided the narrowest range of results, whereas the 'bottom-up' numerical models (i.e. the SBEACH, Leont'yev and XBeach models) produced relatively large ranges. Beach retreats were found to be mostly controlled by the beach type (e.g. dissipative or intermediate sloped-beaches, see Komar (1998)). In order to assess the effects of the beach typology on coastal retreat, the Iribarren number (ξ) was used ($\xi = \beta/(H_0/L_0)^{1/2}$) where β is the beach slope and H_o and L_o the offshore wave height and length, respectively. With the exception of the Bruun model, the results of which are independent of ξ for linear profiles, it was found that coastal retreat decreases (as expected) with increasing ξ. Beach retreat ranges also increase with the decrease of ξ, i.e. for beaches with milder slopes and/or waves with increased steepness (H_0/L_0).

Generally, all model results have been found to be very sensitive to beach slope, with the most sensitive being the Edelman and SBEACH models and the least sensitive the XBeach model. Beach retreat also appears to increase with offshore wave height. Most of the models (with the exception of the Bruun model) appear to be sensitive to wave conditions, with a positive relationship between wave height and beach retreat; XBeach appears to be the most sensitive and the Leont'yev the least sensitive model to the wave climate. The SBEACH and Dean models showed similar sensitivity to wave climate, whereas the sensitivity of the Edelman model increases with SLR.

As rising sea levels are likely to be accompanied by reductions in wave dissipation and intensifications in the mean and extreme wave conditions (IPCC SREX, 2012), the positive correlation between offshore wave height and beach

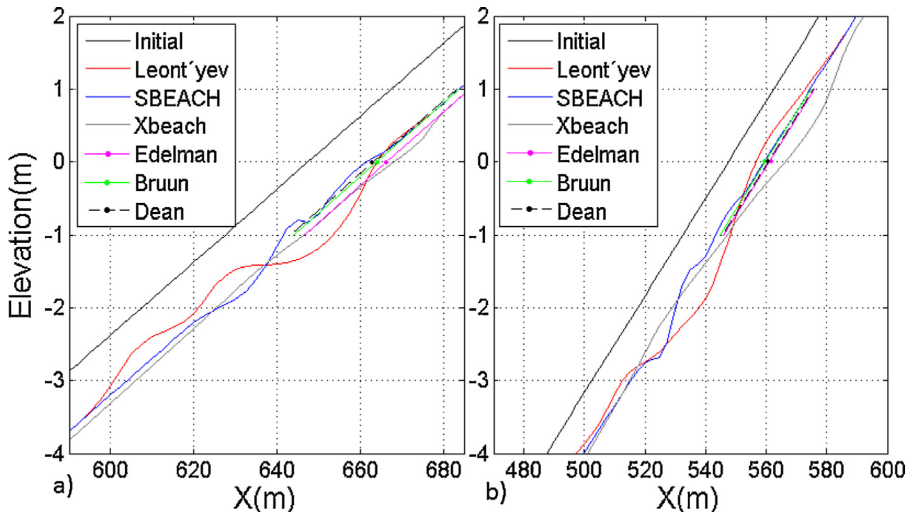

Fig. 4 – Examples of the morphodynamic changes for the upper part of the beach (initial) profile on the basis of the cross-shore ensemble modelling for SLR of 0.82 m, showing significant changes for the initial beach profile. (a) Offshore (at 20 m water depth) wave height H and period T, 2 m and 6 s, 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 5 mm. In both cases, the origin of X axis is at 20 m water depth.

retreat suggests increased risk of beach erosion. Finally, the effect of the sediment texture was not always clear in the numerical modelling results, although a weak trend showing a decrease in coastal retreat with the increase in the median grain-size of the beach sediments was found.

