Chapter 12

Appendices

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12.1 BASIC DEFINITIONS EXEMPLIFIED IN THE FIELD OF UDSM

In order to ensure that communication on metrological terms is free from misunderstanding, this book adopts the 'BIPM (Bureau International des Poids et Mesures) International Vocabulary of Metrology', abbreviated as VIM (Joint Committee for Guides in Metrology [JCGM], 2012) and available here.

As a series of definitions is not the most attractive way to introduce them, we propose a guided tour of the VIM to present, step by step, the most important definitions along with short examples related to UDSM (urban drainage and stormwater management) systems. Each definition from the VIM is given in a frame in italic characters.

Let us consider an operator who needs to know the discharge in a sewer pipe at a given time. The discharge is the *quantity* the operator is interested in. The operator will use *measurement instruments* and *sensors*, parts of the whole *measuring system*, and apply a *measurement procedure* to estimate the discharge, which is named the *measurand*.

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The chapter is from the book Metrology in Urban Drainage and Stormwater Management: Plug and Pray, Jean-Luc Bertrand-Krajewski, Francois Clemens-Meyer, Mathieu Lepot (Eds.).
doi: 10.2166/9781789060119_0471

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quantity

Property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a reference.

measuring instrument

Device used for making measurements, alone or in conjunction with one or more supplementary devices.

sensor

Element of a measuring system that is directly affected by a phenomenon, body, or substance carrying a quantity to be measured.

measuring system

Set of one or more measuring instruments and often other devices, including any reagent and supply, assembled and adapted to give information used to generate measured quantity values within specified intervals for quantities of specified kinds.

measurement procedure

Detailed description of a measurement according to one or more measurement principles and to a given measurement method, based on a measurement model and including any calculation to obtain a measurement result.

measurand

Quantity intended to be measured.

This implies that, when reporting on monitoring results, apart from the experimental set-up applied, the applied methods on data pre- and/or post-processing should be mentioned and described.

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Most sensors are designed to deliver an output as a response to an input which may differ from the measurand. For example, a piezo-resistive sensor delivers a water depth *d* (output) corresponding to a given pressure *P* exerted on its membrane (input). If the sensor membrane is positioned horizontally at the same level as the sewer pipe invert, then the water depth *d* is equal to the water level *h* in the sewer pipe (Figure 12.1(a)) If the sensor membrane is positioned at a different level z_0 above or below the sewer pipe invert, the corresponding offset shall be accounted for in the estimation of *h* (Figure 12.1(b)).

