Flow Characteristics of River Resources for Hydrokinetic Energy Conversion

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ABSTRACT

Most of our knowledge on current energy conversion resource characterization is derived from the wind power industry. River resource characterization for hydrokinetic technologies can certainly borrow from this knowledge base, but must consider unique attributes associated with river hydrodynamics. Published turbulent flow data from large rivers, a water supply canal and a laboratory flume are reviewed to determine the range of velocities and longitudinal turbulence intensities acting on hydrokinetic technologies, and also to evaluate the validity of classical models that describe the depth variation of the time-mean velocity and turbulent normal Reynolds stresses. A key challenge in river flow characterization is the high variability of depth and flow over the design life of a hydrokinetic device. This variation will have significant effects on the inflow mean velocity and turbulence intensity experienced by the hydrokinetic device, which requires further investigation. These effects may significantly alter estimates of energy production, structural loads, and ultimately the cost of energy at a river resource site.

INTRODUCTION

River hydrokinetic energy conversion (HKEC) developers need site velocity and turbulence information over the energy extracting plane of their device (Figure 1) for component design and estimation of power curves, annual energy production, and cost of energy. Measurements of mean velocity and Reynolds stress profiles, however, are not easily obtained for large rivers with depths exceeding several meters and currents greater than 1 m/s, given the challenges of deploying instruments under these hydrodynamic conditions. Rivers can have extreme variations in flow and stage, and measurements on the order of several decades are typically required to obtain meaningful statistics on the flow variability. It is impractical for instrument deployments to span the return periods found in rivers due to instrument limitations and prohibitive costs. Alternatively, classical models developed from laboratory experiments to describe velocity and turbulence profiles in open channel flows may be used to characterize river hydrokinetic resources. These classical models, however, have not been extensively validated for large rivers, particularly for the transverse and vertical components of the normal Reynolds stresses (Nezu and Nakagawa 1993). These models include the power and logarithmic laws for the vertical mean velocity profile of a flat plate turbulent boundary layer flow and exponential decay models developed by Nezu and Nakagawa (1993) for normal Reynolds stresses of depth-limited boundary shear flows in open channel flumes.

These classical models assume steady uniform flow, but unregulated rivers exhibit great variability of discharge and depth over time scales varying from hours to days depending on the size of the drainage basin. The discharge of regulated rivers, such as tailwaters below hydropower dams, can change within minutes, but exhibit less depth and flow variability than regulated rivers. Figure 2 shows daily discharge and stage data on the Missouri River for an approximately twenty year period. The discharge at this site varies over three orders of magnitude, and the stage varies from approximately 1 to 30 m. Also, both unregulated and regulated rivers are rarely uniform along their reaches. Channel geometry, roughness, mean-section depth and bulk velocity typically change along the longitudinal direction. In addition to challenges in characterizing the variations of bulk (section averaged) flow properties, the local mean flow properties of rivers can be highly three-dimensional as a result of variations in river alignment and vortex shedding from in-stream structures. Pressure gradients associated with nonuniform surface profiles cause significant departures in the wake region. Wind shear on the water surface also can cause significant departures from semi-theoretical models that estimate mean velocity and Reynolds stress profiles.

Despite these complexities, river hydraulicians often apply the models cited above for preliminary hydrodynamic characterization even though the laboratory experiments from which they were developed have none of the bathymetric and hydrodynamic complexities found in rivers. Can these classical models provide reasonable prediction for river resource characterization, or are detailed site specific field measurements required? What range of mean velocity and turbulence magnitudes can developers expect in rivers? If the hydrokinetic device is mounted to a rigid structure, the relative centerline of the energy extraction plane (hub height for horizontal axis turbines) with respect to the flow depth will vary as well as the current and turbulence that the device experiences. What are the effects of river depth and flow variability and how can field measurement protocols characterize these effects?

METHODS

The deployment sites of three HKEC industry partners are surveyed to illustrate the variability in the mean velocity and longitudinal turbulence characteristics acting on the hydrokinetic devices as the flow varies. Published turbulent flow profile data from five large rivers, a water supply canal and a laboratory flume were reviewed to evaluate the predictive performance of classical models that describe the depth variation of the time-mean velocity and turbulent normal Reynolds stresses. Large rivers were defined as those having a depth of at least one meter and velocities exceeding 1 m/s. This criterion significantly limited the data reviewed, but these large rivers with fast currents are characteristic of the sites being targeted by the HKEC industry

McQuivey (1973) measured mean velocity and turbulence profiles along reaches of the Missouri River downstream of Omaha, NE, the Mississippi River upstream of Vicksburg, MS, the Rio Grande conveyance channel near the intersection of Interstates 60 and 85 in New Mexico, and a large laboratory flume at Colorado State University. At these sites, mean velocity was first measured with a modified propeller meter, and then turbulence was measured with a hot film anemometer moved to the same location as the propeller meter. At the Missouri and Mississippi Rivers, the propeller meter and hot film instruments were suspended from a cable off the side of a boat, and measurements were conducted at several transverse locations across the channels.

Measurements in the Missouri and Mississippi Rivers were conducted at several different times and discharges. Bedforms consisted of dunes and flat conditions, and no influence from flow unsteadiness was reported at the Missouri and Mississippi River sites. At the Rio Grande conveyance channel, measurements were taken along channel centerline and the shallower depth permitted several propeller meters to be mounted simultaneously to a wading rod. Measurements at the Rio Grande canal were conducted during two different times: one at which large and mobile sand bedforms were present, and during the other condition the sand bed was flat. The laboratory flume was 61m long with a rectangular cross section 2.44m wide by 1.22m deep, and included sections with sand dunes and flat sand beds. The measurements reported herein were taken along the flume centerline 36.6m downstream from the headbox, and at two different discharges.