The above modelling results were used to estimate the ranges of SLR-induced retreat of the Black Sea beaches. As the environmental characteristics vary for each beach, the means (best fits) of the lowest and highest predictions for all morphological, sedimentological and forcing combinations by all models of the ensemble were used (Fig. 5). This approach enables reasonable assessment of potential ranges of beach retreat under marine forcing (i.e. sea levels and waves) on the basis of minimal environmental information. It provides ranges (maximum and minimum) of the horizontal excursion of cross-shore beach retreat that can be then compared to the maximum widths of the Black Sea beaches that have been determined by the remote sensing imagery and stored in the database (see Section 3.1).

On the basis of these ranges, the potential erosion of the Black Sea beaches has been estimated for three SLR scenarios, i.e. for rises of 0.5, 0.82 and 1 m that represent the approximate mean and the high estimates of the mean SLR of IPCC (2013) for the period 2081–2100, and a widely quoted by other sources (Jevrejeva et al., 2010) mean SLR. The projections suggest that rises of 0.5, 0.82 and 1 m will result in significant cross-shore retreats, with significant implications for the Black Sea beaches (Table 1).

Even a moderate mean SLR (0.5 m) results in retreats between 4.1 and 21.4 m, whereas the retreats for higher mean SLR are much higher (Table 1). Comparison of the modelling projections with the spatial characteristics of the Black Sea beaches shows that considerable erosions should be expected. In the case of a SLR of 0.5 m, the analysis shows that, on the basis of the low mean predicted by the ensemble modelling (Fig. 5 and Table 1), the effects would not be severe; few beaches (about 18% of the total) retreat by up to 20% of their maximum width. However, on the basis of the high mean predicted by the modelling, effects would be considerable,

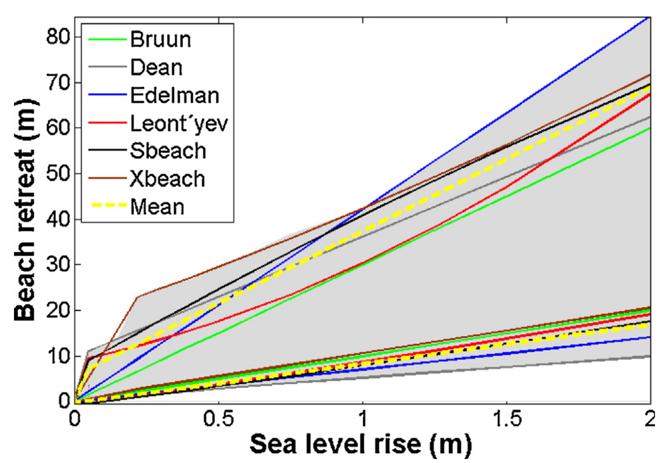

Fig. 5 – Range of results for all the different beach slopes, wave conditions, median (d50) sediment sizes and SLR examined (see text). The best fits (means) for the high and low prediction ranges of the model ensemble (yellow stippled lines) are also shown. The best fit for the lowest predictions from all models is given by $S = 0.2\ \alpha^2 + 8.55\ \alpha - 0.26$ ($R^2 = 0.99$) and the best fit for the highest predictions by $S = -0.04\ \alpha^2 + 31.75\ \alpha + 5.57$ ($R^2 = 0.99$), where S is the beach retreat and α is the SLR. As the XBeach results for very small sea level increases showed some instabilities, these have not been included in the estimations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1 – Projections of the maximum and minimum cross-shore beach retreats (in m) on the basis of the best fits for the lowest and highest predictions from all 6 models of the ensemble (see also Fig.5 and its caption). Beach retreat and/or width loss percentages have been estimated through the comparison of minimum and maximum retreat projections with the maximum beach width of all Black Sea beaches.

SLR scenarios (m)	Ensemble prediction	Beach retreat (m)	Beach retreat equal to the max. width (%)	Beach retreat equal to 50% of the max. width (%)	Beach retreat equal to 20% of the max. width (%)
0.5	Min	4.1	0	0.3	17.8
0.5	Max	21.4	20.6	55.9	92.3
0.82	Min	6.9	0.1	4.8	46.4
0.82	Max	31.6	40.9	75.7	97.6
1	Min	8.5	0.3	11.5	55.9
1	Max	37.3	51.1	81.9	98.9

with more than 90% of the beaches retreating by 20% and about 56% by 50% of their maximum width; about 21% of all beaches retreat (lost or shifted landward) by their entire maximum width (Table 1 and Figs. 6 and 7).