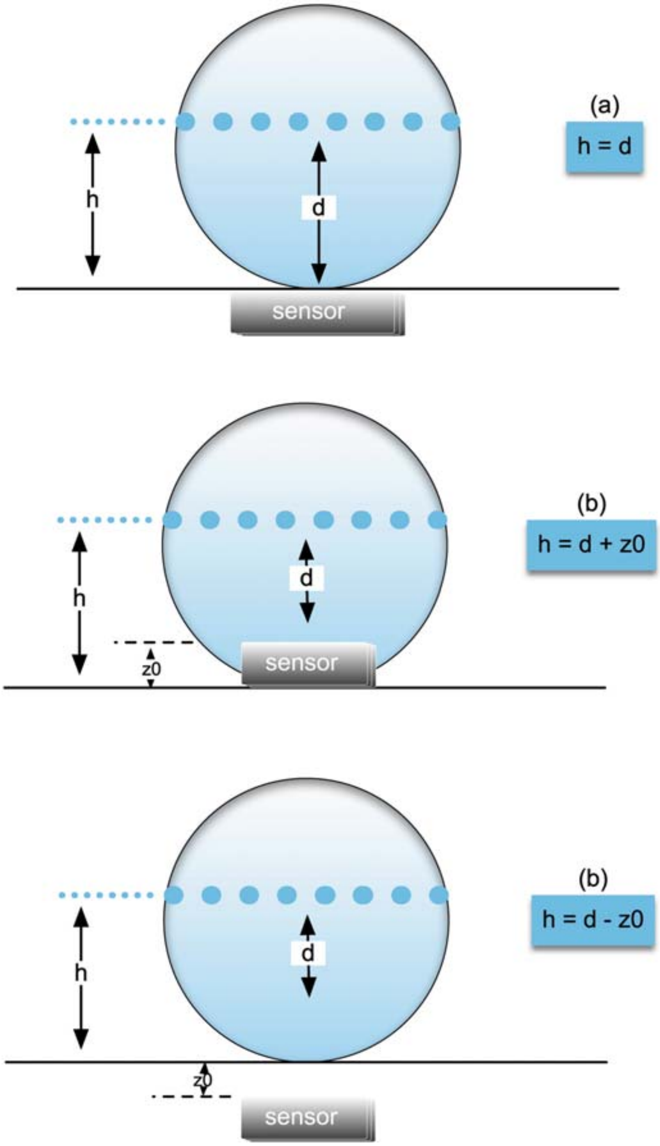

Figure 12.1 Water level measurement with a piezo-resistive sensor, (a) without offset, (b) with positive or negative offset. *Source*: Francois Clemens-Meyer (Deltares/TU Delft/NTNU).

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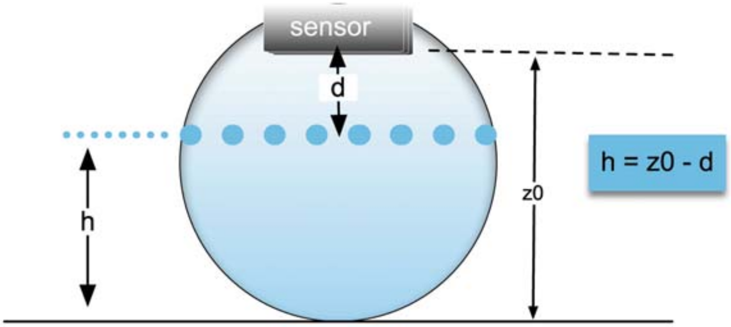

Figure 12.2 Water level measurement with an aerial ultrasonic sensor. *Source*: Francois Clemens-Meyer (Deltares/TU Delft/NTNU).

Similarly, an aerial acoustic sensor converts the time *t* an acoustic wave in the air travels from the sensor to the free surface and return (input) into the distance *d* between the sensor and the free surface and then into the water level *h* (output) determined from the position of the sensor within the cross section (Figure 12.2).

The component of the sensor converting the input into the output is the *transducer*. Transducers are very diverse and based on various laws of physics: mechanics, electricity, magnetism, wave propagation, etc. (see Chapters 2, 3 and 4).

A sensor and by extension a measuring instrument or system is characterized by various specifications including *nominal indication interval*, *sensitivity* and *resolution*.

nominal indication interval (nominal interval)

Set of quantity values, bounded by rounded or approximate extreme indications, obtainable with a particular setting of the controls of a measuring instrument or measuring system and used to designate that setting.

sensitivity of a measuring system (sensitivity)

Quotient of the change in an indication of a measuring system and the corresponding change in a value of a quantity being measured.

resolution

Smallest change in a quantity being measured that causes a perceptible change in the corresponding indication.

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More basic measuring instruments exist, e.g. *detectors* of overflows.

detector

Device or substance that indicates the presence of a phenomenon, body, or substance when a threshold value of an associated quantity is exceeded.

Before the measurement, the value of the discharge is unknown (if not, there is no need to do a measurement…). As no measurement can be absolutely perfect under ideal conditions with a truly flawless sensor, it implies that (i) the true value of the discharge will remain unknown, and (ii) each measurement is considered as an estimation of the true value. The aim of the operator is to obtain an estimation with a required or acceptable level of *accuracy*.

measurement accuracy (accuracy of measurement, accuracy)

Closeness of agreement between a measured quantity value and a true quantity value of a measurand.

All measurements are affected, to various degrees, by *errors*, which can be either *systematic* or *random*. In the case where a *reference quantity value* is available, the systematic error can be estimated: this is the *bias*. In other cases, errors cannot be quantified.

measurement error (error of measurement, error)

Measured quantity value minus a reference quantity value.

systematic measurement error (systematic error of measurement, systematic error)

Component of measurement error that in replicate measurements remains constant or varies in a predictable manner.

random measurement error (random error of measurement, random error)

Component of measurement error that in replicate measurements varies in an unpredictable manner.

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reference quantity value (random error of measurement, random error)

Quantity value used as a basis for comparison with values of quantities of the same kind.

measurement bias (bias)

Estimate of a systematic measurement error.

