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Sensitivity of tidal lagoon and barrage hydrodynamic impacts and energy outputs to operational characteristics

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ABSTRACT

The feasibility and sustainable operation of tidal lagoons and barrages has been under scrutiny over uncertainties with regards to their environmental impacts, potential interactions and energy output. A numerical modelling methodology that evaluates their effects on the hydro-environment has been refined to consider technical constraints and specifications associated with variable turbine designs and operational sequences. The method has been employed to assess a number of proposals and their combinations within the Bristol Channel and Severn Estuary in the UK. Operational challenges associated with tidal range power plants are highlighted, while also presenting the capabilities of modelling tools tailored to their assessment. Results indicate that as the project scale increases so does its relative hydrodynamic impact, which may compromise annual energy output expectations if not accounted for. However, the manner in which such projects are operated can also have a significant impact on changing the local hydro-environment, including the ecology and morphology. Therefore, it is imperative that tidal range power plants are designed in such a way that efficiently taps into renewable energy sources, with minimal interference to the regional hydro-environment through their operation.

1. Introduction

Tidal range power plants are designed on the principle of creating an artificial tidal phase difference by impounding water, and then allowing it to flow through turbines to generate energy, in the form of electricity. The potential power (P) generated at any instant is proportional to the impounded wetted surface area (A) and the square of the water level difference (H) facilitated between the upstream and downstream sides of the impoundment:

$$P \propto A \cdot H^2 \tag{1}$$

Historically, the first large scale tidal range structure has been the La Rance barrage in France, in operation since 1966 [27]. This was followed by the 20 MW single turbine Annapolis Royal generating station in Canada (1984) and the more recent 254 MW Lake Sihwa tidal power station in South Korea [8]. Contrary to their successful performance for sustainable and predictable energy production, there are mounting concerns over the environmental impacts induced by the presence of such renewable energy structures in estuarine and coastal waters. These impacts include alterations to the regional tidal flow characteristics, with interlinked effects on the local geomorphology, ecology and water quality processes [20,43].

The majority of the environmental impacts to-date have been accentuated through research and feasibility studies associated with a Severn Barrage, a prospective impoundment that has the potential of producing more than 5% of the UK's electricity needs [4,6,11,12,44–47]. It has been argued that due to the sensitive characteristics of the Bristol Channel and Severn Estuary, the introduction of such a structure would influence the established tidal resonance and flow structure in the basin; therefore, careful design becomes crucial. Earlier proposals failed to address the environmental and socio-economic concerns in a manner that maintained both the project feasibility and the operational efficiency beyond construction [31,32].

More environmentally friendly options are thought to be delivered through the tidal lagoon concept, where it is proposed that reduced disruption of the existing estuarine hydrodynamic

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conditions will arise [6,14,41,42]. Tidal lagoons effectively operate on the same principles as tidal barrages. Their primary difference is that the majority of the impounded area perimeter is artificial, which enables their development in less environmentally sensitive locations compared to barrages, with the latter mainly restricted to estuary mouths and spanning the entire coastal basin width.

The assessment of tidal impoundments relies on the development of numerical tools that can simulate their operation over time. These span from simplified theoretical and zero-dimensional models [6,25,26,50]; to more sophisticated multi-dimensional hydro-environmental tools [6,12–14,36,44–48] that often require High Performance Computing (HPC) capabilities [43] to be practically applicable.

Results from a refined 2-D hydrodynamic modelling investigation, tailored specifically to tidal power plant assessment, are expounded upon in this study. The aims of this paper are therefore to: (a) review the methodology adopted for the operational simulation over transient conditions, (b) quantify and illustrate the cumulative hydrodynamic impacts of coastally-attached tidal lagoons and a barrage in estuarine flows, and (c) calculate the respective annual energy generation potential for various combinations with particular emphasis on proposals for the Severn Estuary and Bristol Channel.

2. Methodology

Starting from first principles and neglecting losses, the maximum potential energy over the course of a tidal period can be given by Ref. [25]:

$$E_{max} = 4\rho g A h_a^2 \tag{2}$$

where g is the gravitational acceleration ($= 9.807$ m/s^2), ρ the water density ($\approx$ 1025 kg/m^3), h_a the tidal amplitude and A the impounded basin wetted area. According to Prandle's theory, an initial estimate of the actual extractable energy per tidal cycle corresponds to $0.27 \times E_{max}$ and $0.37 \times E_{max}$ for ebb-only and two-way generation respectively. In practise, a more elaborate methodology that provides an insight to the impoundment performance over transient tidal conditions is required, as outlined below.

