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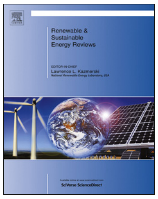

Turbulent inflow characteristics for hydrokinetic energy conversion in rivers

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ABSTRACT

Marine and hydrokinetic technologies, which convert kinetic energy from currents in open-channel flows to electricity, require inflow characteristics (e.g. mean velocity and turbulence intensity profiles) for their siting, design, and evaluation. The present study reviews mean velocity and turbulence intensity profiles reported in the literature for open-channel flows to gain a better understanding of the range of current magnitudes and longitudinal turbulence intensities that these technologies may be exposed to. We compare 47 measured vertical profiles of mean current velocity and longitudinal turbulence intensity (normalized by the shear velocity) that have been reported for medium-large rivers, a large canal, and laboratory flumes with classical models developed for turbulent flat plate boundary layer flows. The comparison suggests that a power law (with exponent, $1/a = 1/6$) and a semi-theoretical exponential decay model can be used to provide first-order approximations of the mean velocity and turbulence intensity profiles in rivers suitable for current energy conversion. Over the design life of a current energy converter, these models can be applied to examine the effects of large spatiotemporal variations of river flow depth on inflow conditions acting over the energy capture area. Significant engineering implications on current energy converter structural loads, annual energy production, and cost of energy arise due to these spatiotemporal variations in the mean velocity, turbulence intensity, hydrodynamic force, and available power over the energy capture area.

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Contents

1. Introduction

The siting and design of river current energy conversion (CEC) technologies requires an assessment of the spatiotemporal variation in the current velocity and turbulence acting on the proposed energy capture area (ECA) of the CEC machine. Fig. 1 illustrates typical profiles of current velocity and turbulence intensity in open channel flows, and demonstrates how the inflow characteristics vary over the ECA of the CEC machine. The average hydrodynamic force and available power estimates over a representative period of record are calculated as

$$\overline{F} = \frac{1}{2} \times \rho \times a \times \overline{u^2} = \frac{1}{2} \times \rho \times a \times (1 + I_u^2) \times \overline{u}^2 \quad (1)$$

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and

$$\overline{P}=\frac{1}{2}\times a\times\rho\times\overline{u^3}=\frac{1}{2}\times a\times\rho\times(1+3I_u^2+\gamma I_u^3)\times\overline{u}^3 \tag{2}$$

where ρ is the fluid density, a is the ECA, u is the instantaneous horizontal current velocity component, and $\gamma=\overline{u'^3}/\sigma^3$ is the skewness coefficient (which is negligible). The instantaneous horizontal current velocity component is assumed to be the predominant velocity component, which is perpendicular to the ECA at all times and is defined as the sum of the mean velocity and velocity fluctuation

$$u=\overline{u}+u' \tag{3}$$

The turbulence intensity is defined as

$$I_u=\sigma_u/\overline{u} \tag{4}$$

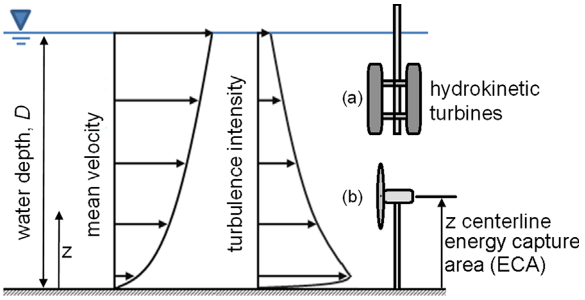

Fig. 1. Typical profiles of velocity and turbulence intensity in an open channel flow. The figure illustrates two possible hydrokinetic turbine configurations: a surface deployed vertical axis turbine (a) and a bottom deployed tower-mounted horizontal-axis turbine (b).

where $\sigma_u=\sqrt{\overline{u'u'}}$ is the standard deviation or root-mean-square (RMS) velocity. Detailed derivations of Eqs. (1) and (2) are provided in Appendix 1. These equations show that accurate assessment of the average hydrodynamic force and available power requires resolution of the turbulent fluctuations and turbulence intensity as well as the mean velocity. For example, a turbulence intensity equal to 20% at hub height of the CEC machine can increase the hydrodynamic force and power by 4% and 12.8%, respectively. The effects of turbulence should therefore be considered in the structural design and energy production calculations of a CEC machine.