For a SLR of 0.82 m (the high estimate of IPCC (2013) for the period 2081–2100) the effects are relatively small if the low mean of the modelling projections is used, with about 46% of the beaches projected to retreat by up to 20% of their maximum widths. However, if the high mean of the predictions is used, then the effects are considerable, as about 76% of the Black Sea beaches are projected to retreat by about 50% of their maximum widths, and about 41% of all beaches retreat by their maximum width (Fig. 6). Finally, a 1 m SLR has catastrophic consequences, with about 51% of the beaches projected to retreat by their entire maximum width (lost or shifted landward), if the high mean of the model ensemble projections is used (Table 1 and Fig. 6). It should be noted that projections on the basis of the low mean of the model ensemble projections refer to steep gravel beaches that are subjected to very low wave energy and, thus, are likely to be considerable underestimations.

Figs. 6 and 7 show the beach retreats along the coasts of the different Black Sea states. It appears that the beaches of all States are under significant erosion risk, but this is going to be higher for the Turkish and Russian, as well as for the eastern Crimean beaches. This is due to the fact that many of these beaches are characterised by small widths as they front the high relief Anatolian, Caucasus and E. Crimean hinterland.

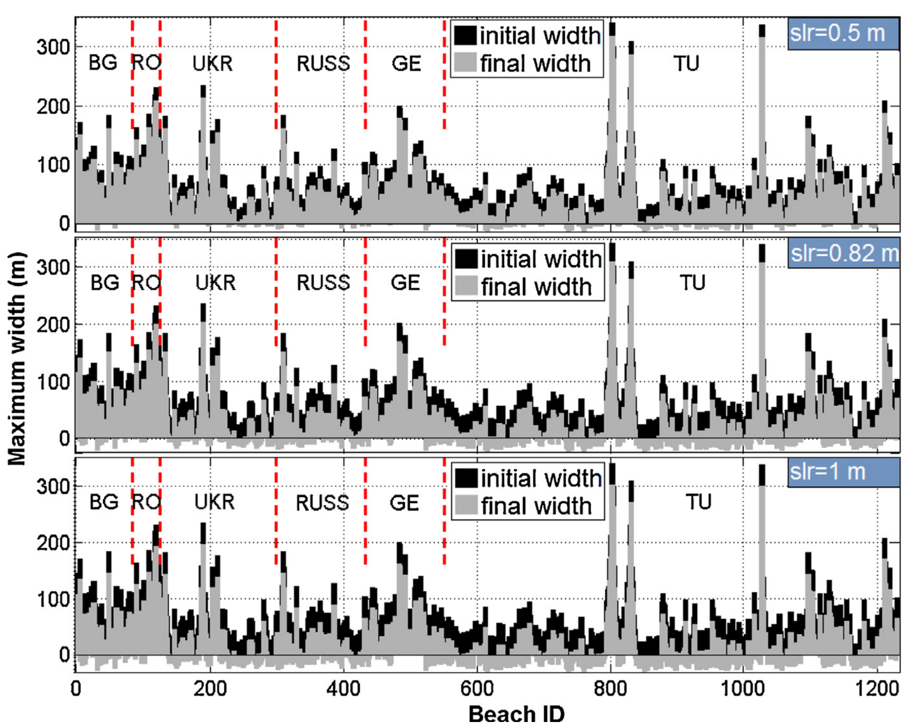

Fig. 6 – Maximum retreat of Black Sea beaches for sea level rises of (a) 0.50 m, (b) of 0.82 m and (c) 1 m estimated on the basis of the high mean of the 6 model ensemble projections. Final widths values less than zero show beaches that will retreat (lost or shifted landward) by their entire maximum width). Beach ID progresses clockwise from the Turkish–Bulgarian border. Beaches with data base IDs 185 and 804 are not shown, as their maximum widths are beyond the figure scale (>350 m).

