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Tidal stream energy site assessment via three-dimensional model and measurements

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HIGHLIGHTS

- ► Tidal power extraction introduces far-field effects on flow speeds and water levels.
- ► Potential power and impacts can be described with a 3-D hydrodynamic model.
- ► Numerical model results should be calibrated and validated with field data.
- ► Velocity profiles influence optimal siting of power extraction equipment.

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ABSTRACT

A methodology for assessment of the potential impacts of extraction of energy associated with astronomical tides is described and applied to a site on the Beaufort River in coastal South Carolina, USA. Despite its name, the site features negligible freshwater inputs; like many in the region, it is a tidal estuary that resembles a river. A three-dimensional, numerical, hydrodynamic model was applied for a period exceeding a lunar month, allowing quantification of harmonic constituents of water level and velocity, and comparison to values derived from measurements, recorded at a location within the model domain. The measurement campaign included surveys of bathymetry and velocity fields during ebb and flood portions of a tidal cycle for model validation. Potential far-field impacts of a generic tidal energy conversion device were simulated by introducing an additional drag force in the model to enhance dissipation, resulting in 10–60% dissipation of the pre-existing kinetic power within a flow cross-section. The model reveals effects of the dissipation on water levels and velocities in adjacent areas, which are relatively small even at the 60% dissipation level. A method is presented to estimate the optimal vertical location for the energy conversion device and the potential power sacrificed by moving to a different altitude.

1. Introduction

Tidally forced flows represent a very appealing source of renewable energy. Many major population centers border or straddle tidal rivers and estuaries, and the flows, while time-dependent, are more predictable than solar, wind, and wave resources. Although biofouling and corrosion are typically more significant concerns than for terrestrial alternatives such as wind power, the much greater density of water allows for viable energy harvesting at much lower flow speeds, given that power grows with the cube of flow speed. Even sites with nominally small tidal ranges may feature locally constricted flows that yield speeds suitable for energy extraction. And as improvements in efficiency and reductions in hardware cost develop, the critical flow speed for viable energy production will drop, increasing the number of exploitable sites.

Tidal power has been harnessed for production of electricity for decades (the tidal barrage at La Rance in France was built in the 1960s, for example), but the field can still be considered as being in its infancy, with few projects actually constructed to date. A barrage or dam will have different environmental impacts than a network of turbines at the same site; here the focus is on this latter scenario, often preferred for water quality, other environmental, and logistical concerns.

Water levels and flows forced by tides are typically represented by linear superposition of sinusoidal components (i.e. a Fourier series) with different frequencies, amplitudes, and phases. Analytical solutions or one-dimensional numerical models for flow within a simplified domain can shed light on the problem (e.g. [1–5]), but

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many of the processes and parameters that must be considered or included for site selection are nonlinear, and problem geometry is typically quite variable and complex. As a result, it is generally infeasible to make use of analytical solutions for any but the simplest problems or geometries, or perhaps for first-order screening of sites. Numerical modeling tools are an obvious choice for use in the site selection process, but some ground-truthing is also required to validate model results and detect other characteristics of a site that might not be revealed by hydrodynamic model results.

Many site assessment investigations have been performed, typically with a focus on power potential and the hydrodynamic implications of energy harvesting (e.g. [6–18]). Methodologies for assessing sites are still in development. Most studies have focused on far-field hydrodynamics, with the energy harvesting system represented by an energy (or power) sink in the model. In this way the results can be assumed independent of many details of the device by which energy is harvested. One-, two-, and three-dimensional numerical models of hydrodynamics have all been employed. Wind, water density gradients, and wave forcing have typically not been included when describing flows; in some cases, flows have also been assumed steady. River inputs are also often neglected. The most frequent result that is cited is the annual power available at the site. The number of previous efforts that have included field data collection specifically for power potential assessment or model validation is surprisingly low.

As noted by Couch and Bryden [19], Garrett and Cummins [20], and Vennell [21], peak flow speed by itself (or the corresponding peak kinetic energy) is not a good measure of site potential; nor is tidal range. High peak flow speed does indicate large pre-development, peak kinetic energy, but energy extraction will modify the flow field and the extracted energy will not match the pre-development, peak kinetic energy. As discussed by Garrett and Cummins [3,20], system efficiency will vary with the type, number, and arrangement of devices, and the size of the device or array relative to the channel cross-section. The extraction of kinetic energy from a flow with a free surface, as considered here, leads to a transfer of potential energy to kinetic form, some of which then also becomes available for extraction.

