The effects of sampling location and turbulence on discharge estimates in short converging turbine intakes

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ABSTRACT
Standards provide recommendations for best practice when installing current meters to measure fluid flow in closed conduits. A central guideline requires the velocity distribution to be regular and the flow steady. Because of the nature of the short converging intakes typical of low-head hydro turbines, these assumptions may be invalid if current meters are intended to be used to estimate discharge. Usual concerns are (1) the effects of the number of devices, (2) the sampling location and (3) the high turbulence caused by the presence of fish diversion screens. These three effects were examined in the present study by using 3D simulated flow fields in both steady-state and transient modes. In the process of describing an application at an existing hydroturbine intake at Ice Harbor Dam, the present work outlined the methods involved, which combined computational fluid dynamics, laboratory measurements in physical models of the hydroturbine, and current meter performance evaluations in experimental settings. The main conclusions in this specific application were that a steady-state flow field sufficed to determine the adequate number of meters and their location, and that both the transverse velocity and turbulence intensity had a small impact on estimate errors. However, while it may not be possible to extrapolate these findings to other field conditions and measuring devices, the study laid out a path to conduct similar assessments in other applications.

Nomenclature

$A_{j,k}$ area cover by a particular $(j, k)$ VCM in the array \((\text{m}^2)\)

$dA$ vector area of faces enclosing a particular cell \((\text{m}^2)\)

$dl$ minimum distance between current meter and wall (m)

$d_{\text{min}}$ minimum distance between current meters (m)

$V$ cell volume \((\text{m}^3)\)

$d_{\text{VCM}}$ diameter of current meter (m)

$L_{\text{eff}}$ effective length measured by current meters (m)

$N_{\text{y}}$ number of current meters across the intake bay

$N_{\text{z}}$ number of current meters in the vertical direction of the intake bay

$Q_{\text{error}}$ discharge error estimate (%)\n
$Q_{j,k}$ partial discharge measured by an individual current meter \((\text{m}^3\cdot\text{s}^{-1})\)

$Q_{\text{ref}}$ reference discharge \((= 386.9\ \text{m}^3\cdot\text{s}^{-1})\)

$T_{\text{sim}}$ simulated time period (s)

$u$ fluid velocity vector \((\text{m}\cdot\text{s}^{-1})\)

$u_i$ fluid velocity component \((\text{m}\cdot\text{s}^{-1})\)

$U_{\text{rms}}$ root-mean-square of streamwise velocity \((\text{m}\cdot\text{s}^{-1})\)

$U$ averaged velocity in the streamwise direction \((\text{m}/\text{s})\)

$U_{j,k}$ streamwise velocity measured by an individual current meter \((\text{m}\cdot\text{s}^{-1})\)

$U_{j,k}'$ streamwise velocity measured by an individual current meter and adjusted by the error \((\text{m}\cdot\text{s}^{-1})\)

$W$ averaged velocity in the vertical direction \((\text{m}/\text{s})\)

$W_{\text{rms}}$ root-mean-square of the vertical velocity \((\text{m}\cdot\text{s}^{-1})\)

$\alpha$ flow angle \((^\circ)\)

$\Delta\delta,\Delta l$ spacing between current meters (m)

$\Delta t$ time step (s)

$\Delta x$ cell size (s)

$\kappa$ turbulent kinetic energy \((\text{m}^2\cdot\text{s}^{-2})\)

$\mu$ dynamic viscosity \((\text{kg} \cdot \text{s}^{-1} \cdot \text{m}^{-1})\)

$\mu_t$ turbulent viscosity \((\text{kg} \cdot \text{s}^{-1} \cdot \text{m}^{-1})\)

$\rho$ water density \((\text{kg} \cdot \text{m}^{-3})\)

$\sigma_{\phi}$ model coefficient for the conservative variable $\phi$

$\phi$ conservative variable

$\omega$ specific dissipation rate of $\kappa$ \((\text{s}^{-1})\)

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Acronyms

ASFM Acoustic Scintillation Flow Meter
CEATI Center for Energy Advancement through Technological Innovation
CFD Computational Fluid Dynamics
cfs cubic feet per second
DES Detached Eddy Simulation
ERDC Engineering Research and Development Center
HPC High-Performance Computing
ISO International Standards Organization
LDV Laser Doppler Velocimeter
RANS Reynolds-Averaged Navier–Stokes
RMS Root-Mean-Square
SCI Short Converging Intake
STS Submersible Traveling Screen
USACE United States Army Corps of Engineers
VBS Vertical Barrier Screen
VCM Virtual Current Meter

1. Introduction

Efficiency estimates of hydroturbines are essential in testing the performance of new turbine designs or reha-
bilitations and in supporting power-sharing decisions. Estimating discharge in the field represents the most
costly and time-consuming task to establish the relationship head–power–discharge of the system. Such com-
plexity varies according to a number of factors encountered in full-scale hydroturbine units, namely the geo-
metric regularity of the intake section, the shape of the cross section and the flow rate itself. For instance, dis-
charges in large hydroturbines pose a greater challenge than those through a small hydroturbine. For that rea-
son, the development of field, laboratory and simulation-based techniques for estimating discharge is an active
area of study in various dam operations around the world. This work presents a simulation-based method for quan-
tifying the accuracy of propeller-type current meters in short converging intakes. The main advantage of this
method is that it can be applied prior to deploying a measuring apparatus in the field. In particular, we eval-
uated the effects that both turbulent and transverse flows could have on the accuracy of discharge estimates. The
method is not restricted to propeller-type current meters and can be equally applied for other types of velocity
measurement instrumentation.

