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Ecosystem management tools to study natural habitats as wave damping structures and coastal protection mechanisms

J.D. Osorio-Cano*, A.F. Osorio, D.S. Peláez-Zapata

Research Group in Oceanography and Coastal Engineering, OCEANICOS, Department of Geosciences and Environment, Universidad Nacional de Colombia at Medellín, Colombia

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ABSTRACT

Tropical countries have island and continental ecosystems of great value for tourism, fisheries and also for their conservation development potential. These natural habitats, including among other beaches, seagrass beds, mangrove forests and coral reefs can dissipate wave energy acting as barriers against high waves and high water levels to eventually protect coastal infrastructure and communities. However, in recent decades, they have been subject to strong anthropic pressure and extreme events due to natural causes as well as to climate change. Therefore, the global trend is to understand the eco-systemic services that these natural environments can provide and their economic value in terms of reducing damages caused by coastal erosion and flooding. A methodological framework is presented in order to quantify the impact of natural ecosystems in coastal protection and their environmental assessment based on numerical models available in the literature. In addition to the methodology, a study of a typical Caribbean fringing coral reef and its response to different sea level rise and extreme events scenarios was conducted. The contribution of these efforts from a technological and scientific point of view, lies in the integration of different disciplines required to combine the physical properties of hydrodynamic studies with biological factors as an input to provide practical socio-economic and environmental solutions in those regions in which these ecosystems predominate. Furthermore, a numerical modeling tool to study wave energy dissipation, focusing the analysis on the impact of natural ecosystems (coral reefs) on coastal erosion and flooding was implemented. This information will help coastal managers and decision-makers understand the coastal protection services provided by nearshore habitats in order to improve and design new coastal development strategies under global change scenarios.

1. Introduction

Nowadays coasts around the world are suffering from damage caused by the pressure they are subjected to due to factors such as population increase, density and urban development, global warming and sea level rise, pollution and deterioration of water quality (Day et al., 2012; Goreau and Hilbertz, 2005; Zhang et al., 2004), leading to the loss and degradation of coastal ecosystems and their ability to protect during extreme events and climate change scenarios (Baldock et al., 2014; Quataert et al., 2015; Storlazzi et al., 2011; Wild et al., 2011). This problem has been traditionally addressed through the implementation of rigid solutions or conventional engineering structures that seek to protect against the impact of waves, prevent flooding and mitigate coastal erosion (Lamberti et al., 2005) but with important ecological impacts on natural habitats (Day et al., 2012; Martin et al., 2005).

Despite the knowledge that exists about the ecosystem services provided by coastal ecosystems (e.g., food production, provision of nursery habitat, carbon sink, recreation and tourism, among others), the use of these habitats as coastal protection mechanisms has not been entirely adopted as an engineering practice and mechanism of adaptation to climate change. Nevertheless, in the last decade research and development of ecosystem-based approaches have advanced considerably, including an improved understanding of biophysical processes and the interaction between engineering structures and coastal ecosystems (Burcharth et al., 2015; Guannel et al., 2015). Additionally, the advances in valuation, modeling and mapping of ecosystem services as well as methodological frame-

* Corresponding author at: Universidad Nacional de Colombia, Sede Medellín, Facultad de Minas, Carrera 80 No.65-223, Bloque M2-202, Medellín, Colombia.
E-mail addresses: jdosori0@unal.edu.co, osoriox@gmail.com (J.D. Osorio-Cano), afosorioar@unal.edu.co (A.F. Osorio), dspelaez@unal.edu.co (D.S. Peláez-Zapata).

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works and eco-engineering tools (Duarte et al., 2013; Sharp et al., 2016; Villa et al., 2011) have allowed the recognition of coastal ecosystems, from the engineering point of view, for their use as a coastal protection mechanism against coastal erosion and flooding (e.g., wave attenuation, shoreline stabilization, declining flood levels, etc.) in the face of global change (Ferrario et al., 2014; Guannel et al., 2015; Temmerman et al., 2013).

A few countries in Latin America (Mexico, Brazil, Chile, Colombia) have joined the idea of promoting interdisciplinary groups made up of biologists, ecologists, and engineers, to develop new strategies to replace and/or implement natural or hybrid solutions as unconventional coastal defense mechanisms, with possibilities for adaptation to climate variability and climate change (Burcharth et al., 2015; Silva et al., 2017). One of the key points on integrating processes from different research fields is about how biological characteristics (species composition and bottom roughness) from natural habitats are included into numerical models to account for wave energy dissipation and morphodynamic changes. Besides the contribution made by different authors (Duarte et al., 2013; Ferrario et al., 2014; Guannel et al., 2015; Quataert et al., 2015; Sharp et al., 2016; Storlazzi et al., 2005), there is still a lack of knowledge in understanding how different scenarios of coastal ecosystem degradation would impact coastal erosion/flooding and which management actions should be taken in order to preserve the protective services provided by the natural habitats.

