RAPPORT

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Uncertainty of discharge measurement methods: a literature review

Litteraturgjennomgang av metoder for beregning av usikkerhet i vannføringsmålinger

Alexandre Christophe Hauet

NVE Rapport 27/2020

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Redaktør:	N/A
Forfatter:	Alexandre Christophe Hauet
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Sammendrag:

Denne rapporten går gjennom eksisterende rammeverk og metoder for beregning av usikkerhet i vannføringsmålinger der vannføringen er målt med flygel, salt og ADCP. Konklusjoner:

Flygel: Usikkerhetsberegningen i ISO 748 er utdatert, men det finnes oppdaterte og alternative varianter: Q +, Fleure og IVE som alle blir beskrevet og diskutert. Rapporten anbefaler Fleure som den beste metoden, selv om den også har svakheter.

Salt: Rapporten går gjennom rammeverkene for beregning av usikkerhet som finnes og konkluderer med at de som finnes ikke et oppdaterte og fullstendige. Se også Uncertainty of salt discharge measurement - The SUNY Framework (Rapport 29/2020, ISBN: 978-82-410-2050-6) hvor et nytt rammeverk blir utviklet.

ADCP: Den beste metoden pr august 2020 er Oursin, men den eneste operasjonelle metoden som finnes er usikkerhetsberegningen i QRev. Qrevs usikkerhetsberegning stemmer godt overens med den ikke-operative metoden Oursin. Det jobbes pr. august 2020 med å få Oursin impementert i Qrev.

This report reviews existing frameworks and methods for calculating uncertainty in discharge measurements where the discharge has been measured with “flygel” (mechanical currentmeter), salt dilution and ADCP. conclusions:

Flygel: The uncertainty calculation in ISO 748 is outdated, but there are updated and alternative variants: Q +, Fleure and IVE which are all described and discussed. The report recommends Fleure as the best method, although it also has weaknesses.

Salt: The report reviews the existing frameworks for calculating uncertainties and concludes that these are not up to date and complete. See also Uncertainty of salt discharge measurement - The SUNY Framework (Rapport 29/2020, ISBN: 978-82-410-2050-6) where a new framework is being developed.

ADCP: The report describes existing frameworks for calculating uncertainty. The best method as of August 2020 is Oursin, but the only operational method available is the uncertainty calculation in QRev. Qrev's uncertainty calculation agrees well with the non-operational method Oursin. It works per. August 2020 to get Oursin implemented in Qrev.

Emneord:

Vannføring, vannføringsmåling, ADCP, nøyaktighet, usikkerhet, usikkerhetsberegning, måleusikkerhet, feilkilder, Oursin, Qrev, Fleure, ISO, Q+

Discharge, discharge measurement, ADCP, accuracy, uncertainty, uncertainty calculation, measurement uncertainty, sources of error, Oursin, Qrev, Fleure, ISO, Q+

Norges vassdrags- og energidirektorat

Middelthuns gate 29 Postboks 5091

Majorstuen 0301 Oslo

Telefon: 22 95 95 95

E-post: nve@nve.no

Internett: www.nve.no

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Forord

Denne rapporten er en av flere rapporter om usikkerhet i vannføringsmålinger skrevet av Alexandre Christophe Hauet, PhD, for hydrometriseksjonen på NVE. Hydrometri - Teknikk og feltdrift HHT, Hydrologisk avdeling, NVE.

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Hege Hisdal

avdelingsdirektør

Morten Nordahl Due

seksjonssjef

Norges vassdrags- og energidirektorat

Report

Uncertainty of discharge measurement methods: a literature review

Alexandre HAUET

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Contents

1 General consideration on uncertainty

Whatever the care taken in carrying out a measurement, error remains even after a right calibration of the instruments. As defined in The Guide to the expression of uncertainty in measurement JCGM 2008, an error is the difference between a measurement result and the true value of the measurand. Neither the value of the realized quantity nor the value of the measurand can ever be known exactly, so that the value of the error is never known. A statistical evaluation of the error is possible, giving a range of possible values for the error: this is called uncertainty.

1.1 Error of measurement

Error sources can be classified in different classes, as illustrated in Figure 1.

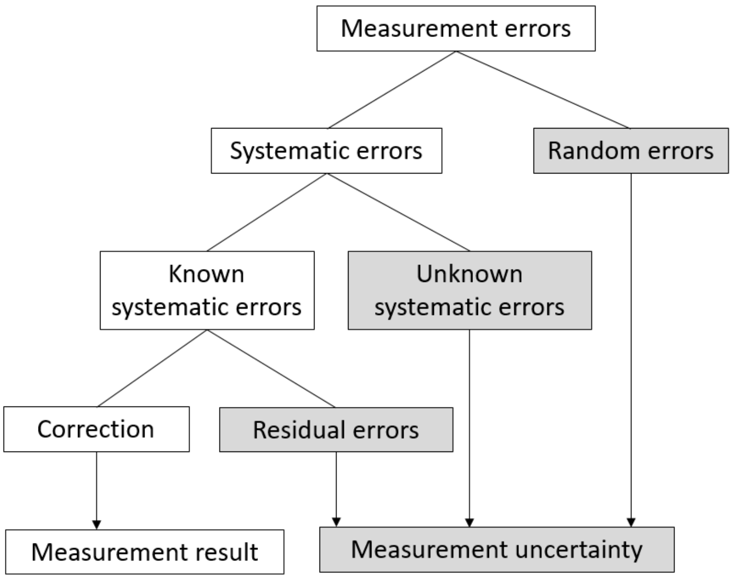


Figure 1: Classes of errors

The known systematic errors must lead to a correction of the measurement and thus do not contribute to the measurement uncertainty. Random errors, unknown systematic errors and residual error remaining after the correction of systematic errors contribute to measurement uncertainty. Unknown systematic errors (e.g. a read error or an input error by the operator) are, by definition, the most difficult to estimate. Random errors can usually be reduced by repetition of the measurement, the uncertainty of the average of n repeted independtant measurements being $\sqrt{n}$ times lower than the uncertainty of the n initial measuremets.

1.2 Uncertainty of measurement

As the true value and the true errors are not known, the statistical distribution of the error must be estimated using an uncertainty analysis. This analysis follows guidelines (ISO standards) and formal mathematics, but it encompasses subjective choices that must be justified by the expertise of the user. The value of a measurement is composed of an averaged value (if repetition of the measurement is possible) and of an uncertainty interval in which the true value is estimated to have a given probability of being, so called the expended uncertainty (but usually reduced to the term uncertainty). A confidence interval of 95% is often used, meaning that it is supposed that statistically in 95 out of 100 cases the difference between the measurement result and the true value is less or equal to the given uncertainty. It is important to note that an uncertainty analysis will be only conducted on measurement respecting the rules of thumb, whit adequate and calibrated equipment, with an adequate protocol and realised by trained people.

2 Methods for estimating uncertainty in hydrometry

Two main different approaches can be used for computing uncertainty: the propagation of uncertainty method and the collaborative inter laboratory experiment method.

2.1 Propagation of uncertainty method (GUM method or up-scaling method)

The method proposed in the Guide to the expression of uncertainty in measurement JCGM 2008, aka GUM, is considered as the reference method for the estimation of uncertainty. It is composed of 4 steps:

1. Analyse of the measurement process: it consists in defining exactly the measurand y and all the input data x_i. The mathematical model relating the measurand to the input data is built as $y = f(x_1, x_2, \ldots, x_N)$

2. The uncertainty $u(x_i)$ of each input value is estimated.In the so-called "Type A evaluation method", the standard uncertainty is computed using the experimental standard deviation of the observed value as in the so-called "Type B evaluation method" the standard uncertainty is evaluated by scientific judgement based on all of the available information on the possible variability of the input.

3. The inputs uncertainties are propagated using a model (often a first-order Taylor series approximation) to compute the combined uncertainty $u_c(y)$ as :

$$u_c^2(y) = \sum_{i=1}^{N} u^2(x_i) + 2 \cdot \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} u(x_i) \cdot u(x_j) \cdot r(x_i, x_j) \tag{1}$$

   where $r(x_i, x_j)$ is the covariance between the inputs x_i and x_j. In most cases, the correlation between the input values are neglected and $r(x_i, x_j) = 0$.

4. The value of the measurement is associated to an expanded uncertainty $U_p(y)$, using a coverage factor k_p to multiply the combined uncertainty, as:

$$U_p(y) = k_p \cdot u_c(y) \tag{2}$$

   It is common to express the expanded uncertainty at a confidence level of 95%,using a coverage factor of 1,96 (following the central limit theorem). This implies that the final uncertainty distribution follow a Gaussian law. If this hypothesis can not be proved, Monte Carlo numerical simulations can be used to obtain the uncertainty at the given confidence level (so called numerical propagation method).