Holmes and Garcia (2008) reported turbulence measurements for a reach of the Missouri River, near St. Charles, Missouri using an acoustic Doppler velocimeter mounted to a sediment sampler suspended from a boat. This site on the Missouri River was fairly straight with sand dune height to water-depth ratios from 1/6 to 1/7, and the measurements were conducted during quasi steady flow conditions when the flow was well within the channel banks. Nikora and Smart (1997) measured turbulence with electronic Pitot tubes on the gravel-bed Hurunui River, New Zealand in the proximity of a bridge. Although these measurements on the Hurunui River were taken during the falling stage of a flood, Nikora and Smart showed that the unsteady effects would not have strongly influenced their turbulence measurements. Carling et al. (2002) measured velocity on River Severn, England during periods of over-bank flow on a nearly straight and deep gravel bed channel downstream of a double-meandering channel bend. The mean velocity profiles reported herein from the River Severn were conducted with a boat-deployed directional current meter over the thalweg, and the flow could be considered quasi steady over the specific period of time of data collection.

Velocity profiles from the reviewed data sets were further screened by inspection. By applying the log-law (Nezu & Nakagawa 1993) which describes the vertical distribution of longitudinal velocity in open channel flows with rough boundaries,

$$\frac{\bar{u}}{u_*} = \frac{1}{\kappa}\ln\left(\frac{z}{k_s}\right) + 8.5,$$

the authors computed the shear velocity, $u_* = \sqrt{\tau_o/\rho}$, from the slope of the best fit line through the time averaged vertical velocity profile. With the exception of the Holmes & Garcia data set, many of the reviewed vertical profiles contained only one or two data points in the wall region (z/D < 0.2) where the log law applies. For these cases, data from the entire vertical profile was used in this fitting method for calculating the shear velocity. Results for shear velocity using this method compared well with the values reported by the original investigators, and also calculated by McQuivey (1973), in which the shear velocity was determined by $u_* = \sqrt{gRS}$. Profiles with significant non-monotonic behavior due to 3D flow effects or vortex shedding were eliminated. This non-monotonic behavior was identified when the fitting procedure for the shear velocity resulted in a poor coefficient of determination, R^2; thus any profiles with R^2 values less than 0.8

were discarded. Of the velocity profiles reviewed, 13% were eliminated because they exhibited non-monotonic behavior or could not be well represented by the log law.

The final dataset included 39 profiles. Bulk flow properties for these open channel flows are summarized in Table 1. All Reynolds numbers are above 400,000 and Froude numbers indicate subcritical flows for all measurements with the maximum Froude number occurring for the Hurunui River in New Zealand (Nikora & Smart 1997).

Table 1. Bulk flow properties of reviewed open channel flow data

investigators	**site**	**Q_m**	**Q^***	**D_{avg}^***	**W^***	**Re^{**}**	**Fr^{**}**
		(m^3/s)	**(m^3/s)**	**(m)**	**(m)**	**(10^6)**	
McQuivey (1973)	Mississippi	19000[a]	7900-9200	7.4-16	570-890	3-9	0.06-0.17
McQuivey (1973)	Missouri	910[b]	890-920	2.9-3.1	200-210	4-38	0.19-0.35
Holmes & Garcia (2008)	Missouri	2200[c]	1400	4.9	350-400	5-9	0.13-0.17
McQuivey (1973)	Rio Grande canal	NR	14-26	0.85-0.91	21-22	0.8-1.3	0.36-0.49
Nikora & Smart (1997)	Hurunui	NR	250	1.2	85-90	1-5	0.70-0.79
Carling et al. (2002)	Severn	NR	100	NR	NR	3-6	0.10-0.16
McQuivey (1973)	2.44m flume	NR	1-2	0.33-0.53	2.44	0.4-0.8	0.69-0.74

NR = not reported
[*] reported by original investigators at time of measurement
[**] derived by authors, using depth averaged velocity and local water depth
[a] mean annual discharge from nearest USGS station #07289000, record period: 2009
[b] mean annual discharge from nearest USGS station #06610000, record period: 1953-2009
[c] mean annual discharge from nearest USGS station #06935965, record period: 2001-2010

The study adopts Reynolds averaging to decompose an instantaneous velocity component in to its mean velocity and turbulent fluctuation

$$u_i = \overline{u_i} + u_i^{'}$$

Substituting this into the Navier-Stokes equation, which represents the conservation of momentum for a fluid element at any instant in time and time-averaging produces the Reynolds-averaged-Navier-Stokes equation

$$\rho \frac{\partial \overline{u}_i \overline{u}_j}{\partial x_j} = \rho g_i - \overline{f}_i + \frac{\partial}{\partial x_j}\left[-p\delta_{ij} + \mu\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) - \rho \overline{u_i^{'} u_j^{'}} \right]$$

This equation states that the rate change of momentum of a fluid element per unit volume is balanced by the forces per unit volume acting on the fluid element. Forces on the right hand side of the equation include the gravitational body force, the drag force, and in brackets, the isotropic hydrostatic pressure force, viscous stresses, which are negligible outside the viscous sublayer, and the Reynolds or apparent stresses due to turbulence. The Reynolds stress tensor is symmetric and includes six terms, three normal stresses along the diagonal, and the three non-diagonal terms, which are shear stresses

$$\begin{bmatrix} \rho\overline{u'u'} & \rho\overline{u'v'} & \rho\overline{u'w'} \\ & \rho\overline{v'v'} & \rho\overline{v'w'} \\ & & \rho\overline{w'w'} \end{bmatrix}$$

The square root of the normal stresses divided by the density, $\sqrt{\overline{u'u'}}$, $\sqrt{\overline{v'v'}}$, $\sqrt{\overline{w'w'}}$, are the longitudinal, transverse and vertical turbulence intensities. For turbulent boundary layer flows, if the dominant flow direction is longitudinal, then the longitudinal turbulence intensity is the dominant intensity. In the wind energy industry, the percentage of this term with respect to the local longitudinal mean velocity $\bar{u}$ at the centerline of the energy extraction plane (hub height for horizontal axis turbines) is used to characterize the turbulence of the inflow for wind turbine design.

