ECOSYSTEM-BASED ADAPTATIONS FOR STEPPED REVETMENTS: AN APPLICATION TO STRAND, SOUTH AFRICA

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Abstract

Conventional hard coastal structures such as stepped revetments have significant environmental impacts. This paper investigates how a conventional stepped revetment can be adapted to mitigate or to reduce its environmental impacts. As a first step, the potential environmental impacts of a conventional stepped revetment are identified. Considering these impacts, possible ecosystem-based adaptations are proposed. Since the feasibility of these adaptations will differ from site to site, a case study is selected to investigate the implementation of an ecosystem-based stepped revetment. The study site and its environmental and ecological conditions are described. A discussion on the site selection for the implementation of a possible ecosystem-based stepped revetment is also included. Finally, an ecosystem-based stepped revetment is proposed for the study site.

1 Introduction

Even though there has been a shift towards the implementation of soft shoreline protection measures, hard coastal structures still form a vital component of coastal protection strategies. Hard coastal structures have generally been designed with little or no consideration of their potential impacts on the environment. One solution to address this shortcoming in the traditional design procedure is to incorporate ecosystem-based adaptations for traditional coastal structures.

A stepped revetment is classified as a hard coastal structure (non-erosive). From a coastal engineering point of view, the main advantage of a stepped revetment (in comparison to a smooth slope revetment or dike) is that the steps on the revetment create roughness elements which results in a reduction of wave run-up and wave overtopping. In addition, a stepped revetment is multi-functional. It can be an aesthetical coastal protection measure that promotes tourism and recreation by providing access to water areas, creating walkways and/or serve as a bench (Figures 1 and 2). An economic advantage of a stepped revetment is that the steps can be constructed with precast concrete elements. Stepped revetments are typically applied as coastal structure in cities, where available space is constrained.

One main disadvantage of a conventional stepped revetment is its potential environmental impacts. However, ecosystem-based adaptations to a conventional stepped revetment can mitigate or reduce its environmental impacts.

2 General

2.1 Objectives

The overall objective of this research is to develop ecosystem-based adaptations for stepped revetments to mitigate or to reduce its environmental impacts. General adaptations will be considered. However, the environmental, ecological and social conditions of the site, where the structure will be implemented, have to be taken into account in order to develop optimal ecosystem-based adaptations for a specific case. A study site in Strand, South Africa was selected as a case study to consider the implementation of an ecosystem-based stepped revetment. (Note that the author has not been involved in the design and construction of the seawall that is presently (July 2017) being built at the Strand. Neither have the designer and contractor of the seawall been part of this hypothetical case study.)

The paper defines the scope of the research and gives an overview of previous studies on stepped revetments. The prospective methodology to reach the research objectives is described. The focus then shifts to the case study for Strand, South Africa. A description of the Strand study site and its environmental and ecological conditions are presented. Social conditions at a study are also very important, but are not in the scope of this study. Finally, an adaptation for a stepped revetment for the case study is proposed.

Figure 1: Stepped revetment at Margate, United Kingdom

Figure 2: Stepped sea organ at Zadar, Croatia

2.2 Background

The traditional thinking of engineers often causes them to perceive environmental considerations as a 'chore' that comes as part of the profession. When an engineer has this mind-set, optimal and innovative coastal engineering solutions, which are also favourable or less harmful to the environment, will not be achieved. Since research on stepped revetments is ongoing, it is possible to include environmental considerations for stepped revetments in the development of design guidelines.

This research aims to complement the research project *waveSTEPS*. Project *waveSTEPS* is funded by the German Federal Ministry of Education and Research (BMBF) through the German Coastal Engineering Research Council (KFKI, 03KIS118 and 03KIS119) and focusses on the development of design guidelines for conventional stepped revetments. The investigation to develop an ecosystem-based stepped revetment is not within the scope of project waveSTEPS and is the focus of this paper.

