The power of wave energy converters arrays to mitigate coastal erosion

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I. Introduction

In recent decades, energy demands has increased considerably. According to the International Energy Agency, global energy demand is expected to grow by 2.1% per year between 2021 and 2026 [1]. However, only 28% of the global energy matrix comes from renewable resources [2] [3]. This scenario shows that, we are heavily reliant on fossil fuels which are a major source of greenhouse gas emissions. We need to make a transition from fossil fuels to renewable energy resources in order to achieve a sustainable development that requires an actualization of our models of governance and different methods of energy production.

While numerous governments are currently engaged in research and development initiatives on alternative energy sources, it is crucial to emphasize the importance of global replication of these efforts [4] [5] [6] [7]. The utilisation of marine energy derived from wind farms, tidal currents, and wave converters holds great potential in addressing the gaps within the global power generation supply [8] [9] [10].

Wave energy converter (WEC) are devices that convert the energy in the waves into electricity. WECs can be deployed in arrays or wave farms to increase the range of wave reception and optimize the use of materials such as submarine cables to transmit the generated electricity to land. WECs have been tested on the coast of many countries, such as the UK [11]; Portugal [12]; China [13]; Italy [14]; Japan [15]; USA [16]; Spain [17]. However, data regarding their impact on the environment is still scarce. One of the main coastal features that is exposed to impact by WECs is the nearshore bathymetry [18].

There are several works regarding the effects of WECs on sediment transport and beach morphology, [19] [20] [21] [22] some experimental [23], [24]. In [25] the performance of different WEC arrays is discussed, along with their effects on coastal erosion due to the cumulative forces of waves, currents, and tides.

The variety of WEC configurations and arrays has been the object of study [26], since the sets configurations and the distance between the WECs directly influence the energy production due to the reflection and refraction processes generated by the devices. An optimal layout is chosen to establish a WEC matrix to maximize power conversion and offer the opportunity for infrastructure to protect the coast and generate power from clean, sustainable sources.

The present research focuses on determining the beach response to the hypothetical placement of a WEC array off the coast at Riohacha, in northern Colombia, by computing the modified wave field produced. For this, the wave module of the Delft-3D model was tuned to estimate the extraction and transmission of wave energy by each WEC. Then, the XBeach model was used to calculate the nearshore wave field and the evolution of the coastline.

Section and subsection headings should have only the first letter and proper nouns in capitals, not each word capitalized or all uppercase. The first word of the first section is capitalized, with the first letter as a "drop cap" spanning two lines.

II. Methods

The study area

The study area includes the beaches of Riohacha (La Guajira Department), located in the Colombian North Caribbean (Fig. 1a). The coast's morphology is diverse, with straight beaches formed by the sustained action of the marine conditions and coastal process. Several sectors present coastal wetlands with well-defined tidal channels that maintain their hydraulic capacity in equilibrium [27]. Some of the beaches of Riohacha have experienced considerable erosion in recent years and to mitigate erosion, contingent actions have been taken, including the

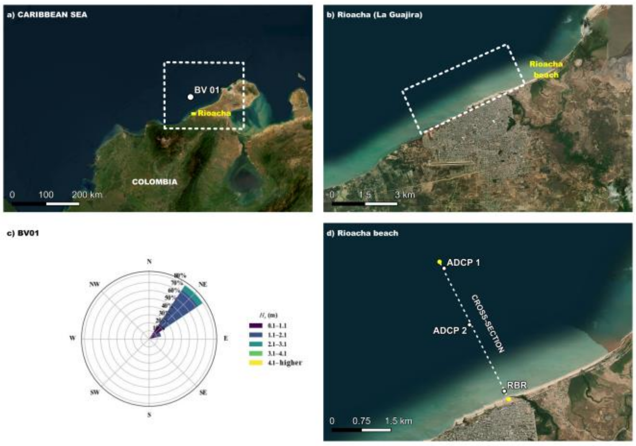

Fig. 1. a) Geographical location of Riohacha and the virtual buoys within the Colombian central Caribbean (VB01: 11° N, 73° W). b) Location of Riohacha beaches in Riohacha respectively. d) Wave roses for the maritime climate over the last 40 years in Riohacha (VB01). d) Field campaigns sensors array scheme of Riohacha.

construction of hard coastal works. However, these measures have only exacerbated the problem. Riohacha's beaches are characterized by the presence of 7 groins and an emerged breakwater (Fig. 1b).