RESULTS

Velocity and Turbulence Distributions and Magnitudes

Figure 3a shows the 39 mean longitudinal velocity profiles. As expected, the mean velocity $\bar{u}$ is lowest near the channel bottom and increases as it approaches the free water surface $z=D$. The maximum $\bar{u}$ is usually near the free water surface. Maximum $\bar{u}$ values range from 1 to 4 m/s and depths z from 1 to 35 m for the data reviewed. Given that flow measurements for the Mississippi River by McQuivey (1973) were taken when the flow was well below the mean annual discharge Q_m (Table 1), one would expect higher maximum $\bar{u}$ at higher z and flows $Q>Q_m$. Figure 3b shows the corresponding longitudinal turbulence intensity profiles. These also follow known trends with an exponential increase from the free water surface to the near wall region. When comparing the velocity and turbulence profiles in Figure 3, one observes that the longitudinal turbulence intensity $\sqrt{\overline{u'u'}}$ ranges from approximately 0.05 to 0.5 m/s, and increases with $\bar{u}$. The no-slip condition requires that the turbulence intensity, and all components of the Reynolds stress tensor, is zero at the bottom of a fixed boundary, but field measurements are currently limited within the near wall region, even with state-of-the-art hydroacoustic instruments, and rivers typically have mobile beds with a non-zero mean velocity and Reynolds stresses. The minimum and maximum range of elevations for measurements by McQuivey, Holmes and Garcia, Nikora and Smart, and Carling et al. were z/D=0.03-0.91, 0.02-0.96, 0.27-0.93 and 0.06-0.77, respectively.

Figure 4 shows longitudinal turbulence intensity profiles with z normalized by the flow depth D. The turbulence intensity $\sqrt{\overline{u'u'}}$ is normalized by the local mean velocity $\bar{u}$ and multiplied by 100 to determine the turbulence intensity percentage with respect to the local mean velocity; a common way to non-dimensionalize turbulence intensity in the wind-energy industry for wind resource characterization. The turbulence intensity $\sqrt{\overline{u'u'}}$ is plotted on a logarithmic scale to show the large variation if turbulence. The plot shows that extreme values of turbulence intensity typically occur very close to the bed. When non-dimensionalized by the local $\bar{u}$, $\sqrt{\overline{u'u'}}$ increases exponentially from the free water surface z/D=1 into the near wall region

z/D<0.1, but the large scatter indicates that $\sqrt{\overline{u'u'}}$ does not scale with $\bar{u}$ to develop a simple one-to-one empirical relationship.

Comparison with Classical Models

Figure 5 compares field measurements of $\bar{u}$ non-dimensionalized by $\bar{u}_{\max}$ with the power law equation

$$\frac{\bar{u}}{\bar{u}_{\max}} = \left(\frac{z}{D}\right)^{1/\alpha}$$

Based on the power law assumption, $\bar{u}_{\max}$ occurs at the surface (z/D = 1), but the measured data shows that $\bar{u}_{\max}$ can occur beneath the surface due to wind, wave and three-dimensional flow effects.

The power law exponent $1/\alpha$ was observed to vary from 1/3 to 1/12 between individual profiles, with a best fit value of 1/5.4 through all the data. Variation in the exponent can be attributed to a number of causes, including measurement error, pressure gradients, roughness and three-dimensional flow effects. The significant differences between the exponents would translate in to more significant errors in drag and power acting on the energy extraction plane since drag and power are proportional to $\bar{u}$ to the second and third powers.

Figure 6 compares field measurements of normal stresses, e.g. $\sqrt{\overline{u'u'}}$, normalized by shear velocity $u_* = \sqrt{\tau_o/\rho}$ with exponential decay models developed by Nezu and Nakagawa (1993) for steady uniform flow in smooth laboratory flumes

$$\sqrt{\overline{u'u'}}/u_* = 2.30\exp(-z/D)$$
$$\sqrt{\overline{v'v'}}/u_* = 1.63\exp(-z/D)$$
$$\sqrt{\overline{w'w'}}/u_* = 1.27\exp(-z/D)$$

These expressions are universal for smooth boundaries between (0.1-0.2)< *z/D*<0.9, independent of Reynolds and Froude number, and show that $\sqrt{\overline{u'u'}}/u_* > \sqrt{\overline{v'v'}}/u_* > \sqrt{\overline{w'w'}}/u_*$. They do not apply near the wall approximately *z/D*<(0.1 to 0.2) as the no slip condition requires turbulence intensities to decrease from a maximum value to zero at *z/D*=0. Nor do they apply in the free surface region above *z/D*<0.9, where $\sqrt{\overline{w'w'}}/u_*$ is damped. A peak value of $\sqrt{\overline{u'u'}}/u_*$ =2.8 is observed in the near-wall region in wall coordinates at *z*+=17, where $z^+ = zu_*/\nu$ (Nezu and Nakagawa 1993). A peak in $\sqrt{\overline{u'u'}}/u_*$ could not be observed in any of the data reviewed because the measurements were not taken close enough to the bed.

The comparison indicates that the field measurements are in reasonable agreement with the exponential decay models developed from laboratory flumes, although there is considerable scatter. Measurement error as well as complex hydrodynamic effects summarized above are possible causes. The measurements by Holmes and Garcia (2008) are the only measurements known by the authors of the normal Reynolds stresses $\sqrt{\overline{v'v'}}/u_*$ and $\sqrt{\overline{w'w'}}/u_*$ in large rivers (depths > 1 m and currents > 1m/s). These turbulence measurements are in fair agreement with the exponential decay models, except near the surface where the models underestimate the data. Field measurements near the free water surface, however, are likely prone to error from wave motion and wind shear effects.