Short Converging Intakes (SCIs) are common struc-
tures for controlling and guiding water flow in low-head hydropower plants. SCIs tend to produce larger flow
instabilities, swirl, secondary flows, and skewness com-
pared with long penstocks (Cervantes, Andrée, Klason,
& Sundström, 2012). Such hydraulic conditions increase
both the variability in velocity recordings and the uncer-
tainty of discharge estimates. Past studies examined and
compared methods for estimating discharges in SCIs
with propeller-type current meters, which are afford-
able for sampling velocities at multiple points over a
cross section of the intake. Doering and Hans (1998)
found that both the location and number of measure-
ment points have a considerable effect on the discharge
estimates. Other techniques such as acoustic transit time
(Taylor, Almquist, & Walsh, 2010) and Acoustic Scintilla-
tion Flow Meters (ASFM) (Proulx, Lemon, Billenness, &
Aqflow, 2009; Taylor, Almquist, & Walsh, 2010) have also
been deployed and cross-compared, providing in general
similar discharge estimates. These studies also included
one field study from the Center for Energy Advance-
ment through Technological Innovation (CEATI, 2011)
which reported that the three aforementioned methods
deployed in an SCI at Kootenay Canal (British Columbia,
Canada) yielded acceptable discharge errors within 1.4%.

A common theme in these field studies is that flow
conditions in SCIs make it difficult to meet the require-
ments of standards that recommend best practices for
installing current meters to measure fluid flow in closed
conduits. This circumstance, in turn, affects discharge
estimates based on recorded velocities. Such standards
include PTC-18 (ASME PTC, 2011) and IEC-41 (1991),
which are based on the International Standards Orga-
nization's ISO 3354 (2008a) for steady flows with uni-
form velocity distribution. Complex scenarios of current
meter measurements in asymmetric and swirling flow
conditions are addressed in ISO 7194 (2008b) for flows
in circular ducts. Inferences and on-site observations
have identified that such assumptions are invalid in SCIs.
For preliminary evaluations of the feasibility of any flow
metering strategy, a computer-based representation of
the instrument deployment can aid in the design of field
studies.

In the present study, we used computational modeling
tools to estimate discharge errors from Virtual Current
Meters (VCMs) in an SCI subjected to three test condi-
tions: the number of VCMs, the sampling location, and
the presence/absence of flow-blocking structures (fish
guidance screens). To support that purpose, this docu-
ment is organized in the following manner. The site is
briefly described in Section 2. Then, simulated velocity
fields are described and compared against correspond-
ing velocity data from physical models (Section 3). Next,
the effects of the number and location of VCMs on the
discharge are estimated by using steady-state flow fields
(Section 4.1). Because highly transient flows are present
in the SCI, we also examined the effects of transverse
velocities and turbulence intensity on discharge estimates.
(Section 4.2). Each section contains a brief literature review followed by the methods and the results. Finally, we discuss and summarize our findings, and present conclusions at the end of the document.

2. Site description and discharge condition

The Ice Harbor Dam is operated by the US Army Corps of Engineers (USACE) Walla Walla District and is located in the US State of Washington, on the Snake River at river kilometer 15.6. The average annual river flow is approximately 1383 m$^3$/s (48,840 cfs). The dam consists of a concrete powerhouse, navigation lock, two fish ladders, a removable spillway weir, and a juvenile fish bypass facility. Construction of the Ice Harbor Dam began in 1956, three turbines and generators were put in operation in 1961, and three more units began production in 1976. The powerhouse has an overall length of 205 m. The 10-bay spillway is 180 m long and includes ten 15.24 m tainter gates. For a map of the dam location, an aerial view, and more details about the turbine units, see the corresponding section in the publicly available report of Harding, Romero-Gomez, and Richmond (2017).

At the dam, turbine units 1 through 3 have the same intake geometry with 20 wicket gates that have a maximum opening of 53$^\circ$ but rarely exceeding 47$^\circ$, and 19 stay vanes (see Figure 2.3 in Harding et al., 2016). The intake model simulated herein consists of three bays (labeled A, B, and C in Figure 1). The main structural components of the trash racks produce an initial level of flow variability that is further increased by the Submersible Travel Screens (STSs) deployed in each bay during nine months of the year. These STSs have the purpose of routing the juvenile salmonids toward the gate wells for safer passage during their downstream migration period. Vertical Barrier Screens (VBSs) are also deployed to further guide fish-carrying flows into outlet orifices so salmonids bypass the operating turbines and travel instead in a safer flow channel. The efficiency losses associated with the deployment of STSs is 1 to 3% in comparison with the absence of the STS (reported for McNary Dam–Unit 5 with ASFM in Lemon, Bilenness, and Lamp, 2003). This loss is partly related to increased velocity variability in the directions orthogonal to the stream flow. Such a large flow disturbance also has potential effects on the performance of a current meter installed in the intake. The present work compared the flows arising from the two scenarios – with and without STS – in a quantitative manner.

