University of Belgrade, Faculty of Civil Engineering

Uncertainty assessment of flow measurements at Iron Gate 2

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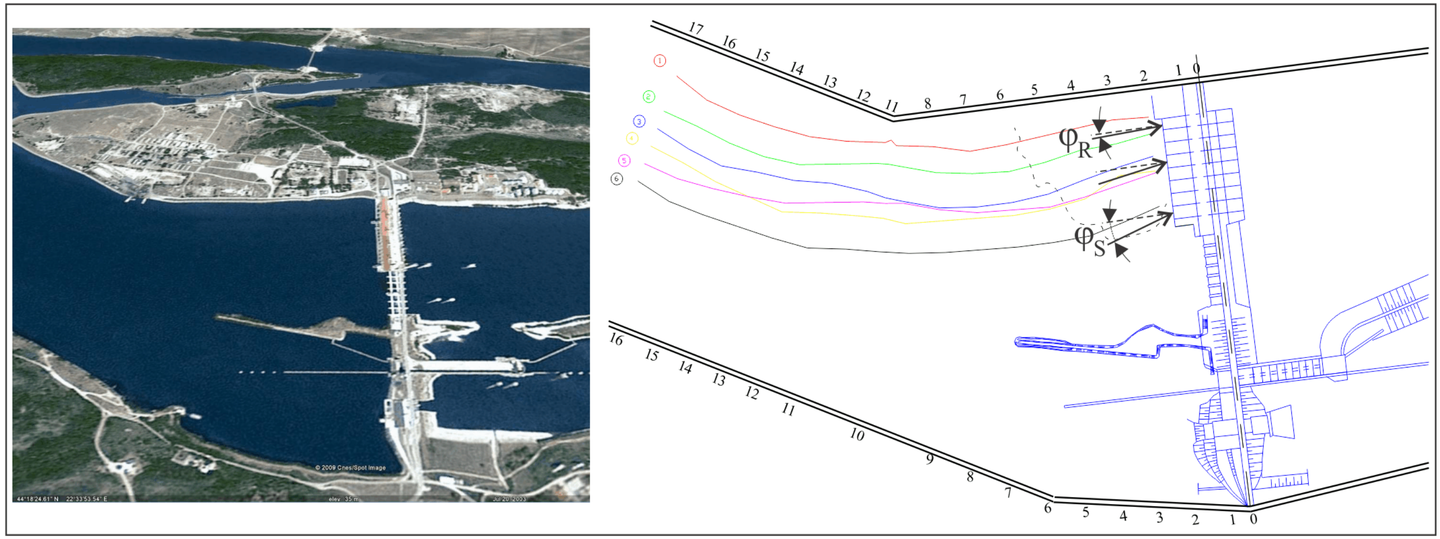
Iron Gate 2 HPP: Measurement features

- Recapitulation

1. Incremental mode (primary mode):

Steel frame is incrementally traversed between equidistant (~1.0 m) profiles.

Measurement time ~ 4 hours (> 10 min per profile)



2. Continuous mode (secondary mode):

Steel frame is continuously traversed from bottom to the top.

Constant traversing speed ~ 0.05 m/s (average water depth ~ 26.0 m)

Measurement time up to 9 minutes

Iron Gate 2 HPP: Measurement features

- Recapitulation

1. We assume the **analogy** EM meter ~ Current meter
2. **Incremental** mode > **7200** measurements with each probe

   Continuous ~ **270** measurements with each probe
3. Measurements were made in "**constant power**" turbine operating mode.
4. In incremental mode, flow rate fluctuations exist (constant power regime – guide and runner vane movements). **Measured velocities are linearly corrected** to compensate for the effect on the discharge measurements.
5. **Extrapolation of the velocity field** in the peripheral flow area - both with **power** (wall and bottom) and **linear law** (top – free surface).
6. **Negative velocities** (stemming from the large-scale turbulent structures with vertical and horizontal axis perpendicular to the inlet) were measured near the free surface
7. **High incident flow angles** up to 40^{o} were commonly observed.
8. During the measurements **large chunks of river vegetation and debris** were seen to pass the measurement system and/or get attached to it.

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Are these features considered in the uncertainty procedures suggested by standards?

Iron Gate 2 HPP: Measurement uncertainty

- What are the standards suggesting?
- IEC 60041 → **ISO 3354**

Measurement of clean water flow in closed conduits — Velocity-area method using current-meters in full conduits and under regular flow conditions

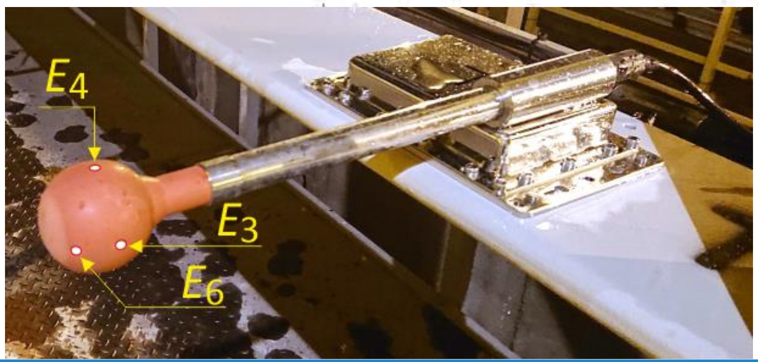
I. We have free surface flow not the full conduit
II. We actually do not have the regular flow conditions
III. But we do have "a special measuring technique" = 3D EM current meter

10.2.4 *Measurements in short penstocks or intake structures*

10.2.4.1 General

A penstock is defined as short if the straight length is less than 25 diameters.

