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Tidal stream energy impacts on estuarine circulation

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ABSTRACT

Among the impacts on the marine environment associated with the operation of a tidal farm, the alteration of the transient and residual flow velocities must be assessed in detail, for they constitute the driving force of important environmental processes such as sediment and pollutant transport, and nutrient dispersion. The objective of this study is to assess the impacts caused by the operation of a tidal farm on the transient and residual flow by means of a case study: a tidal stream farm in Ria de Ribadeo, an estuary in NW Spain. For this purpose a 3D numerical model of the estuary is implemented and successfully validated based on field data of tidal levels and flow velocities. The energy extracted by the tidal stream farm from the flow is accounted for by adding a momentum sink term in the equations of the model. Two scenarios representative of typical winter and summer conditions are considered. The results show that the disturbances to the transient flow patterns are concentrated in the proximity of the farm, with a weakening of the flow upstream and, especially, downstream of the farm (up to 0.25 ms^{-1}) and an intensification on both sides (up to 0.10 ms^{-1}). As for the residual flow, we find that the operation of the tidal farm does not disrupt the complex 3D residual circulation of the ria, but it does lead to modifications of the residual flow of up to 0.025 ms^{-1}, or approximately 10% of the baseline residual flow, which affect a much larger area than in the case of the transient flow (up to approximately 2 km from the farm). The repercussions of these alterations of the transient and residual flow patterns of the estuary for its sedimentary and biological processes warrant further research. Overall, these results confirm the importance of assessing the impacts of a tidal stream farm on the flow.

1. Introduction

As a result of the problems associated with the traditional energetic model, the contribution of renewable energy sources to the total energy production has been increased over the last years [1–6]. Initiatives such as EU's 20-20-20 program [7], which aims to supply 20 percent of the energy demand with renewable energy by 2020, are inscribed in this context. In order to achieve these goals the energy mix should include marine energies [8], among which tidal stream energy is one of the most promising [9–11].

The conventional exploitation of tidal energy is based on tidal barrages that use the potential energy generated from sea level variations to generate electricity. The best tidal barrage power plant in La Rance (France), with an installed capacity of 240 MW [12], is a good example. Tidal stream energy arises as an alternative to exploit the tidal resource for its advantages in terms of environmental impacts and investment costs [13,14]. It harvests the kinetic energy contained in the tidal currents by means of Tidal Energy Converters (TECs) placed directly in the flow. Tidal streams are generated in coastal regions by the tide-driven variation of the sea level and can be locally amplified by the coastline shape and bathymetry. Despite a growing interest over the last years, which is reflected in the resource assessments carried out [15–19], tidal stream energy is still in its first stages of development with only a few projects in operation and TEC technology still evolving [12].

In addition, the understanding of the potential impacts on the marine environment of the extraction of energy from the tidal flow is far from complete. Recent research has shown that the operation of a tidal farm may alter both the transient and residual circulations [20,21]. These alterations may be noticeable at considerable distances from the farm, from tens to hundreds of kilometers for the transient and residual circulation, respectively; consequently, numerous variables related to the circulation patterns such as sediment transport rates, pollutant dispersion and nutrient concentrations may be affected [22–28]. Moreover, the 3D circulation patterns that are present in many estuaries [29,30] may also be altered by the operation of a tidal farm.

The present study assesses the 3D impacts of a tidal stream farm on the transient and residual circulation of an estuary in a case study: Ria de Ribadeo, Galicia (NW Spain) (Fig. 1). Rias are

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Nomenclature

A	cross sectional area of turbine rotor (m^2)
c	salinity or temperature (transported substance)
C_T	thrust coefficient
C_{2D}	2D-Chézy coefficient
C_{3D}	3D-Chézy coefficient
C_d	dimensionless drag coefficient
d	local water depth (m)
D_h	horizontal eddy diffusivity ($m^2\ s^{-1}$)
F_x	x component of the flow retarding force per unit volume (N)
F_y	y component of the flow retarding force per unit volume (N)
f	Coriolis parameter
g	gravitational acceleration ($m\ s^{-2}$)
H	total water depth (m)
M_x	x component of the momentum generated by an external force (N m)
M_y	y component of the momentum generated by an external force (N m)
n	manning coefficient
Q	intensity of mass sources per unit area ($m^2\ s^{-1}$)
R	source term per unit area
u	eastward component of the flow velocity ($m\ s^{-1}$)
$\vec{U}_{10}$	wind velocity at 10 m height above the sea surface ($m\ s^{-1}$)
$\vec{u}_b$	horizontal velocity in the bottom layer ($m\ s^{-1}$)
U	flow velocity ($m\ s^{-1}$)
V	volume of control (m^3)
v	northward component of the flow velocity ($m\ s^{-1}$)
w	vertical component of the flow velocity ($m\ s^{-1}$)

