Case study on implementing GUM to streamflow measurements acquired with Acoustic-Doppler Velocimeters

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Measurement uncertainty in meteorology and climatology

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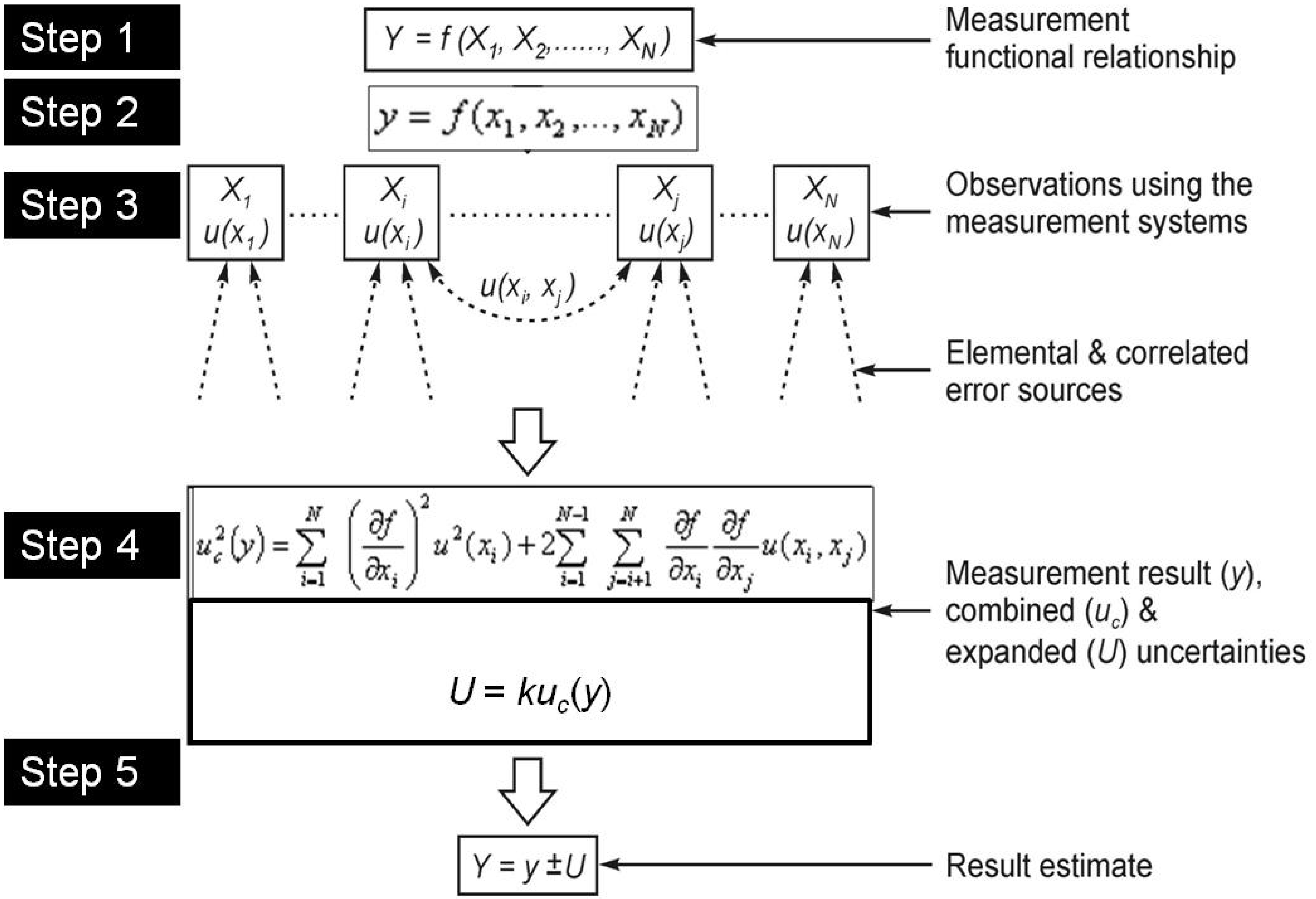
Purpose & Talking Points

To illustrate implementation of GUM-based Uncertainty Analysis to a common hydrometric measurement

- **Essentials of GUM framework**
- **Case Study**
  - **Methods & instrumentation**
  - **Study site & experimental conditions**
  - **Measurement protocols**
  - **Estimation of elemental uncertainty sources**
  - **Estimation of the expanded uncertainty in streamflow measurement**
- **Discussions**
- **Conclusions**