2.3 Definitions

For this paper a stepped revetment is defined as a coastal defence constructed parallel to the coast to reduce the impacts of waves. A conventional stepped revetment is defined as an impermeable concrete structure typically located at the back of a beach (Figure 1) or at waterfront areas (Figure 2).

For a design water level, wave height and wave period, the crest level for a stepped revetment will be determined by the allowable wave run-up or wave overtopping. Wave run-up is defined as the maximum vertical distance above the still water level, to which a wave rushes up on the stepped revetment. Wave overtopping occurs when wave action discharges water over the crest of the stepped revetment and is defined as the discharge of water (m^3/s) over 1 meter of crest length.

In [1], two approaches are described, whereby ecology is integrated into coastal protection measures. The first approach is to use ecosystem engineering species that change their environment. An example of the first approach is to use organisms (such as mussels or seagrass) to trap sediment and to attenuate waves. The second approach is to adapt coastal structures to enhance local biodiversity and ecosystem functioning.

The focus of this paper will only include the second approach. Therefore, the adaptations to a conventional stepped revetment are aimed at enhancing the ecological value of the structure. Only ecosystem-based adaptations in small (<10 cm) to medium (1-10 m) spatial scales will be considered. Microscale adaptations such as building material composition and surface roughness are not within the scope of the research [2].

2.3 Previous studies on stepped revetments

Research on stepped revetments has a history of more than 60 years. A thorough summary and evaluation on this research history of stepped revetments is provided by [3]. Through the literature review, which includes almost 30 publications, [3] identified a number of areas where additional research on stepped revetments are required.

Firstly, no comprehensive study could be identified that conducted physical model tests on a wide range of dimensionless parameters. Due to different scales and boundary conditions of the model tests, it is not possible to develop empirical predictions for wave run-up, wave overtopping, and the wave impacts. Therefore, there is a need for systematic research to provide generic design guidelines for stepped revetments. The knowledge gaps identified by [3] were the research motivation for the comprehensive study of [4].

[4] conducted an experimental and theoretical study of the wave-induced response of stepped revetments. Physical model tests were conducted for a large range of geometric and hydraulic boundary conditions. Based on these model tests, [4] derived empirical predictions for wave reflection, wave run-up, wave overtopping, and the wave loads of stepped revetments.

Although [4] presents predictions applicable for a wide range of dimensionless parameters, there are still certain ranges of boundary conditions with little or no data points. The project *waveSTEPS* aims to focus on these certain ranges of boundary conditions. Another uncertainty is the scale effects that the model tests are subjected to. As part of *waveSTEPS,* the scale effects will be assessed by conducting full scale model tests.

The development of ecosystem-based adaptations for stepped revetments complements the present research and will raise new research questions for future research.

3 Methodology

This section describes the methodology that was followed to achieve the research objectives. As a first step, the general potential environmental impacts of stepped revetments are described. This step is important to consider, since the ecosystem-based adaptations aim to mitigate or to reduce the environmental impacts.

Once the key environmental impacts have been identified, three possible adaptations will be considered based on literature research. Since the adaptations will differ from site to site, the study site at Strand, South Africa is considered. A description of the environmental and ecological conditions for Strand is given. These conditions are taken into account in order to select the most suitable adaptation for the study site, which is the final step of the methodology.

4 Results and Discussion

4.1 Environmental impacts

Environmental impacts are defined as any modifications (deliberate or accidental) made to the environment and/or biological resources by anthropogenic activities [5]. When environmental impacts are considered it is important to take into account that these impacts are subjected to different spatial and temporal scales. For this research, only impacts in terms of the local spatial scale (1-10 km) are considered, since the ecosystem-based adaptations are aimed to reduce or to mitigate environmental impacts on the local scale.

A stepped revetment will cause changes to the coastal environment in terms of wave conditions and sediment transport (erosion and deposition patterns). In the case of a stepped revetment, constructed along a shoreline that experiences long-term net erosion, the shoreline will migrate landward resulting in loss of beach width. The revetment also interrupts the sand supply between the beach and backshore which influences the cross-shore transport processes. The changes in the sediment transport also impacts the characteristics in terms of grain size, content of organic matter, and redox conditions [5].

