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Assessment of the Potential of Harnessing Tidal Energy in the Khowr-e Musa Estuary in the Persian Gulf

Zohreh Hashemi Aslani[a], **Mohammad Hossein Niksokhana**[a,*], **Masoud Montazeri Namin**[b]

[a] Graduate Faculty of Environment, University of Tehran, Tehran, Iran
[b] School of Engineering, University of Tehran, Tehran, Iran

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Abstract
Today, the widespread use of fossil fuels is caused many problems in the world, which include: Ozone depletion, the increase carbon dioxide in the atmosphere, growing recognition of climate change impacts and decreasing fossil fuel resources. These issues have led to an increased interest in the mass generation of electricity from renewable sources such tidal energy. The Khowr-e Musa Estuary, located in the west-north of Persian Gulf, has a spring tidal range approaching 5 meters. Doragh estuary branches of Musa estuary are located in the Persian Gulf at a distance of five kilometers from Bandar Imam Khomeini. In this study, a widely used 2D hydrodynamic model, namely MIKE21HD, was applied to estimate the potential of harnessing tidal energy. Therefore, this research provides the hydrodynamic details of the assessments carried out to estimate the potential of electricity generation by using two proposed barrages in the Doragh estuary. The results have shown that the total electricity generated being about 150 MWh for the first barrage and 535.98 MWh for the second one over a typical mean spring tidal cycle.

Keywords: Tidal Energy, barrage, Khowr-e Musa Estuary, Doragh Estuary, Model, Electricity generation.

Introduction

Today, the widespread uses of fossil fuels are caused many problems in the world, which include: Ozone depletion, the increase carbon dioxide in the atmosphere, growing recognition of climate change impacts and decreasing fossil fuel resources. These issues have led to an increased interest in the mass generation of electricity from renewable sources. Marine particularly tidal energy resource has become a important candidate for energy supply in the near future, especially in places with a tidal height of about 4 meters or more (Kadiri et al., 2012). The Musa Estuary constitute a large, semienclosed body of water in the northwest part of the Persian Gulf with a spring tidal range approaching 5 meters (Evans and Robert, 1982), see Figure 1. The Doragh Estuary in the Musa Estuary is an ideal site for constructing a tidal power project. Traditionally, tidal energy is exploited by surrounding a bay with a barrier containing numerous sluices and turbines (Sutherland et al., 2007). For tidal power extraction

* Corresponding author E-mail: niksokhan@ut.ac.ir

some conditions such enough tidal range, enough capacity for water storing and adjacency to consumers should be in the study area (Grubb and Vigotti, 1995).

The tidal hydrodynamic processes in the Khowr-e Musa Estuary have therefore been studied by researchers and organizations using numerical models. Xia et al. in 2010 used a two-dimensional hydrodynamic model based on an unstructured triangular mesh .Their model employed a TVD finite volume method to solve the 2D shallow water equations and predicted the hydrodynamic processes with a barrage (Xia et al., 2010). Abbaspour and Rahimi in 2011 used the hydrodynamic model in the MIKE 21 Flow Model (MIKE 21HD), with validation using tidal elevation measurements and tidal stream diamonds to estimate available tidal energy resources at the Persian Gulf (Abbaspour and Rahimi, 2011). Sadrinasab and Shoaib in 2011 employed a three dimensional hydrodynamic model (COHERENS) to assess the tidal power of the Doragh estuary. Their simulation indicated that using one basin project at the estuary, where the average tidal range is 5 meters, can obtain about 30 MW of electrical power (Sadrinasab and Shoaib, 2011).

Area of interest

A set of two hydrodynamic models has been set up. A regional model covering the entire Khowr-e Musa Estuary, and one local model of Khowr-e Doragh. The regional and local models were run independently. Khowr-e Musa is a combination of tidal channels in the North West part of the Persian Gulf. The average of tidal range in Khowr-e Musa is about 3.2 meters and increasing to 5.5 meters into the Doragh estuary (Sadrinasab and Shoaib, 2011). Doragh estuary branches of Musa estuary is located in the Persian Gulf at a distance of five kilometers from Bandar Imam Khomeini. The datasets used for the water level analysis are acquired from Iran Ports and Maritime Organization (PMO).

