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Research Article

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Tidal current energy potential of Nalón river estuary assessment using a high precision flow model

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Abstract: Obtaining energy from tide currents in onshore locations is of great interest due to the proximity to the points of consumption. This opens the door to the feasibility of new installations based on hydrokinetic microturbines even in zones of moderate speed. In this context, the accuracy of energy predictions based on hydrodynamic models is of paramount importance. This research presents a high precision methodology based on a multidimensional hydrodynamic model that is used to study the energetic potential in estuaries. Moreover, it is able to estimate the flow variations caused by microturbine installations. The paper also shows the results obtained from the application of the methodology in a study of the Nalón river mouth (Asturias, Spain).

1 Introduction

Ocean energy is still in its infancy; however, the high amount of distributed resource around the world has attracted the interest of the main energy actors. At the end of year 2015, different countries had ocean test sites and different policies to stimulate the development of this new industry [1].

Tidal current, is a predictable energy resource that results from the filling and emptying of coastal regions. In the recent years obtaining electrical energy from tidal currents has been the objective of intense investigation using designs based on adaptations of wind turbines [2]. The first approach has been based on high-power turbines (>1MW) in off-shore locations. This implies high investments as well as operation and maintenance costs resulting in a poor feasibility scenario [3].

Historically, the most common way to harness the energy from the tides is based primarily on tidal dams that take advantage of the potential energy of the tides. Although this technology can be considered fully developed, the exploitation of these facilities has significant repercussions on the environment, which often directly affect the ecosystem. All this together with the high costs of construction and maintenance of these projects [4], has resulted in only five operating tidal dams so far. This includes France (La Range, 240 MW), Canada (Annapolis, 20 MW) and South Korea (Sihwa Lake, 254 MW).

In order to take advantage of the amount of energy provided by our coasts, during the last decade, a line of more rigorous research emerged on the design of tidal current energy devices based on wind turbine designs, called hydrokinetic microturbines [5]. But the installation and maintenance costs have not been reduced yet; so their use is reduced to specific areas with a large volume of generation.

Recently, microturbine arrays in on-shore locations (even in low velocity sites), obtaining energy where it is consumed, is presented as a feasible alternative [6, 7]. In this scenario, having an accurate estimation of the tidal flow energy potential to assess the correct array location, is a key factor to guarantee its feasibility [8]. Examples of developments are the Maine project in the Bay of Fundy (Canada) and the RITE project in New York.

The prototypes are suitable for locations on land where high kinetic energy can be exploited (due to the influence of tides) with a significant reduction of the effects on the environment and investment and operating costs. Its convenient location makes it possible to use the energy generated in nearby energy loads [9].

Up to now, the studies of tidal flows have been carried out using different numerical models (with regard to the codes used and equations solved). There are many examples of one dimensional (1D) [10], two dimensional (2D) [11] and three dimensional (3D) [12] studies. However,

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they have focused on extensive areas with low resolution meshes (>100 m).

This investigation presents a precise estimation of optimal sites for array installations in the estuary of Nalón river (Spain) [13]. For this purpose, a multidimensional open-source code with an accurate mesh is used. Additionally, the effect of the installation of a row of microturbines has been evaluated. It continues from a first basic approach using a one dimensional code [7].

2 Hydrodynamic Model Code

The free, open-source Delft3D-FLOW code [14] has been used. The model solves the Reynolds Navier-Stokes (RANS) equations for an incompressible fluid under shallow water and Boussinesq assumptions. It allows to include the effects of tides, wind, atmospheric pressure, density differences (due to salinity and temperature), waves, turbulence and Coriolis forces, with optional sediment transport and morphologic modules.

It is a multi-dimensional code, which can be used for 2D or 3D calculations. In 2D mode, the code solves a set of three equations: one continuity equation and two momentum conservation equations in the horizontal plane. In 3D mode, the code solves a third momentum conservation equation for the vertical direction. In this equation, the vertical acceleration is neglected which leads to a hydrostatic pressure equation.

These governing equations, in combination with the appropriate initial and boundary conditions, are solved using a finite difference ADI scheme over a structured grid of quadrangles with an orthogonal curvilinear coordinate system. This meshing technique is handy because the boundaries of river, estuary or coastal regions are generally curved and are not faithfully represented by rectangular meshes, which can induce discretization errors. For 3D models, the vertical direction is discretized with a sigma-type coordinate system, in which each layer thickness is defined as a fixed proportion of the total water depth. The number of layers in the vertical direction is constant for the entire study area.

The flow can be forced by tides in the open boundaries, pressure gradients due to the free surface gradient (barotropic) or density gradients (baroclinic). Source and sink terms are included in the equations to model the discharge and withdrawal of water.

The code has also parallel computation capabilities through automatic domain decomposition, reducing computational times on multi-core processors and computational cluster.

