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Tidal stream energy impact on the transient and residual flow in an estuary: A 3D analysis

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HIGHLIGHTS

- The impact of a tidal stream plant on the estuarine hydrodynamic was analysed.
- A 3D model was used to determine the hydrodynamics on the estuary.
- The model was successfully validated with field measurements.
- A momentum sink was introduced in the model equations to simulate energy extraction.
- The alteration on the 3D transient and residual circulation is presented.

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ABSTRACT

The interest in the exploitation of the tidal stream energy has increased significantly over the last years and several tidal farms have been proposed. In spite of this, only a few studies dealt with the potential impacts on the environment resulting from the extraction of this energy, most of them by using 2D numerical models. However, some of the areas of interest for tidal stream exploitation, such as the Galician Rias, present complex transient and residual circulation patterns which in turn result in one of the largest oceanic productivities in the world and whose potential changes cannot be properly studied by means of 2D models. In this work, a 3D numerical model was implemented in Ria de Ortigueira, a promising region for tidal stream energy exploitation, to study the potential flow changes due to the operation of a power plant, including the assessment of the potential impacts on the 3D residual flow in a real estuary. First, the model was validated on the basis of current velocity measurements, then, it was used to describe the potential effects resulting from the operation of a previously proposed tidal stream farm during typical winter and summer conditions. For this purpose, the momentum sink approach was used. Overall, it was found that the resulting transient flow modifications were concentrated in the area occupied by and next to the farm, with nearly negligible effects outside the inner ria. Furthermore, important asymmetry effects were also observed; although the inner part of the estuary is flood dominated, the most important effects occur during the ebb as a result of the complex geometry of this area. Finally, the effects on the residual flow are of the same order, in terms of percentage of velocity variation, as in the case of the transient flow; however, they extend over a wider region, affecting the middle ria, where a complex 3D circulation pattern (a positive estuarine circulation) develops. Nevertheless, the operation of the tidal plant is not capable of modifying the general 3D flow structure in this area.

1. Introduction

During the last years there has been an increasing interest towards the exploitation of marine energies and, in particular, of tidal energy. In the past, the extraction of this type of energy was based on the barrage approach, in which the water level differences between ebb and flood were used to generate electricity. Nevertheless, the environmental consequences derived from the installation of a barrage in an estuary, together with the associated costs, cause the attention to be currently focused on its kinetic energy or tidal stream energy [1].

Tidal stream energy is intended to be exploited in regions of high tidal currents (in excess of 1 ms^{-1}) [2]. In Europe more than 100 potential sites, most of them being located in the UK [3], where current velocities above 2 ms^{-1} have been identified. Nevertheless, these locations are not only restricted to sites with high tidal range [4]. Channel constrictions within coastal areas with medium to

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high tidal range, as is the case of specific locations in the Galician Rias [5–7] can also represent interesting locations for tidal stream energy exploitation.

At present, there are different types of Tidal Energy Converters [8,9], among which Tidal Current Turbines seem to be the most promising solution to efficiently harvest this kind of energy [10,11]. This technology is developing quickly and as a result there are already several projects in commercial stage. The growing interest also explains the great number of resource assessments [5–7,12–16] conducted in the last decade with the aim of evaluating the tidal power available and to determine the most powerful locations for its exploitation. However, only some studies dealt with the potential impact on the system as a result of energy extraction [17–21].

Nevertheless, although the impact of tidal stream farms is expected to be much less than that of a barrage, there are numerous environmental variables likely to be altered. Recent research has shown that a high power plant may produce a modification of the transient circulation as far as tens of kms away from its location and of the residual circulation as far as a 100 km away [21]. This is of particular interest in the case of the Galician Rias, where their complex residual circulation patterns have shown to result in one of the largest oceanic productivities in the world [22]. Furthermore, the environmental variables driven by the currents that are altered are numerous, the most important being the sediment dynamics, the nutrient dispersion and pollutant concentrations. Furthermore, it is necessary to note that the estuarine circulation commonly presents a 3D behaviour, at least in its middle and outer areas, as is the case of the Galician Rias [23–26]. Therefore, its modification as a result of tidal energy exploitation should be analysed by means of 3D modelling; in spite of this, only very limited studies included a 3D model [14,27,28]. In particular, the alteration on the residual flow has been only previously analysed through 3D modelling in an idealised estuary [28].

Ria de Ortigueira (Fig. 1), an estuary delimited in the Galician coast by Cape Ortegal and Pt. Estaca de Bares, has been shown to offer a great potential for tidal stream energy exploitation as a result of its tidal range (maximum of 4.5 m) and complex morphology. The ria has two important constrictions where the highest current velocities occur. One is located to the East, between the main part of the ria and the Ladrido Anse, and the other to the West in its inner part, in the narrow channel in front of Pt. Postiña, and identified as a promising site for tidal stream exploitation [30]. The present study investigates the environmental impacts of tidal energy extraction in Ria de Ortigueira.