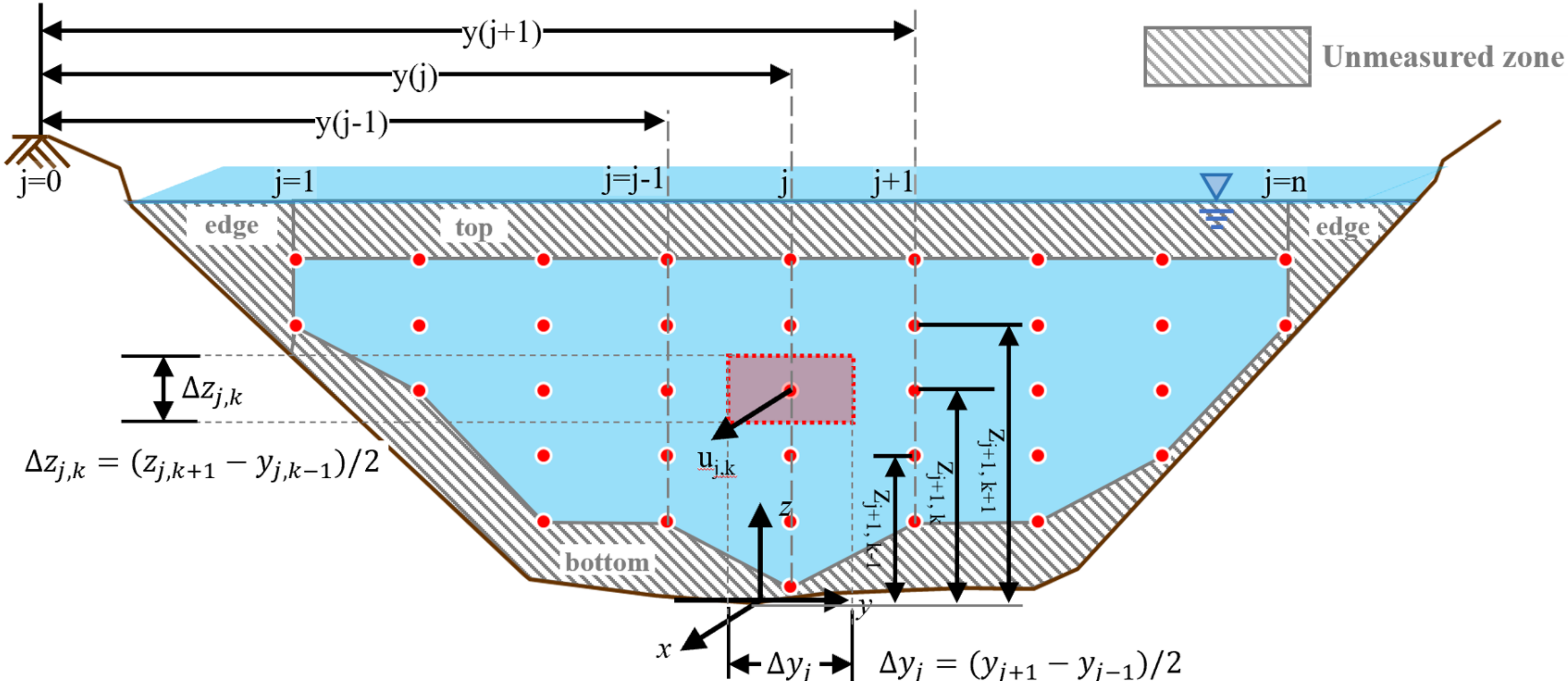
GUM Essentials

GUM Implementation protocol
(JCGM100/2008)



Case study: Methods

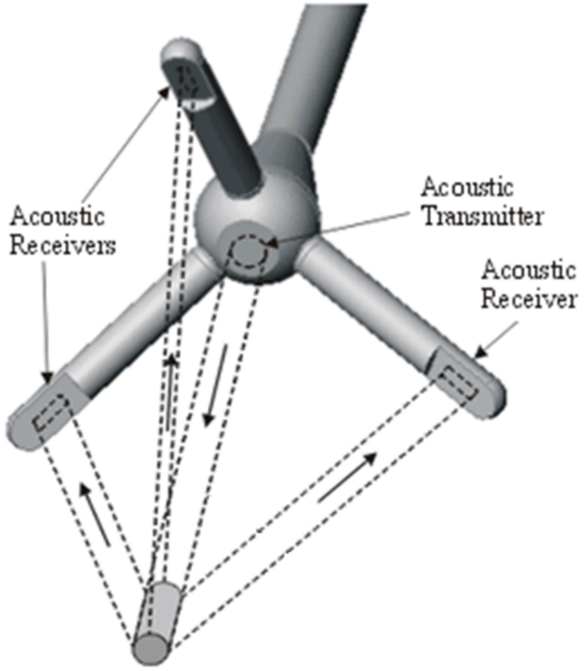
Velocity- area (VA) method (HUG, 2020)



$$Q = Q_m + Q_p = F_y F_z \sum_{\substack{j=1,n \\ k=1,m}} u_{jk}\,\Delta y_j \Delta z_{j,k} + Q_{top} + Q_{bottom} + Q_{edges}$$

Case study: Instrumentation (main)

Acoustic Point Velocity Meter: 16 MHz MicroADV (www. sontek.com)



Micro-ADV Specifications	
Sampling Rate	0.1 to 50 Hz
Sampling Volume	0.09 cm^3
Distance to Sampling Volume	5 cm
Resolution	0.01 cm/s
Velocity Range	3 - 250 cm/s
Resonance Pressure Transducer (RPT) - Accuracy	0.01%
Compass/Tilt Sensor — Heading Accuracy	±2°
Compass/Tilt Sensor — Pitch, Roll Accuracy	±1°
Pressure Sensor Strain Gauge - Accuracy	0.1%
Overall Accuracy	1% velocity or 0.25 cm/s

3-component point velocities (*u, v, w*)

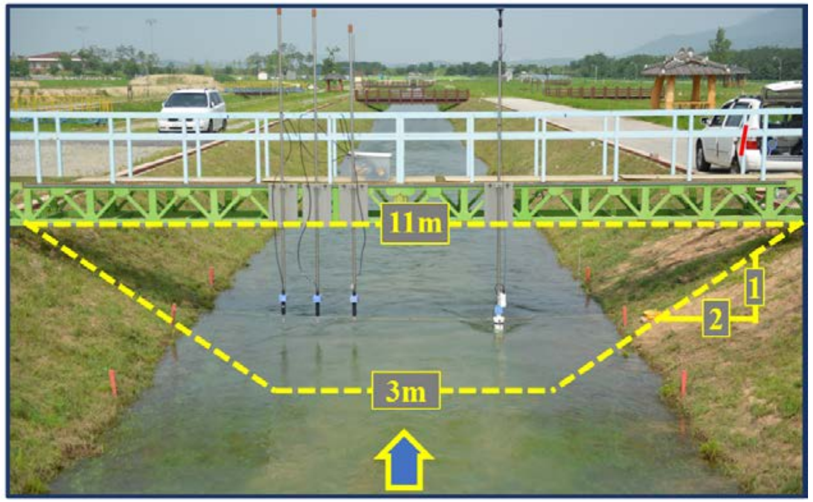
$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = G_3^{-1} \frac{c}{f_0} \begin{bmatrix} f_{D1} \\ f_{D2} \\ f_{D3} \end{bmatrix}$$

- G_3 - geometrical transformation matrix;
- c - speed of sound in water;
- f_D - difference in the frequency of emitted (f_0) and return (f_B) pulses due to Doppler shift.