Methodology

Numerical model

The hydrodynamic model in the MIKE21 Flow Model (MIKE21HD) was applied for the simulation of water levels. It simulates unsteady two-dimensional flows in one layer fluids and has been used in a large number of studies. The following equations, describes the flow and water level variations, as shown in MIKE manual (MIKE 21 Manual, 2005):

$$\frac{\partial \eta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = q_{source} \tag{1}$$

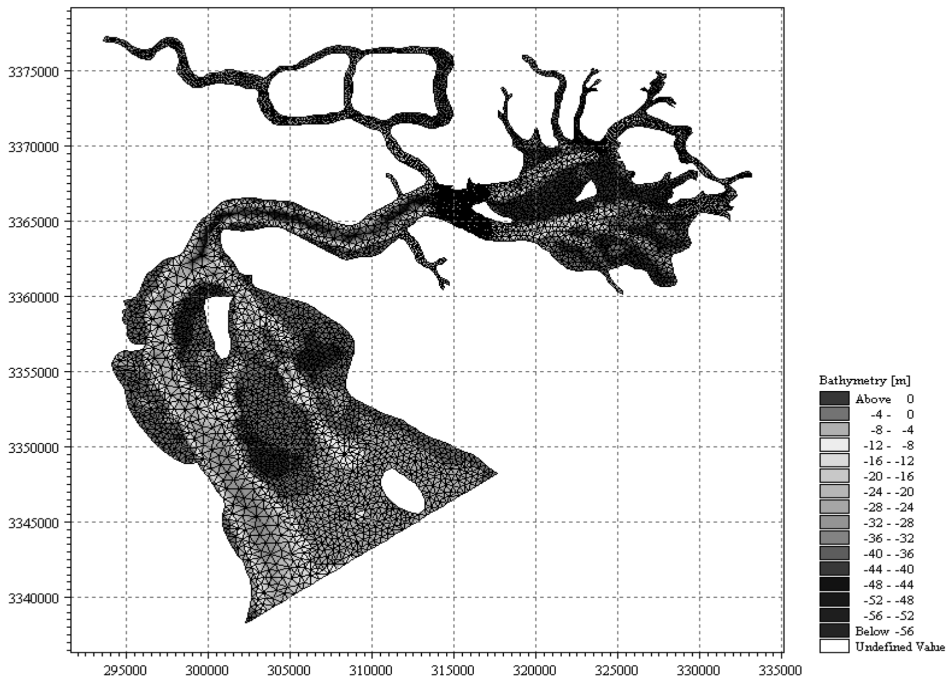
$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}\left(\frac{p^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) - \Omega q + gh\frac{\partial \eta}{\partial x} - \frac{C_f p\sqrt{p^2+q^2}}{\cos(\beta)h^2} - \frac{\rho_{air}}{\rho_0} C_d u_w \sqrt{u_w^2+v_w^2} = \frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial x} + \frac{\partial}{\partial x}\left(\nu_h\left(\frac{\partial\left(\frac{p}{h}\right)}{\partial x}\right)\right) + \frac{\partial}{\partial y}\left(\nu_h\left(\frac{\partial\left(\frac{p}{h}\right)}{\partial y}\right)\right) \tag{2}$$

$$\frac{\partial q}{\partial t}+\frac{\partial}{\partial y}\left(\frac{q^2}{h}\right)+\frac{\partial}{\partial x}\left(\frac{pq}{h}\right)+\Omega p+gh\frac{\partial \eta}{\partial y}-\frac{C_f q\sqrt{p^2+q^2}}{\cos(\beta)h^2}-\frac{\rho_{air}}{\rho_0}C_d v_w\sqrt{u_w^2+v_w^2}=$$
$$\frac{\partial S_{yy}}{\partial y}+\frac{\partial S_{xy}}{\partial y}+\frac{\partial}{\partial x}\left(h v_h\left(\frac{\partial\left(\frac{q}{h}\right)}{\partial x}\right)\right)+\frac{\partial}{\partial y}\left(h v_h\left(\frac{\partial\left(\frac{q}{h}\right)}{\partial y}\right)\right) \quad (3)$$