The main advantages of the propagation method is that it can be applied to any measurement, and that it allows to evaluate the impact of each input to the final uncertainty. Thus, it is possible to adapt the measurement protocol in order to decrease the uncertainty.

2.2 Collaborative inter laboratory experiment method (or downscaling method)

This method consists in several measurements of the same measurand which is suppose to be stable and invariant in time) by sevreral so-called laboratory (in application to hydrometry, a laboratory would be a group of an instument and an operator). This method is monitored by four prescriptive referential: ISO 5725-1 ISO 1994a, ISO 5725-2 ISO 1994b, ISO 21748 ISO 2017 and ISO 13528 (ISO 2015).

In collaborative inter laboratory experiment, the experimental result Y (the discharge estimation) is expressed as :

$$Y = m + B + \epsilon \tag{3}$$

where m is the average of all the measurement (i.e. an approximation of the true value of the measurand), B is the bias introduced by the laboratory (instrument and operator) and ϵ is the random uncertainty. B and ϵ are realizations of random variables following respectively a normal law of standard deviation σ_L and σ_r. The variance of the measurement result s_R^2 is computed from the empirical standard deviations of repeatability (s_r) and interlaboratory (s_L) as :

$$s_R^2 = s_r^2 + s_L^2 \tag{4}$$

Let $i = 1, ..., p$ and $k = 1, ..., n_i$ the indexes of the laboratory and of the measurement repetition respectively. The repetability standard deviation s_r is computed using the empirical standard deviations s_i of the n_i repetitions of the measurement $Y_{i,k}$ given by each laboratory i as:

$$s_r^2 = \frac{\sum_{i=1}^{p} (n_i - 1) \cdot s_i^2}{\sum_{i=1}^{p} (n_i - 1)} \tag{5}$$

with

$$s_i^2 = \frac{1}{n_i - 1} \sum_{k=1}^{n_i} \left(Y_{i,k} - \bar{Y}_i\right)^2 \tag{6}$$

where $\bar{Y}_i$ is the mean of the k repetitions of the measurements realized by the laboratory i. The inter laboratory variance s_l^2, characterizing the dispersion of the mean results of the laboratories, is computed as:

$$s_l^2 = \frac{s_d^2 - s_r^2}{\bar{n}} \tag{7}$$

with

$$s_d^2 = \frac{1}{p-1} \sum_{i=1}^{p} n_i \left(\bar{Y}_i - Y_{moy} \right)^2 \tag{8}$$

and

$$\bar{n} = \frac{1}{p-1} [\sum_{i=1}^{p} n_i - \frac{\sum_{i=1}^{p} n_i^2}{\sum_{i=1}^{p} n_i}] \tag{9}$$

Y_{moy} is the grand mean of all the measurements (all the repetitions of all the laboratories). The expended uncertainty U is finally expressed as:

$$U(Q) = k \cdot \sqrt{s_R^2 + u^2(\widehat{\delta})} = k \cdot \sqrt{s_r^2 + s_L^2 + u^2(\widehat{\delta})} \tag{10}$$

with k the coverage factor and $u^2(\widehat{\delta})$ the uncertainty of the estimation of the measurement method bias.

2.3 Synthesis

There are two different methods for estimating uncertainty in hydrometry:

- The propagation of uncertainty method, or up-scaling method
- The collaborative inter laboratory experiment method, or down-scaling method.

Both methods have advantages and drawbacks. For applying the propagation method, one need to be able to model the measurement process, which is not always possible, and rarely simple. One need also to be sure to have encompass all the input values. For hydrometry, input values can be related to the environment (morphology of the section) or to the operators (skills of operators), which are not easy to define formally. But propagation method allows to compute an uncertainty for each gauging, realized in any conditions. Inter laboratory experiments demand a complex and heavy organization, because a lot of repetitions are needed, which means that a lot of teams and equipment need to be measuring together. This methods gives an experimental value of the uncertainty, in the conditions of the measurements. The uncertainty results obtained can not be generalized to other conditions.

Propagation methods are so needed in order to compute an uncertainty value for every discharge measurement. Inter laboratory are needed to compute an experimental uncertainty value that can be compared with propagation method for the conditions of the experiment.

In this report, we focus on the propagation of uncertainty methods for the following discharge measurement techniques:

- Current meter measurements using the Velocity-Area method,

- Tracer dilution measurements
- ADCP measurement

For each measurement method, a review of the existing methods for computing uncertainty is detailed, focusing on NVE's hydrometric protocols.

3 Current-meter measurement using the Velocity-Area method

3.1 Definition of the measurement method

The Velocity-Area method consists of a discrete integration of flow velocity over the channel cross-section. Velocities and water depths are sampled at given positions on verticals distributed throughout the section. At a given vertical i $(1 \leq j \geq m)$, the following parameters are measured: distance from the start edge y_i, water depth d_i, and point velocities perpendicular to the cross-section $v_{i,j}$ measured at depths $d_{i,j}$. Distances are measured using conventional calibrated devices. Point velocities are measured with either mechanical (propellers), electro-magnetic (Hall effect based), or acoustic (Doppler effect based) current-meters, which are typically mounted on a wading-rod, or deployed from a cableway or from a bridge. Depth-averaged velocity of a given vertical is computed using the measured point velocities. At NVE, a reduced number of point is used, meaning that only 1, 2 or 3 points $v_{i,j}$ are measured per vertical, and the depth-averaged velocity is computed as :

$$V_i = v_{i,0.6D} \text{ for a 1 point measurement} \tag{11}$$

$$V_i = 0.5 * (v_{i,0.2D} + v_{i,0.8D}) \text{ for a 2 points measurement} \tag{12}$$

$$V_i = 0.25 * (v_{i,0.2D} + 2 * v_{i,0.6D} + v_{i,0.8D}) \text{ for a 3 points measurement} \tag{13}$$

where $0.2D$, $0.6D$ and $0.8D$ represent the relative depths from the surface of 20, 60 and 80% respectively. Those formulas assume a theoretic log-law vertical distribution of the velocity.

Following NVE guidline, the mid-section method is then used to compute discharge. The depth D_i at a vertical i is multiplied by the width B_i, which extends halfway to the preceding vertical $i-1$ and halfway to the following vertical $i+1$, to develop a cross-sectional area. The product of this area and the depth-averaged velocity V_i at the vertical gives the discharge Q_i for the partial section between the two halfway points as :

$$Q_i = B_i \cdot D_i \cdot V_i \tag{14}$$

The total discharge, Q, is the sum of partial discharges Q_i over the N subsections i of the cross-section:

$$Q = \sum_{i=1}^{N} Q_i = Q_{banks} + \sum_{i=1}^{N} B_i \cdot D_i \cdot V_i \tag{15}$$

3.2 Inventory of error sources

Using Equation eq. (15), the following uncertainty sources can be identified:

- Uncertainty in the measurement of the width $u(B_i)$;

- Uncertainty in the measurement of the depth $u(D_i)$;
- Uncertainty in the estimation of the depth-averaged velocity $u(V_i)$, that encompasses :
  - the uncertainty of the imperfect calibration of the current meter $u_c(v_{i,j})$;
  - the uncertainty due to the limited exposure time compared to the turbulence and the pulsations of the flow $u_{exp}(v_{i,j})$;
  - the uncertainty due to the limited number of points per vertical used to compute the depth-averaged velocity $u_p(V_i)$;
- Uncertainty in the estimation of the total discharge $u(Q)$, due to the method used for computing the discharge that encompass :
  - the limited number of verticals used for measuring the depth and the depth-average velocity;
  - the method used to interpolate between the measured verticals;
  - the computation of the banks' discharge.

To those error sources related to the measurement's method (including the instrument, the protocol and the computations), one must add

- Errors sources related to the hydraulic conditions such as the uncertainty due to the unsteadiness of the flow;
- Uncertainty due to the skill of the operator.

3.3 Uncertainty of current-meter measurements

Current meters have been used since a long time, and they are the most used measurement method in the world, as illustrated by fig. 2 from a survey realized by the WMO in 2009 (J. Fulford and Buzás 2009). As a consequence, there are numerous papers dealing with the current meters uncertainty, as noted by Pelletier 1988. The first papers published in journal appear in the 60's (Carter and Anderson 1963) but most of the development were realized in the seminal work published by Herschy (Herschy 1975, Herschy 2002). Those last publications have been used for the definition of the standard ISO 748 (ISO 2009). Since the 1990's, few studies were conducted, probably due to the development and the increasing used of ADCP. This review focuses on the latest and most used method for computing uncertainty of current meter measurement : ISO 748, Q+, FLAURE and IVE methods.