The changes of the coastal environment in turn affect the composition, abundance, and trophic structure of the benthos [5, 6]. The construction of a stepped revetment will also result in a loss of soft-bottom habitats and associated fauna and flora as well as result in an increase in (artificial) hard-bottom substrata [5]. Fish and mobile fauna are to be affected as well. When a stepped revetment is built in an environment, which has mostly sandy habitats, changes in the local biodiversity can be a consequence [5, 7].

4.2 Ecosystem-based adaptations

This section considers three possible adaptations to conventional stepped revetments to reduce or mitigate the environmental impacts of stepped revetments. The suitability of the adaptations should be based on the environmental, ecological and social conditions of a specific site, and should consider whether the functionality of the structure is retained (coastal safety, recreational value, multi-functionality, providing safe access).

4.2.1 Incorporating vegetation

To provide habitat and to improve aesthetical value of stepped revetments, sections of native vegetation can be incorporated to the steps on the revetment. The incorporation of vegetation in combination with harder material is one of the principles of the broad term 'living shorelines' [8]. One disadvantage of this adaptation is that the construction of such a stepped revetment with vegetated sections can be challenging. Good monitoring and maintenance is required, especially as it is uncertain if the vegetation growth will be successful.

4.2.2 Porosity sections

Adding porosity to a stepped revetment has the benefits that wave run-up can be reduced and habitats can be created. However, adding porosity to a stepped revetment by means of rock-filled sections can have a negative impact on a stepped revetment's recreational function, as rough structures are not convenient to sit or walk on. As an alternative, porosity can be added by incorporating a prototype habitat enhancement unit as the BIOBLOCK. The BIOBLOCK offers multiple habitat types while simultaneously dissipating wave energy [2].

4.2.3 Rock pools

Artificial rock pools can be added to coastal structures to add habitat to hard coastal structures [2, 7]. Not only can the rock pools add intertidal habitats and increase the diversity of species, but also a recreational feature to the coastal structure.

4.3 Case study

4.3.1 General

Strand is located on the north-eastern coast of one of South Africa's largest natural bays (approx. 1000 km^2), False Bay (Figure 3). The Bay's opening is orientated to the south and situated in the Atlantic Ocean.