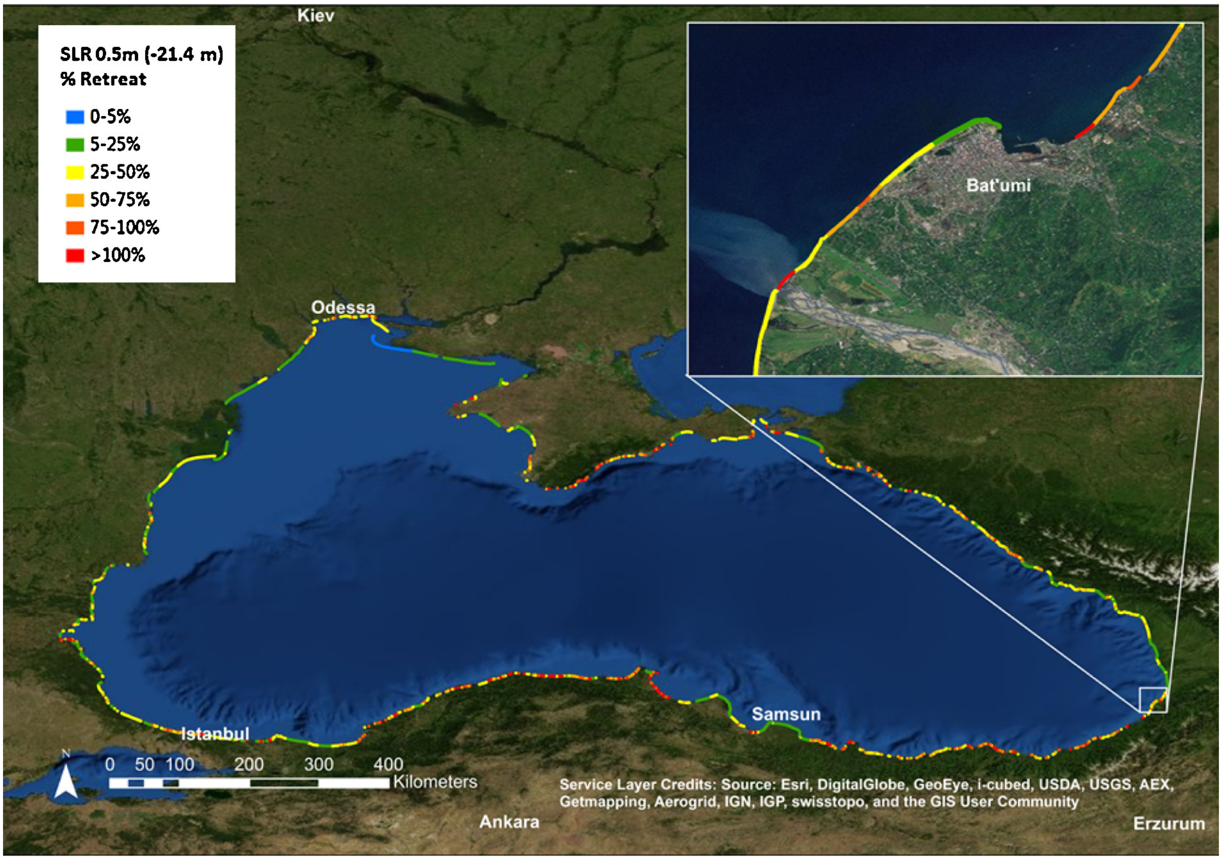

Fig. 7 – Maximum beach retreat (in percentage of the maximum beach width) predicted by the model ensemble for the Black Sea beaches under a 0.5 m SLR. Coastal erosion at the Georgian coast near the city of Batumi (inset), which is projected to be already moderate/severe under a SLR of 0.5 m, will probably be exacerbated due to the diminishing sediment supply caused by the constructed/planned dams along the Chorokhi river, which is the main supplier of coastal sediment in this part of the Georgian coast (Iashvili, 2006; Klaphake and Scheumann, 2011).