2.1. Hydraulic structure representation

The performance of tidal impoundments is dictated by the regulation and specifications of their constituent hydraulic structures, i.e. turbines and sluices. While turbines provide the power generation facilities of the power plant, sluice gates supplement the transfer of water volume at certain stages of the operation, generating greater head potentials on the subsequent half or full tidal phase. A straightforward approach used to calculate the flow driven through a hydraulic structure by a water head difference H is by the orifice equation:

$$Q = C_d A_f \sqrt{2gH} \tag{3}$$

where Q is the flow rate in m^3/s, A_f the flow area in m^2, and C_d the discharge coefficient, given the value of unity herein as recommended by Ref. [10] with more recent experimental results by Ref. [29] indicating that C_d values for certain sluice gate designs can exceed a value of 1 with superior performance. Further details about the sensitivity of tidal impoundment simulations to C_d can be found in Ref. [11]. Equation (3) has been extensively applied to model the behaviour of sluice gates (e.g. Refs. [44,47,48]) and turbines alike [4,49].

However, the representation of low head bulb turbines can be refined to incorporate the characteristics specific to their design, as in Ref. [13]. The speed of the turbine S_p is given by:

$$S_p = \frac{2 \cdot 60 \cdot f_g}{G_p} \tag{4}$$

where f_g is the electricity grid frequency and G_p the number of generator poles. The unit speed (n_{11}) of a double regulated bulb unit can be expressed as [3] [13];:

$$n_{11} = \frac{S_p \cdot D}{\sqrt{H}} \tag{5}$$

where D is the turbine diameter in m. The specific discharge Q_{11} is normally calculated as:

$$Q_{11} = \frac{Q}{D^2 \cdot \sqrt{H}} \tag{6}$$

Alternatively, Q_{11} can be represented as a function of n_{11} through the following empirical expressions [3]:

$$\begin{array}{ll} Q_{11} = 0.0166 \cdot n_{11} + 0.4861 & \text{if } n_{11} < 255 \\ Q_{11} = 4.75 & \text{if } n_{11} \geq 255 \end{array} \tag{7}$$

As a result, equation (5) is transformed and the turbine flow rate Q is calculated as:

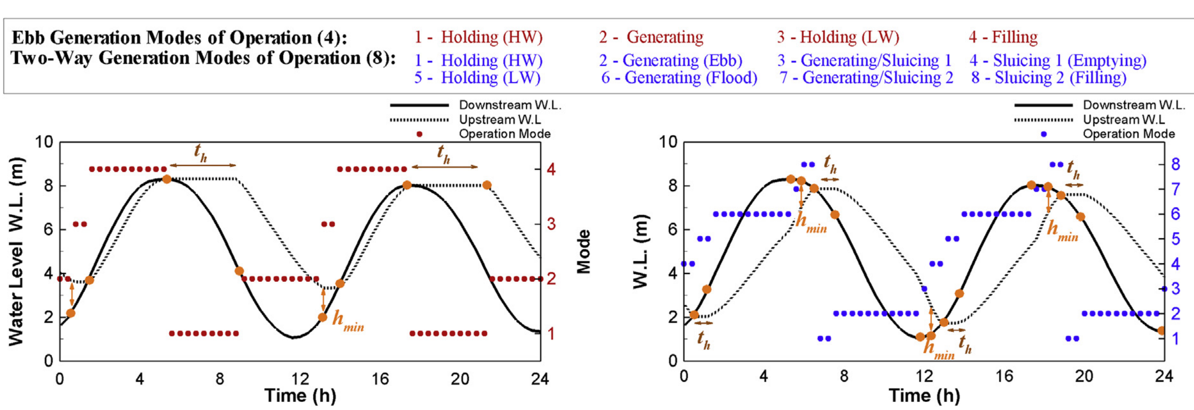

Fig. 1. Ebb-only and Two-way generation modes, illustrating upstream and downstream water levels over time as well as the trigger points that dictate the impoundment operation.