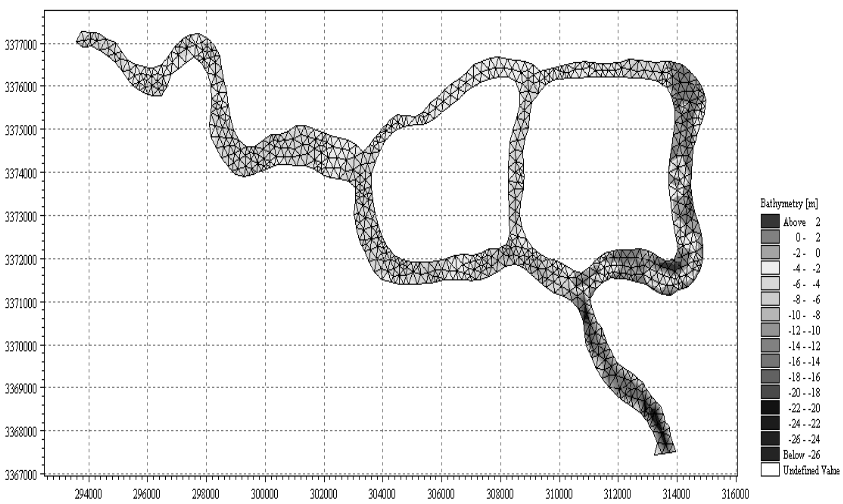
Where: h(x,y,t) is water depth,C_f is the bed roughness coefficient, C_d is the air drag coefficient, Ω(x,y) is Coriolis Parameter-Latitude, η(x,y,t) is surface elevation, V_h is the Turbulence coefficient, u_w,v_w stand for wind speed and components in X- and Y directions, p,q(x,y,t) represent flux densities in X- and Y-direction (m^3/s/m)=(vh,uh), (v,u)= depth-averaged velocities in X- and Ydirections, β is The angle with the horizontal bed that is equal to $\sqrt{1+\left(\frac{\partial z_b}{\partial x}\right)^2+\left(\frac{\partial z_b}{\partial y}\right)^2}$, S_{xx} ، S_{xy} و S_{yy} are components of wave radiation stress.

Figure 1. Map of the Musa and Doragh Estuary.

The bathymetry used to produce the mesh was provided by National Cartographic Center of Iran-Department of Hydrography. The mesh was made using the Bathymetries program (part of the MIKE Zero program) and is shown in Figure 2(a,b). The Musa model domain was divided into 6020 unstructured triangular cells and The Doragh model domain was divided into 887 unstructured triangular cells. The computational grid was refined locally to give a higher resolution around the deep channels. The model is run with a time step of 5 s. In this study, The Khowr-e Musa Estuary is regional and the Doragh Estuary is local hydrodynamic model.



a. The Khowr-e Musa Estuary



b. The Doragh Estuary

Figure 2. Bathymetry of the study area

Calibration of hydrodynamic model

The accuracy of the local hydrodynamic model is a result of the accuracy of the regional model. There is shown one comparison of simulated and measured tidal elevations presumably in Musa Estuary, see Figure 3. For spring tides, the predicted tidal ranges were underestimated by about 0.3 m. For neap tides, the predicted tidal ranges were overestimated, 1 m. The degree of accuracy was regarded as acceptable, particularly when considering the complexity of the tidal flows in such a large model domain and for such extreme tidal conditions. Apart from an apparent small shift in mean sea level that does not seem to be important, the accuracy is satisfactorily. This is probably due to inaccuracy of the mean level between model and measurements.

The amount of the Manning roughness coefficient was calibrated by comparing the predicted tidal ranges at Imam Khomeini site in the estuary with the observed data, and with the closest agreement being obtained when the Manning roughness coefficients were 32 $m^{1/3}/s$ for spring tides.