As the ensemble contains equally weighed results by models that can deal with the effects of storm events (i.e. the SBEACH, Leont'yev and XBeach models), the above projections might be also used to assess effects of storm-generated surges and/or effects of combined mean seal level and storm surge rise. Therefore, beach retreats such as those projected in the present study may occur (temporarily) much earlier than 2100.

Finally, the above results are considered to be conservative, as they refer only to the effects of SLR without taking into account impacts from the diminishing coastal sediment supply (e.g. Mikhailov and Mikhailova, 2008; Stanica et al., 2011), the increased vulnerability of particular coasts, such as those associated with inlets, limans and lagoons (e.g. Buynevich, 2007; Ranasinghe et al., 2013) and the effects of storm groups (e.g. Vousdoukas et al., 2012a).

5. Discussion

The present study represents a first attempt to record all Black Sea beaches and provides a rapid assessment of their erosion risk in response to different SLR scenarios (see also Velegrakis et al., 2009). It is important to state that the completeness/accuracy of the information recorded in the Black Sea beach database is subject to certain constraints. For instance, the completeness of the inventory was limited by the availability of usable satellite images, i.e. images in which beach view was not obstructed by the presence of clouds or hidden by coastal cliff shadows. Errors in beach delimitation (visually estimated at approximately ± 2 m), the lack of precise projections that may result in shifts of about ± 20 m between different images (causing severe offsets when these images refer to the same beach) are undoubtedly sources of potential inconsistencies.

In addition, the available remote sensing images are not synoptic at the basin scale i.e. they have been collected in different years and seasons (within the period October 2000–January 2011) and during different tidal and wave run-up conditions (e.g. Vousdoukas et al., 2009). Therefore, although tidal effects can be regarded as small due to the microtidal regime of the Black Sea coast (tidal ranges less than 0.15–0.20 m, see e.g. Korotaev et al. (2001) and Tsimplis et al. (2004)), beach geo-spatial characteristics obtained on the basis of temporally varying remote sensing images may introduce uncertainties in their comparison. Nevertheless, such uncertainties cannot be avoided when working at the basin scale.

With regards to the beach retreat projections, the approach adopted in the estimation of SLR-induced reduction in beach width has been based on the following proposition. As different models have differential sensitivity to the controlling environmental factors, their common (ensemble) application can provide more reliable prediction ranges than the individual models. These ranges have been used to forecast beach exposure to SLR on the basis of the horizontal beach spatial characteristics (e.g. beach width and area) and the extent of human development, parameters that could be easly defined by available, web-based, remote-sensed beach imagery. Consequently, the methodology has not been limited by the availability of information concerning beach morphology (e.g. bed slope), sediments and wave regime (e.g. McLeod et al., 2010), as the range estimations of beach retreat are based on numerous combinations of these parameters.

Nevertheless, there are also constraints. First, predictions are based on the assumption that beaches comprise a sediment reservoir, with no lateral and/or offshore sediment losses. Cross-shore modelling cannot resolve such issues as detailed 2-D and/or 3-D morphodynamic modelling is required that will be based on detailed information on morphology, sedimentology and hydrodynamics and trained/validated by appropriate field observations. Secondly, the approach does not account for other erosion controlling factors, such as geological controls, coastal sedimentary budgets, the presence of inlets, extreme event duration and sequencing (e.g. Corbella and Stretch, 2012; Ranasinghe et al., 2013) and the presence of artificial beach protection schemes and of protecting near-shore ecosystems (e.g. Vousdoukas et al., 2012b). Against this background, the present results may underestimate beach retreat, as well as the inundation exposure of the Black Sea beaches. However, as has been stated earlier, the aim of the present approach is not to replace detailed beach monitoring and modelling studies (Nicholls et al., 2013), but rather to provide a rapid assessment of the potential ranges of retreat of the Black Sea coast under different scenarios of SLR.