Case Study: Study site

Civil Engineering and Building Technology's River Experiment Center (KICT-REC), Andong, Korea
(https://www.kict.re.kr/menu.es?mid=a20302030000)

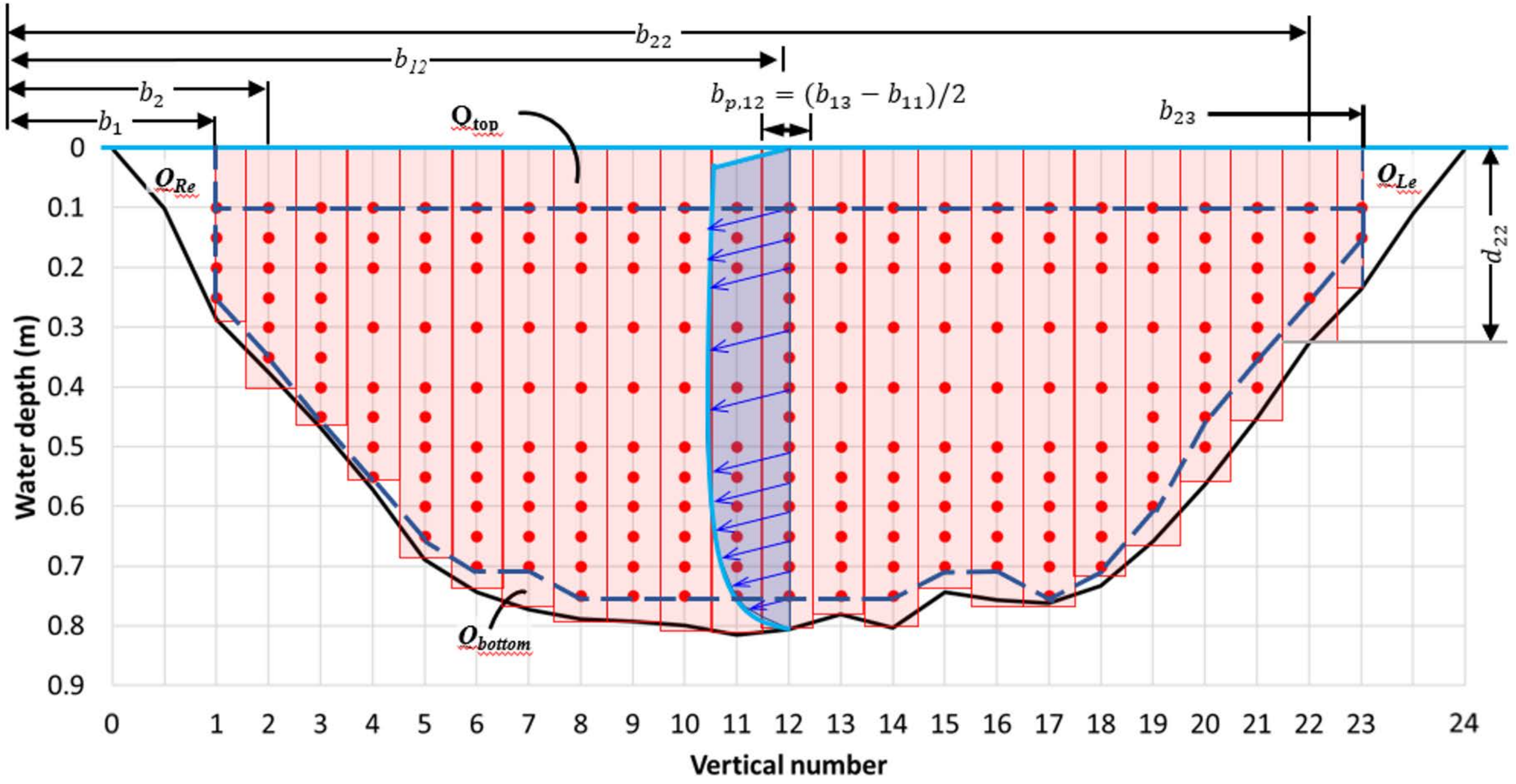
Test cross section & experimental conditions



Discharge	2.09 m^3/s
Channel width	6.5 m
Averaged velocity	0.56 m
Maximum velocity	0.89 m
Averaged depth	0.61 m
Maximum depth	0.82 m
Aspect ratio	10.72
Reynolds number	308,209
Froude number	0.23

Case study: Measurement protocol & Steps 1-2 of GUM

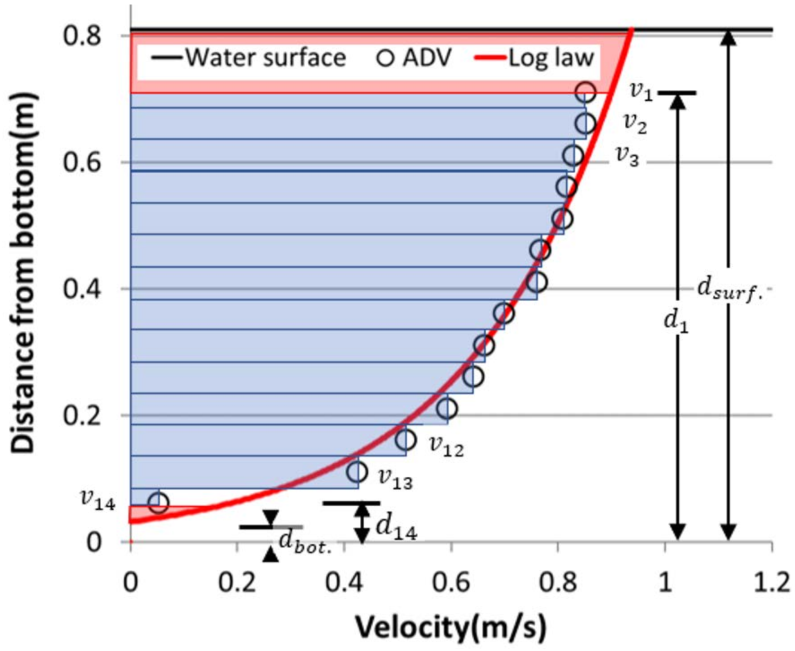
Mid-Section VA method (102 point measurements)



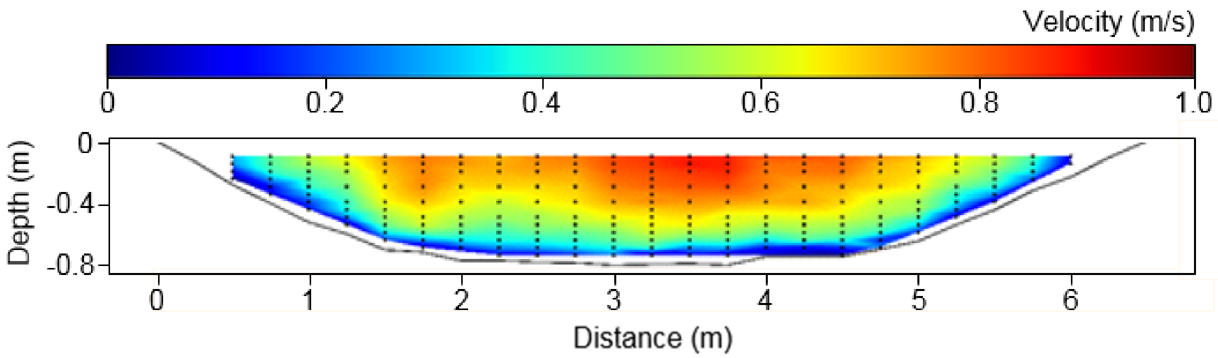
$$Q_t = U_1 \times d_1 \times \left(\frac{b_2 - b_1}{2}\right) + \sum_{j=2}^{22}\left(U_j \times d_j \times \left(\frac{b_{j+1} - b_{j-1}}{2}\right)\right) + U_{23} \times d_{23} \times \left(\frac{b_{23} - b_{22}}{2}\right) + Q_{Re} + Q_{Le} \qquad \text{Eq. (1)}$$