In medium to large rivers that are desirable sites for commercial scale CEC development, defined here as open-channel flows with 50th percentile depths that exceed one meter and 50th percentile currents greater than 1 m/s, collecting accurate measurements of the instantaneous velocity u needed to calculate basic inflow metrics (such as $\overline{u}$, I_u, $\overline{F}$, and $\overline{P}$) is challenging [1]. River flows also exhibit great temporal variability of discharge and depth over time scales varying from minutes to days. For example, the USGS gage data for daily discharge and stage on the Missouri River, illustrated in Fig. 2, shows that discharges and water stages can increase tenfold during extreme episodic flood events over an approximately thirty-year period. This large variability in river discharge and depth is commonly observed and will affect the magnitude and distribution of mean velocity and turbulence over the ECA of a CEC machine over its design life. However, profile measurements needed to obtain meaningful statistics on the spatiotemporal variability of such important inflow metrics would rarely if ever be available due to the high cost and difficulty in obtaining such measurements. To obtain such measurements, an acoustic Doppler current profiler (ADCP) is the most practical and

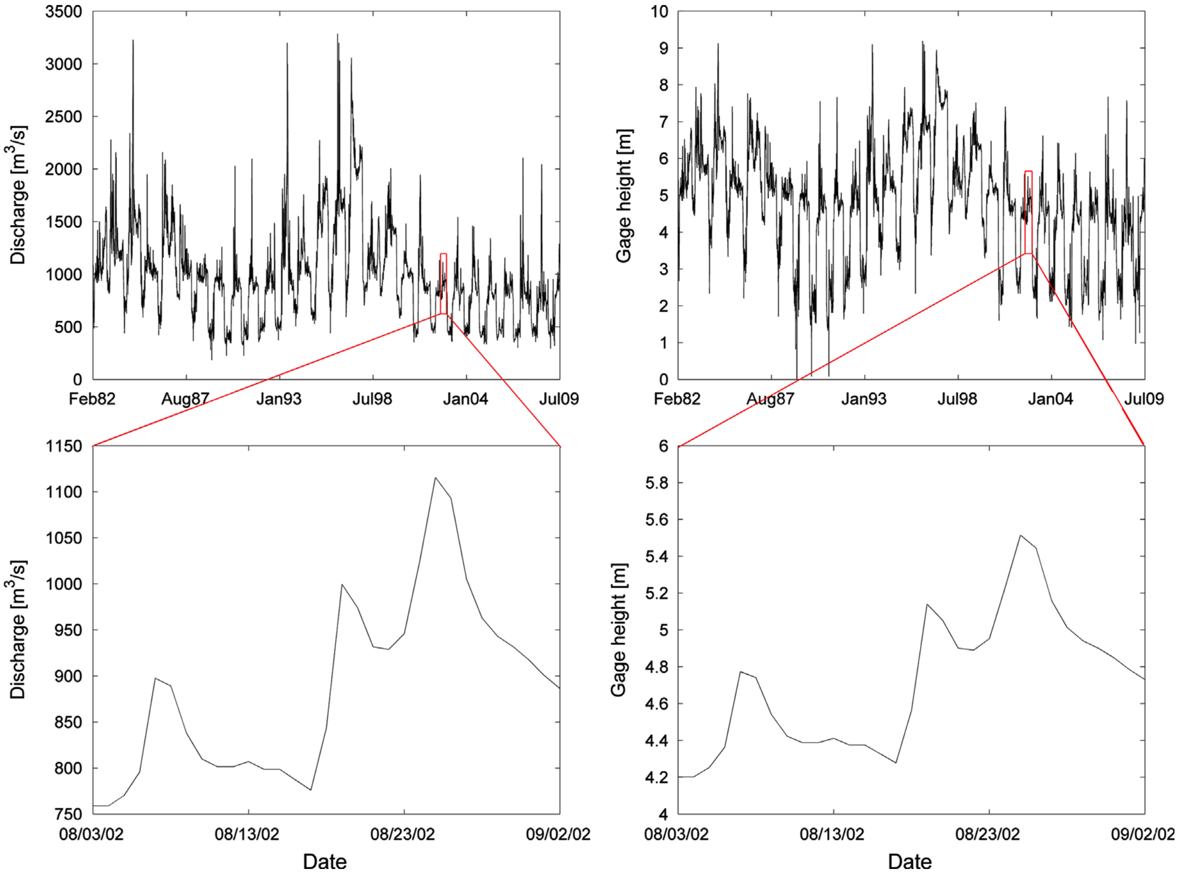

Fig. 2. Daily flow and gage height time-series record for approximately thirty-year period of record (POR) on the Missouri River, Nebraska (USGS 06610000). The inset plots show the flow and gage height time series during field measurements by Holmes and Garcia (2009).

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