For this purpose a 3D numerical model, Delft3D-FLOW, which simulates the tidal energy extraction by incorporating a momentum sink in model equations, is implemented and validated in the area of interest. After validation, the model is used to determine the potential impacts of tidal energy extraction on the transient and residual flow.

2. Methodology

2.1. Model description

Delft3D-FLOW is an open source finite difference code, widely used to investigate coastal hydrodynamics, in particular, the hydrodynamics conditions in semi-enclosed water bodies like rias, estuaries and inlets [5,23–25,29–32]. It solves the 3D baroclinic Navier–Stokes and transport equations [33], which under the shallow-water and Boussinesq assumptions read:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=Q, \tag{1}$$

$$\left.\begin{aligned}\frac{Du}{Dt}&=fv-g\frac{\partial \zeta}{\partial x}-\frac{g}{\rho_0}\int_{z'=z}^{z'=\zeta}\frac{\partial \rho}{\partial x}dz'+\upsilon_h\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\upsilon_v\left(\frac{\partial^2 u}{\partial z^2}\right)\\ \frac{Dv}{Dt}&=-fu-g\frac{\partial \zeta}{\partial y}-\frac{g}{\rho_0}\int_{z'=z}^{z'=\zeta}\frac{\partial \rho}{\partial y}dz'+\upsilon_h\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\upsilon_v\left(\frac{\partial^2 v}{\partial z^2}\right)\end{aligned}\right\}, \tag{2}$$

$$\frac{\partial p}{\partial z}=-\rho g, \tag{3}$$

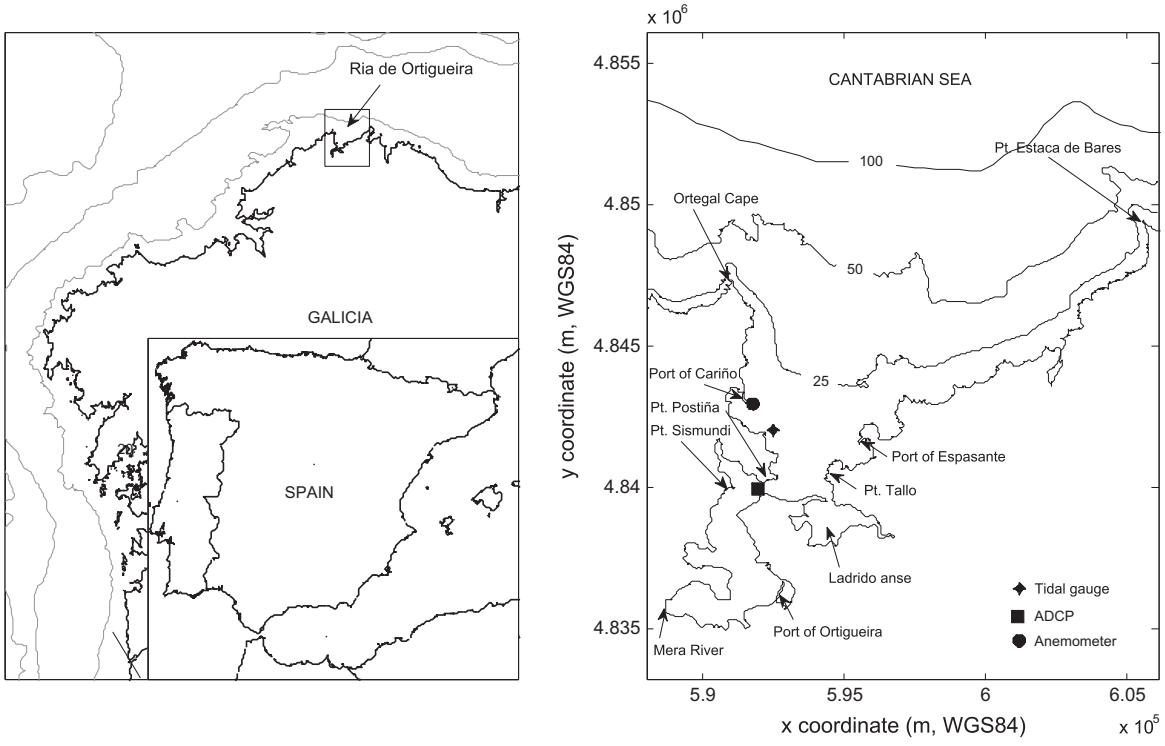

Fig. 1. Location of Ria de Ortigueira in the North of Spain.