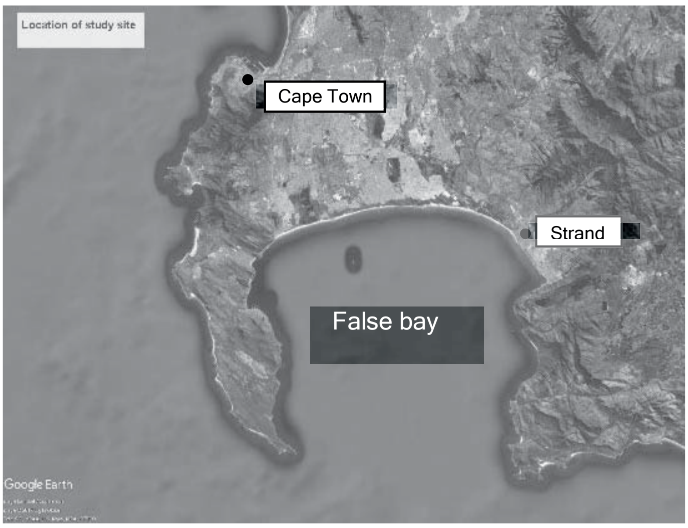

Figure 3: Location of Strand in the north-east of False Bay

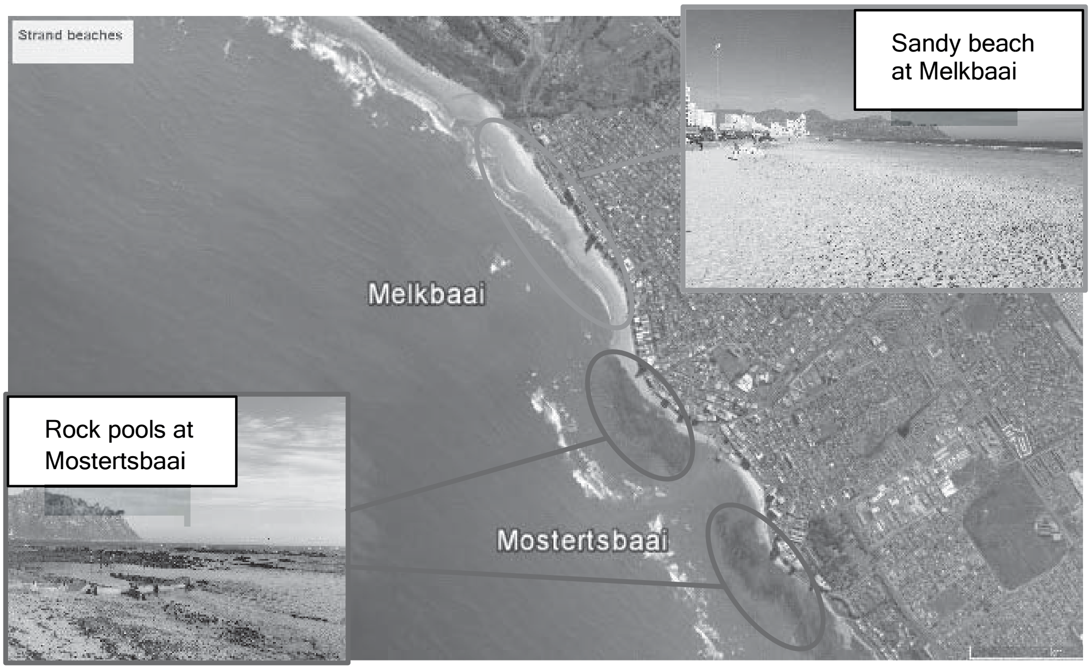

Figure 4: Location of Strand's beaches

The coastal town of Strand has a population of over 55,500 people [9]. Strand attracts many locals and tourists to its popular recreational beaches, Melkbaai and Mostertsbaai (Figure 4). Melkbaai, the northern beach, stretches over approximately 1.5 km. The beach is sandy and offers good conditions for swimming and other recreational activities such as kitesurfing. Mostertsbaai is characterised by its rock reefs and is popular for fishing and exploring the sea life in the rock pools.

Strand's coastline is regularly subjected to storm events. A scenic road, Beach Road, and an adjacent promenade stretch along the coastline (Figure 5). High rise buildings are located landwards along Beach road. The present coastal defences comprise natural sand dunes, vertical seawalls and recurved seawalls. The natural dunes along the coastline have been damaged due to human intervention and, therefore, do not provide sufficient safety. The vertical seawall was constructed in the 1940s and originally designed to prevent wind-blown sand from the dunes to reach the adjacent pavement and road [10]. Therefore, the vertical seawall was not designed to offer protection against overtopping. Since the dunes are damaged and the vertical seawall has reached the end of its design life, the coastline is left vulnerable to storm events.

The pictures presented in Figure 6 are not an uncommon sight along Strand's coastline and illustrate the severity of the wave overtopping events.

In order to address the hazardous wave overtopping events that Strand experiences, coastal protection measures need to be implemented. One possible coastal protection measure is to implement a stepped revetment. A stepped revetment would provide safe access to the beach while simultaneously protecting the hinterland from overtopping.

Figure 5: Promenade and Beach Road along Strand's coastline

However, in 2016, the refurbishment of the seawall along Strand’s coastline commenced, which will take place in three project phases. Phase 1 is currently under construction. The new coastal defence is a recurved wall constructed from precast elements (Figure 7).