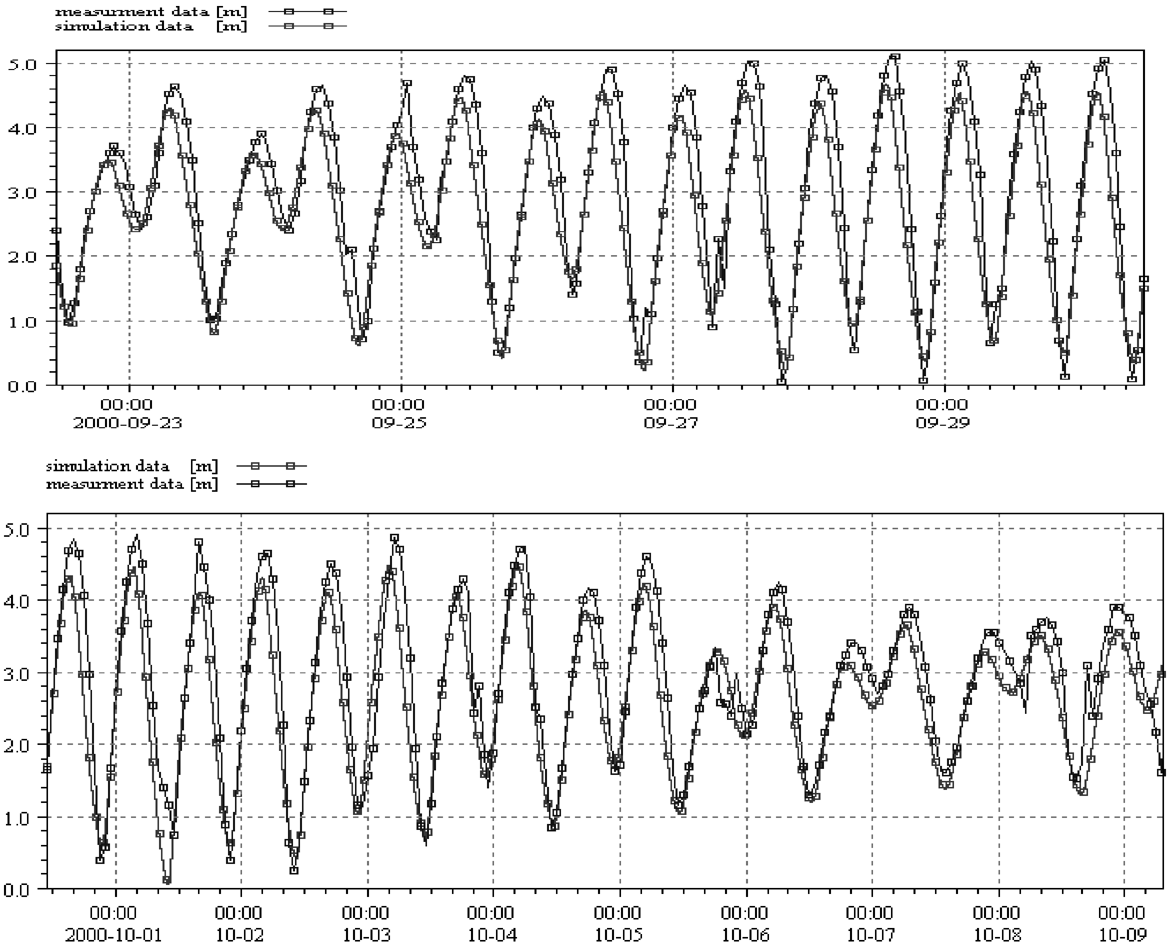


Figure 3. Calculated and observed tidal levels

Model application

The model was applied to predict the potentional power of constructing two proposed tidal barrages on the hydrodynamic processes in the Doragh Estuary, as shown in Figure. 4. The first proposed barrage would be 870m and the second proposed barrage would be 1100m long. In this study, the first proposed barrage was assumed combining 10 bubl turbines and 7 sluice gates and for the second barrage was combined with 14 bulb turbines and 11 sluice gates. Both of barrages would have fish passage and ship lock. In the current study, to simulate the hydrodynamic processes caused by the barrage operation, a technique of domain decomposition was applied to calculate the complex distributions of water levels in the vicinity of the hydraulic structures (Xia et al., 2010). This technique is an efficient way of simulating complex physical processes. The model domain was divided into two subdomains, as shown in Figure 5. Two sub domains were linked dynamically using by Q–H relationship at the barrage site (Xia et al., 2010). The discharge Q through a barrage, was achieved by linking Q with the difference between the upstream and downstream water levels and given by:

$$Q = C_d A\sqrt{2gH} \quad (3)$$

Where C_d=discharge coefficient of sluice or turbine; A=wet flow through area; H=Zu-Zd; Zu and Zd=upstream and downstream water levels. In this study like the barrage of Severn Estuary, it was assumed that the discharge coefficient of 0.75 could be used for both the sluice gates and turbines and the mean opening area of each sluice gate was set to 210.8 m2 and for wet flow-through area of each turbine was set to 63.6 m2 (STPG, 1989). Then by Eq.(3) , Q was determined.