Effects of Depth Variability

Figure 7 illustrates the effects of large depth variability on the location of the energy extraction area and its centerline relative to the velocity and turbulence characteristic profiles. Two river hydrokinetic devices at sites with a large range of depth variability are compared to a tidal site where depth variability is not nearly as large. The centerline and height of the energy extraction plane is also non-dimensionalized with *D*, which causes the centerline and height to decrease with greater depth. In theory, the normalized velocity and turbulence distributions would remain unchanged with depth and flow changes. Therefore, Figure 7 illustrates the additional variation in velocity and turbulence that a device will experience over its design life as a result of moving up and down the relative depth *z/D*.

DISCUSSION

River resource characterization for HKEC will require new protocols and tools for field measurements and modeling in order to design device components against hydrodynamic loadings and to derive accurate estimates for annual energy production and cost of energy. The review of mean flow characteristics for rivers indicates that the classical flow models should be used with caution when applied to river resource characterization for HKEC devices.

At elevations above the river bottom of 0.5 m, velocities up to 4 m/s and longitudinal turbulence intensities up to 15 % are observed. For the data set observed in this study, 13% of the large river profiles were non-monotonic because of the hydrodynamic complexities of rivers. Of those that did exhibit monotonic behavior and fit the log law well, no universal exponent for the power law model was observed and considerable scatter was observed around the best fit line with an exponent of 1/5.4. The power law exponent varied from 1/3 to 1/12 for the data observed. Significant scatter was also observed for all three components of turbulence intensity when normalized by the shear velocity. Taking into consideration the reduced accuracy of velocity and turbulence measurements in large rivers and the uncertainty in calculation of the shear velocity, the reviewed turbulence measurements coincide fairly well with the semi-theoretical equations developed by Nezu and Nakagawa (1993). Although significant scatter is seen in the data, it is encouraging that the velocity and turbulence measurements clearly follow the trends of the logarithmic, power law and exponential decay models. This shows that these classical flow models can be used to provide coarse estimates of the vertical distribution of velocity and turbulence magnitudes in large rivers. However, detailed component design and estimations of

energy production will require higher accuracy than these classical flow models can provide, and site specific measurements are recommended by the authors for device design.

Depth and flow variability present challenges for characterizing river resources. The United States Geological Survey (USGS) provides flow and stage time series, but the gages may not be in close proximity to sites where resource characterization is desired, the period of record may be too short to be statistically meaningful, and river resource characterization requires accurate velocity time series to calculate energy production, structural loads, and cost of energy. Many hydrologists now believe that regional land use changes in river basins and climate change make statistical forecasting based on historical extrapolation questionable (Clarke 2007, Lima and Lall 2010).

More field measurements in rivers using state-of-the-art hydroacoustic instruments, such as acoustic Doppler current profilers (ADCP) and acoustic Doppler velocimeters (ADV), are needed to expand the limited data presently available for big rivers. Measurements of all six Reynolds stresses for big rivers with an ADV have yet to be reported and should be undertaken. Also, the river discharge during the period of measurement should be measured and compared to the mean annual discharge and other statistical measures for low flow and flood conditions at the closest USGS gage site. Field measurements should be taken during flows that are above, close to, and below the mean annual discharge to characterize the wide range of flow conditions at a river site.

ACKNOWLEDGMENTS

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NOTATION

$\bar{u}_{max}$	=	maximum longitudinal time-averaged velocity in vertical profile, m s^{-1}
u_*	=	shear velocity, $\sqrt{\tau_o/\rho}$, m s^{-1}
τ_o	=	bed shear stress, N m^{-2}
κ	=	Von Kármán constant
k_s	=	characteristic roughness length scale, m
g	=	gravitational acceleration constant, m s^{-2}
P	=	wetted perimeter, m
A	=	flow section area, m^2
R	=	hydraulic radius, A/P, m
S	=	water slope
Q	=	discharge, m^3 s^{-1}
Q_m	=	mean annual discharge, m^3 s^{-1}
W	=	local channel width, m
D	=	local water depth, m
D_{avg}	=	cross sectional average water depth, m
Re	=	Reynolds number, $\frac{U_{Davg} D}{\nu}$
Fr	=	Froude number, $\frac{U_{Davg}}{\sqrt{gD}}$
U_{Davg}	=	depth averaged longitudinal velocity, m s-1
u,v,w	=	instantaneous longitudinal, lateral, and vertical velocities, m s^{-1}
$\bar{u},\bar{v},\bar{w}$	=	time-averaged longitudinal, lateral, and vertical velocities, m s^{-1}
u',v',w'	=	instantaneous longitudinal, lateral, and vertical fluctuating velocities, m s^{-1}
$\sqrt{\overline{u'u'}}, \sqrt{\overline{v'v'}}, \sqrt{\overline{w'w'}}$	=	standard deviation of the longitudinal, lateral, and vertical velocities, m s^{-1}
x, y, z	=	longitudinal, lateral, and vertical coordinate distance, m
$\bar{f}$	=	body force per unit volume of fluid, N m^{-3}
p	=	isotropic hydrostatic pressure force, N m^{-2}
ρ	=	fluid density, kg m^{-3}
ν	=	kinematic viscosity, m^2 s^{-1}
μ	=	dynamic viscosity, N s m^{-1}
α	=	power law exponent (1/α)