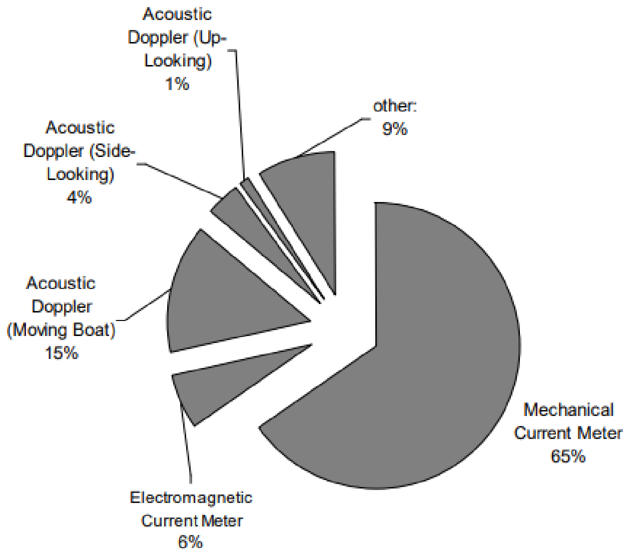


Figure 2: Caption

3.4 Uncertainty computation using ISO 748

3.4.1 Description of the method

The uncertainty computation proposed in the standard ISO 748 ISO 2009 is a direct application of the GUM method on Equation eq. (15). The combined uncertainty is expressed as :

$$u^2(Q) = u_s^2 + u_m^2 + \frac{\sum_{i=1}^{N} Q_i^2 \left[u^2(B_i) + u^2(D_i) + u_p^2(V_i) + \frac{1}{n_i} \left\{ u_c^2(v_i) + u_{exp}^2(v_i) \right\} \right]}{\left(\sum_{i=1}^{N} Q_i \right)^2} \tag{16}$$

where :

- u_s is the uncertainty due to variable responsiveness of the current-meter, width measurement instrument and depth sounding instrument;
- u_m is the uncertainty due to the limited number of verticals, with N the number of verticals;
- $u(B_i)$ and $u(D_i)$ are the relative uncertainties in the width and depth measured at vertical i;
- $u_p(V_i)$ is the uncertainty due to the limited number of measurements n_i of velocity used for the computation of the depth-averaged velocity V_i of the vertical i;

- $u_c(v_i)$ is the uncertainty in the velocity due to lack of repetability of the current-meter;
- $u_{exp}(v_i)$ is the uncertainty in point velocity due to velocity fluctuations (pulsations) in the stream during the exposure time of the current-meter.

Assuming a full compliance with the measurement protocol given in ISO 2009[1], the ISO 748 propose the following values :

- $u_s = 1\%$
- $u(B_i) = u(D_i) = 0,5\%$
- values of u_m are given in the Table E.6 of ISO 2009.

Number of verticals	5	10	15	20	25	30	35 and more
u_m **(%)**	7,5	4,5	3,0	2,5	2,0	1,5	1,0

Table 1: Uncertainty (at the confidence level of 68%) in the limited number of verticals u_m.

- values of $u_p(V_i)$ are given in the Table E.4 of ISO 2009

Method of measurement	Velocity distribution	5 points	3 points	2 points	1 point	Surface point
$u_p(V_i)$ **(%)**	0,5	2,5	3,5	5	7,5	15

Table 2: Uncertainty (at the confidence level of 68%) in the measurement of depth-averaged velocity at a vertical, due to limited number of points in the vertical $u_p(V_i)$.

- values of $u_c(v_{i,j})$ depends on the kind of instrument used for measuring the velocity. Table E.5 of of ISO 2009 gives the following value for rotating-element current-meter:

Velocity Measured	0,03	0,1	0,12	0,25	0,5	Over 0,5
$u_c(v_{i,j})$ **(%)**	10	2,5	1,25	1,0	0,5	0,05

Table 3: Uncertainty (at the confidence level of 68%) in point velocity measurement due to mechanical current-meter rating error $u_c(v_{i,j})$.

- values of $u_{exp}(v_{i,j})$ are given in Table E.3 of of ISO 2009

The standard ISO 748 ISO 2009 indicates that all the uncertainty values are given as a guide and should be verified by the user.

[1]especially the number of verticals regarding the width of the river and the ratio of $\frac{Q_i}{Q}$

Velocity m/s	Points in vertical 0,2D, 0,4D, or 0,6D				Points in vertical 0,8D or 0,9D			
	Exposure time (min)							
	0,5	1	2	3	0,5	1	2	3
0,05	25	20	15	10	40	30	25	20
0,10	14	11	8	7	17	14	10	8
0,20	8	6	5	4	9	7	5	4
0,30	5	4	3	3	5	4	3	3
0,40	4	3	3	3	4	3	3	3
0,50	4	3	3	2	4	3	3	2
1,00	4	3	3	2	4	3	3	2
over 1,00	4	3	3	2	4	3	3	2

Table 4: Uncertainty (at the confidence level of 68%) in point velocity measurements due to limited exposure time $u_{exp}(v_{i,j})$.

3.4.2 Limitations of the ISO 748 method for computing uncertainty

So far, the ISO 748 standard ISO 2009 is the only normative framework for estimating the uncertainty of gaugings by the velocity area method. But several limitation scan be highlighted :

- As noted by several authors (A. Despax 2016,LeCoz et al. 2012), the values of uncertainty given by the ISO 748 ISO 2009 were computed from experiments conducted in large and calm rivers, with ideal measurement conditions. Their use for every gauging can conduct to underestimation of the composed uncertainty. As an example, the uncertainty on the depth-averaged velocity estimation $u_p(V_i)$ is only related to the number of points of velocity measurements used per vertical, and not to the flow complexity. If the vertical distribution of velocity does not follow a log-law, the uncertainty will be underestimate.

- The ISO 748 ISO 2009 indicates that all the uncertainty values should be verified by the user, but this is clearly not feasible in operational hydrometry, as every input source would require a prior study taking a very long time.

- Some errors are not taken into account, especially errors related to the unsteadiness of the flow, to the estimation of banks' discharge and to the skills of the operators. In a study for the WMO, J. M. Fulford 2015 proposed to add those input sources. The uncertainty due to skills of the operators was estimated, using repeated measurement, as $u_{operator} = 2\%$, but authors admitted that this approach is very simplistic. They also propose to estimate the uncertainty due to increasing or decreasing discharge using the rating curve of the site and the stage measured at the beginning and the end of the measurement.

- As shown by Equation eq. (16), the uncertainty due to the limited number of verticals u_m, is predominant in the combined uncertainty computation. However, u_m is computed in ISO 2009 using the total number of verticals only (see Table table 1) and not taking into account the spatial distribution of the verticals, or the adequacy between the river complexity (in terms of bed topography anf flow) and the sampling verticals.

3.5 Uncertainty computation using Q+

3.5.1 Description of the Q+ method

The Q+ method was proposed by LeCoz et al. 2012. It is an improvement of the ISO 748 standard for uncertainty. Instead of the single term u_m of the ISO 748 standard, the transversal integration uncertainties in each subsection-averaged depth, $u_m(D_i)$, and in each subsection-averaged velocity, $u_m(V_i)$, are computed. Combining those new terms in Equation eq. (16) gives:

$$u^2(Q) = u_s^2 + \frac{\sum_{i01}^{N} Q_i^2 \left[u^2(B_i) + u^2(D_i) + u_p^2(V_i) + u_m^2(D_i) + u_m^2(V_i) + \frac{1}{n_i} \left\{ u_c^2(V_i) + u_e^2(V_i) \right\} \right]}{\left(\sum_{i=1}^{N} Q_i \right)^2} \tag{17}$$

This approach allows to estimate the contribution of both the lateral sampling of the bathymetry and the lateral sampling of the velocity, and so allows to improve the sampling strategy of a measurement:

- $u_m(D_i)$ is computed using the maximal possible variation of the area of a subsection i. The min/max realistic subsections areas are estimated thanks to a user-defines angle α to account for the maximum bottom transverse slope as illustrated on fig. 3. $u_m(D_i)$ is computed using a rectangular probability distribution:

$$u_m(D_i) = \frac{b_{i+1}^2 + b_i^2}{2\sqrt{3}\,(b_{i+1} + b_i)\,D_i} \tan\alpha \tag{18}$$