Hydraulic performance data were collected from a physical model at the selected discharge ($Q_{ref}$) of 386.9 m$^3$/s (13,660 cfs) at the Engineering Research and Development Center (ERDC), a USACE facility located in Vicksburg, Mississippi (Personal communication, ERDC, 2015). The scaling factors of the physical model followed a Froude scale ratio for length ($\lambda$) of 25 with respect to the prototype. During the laboratory test, LDV measurements were collected in Bay A at a location downstream from the STS (crosses in Figure 1) that lie between the two cross sections where VCM distributions were examined in the present study (VCM1 and VCM2). For the ‘STS model’, mean and root-mean-square (RMS) velocities were available in the streamwise and vertical directions ($U$ and $W$ velocities, respectively). To validate the modeling results at the prototype scale, these velocity measurements were multiplied by a Froude scale factor for velocity ($\lambda^{1/2} = 5$). No LDV data were available for the ‘No STS’ version of the model, and for that reason and because the meshing and solver settings remained the same in both model versions, we assumed that the numerical solution was of quality similar to that of the ‘STS’ version.

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![Figure 1](image-url)  
*Figure 1*. The intake model geometry included the STS and supplied flow data over both cross sections where the VCMs were located (VCM1 and VCM2) as well as on Laser Doppler Velocimeter (LDV) measurement locations (×) from the corresponding reduced-scale physical model (Personal communication, ERDC, 2015).
3. Computational fluid dynamics

The velocity fields within the intake were computed in transient mode using CFD simulations. The commercial CFD software STAR-CCM+® v9 (CD-adapco, 2014) was used for mesh generation and flow simulations at the prototype scale. The 3D-flow modeling approach herein was primarily based on the abundant literature about CFD applications in hydroturbine flows. Steady-state Reynolds-Averaged Navier–Stokes (RANS) formulations are the core of industry practice for calculating flows around hydroturbines and supporting structures (Hellström, Marjavaara, & Lundström, 2007; Khan, Wicklein, Rashid, Ebner, & Richards, 2004; Maruzewski et al., 2010; Nennemann, Vu, & Farhat, 2005; Prasad, 2012; Roh, Suh, Jung, & Jh, 2010; Wu, Shimmei, Tani, Niikura, & Sato, 2007). Alternatives to RANS formulations are the so-called eddy-resolving techniques, e.g. Detached Eddy Simulation (DES), which explicitly resolve a large extent of the flow transients and apply modeling formulations for velocity fluctuations near walls and at sub-grid scale. The DES strategy has been applied in reduced-scale models (Minakov, Sentyabov, Platonov, Dekterev, & Gavrilo, 2015; Paik, Sotiropoulos, & Sale, 2005) but has not been widely adopted for prototype-scale systems because of its computational cost. In the present application, we used High-Performance Computing (HPC) resources to apply a DES formulation that provided the flow conditions to conduct the VCM analysis.

The CFD technique consists of solving the transport equations of mass, momentum, and turbulence over a domain defined by the intake geometry and discretized into finite volumes. The general formulation of Equation (1) models the conservation principles of mass, momentum, and turbulence quantities, and establishes that the transient changes (first term on the left-hand side) are a result of convective fluxes through the cell boundaries (second term on the left-hand side), the diffusion processes acting on the bounding faces (first term on the right-hand side), and the dissipation and production of the conserved quantity (last term).

\[
\frac{\partial}{\partial t} \int_V \rho \phi \, dV + \int_A \rho \phi \mathbf{u} \cdot d\mathbf{a} = \int_A (\mu + \sigma_\phi \mu_\tau) \nabla \phi \cdot d\mathbf{a} + \int_V P_\phi \, dV. \tag{1}
\]

The values of \( \phi \) (the conservative quantity) and \( P_\phi \) (its rate of dissipation and production) take a form according to each equation: \( \phi = 1 \) and \( P_\phi = 0 \) for mass, \( \phi = u_i \) and \( P_\phi = 0 \) for momentum, \( \phi = \kappa \) and \( P_\phi = P_\kappa \) for turbulent kinetic energy, and \( \phi = \omega \) and \( P_\phi = P_\omega \) for the specific rate of dissipation of \( \kappa \). The treatment of the term \( P_\phi \) for \( \kappa \) and \( \omega \) constitutes the distinctive feature of the DES model, which was developed by Menter and Kuntz (2002) to enhance the prediction accuracy of unsteady separated flows behind moving vehicles. A description of the development and application of the DES method in general can be found in Spalart (2009), and of the detailed model formulation in the software manual CD-adapco (2014). The time-scale coefficient (\( C_{\kappa\omega} \)) for the blended upwind scheme was set to a value of 0.1 as in the original formulation (Travin, Shur, Strelets, & Spalart, 2002).