The hydro-climatology of this region is shaped by the movement of the Intertropical Convergence Zone (ITCZ), which is a belt of low pressure belt that encircles the earth near the equator. The ITCZ migrates seasonally between northern and southern hemispheres, influencing the climatic patterns of the Colombian Caribbean. As a result of this movement, the region experiences a bimodal climate regime with two dry seasons (December–March and June–July) and two wet seasons (April–May and August–November) [28]. The displacement of ITCZ plays a significant role in determining the seasonal variations in rainfall and overall weather patterns in the area.

The waves on these beaches are heavily influenced by the trade winds in the Colombian Caribbean, and they tend to be more energetic through the dry seasons. Generally, 60 % to 70 % of waves come from the northeast (Fig 1c). Waves coming from the east-northeast and north have less influence, representing a probability of occurrence of 5–10% for each direction. Waves traveling from remaining directions represent only 20% of the total, and most of them are generated by local winds [28]. The studied beaches are classified as microtidal, with tides ranging from 0.2 to 0.3 m [29].

Field data

Hydrodynamic and morphological data were collected from beaches at Riohacha in the 2021 rainy season (November), using a pressure sensor (RBR) and two current profilers (ADCP), Fig. 1d. The current profilers were set to burst mode, with measurements at a frequency of 1 Hz, while the pressure sensor was programmed with a sampling rate of 1 Hz in continuous mode. The hydrodynamic data collected in the field survey were divided into 1-h sea states.

Table I

WEC configuration, transmission coefficient (Kt) and reflection coefficients (Kr) analyzed at 1.3 km from shoreline

Case study	Geometrical configuration	Kt	Kr
Csb	without matrix	0.7	0.35
Cs1	linear - parallel	0.7	0.35
Cs2	semicircular - perpendicular	0.7	0..35
Cs3	semicircular – oblique	0.7	0.35

Wave conditions: significant wave height (Hs =1.5 m), peak period (Tp = 6.5 s), direction (θ = 70°),

Modelling cases

A numerical simulation was carried out to estimate the beach profile response and the wave transformation under different wave train scenarios. XBeach was chosen for its capability of determining sediment grain distribution, owing to hydrodynamic forcings. The different modelling cases consider the influence of boundary definition, taking into account the wave and tide action on the beach. One of the goals of this simulation was to establish the scenarios that activate the sediment transport dynamics. To quantify the impact in coastal protection, as well as the reduction in installation and maintenance costs of a WEC array, three scenarios were considered, of different settings and orientations at 1.3 km from shoreline (see Table I).

The simulated WEC farm was composed of a two-row, WaveCat array, of 8 and 7 WEC units, respectively. The spacing between the WECs was 230 m according to [21] [22] [23] [30]. In their investigation, found that the effects of the WECs on the flow are described by the generation of eddies and the flow wake at the rear of the devices, which create turbulence processes. The results indicate that the effects of turbulence propagate towards the coast at distances of 2.5 and 4 times the width of the devices. In this case, the width (B) corresponds to 90 m, therefore a value of 230 m was chosen between the devices, with distances of 180 m between the different elements.