- $u_m(V_i)$ is computed using max/min depth-averaged velocity at the subsection limits. A linear interpolation of the Froude number between two verticals is used to compute the Froude number at the subsection limits, then allowing the computation of the min/max velocities ($V_{i,min}$ and $V_{i,max}$, respectively) using the min/max depth considering the angle α ($d_{j,min}$ and $d_{j,max}$ respectively, see fig. 3). $u_m(V_i)$ is finally expressed using a rectangular probability distribution as:

$$u_m(V_i) = \frac{V_{i,max} - V_{i,min}}{2\sqrt{3}V_i} \tag{19}$$

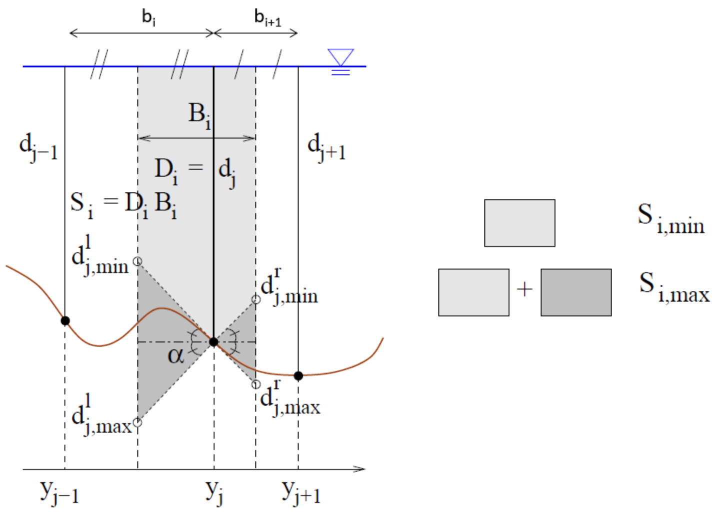


Figure 3: Caption

3.5.2 Limitation of the Q+ method

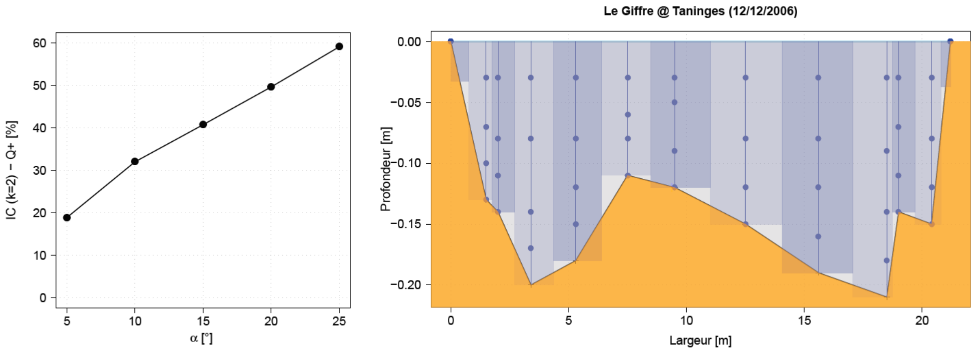
The Q+ method is a nice improvement of the ISO 748 standard, but the main limitation comes from the user estimation of the α angle (maximum possible variation of the bed bathymetry). This parameter is very hard to apprehend, and the final uncertainty $u(Q)$ computed from eq. (17) is extremely sensitive to α, especially when the aspect ratio (width / depth) of the river is high, and when the number of vertical is reduced. Figure 4 illustrates the impact of the value of α on the expended uncertainty $U(Q)$ of a gauging: for α ranging from 5 to 25°, $U(Q)$ ranges from 20 to 60%.

3.6 FLAURE method

3.6.1 Description of the method

The FLAURE method was proposed by A. Despax 2016 and A. Despax et al. 2016 and is an improvement of the Q+ method of LeCoz et al. 2012 in the estimation of the uncertainty component relating to the limited number of verticals. Reference gaugings realized with a high number of verticals (> 50 verticals) are used to assess the uncertainty component through a statistical analysis. Those reference gaugings are subsampled (10000 gaugings with a range of 5 to 50 verticals are simulated) to produce probable realistic gaugings. Instead of subsampling purely randomly, a subsampling method is developed in a way that mimics the behaviour of a field hydrologist:

- At least 5 vertical are used;



(a) (b)

Figure 4: Caption

- The probability of picking a vertical is related to the product of the depth and depth-averaged velocity of each vertical;
- the probability of picking a vertical is related to the distance to the already selected verticals.

The uncertainty due to the sampling u_m is computed as the distribution of the difference of discharge between the subsampled gaugings and the complete reference gauging.

A sampling quality index (SQI) is suggested and appears to be a more explanatory variable than the number of verticals. This index takes into account the spacing between verticals and the lateral variation of depth and velocity between two verticals and is expressed as :

$$SQI(D) = \frac{\sigma(\Delta D)}{\sigma(D)} \cdot \frac{\sum_{i=1}^{m} (\Delta x_i \Delta D_i)}{A} \tag{20}$$

$$SQI(V) = \frac{\sigma(\Delta V)}{\sigma(V)} \cdot \frac{\sum_{i=1}^{m} (\Delta x_i \Delta V_i)}{V_{int}} \tag{21}$$

where $\Delta D_i = |D_{i-1} - D_i|$, A is the total area, $\Delta V_i = |V_{i-1} - V_i|$ and V_{int} is the integral of the lateral distribution of the velocity (area under the curve $V_i = f(x)$

This dimensionless criterion has the advantage to take into account:

- The spacing between verticals (Δx_i) which will increase SQI if they are widely spaced;
- The variation of the depth and the velocity between two adjacent verticals (ΔD_i and ΔV_i) which will also increase SQI if changes in flow distribution are not enough sampled;

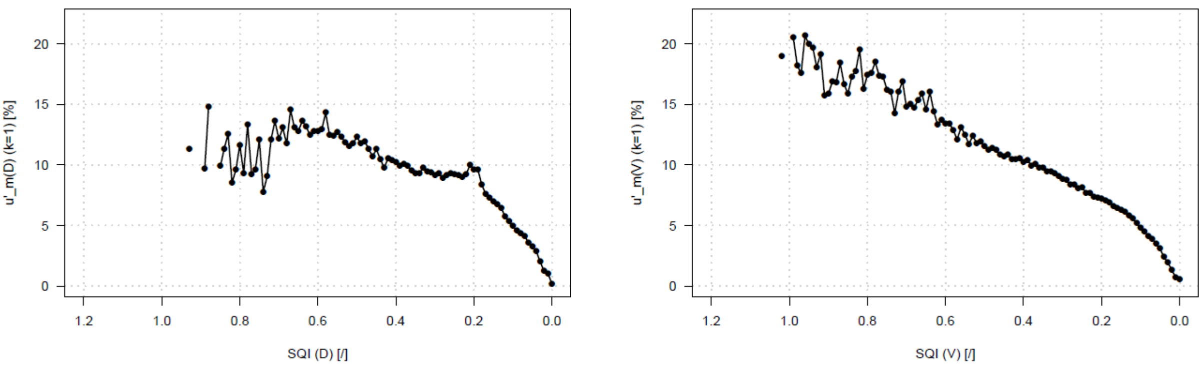


Figure 5: Relationship between the uncertainty of the bathymetry and the velocity due to the sampling and the corresponding SQI

- A ratio between the standard deviation of depth and velocity of adjacent measurements and the total standard deviation of those quantities. The denominator of the ratio is quite stable while the numerator must reduce when the number of verticals increases and variations between adjacent verticals are low.

A theoretical value of $SQI = 0$ means that the spacing between verticals is infinitesimally small. $SQI(D)$ can reach 0 if the depth is constant, like for a rectangular concrete channel. On the other hand, SQI shall reasonably not exceed a value of 1.

For each subsampled gaugings, $SQI(D)$ and $SQI(V)$ are computed and the uncertainty due to the sampling on the estimation of the area $u_m(D)$ and the estimation of the velocity $u_m(V)$ is expressed depending of $SQI(D)$ and $SQI(V)$ respectively. A general model relating $u_m(D)$ and $SQI(D)$, and $u_m(V)$ and $SQI(V)$, is proposed by A. Despax et al. 2016 as illustrated in fig. 5.