3 Model implementation

The coastline was digitized from georeferenced satellite images using an UTM 21N coordinate system. Using Deltf3D utilities, the computational domain, which covers the last 7 Km of the Nalón river up to the estuary mouth, was meshed with a total of 43.000 quadrangular elements, with cell sizes between 5 and 10 m (Figure 1). The vertical direction was discretized using a single cell, with the code running in 2D mode.

A digital elevation model for the bottom was constructed by interpolating the cross sections of a previously constructed HEC-RAS model [7]. The resulting depths, relative to the mean sea level plane are presented in Figure 2.

Bottom roughness was modelled using the Manning equation, with a fixed coefficient of 0.03. A free slip boundary condition was used for lateral walls.

The tests consisted of simulating the river estuary hydrodynamics through one year (2013). Two boundary flow forcing boundary conditions were applied: tidal level on the river mouth (downstream condition) and flow rate of Nalón river (upstream condition).

The tidal levels were interpolated from hourly data records obtained from the tide gauge REDMAR Gijón2, between January 1 and December 31, 2013. The tidal amplitude has a magnitude of up to 4 m.

Flow rates of the Nalón River were only available as monthly averages, as recorded by the tide gauge 1346 in Grado. Hence, those flow rates were kept constant for the duration of each month. Mean monthly flow rates range from 14.5 on October to 91.0 m^3/s on December. More detail about this boundary conditions may be found on [7].

The whole year 2013 was simulated with a time step of 6 s. The model was run in parallel using 8 cores of the computational cluster from the National Institute for Water of Argentina.

4 Tidal flow energy potential evaluation

To obtain the tidal energy potential, it is necessary to calculate the velocity field along the estuary. The velocity components were interpolated to cell centers, at which depths are defined and stored at intervals of 2 hours.

Figure 1: Computational mesh.

Figure 2: Bottom depth below ref. plane (m).

With these data, for each surface cell, the hydrokinetic potential was obtained by integrating the instantaneous hydraulic power over the water column and the duration of the simulation:

$$E(x, y) = \int \frac{1}{2} C_p \rho h(x, y) \left|V(x, y)\right|^3 dt \qquad (1)$$

Where, C_p is the coefficient of performance of the microturbine, ρ is the water density, $h(x, y)$ and $V(x, y)$ are the water depth and depth-averaged velocity of each (x, y) point respectively. In this specific case, a Gorlov turbine (Figure 3) has been selected for its high performance $C_p = 0.35$ with a cut-in velocity of $V_{min} > 0.5$ m/s. The percentage of time during which the flow velocity is above the cut-in velocity is presented in Figure 4. The annual potential energy is presented in Figure 5.

The maximum value of annual energy is obtained at the river mouth. However, the installation of microturbines at this zone will disrupt marine traffic. For that reason, a microturbine set is proposed to be installed in the zone designated as "Elbow" (Figure 5).

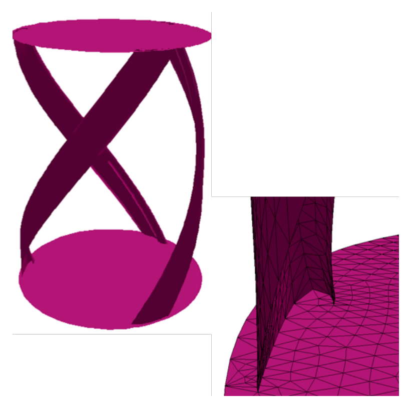

Figure 3: Gorlov Turbine (CFD design).

5 Effect of the installation of tidal microturbines

Delft3D has no dedicated implementation of tidal turbines. However, these, along with their support structures, may be approximated by porous plates, which can be specified on the boundary between any two given cells of the

