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A modeling study of tidal energy extraction and the associated impact on tidal circulation in a multi-inlet bay system of Puget Sound

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A B S T R A C T

Previous tidal energy studies in Puget Sound have focused on major deep channels such as Admiralty Inlet that have a larger power potential. This paper focuses on the possibility of extracting tidal energy from minor tidal channels of Puget Sound by using a hydrodynamic model to quantify the power potential and the associated impact on tidal circulation. The study site is a multi-inlet bay system connected by two narrow inlets, Agate Pass and Rich Passage, to the Main Basin of Puget Sound. A three-dimensional hydrodynamic model was applied to the study site and validated for tidal elevations and currents. We examined three energy extraction scenarios in which turbines were deployed in each of the two passages and concurrently in both. Extracted power rates and associated changes in tidal elevation, current, tidal flux, and residence time were examined. Maximum instantaneous power rates reached 250 kW, 1550 kW, and 1800 kW, respectively, for the three energy extraction scenarios. Model results suggest that with the level of energy extraction in the three energy extraction scenarios, the impact on tidal circulation is very small. It is worth investigating the feasibility of harnessing tidal energy from minor tidal channels of Puget Sound.

1. Introduction

International Energy Outlook 2016 [1] projects worldwide energy demand will increase 48% from 549 quadrillion British thermal units (Btu) in 2012 to 815 quadrillion Btu in 2040. While fossil fuels will still account for 78% of energy use in 2040, renewable energy sources (e.g., solar power, hydropower, wind and tidal energy) remain the world's fastest-growing energy source over the projection period with an average increase rate of 2.6% per year between 2012 and 2040. Within this context and driven by the pressure in mitigating the threat of climate change, there has been a growing interest in harvesting energy from tidal currents with marine and hydro-kinetic (MHK) energy extraction devices because of the potential for tidal energy to be a viable source of clean and renewable energy. Compared to wind and solar energy, tidal energy is highly predictable in space and time. A rough estimate of total harvestable coastal tidal energy is around 1 TW worldwide [2]. With recent advancement in turbine design technology (e.g., SeaGen [3]), the economic and environmental costs of tidal energy development are expected to be competitive with other energy sources. As a result, a series of tidal power demonstration projects have been carried out or planned to investigate the feasibility of commercial scale tidal energy development [3–5].

Meanwhile, a better understanding of the potential environmental and ecological impacts resulting from tidal energy development is needed [6]. Besides the "blade strike" threat to large marine organisms such as marine mammals, the interactions between tidal energy devices and the physical environment can lead to localized and even system-wide changes inflow fields and sediment transport [7,8]. For example, Neill et al. [8] demonstrated that a small amount of energy extracted from a tidal system can lead to a significant impact on the sediment dynamics, depending on tidal asymmetry at the point of extraction. Removal of a large amount of tidal energy can also result in substantial changes in tidal regime, potentially affecting communities living in intertidal zones [6,9,10]. In a modeling study conducted by Nash et al. [9] in Shannon Estuary, Ireland, the authors reported that the introduction of tidal stream turbines into the estuary can cause inter-tidal zones upstream of the turbine farm to be predominately inundated. Moreover, there is a practical need in determining the most suitable locations and turbine array configurations for energy extraction. To address the emerging needs associated with in-stream tidal energy

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development, numerical hydrodynamic models have been widely used to support tidal energy development [7–17]. These modeling studies covered a broad range of topics on tidal energy, including assessing the power potential and quantifying associated changes in near- and far-field velocity field, tidal regime, flushing rate and sediment transport. It was found, in general, that the effect of energy extraction on tidal regime and mass transport could be significant, depending on the amount and location of tidal energy extracted from the system. Therefore, it is highly recommended for in-stream tidal energy projects that a numerical modeling study should be conducted to evaluate potential project impacts on the physical environment and to provide critical information for making siting decisions.

The U.S. Pacific Northwest is considered a prime site for tidal energy development due to its unique geographic setting, which is characterized by a meso-macro tidal regime and numerous deep and constricted channels that feature strong tidal currents. For instance, harvesting tidal energy from Admiralty Inlet of Puget Sound, Washington to power residential homes has been a near decade-long joint effort by local, state and federal agencies and the power industry [18,19]. Besides Admiralty Inlet, other identified potential candidate sites in Puget Sound include constricted channels such as Tacoma Narrows, Deception Pass, Agate Pass and Rich Passage [18,20]. Previous modeling studies by Polagye et al. [21] and Yang et al. [22] also suggested that extracting a small fraction of available tidal energy from major channels like Admiralty Inlet and Tacoma Narrows is unlikely to have any significant system-wide impact.