The CFD model used herein is the outcome of iterative improvements in accuracy of the modeling results. The model orientation was such that the streamwise velocity direction lined up with the X-axis, the lateral velocity with the Y-axis, and the vertical direction with the Z-axis (see axis orientation in Figure 1). The X- and Y-origins are located on the runner’s axis of rotation. The accuracy was judged based on the LDV data sets, and reported in the work of Harding et al. (2016). The mesh of 127.5 million cells was mostly composed of hexahedra with a base cell size (\( \Delta x \)) equal to 5 cm. This base cell size derived from a mesh dependency test done on a single bay. The simulation time step (\( \Delta t = 20 \) ms) was calculated by considering a reference flow velocity of 2 m/s to ensure that the Courant condition was lower than one. For boundary conditions, water surfaces at the forebay and tailrace were set as slip walls, solid boundaries were defined as no-slip walls, the inlet was set as a constant inlet velocity to match the selected discharge (\( Q_{\text{ref}} \)), and the outflow velocities were extrapolated from the adjacent cell value by applying reconstruction gradients. The screens and perforated plates at the STS were modeled as porous baffles with inertial resistance coefficients of 0.55 and 1.78, and porosities of 58 and 45%, respectively. More details of the CFD solution are documented and discussed in the work of Romero-Gomez and Richmond (2017).

The flow simulations were ‘warmed up’ for 60 seconds; once the velocity and pressure fields reached statistical steadiness, they were averaged for an additional period of 30 seconds (\( T_{\text{sim}} \)). To provide a general idea of the computational cost, the DES solution was completed in approximately 60,000 core-hours (nodes are dual Intel Haswell E5-2670 2.3 GHz CPUs, giving 24 cores per node).

Contours of both mean and RMS velocities from the LDV measurements and the CFD results are presented in Figure 2. The grid of points corresponds to the LDV measuring locations, all with \( X = -19.4 \) m in prototype scale. The CFD mesh on the LDV plane consisted of 103,500 faces. The face counts on the VCM planes were 104,700 and 103,500 for VCM1 and VCM2, respectively. Based on mass flow reports, approximately 20% of the
Figure 2. Contours of mean ($U$ and $W$) and root-mean-square ($U_{rms}$ and $W_{rms}$) velocity components from laser Doppler velocimetry recordings (top row), from CFD simulations with STS (middle row) and from CFD simulations without STS (bottom row). The color range for each velocity component (in m/s) is valid for the three data sets.

total incoming discharge passed through the STS porous regions. The STS caused the fluid flow to accelerate through the lower portion of the intake bay, causing a strong flow recirculation behind the screen. This gave rise to a mixing-layer type of flow downstream of the STS, a flow condition that extended into the distributor. The lower section exhibited larger streamwise velocities ($U$) than the upper portion ($Z < 3.5\text{ m}$). The upper portion of the cross section, however, showed comparatively larger RMS velocities due to the influence of the STS. The vertical velocity component ($W$) was mostly negative and qualitatively showed a degree of agreement similar to the streamwise velocities. The absence of the STS resulted in greater uniformity in the mean and fluctuating velocities over the cross section, and the greatest velocity gradients were found in the boundary layers. Overall, we considered that the agreement between CFD results and laboratory LDV data sufficed to conduct a VCM analysis.
based on simulated flows. More details about the solutions and depictions of flow features can be found in Harding et al. (2016).

4. Virtual current meter analysis

Because current meters are used for estimating discharge in hydropower intakes (CEATI, 2011; Lemon, Almquist, Cartier, March, & Brice, 1998; Proulx, Lemon, Billeness, & Aqflow, 2009; Slettenmark, 1940), we examined potential errors in velocity measurements caused by the strong flow disturbances within the intake. According to Lemon, Topham, Bouhadji, and Lampa (2004), the main error sources in turbine discharge estimates are related to the physical spacing between the measuring devices, the boundary effects from the solid walls and the large variability in velocity and turbulence fields caused by the trash racks and other supporting structures. CFD models have already been used for the evaluation of errors in acoustic Doppler profiler velocity measurements in streamflows (Mueller et al., 2007) and of ASFM bias in low-head hydropower intakes (Lemon, Bouhadji, Jiang, & Topham, 2004). In the present section, we have quantified the estimate errors from such sources using virtual measuring locations within the numerically simulated flow domains.

4.1. VCM analysis – effects of device location and array density

VCMs were set up in the intake bays as points sampling the velocity fields calculated with CFD (Section 3) and did not cause any flow blockage in the CFD simulation. They were located on the cross sections VCM1 and VCM2 in Figure 1. The total intake discharge was determined by using the velocity data interpolated on the VCMs and the velocity–area integration method. The VCM array was thus assumed to be a stationary array collecting velocities at all of the sampling locations concurrently over the same timespan. We assumed that measurements were made with an OTT C31 Type R current meter. The reasons for selecting this device were threefold: (1) this same meter has been used in studies of discharge estimates at an SCI (CEATI, 2011); (2) the device has been calibrated for performance with respect to flow angle (CEATI, 2011); and (3) the device has been calibrated for performance with respect to turbulence intensity (Fulford, 1995). The latter two features became useful for the transient analyses presented in Section 4.2. However, this meter was selected for the reasons above and this choice does not constitute either endorsement or approval by the authors. The current meter has a diameter ($d_{vcm}$) of 100 mm, and the VCM axes were perpendicular to the sampled plane.