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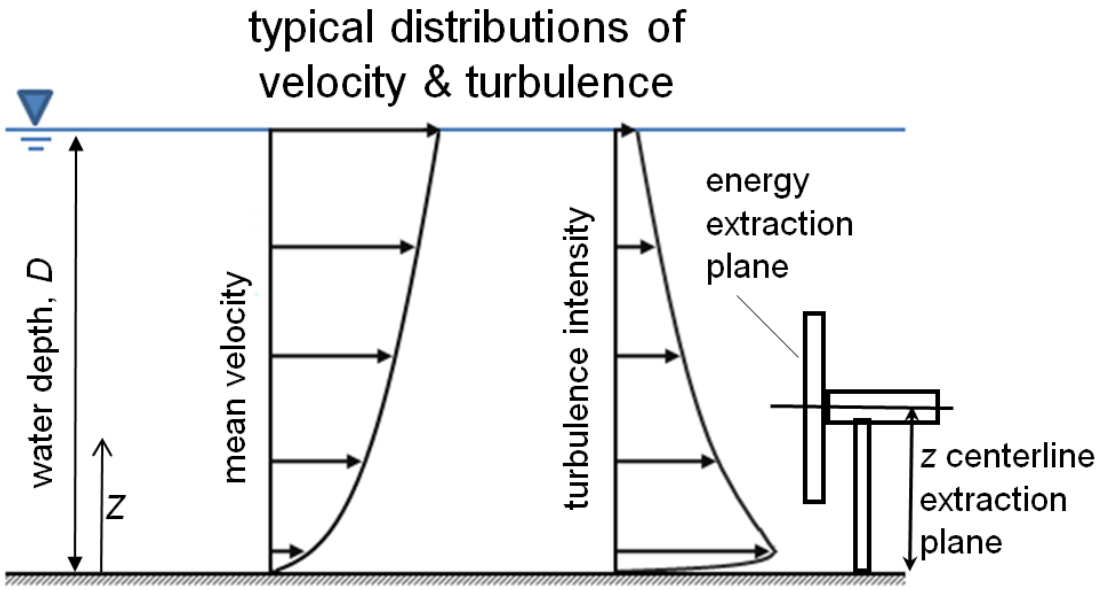

Figure 1. Typical distributions of velocity and turbulence and sketch of horizontal-axis hydrokinetic turbine.

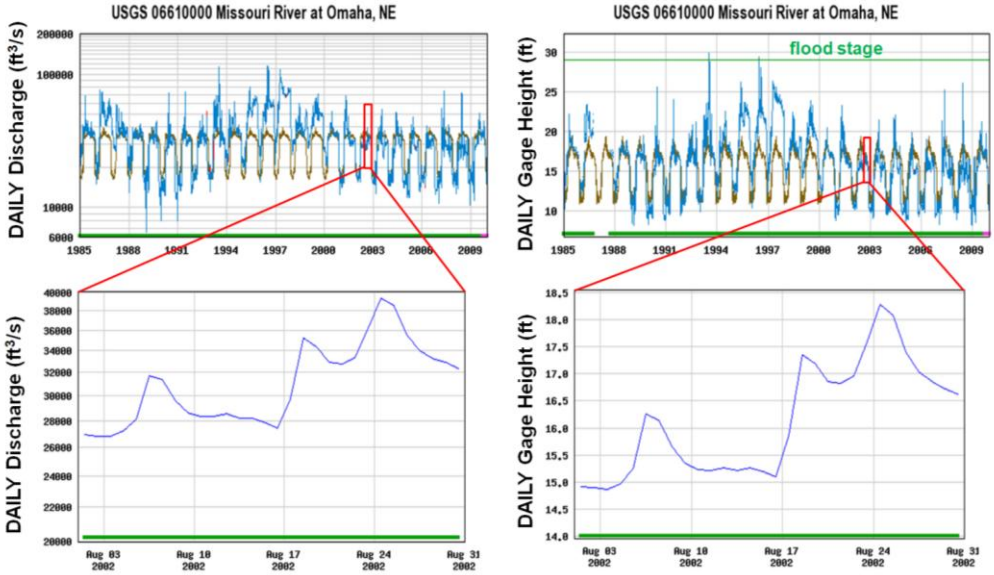

Figure 2. Daily flow and depth time-series record for approximately twenty-year period of record (POR) on the Missouri River, Nebraska (USGS 06610000). Blue indicates the daily values. Brown indicates the daily mean values for the (POR). The inset plots show the flow and depth time series during field measurements by Holmes and Garcia (2009).