For this reason, this study aims to develop and implement a methodological approach considering not only the role of biological factors in protecting coastal areas, but also the selection of an appropriate numerical model, able to describe the hydrodynamic and morphodynamic processes with a high level of accuracy. This information can be used to help decision-makers, coastal managers and other stakeholders understand the coastal protection services provided by natural ecosystems as well as to identify future research lines and coastal development strategies.

The present study is structured as follows: Section 2 presents a summary of the main ecosystem assessment frameworks and tools, which are available to scientists (engineers, biologists, and ecologists), managers and administrators to study coastal ecosystems as wave energy dissipation structures and coastal protection mechanisms. Section 3 presents a methodological framework for the study of coastal ecosystems based on the implementation of numerical models as mechanisms of analysis and decision making based on technical/scientific knowledge and in Section 4 some of these tools are applied (use of a numerical model) to understand the role played particularly by coral reefs in wave dissipation and its impact on coastal erosion and flooding. Finally, the discussion and conclusions are presented in Section 5 and 6 respectively.

2. Ecosystem assessment frameworks and tools

Based on the recent interest in the importance of valuing the ecosystem services provided by the different natural habitats (Duarte et al., 2013; Ferrario et al., 2014) a great variety of support tools that integrate ecology, economics and geography have emerged for managers and decision makers. In general, the main objective of these kinds of models is to produce functions using simplified underlying biophysical models or “ecological production functions” (Bagstad et al., 2013) that define how changes in an ecosystem's structure and function are likely to affect the flows and values of ecosystems services across lands or seascapes. In Bagstad et al. (2013) a comparative analysis of 17 different ecosystem services tools is presented, with particular emphasis on describing each tool with its applications, modeled services, analytical approaches, inputs and outputs of the models as well as the time required to execute them. The comparison is made based on eight evaluative criteria, including: 1) Quantification and uncertainty. 2) Time requirements. 3) Capacity for independent application, 4) Level of development and documentation, 5) Scalability, 6) Generalizability, 7) Nonmonetary and cultural perspectives, 8) Affordability, insights, integration with existing environmental assessment. Some of those ecosystem services tools that can support an integrated ecosystem assessment to inform decision-making globally and at multiple scales are: Integrated Valuation of Ecosystem Services and Tradeoffs – InVEST (Kareiva et al., 2011; Sharp et al., 2016); Artificial Intelligence for Ecosystem Services – ARIES (Bagstad et al., 2011; Villa et al., 2011); LUCI – formerly Polyscape (Jackson et al., 2013); Multi-scale Integrated Models of Ecosystem Services/Marine Integrated Decision Analysis – MIMES/MIDAS (Boumans et al., 2015); Ecosystem Portfolio Model – EPM (Labiosa et al., 2013); among others. More details about each model, their performance, limitations and scale of modeling can be found in Bagstad et al. (2013).

It is also important to mention that, through its nearshore wave and erosion module, InVEST represents the only model among the aforementioned ecosystem modeling tools which fully addresses the contribution of natural habitats (e.g., mangroves, seagrass, coral reefs, oyster beds) to coastal protection. In this way, this tool is able to preliminarily quantify the impact of a particular wave boundary conditions on coastal erosion and flooding, considering a deterministic wave propagation model and taking into account the main hydrodynamic processes (e.g., wave energy dissipation due to wave breaking and bottom friction, wave setup, wave run-up). InVEST is an open source tool based on mapping and valuing goods and services provided by ecosystems as natural barriers against erosion and flooding (Guannel et al., 2015; Sharp et al., 2016). The valuation includes social preferences and allows the estimation of economic and social metrics based on the differences in damage due to erosion and flooding under different scenarios. Therefore, the cost of the avoided coastal erosion and further storm damages can be used as an indicator of the value of those coastal ecosystems.

Besides the fact that InVEST model may support management decisions demonstrating the protective capabilities of natural habitat, it also presents important limitations such as (Sharp et al., 2016): (i) non-linear processes in wave propagation are being ignored; (ii) extreme events such as storm surges are being underestimated; (iii) since the model is a 1D process-based tool, it ignores any complex wave transformations that occur offshore of the site of interest; (iv) an option to calibrate is not offered; (v) simple empirical equations are used to compute the wave profile, wave setup and wave run-up; and finally (vi) when erosion processes occur, the dynamic response and feedback between wave and bed profile during the storm is not taken into account. Despite all these disadvantages which may be overcome through the use of more robust hydrodynamic and morphological models as suggested in the methodology approach that is presented in Section 3, InVEST can still be applied for a first preliminary assessment of the hydrodynamic and morphodynamic performance of habitats.

With the implementation and improvement of all these ecosystem management tools, the aim is to identify coastal ecosystems with potential to be incorporated into traditional coastal protection schemes, based on analysis that allows them to evaluate under which conditions they can protect against erosion and coastal flooding. In this sense, the interaction between engineers, biologists and ecologists is of great importance as the knowledge of each discipline may contribute to optimize the functionality of these ecosystems and motivate ecological restoration processes. Similarly, inputs are obtained to quantify the degree of degradation or renewal of ecosystems before and after an extreme event and their impact on the ecosystem services they typically provide (Duarte et al., 2013; Ferrario et al., 2014) for comparison with traditional defense structures.