The VCM1 section (Figure 1) was defined as the downstream face of the second gate slot ($X = -24.2$ mm). This location represented the measurement plane of a pre-assembled array of upstream-facing current meters deployed down the gate slot, given that this strategy had proven to be both practical and cost-effective in field studies (CEATI, 2011). Given its relatively close distance from the gate well, velocities at VCM1 are strongly influenced by recirculating flows behind the STSs, as well as by the residual discharge returning from the gate wells. Section VCM2 was defined at a downstream location before the three bays begin to converge into the scroll case ($X = -17.9$ mm). This cross section lies at the maximum possible distance for the intake flow to develop toward more uniform conditions than those at VCM1. We recognized that the deployment and maintenance of an instrument array at VCM2 would entail significant technical and financial challenges that may potentially make it impractical. But this study aimed to use VCM2 as a reference point against which the discharge estimates at VCM1 were compared. In this way, we examined the benefits of flow uniformity in reducing estimate errors.

ISO 3354 (2008a) prescribes a number of recommendations pertaining to the spacing of current meters:

1. a minimum of 25 instruments is required for a rectangular cross section – see Section 4.4.3 of ISO 3354 (2008a) – with a minimum of five straight lines running parallel to each of the cross-section boundaries;
2. a minimum distance of $d_{bl} = 0.75 \cdot d_{vcm}$ is required between the outermost current meter and the wall – see Section 4.4.1 of ISO 3354 (2008a);
3. a minimum distance of $d_{min} = d_{vcm} + 0.03 \ m$ is required between the axes of two adjacent current meters – see Section 4.4.1 of ISO 3354 (2008a);
4. a maximum blockage effect of 6% is acceptable, above which the standard does not apply.

Following the above-listed requirements, two schemes for the lateral and vertical spacings between VCMs were tested in evaluations of the effects of the number of devices (shown as ‘(a)’ and ‘(b)’ in Figure 3). Both configurations set the first instrument at the recommended distance ($d_{bl}$). The spacing scheme covered an effective length ($L_{eff}$) along the width and the height of each bay ($W$ and $H$) with laterally ($N_y$) and vertically ($N_z$) arranged VCMs, e.g. $L_{eff} = W - 2 \cdot d_{bl}$ in the lateral direction. We applied the configuration (a) when $N_y < 14$ and $N_z < 20$, and configuration (b) for a number of instruments $N_y > 14$ and $N_z > 20$. For the
cases \(N_y = 14\) and \(N_z = 20\), the distribution of VCMs followed the lateral and vertical positioning tested in the field and reported by CEATI (2011). Because configuration (a) used fewer meters, the location of the \(i\)th meter followed a parabolic positioning with respect to the near-wall instrument, thus resulting in spacing between two VCMs \((\Delta_i)\) equal to

\[
\Delta_i = \frac{2 \cdot L_{\text{eff}}}{(N - 1)^2} (2i - 3).
\]

Because of the larger number of available meters in configuration (b), we could theoretically ‘afford’ to set up four uniformly spaced VCMs near the wall to better account for the effects of the boundary layer \((d_{bl} + 3 \cdot d_{\text{min}})\). The meters outside of this boundary region were placed at a uniform spacing of \(\Delta\):

\[
\Delta = \frac{L_{\text{eff}} - 6 \cdot d_{\text{min}}}{N - 6}.
\]

The two configurations comply with recommendations (1) through (3) from ISO 3354. For recommendation (4), we used the maximum blockage area to determine the maximum number of meters in both directions. Field tests have revealed that discharge estimates with current meters are neither practical nor affordable in a fixed two-dimensional array of instruments simultaneously recording velocities. Instead, a moving frame and carriage system traveling vertically in the gate slot has proven to be feasible, efficient, and sufficiently accurate for discharge estimates in SCs. Therefore, we assumed that recommendation (4) was applicable to the blockage effect caused by a row of meters measuring an effective area defined by \(L_{\text{eff}} \cdot \Delta\), i.e. the gray square around the VCM in Figure 3(b) has an area of \(\Delta^2\). The values of \(d_{\text{vcm}}\), \(W\), and \(H\) made the maximum number of units in the horizontal and vertical directions \((N_y\) and \(N_z\)) equal to 21 and 38, respectively. Therefore, the discharge error relative to the reference discharge \((Q_{\text{ref}})\) was computed for each combination of vertical and lateral meters within the ranges \(5 < N_y < 21\) and \(10 < N_z < 38\).