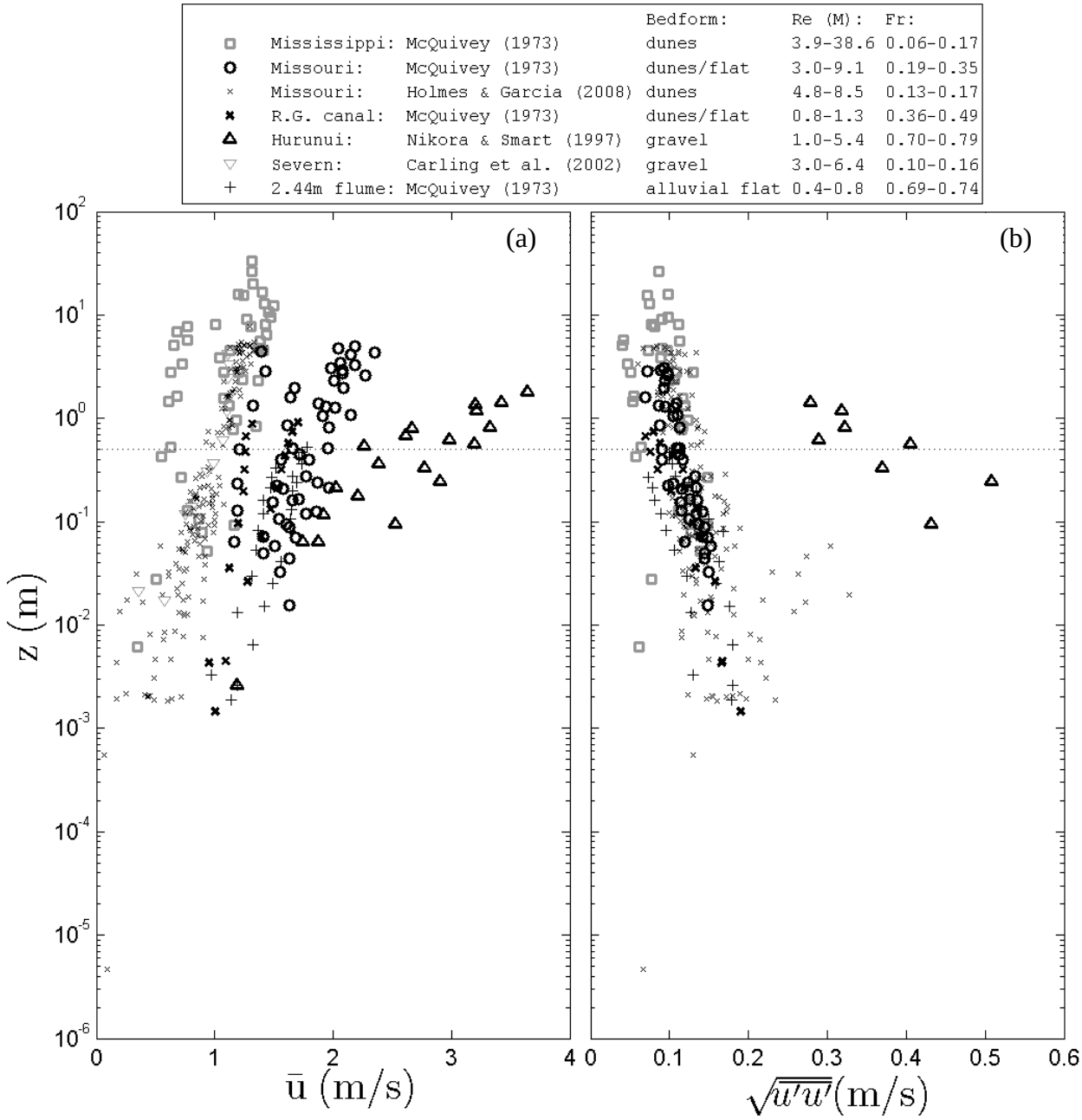

Figure 3. (a) Mean longitudinal velocity profiles. (b) Longitudinal turbulence intensity profiles. The dashed horizontal line indicates z = 0.5 m. HKEC devices will typically operate at depths greater than 0.5m off the bed.

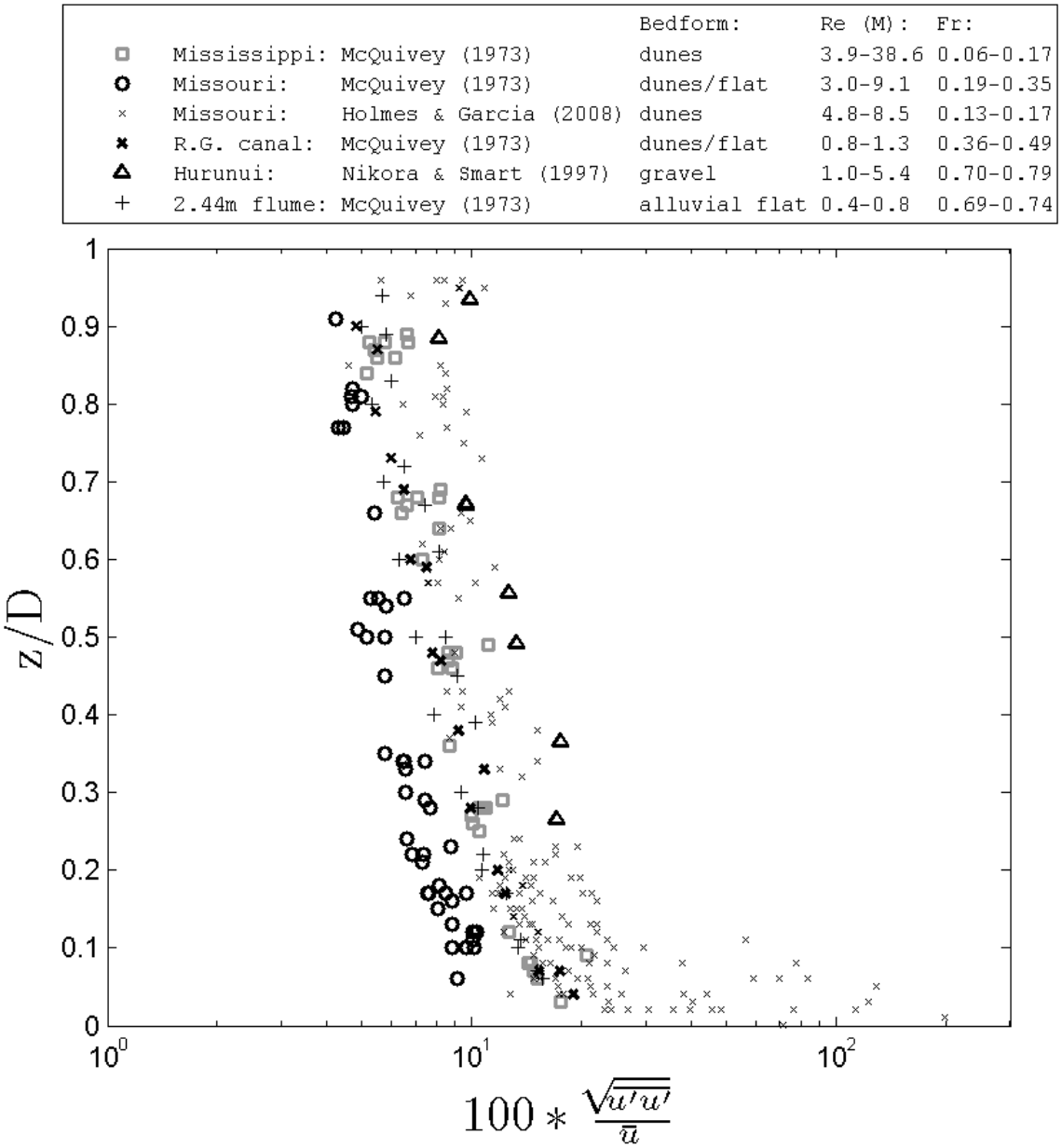

Figure 4. Longitudinal turbulence intensity profiles with z normalized by the flow depth and the turbulence intensity normalized by the local mean velocity and multiplied by 100 to determine the percentage of turbulence intensity with respect to the local mean velocity.