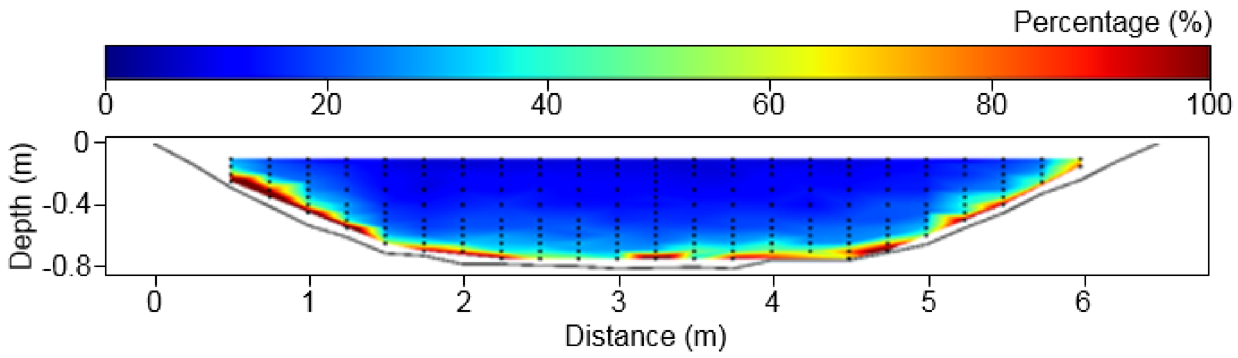
Case Study: Reference for UA (benchmark dataset)

KICT-REC Andong offers ideal conditions for obtaining a high-quality reference (i.e., natural stream flow & boundary roughness, calibrated data acquisition equipment, trained operators, and controlled, stable, and repeatable experiments)



Cross-section distributions: mean streamwise velocity and normalized streamwise turbulence intensity





Case Study: Elemental uncertainty source

The elemental sources of uncertainty are grouped around the variables in the data reduction Equation (1):

- mean depth-averaged velocity, $\boldsymbol{U_j}$
- depth of the verticals $\boldsymbol{d_j}$
- distance between verticals, $\boldsymbol{(b_{j+1}-b_{j-1})/2}$
- model for discharge estimation (includes measured & unmeasured areas), $\boldsymbol{Q_{MO}}$

Estimates for all elemental uncertainty sources (17) are needed:

- 12 Type A (determined from own measurements & judgements)
- 5 Type B (other information sources)

Notes:

- 9 uncertainty sources Type A directly estimated in KICT-REC
- No uncertainty estimates for "Correlated bias errors" available
- Given the ideal measurement conditions for the KICT-REC facility, the "Operational conditions" sources are assumed negligible.

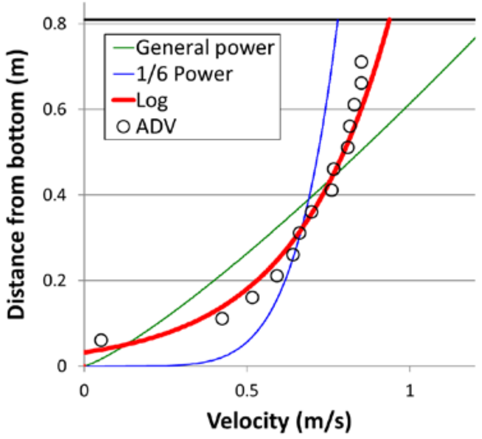
Elemental uncertainty	ID	Type	Standard uncertainty*
i. Mean velocity in verticals, $u(U_j)$			
Instrument accuracy	$u(U_{ac})$	B	1.0 %
Sampling duration	$u(U_{sd})$	A	0.7 %
Vertical sampling model	$u(U_{vd})$	A	1.6 %
Vertical velocity model	$u(U_{vm})$	A	0.3%
Correlated bias errors	$r(U_j, U_{j+1})$	-	N/A
Operational conditions	$u(U_{op})$	A	Negligible
ii. Depth in verticals, $u(d_j)$			
Instrument accuracy	$u(d_{ac})$	B	0.0005 m
Correlated bias errors	$r(d_j, d_{j+1})$	-	N/A
Operational conditions	$u(d_{op})$	A	Negligible
iii. Distance between verticals, $u(b_j)$			
Instrument accuracy	$u(b_{ac})$	B	0.0005 m
Correlated bias errors	$r(b_j, b_{j+1})$	-	N/A/
Operational conditions	$u(b_{op})$	A	Negligible
iv. Discharge model, $u(Q_{MO})$			
Discharge model	$u(Q_{mo})$	B	0.5%
Number of verticals	$u(Q_{nv})$	A	1.5%
Edge discharge model	$u(Q_{eg})$	A	1.7%
Near-bed effects	$u(U_{bd})$	A	2.1%
Operational conditions	$u(Q_{op})$	B	Negligible

Case Study: Step 3 of GUM

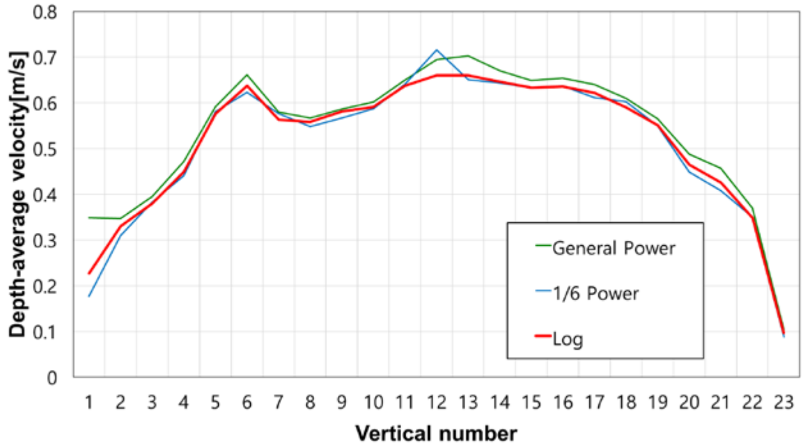
Step 3 of GUM is the most complex and expensive aspect of GUM implementation