Even though Strand’s municipality already selected a new coastal defence strategy, the hypothetical case study for implementing a stepped revetment at Strand is valuable. Strand with its sandy beaches, partly rocky shoreline and abundant marine life make it a representing location for a case study to investigate ecosystem-based adaptations for stepped revetments.

In the next subsections, the environmental conditions (wind, waves, and beach characteristics), ecological conditions (habitats and species) as well as the site selection for the ecosystem-based stepped revetment will be discussed.

Figure 6: Wave overtopping events at Strand

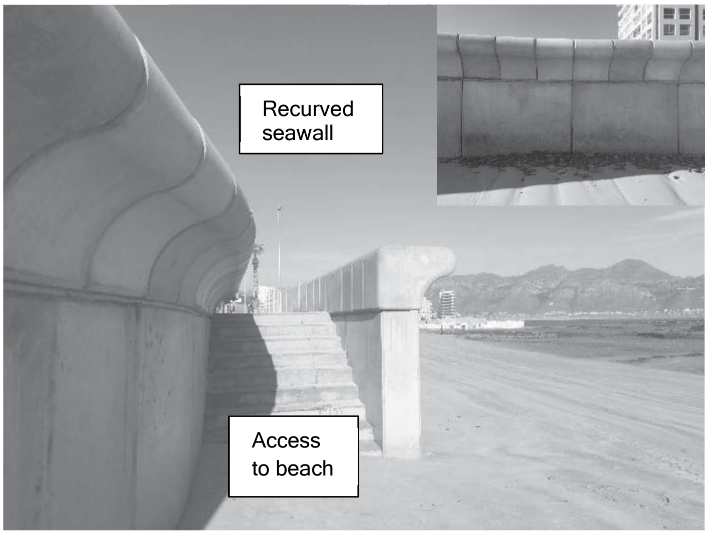

Figure 7: New recurved seawall

4.3.2 Environmental conditions

Strand is not only known for its beaches but also for being windy. It is estimated that Strand annually experiences only between 14.6 to 18.3 percent of the time calm conditions, i.e. defined as wind velocities below 8.6 m/s [11]. During winter, Strand predominantly experiences northerly wind conditions, while during the other seasons a south-easterly wind is dominant [10]. Based on 11 years of wind measurements, the average wind speed is 4 m/s [10].

Strand experiences semi-diurnal tides with mean spring tidal range of approximately 1.5 m [12].

Strand's coastline is mostly exposed to waves from a south-westerly (SW) to south-south-westerly (SSW) direction. The mean nearshore significant wave height at 15 m below the Mean Sea Level (MSL) is 1.13 m, while the significant wave height with a 1 year return period at 15 m below MSL is 3.40 m with a peak wave period of 13 s [11].

The beaches at Strand are on average between 30 and 100 m wide and characterised by mild beach slopes. The average beach slope is approximately 1:67. As a consequence, the beaches have wide surf zones. The sediment at the study site is classified as fine with a mean diameter of D_{50} = 0.15 mm [11].

Furthermore, the beaches of Strand are classified as dissipative. In other words, most of the wave energy is dissipated in the surf zone. Dissipative beaches are characterised by their finer sediments, mild slopes, wide surf zones, and wide beach widths. This classification, therefore, confirms the beach characteristics of Strand as described above. In addition, dissipative beaches have multiple lines of breakers, which are also distinctive in Strand [11].

The potential for aeolian sand transport is high because of the wide beaches and the windy conditions.

4.3.3 Ecological conditions

(This section is not meant as a complete or comprehensive overview of the ecology. It gives rather few facts that can serve as background for the case study, enabling engineers to apply adaptations.)

The Strand coastline offers habitat to a vast array of species. The habitats are divided into two types; namely sandy beaches and rocky shores.