Greek

Δz_b	vertical distance from the seabed to the computational grid (m)
κ	von Karman constant
ζ	water level (m)
λ_d	first order decay process
ρ_o	water reference density ($kg\ m^{-3}$)
ρ	seawater density ($kg\ m^{-3}$)
ρ_a	air density ($kg\ m^{-3}$)
$\vec{\tau}_s$	Wind stress on the sea surface ($N\ m^{-2}$)
$\vec{\tau}_b$	shear stress at the bottom ($N\ m^{-2}$)
υ_h	horizontal eddy viscosity ($m^2\ s^{-1}$)
υ_v	vertical eddy viscosity ($m^2\ s^{-1}$)

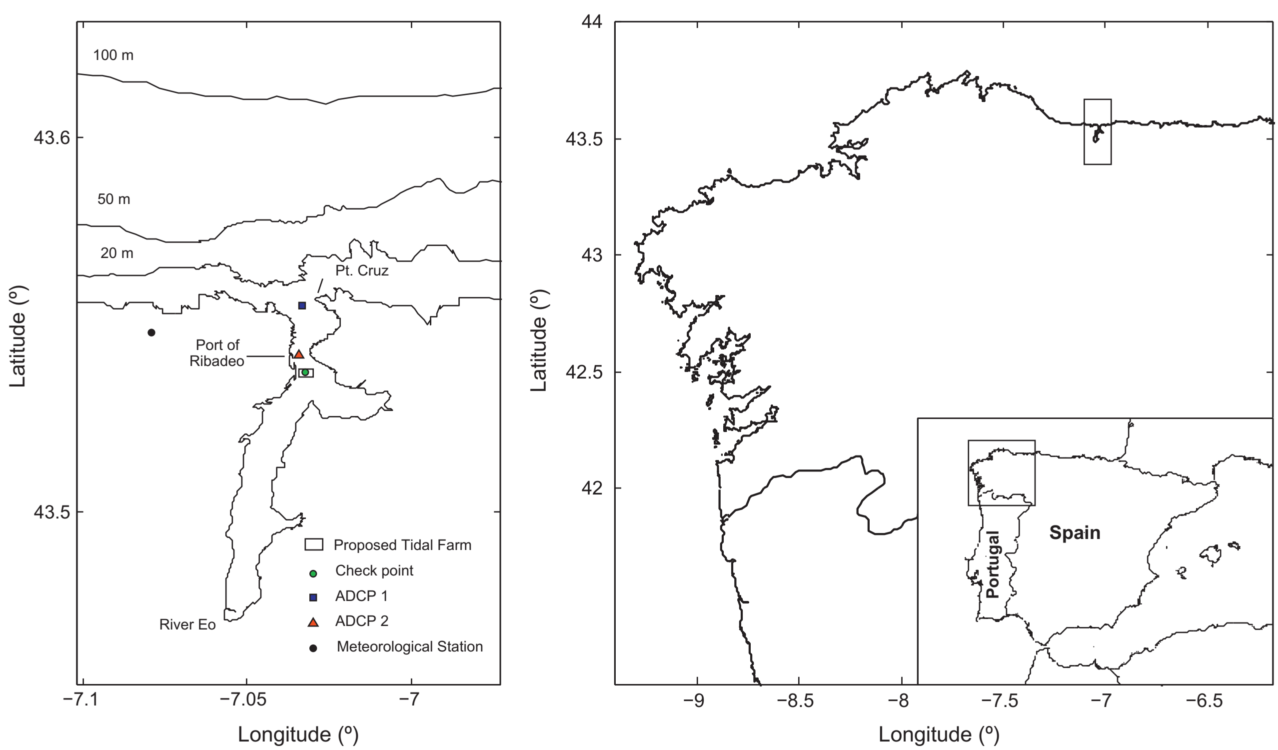

Fig. 1. Location of Ria de Ribadeo (left) in NW Spain (right).

inundated fluvial valleys [31], a particular type of estuary in which sediment deposition has not kept pace with sea level rise, so that the coastline and bathymetry very much reflect the geometry of the river valley from which they stem. Galician rias are classified into two groups, Rias Altas and Rias Baixas, according to their tectonic predetermination [32], Ria de Ribadeo belonging to the first group. The morphologic characteristics of Ria de Ribadeo alongside its substantial tidal range, up to 4.6 m in spring tides, combine to produce strong tidal currents in certain areas of the ria [28]; therefore, Ria de Ribadeo constitutes an excellent location for installing a tidal stream farm and to assess the potential impacts on the estuarine circulation.

This work investigates the impacts of a tidal farm not only on the transient circulation of the ria, but also on its residual circula-