To simulate the WEC-wave interaction with the Delft-3D model, the presence of an obstacle Matrix of porous layers with a constant reflection/transmission coefficient throughout the obstacle was indicated

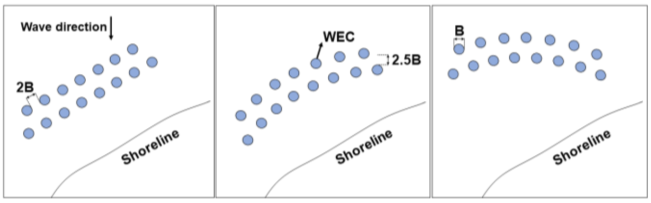

Fig. 2. The three WEC farm orientations, at a distance of 1.3 km from the coast. a) Case study Cs1. b) Case study Cs2. c) Case study Cs3.

III. Results

In this work numerical modelling was used to evaluate coastal erosion processes, and assess the interaction of

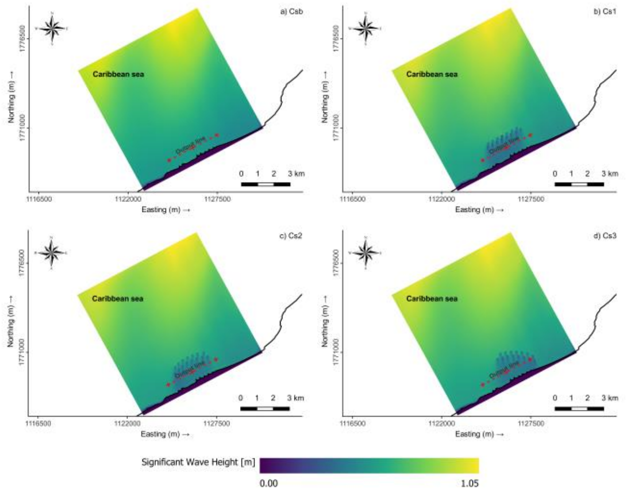

Fig. 3. Significant wave height [m] in the baseline scenario and with the WEC farm at a distance of 1.3km for different configurations. a) Case study Csb. b) Case study Cs1. c) Case study Cs2. d) Case study Cs3.

WEC farms in wave transformation, hydrodynamics and morphology changes on the coast.

The baseline scenario correspond to the situation without the wave park. The wave park for various configurations at 1.3 km from shoreline, were analysed the significant wave heights near the shore to validate their efficiency in wave energy transformation (see Fig 3).

The Delft-3D model results clearly demonstrate that different configurations have distinct effects on wave behavior. The linear and perpendicular arrangements, aligned with the coastline (Cs1), significantly influence the transformation of wave fronts, resulting in enhanced coastal protection. Oppositely, the semicircular and perpendicular (Cs2) arrangements exhibit a lesser protective effect and are therefore not as effective in stabilizing the coastal profile.

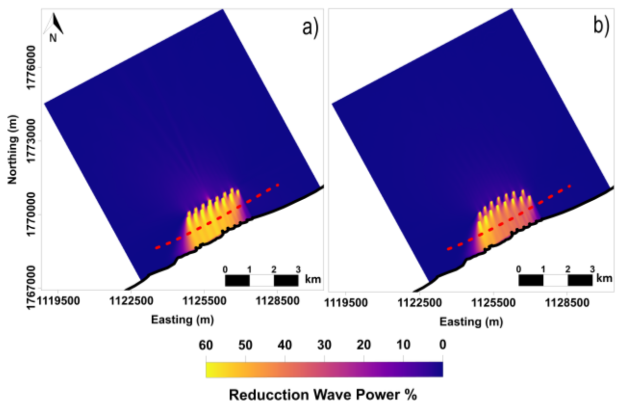

Fig. 4. Reduction of the wave power (%) with the wave farm at a distance of: 1.3km a) Cs1. b) Cs2.

The results reveal that the most substantial decreases in wave energy occur in the second row of the linear array, with reductions of up to 50% (Fig. 4a). Similarly, at a distance of 400m from the second row in the first case, the greatest reduction is 45%. This reduction is attributed to wave transmission induced by the first and second rows of devices. The semi-circular configuration (Fig. 4b) exhibits lower efficiency compared to the linear scenario, resulting in a lesser reduction in energy potential.