Sample of Type A uncertainty estimation: Velocity model for obtaining the depth average velocity, $u(U_{vm})$

One vertical



All verticals



All verticals & various distribution models for velocity profiles

	Log law	Power law	1/6 Power law	10pt. Method
Discharge (m^3/s)	2.050	2.128	2.044	2.024
Discharge difference (m^3/s)	-	0.078	-0.005	-0.026
Uncertainty [%]	-	**3.82**	**-0.26**	**-1.25**

Derivations for 9 other Type A uncertainty sources determined in the KICT-REC facility in: Kim, J-M, Muste, M., Kim, D. and Despax, A. (2022). Implementation of Standardized Uncertainty Analysis for Streamflow Measurements Acquired with Acoustic Doppler Velocimeters, paper in preparation & report to be submitted for input to Project-X and ET-MU teams

Case Study: Steps 4-5 GUM

Propagation of elemental uncertainties to the final result (combined standard uncertainty)

$$\boldsymbol{u_c(Q_t)} = \sqrt{\sum_{j=1}^{23} u(U_j)^2 \left(\frac{\partial Q_t}{\partial U_j}\right)^2 + \sum_{j=1}^{23} u(d_j)^2 \left(\frac{\partial Q_t}{\partial d_j}\right)^2 + \sum_{j=1}^{23} u(b_j)^2 \left(\frac{\partial Q_t}{\partial b_j}\right)^2 + 2\sum_{j=1}^{22}\sum_{j+1}^{23}\left(\frac{\partial q_{n,j}}{\partial U_j}\right)\left(\frac{\partial q_{n,j+1}}{\partial U_{j+1}}\right) u(U_j)u(U_{j+1})\,r(U_j,U_{j+1}) +}$$
$$\sqrt{+2\sum_{j=1}^{22}\sum_{j+1}^{23}\left(\frac{\partial q_{n,j}}{\partial d_j}\right)\left(\frac{\partial q_{n,j+1}}{\partial d_{j+1}}\right) u(d_j)u(d_{j+1})\,r(d_j,d_{j+1}) + 2\sum_{j=1}^{22}\sum_{j+1}^{23}\left(\frac{\partial q_{n,j}}{\partial b_j}\right)\left(\frac{\partial q_{n,j+1}}{\partial b_{j+1}}\right) u(b_j)u(b_{j+1})\,r(b_j,b_{j+1}) + u(Q_{MO})^2 + u(Q_{Re})^2 + u(Q_{Le})^2} \quad (2)$$

$$\boldsymbol{u(U_j)} = \sqrt{u(U_{ac})^2 + u(U_{sd})^2 + u(U_{vd})^2 + u(U_{vm})^2 + u(U_{op})^2} \quad (3)$$

$$\boldsymbol{u(d_j)} = \sqrt{u(d_{ac})^2 + (d_{op})^2} \quad (4)$$

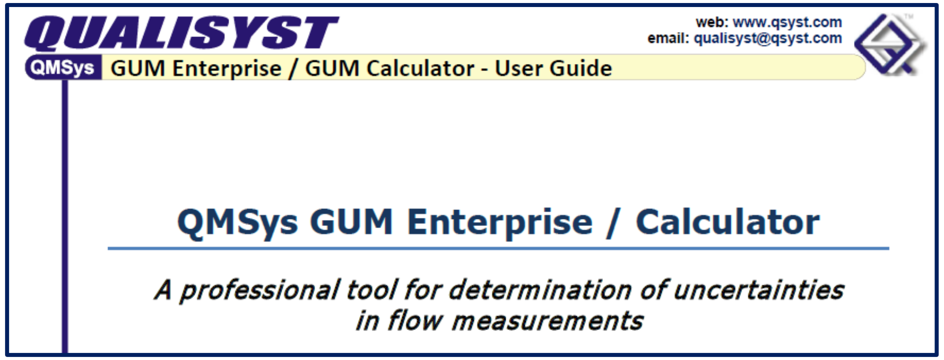
$$\boldsymbol{u(b_j)} = \sqrt{u(b_{ac})^2 + u(b_{op})^2} \quad (5)$$

$$\boldsymbol{u(Q_{MO})} = \sqrt{u(Q_{mo})^2 + u(Q_{nv})^2 + u(Q_{eg})^2 + u(U_{bd})^2 + u(Q_{op})^2} \quad (6)$$

The expanded uncertainty:

$U(Q_t) = ku_c(Q_t)$ 95% confidence level (7)

Calculations executed with QMSys GUM software (equipped with an interface for hydrometry developed through WMO funding)