No existing standard deals with discharge measurements in short penstocks or intakes, especially for low-head plants. ISO 3354 may be used as a guide especially the clauses stating general requirements and those dealing with rectangular cross-sections. Also applicable are the general requirements of 10.2.2 of the present standard. The main difficulty with this type of gauging arises from the fact that the measuring section may be located in a short converging conduit with uneven and/or unstable velocity distributions as well as oblique flow to the current-meters. Attempts should be made to remedy these difficulties either by a straightening device (see 10.2.4.2) or by special measuring techniques (see 10.2.4.3).



Clearly, to estimate the discharge measurement uncertainties a custom-tailored procedure is needed!

Iron Gate 2 HPP: Measurement uncertainty

- Velocity-area discharge measurement

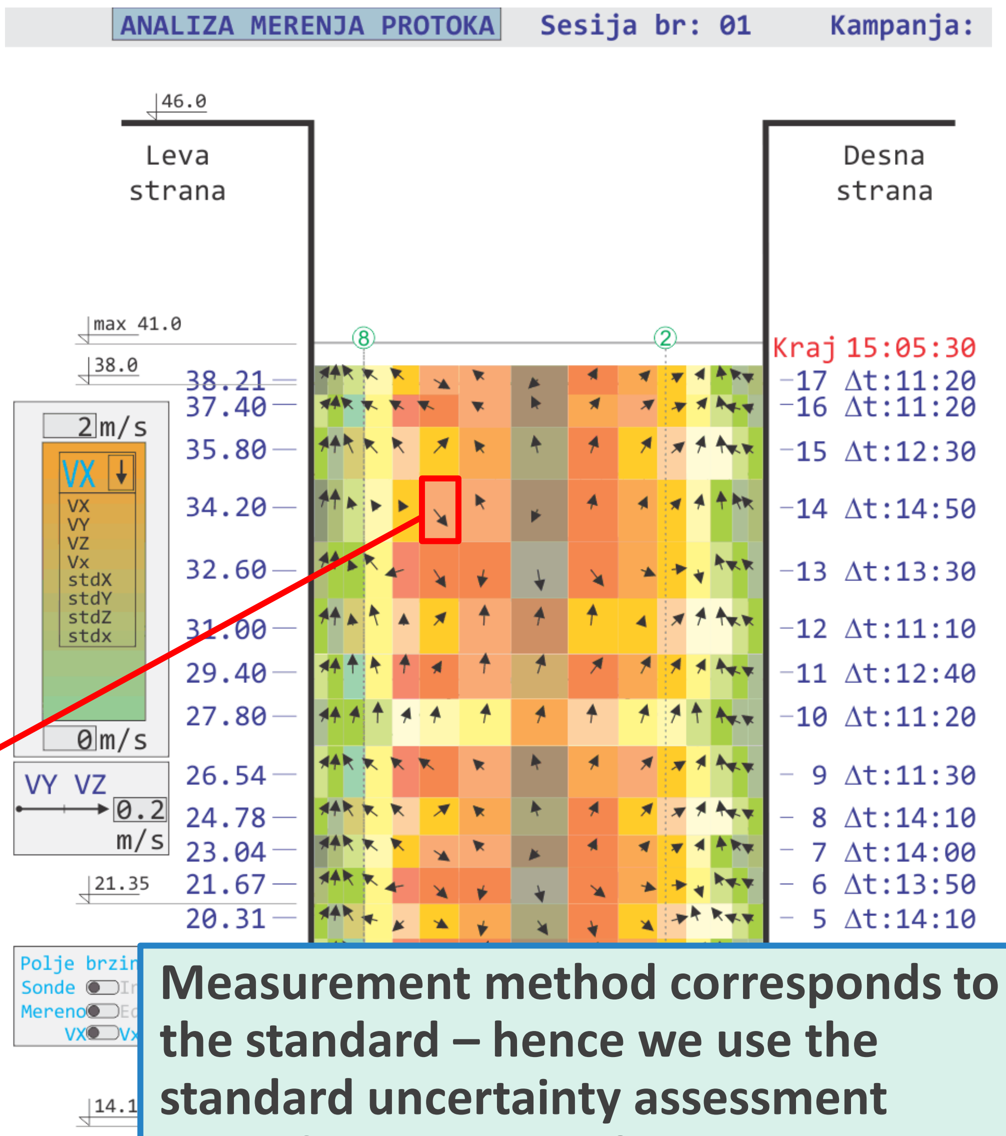
1. Discharge – Q

$$Q = V \cdot A$$

2. Mean axial velocity - V

$$V = \frac{\sum_{i=1}^{N_V}\sum_{j=1}^{N_H}(k_{i,j} \cdot V_{i,j})}{\sum_{i=1}^{N_V}\sum_{j=1}^{N_H} k_{i,j}} = \frac{\sum_{i=1}^{N_V}\sum_{j=1}^{N_H}(w_i \cdot d_j \cdot V_{i,j})}{\sum_{i=1}^{N_V}\sum_{j=1}^{N_H}(w_i \cdot d_j)} = \frac{1}{A}\sum_{i=1}^{N_V}\sum_{j=1}^{N_H}(A_{i,j} \cdot V_{i,j})$$