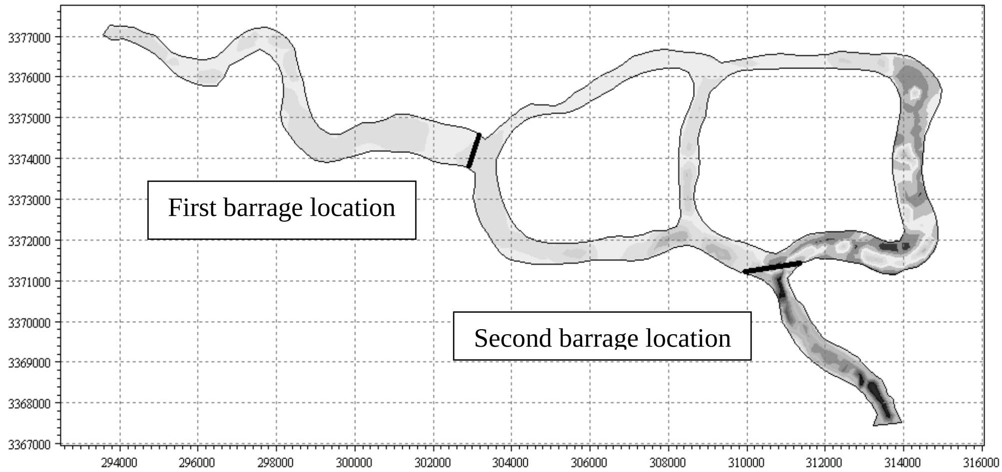
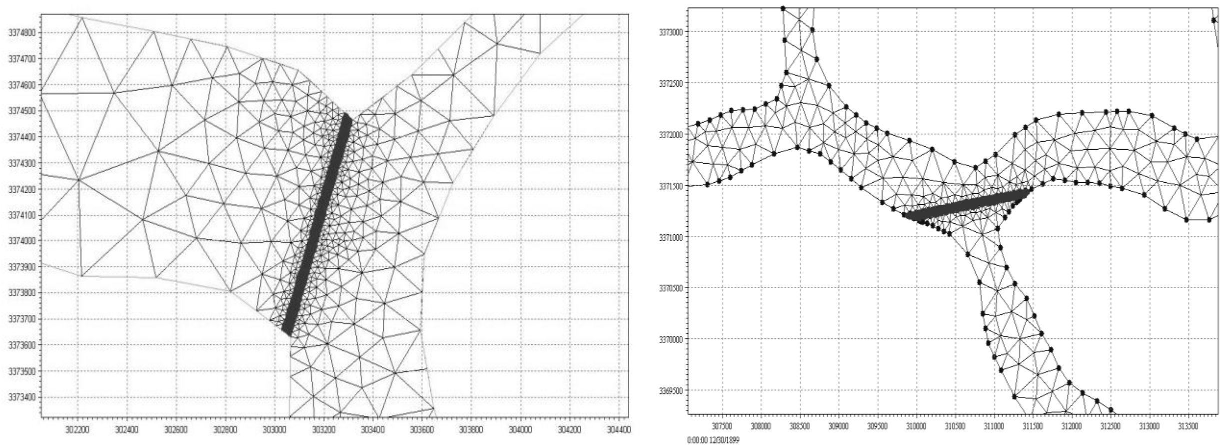


Figure 4. Location of barrages



a. First barrage b. Second barrage

Figure 5. Sketch of the domain decomposition

Tidal power output for ebb generation mode

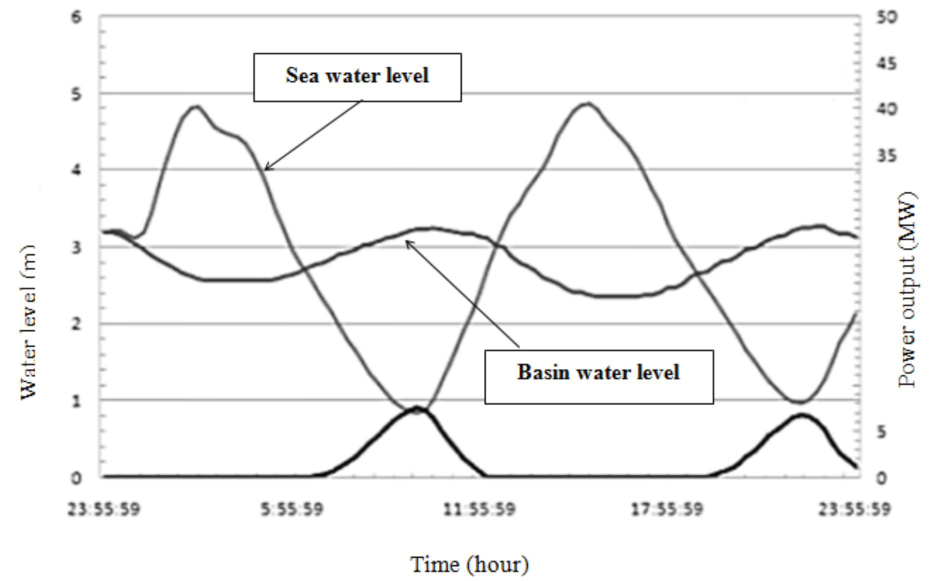
Extractable potential of tidal energy is obtained from the following equation (Sadrinasab and Shoaib, 2011):

