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National geodatabase of tidal stream power resource in USA

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ABSTRACT

A geodatabase of tidal constituents is developed to present the regional assessment of tidal stream power resource in the USA. Tidal currents are numerically modeled with the Regional Ocean Modeling System (ROMS) and calibrated with the available measurements of tidal current speeds and water level surfaces. The performance of the numerical model in predicting the tidal currents and water levels is assessed by an independent validation. The geodatabase is published on a public domain via a spatial database engine with interactive tools to select, query and download the data. Regions with the maximum average kinetic power density exceeding 500 W/m^2 (corresponding to a current speed of ∼1 m/s), total surface area larger than 0.5 km^2 and depth greater than 5 m are defined as hotspots and documented. The regional assessment indicates that the state of Alaska (AK) has the largest number of locations with considerably high kinetic power density, followed by, Maine (ME), Washington (WA), Oregon (OR), California (CA), New Hampshire (NH), Massachusetts (MA), New York (NY), New Jersey (NJ), North and South Carolina (NC, SC), Georgia (GA), and Florida (FL).

Contents

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1. Introduction

In the past two centuries, the energy consumption per capita increased by a factor of 20, in excess of the six-fold increase in the world population. Presently, more than 80% of the global primary energy is met by fossil fuels, and only 13.5% by renewable resources [1]. A recent study estimates the global coal reserves to last for another century, while the oil and gas to be depleted within a few decades [2]. In addition, the increasing energy demand and the depletion rate of nonrenewable energy resources raise environmental concerns. For example, as a result of exploiting fossil fuels to meet the demand, CO_2 emission from electric power generation in the USA increased by 32% from 1990 to 2007 [3]. However, more than half the USA population lives within 80 km of coastlines, near tidal stream resources. Tidal streams, driven mainly by the gravitational force of the moon and sun, are highly predictable sources of renewable energy that may meet some of the energy demand without adding CO_2 emissions. The extent of their potential can be determined through an assessment of the scale of the available power and its spatial distribution. For this purpose, the tidal streams along the USA coasts are numerically modeled and an interactive geodatabase has been created to support further exploration.

According to the Assessment of Tidal Energy Resource guide by the European Marine Energy Centre Ltd (EMEC), tidal stream resource assessments may be categorized into four stages based on the extent and the detail of the assessment [4]. The first stage is the “Regional Assessment”, which is an assessment on a regional or country level and aims at understanding the scale and characteristics of the tidal resource by performing numerical simulations. The second stage is the “Pre-Feasibility Study” which explores in detail the specific resource locations that are previously identified on a regional scale. Exploratory field surveys may accompany numerical simulations at this stage. For both of these stages, it is recommended to have a minimum simulation duration of 30 days with a minimum of 2 or 4 harmonic constituents forcing the models. A minimum grid resolution that is on the order of a few kilometers at the location of interest is satisfactory for a regional assessment, whereas grid points spaced less than 500 m are suggested for a pre-feasibility study. The third and fourth stages are the “Full-Feasibility Study” and the “Design Development” stages which include detailed economic models and development of the final design. These stages require a minimum of 8 constituents to drive the model, longer periods of simulations and longer records from field surveys, and an order of magnitude finer grid spacing. The impacts of the power extraction also need to be addressed at these stages. The scope of this study is to provide a regional assessment, yet the modeling is done at a pre-feasibility study level. Instead of field campaigns, data reported in the literature are used for model calibration and validation.

The “available power” is defined as the power that is associated with the undisturbed, natural flow conditions. It is different than the “absorbed power” (aka dissipated power), which is the power removed from the system by a converter or the “captured power” (aka extracted power), which is the useful power delivered by it. The final modeling results are stored in a geodatabase, a data repository specifically designed to store and query geospatial data. The U.S. Department of Energy keeps an inventory of reports and digital maps of national renewable resource that provide information on the scale and spatial distribution of various resources such as wind, solar, geothermal, hydropower and biomass [5]. Despite being static images, these maps constitute a good source of regional assessment when combined with the reports. However, the previous lack of a full spatial–temporal assessment of tidal currents for the USA is a barrier to the comprehensive development of tidal current energy technology. The recent efforts include a series of reports by the Electric Power Research Institute, EPRI [6], which are limited to few representative sites; and a few other isolated cases for planned local projects [7]. By creating a national database of tidal stream energy potential, as well as an interactive GIS tool usable by the industry in order to accelerate the market for tidal energy conversion technology, the present study is an addition and improvement to the inventory of renewable resources.

The development stages described here include numerical modeling of tidal streams, calibration of the model for each grid, validation of the model results, development of the geodatabase and dissemination of data to the public.

2. Numerical modeling of tidal streams

The tidal stream modeling is based on Regional Ocean Modeling System (ROMS). The coast is divided into a number of individual subdomains for modeling, and the results for water levels and depth integrated tidal currents are used to calibrate the model against the available data for each subdomain.

2.1. Model set-up

ROMS is a member of a general class of three-dimensional, free surface, terrain following numerical models that solve three dimensional Reynolds-averaged Navier–Stokes equations (RANS) using the hydrostatic and Boussinesq assumptions [8]. ROMS uses finite-difference approximations on a horizontal curvilinear Arakawa C grid and vertical stretched terrain-following coordinates. Momentum and scalar advection and diffusive processes are solved using transport equations and an equation of state computes the density field that accounts for temperature, salinity, and suspended-sediment concentrations. The modeling system provides a flexible framework that allows combinations of various components depending on user needs. In this study, the model is run in multiple processors using distributed-memory, with a three-dimensional barotropic configuration for simulating the tides. The computational grids are set up and the results are calibrated following the outlines of tidal stream modeling efforts for a regional study [9].

The USA coastline is divided into 52 subdomains with an average grid spacing of 350 m as shown in Fig. 1. The only exception is the Puget Sound grid for which the results from an earlier study are used [10]. The coastline data, used for masking the land nodes, is obtained from the National Ocean Service (NOS) Medium Resolution Coastline via the Coastline Extractor [11] and processed in MATLAB to fill in gaps. Raw bathymetry is obtained from the NOS Hydrographic Surveys Database [12]. The bathymetry data in the NOS database are generally referenced to Mean Lower Low Water (MLLW) while ROMS bathymetry is defined with respect to Mean Water Level (MWL) or Mean Tidal Level (MTL). A conversion from MLLW to MTL referenced values is performed based on the data provided by the National Oceanic and Atmospheric Administration (NOAA) at the tidal stations [13] or NOAA Vertical Datum Transformation software (VDatum) [14]. Supplementary data to replace missing bathymetry points are acquired from NOAA Electronic Navigational Charts [15] and National Geophysical Data Center Geophysical Data System database (GEODAS) [16].

The additional water volume supplied by the wetlands is implemented in the computational model through the wet-dry module in ROMS, which allows for computational nodes to be defined as land or sea nodes dynamically with respect to the water content. Wetland boundaries are acquired from the National Wetland Inventory of the US Fish & Wildlife Services [17]. Elevation data for wetlands is cropped from the one-arc second topography data downloaded from USGS Seamless Server [18]. The topography data is referred