In addition to available power, many other factors should also be considered for site selection: proximity to consumption sites, available infrastructure, impacts on waterway navigability, available depth and cross-section size, potential for scour and changes in sedimentation patterns [22,17,23], and environmental impacts, among other factors. Here, the focus is on power potential and far-field fluid mechanics effects of power extraction.

Many of the sites investigated to date are in Europe; within North America, the Bay of Fundy, British Columbia and Alaska have received the most attention. The southeastern United States has received little attention in this regard, because of smaller tidal ranges. Defne et al. [18] describe the tidal power potential throughout the US state of Georgia, representing part of a larger effort to quantify tidal power potential for the entire US via hydrodynamic model results. The Georgia Bight features the largest tidal range within the southeastern US, and many sinuous rivers (estuaries) that in some locations lead to potentially suitable flows for extraction of tidal power.

Here a combined effort involving both numerical modeling and field measurements is described, focusing on a site on the Beaufort River in South Carolina, USA, at the US Marine Corps Recruit Depot at Parris Island. The site features negligible freshwater inputs, and negligible variation in salinity through a tidal cycle. Field measurements were used to validate results from a three-dimensional numerical model of tidally forced hydrodynamics. In addition to site-specific results defining the potential for power production at the site, the overall strategy for assessment of site suitability based on hydrodynamic characteristics and the optimization of the vertical location of energy harvesting equipment within the water column are also addressed.

2. Site description and field measurements

The site that was the focus of the investigation is situated between the confluence of the Broad and Beaufort Rivers in coastal South Carolina, USA (Fig. 1). These rivers are tidally dominated, and feature relatively large tidal ranges for the southeastern United States, with mean and diurnal ranges of 2.3 and 2.5 m, respectively. The Parris Island Marine Corps Recruit Depot already has much of the necessary land-based infrastructure in place to receive renewable power, and a deeper section of the Beaufort River abuts the eastern side of Parris Island, making it a good candidate site. It is roughly 15 km upstream of the entrance to Port Royal Sound, and as a result is sheltered from ocean wave energy, although some locally generated wind wave energy exists at times. The site lies between the Intracoastal Waterway and Parris Island, and the area features extensive tidal marshes, mudflats and oyster beds.

A field measurement campaign was designed with three goals: (1) acquire bathymetric survey data, (2) measure spatial (and to some degree, temporal) variations in ebb and flood flow fields, and (3) document longer-term (lunar month) variability in tidal characteristics at a promising location. Each component of the field investigation is considered below.

2.1. Bathymetric survey

The survey was performed in 1 day from a small boat, using a 200 kHz acoustic depthsounder and a pair of survey-grade, dual-frequency GPS receivers, one deployed as a fixed base station and the other on the boat. The boat followed a pre-defined track with survey transects roughly 250 m apart. The data were sampled at 5 Hz, resulting in decimeter-level horizontal resolution along the boat survey track. The larger scale bathymetric grid shown in Fig. 1 was derived from US National Ocean Service data for the numerical modeling discussed below. The new survey provided higher-resolution data to investigate site suitability in terms of water depth, and to show that the larger bathymetric dataset (based on an assimilation of many years of data) provided a reasonable depiction of site bathymetry. Compared to most potential tidal power extraction sites described previously by other investigators, the Beaufort River site is quite shallow (<10 m), but one option being considered is the deployment of a turbine suspended from a floating barge, which could be feasible for modest turbine sizes.

2.2. Roving velocity measurements

A 1200 kHz acoustic Doppler current profiler (ADCP) equipped with bottom-tracking firmware was deployed in down-looking mode from the bow of the survey vessel as it transited the area for the bathymetric survey. The instrument acquired data at 2 Hz with the velocity profile measured with 0.5 m vertical resolution from a point 0.75 m below the water surface down to the riverbed. Estimated speed uncertainty in the measurements with this configuration is ±6 cm/s.

The measurements were taken on a day which was roughly halfway between the spring and neap portions of the tidal cycle. The tidal cycle during which the measurements were taken was the larger of the two on that day and featured a range of 2.2 m, i.e. close to the mean range for the site. Data were acquired over a 2.5-h window bracketing the flood tide, and then another 2.5-h window bracketing the ebb portion of the tidal cycle. Flow speeds