$$P = \frac{1}{2}\rho g A R^2 \quad (4)$$

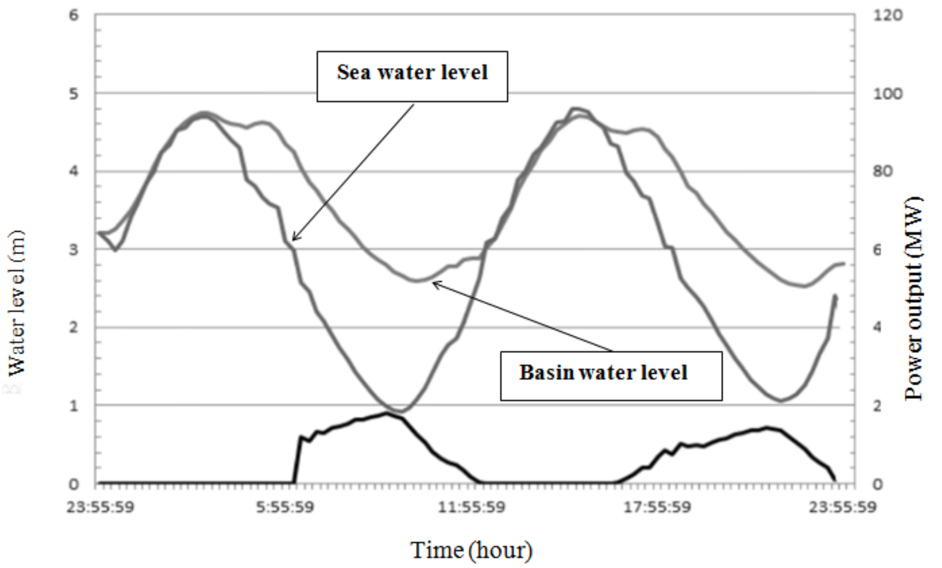
$$P_{max} = 0.22AR^2 \quad (5)$$

Where:
P: tidal power (watt), ρ: density of water (kg/m3), g: acceleration due to gravity (m/s^2), R: tidal range (m).

Figure 6 shows the water level time series, both upstream and downstream of the barrages, together with the maximum power output value for mean spring tides.



a. The first barrage



b. The second barrage

Figure 6. Predicted water levels and power output for the barrage operating regime

Analysis of model results

Barrage operating regime included four steps for a cycle: (i) filling, (ii) holding, (iii) generating and (iv) holding (Xia et al., 2010). In the first step, the sluice gates and turbines were both opened at the flood tide and was allowed the water to flow into the basin upstream of the barrage. Then before the high tide, the sluice gates and turbines were both closed. When the water head between the basin level and the downstream sea level was a adequate value to enable efficient electricity generation, the water upstream of the barrage was allowed to discharge out of the basin. This process of power generation lasted about 5hr, with the maximum water head reaching over 2.5m for the first barrage and 1.8m for the second ones and with a corresponding maximum power output being about 7.5 MW for the first barrage and 17.93 MW for the second one. In the final step, the turbines were closed and the sluice gates remained closed until the next rising tide. From Fig. 6, it can be seen that the total electricity generated being about 150 MWh for the first barrage and 535.98 MWh for the second one, as shown in Table. 1.

Table. 1. Details of barrages

Barrages	Length(m)	Basin Area(km^2)	maximum water head for generation	Pmax(MW)	Total P for two spring tides (MWh)
The firste barrage	870	5.56	2.5	7.5	150
The second barrage	1100	25	1.8	17.93	535.98

Conclusions

In this paper, a two-dimensional hydrodynamic model based on an unstructured triangular mesh, namely MIKE21, has been used to assess the power potentional of tidal barrage across the Doragh Estuary. Water levels were given of the model calibration and verification processes, which indicate that the numerical model predictions generally agreed closely with the observed data. The model was then applied to predict the water levels in the Doragh Estuary, both without and with the proposed barrages. The results have shown that the total electricity generated being about 150 MWh for the first barrage and 535.98 MWh for the second one over a typical mean spring tidal cycle.

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