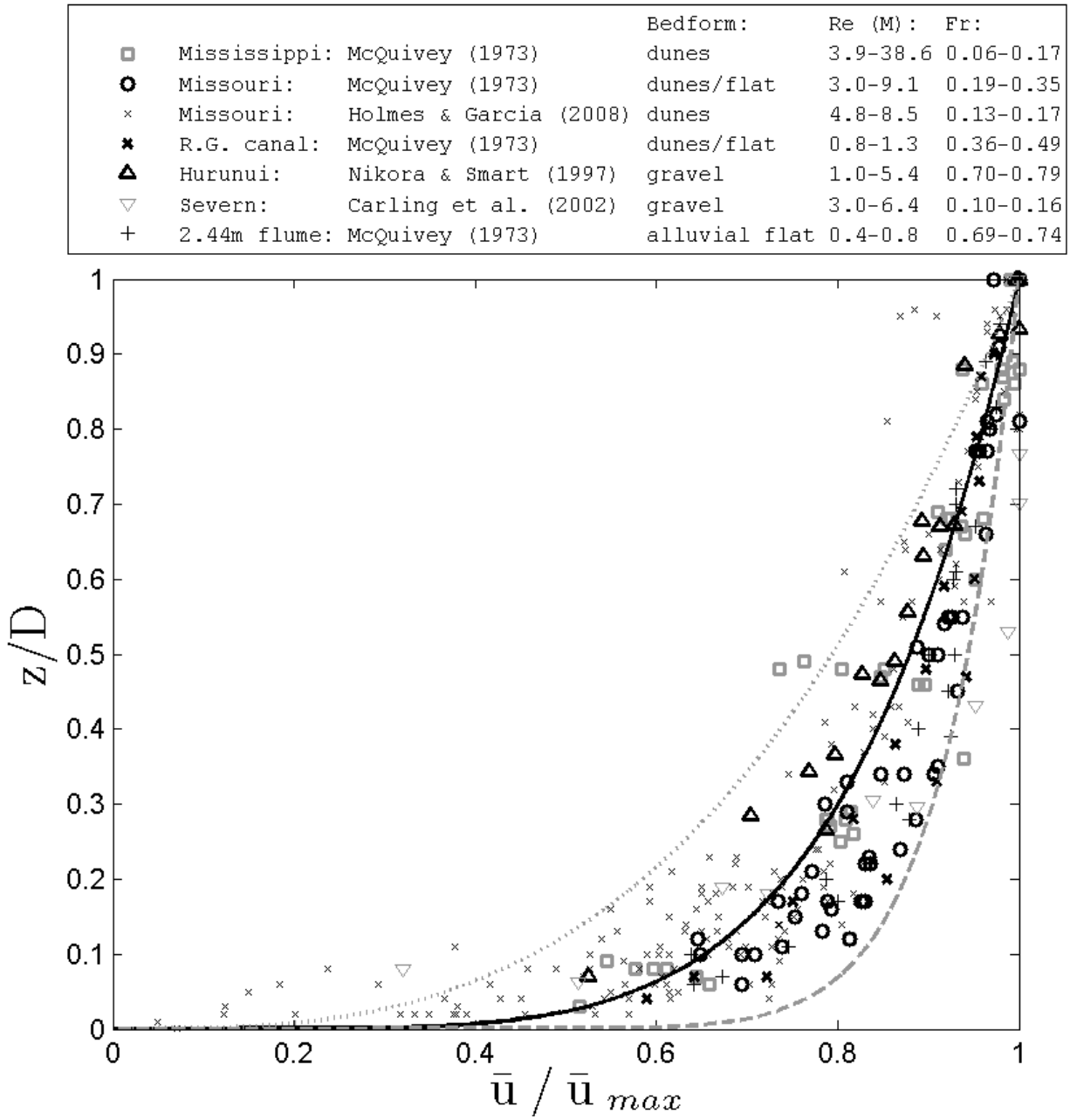

Figure 5. Power law velocity profiles with *z* normalized by *D* and $\bar{u}$ normalized by $\bar{u}_{max}$. The solid black line represents the best fit of the power law with exponent 1/α through the data, and the resulting best fit α = 5.4 (R^2 = 0.999). The dotted and dashed lines represent the power law with exponent 1/3 and 1/12, respectively.