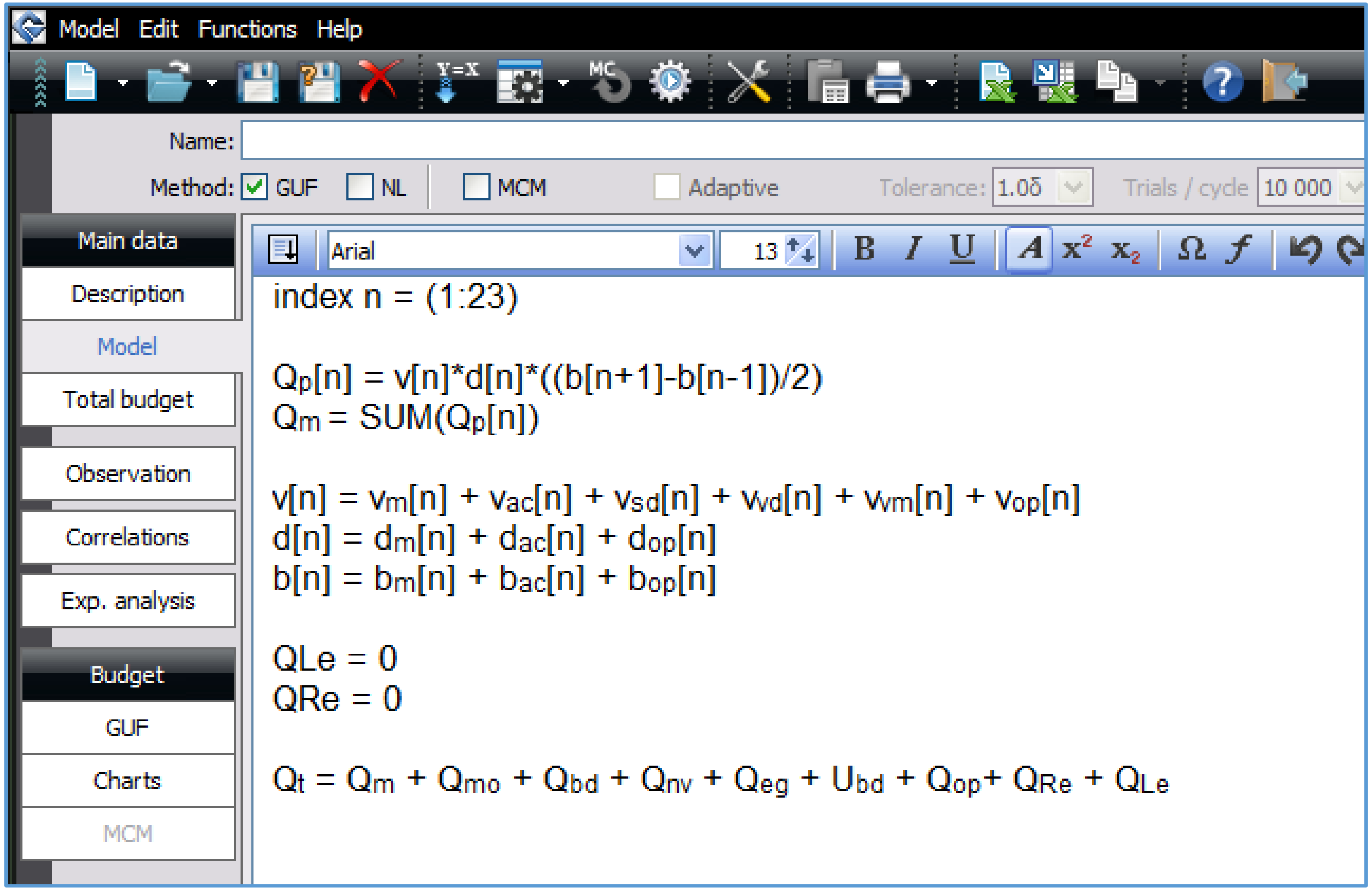

QUALISYST
web: www.qsyst.com
email: qualisyst@qsyst.com
QMSys GUM Enterprise / GUM Calculator - User Guide

