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Numerical modelling of the wave energy in Galway Bay

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ABSTRACT

A coupled modeling system was implemented to characterize the wave conditions and assess the wave energy potential at Galway Bay using WAVEWATCH IIII (WWIII) for wave generation and deep water propagation and SWAN model for wave propagation in intermediate and shallow water. Wind fields were taken from ECMWF's ERA Interim data base. Validation tests were carried out for the period between 2007 and 2010 with buoy data so that the model's performance could be evaluated.

The wave parameters considered for the comparisons in the time domain are significant wave height and mean period. Statistical analysis of the results is made and its time series evolution is also presented. For the energy assessment an evaluation of the spatial distribution of wave power is done and, since Galway Bay is a quarter scale test site for wave energy devices, statistical results were presented for three years of data, providing statistics of the expected wave energy resource in the Bay.

1. Introduction

The wave power industry is developing, but this sector needs experimentation and demonstration of feasibility of the various concepts. The limited experience with many of the concepts and devices being developed makes it possible to form only an incomplete picture of the full output that can be obtained by wave power devices. There are also difficulties facing wave power developments, related with the knowledge of the long term availability of wave power and with the structural loading in the event of extreme weather conditions. On the other hand, the advantages of wave energy are obvious, and this has been reflected in the variety of solutions and equipment that is under development [1].

The wave climate off the West coast of Ireland is one of the most energetic in the world. The average annual wave height in deep waters off the Mayo/Donegal coast is over 3.5 m, with a period of close to 10 s. In winter months the figures are much higher. In energy terms, theoretical wave energy resource for January regularly exceeds 150 kW/m length [2]. When considering how much of this theoretical energy could be captured and converted into electricity, it is important to consider the constraints associated with WEC.

Various wave energy technologies are currently being developed based on different principles. The different systems may be classified according to their proximity to the coastline as shoreline, nearshore and offshore systems [3]. To decide where to deploy WECs or how to choose a test site, the wave climate must be analyzed. Real data can give a general idea of the existing conditions, but there are some limitations due to the fact that the time period of measurements may be limited. This issue may be resolved by using a system that is able to predict the wave characteristics in various locations for whatever period of time, and it can be done with numerical models. Several authors have used numerical models to predict wave energy resources, as mentioned later in this paper. However, the assessment of the wave resource needs, then, to be combined with information about each WEC, so as to yield information about the energy really captured [4,5].

The characterization of the wave climate has been done before for other purposes, namely navigation and harbor, coastal and offshore engineering. In the context of the HIPOCAS project [6], 44-year wave hindcast for the North East Atlantic European coast has been performed by Pilar et al. [7]. The hindcast wave model WAM was used. The output parameters were significant wave height, wave direction, mean and peak period, wind speed and direction, *Hs* for wind sea, direction of wind sea, *Tm* for wind sea, *Hs* for swell, direction for swell and *Tm* for swell. For nearshore evaluation, the previous study was complemented by another one developed by Rusu et al. [8], which couples numerical models WAM and SWAN. However the information output from the studies mentioned before does not coincide with what is needed in wave energy utilization planning and design. Therefore, the system coupling WAM

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and SWAN was afterwards used to produce estimates of wave energy in coastal areas [9–11].

The present paper is part of a wider effort to characterize the wave energy in the Atlantic coasts of Europe, in particular in the test sites for wave energy devices. Within the same European project, studies were done by Bento et al. [12–14], Gonçalves et al. [15,16] and Silva et al. [17] in order to assess wave energy potential for various European coastal areas. In all these studies the wave conditions in were simulated by coupling the wave models SWAN and WAVEWATCH III. Different wind fields were considered in these studies: NCEP's Reanalysis 2, ECMWF (European Center for Medium Range Wave Forecast) ERA 40 and ERA- Interim data bases and MM5's downscaling results. Validation tests were carried out with buoy data and specific test sites were analyzed, such as Galway and Belmullet in Ireland's case [12], Cornwall and Pembrokshire in UK's [13] case, Le Croisic, in the coast of France [15] and Gran Canaria Island, in Spain [16]. For the Spanish coast only a qualitative evaluation was made, regarding the spatial distribution of wave energy [14]. However there are several other studies available about the conditions in Spain such as Iglesias and Carballo [18] and the references indicated there. All the studies referred, considering different winds and areas, culminated in a final paper that describes the common methodology for all areas, in order to allow a consistent comparison of wave energy potential between the different Atlantic coastal areas [19] avoiding thus that differences are the results of different methods of analysis instead of different climatological conditions.