$A_{i,j}$ - attributed area
w_i - width
d_j - height
$k_{i,j} = A_{i,j}$ - sensitivity coefficient



Measurement method corresponds to the standard – hence we use the standard uncertainty assessment procedure as a template…

Iron Gate 2 HPP: Measurement uncertainty

- Workflow of the standard procedure ISO 3354

1. Combined uncertainty in local velocity measurements
   1. Random uncertainties in local velocity measurements
      1. ~~Due to the rotational frequency of the meter~~
      2. Due to the slow oscillations
   2. Systematic uncertainties in local velocity measurements
      1. Arising from the calibration
      2. Due to the turbulence and velocity fluctuations
      3. Due to the velocity gradient
      4. ~~Due to the misalignment of the meters~~
      5. Due to the conduit blockage

Correlated vs uncorrelated

3D but…

Negligable…

2. Uncertainty in mean axial velocity
3. Combined uncertainty in discharge measurements
   1. Random uncertainties in discharge measurements
      1. Arising from local velocity measurements
      2. Arising from the estimation of the boundary layer coefficient – *m*
      3. Arising from the positioning of the current meters
   2. Systematic uncertainties in discharge measurements
      1. Arising from the measurements of the conduit dimensions
      2. Arising from the numerical integration technique
      3. Due to the number of measuring points

Linear extrapolation?

Depth measurements?

Iron Gate 2 HPP: Measurement uncertainty

- Workflow of the standard procedure ISO 3354

1. Combined uncertainty in local velocity measurements
    1. Random uncertainties in local velocity measurements
        1. Due to **Linear correction of the measured velocities**
        2. Due to the slow oscillations
    2. Systematic uncertainties in local velocity measurements
        1. Arising from the calibration
        2. Due to the turbulence and velocity fluctuations
        3. Due to the velocity gradient
        4. Due to the **Higher incident angles**
        5. Due to the conduit blockage

Correlated vs uncorrelated

Negligable…

2. Uncertainty in mean axial velocity
3. Combined uncertainty in discharge measurements
    1. Random uncertainties in discharge measurements
        1. Arising from local velocity measurements
        2. Arising from the estimation of the boundary layer coefficient – *m*
        3. Arising from the positioning of the current meters
        4. **Arising from the depth measurements**
    2. Systematic uncertainties in discharge measurements
        1. Arising from the measurements of the conduit dimensions
        2. Arising from the numerical integration technique
        3. Due to the number of measuring points

Linear extrapolation?

Modifications and rearrangements…

Iron Gate 2 HPP: Measurement uncertainty

- Random uncertainty in local velocity measurements

1. Due to the slow oscillations

- Measurement time is not long enough to allow for the correct integration of the slow oscillations in velocity
- **Natural drivers + "constant power regime"**
- Slowest oscillations (*t*) estimate 1 – 2 min
- Two measurement modes are treated differently (incremental and continuous)
- Oscillations (ΔV) are smaller than 10% of average measured velocity (*V*)

1.1. Incremental mode:

$$\left(u_{r,i,j}\right)_o^{ink} = 0.1 \cdot \frac{t}{T} \cdot \frac{\Delta V_{i,j}}{V_{i,j}} \cdot 100\ [\%]$$

1.2. Continuous mode:

Uncertainty correlated with the Discharge oscillations from W-K!

$$\left(u_{r,i,j}\right)_o^{cont} = \frac{\sigma_{Q_{WK}}}{Q_{WK}} \cdot 100\ [\%]$$

Iron Gate 2 HPP: Measurement uncertainty

- Random uncertainty in local velocity measurements

2. Due to the linear correction of the measured velocities

- ISO 3354 recognizes the need to linearly correct the measured velocities if the all the measurements are not simultaneous

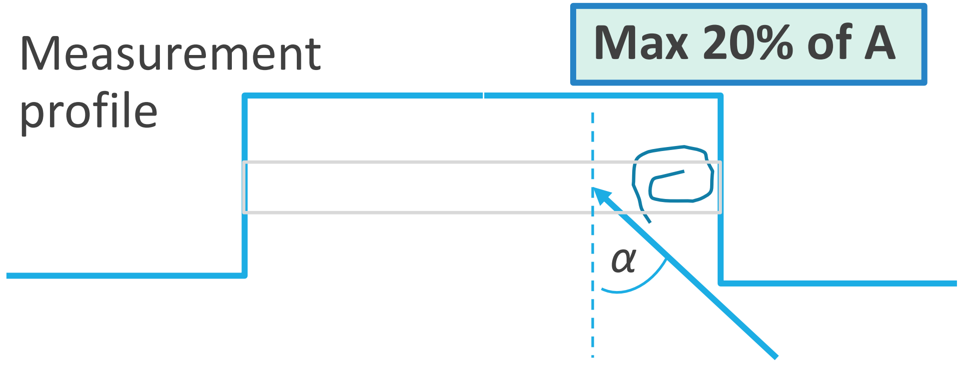
When the curve of the reference velocity, v_r, has been plotted against time, this curve is used to relate all velocity measurements to the same reference flow-rate, q_0 (preferably that which corresponds to the mean of the reference velocity measurements). For comparatively small changes in the reference velocity, the velocity, $v_{i,t}$, measured at any point at time, t, can be corrected by multiplying by the ratio of the reference velocity, $v_{r,0}$, corresponding to the flow-rate, q_0, to reference velocity, $v_{r,t}$, at time, t:

$$v_{i,0} = v_{i,t}\left(\frac{v_{r,0}}{v_{r,t}}\right)$$

where $v_{i,0}$ is the velocity at point i to be used for the integration.