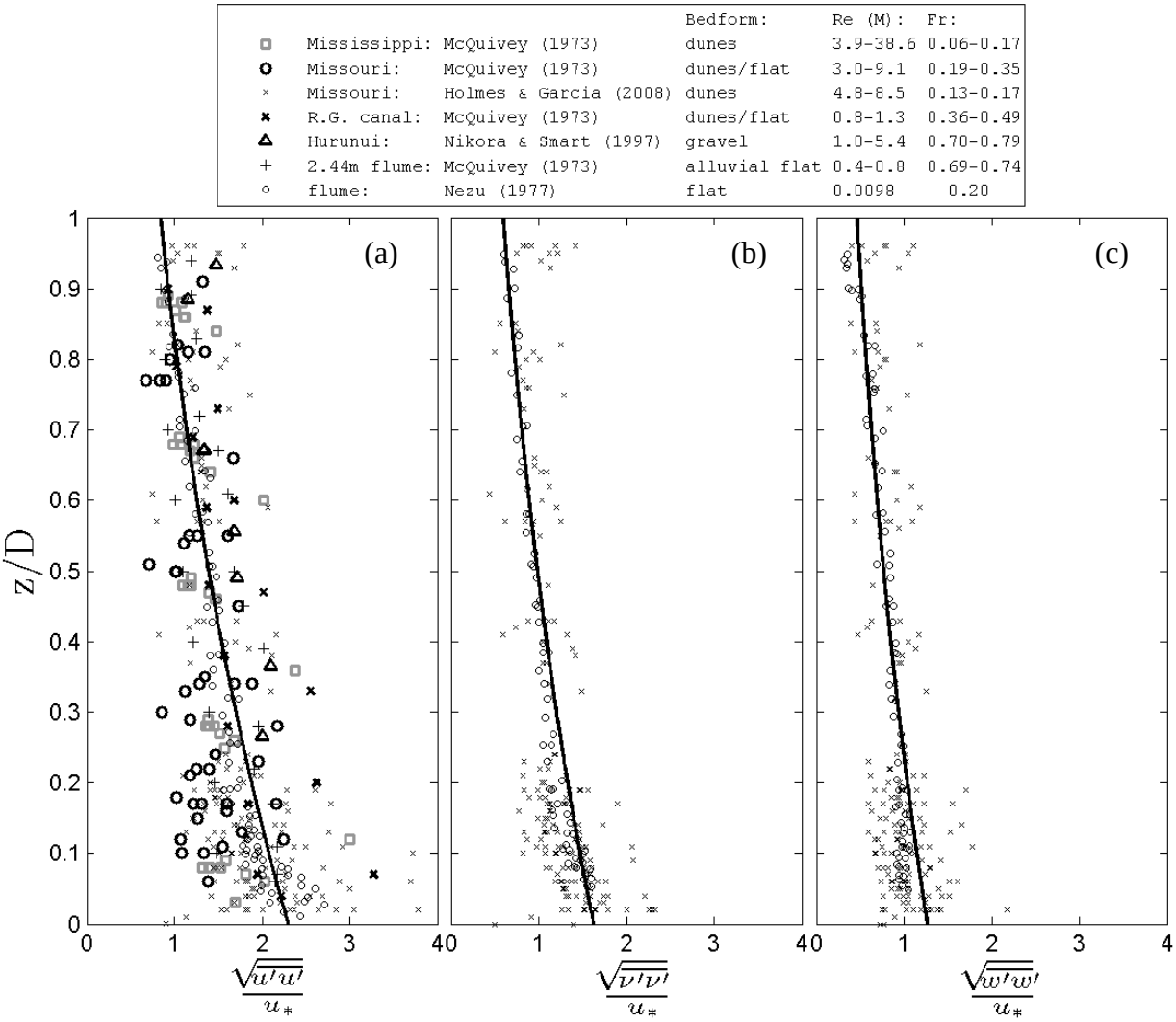

Figure 6. Exponential decay law profiles by Nezu and Nakagawa (1993) compared to field measurements, with *z* normalized by *D* and normal stresses, e.g. $\sqrt{\overline{u'u'}}$ normalized by shear velocity $u_* = \sqrt{\tau_o / \rho}$.

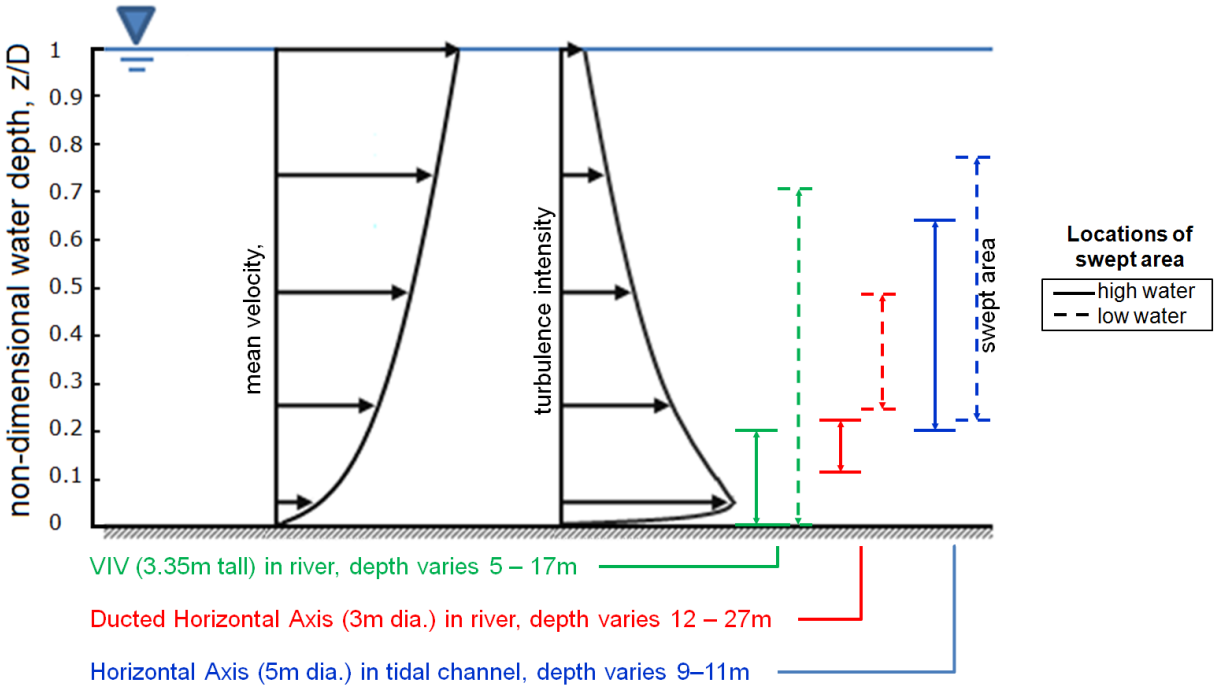

Figure 7. Effects of large depth variability on the location of the swept area (energy extraction area) relative to the velocity and turbulence profiles.