To compute the uncertainty component for any routine gauging the following framework is applied:

- Compute the $SQI(D)$ and $SQI(V)$ of the gauging using eq. (20) and eq. (21);
- Compute $u_m(D)$ and $u_m(V)$ using the model illustrated in fig. 5;
- Compute gauging uncertainty using the value of $u_m(D)$ and $u_m(V)$ in the Q+ equation eq. (17)

3.6.2 Limitations of the FLAURE method

The FLAURE method is an improvement of the Q+ method, based on the ISO 748. It gives an objective and appropriate solution for the computation of the uncertainty due to the sampling u_m. The framework used is complex, and one should note that the FLAURE method does not improve all the other uncertainty sources, so that the values given by ISO 2009 and listed in section 3.4.1 are used with all the limitations cited in section 3.4.2.

3.7 Uncertainty computation using the Interpolation Variance Estimator (IVE) method

3.7.1 Description of the IVE method

In the Interpolation Variance Estimator (IVE) method proposed by Kiang, Cohn, and Mason 2009 and Cohn, Kiang, and Mason 2013, the uncertainty of the spatial sampling is computed considering a model of linear evolution of the depth and velocity between the verticals.

For the depth, an estimated value $D_{i,est}$ is computed for vertical i from linear interpolation form adjacent verticals as :

$$D_{i,est} = \omega_i D_{i-1} + (1 - \omega_i) D_{i+1} \tag{22}$$

with

$$\omega_i = \frac{x_{i+1} - x_i}{x_{i+1} - x_{i-1}} \tag{23}$$

The difference $\Delta_{i,D}$ between the measured depth D_i and the interpolated depth $D_{i,est}$ can be computed for each vertical, as illustrated in fig. 6.

The uncertainty related to the depth is then estimated using the standard deviation of $\Delta_{i,d}$ for the m verticals as :

$$u_{IVE}(D_i) = s_D = \sqrt{\left(\frac{1}{m-5}\right) \cdot \sum_{i=3}^{m-2} \frac{\left(\Delta_{i,D}\right)^2}{2\left(1 - \omega_i + \omega_i^2\right)}} \tag{24}$$

The same approach for the lateral distribution of the depth-averaged velocity leads to :

$$u_{IVE}(V_i) = s_V = \sqrt{\left(\frac{1}{m-5}\right) \cdot \sum_{i=3}^{m-2} \frac{\left(\Delta_{i,V}\right)^2}{2\left(1 - \omega_i + \omega_i^2\right)}} \tag{25}$$

The combined relative uncertainty is finally expressed as:

$$u^2(Q) = u_s^2 + \frac{\sum_{i=1}^{m} Q_i^2 \left[u^2(B_i) + u_{IVE}^2(D_i) + u_{IVE}^2(V_i)\right]}{\left(\sum_{i=1}^{m} Q_i\right)^2} \tag{26}$$

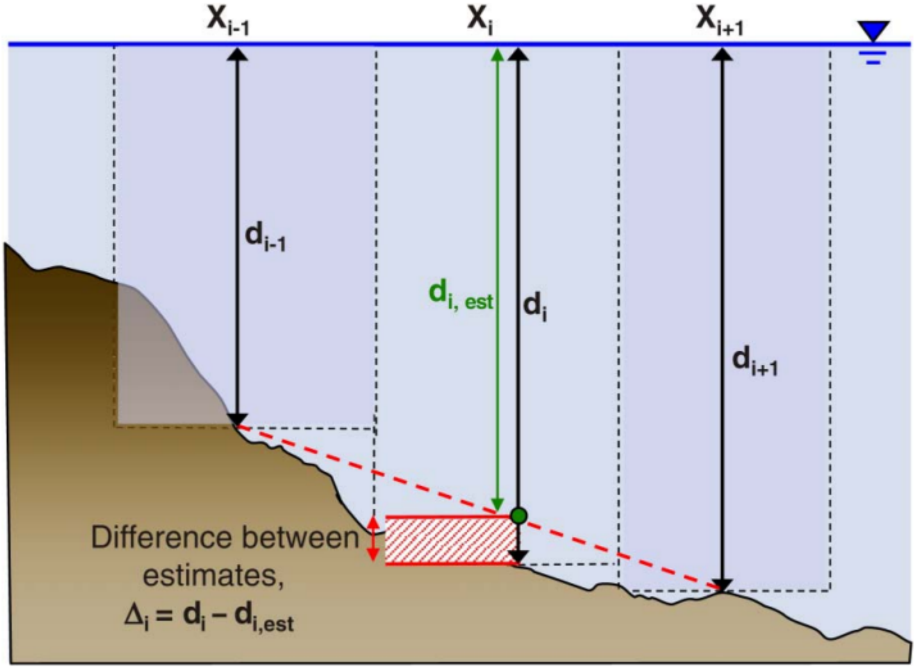


Figure 6: Measured depth d_i, provides an estimate of the average depth of the vertical; a second estimate of the depth, $d_{i,est}$, can be obtained at each vertical by interpolating from adjacent verticals; Δ is the difference between this original measurement, d_i, and the interpolated estimate, $d_{i,est}$, from Cohn, Kiang, and Mason 2013.

3.7.2 Limitations of the IVE method for computing uncertainty

The method relies on the linear evolution of depth and velocities between adjacent verticals. However, it is unclear how departure from linearity can capture all the sources of error on depth or velocity ($u_p(V_i)$, $u_c(V_i)$ and $u_e(V_i)$ for instance). Moreover, this assumption may be false when few verticals are made.

The components of uncertainty $up(V_i)$, $u_c(V_i)$, $u_e(V_i)$ and $u(D_i)$ are supposed to be included in $u_{IVE}(V_i)$ and $u_{IVE}(D_i)$. Consequently the IVE method does not allow the computation of the contribution of each error source and does not provide insight into strategies that might be applied to reduce the final uncertainty. Furthermore, errors due to extrapolation are not taken into account since the index varies between $i = 3$ and $i = m - 2$.

3.8 Summary of uncertainty methods for current meter measurements and perspectives

All the analytical methods for uncertainty of current meter measurements are derived from the GUM approach. The ISO 748 (ISO 2009) is the only normative framework, but it suffered several limitation, especially the weak definition of the predominant uncertainty due to the limited number of verticals u_m. This is a very strong drawback, that makes this method not applicable operationally. The Q+ (LeCoz et al. 2012) and FLAURE (A. Despax et al. 2016) methods have improved the computation of the term u_m, by taking into account the adequacy between the sampling and the river bed and velocity complexity. The framework used is complex, and one should note that the FLAURE method does not improve all the other uncertainty sources. The IVE method (Cohn, Kiang, and Mason 2013) is more straightforward, but it relies on the assumption of a linear evolution of depth and velocities between adjacent verticals that requires a very high number of verticals to be respected.

Finally, the most recent methods (Q+, FLAURE and IVE) are interested, but they are maybe not all well adapted for the gaugings' protocols used at NVE. They need to be applied to NVE's gaugings database to stress their limitations. As no reference value of discharge exists in natural rivers, the results of the uncertainty methods must be evaluated against expertise from field hydrologists.

4 Dilution method using slug injection of salt

4.1 Definition of the measurement method

In the slug injection method, a known mass of salt M_{inj} (in g) is injected as a near-instantaneous slug at one location in the stream. Following injection, the salt solution mixes rapidly throughout the depth of the stream and less rapidly across the stream width as it travels downstream with the general flow of water. Because some portions of a stream flow faster than others (flow tends to be faster in the centre than near the banks), the cloud of salty water "stretches" downstream in a process called longitudinal dispersion, as illustrated in fig. 7. Assuming a conservation of the mass of salt injected, the mean concentration of

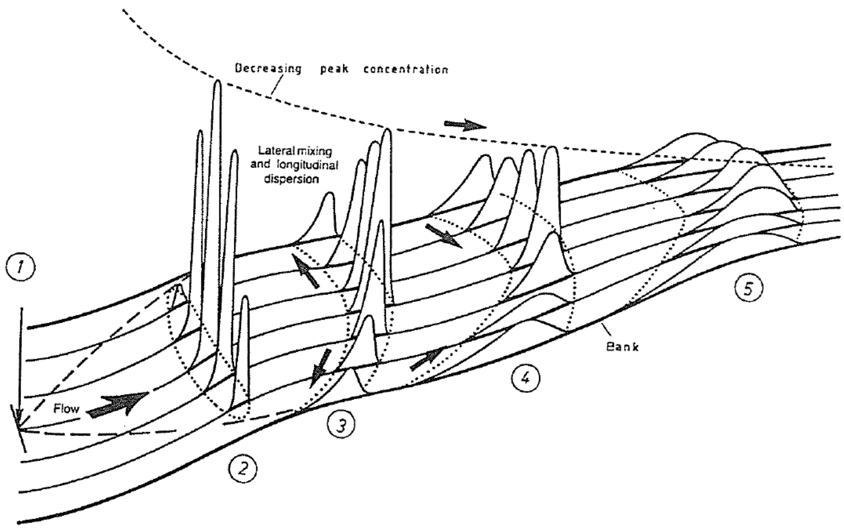


Figure 7: Model of lateral and longitudinal mixing of an instantaneously injected tracer, from Benischke and Harum 1990

the tracer cloud multiplied by the volume of the cloud must be equal to the injection mass. Thanks to sensors (classically two) located downstream the mixing length, the temperature-corrected electrical conductivity of the stream water is measured as the difference between the conductivity measured at time t Cd_t ($\mu S \cdot cm^{-1}$) and the background conductivity of the stream water Cd_b ($\mu S \cdot cm^{-1}$). This is linearly related to the concentration of salt Cc_t. The record of tracer concentration with time at the measurement location is called a tracer breakthrough curve. A typical breakthrough curve is illustrated in fig. 8.