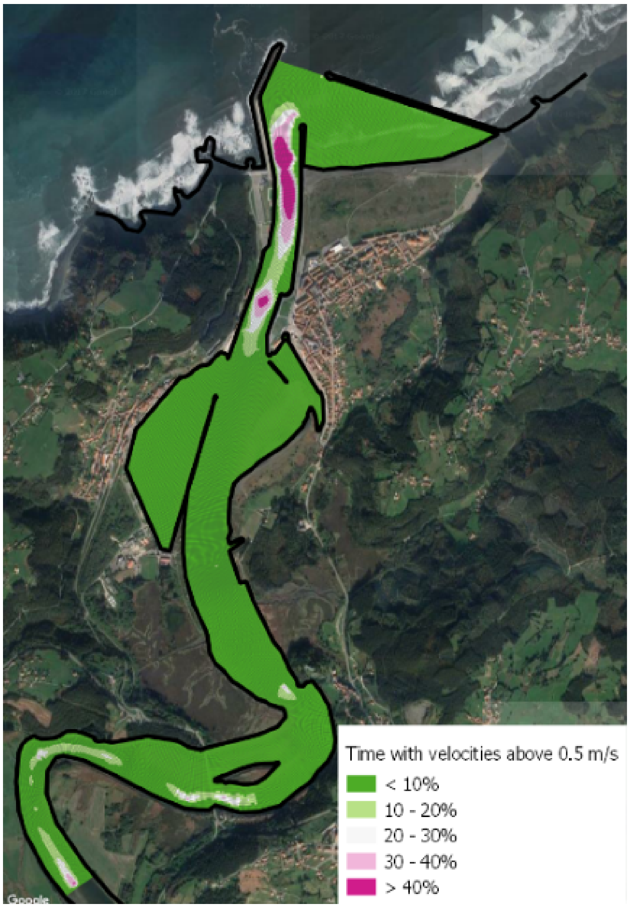

Figure 4: Percentage of time with velocity above 0.5 m/s.

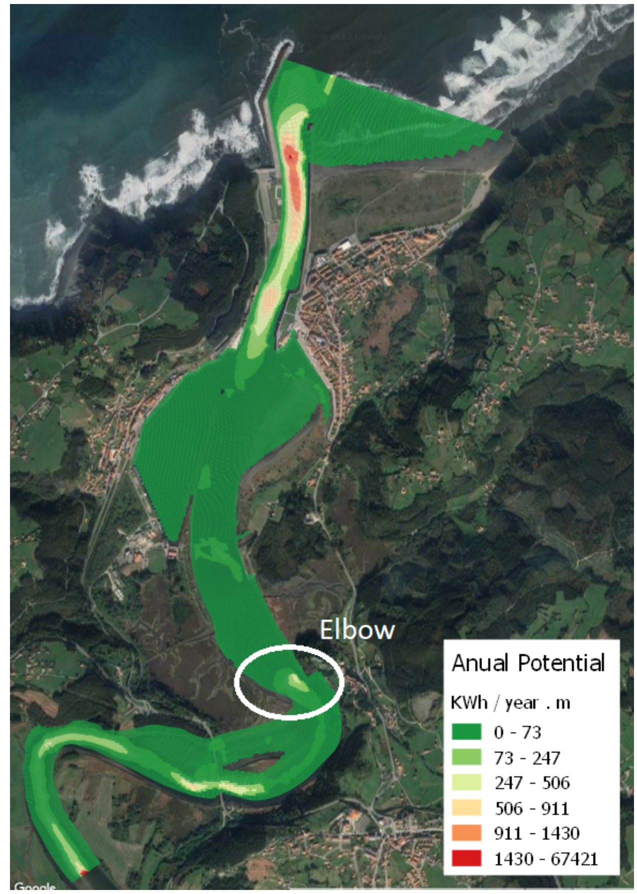

Figure 5: Annual potential energy.

grid. However, for this purpose, Delft3D has some specific limitations.

First, the model does not support variable drag coefficients for the plates, so a characteristic fixed coefficient has to be chosen.

Second, drag is only applied perpendicular to the direction of the porous plate, which is fixed in time. This prevents simulating turbines with horizontal axis rotating over time, and produces an underestimation of drag unless the flow remains mostly perpendicular to the plate.

Lastly, as previously mentioned, in 3D mode the program uses a "sigma" coordinate system, and the vertical layers move following the changes in free surface elevation. The position of the porous plate is specified as covering some or all of these layers, so that the modelled turbines will appear to grow and shrink in the water column depending on whether the tide rises or falls. This is especially problematic if the change in water surface elevation is large in relation to the mean water depth. Under these conditions, for the current case of study, there is little precision to be gained from simulating flow in 3D, as the porous plate loss would be applied to incorrect portions of the vertical velocity profile most of the time. That is the reason why a 2D treatment has been used so far for the Nalón estuary.

To evaluate the effect of an installation of tidal microturbines, an example based on [7] composed of 14 vertical axis (VAT) hydrokinetic microturbines was selected. Each unit have a swept area of 1 m^2 (diameter of 0.7 m and length of 1.5 m) . The microturbines are arranged in a row located in the normal direction to the river current.

The effect of the microturbines in the river flow has been modelled with the momentum sink term of Delft3D for porous plates [15].

$$M_\epsilon = -C_{loss} \cdot \frac{1}{\Delta x} \cdot V_{(x,y)} \cdot \left|V_{(x,y)}\right| \tag{2}$$