In this paper, we investigated the possibility of extracting tidal energy from two narrow inlets of Puget Sound, namely Agate Pass and Rich Passage of West Puget Sound, as a continuation of our earlier study in Tacoma Narrows [22]. This study had dual objectives: to characterize the general tidal circulation pattern in a multi-inlet bay system that is connected to the main Puget Sound via Agate Pass and Rich Passage, and to quantify the potential impact on water circulation as a result of tidal energy extraction. This effort is the first modeling study in the Puget Sound region to investigate extracting tidal energy from relatively small-scale tidal channels. The results will provide useful information to stakeholders and the general public who are interested in harnessing tidal energy from Puget Sound waters.

2. Study site

Puget Sound is a complex, fjord-like estuarine system consisting of many interconnected marine waterways and basins that are connected to the East Pacific Ocean through the Strait of Juan de Fuca to the west and the Strait of Georgia to the north (Fig. 1). Located along the northwestern coast of the U.S. state of Washington, Puget Sound is the largest estuary in the country by volume and can be divided into four deep basins connected by shallower sills: Hood Canal, Whidbey Basin, South Sound, and the Main Basin, which is further subdivided into Admiralty Inlet and the Central Basin. With more than 4.5 million people living in the Puget Sound region and another 2.5 million expected by 2040, there has been a growing interest in harnessing tidal energy from the energetic waters of Puget Sound as a clean renewable energy source [18–20].

Previous tidal energy studies in Puget Sound focused primarily on major channels that have the highest power potential, such as Admiralty Inlet and Tacoma Narrows. While these major channels have the highest power potential, they also pose greater techno-economic challenges and environmental impacts, e.g., the high cost of installation and maintenance of energy extraction devices as well as the potential impacts on marine mammals and hydrodynamic circulation in the entire Puget Sound. In comparison, the tidal energy extraction sites in this study, Agate Pass and Rich Passage (Fig. 1), are much smaller tidal channels that pose fewer techno-economic challenges. Water depth in Agate Pass is generally shallower than 10 m (NAVD 88) and the width varies from 300 to 500 m. Rich Passage is deeper and wider; its depth mostly varies from 20 to 30 m and it has a minimum width about 600 m. Together, Agate Pass and Rich Passage connect a multi-inlet bay complex (e.g., Port Orchard Passage, Liberty Bay, Dyes Inlet, and Sinclair Inlet) behind Bainbridge Island to the Central Basin of Puget Sound. This multi-inlet bay system forms the majority of West Puget Sound, a geographic action area defined in the Puget Sound Action Agenda [23]. As a tidally dominated system with an average freshwater to tidal prism ratio of 0.3%, tides propagate into the multi-inlet bay system through two narrow inlets and produce currents greater than 2 m/s that are sufficient to drive tidal turbines. On the other hand, extracting energy from Agate Pass and Rich Passage may reduce tidal flows through these passages and potentially affect tidal circulation in the system. Therefore, the model domain covered a much broader area with a focus on the multi-inlet bay system.

3. Methodology

3.1. Hydrodynamic model with an embedded MHK module

The hydrodynamic model used for this study is the unstructured-grid, finite-volume, community ocean model (FVCOM) [24–26]. As a general purpose three-dimensional (3-D) coastal ocean model, FVCOM simulates water surface elevation, velocity, salinity, temperature, sediment, and other scalar constituents in an integral form by computing fluxes between non-overlapping horizontal triangular control volumes. By using unstructured triangular cells in the horizontal plane and a sigma-stretched coordinate system in the vertical direction, the model is especially suitable for representing the complex horizontal geometry and bottom topography of estuaries like Puget Sound [27]. It also allows for greater flexibility and computational efficiency in simulating tidal energy extraction that often requires fine grid resolution in the region of a tidal turbine farm embedded within a large model domain [17,22].

To simulate the effect of tidal energy extraction, a MHK module has been implemented in the FVCOM model using the momentum sink approach [14]. The MHK module was validated against both the analytical solution [14] and laboratory flume experiment [28], and was subsequently applied to study tidal energy extraction in Tacoma Narrows [22]. Specifically, the momentum governing equations for Reynolds-averaged turbulent flows with momentum sink terms due to energy extraction have the following general form [14]:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - fv = -\frac{1}{\rho_o}\frac{\partial p}{\partial x} + \frac{\partial}{\partial z}\left(K_m\frac{\partial u}{\partial z}\right) + F_x - F_x^M \quad (1)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + fu = -\frac{1}{\rho_o}\frac{\partial p}{\partial y} + \frac{\partial}{\partial z}\left(K_m\frac{\partial v}{\partial z}\right) + F_y - F_y^M \quad (2)$$

where (x, y, z) are the east, north, and vertical axes in the Cartesian coordinates; (u, v, w) are the three velocity components in the x, y, and z directions; (Fx, Fy) are the horizontal momentum diffusivity terms in the x and y directions; Km is the vertical eddy viscosity coefficient; ρ is water density; p is pressure; and f is the Coriolis parameter. $\overrightarrow{F^M} = (F_x^M, F_y^M)$ are the turbine-induced momentum sink