The velocities \((U_{j,k})\) on each array were linearly interpolated from the 30-second two-dimensional field means on each of the VCM planes. The area covered by each VCM \((A_{j,k})\) in the array was defined by the mid-points between adjacent VCMs (or by the wall, for the outer-most locations). The total discharge for each array was calculated as the sum of all partial discharges \((Q_{j,k}\) in Equation 4) with the relative estimate error \((Q_{\text{error}}, \text{in } \%)\) being calculated with respect to \(Q_{\text{ref}}\) with Equation (5):

\[
Q = \sum_{j=1}^{N_y} \sum_{k=1}^{N_z} U_{j,k} \cdot A_{j,k}
\]

\[
Q_{\text{error}} = 100 \times \frac{Q - Q_{\text{ref}}}{Q_{\text{ref}}}. \quad (5)
\]

The discharge error from VCM planes from both model configurations (the ‘STS’ and ‘No STS’ cases) is presented in Figure 4 in the form of \(|Q_{\text{error}}|\) to illustrate qualitatively that the combinations of \(N_y < 10\) and \(N_z < 15\) yielded the largest deviations to the target discharge. Beyond such limits, the discharge error is small and only slightly affected by the test conditions selected in this study. By visual inspection, the placement of VCMs in a downstream cross section (VCM2) yielded slightly lower values of \(|Q_{\text{error}}|\) in coarse VCM arrays \((N_y < 10\) and \(N_z < 15\)). However, dense VCM arrays produced as much \(|Q_{\text{error}}|\) in both cross sections. The deployment of the STSs increased \(Q_{\text{error}}\) for the most part in both measuring locations, but the increment cannot be considered critical for deployment purposes. Therefore, the main outcome of a qualitative analysis based on the contour plot is that neither the VCM location nor the presence of the STS had a considerable influence on the discharge estimates. Furthermore, any array denser than \(N_y = 10\) and \(N_z = 15\) likely ensures that the discharge estimate errors remain low.

The tested arrays in Figure 4 spanned the full range of \(N_y\) and \(N_z\) that complied with the standard’s requirements, but field deployments would likely maintain a relatively similar spacing in both directions. A gradual increase in velocity sampling resolution in both directions is achieved by the combinations of \(N_y\) and \(N_z\) on the diagonal line shown in the upper left contour plot of Figure 4. The results from such combinations were selected and shown in Figure 5. This figure further reinforces in a quantitative manner the above-mentioned statement about the effects of the test conditions, where considerable improvements in discharge estimate took
place from (5, 6) to (9, 17), but diminishing benefits were observed beyond that point. Beyond the combination \((Ny, Nz) = (14, 26)\), a slight monotonic increase in discharge error for all of the curves indicated that the error source was not related to the array density but instead to the calculation method, which consisted of linearly interpolating flow velocities onto the VCM arrays and calculating discharge using the velocity–area integration method.

4.2. VCM analysis – effects of transverse velocities and turbulence intensity

The calibration of current meters usually consists of comparing meter readings against reference velocities that are highly controlled in laboratory settings (Camnasio & Orsi, 2010; Fulford, 2001). However, flow conditions in the laboratory and the field deployments are hardly ever commensurate, a fact that encourages the pursuit of studies to quantify the differences in devices’ performance between the two environments. Kallio (1996) conducted experimental work to determine the effect of transverse velocities on the performance of propeller-type current meters by subjecting the devices to a periodic vertical motion. This simulated a bobbing boat from which meters would be fixed in field operations. The study reported the largest errors in velocity measurement for instances when the ratio vertical-to-stream-velocity increased. Such large deviations originated primarily from an observed hydrodynamic unbalance of the device during the oscillatory motion, which was caused by the long tailpiece. CEATI (2011) carried out the calibration of current meters deployed in the field for discharge measurement by establishing the velocity recording error as a function of the flow angle \(\alpha\), defined with respect to the current meter axis. Because the recorded velocity should theoretically show a cosine response to off-axis flows, they plotted the error curve with respect to \(\alpha\) (shown in Figure 6(a)). Although measurements in the range \(-15^\circ < \alpha < 15^\circ\) did show very small errors,

![Figure 4. Comparisons of discharge error (in %) as a function of the number of instruments in the horizontal direction \((Ny)\) and vertical direction \((Nz)\).](image)

![Figure 5. \(Q_{\text{error}}\) (in %) as a function of a gradual bi-directional increase in the number of VCMs (the dotted diagonal line shown in the upper left contour plot of Figure 4).](image)
they were set equal to zero because the device was constructed to account for the so-called component effect within such an angle range, as described in the technical specifications.

In addition to transverse velocities, the effects of velocity pulsations in the streamwise direction on meter accuracy have also been investigated with laboratory runs by Jepson (1967) and Fulford (1995). In both studies, the pulsating effect was achieved by subjecting the meters to a sinusoidally oscillating motion derived from a Scotch-yoke apparatus rotating at a prescribed frequency \( \omega \). Jepson (1967) observed monotonically increasing overestimations of registered velocity in a small three-bladed meter (3 cm diameter) operated at high frequencies (2.62, 5.25, and 10.5 Hz). Fulford (1995) determined recording errors specific to the current meter used in the present study at small frequencies (0.03–0.2 Hz). These frequencies are also representative of large-scale turbulence in hydroturbine intakes. The response of the current meter at three mean flow velocities \( U_0 \) as a function of the turbulence intensity \( u_{rms}/U_0 \) is shown in Figure 6(b). Because the turbulence intensity was computed with respect to the mean flow, the errors associated with \( U_0 = 0.008 \text{ m/s} \) were negatively large for values \( u_{rms}/U_0 < 0.5 \) but positive beyond that point. In our application, such low-velocity conditions have a very limited contribution to the discharge (the partial discharge from a near-zero velocity measurement is small).