- ISO 3354 **does not identify** the need for additional uncertainty component.
- However, we believe that the velocities **do not follow the linear increase** throughout the cross-section *A*

$\overline{Q_{WK,j}}$



$$\left(u_{r,i,j}\right)_{lk}^{ink} = 0.2 \cdot \frac{2 \cdot \sigma_{\overline{Q_{WK,j}}}}{Q_{WK}} \cdot 100\ [\%]$$

Iron Gate 2 HPP: Measurement uncertainty

- Systematic uncertainty in local velocity measurements

1. Arising from the calibration

- 15 EM meters
- Calibration on the towing tank
- EM calibration uncertainty – 1% (0.5% standard uncertainty)
- **Correlated part** (towing tank rig, position transducer)
- **Uncorrelated part** (random in nature/divided by square root of number of EM meters)

$$\left(u_{s,i,j}\right)_{c}^{ink+cont} = \left(0.3 + \frac{0.2}{\sqrt{15}}\right) \cdot 100\ [\%]$$

2. Due to the turbulence and velocity fluctuations

3. Due to the velocity gradient

- ISO 3354 suggests to treat this two components in a similar manner
- **Spherical construction and integrative method** (control volume is 0.15 m in diameter)
- The effects on the measurement are “smeared”
- Resulting uncertainty from 2. and 3.:

Incremental $$\left(u_{s,i,j}\right)_{t+vg}^{ink} = \frac{\sigma_{V_{i,j}}}{V_{i,j}} \cdot 100\ [\%]$$

Continuous $$\left(u_{s,i}\right)_{t+vg}^{cont} = \frac{\sigma_{V_i}}{V_i} \cdot 100\ [\%]$$

Iron Gate 2 HPP: Measurement uncertainty

- Systematic uncertainty in local velocity measurements

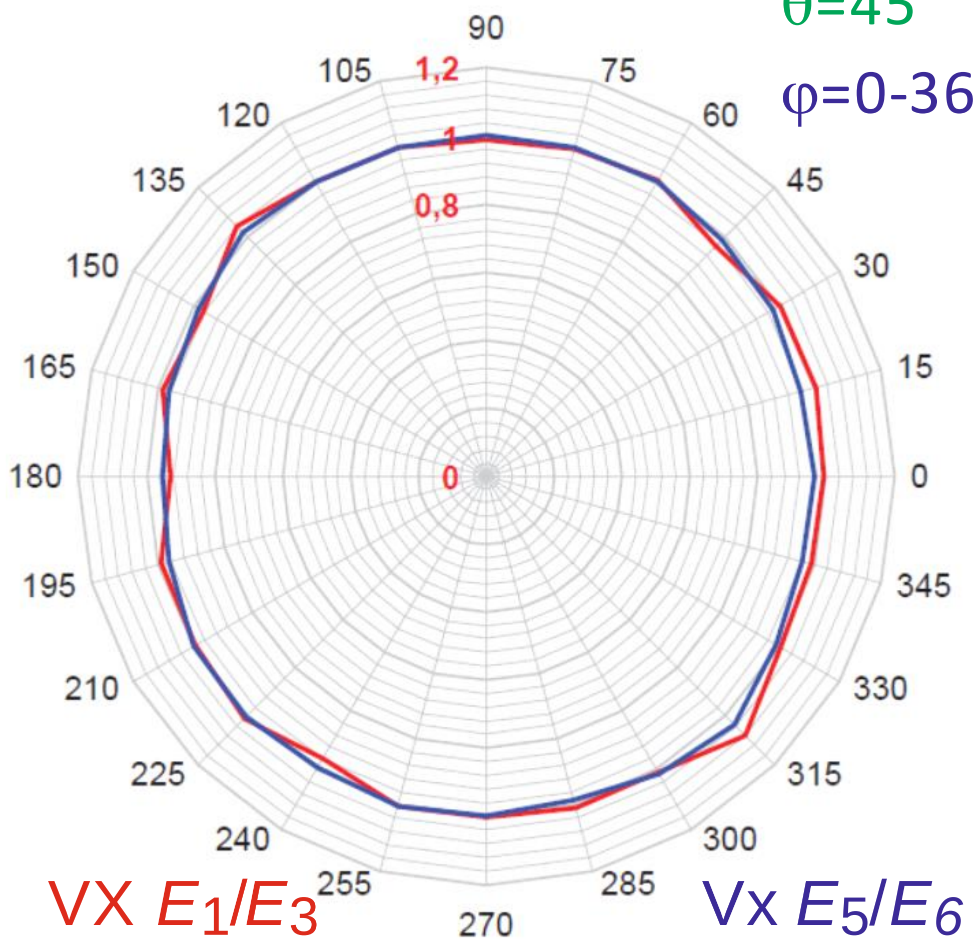
4. Due to the higher incident angles (former misalignment of the meters)