In Fig. 5, two profiles are shown representing different sections of the beach after the analyzed storm. These sections were identified based on their distinct responses to the storm: (i) the northeast section of the beach (P1 in Fig. 5) is characterized by the presence of groins. The intertidal zone in this section has a gentle slope, and there are dunes formed as a result of sediment retention by the groins and (ii) the southwestern section of the beach (P2 in Fig. 5) is also a cliff area, but without the presence of protection structures. The mean sea level in this section was above the foot of the cliff.

In the profile P1 the main erosion occurred on the face of the beach, and the eroded material moved to the submerged beach. Instead, in the profile P2 erosion was detected at the foot of the slope, but it was not deposited in the submerged beach.

In the comparison between scenarios, the wave farm Cs1 caused greater reduction of the erosion along the beach than the other scenarios, in which areas with significant reductions of erosion were combined with negligible values or even accretion.

IV. DISCUSSION & CONCLUSION

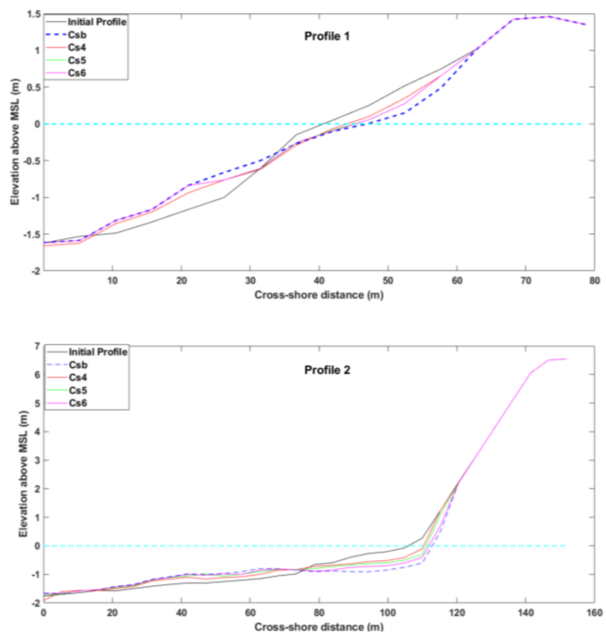

Fig. 5. Profiles P1 and P2: initial profile (black line) and at the end of the storm in Csb baseline scenario (dashed blue line) and with the wave farm Cs1 (red line), Cs2 (magenta line) and Cs3 (green line).

Nearshore WEC array have the dual function of extracting wave energy and protecting against coastal erosion, as they influence wave and sediment dynamics. As there are limited numerical methodologies concerned with the potential impacts of such farms, this research proposed a coupled numerical method to quantify the reduction in magnitude of wave heights, the area of wake influence, morphodynamic and beach profile evolution.

In this analysis, the location of the WEC array was carefully considered to beat a balance between energy harvesting and shoreline protection. The optimal location was determined to be 1.3 km from the coast at a depth of 6-8 m. Subsequently, different configurations and orientations of offshore devices at this location were examined.

The first case (natural condition - Csb) served as a baseline to understand beach behavior during the evaluated storm event without a WEC farm. In the linear configuration (Cs1), where devices were installed parallel to the beach, substantial reductions in wave energy and coastal erosion were observed, covering a width of 2.8 km along the coast. The mean reduction in significant wave height was 35% (depicted by the suspended red line). For Cs2 (semicircular configuration), an average reduction of 25% at the shoreline was observed, with coastal erosion mitigation effects extending along a 3.8 km area of the coast.

From the results of this research, the degree of coastal protection provided by a WEC farm varies significantly depending on its distance from the coast, layout, and orientation to the coastline. Therefore, an important key element during the selection of WEC park, are the layout and location of the devices to transform wave trains and reduce the dynamic of the profile evolution, mainly during the storms. And at the same time, it is possible to obtain energy from the ocean for populations that live in remote areas, according to the United Nations (UN) that established the framework for Community Based-Adaptation.

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