QMSys GUM Enterprise / Calculator

A professional tool for determination of uncertainties in flow measurements

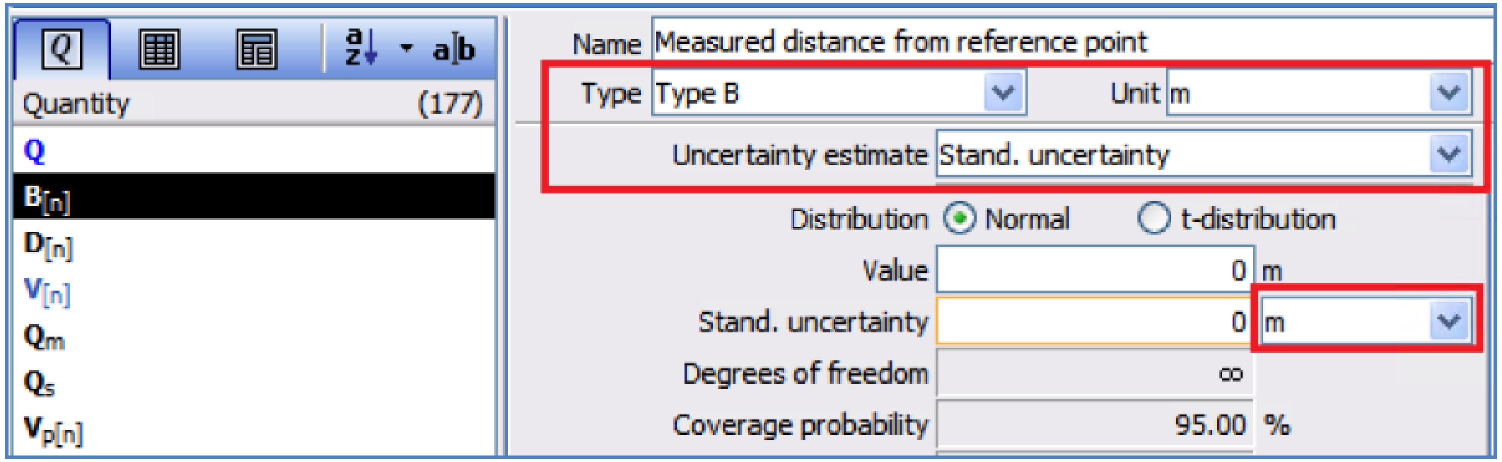
Case Study: GUM execution

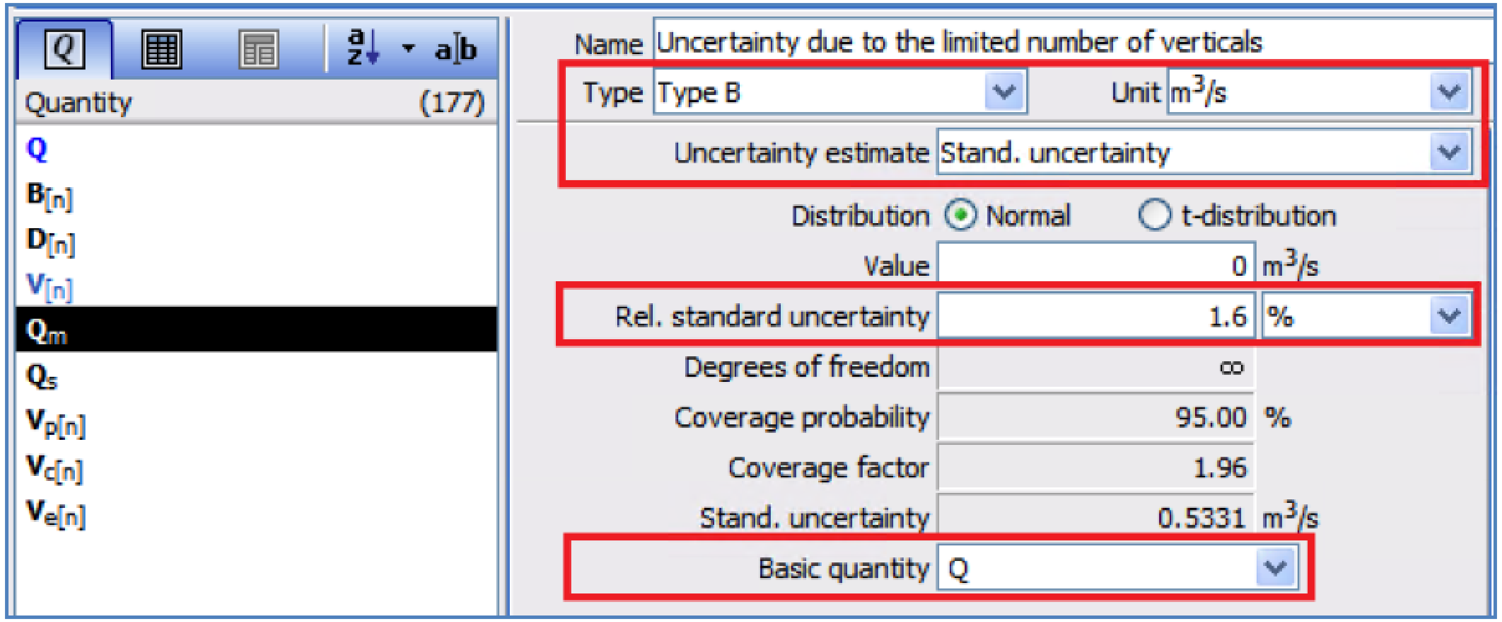
QMSys interface for user input: measurement definition and elemental uncertainty sources (Steps 1-2 GUM)



Case Study: GUM execution

QMSys interface for user input: values for elemental uncertainty sources (Step 3 GUM)





δ

Case Study: GUM execution

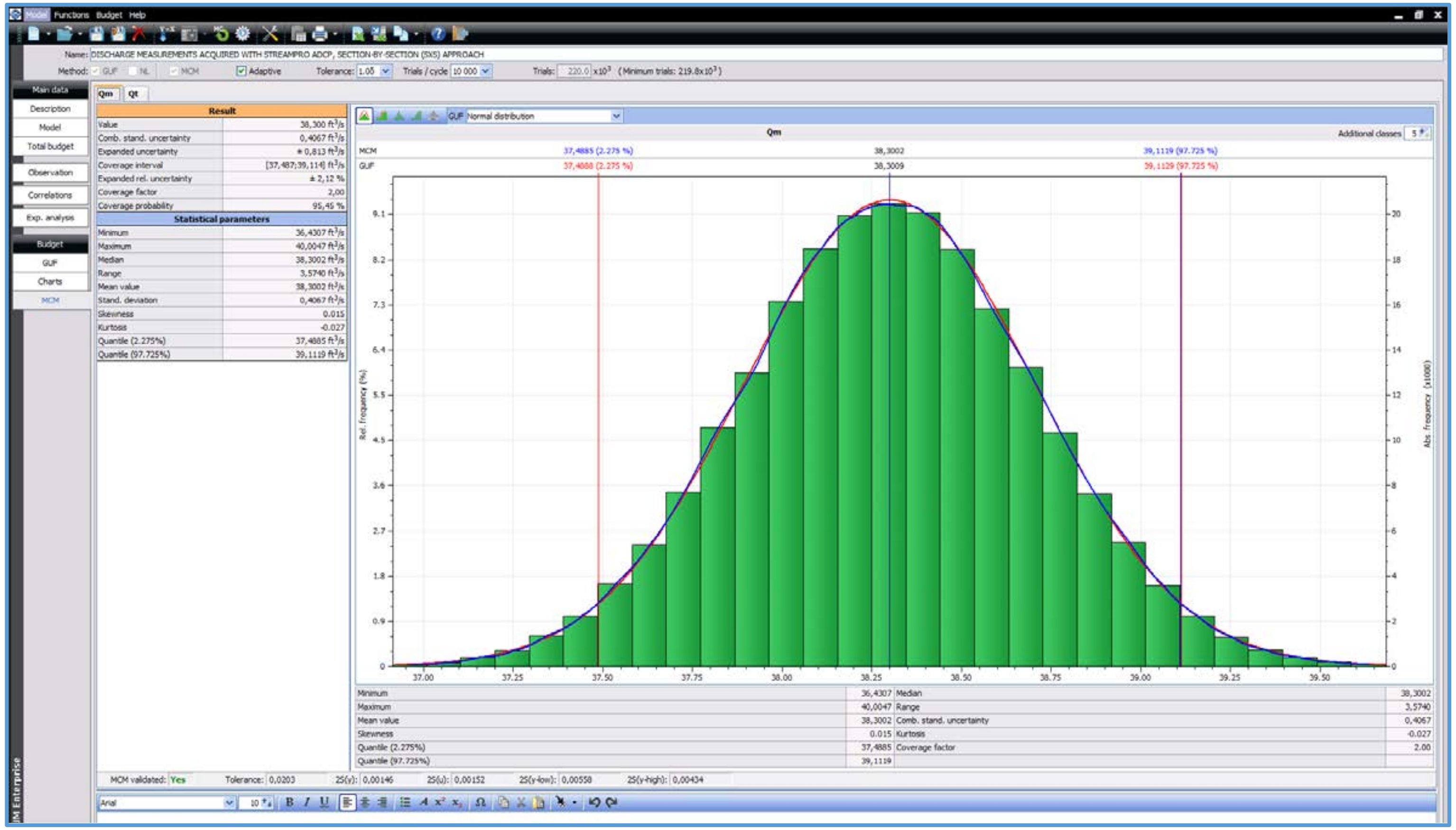
QMSys output: total uncertainty in discharge using (Step 4 GUM) obtained with:

- GUM framework (*GUF in QMSys)
- Monte Carlo method

Assessment Method	Number of trials (M)	Estimated mean (Q_m) (m^3/s)	Combined Standard Uncertainty ($u_c(Q_m)$) (m^3/s)	Expanded standard uncertainty (at 95 % confidence interval)		d_{low}	d_{high}	Numerical tolerance δ	GUF** Validated?
				(m^3/s)	(%)				
*GUF	n/a	2.048	± 0.054	± 0.109	± 5.30	n/a	n/a	n/a	n/a
MCM	10^6	2.048	± 0.054	± 0.109	± 5.30	1.939	2.157	-	Yes