- EM meters measuring bidirectional X, Y and Z
- Declared calibration uncertainty **is for angles *α* up to 15º** (in reference to the X axis)
- For larger angles, **uncertainties are increasing up to 5% for *α* = 180º**
- If the diagram is unwrapped and normalized for the angles in vertical plane a second-order polynomial could be used for estimation of the uncertainty:

$$\left(u_{s,i,j}\right)_{\alpha}^{inc+cont} = 6 \cdot 10^{-5} {\alpha_{i,j}}^{2} + 0.0133 \cdot \alpha_{i,j} - 0.2121 [\%]$$

$\theta=45^0$

$\varphi=0\text{-}360^0$



Iron Gate 2 HPP: Measurement uncertainty

- **Combined uncertainty in local velocity measurements**
  - Random uncertainty: $$(u_{r,i,j}) = \sqrt{(u_{r,i,j})_o^2 + (u_{r,i,j})_{lk}^2}$$
  - Systematic uncertainty: $$(u_{s,i,j}) = \sqrt{(u_{s,i,j})_c^2 + (u_{s,i,j})_{t+vg}^2 + (u_{s,i,j})_\alpha^2}$$
  - Combined uncertainty: $$(u_{i,j}) = \sqrt{(u_{r,i,j})^2 + (u_{s,i,j})^2}$$
- **Uncertainty in mean-axial velocity**
  - As previously stated, the sensitivity (weighting) coefficient is equal to the attributed area for each current meter position $A_{i,j}$

$$(u_V) = \sqrt{\frac{\sum_{i=1}^{N_V}\sum_{j=1}^{N_H}\left({A_{i,j}}^2 \cdot (u_{i,j})^2\right)}{A^2}} = \sqrt{\frac{\sum_{i=1}^{N_V}\sum_{j=1}^{N_H}\left({k_{i,j}}^2 \cdot (u_{i,j})^2\right)}{A^2}}$$

Iron Gate 2 HPP: Measurement uncertainty

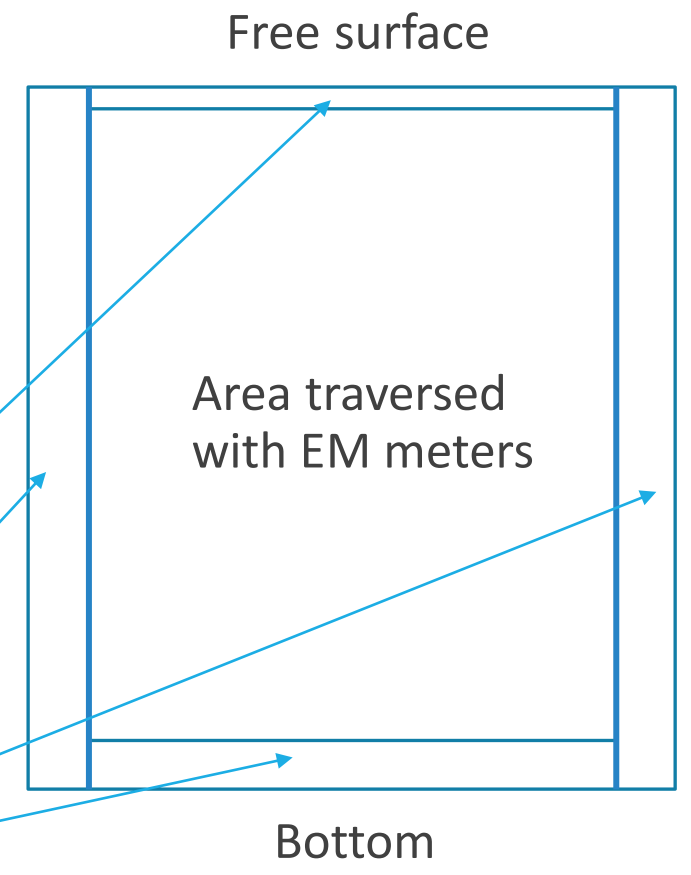
- Random uncertainty in discharge measurements

1. Arising from local velocity measurements

- Equal to the uncertainty in mean-axial velocity

2. Arising from the estimation of the boundary layer coefficient – *m*

- Additional investigation reveled that different extrapolation in different zones of peripheral flow is needed
- **Stiff boundaries – power law *m* = 9** (as per standard but with different scaling coefficients due to the asymmetry)
- Peripheral area stiff boundaries around 6 – 6.5%
- **Free surface – linear law** (assuming hypothetical *m* = 9)
- Peripheral area 0.8 – 1.3%



$$(u_{Q,r})_m = \sqrt{\left(\left(u_{r,i,j}\right)_{p,st}\frac{A_{p,st}}{A\cdot m}\right)^2 + \left(\left(u_{r,i,j}\right)_{p,sf}\frac{A_{p,sf}}{A\cdot m}\right)^2}$$