The errors associated with the turbulent fluctuations could also be determined from averaged 3D fields of velocity in a manner similar to the evaluation done in Section 4.1, but we used transient velocities instead. The reason for this is that neither \( \alpha \) nor its associated error is a linear operator that can be averaged over time. An analysis in transient mode is therefore required. For a detailed examination of representative VCM arrays, the following three configurations were selected to investigate the effects of both the transverse velocities and the turbulence intensity on meter performance:

- a coarse grid, \( N_y = 5 \) and \( N_z = 10 \),
- a mid-density grid, \( N_y = 14 \) and \( N_z = 20 \),
- a fine grid, \( N_y = 21 \) and \( N_z = 38 \).

In each VCM array, the instantaneous error due to transverse velocities was calculated dynamically from 2D velocity fields over the planes VCM1 and VCM2 (\( T_{sim}/\Delta t = 30/0.02 = 1500 \) planes with 2D-velocity fields were exported during the CFD simulation). The velocities were interpolated on the VCM array. Figure 7 (top chart) shows an example of the transient series of streamwise \( U \) velocity and the velocity magnitude sampled near the center point of Bay B at location VCM1. With such values, the instantaneous flow angle was determined over the entire simulation period (middle plot), as well as its associated error (bottom plot) based on the empirical relationship in Figure 6(a). Notice that only values of \( \alpha > 15^\circ \) resulted in a non-zero error. To quantify the overall effect of these errors, we computed discharges based on two time series: one with the streamwise velocity without including the error, or \( U_{j,k}(t) \), and the other accounting for the underestimation as \( \bar{U}_{j,k}(t) = [1 - error(t)] \cdot U_{j,k}(t) \). The latter represented the velocity reading from the meter.

Because the time interval was constant in both series \( U_{j,k}(t) \) and \( \bar{U}_{j,k}(t) \), we averaged them out to obtain mean velocities \( U_{j,k} \) and \( \bar{U}_{j,k} \), respectively, at each VCM. With these values, Equations (4) and (5) were used to estimate discharges and their \( Q_{error} \) with respect to the target, respectively. The results are listed in Table 1.
Figure 7. Transient streamwise velocity and velocity magnitude (top), velocity angle around the VCM axis (middle) and the associated error due to the influence of the flow angle on the meter recordings as stipulated by Figure 6.

Table 1. Discharge estimate errors (in %) due to the effects of transverse velocities, from three selected VCM arrays at locations VCM1 and VCM2 under both STS configurations, with respect to the reference value of 386.9 m$^3$/s.

| Array      | VCM1 | VCM2 | VCM1 | VCM2 |
|------------|------|------|------|------|
| 5 x 10     | −1.48| −1.07| −1.02| −0.10|
| 14 x 20    | 1.29 | 0.43 | 0.81 | 0.47 |
| 21 x 38    | 0.38 | 0.16 | 0.31 | 0.19 |

Table 2. Discharge estimate errors (in %) due to the effects of turbulence intensity, from three selected VCM arrays at locations VCM1 and VCM2 under both STS configurations, with respect to the reference value of 386.9 m$^3$/s.

| Array      | VCM1 | VCM2 | VCM1 | VCM2 |
|------------|------|------|------|------|
| 5 x 10     | −1.48| −1.07| −1.02| −0.10|
| 14 x 20    | 1.29 | 0.43 | 0.81 | 0.47 |
| 21 x 38    | 0.38 | 0.16 | 0.31 | 0.19 |

The transverse velocity had only a slight impact on the estimate errors. Notice that the coarse grid ($N_y = 5 \times N_z = 10$) lies outside the recommended limit discussed in Section 4.1 ($N_y > 10$ and $N_z > 15$ for minimum estimate error). In the transient analysis, the maximum error due to the transverse velocities in a coarse grid was $−2\%$ (from VCM1 when STS was deployed). Upon increasing the VCM array size, only marginal improvements were observed from the middle-density to the fine grid. These calculations based on transient velocities further confirmed the benefit of selecting a downstream location for velocity sampling; i.e. VCM2 yielded lower absolute errors than VCM1 did, all other things being equal. However, the influence of the STS is not settled; i.e. errors neither consistently increase nor decrease in a ‘No STS’ configuration. The selection of various cross sections along the intake and of more arrays could probably reveal a trend in either direction. Overall, changes in discharge estimates were so small for the three modeling treatments (array size, STS deployment and VCM location) that no meaningful impact can be claimed. We hypothesize that the reason for this could be the following. It is true that intake flows in low-head turbine units do develop large transverse velocities in comparison with other flow-directing structures such as penstocks, natural streams, and open channels (where current meters are commonly used). However, the recording error curve used herein accounted for transverse velocities relative to
considerably large streamwise velocity (due to the contracting geometry), thereby yielding relatively small flow angles. This velocity ratio may have mitigated the errors to a large extent.