Sandy beaches are dynamic systems as they are continuously influenced by wind, waves and currents. Three main zones can be distinguished for sandy beaches: the surf zone, the beach (including the intertidal and backshore zones) and the dunes. Dune vegetation is essential as it stabilises dunes while simultaneously providing habitat for beach fauna. The moist areas between sand grains provide habitat to meiofauna, which is important for breaking down organic matter and recycling nutrients. The intertidal zone is habitat to a large number of species, including plough snails, sand mussels and crabs. Offshore the sandy beach, zooplankton as well as a variety of fish species can be found [13, 14].

The rocky outcrops along Mostertsbaai serve as habitat to a number of species. The rock habitat can be divided into four distinct zones: the infratidal, the cochlear, the balanoid, and the littorina zones. The infratidal is habitat to sea urchins, mussels, starfish etc., and is only exposed above water during extreme low tides. The cochlear zone is located between low water neap and low water spring tide. This zone is named after the organism, which is most common in this zone, the pear limpet (*Scutellastra cochlear*). The balanoid zone is covered by high tide twice a day and offers habitat to mussels, anemones and barnacles. The last zone, the littorina zone, is the uppermost zone and is located between high water spring tide and high water neap tide. The most common organism in this zone is the *Littorina* snail. These rocky reefs are also habitat to a number of fish species including the Roman (*Chrysoblephus laticeps*) and Galjoen (Dichistius capensis) [13, 14].

4.3.4 Site Selection

To minimise the effect of a stepped revetment on the Strand environment, it is important to investigate what the most suitable location for such a coastal structure would be. A description of the current coastal defences along the coastline of Melkbaai and Mostertsbaai follows.

Figure 8 indicates the three different zones along Melkbaai. The northern part of Melkbaai, indicated as Zone A is protected by vegetated dunes and a vertical seawall. The vertical seawall is located on the landward side of the dunes. Currently, this zone offers sufficient coastal safety.

Zone B offers inadequate protection since the dune system has been damaged and the crest level of the seawall is too low. In addition, the seawall has reached the end of its design life.

Figure 8: Coastal defences along Melkbaai's coast

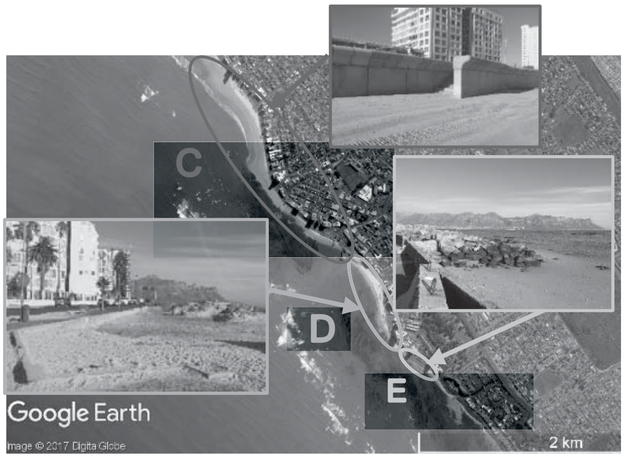

Figure 9: Coastal defences along Mostertsbaai's coast

The newly constructed seawall is located in Zone C (Figures 8 and 9). The seawall consists of a recurve sited on top of a vertical wall. The wall is constructed of precast concrete units. Zone D offers insufficient coastal safety, as the seawall has a very low crest level (Figure 9). Zone E is protected by a rock revetment, which stretches over approximately 150 m and is located seawards of the original seawall. This rock revetment was implemented as emergency temporary protection measure after a storm in 2008. This protection is currently still in place [10].

When selecting the most suitable site for a stepped revetment, a number of aspects need to be considered. (Note the aspects mentioned here is not an exhaustive list.) Firstly, the stepped revetment has to be able to provide sufficient coastal safety at the particular site for the design wave conditions and water level. In addition, the local conditions such as available space, the beach level and the level of the hinterland, should be considered. As the promenade along the beachfront is popular for tourism, the line of site to the beach for promenade and road users should preferably not be affected. Furthermore, as the stepped revetment will provide access to the beach and promote tourism, the structure should be implemented at an attractive location for recreation. Aeolian sand transport is another aspect that should be taken into consideration in the site selection. Moreover, the selected site should also be based on, where the environmental impacts would be a minimum. In the case of Strand, it should be considered that along some stretches of the coast, and where there is space, it would be more beneficial to restore the damaged dune system. As the focus of the present research is to develop ecosystem-based adaptations for stepped revetments, and not to provide design recommendations, the only criteria for the site selection will be the minimisation of environmental impacts.