Both SWAN and WWIII, coupled or not, have been used by various authors, making wave energy evaluations around the globe. Randi et al. [20] developed a WWIII hindcast study with surface winds from ECMWF providing 10 years of spectral wave data around the world. Stopa et al. [21] used WWIII to produced boundary conditions for the SWAN model and then obtain 10 years of hindcast data from a system of mesoscale atmospheric and spectral wave models in order to quantify the wind and wave climate as well as nearshore wave energy resources in Hawaii. Here, surface winds to force WWIII were taken from the Final Global Tropospheric Analysis (FNL) which reproduces the swell and seas from the far field, while the high-resolution wind fields implemented in SWAN were produced by the Weather Research Forecast (WRF) model. Regarding the SWAN model, Liang et al. [22] implemented it to simulate wave parameters of the Shandong peninsula in China for a 16 years hidncast. The wind parameters used to simulate waves were obtained by the WRF model.

In order to improve the evaluation strategy of the potential wave power that can be extracted at a given sea site, Barbariol et al. [23] have implemented the SWAN model in the northern Adriatic Sea, in particular in the Gulf of Venice. The model was coupled with the Regional Ocean Modeling System (ROMS [24])on the same computational grid. The atmospheric forcing was provided by the high-resolution model COSMO-I7 [25].

In this paper, the focus will be the performance analysis of a wave prediction system for an enclosed bay, coupling two wave models, WWIII and SWAN, having a fine grid inside the closed area of Galway Bay. This prediction system aims to reproduce Galway's Bay wave conditions and its wave power potential. Most studies mentioned have been applied to open coastal areas, with not so intricate bathymetries or barriers to the propagation of waves in enclosed spaces, such as a bay. Considering also that the Bay is used as a test site for ¼ scaled WECs, it is also important to have an idea of where to deploy these prototypes, as they too have restrictions about the type of wave climate needed for testing. It has also been shown by Ashton et al. [26] that there is spatial variability of wave conditions within a marine energy test site and that should be assessed and taken into account. The site has an area of 37 ha with depths ranging from less than 30 m up to 70 m and tidal range of 4 m. A natural barrier is formed by the Aran Islands, protecting the Bay from the open Atlantic Ocean, linking with the ocean only through four channels. The dynamics are a result of the oceanic flows to the bay from the adjacent shelf; freshwater discharges, primarily from the River Corrib; and wind driven currents. The entry and exit of water through the sounds of Galway Bay may be significantly affected by wind speed and direction along with tidal effects [27]. Due to its semi-enclosed nature (Fig. 1), the site usually experiences favorable conditions, defined by local, fetch-limited wind seas, with swell waves entering from the west and southwest. According to the HMRC report [28], these wind seas provide a good representation, at quarter scale, of the wave climate that would be expected at exposed Atlantic Ocean locations. This unique relationship provides users of the site with the ability to easily extrapolate test results to predict the performance of commercial-scale devices in the open ocean. There are currently a number of wave energy devices being tested in the Galway Bay test site, on the west coast of Ireland, for quarter devices. Since this test area was established in 2006, it has hosted successful sea trials by WEC developers Ocean Energy and Wavebob [29]. For this reason it is important to be able to predict accurately the level of wave energy inside the bay so that the performance of wave energy devices can be properly assessed as described in Silva et al. [5].

2. Modeling the wave climate in the Irish west coast

The wave prediction system implemented consists of the coupling of two models: WW III model [30] and SWAN model [31], which are full-spectral third generation wind-wave models. WWIII was developed at the Marine Modeling and Analysis Branch (MMAB) of the Environmental Modeling Center (EMC) of the National Centers for Environmental Prediction (NCEP) while SWAN was developed at Delft University of Technology. Both models solve the spectral action balance equation, which determines the evolution of the action density in space and time. The action density is defined as energy density divided by wave frequency and the energy density is specified using the linear two dimensional wave spectrum, with wave energy distributed over frequency and propagation direction.

$$\frac{\partial}{\partial t}E + \frac{\partial}{\partial x}C_x E + \frac{\partial}{\partial y}C_y E + \frac{\partial}{\partial \sigma}C_\sigma E + \frac{\partial}{\partial \theta}C_\theta E = \sum S$$

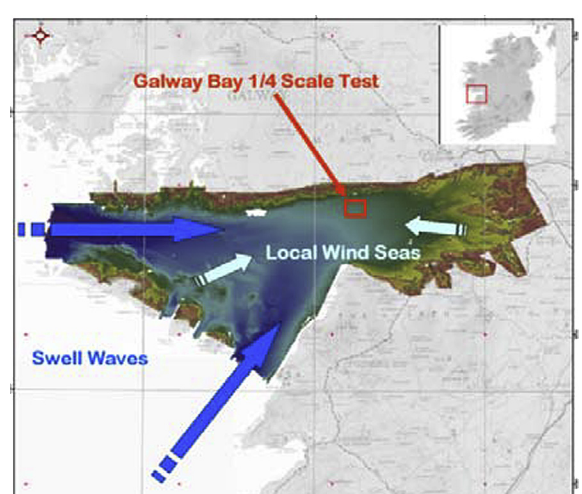

Fig. 1. Location and bathymetry of the ¼ scale wave energy test site in Galway Bay.