Amongst the plethora of potential applications, the database and beach erosion projections could serve Black Sea coastal managers and policy makers to: rapidly identify beaches with increased risk of erosion; valuate accordingly coastal assets and infrastructure (Parsons and Powel, 2001); estimate beach capacity for touristic development purposes (Yang et al., 2012); and rapidly assess direct and indirect costs and benefits of beach protection schemes, including beach nourishment schemes (e.g. Van Rijn, 2011; Hinkel et al., 2013)

Both beach characteristics, as well as beach erosion projections, can be easily accessible on GIS software (e.g. Fig. 7), providing an overview of the beach erosion problem of the Black Sea coast. It forms a part of a developing Spatial Data Infrastructure (SDI) for the Black Sea which, through data and tool sharing, will avoid duplication of work and optimise the use of funds and resources; this approach was chosen/promoted by both the FP-7 EnviroGRIDS (Lehmann et al., 2014) and PEGASO (Breton et al., 2012) projects, in order to provide an easy and interoperable access to geospatial data and services. The Black Sea SDI, which aims to provide standardised geo-information and services from various suppliers, will allow seamless continuation of coastal zone research in the Black Sea. It will also provide the necessary inputs to advance discussions relevant to the integrated coastal zone management (ICZM) of the Black Sea and can act as a bridge between scientists, policy makers and stakeholders; by making useful information easily available and comprehensible will assist in the formulation and implementation of ICZM regulation.

Despite not diminishing the need for precise ground observations, the database presented in this paper represents an important step forward in providing a much-needed synoptic record of the geo-spatial characteristics of the Black Sea beaches. The data made available are especially convenient to feed web-GIS portals (i.e. coastal atlases) for visualisation purpose, spatial queries, or spatial indicators calculations. For instance, two examples of coastal atlases using digital beach datasets are: the Washington State Coastal Atlas – which allows the user to map public beaches giving information on facilities and possible activities, but also alert on swimming beach closures (https://fortress.wa.gov/ecy/coastalatlas/default.aspx); and the NIWA (National Institute of Water and Atmospheric Research) coastal explorer – which provides a beach report card including classification of beach type, photos and information on water and use safety (https://www.niwa.co.nz/node/105652) and a coastal sensitivity index for coastal change and inundation (https://www.niwa.co.nz/coasts-and-oceans/nz-coast/coastal-explorer/sensitivity-index).

In the future, such data may become fully dynamic through the use of SDIs. This enables the update, correction and integration of both remotely sensed and ground information (provided that there would be a rigorous quality control). With the increasingly widespread use of smartphone and tablet, crowdsourcing initiatives could even be envisaged to improve validation and maintenance of attributes of such datasets (Fienen and Lowry, 2012).

Regulation development and implementation i.e. the introduction of appropriate policy and regulatory instruments is the main tool for governments and regional organisations to manage assets and economic activities at risk and decrease costs for their protection and rehabilitation. In these aspects, the region shows good progress at national level since 2004 (Antonidze, 2010). However a regional supra-national level legal instrument could harmonize approaches and interpretations (Abaza et al., 2011), fill gap in national legal frameworks, strengthen institutions in place or emerging and finally rationalise efforts towards sustainable coastal management (Rochette and Billé, 2012).

A tenet of coastal management policies under a virtually certain deteriorating erosion regime should be the precautionary control of the location of future development, i.e. 'building out of harm's way'; consequently, set-back policies, i.e. policies to create a buffer zone behind the retreating coastlines, are now considered in many coastal management regulation instruments (e.g. national instruments, the ICZM Protocol to the Barcelona Convention). However, there are certain challenges to demarcate set-backs, particularly under changing environmental conditions. These challenges can be only addressed by sound policies that include evaluative criteria and decisions that are both dynamic and transparent.

In this context, the results of the present study form a significant step forward, as they may provide the 'nucleus' of an effective system of relevant data and tool sharing platform. Nevertheless, the implications of the designing and implementing provisions relevant to coastal setbacks are likely to vary depending on the management settings of the different Black Sea States; this was also one of the critical issues faced during the negotiations leading to the approval of the final text of the Mediterranean ICZM Protocol (Sanò et al., 2011).

