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Efficiency in the design of coastal erosion adaptation strategies: An environmental-economic modelling approach

Peter Roebeling[a,*], Eleonora d'Elia[b], Carlos Coelho[c], Tania Alves[d]

[a] *CESAM and Department of Environment and Planning, University of Aveiro, Aveiro, Portugal*
[b] *Department of Economics "Cognetti de Martiis", University of Turin, Turin, Italy*
[c] *RISCO and Department of Civil Engineering, University of Aveiro, Aveiro, Portugal*
[d] *Department of Environment and Planning, University of Aveiro, Aveiro, Portugal*

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ABSTRACT

Coastal zones host between 15% and 40% of the world population, important residential, tourism and port infrastructures, and a wide variety of terrestrial, aquatic and coastal ecosystems. These built and natural capitals, corresponding services and associated values may be lost due to coastal erosion. Coastal erosion adaptation strategies are frequently based on the adoption of adaptation measures at the local scale (i.e. 'best practices') – we argue that the factual costs, impacts and benefits of coastal erosion adaptation strategies are determined by the suit of adaptation measures at the landscape scale. Sustainable economic development of coastal regions requires balancing of the marginal costs and associated marginal benefits from coastal erosion adaptation strategies. In this paper, we develop and apply the Coastal Erosion Adaptation Strategies (CEAS) approach, a spatially explicit environmental-economic modelling approach that allows for the identification of efficient (welfare maximizing) coastal erosion adaptation strategies in coastal socio-ecological systems. Results for the case of groin systems along the Central Portuguese coast show that while the protection of urban as well as natural areas may be optimal from an environmental-economic perspective, budget constraints provoke the loss of natural areas in favour of the protection of urban areas.

1. Introduction

Coastal zones experience increased rates of erosion due to rising sea levels, increased storm surge frequencies, reduced sediment delivery to the coast and anthropogenic transformation of coastal areas (Nicholls et al., 1995; Nicholls, 2002; EEA, 2006; Roebeling et al., 2011, 2013). Even though the direct impacts of coastal erosion are limited to coastal areas, these areas host between 15% and 40% of the world population, important residential, tourism and port infrastructures, and a wide variety of terrestrial, aquatic and coastal ecosystems (EEA, 2006; Martinez et al., 2007). Hence, these built and natural capitals, corresponding services and associated values may be lost because of coastal erosion (EEA, 2006; Nicholls and Tol, 2006; Alves et al., 2009; Costa et al., 2009).

The IPCC identified three main strategies to respond to coastal erosion, flooding and sea level rise risks (see EEA, 2006): i) retreat is a response strategy used to limit the effect of a potential dangerous event, and implies moving and resettlement of population centres and economic activities from the coastal zone to the inland, ii) accommodation includes all strategies necessary to increase the society's resilience to natural catastrophes, including land use change, emergency planning and hazard insurance, and iii) protection involves all defence techniques used to preserve vulnerable areas, such as population centres, economic activities and natural resources.

Traditionally, coastal erosion problems and responses were assessed using civil engineering approaches, such that the physical effectiveness of coastal erosion adaptation measures was assessed without considering associated cost and benefit considerations. Over the last decades the focus of studies moved from physical effectiveness to a more holistic perspective that entails the comprehensive management of coastal zones (Integrated Coastal Zone Management, 2002/413/EC), evaluating coastal erosion adaptation measures with economic tools such as cost-effectiveness, cost-benefit and efficiency analyses (see Breil et al., 2007). Cost-effectiveness studies, that provide insight in what adaptation measures achieve coastal protection objectives at least cost, have for example been used to evaluate and compare hard (e.g. groins) and soft (e.g. artificial nourishments) engineering measures (Taborda et al., 2005; Chu et al., 2014). Cost-benefit studies, that provide insight in what adaptation measures/strategies yield largest net benefits, have been used to assess the costs (installation and maintenance), benefits

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* Corresponding author.
E-mail addresses: peter.roebeling@ua.pt (P. Roebeling), eleonora.delia23@gmail.com (E. d'Elia), ccoelho@ua.pt (C. Coelho), tania.peralta@ua.pt (T. Alves).

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(avoided costs) and net benefits (benefits minus costs) of individual and combinations of engineering measures (e.g. Turner et al., 2007; Roebeling et al., 2011; Alexandrakis et al., 2015; Martino and Amos, 2015; Coelho et al., 2016). Efficiency studies, that enable the identification of optimal adaptation measures/strategies (i.e. that provide largest net benefits and, thus, maximize welfare), have mainly been applied at the regional and global scale (e.g. Darwin and Tol, 2001; Bosello et al., 2007; Costa et al., 2009; Neumann et al., 2011) while only few have been applied at the local and landscape scale. These latter studies have the advantage that they consider local and spatially explicit coastal dynamics and environmental-economic considerations and, therefore, they can effectively contribute to the definition of coastal zone protection strategies. For example, Smith et al. (2009) and Landry (2011) analyse when and how much sediment is necessary to have an optimum artificial beach nourishment rotation, while Tsvetanov and Shah (2013) assess the optimal timing of investment in a pre-defined increase in the height of seawalls/levees.

There is growing awareness that coastal erosion adaptation strategies need to be defined using system-based approaches at the landscape scale (EEA, 2013, 2016). Suites of adaptation measures need to be identified, planned and managed integrally across time and space, so that they provide largest social, environmental and economic benefits (e.g. Roebeling et al., 2009; Marinoni et al., 2011; Carnevale et al., 2012). We argue that current coastal erosion adaptation strategies are often based on the adoption of adaptation measures at the local scale (i.e. ‘best practices’), while the factual costs, impacts and benefits of coastal erosion adaptation strategies are determined by the suit of adopted adaptation measures at the landscape scale.