Iron Gate 2 HPP: Measurement uncertainty

- Random uncertainty in discharge measurements

3. Arising from the current meter positioning

- Position of the traversing frame **is monitored with two position transducers** at both ends
- From the declared instrument data, and by assuming rectangular distribution, the uncertainty of the position transducers is estimated at 10 mm (0.02% of 50 m range)
- In post-processing software, if the measurement profiles are shifted by ΔZ = 10 mm a ΔQ can be estimated

$$\left(u_{Q,r}\right)_{pos} = \sqrt{\sum_{i=1}^{N_V} \sum_{j=1}^{N_H} \left(\frac{\Delta Z \cdot \Delta Q}{Z}\right)^2}$$

(Muciaccia et al., 2018)

4. Arising from the depth measurements

- Two pressure transducers + four sonar data on bottom shape
- In all the measurements sonars gave the readings indicating the bottom was horizontal (without sediment deposits)
- Hence **only pressure transducers uncertainty** affected the depth measurements:

$$\left(u_{Q,r}\right)_{dm} = \frac{\sigma_{H_{i,j}}}{\sqrt{2} \cdot H} \cdot 100\ [\%]$$

Iron Gate 2 HPP: Measurement uncertainty

- Systematic uncertainty in discharge measurements

1. **Arising from the conduit dimension measurements**

- Depth was already discussed previously
- Width uncertainty is stemming from the survey data and construction drawings
- Assumed to be: $\left(u_{Q,s}\right)_A = 0.15\ [\%]$.

2. **Arising from the numerical integration technique**

- Inversely proportional to the measuring points density (capturing the important flow characteristics)
- For non-uniform flows IEC 60041 suggests:

$$24 \cdot \sqrt[3]{A} < No < 36 \cdot \sqrt[3]{A}$$

- Median case here (26 m depth):

$$240 < Z < 285$$

- **Both incremental** (above 13 profiles) **and continuous mode satisfy** the condition
- Bilinear interpolation and arithmetic integration
- Assumed value:

$$\left(u_{Q,s}\right)_{in} = 0.3\ [\%]$$

3. **Due to the number of measuring points**

- Simultaneous measurements could not be performed hence:

$$\left(u_{Q,s}\right)_{nm} = 0.2\ [\%]$$

Iron Gate 2 HPP: Measurement uncertainty

- **Combined uncertainty in discharge measurements**

  - Random uncertainty:

$$\left(u_{Q,r}\right) = \sqrt{A \cdot (u_V)^2 + \left(u_{Q,r}\right)_m^2 + \left(u_{Q,r}\right)_{pos}^2 + B \cdot V \cdot \left(u_{Q,r}\right)_{dm}^2}$$

  - Systematic uncertainty:

$$\left(u_{Q,s}\right) = \sqrt{V \cdot H \cdot \left(u_{Q,s}\right)_A^2 + \left(u_{Q,s}\right)_{in}^2 + \left(u_{Q,s}\right)_{nm}^2}$$

  - Combined uncertainty:

$$\left(u_Q\right) = \sqrt{\left(u_{Q,r}\right)^2 + \left(u_{Q,s}\right)^2}$$

Analysis of the selected measurements from 2020.

Iron Gate 2 HPP: Analysis of the measured data

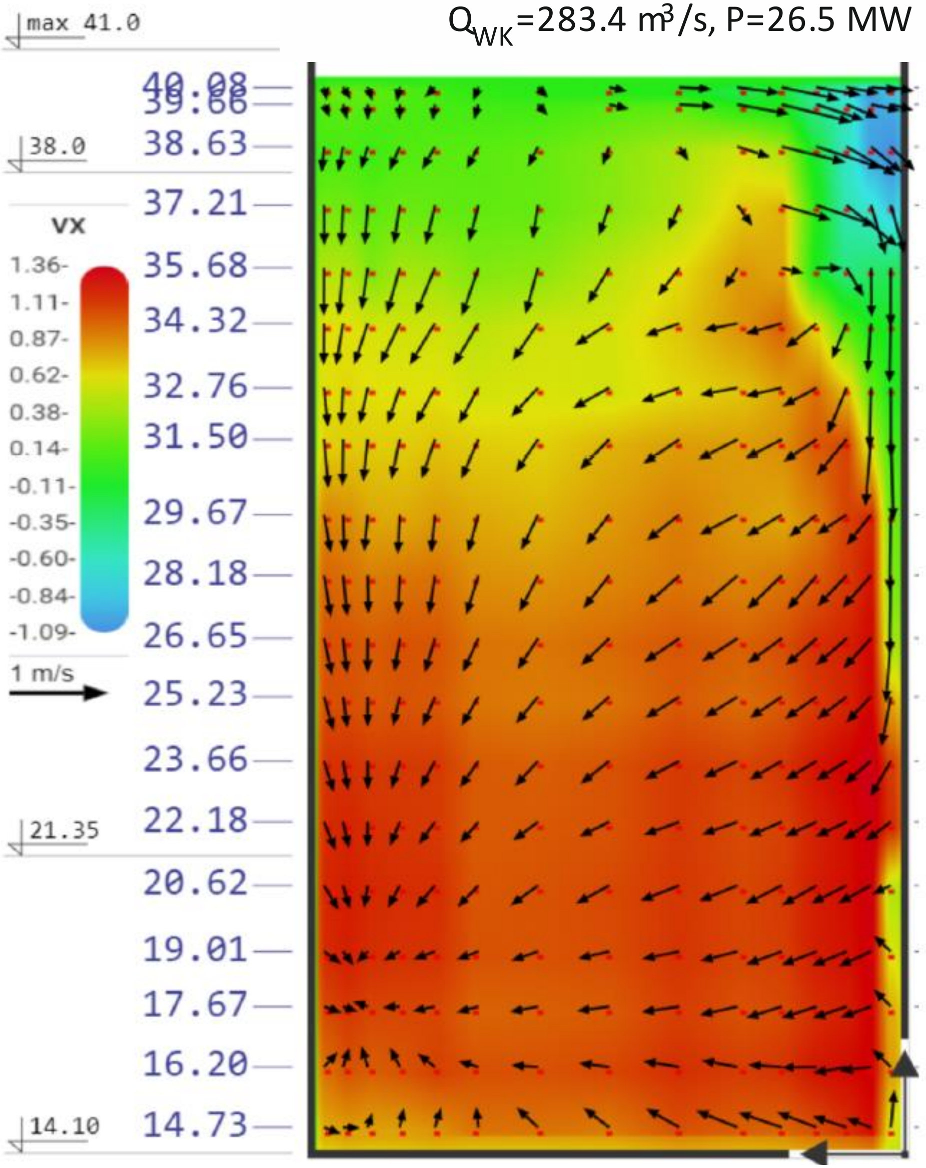
- In 2020. measurements were made on A1 and A7 turbines