The discharge estimate errors accounting for turbulence intensity are shown in Table 2. In comparison with the transverse velocity effects, accounting for the turbulence intensity yielded an overall underestimation in discharge for the three treatments tested (array size, STS presence, and VCM location). In addition, the turbulence intensity tended to produce greater estimate errors (by approximately 0.5–1.5%) than the transverse velocity did. The CFD results for turbulence intensity revealed high levels in the STS configuration (area-weighted average of turbulence intensity equal to 15.7 and 21.8% in VCM1 and VCM2, respectively). This might at first suggest that the effects from turbulence intensity should be considerable. However, streamwise velocities at VCM1 and VCM2 are greater than the highest \( U_0 \) value from the curves in Figure 6(b). In such velocity conditions, the current meter exhibited very low errors regardless of the turbulence intensity value. In this context, it is relevant to mention that the various meter devices reported by Fulford (1995) exhibited similar low-level errors at \( U_0 \approx 1.0 \, m/s \), thereby suggesting that any such devices would likely yield small estimate errors associated with turbulence intensity. Based on the same rationale, it is likely that lower streamwise velocities (e.g. from low discharge operating points) would produce greater discharge estimate errors than the ones calculated with the selected discharge (\( Q_{ref} \)).

The estimate errors should be put in context with field estimates and standard requirements. In the field deployments, the performance of current meters has been compared with that of ASFMs at various large dams in a wide range of operating points. Differences in discharge of 1.1% (Proulx et al., 2009) and 1.8% (Proulx, Cloutier, Bouhadji, & Lemon, 2007) between the two methods were reported, with greater deviations occurring at low discharges. In ISO 3354 (2008a), the guidelines aim at achieving an uncertainty in flowrate that is no greater than \( \pm 2\% \) when the STSs were deployed. Therefore, the present results reinforce the conclusion that discharges measured by the mid and fine arrays yield acceptable estimate errors, even when the effects of transverse velocity and turbulence intensity are included in the calculation.

5. Conclusions

This study examined three factors affecting the performance of current meters for estimating discharge in short converging intakes of hydroturbine units: the number of devices used for sampling velocity, the sampling location, and the turbulence conditions. The analyses were conducted based on flow conditions simulated using CFD in both steady-state and transient modes at high spatiotemporal resolution. Such simulated data were favorably validated with corresponding velocity measurements in a physical model and constituted an accurate data source to feed into laboratory-determined relationships of the response of the selected current meter model as a function of transverse and pulsating flows. In this way, the study linked 3D simulated velocity fields, laboratory velocity measurements of intake flows, and current meter performance tests in laboratory settings.

Steady-state flow fields sufficed to determine the optimal number of current meters to maintain the discharge estimate errors within an acceptable level (\(< 0.5\%\)). In the present application, the optimal VCM array size was valid in both measuring locations examined (\( N_x = 10 \) and \( N_z = 15 \) in the horizontal and vertical directions, respectively). The minimum array size tended to yield large estimate errors even though it followed the guidelines from standards. General guidelines suggest that the device performance could increase considerably in uniform flows, which in a hydroturbine intake translates into locations that are technically challenging to access when the STSs are in place. But our study revealed that the benefits of sampling velocities further downstream from the STSs are rather marginal.

The transverse velocities made a limited contribution to discharge estimate errors because, in combination with the axial velocities, they tended to produce flow angles below the angle limit at which effects begin to emerge. In fact, the selected device had the largest angle range among the considered models. More sensitive devices will likely yield estimate errors greater than those observed using the selected meter. The turbulent conditions of the intake flows were relatively high (15.7–21%) but did not affect the discharge estimates considerably, mainly because the fluid velocities were for the most part at large values (> 1 m/s) where the selected current meter did not show any considerable response to turbulence. This conclusion should not be extrapolated to other field conditions where low velocities may prevail or to other current meters that are more sensitive to turbulence intensity. In addition, other likely sources of measurement error in the field were not examined in the present study; for instance, the frame and carriage supporting the meters, the vibrations induced by the flow on the assembly/instrument, and the presence of suspended material in the flow.

The present study laid out a method for using computed flow fields to design field studies of discharge
estimates in large intakes. The approach described here can be used to analyze the performance of other types of discharge measurement instrumentation. Although we based our analyses on high-resolution flow fields, dam operators and managers with access to low-resolution flow models (e.g. RANS-based) could potentially conduct preliminary experimental designs of measuring equipment for discharge estimates.

Acknowledgments
The computations described herein were performed using the facilities of the Pacific Northwest National Laboratory institutional computing center.

Disclosure statement
No potential conflict of interest was reported by the authors.

Funding
This research was funded by the US Department of Energy, Energy Efficiency and Renewable Energy, Wind and Water Power Program. The Pacific Northwest National Laboratory (PNNL) is operated for the US Department of Energy by Battelle [Contract No. DE-AC06-76RLO 1830].

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