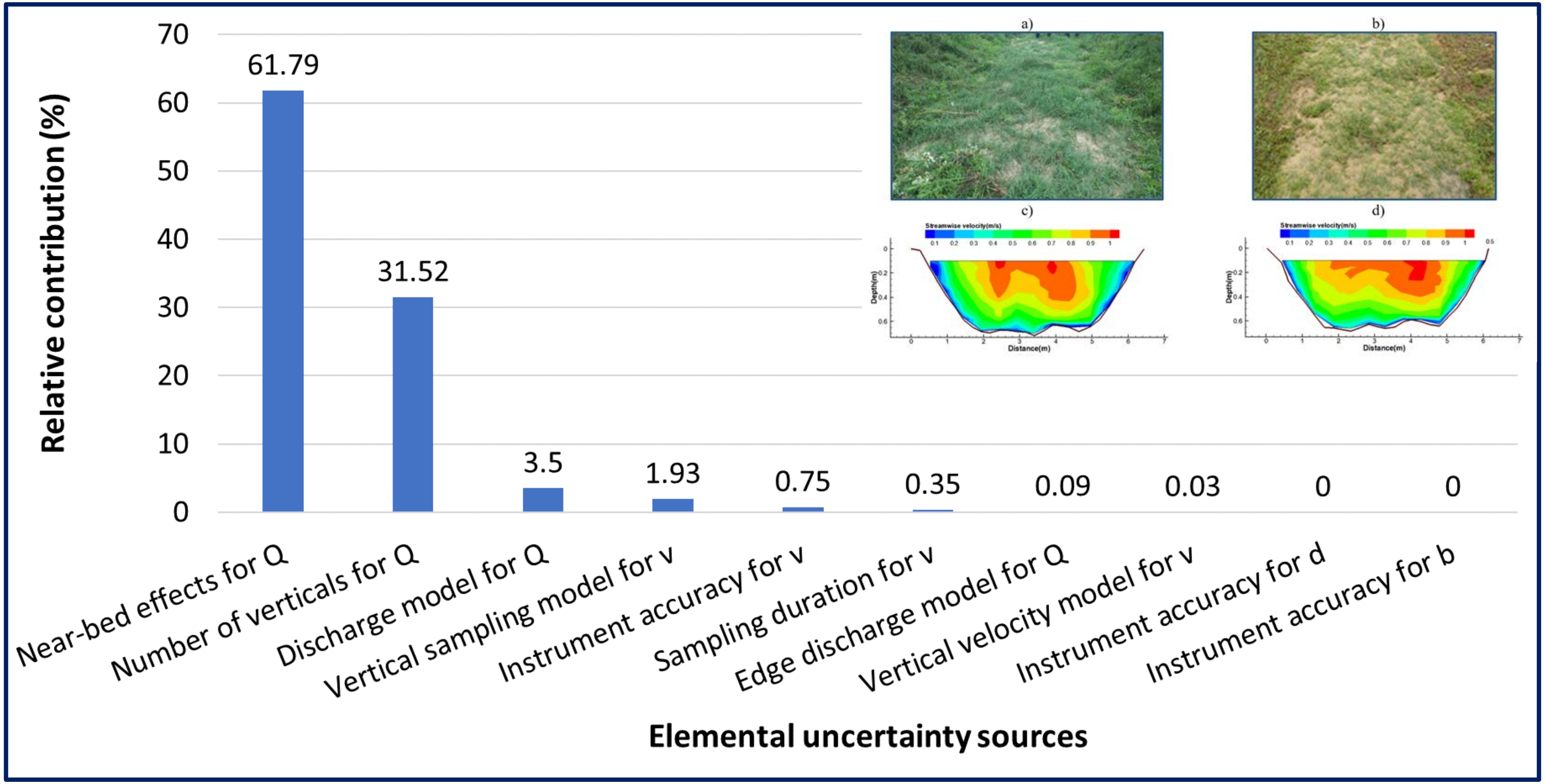
Notes:

- The relatively low values for the total discharge uncertainty are indicative for the favorable measurement environment, instrumentation, and measurement protocols used in the KICT-REC case study.
- In can be stated that the uncertainties in discharge provided by this study represent the mimimum expected uncertaitnty (baseline) compared with other measurement sites.



Case Study: GUM execution

QMSys output: uncertainty budget



Discussions: GUM in Hydrometry

Unsettled Issues

- **Is the use of relative uncertainties lumped as in ISO 748 for estimation of the total uncertainty equivalent to the GUM propagation using absolute values?** Use of relative uncertainties eliminates the sensitivity coefficients prescribed in GUM, preclude probability distributions other than normal distribution for estimation of the uncertainty sources (e.g., ISO 1088)
- **How to determine the "difficult-to-estimate" uncertainties?** Often time these sources dominate the uncertainty budget.

Challenges

- **The case specific vs. generalized UA requires conceptualization for uniform application**
- **Alternative approaches** (more or less conform with GUM framework) **continue to be used**. The **various approaches provide quite different uncertainties. How do we mediate the differences?**
- **Given the multiple approaches used for conducting UA in hydroscience, specialized institutions** (such as WMO, ISO**) have to agree and prescribe convergent, interoperable methodologies**
- **Overall there is still a considerable resistance to UA adoption** (hydrometry is a special case as the measurement environment is complex)

Conclusions: Lessons learned from GUM implementation

- **UA protocols converge toward common ground** (compared with 50 years ago); e.g., JCGM works toward unifying and grouping standards (GUM-based) rather than expanding them (the ISO approach)
- **WMO proposed the adoption of the GUM (1993)** for UA for measurements and modeling of hydrologic processes (WMO Report No. 1097, 2017)
- **GUM framework implementation is doable** (irrespective of instrument and measurement protocol)
- **It is possible to automate the laborious UA calculations with generic software (e.g., QMSys)**
- **Uncertainty analysis brings along a suite of benefits***
    - Provide confidence that the measured data can stand scientific and legal scrutinies
    - Minimize the measurement cost for a given output accuracy
    - Improve the measurement process
    - Inform field operators on optimal measurement strategy for a specific site

* Kim, J-M, Muste, M., Kim, D. and Despax, A. (2022). Implementation of Standardized Uncertainty Analysis for Streamflow Measurements Acquired with Acoustic Doppler Velocimeters, paper in preparation & report to be submitted for review to Project -X and ET-MU teams

Questions?