One hypothetical location for a stepped revetment has been selected (Figure 10). The developed ecosystem-based adaptations for stepped revetments will be considered for this location. The selected location is situated along the rocky outcrops in Mostertsbaai. This location is popular for walking at the rock pools as well as swimming in the tidal pool (location indicated in Figure 10). This particular location was selected for its recreational value and the potential low environmental impacts of the stepped revetment in this location than along the sandy beaches.

Figure 10: Possible locations to implement a stepped revetment

4.3.5 Selection of ecosystem-based adaptation for study site

In order to select the most suitable adaptation for the study site, the environmental, ecological and spatial conditions of the study site are taken into account. The adaptations to include porosity or rock pools would be the most suitable options as the selected location is characterised by rock habitats with no significant vegetation at the particular site. As the addition of porosity to the stepped revetment can have negative impacts on the recreational value of the stepped revetment, the option to include artificial rock pools in the stepped revetment is the preferred adaptation for the selected location. Furthermore, the rock pools can add additional recreational value to the structure and potentially offer the best resemblance to the current rock habitats. The rock pools offer mitigation by creating novel habitats.

5 Conclusions

The research investigates how the ecological value of stepped revetments can be increased by including ecosystem-based adaptations to conventional stepped revetments. Potential environmental impacts of stepped revetments have been described and three potential ecosystem-based adaptations were proposed. Only small to medium adaptations are considered. As the feasibility of the adaptations is subjected to conditions and characteristics at a particular location, a site at Strand, South Africa was selected as hypothetical location to implement a stepped revetment. The most suitable adaptation for the selected location has been identified to include artificial rock pools in the stepped revetment. The rock pools offer novel habitats and imitate the existing natural rock pools found along the coastline.

It is recommended that further research should be done for the detail design of the rock pools in order to determine the quantitative impacts of rock pools on coastal safety and the ecological value of these structures.

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COASTAL ECOSYSTEM SERVICES PROVIDED BY CORAL REEFS AT TESORO ISLAND, COLOMBIA

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Abstract

Coral reefs are coastal environments along a large number of world's coastlines, which constitute protection against sea waves and provide shelter and food for at least 25% of the ocean species. Pressure from tourism, fishing and recreation are among the anthropogenic activities that generate high impacts over the conservation and preservation of these natural habitats. Understanding the ecosystem services provided by coral reefs is fundamental for determining their value and contribution for reducing damages due to human actions combined with the effects of natural extreme events and climate change, which also contributes to coastal erosion and flooding hazards. A lack of knowledge currently exists in Latin American countries for the quantification of ecosystem services provided by coral reefs and the appropriate methodologies to support decision-makers and coastal managers. For this purpose, the current work considers a multidisciplinary approach aiming to combine results from hydrodynamic studies with biological factors, particularly regarding wave-transformation processes and energy dissipation under normal and extreme wave climate conditions. A typical fringing reef from the Colombian Caribbean Sea is selected as case study to quantify specific ecosystem services for practical socio-economic and environmental solutions in those regions, in which coral reefs predominate.

1 Introduction

Tourism, fisheries and ecosystem conservation have a large economic and environmental impact in tropical countries both islander and continental coastal ecosystems (e.g., coral reefs, beaches, seagrass beds, and mangrove forests). These natural habitats provide several ecosystem services such as coastal protection, fishing, navigation, food, and shelters. Wave energy dissipation is among the hydrodynamic processes in coral reefs relevant for its contribution to the ecosystem services as protecting barriers against waves under different water levels, and eventually protects