Finally, the management planning of the Black Sea coast requires a thorough understanding of the 'drivers' for change (i.e. climatic changes, urban development, social pressures and the environment), together with an assessment of the useful life of the existing coastal defences (dominant in some coastal sections, see Section 4.1) and other coastal infrastructure. Coastal management planning should better anticipate and prevent coastal erosion threat incorporating projections of coastline retreat useful for spatial and contingency plans rather than fighting against nature with unsustainable and expensive coastal engineering works (Abaza et al., 2011).

Depending on the SLR scenario, various types of measures may be considered, including beach nourishment and/or construction of 'hard' coastal defences. However, it should be kept in mind that hard coastal defences may transform morphologically dynamic coasts into 'petrified' coastal landscapes with a lower potential to respond/adapt to further environmental changes, such as those in the sea level and the wave regime; this will decrease both resilience and the adaptation potential of the Black Sea beaches. In such cases, there will be 'no way back', as beach morphodynamics cannot be re-introduced without exposing coastal communities and ecosystems to sea flooding; thus, the Black Sea coastal zone will be committed to continuing and ever-increasing dependency on coastal erosion/flood defences, as changing environmental conditions will require regular infrastructure upgrading. Therefore, effective, efficient and integrated adaptation measures that take into consideration the above issues should be planned and implemented without delay; *ad hoc* measures are likely to create a complicated and difficult to manage system and, ultimately, increase adaptation costs.

6. Conclusions

The present study represents the first comprehensive attempt to record all Black Sea beaches and provide a rapid assessment of their erosion risk under different scenarios of SLR. Using an approach that is based on the digitisation of freely available remote-sensed images on the web, information on the spatial characteristics and other attributes (e.g. sediment type, presence of coastal defences, urban development) of all Black Sea beaches has been assembled. These data were stored and made available through the enviroGRIDS and PEGASO Spatial Data Infrastructures, allowing spatial queries, visualisation and data sharing.

In order to assess the erosion risk of the Black Sea beaches, estimations of the SLR-induced retreat of the Black Sea beaches have been obtained through an ensemble of six 1-D analytical and numerical morphodynamic models. More than 17,000 experiments were carried out using different combinations of wave conditions, beach sediment textures and slopes and 11 scenarios of SLR (up to 2 m) and the means (best fits) of the lowest and highest projections by the model ensemble were estimated; these were then compared to the maximum widths of the Black Sea beaches.

Results show that SLR may have highly significant impacts on the Black Sea beaches. Projections suggest that, in a 0.5 m SLR scenario, effects are considerable with about 56% of all beaches projected to retreat by up to 50% of their maximum width, if the high mean of the ensemble projections is considered. For a 0.82 m SLR (the high IPCC estimate for the period 2081–2100), 76% of the Black Sea beaches are projected to retreat by up to 50% of their maximum widths and about 41% of all beaches to retreat by their maximum width, whereas for 1 m SLR about 50% of all Black Sea beaches are projected to retreat by their maximum width (drowned or shifted landward), if the high mean of the model ensemble projections is used. As these results refer only to the effects of SLR and do not take into account impacts from the diminishing coastal sediment supply, the increased vulnerability of coasts associated with inlets, limans and lagoons and the effects of storm groups, they are considered to be conservative. Our results indicate beach erosion as a major environmental problem along the Black Sea coast, which therefore needs to be taken into account in any future coastal management plans, as a matter of urgency.

The results of the present study (database and projections) could assist Black Sea coastal managers and policy makers to rapidly identify beaches with increased risk of erosion, evaluate accordingly coastal assets and infrastructure, estimate beach capacity for touristic development purposes, and rapidly assess direct and indirect costs and benefits of beach protection options. They will also provide the necessary inputs to advance discussions relevant to the integrated coastal zone management of the Black Sea.

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