The discharge Q of a stream can be determined from the integral of the breakthrough curve (approximated as a summation of discrete measurements) and the initial mass of

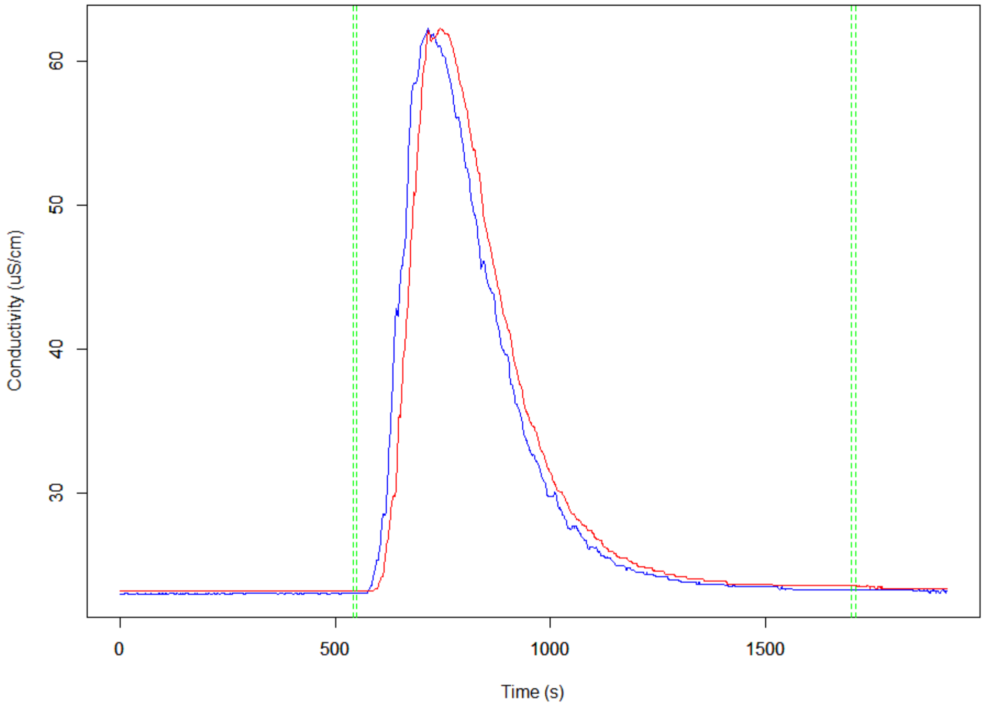


Figure 8: Typical breakthrough curve for a salt dilution

injected salt, as follows:

$$Q = \frac{M_{inj}}{\int_{T_{begin}}^{T_{end}} ((Cd_t - Cd_b) \cdot CF \cdot dt)} = \frac{M_{inj}}{\sum_{T_{begin}}^{T_{end}} (Cd_t - Cd_b) \cdot \Delta t \cdot CF} \tag{27}$$

where CF is a calibration constant relating salt concentration to electrical conductivity $(g \cdot cm \cdot \mu S^{1-} \cdot m^{-3})$, dt is the time interval between successive measurements (s), and n is the number of conductivity measurements. To determine the calibration constant CF , a solution of salt and water (known as the calibration solution) is added to a sample of stream water in increments. The resulting conductivity Cd_i and salt concentration Cc_i after each addition i of calibration solution is recorded. Cc_i is plotted as a function of Cd_i , and the slope of the line CF is determined by linear regression.

4.2 Uncertainty of salt dilution using slug injection

Even if the method was first developed in the middle of the 19th century (Schlœsing 1863), its first operational applications date from the middle of the 20th century and main considerations about uncertainty appeared in the late 1970's. At that time, there were not high frequency conductivity probes that could measure in real-time in the water. Church 1975 and Day 1976 listed three principal sources of error: (i) volumetric errors associated with pipette usage and the preparation of the calibration solutions; (ii) statistical error of the calibration curve fitted to the calibration points and (iii) errors of the conductivity values as read during the experiment. The last two sources are related to the conditions of the time, including computing capacity and to the instruments, and are not up-to-date considering current technologies. They stated that the uncertainty of salt dilution ranges normally from 4 to 7 %, with extreme boundaries reaching 10 to 20%.

The work of Kilpatrick and Cobb 1984 has inspired the Iso Standard 9555-1 ISO 1994c framework that will be described in section 4.2.1.

In the 90's, less papers dedicated to dilution methods have been published. Benischke and Harum 1990 and Okunishi, Saito, and Yoshida 1992 compared salt dilution to current meters measurements and found differences ranging 5 to 10%.

In the last 10 years, in situ, high frequency, high resolution sensors and their associated computing systems have been developed, allowing an upsurge of dilution methods. In British Columbia, Hudson and Fraser 2005 and R. D. Moore 2005 gave qualitative values of uncertainties of about 5% under suitable conditions. For winter conditions, Dahl 2019 showed that salt measurement were closer to a reference discharge than other methods, and highlighted that most of the uncertainty came from calibration and operators' skills. Richardson 2015 and Sentlinger 2015 have developed quantitative frameworks that are presented in section 4.2.2 and section 4.2.3, respectively.

4.2.1 Iso 9555

The Iso 9555 (ISO 1994c) is the only normative reference for the computation of the uncertainty of salt dilution. It is based on a GUM approach, and it distinguishes systematic and random errors that can affect a measurement. Systematic errors are :

- Error associated with the tracer, if the tracer reacts with the water flowing or with the sediments, vegetation or the bed and banks of the channel. This effect is very limited when using salt as a tracer, compared to fluorescent tracers. The standard does not propose a computation for this error.
- Error associated with the duration of the gauging, if the measurement is stopped before the conductivity is back to the baseline. The standard does not propose a computation for this error.
- Error associated with poor mixing in the gauging reach. The standard proposes to estimate the degree of mixing x using several probes m over the sampling section as:

$$x = 100 \cdot \left(1 - \frac{\sum_{i=1}^{m} |A_i - \overline{A}|}{2m\overline{A}}\right) \tag{28}$$

where A_i is the area under the breakthrough curve of sensor i, and $\overline{A}$ is the average of the areas for all the m sensors. Iso 9555 stands that, for x greater than 90%, error associated with poor mixing is $2 \cdot (100 - x)$.

- Error associated to unsteadiness of the flow, if the discharge is changing during the gauging. The standard does not propose a computation for this error.
- Error associated with sampling and analysis of samples, related to the quality of the flask end pipettes used. The standard does not propose a computation for this error.

Iso 9555 identifies three random uncertainty sources :

- Uncertainty of the quantity of injected salt, that should be calculated using laboratory experiments (repeated weighings);
- Uncertainty associated to the accuracy of the time device used for the sampling. At the time of the publication of the standard, the sampling were performed manually.
- Uncertainty associated to the conductivity of each sample.

The Iso 9555 method is not up to date, as the equipment and the measurement protocol have drastically changed thanks to in situ high frequency sensors. Most of the issues listed in Iso 9555 issues are still relevant, but the framework and the associated computations are not usable.