Where, M_ϵ, is the acceleration that represents the change in the momentum, C_{loss} is the quadratic friction coefficient, and Δx is cell size in the flow direction. By the application of the porous plate theory, the coefficient can be determined by [16],

$$C_{loss} = \frac{C_d \cdot N \cdot A}{2 \cdot \Delta y \cdot H} \tag{3}$$

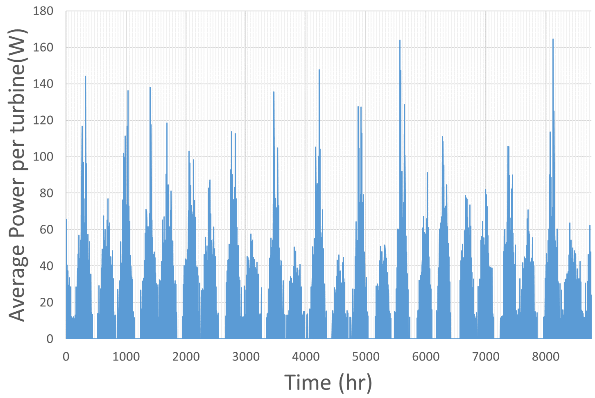

Figure 6: Average power per turbine.

Table 1: Results from the study cells.

Cell	671,50	671,51
Max. U (m/s)	1,024	0,936
Max. E (w/m^2)	187,75	143,70
Annual E per m^2 (kW.h/m^2.year)	86,24	

Where, C_d is the turbine drag coefficient, N is the number of microturbines assigned to the boundary between cells, A is the area swept by each microturbine, Δy is the size (in the direction normal to the flow) and H is the mean height of the porous plate, which, for a 2D calculation, is the mean water depth in the cells.

For the current case, the row of microturbines is 11.5 m wide, covering the width of two cells of $\Delta y = 5.75$ m each, $C_d = 0.85$ for a Gorlov microturbine, $H = 2.5$ m and $N \cdot A = \Delta y 1.5 \text{ m} = 8.27 \text{ m}^2$. Consequently, $C_{loss} = 0.255$.

The water depth oscillates between 1.5 m and 3.5 m for this zone, which, as mentioned above, is a big fluctuation relative to the mean water depth of 2.5 m.

The numerical model modified to include the effect of the microturbine simulated a whole year (2013). The values of power and energy per turbine were obtained(Figure 6).

Additionally, the effect of the microturbine row in the river flow, was obtained as the average velocity change in each cell,

$$\Delta U = \int \frac{\left(\left|V_b(x,y)\right| - \left|V_a(x,y)\right|\right)}{t_f - t_i} dt \quad (4)$$

Where, $V_b(x, y)$, is the depth-averaged velocity field without microturbines, $V_a(x, y)$ is the depth-averaged velocity field with microturbines, t_i and t_f are the initial and final times of the simulation. In this case, in one year The results for this case for one year are shown in Figure 7.

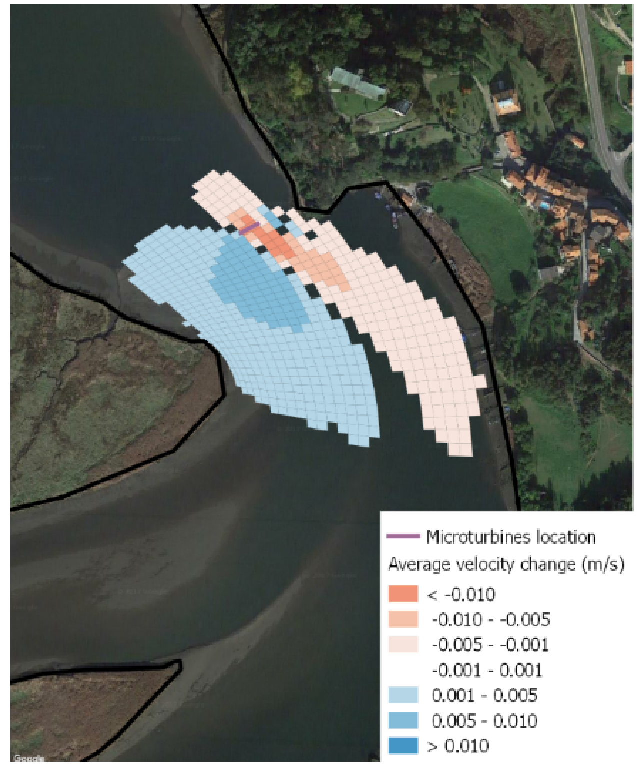

Figure 7: Average velocity change (annual).

As for the economic analysis and according to a study of similar characteristics [17], with 20 turbines farm, the viability of the projects is achieved with investments around 1500 €/ Kw, with a payback period of 6 years.

6 Conclusions

A methodology for an accurate estimation of tidal energy in estuaries by using a high precision numerical model is presented. It can be used to obtain information about the velocity field, energy potential and simulates the effect in the flow of a tidal microturbine installation. The possibility of using ranges of small speeds with these microinstallations is a very attractive alternative to provide energy to areas near their sites, without the need for large investments or costly maintenance. With this methodology, we can optimize the site selection for maximum energy extraction. It has been applied to the data obtained from the Nalon river (Asturias, Spain) and interesting results were found.

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