Sustainable economic, welfare maximizing, development of coastal regions requires balancing of the marginal costs and associated marginal benefits from coastal erosion adaptation strategies. Hence, the objective of this study is to develop and apply a spatially explicit environmental-economic modelling approach at the landscape scale that allows for the identification of efficient (welfare maximizing) coastal erosion adaptation strategies in coastal socio-ecological systems. The Coastal Erosion Adaptation Strategies (CEAS) approach combines the shoreline evolution model LTC (Long-Term Configuration; Coelho, 2005) and environmental cost-benefit analysis techniques (Zerbe and Dively, 1994) with a combinatorial optimization approach (Souza, 2010), as to explore the types, dimensions and locations of coastal erosion adaptation measures that provide largest welfare gains.

An application is provided for the case of groin systems along a highly energetic sandy coastal stretch in Central Portugal, which is recognized as one of the regions in Europe most vulnerable to coastal erosion (EUROSION, 2004; Ferreira and Matias, 2013). Portuguese coastal zone management plans have resulted in notable coastal protection investments for the Central Portuguese coast, with an average of about 0.75 m€/yr over the period 1998 to 2012 (see Cruz et al., 2015; Coelho et al., 2016), including groins, seawalls, breakwaters, beach nourishments, sand ripping and artificial dunes (Coelho, 2005). These investments have mostly been targeted towards protection of urban areas by means of groins, and to minor extent seawalls, to trap sediment updrift and reduce sediment losses to the south (Veloso-Gomes et al., 2004; Costa and Coelho, 2013; Cruz et al., 2015). Given the extensive ecosystem service values provided by coastal areas (Martinez et al., 2007; Roebeling et al., 2013), we argue that it may have been worthwhile to protect not only urban areas but also natural areas.

The next section describes the CEAS approach and the data used for the numerical application of the CEAS approach to the case of groin systems in Central Portugal. Section 3 provides a description of the case study area as well as the scenarios considered, and Section 4 presents the results for the baseline scenario (without groin system), scenario simulations (without and with budget constraints) and sensitivity analysis (variations in costs, benefits and time discount rates). Finally, results are discussed, conclusions drawn and caveats presented.

2. Methods and data

The CEAS approach combines three components (Fig. 1): i) a shoreline evolution model, ii) environmental cost-benefit analysis, and iii) a combinatorial optimization approach. All components share a common database, containing physical, engineering, geographical and economic data and information.

In short, the shoreline evolution model LTC (Long-Term Configuration; programmed in Fortran) assesses the impact of different adaptation strategies on shoreline evolution (see Coelho, 2005) and subsequent land cover class losses (through intersection; using ArcGIS 10.4). In turn, environmental cost-benefit analysis (see Zerbe and Dively, 1994) is used to determine and compare costs (initial investment and recurrent maintenance costs) and benefits (recurrent avoided land loss costs) of adaptation strategies based on cost-benefit indicators (using Microsoft Excel, 2016). Finally, combinatorial optimization (see Souza, 2010) is used to rank adaptation strategies that provide largest welfare gains subject to an annual budget constraint (using Microsoft Excel, 2016). As an example, the CEAS approach is applied to explore the dimensions and locations of groins (i.e. groin systems) providing largest welfare gains along a coastal stretch in Central Portugal.

2.1. Shoreline evolution model

The LTC model is a numerical model that simulates shoreline evolution, and is developed to support coastal zone planning and management in relation to coastal erosion problems. LTC is used to simulate medium (10 year) to long-term (50 year) shoreline evolution patterns and resulting land cover losses, as a function of intervention measures (see Coelho, 2005; Coelho et al., 2007, 2009a, 2013). It combines a classical one-line model with a rule based model, and is designed for sandy coastlines where the main cause of shoreline evolution is the alongshore sediment transport – the latter essentially dependent on the wave regime, sediment characteristics and sediment availability. Using three-dimensional topographic and bathymetric data that are continuously updated during simulation, the model assumes that each wave acts during a certain period (computational time step) and is able to generate sediment transport.

The volumes of alongshore sediment transport are estimated using the CERC formula (USACE, 1984), that considers the breaking wave angle and height (Coelho et al., 2009a). The wave transformation by refraction, diffraction and shoaling is modelled in a simplified manner to estimate wave breaking characteristics (see Coelho et al., 2007). The variations in sediment volumes along a coastal stretch are determined by sediment transport gradients between modelled cells (defined as the coastal segments between each cross-shore profile of the numerical grid) where, similar to one-line models, sediment volume balances are defined by the continuity equation. The difference in volumes of sediment transport represents a variation in depth of points in the same profile (Coelho et al., 2007, 2013).

Considering that erosion along sandy coasts is independent of land use and that coastal protection works are maintained over time (not allowing shoreline retreat at these locations), the impact of different intervention measures on shoreline evolution can be assessed using the LTC model. In this study, the LTC model is used to assess the extent to which groin systems reduce shoreline evolution and subsequent land cover class losses over the period 2010 to 2060. For the baseline scenario without groin system ($i = none$) the position of the shoreline is determined for 2010 (current position) through to 2060, and the corresponding land area $a_{i=none,j,t}$ (in ha) per land cover class j in each period t is calculated through intersection of the respective shoreline positions with the 2010 (current) land cover map. Similarly, for any scenario with groin system ($i \neq none$) the land area $a_{i \neq none,j,t}$ (in ha) per land cover class j in each period t is calculated. Avoided land cover class losses in each period t are determined by the difference between the