4.2.2 University of British Columbia

Following the GUM methodology, Richardson 2015 expressed the uncertainty of salt dilution measurement as :

$$\frac{\delta(Q)}{Q} = \sqrt{\left(\frac{\delta(M_{inj})}{M_{inj}}\right)^2 + \left(\frac{\delta(A)}{A}\right)^2 + \left(\frac{\delta(CF)}{CF}\right)^2} \tag{29}$$

with $\delta(M_{inj})$, the uncertainty of the injected mass of salt, being typically 0.1 g. The uncertainty associated with the area under the breakthrough curve, $\delta(A)$, is determined by $\delta(A) = 2 \cdot n \cdot \sigma$, where n is the number of conductivity measurements and σ is the standard deviation of the conductivity measurements before and after the tracer wave. If the recorded conductivity is completely stable, then σ is the resolution of the probe. Each measurement point has two sources of uncertainty: the measurement itself and the background conductivity subtracted from the measurement, thus the multiplication by two. Richardson 2015 computes the uncertainty in CF using the observed variability of this coefficient during their experiments.

This framework does not encompass all the uncertainty sources, and the evaluation of $\delta(CF)$ can not be applied to any gauging. The systematic errors identified by the Iso 9555 are not taken into account, and the evaluation of $\delta(A)$ is too simplistic.

4.2.3 QiQuac method

In the QiQuac manual, Sentlinger 2019 writes the uncertainty:

$$\frac{\delta Q}{Q} = \frac{\delta M_{inj}}{M_{inj}} + \frac{\delta \Delta t}{\Delta t} + \frac{\delta CF}{CF} + \frac{\delta \left[\sum \left(Cd_t - Cd_b\right)\right] \cdot DT}{\sum \Delta t \left(Cd_t - Cd_b\right)} \tag{30}$$

where:

- the uncertainty on the mass of injected salt $\frac{\delta M_{inj}}{M_{inj}}$ is supposed to be 0.5% by default;
- the uncertainty in the time measurement $\frac{\delta \Delta t}{\Delta t}$ is set to 0 and ignored;
- the uncertainty in CF, $\frac{\delta CF}{CF}$ is set to 2%, corresponding to the equipment (pipettes and flasks) provided with the QiQuac system;
- the uncertainty in the area under the curve $\frac{\delta[\sum(Cd_t - Cd_b)] \cdot DT}{\sum \Delta t(Cd_t - Cd_b)}$ is taken as the maximum between the sensor resolution and the standard deviation of the base conductivity before and after the tracer wave.

The uncertainty due to poor mixing is computed using the difference, in %, between the discharge computed by several sensors.

This approach is incomplete, as all the systematic errors are not taken into account. The fixed value for $\frac{\delta CF}{CF}$ can not reflect different calibration protocols. The computation of $\frac{\delta[\sum(Cd_t - Cd_b)] \cdot DT}{\sum \Delta t(Cd_t - Cd_b)}$ is still too simplistic, and does not account for the stability of the base conductivity, or the position of the end and beginning of the tracer wave.

4.3 Summary of uncertainty methods for salt dilution measurements and perspectives

There are few papers dealing with salt dilution uncertainty. The Iso 9555 (ISO 1994c) standard is the only normative framework, but it is not adapted to recent equipment and methods (it was published in 1994 for manual water samplings). The methods proposed by Richardson 2015 and Sentlinger 2019 are valuable improvements of the Iso approach, but they are incomplete, as some uncertainty values are fixed (like for CF) or ignored.

A complete framework is missing, that could be applied for any gauging and future work should focus on its development.

5 Moving-Boat ADCP Discharge Measurements

5.1 Definition of the measurement method

Acoustic Doppler Current Profilers (ADCPs) have become one of the most used instruments for measuring discharge in rivers throughout the world (Boldt and K. A. Oberg 2015; Le Coz 2017). This report presents the state of the art concerning the estimation of the uncertainty of an ADCP discharge measurement computed with the propagation method. We only consider gauging using the moving-boat method. For a review of uncertainty estimation using the field interlaboratory method, readers could refer Aurélien Despax et al. 2019.

The technology and general guidance for making ADCP discharge measurements are presented in various guides such as the WMO 2010 manual on streamgauging. The ADCP is mounted on a boat or on a small float that transects a river cross-section. The ADCP uses the transit-time of sound waves to measure water velocity and depth. Due to physical limitations of the instrument, velocities are measured throughout a limited portion of the cross-section. The measured area is decomposed vertically into cells (or bins) that are distributed horizontally into n ensembles (see fig. 9). The discharge of a cell $Q_{i,j}$ is computed as the vector product of the boat speed $\overrightarrow{v_i}$ (referenced by bottom-tracking (BT) or GNSS tracking (GPS)), the unit vector $\overrightarrow{n_i}$ normal to the boat velocity, the water-velocity $\overrightarrow{w_{i,j}}$, the depth-cell size ($\mathrm{d}z_{i,j}$) and the time interval between ensembles $\mathrm{d}t_i$:

$$Q_{i,j} = (\overrightarrow{w_{i,j}} \wedge \overrightarrow{n_i}) \, |\overrightarrow{v_i}| \; \mathrm{d}t_i \mathrm{d}z_{i,j} \tag{31}$$

In the unmeasured areas (see Figure 9), discharge has to be estimated. The missing or invalid cells and ensembles are reconstructed based on contiguous valid data. The discharge is extrapolated near the riverbed (bottom discharge), near the water surface (top discharge) and near the banks (right and left discharges). Thus, the total discharge Q_k is a sum of partial discharges: the measured (the sum of individual cell discharges), interpolated ($Q_{inv\ cell}$ and $Q_{inv\ ens}$), top Q_{top}, bottom Q_{bot}, left Q_{left} and right Q_{right} edge discharges:

$$Q_k = \sum_{i=1}^{n} \sum_{j=1}^{m_i} Q_{i,j} + Q_{inv\ cell} + Q_{inv\ ens} + Q_{top} + Q_{bot} + Q_{left} + Q_{right} \tag{32}$$

An ADCP discharge measurement $\overline{Q}$ is the average of a number p single-transect discharge Q_k from successive crossings of the stream, under approximately steady-flow conditions:

$$\overline{Q} = \frac{1}{p} \sum_{k=1}^{p} Q_k \tag{33}$$

The average should include pairs of reciprocal transects to minimize any potential directional biases in measured discharges (David S Mueller et al. 2013). Best practices vary

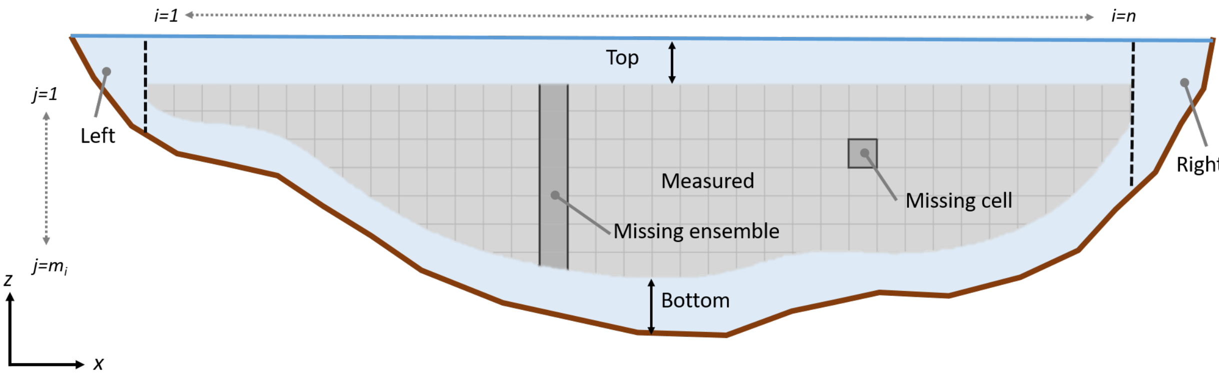


Figure 9: Decomposition of a cross-sectional transect showing measured areas (light gray), missing samples (dark gray) and unmeasured areas (in blue). The x-axis is the transverse direction, z-axis is the vertical direction.

across agencies. The U.S. Geological Survey (USGS) recommends performing at least one pair of reciprocal transects acquired during at least 720 second (K. Oberg and David S. Mueller 2007). Prior to the Uncertainty Analysis (UA), a data quality review has to be performed using a quality assurance/quality control (QA/QC) process. A powerful tool to conduct a QA/QC process is the QRev software (David S Mueller 2016.) It helps to clean ADCP measurements from avoidable errors and to homogenize the discharge computations irrespective of the instrument manufacturer and model. This study assumes that the general rules and guidance for making ADCP discharge measurements David S Mueller et al. 2013 are followed and a QA/QC process is conducted prior to the UA.

5.2 Inventory of error sources

During an ADCP discharge measurement, several errors may occur due to the limited accuracy of the ADCP, the estimation of unmeasured discharges, the environmental and the operator induced errors. Error sources in ADCP discharge measurements have been listed by Juan A. González-Castro and Muste 2007, Kim and Yu 2010 or Aurélien Despax et al. 2019. Juan A. González-Castro and Muste 2007 enumerated no less than 20 possible error sources, most of them being complex to estimate, as illustrated in fig. 10. As a consequence, the full framework for computing the uncertainty appeared to be too complex, and needed simplification for an operational use.