- Combined discharge uncertainties:

Incremental mode	**0.96 – 2.28%**
Continuous mode	**1.47 – 4.62%**

- Here we analyze 1 incremental and 3 continuous measurements on A1 with similar flow rates

Turbine A1: Q_{MEAS}= 295.2 m^3/s (unc. 1.1%)
Q_{WK}=283.4 m^3/s, P=26.5 MW



Velocity field for the analyzed incremental measurement on A1

Iron Gate 2 HPP: Analysis of the measured data

Measured data	Incremental measurement	Continuous measurements		
		n°1	n°2	n°3
Q [m³/s]	295.20	296.99	296.80	299.87
Q_{WK} [m³/s]	283.41	284.87	283.16	280.88
Uncertainty components	/	/	/	/
Random velocity [%]	±0.80	±1.61	±1.22	±1.59
Systematic velocity [%]	±0.58	±0.77	±0.69	±0.66
Random flow rate [%]	±1.00	±1.79	±1.41	±1.74
Systematic flow rate [%]	±0.39	±0.48	±0.50	±0.48
Combined flow rate [%]	±1.08	±1.85	±1.50	±1.80
Combined flow rate [m³/s]	±3.17	±5.51	±4.45	±5.40

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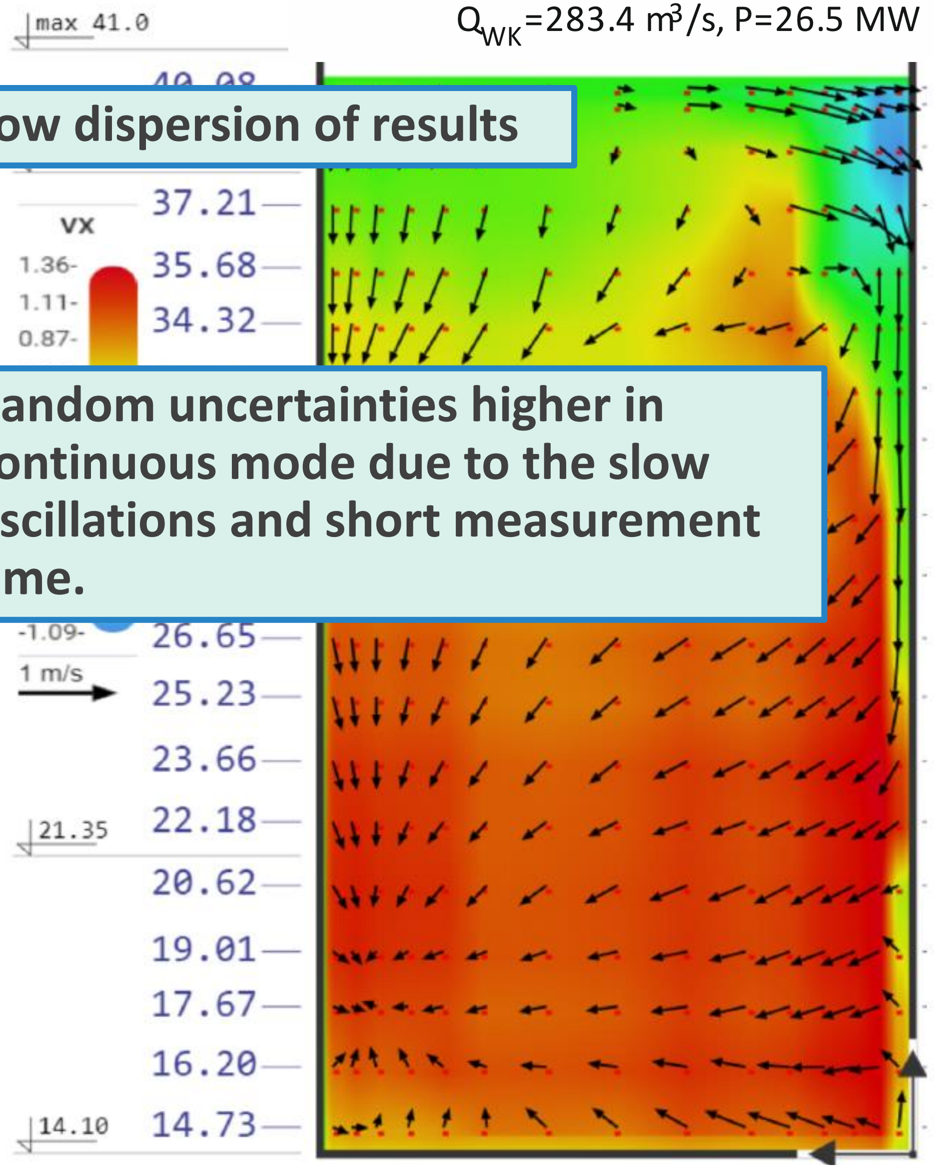
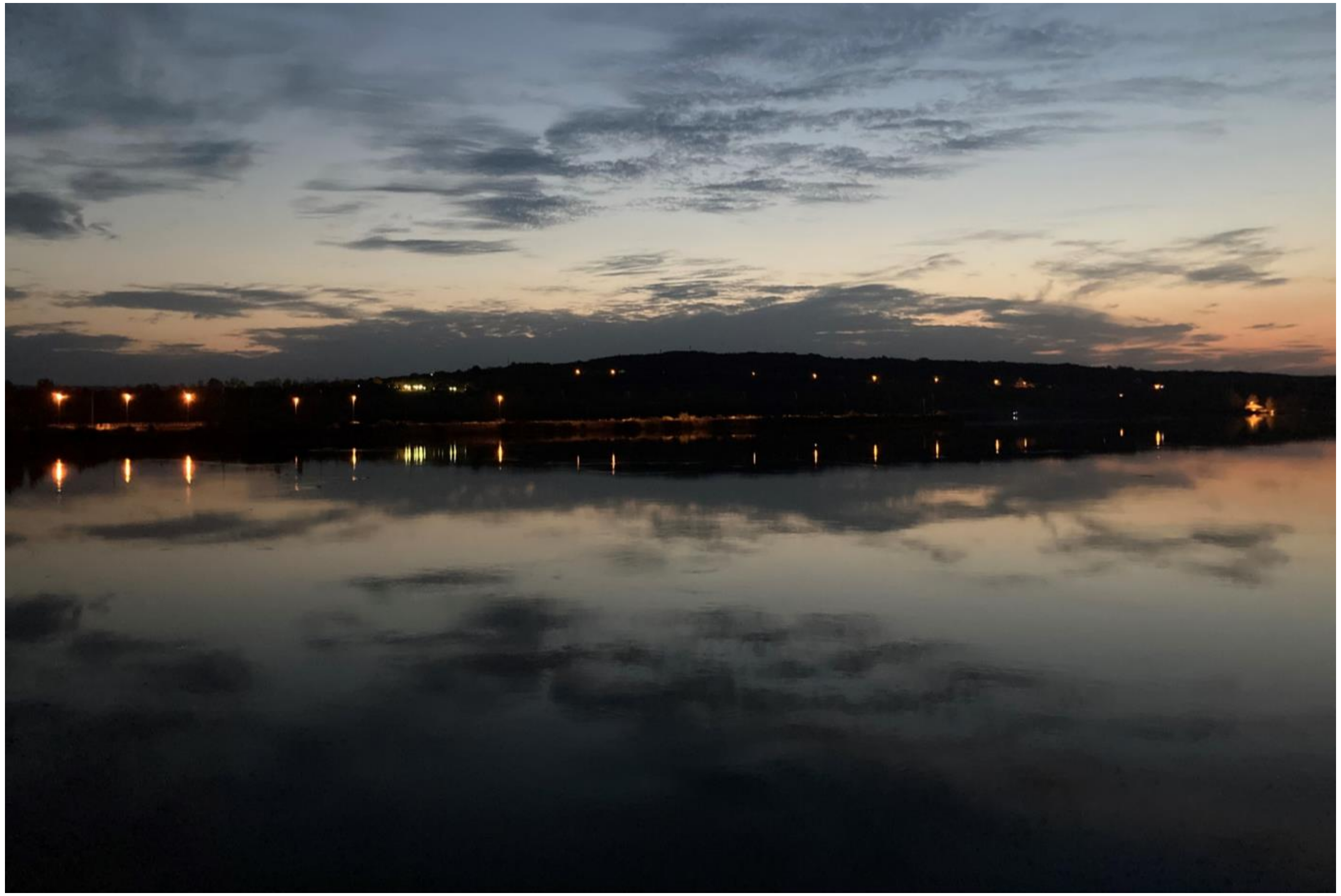


Low dispersion of results

Random uncertainties higher in continuous mode due to the slow oscillations and short measurement time.

Conclusions and future work

- To accommodate the specific features of the EM meter-based discharge measurement technique, modifications of the IEC 60041 – ISO 3354 uncertainty assessment procedure are suggested here.
- Two measurement modes are discussed and analyzed: Incremental and Continuous (Direct integration as per IEC 60041).
- As expected, the faster continuous mode yielded higher measurement uncertainties.
- Further investigation is needed as the dispersion of results between two modes is low.



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