We present a literature review, describing each existing methods and highlighting the pros and cons. We detail the operational uncertainty frameworks that have been published so far, i.e. RiverFlowUA, QUant, QRev-UA and Oursin.

Source	Biases estimation of	Accounted in reduction equations through[a]	Depends upon	Can be estimated from
e_1: Spatial resolution	Water and boat velocities, depths	†	ADCP, mode, settings, boat speed	End-to-end calibration[b]
e_2: Doppler noise	Water and boat velocities	B_{va}, B_{vb}	ADCP frequency, mode, settings, speed of sound, gating time	UA of signal processing algorithms, instrument intercomparison
e_3: Velocity ambiguity	Water and boat velocities	†	Mode, settings	End-to-end calibration
e_4: Side-lobe interference	Discharge through unmeasured areas	*	Beam angle, settings, bathymetry	End-to-end calibration
e_5: Temporal resolution	High frequency velocity components	†	Settings	End-to-end calibration
e_6: Sound speed	Water and boat velocities, depths	B_C	Water properties	UA of C(salinity, temperature) with data from reference meter
e_7: Beam angle	Water and boat velocities, depths	B_θ	ADCP	Manufacturer's specifications
e_8: Boat speed	Water and boat velocities, depths	†	Site, flow, boat operation	End-to-end calibration
e_9: Sampling time	Long-term means	†	Frequency of large-scale flow structures[c]	Instrument intercomparison based on long data records under steady conditions
e_{10}: Near transducer	Velocities near the ADCP	B_{nt}	ADCP, draft, settings, velocity, flow depth	Experimental measurements and CFD modeling
e_{11}: Reference boat velocity	Water and boat velocities, depths	B_{vb}	Sediment concentration, flow[d]	Manufacturer's specifications
e_{12}: Depth	Discharge through unmeasured areas	B_{Da}, B_{Dp}, B_{Dp}, B_{Do},B_{Davg}[e]	ADCP, settings, draft, bathymetry, water properties, time gating	UA of depths as f(C and gating time) and B_C, B_t and B_{DADCP} and concurrent depth range measurements
e_{13}: Cell positioning	Measured and unmeasured discharge	B_t, B_{Da}, B_{Dp}, B_{Do}, B_{Davg}	ADCP, setting, water properties	√
e_{14}: Rotation	Water and boat velocities, depths and geographic orientation	B_p, B_r, B_h	ADCP, setup, site	Manufacturer's specifications
e_{15}: Timing	Distances by gating and discharge	B_t	ADCP, speed of sound, gating time	Manufacturer's specifications
e_{16}: Edge	Discharges through channel edges	B_θ, B_L	ADCP settings, bathymetry, cross section, edge distances	Manufacturer's specifications
e_{17}: Vertical profile model	Discharge through unmeasured top and bottom areas	B_{Q1}[f]	Velocity distribution model, turbulence intensity	Field and laboratory experiments with reliable CFD-LES modeling
e_{18}: Discharge model	Discharge through measured area	B_{Q2}[f]	Discharge model	Highly resolved data/End-to-end calibration
e_{19}: Finite summation	Discharge through measured area	B_{Q3}[f]	ADCP settings, boat velocity	√
e_{20}: Site conditions & operation	Total discharge	†	Site, boat operation	Concurrently measured data

[a](†) refers to biases that cannot be accounted for through the reduction equations; (*) indicates that the bias is somewhat minimized by the ADCP processing algorithm.

[b]In end-to-end calibrations, bias and precision limits are estimated from one or multiple sources of error at a time using repeated measurements and analyzing the statistics of the result. Unlike systematic errors that can be estimated from large samples, measurement bias must be estimated using a reference instrument of accuracy traceable to standards.

[c]The characteristic frequency of large-scale flow structures is discussed in the text.

[d]When boat velocity is estimated by DGPS, bias is due to DGPS positioning or DGPS velocity errors.

[e]Biases that can be estimated by UA of time gating algorithms.

[f]Model biases which relative contribution to total uncertainty cannot be accounted through UA based on the DREs.

Figure 10: List of error sources, from Juan A. González-Castro and Muste 2007

5.3 ISO 24578 standard

The standard ISO 2012 is dedicated to ADCP measurements. Chapter 8 focuses on uncertainties, but it does not give a complete list of the uncertainty sources, nor the computations for estimating them. There are only recommendation on the gauging protocols to reduce the uncertainty.

5.4 RiverFlowUA

RiverFlowUA was developed by J. González-Castro, Buzard, and Mohamed 2016, at the South Florida Water Management District, to compute the uncertainty in Teledyne RDI ADCP discharge measurements only. RiverFlowUA uses a first-order Taylor approximation of the data reduction equation and accounts for the correlation between the velocities measured in contiguous cells. The method combines the uncertainties estimated from multiple transects and calibration uncertainties in the measured portion. The main limitation of the RiverFlowUA method lies in the fact that it does not account for the uncertainties due the discharges in the unmeasured areas, which often contribute most of the total uncertainty.

5.5 QUant

QUant, developed by S. A. Moore et al. 2016 at Water Survey of Canada, uses Monte Carlo simulations for assessing the uncertainty, accounting for both random and systematic errors (especially in the non-measured areas). The simulations account for uncertainty of each input quantity. For each iteration, the input quantities are randomly sampled from their respective probability distributions and the discharge is computed using these values. 1000 iterations of calculation are required, making the method time-consuming (around 30 minutes per measurement). To our best knowledge, QUant is not used operationally.

5.6 QRev

The QRev-UA method, developped by David S Mueller 2016 at the US Geological Survey, is based on a simplistic approach that combines the uncertainty due to random errors (based on the coefficient of variation of the transect discharges), the uncertainty due to systematic errors (1.5 %), the uncertainty due to moving bed (0, 1.5 or 3 %), the uncertainty due to invalid data (10 % of the interpolated discharge), extrapolation (based on the percent difference in discharge between possible extrapolation methods) and edge discharge (15 % of the discharge in the edges). Although the method is simplistic, QRev-UA is the only tool that is routinely used by hydrometry staff throughout the world. The USGS recommend that the user must review in detail the uncertainty estimation computed by QRev, and must give a subjective uncertainty as a rating (poor $> 8\%$ / fair $5\% - 8\%$ / good $2\% - 5\%$ /

excellent $< 2\%$). If the automatic uncertainty computation and the user's estimation are not in agreement, the user rating should be preferred.

5.7 Oursin

The Oursin method is developped by Aurélien Despax et al. 2019 and the French hydrometric group (so called Groupe Doppler). The uncertainty of discharge in the measured area is estimated based on theoretical models, statistical analysis of the acquired data and best available sources of information. The uncertainties due to discharges in unmeasured areas are estimated by sensitivity analysis. By varying some of the parameters, possible discharges are computed as an alternative to the Monte Carlo approach and used to evaluate the standard uncertainty of each unmeasured portion. It has been coupled with the QRev software which provides an ADCP data quality review prior to the uncertainty analysis.

5.8 Summary of uncertainty methods for moving-boat ADCP measurements and perspectives

Due to the high complexity of the ADCP data workflow, the above mentioned tools do not account for all relevant error sources, in particular errors related to the operator or the measurement conditions, and possible correlations among the various uncertainty sources, resulting in simplifications. The input elemental uncertainties are also poorly known. For instance, the ADCP manufacturers do not disclose complete information about the uncertainty of instrumental errors, due to proprietary technologies. The uncertainties due to the measuring environment and the uncertainties due to the operators are even more difficult to model than instrumental errors. Therefore, the input uncertainties are generally derived from site-specific experiments, based on expert judgement or based on available information.

Among the listed method, QRev-UA is the only tool that is routinely used by hydrometry staff throughout the world. In Aurélien Despax et al. 2019, ADCP uncertainty computed from an interlaboratory experiment showed good agreement with the QRev-UA estimates. The improvement of the QRev-UA thanks to the Oursin method, both included in one software allowing the quality analysis and the uncertainty analysis, will be a great improvement and as of June 2020 Despax and Mueller are working on implementing this.

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NVE

Norges vassdrags- og energidirektorat

MIDDELTHUNS GATE 29
POSTBOKS 5091 MAJORSTUEN
0301 OSLO
TELEFON: (+47) 22 95 95 95

www.nve.no