If the operator uses a water level sensor and the sensor is not positioned correctly in the sewer (e.g. too low or too high compared to the pipe invert or pipe ceiling), all water level measurements will be affected by an offset: this is a systematic error. If a reference quantity value is available (i.e. if it is possible to use e.g. some reference shim), the bias can be estimated and the *correction* can compensate the systematic error. Using reference quantity value thus allows correction of systematic errors and estimating biases. But there is no means to correct random errors which, by definition, differ for each measurement: they are due to sensors flaws and defects, their use under non-nominal conditions, noise and artefacts in components, the operator behaviour and actions, and variable environmental conditions affecting the measurement without being controlled (temperature, pressure, humidity, electromagnetic disturbances, radiations, non-stationarity of power supply, etc.).

correction (bias)

Compensation for an estimated systematic effect.

Let us assume that the pipe where the discharge shall be measured is a circular pipe. Its diameter is a quantity that needs to be known to estimate the wet cross section and then the discharge. The operator can obtain the value of the diameter from various sources: reports, maps, data bases, GIS software tools, etc. However, the most recommended option is to measure the diameter *in situ* with a meter, a laser or any other appropriate instrument, as it is the operator's responsibility (quality assurance) to check and verify all quantity values to be used in the measurement procedure.

The operator may do a single measurement of the diameter. But as measurements in sewers are difficult due to harsh conditions (obscurity or reduced light, humidity, odours, lack of space, use of thick gloves, presence of water, sediments, pipe structure defects, etc.), he/she may decide to proceed to multiple consecutive measurements, carried out by the same person under unchanged conditions: in this case, the operator is working with *repeatability conditions*.

repeatability condition of measurement (repeatability condition)

Condition of measurement, out of a set of conditions that includes the same measurement procedure, same operators, same measuring system, same operating conditions and same location, and replicate measurements on the same or similar objects over a short period of time.

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If the operator decides to do multiple measurements but with various measuring systems (various instruments or sensors), carried out by different persons under various conditions, he/she is working with *reproducibility conditions*.

reproducibility condition of measurement (reproducibility condition)

Condition of measurement, out of a set of conditions that includes different locations, operators, measuring systems, and replicate measurements on the same or similar objects.

Intermediate precision conditions may also be encountered.

intermediate precision condition of measurement (intermediate precision condition)

Condition of measurement, out of a set of conditions that includes the same measurement procedure, same location, and replicate measurements on the same or similar objects over an extended period of time, but may include other conditions involving changes.

In the case of repeated measurements, the values of the pipe diameter will show some dispersion around the mean value due to random errors, as it is unexpected that all of them will be exactly the same. The dispersion may be quantified by the standard deviation of the repeated measurements results (see Chapter 8). Moreover, the dispersion usually tends to increase with the number of repeated measurements. As additional sources of errors and variability are present in reproduced measurements, the dispersion of the diameter values will be larger than with repeated measurements.

It may happen that all successive repeated measurements of the pipe diameter are slightly different and rather close to each other, with a small dispersion. In that case, the measurements show a high *precision*. If the successive values are more dispersed, the measurement precision is low.

measurement precision (precision)

Closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions.

However, a high measurement precision does not necessarily mean that the pipe diameter value is close to the true value if significant systematic errors are present. The closeness between the repeated diameter values and the true diameter value is described by the *measurement trueness*.

measurement trueness (trueness of measurement, trueness)

Closeness of agreement between the average of an infinite number of replicate measured quantity values and a reference quantity value.

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Unfortunately, the definition of the trueness involves an infinite number of measurements, which is not convenient in practice. In the case of a single measurement or a finite number of repeated measurements, one thus considers the trend toward trueness and also the measurement *accuracy* if the true value is known or assumed to be known (reference value).

Precision, trueness and accuracy are different concepts that may be related to systematic and random errors. Four typical cases are possible, conceptually represented in Figure 12.3:

(a) If the successive repeated measurements of the pipe diameter are both close to each other and to the true or reference value, the measurements are precise, true and accurate. There are no significant systematic (trueness and accuracy) or random (precision) errors. A limited number of measurements is sufficient to obtain an accurate estimation of the true value of the diameter. In the ideal case, one single measurement could be enough (but remember that in practice, measurements in UDSM systems are far from being ideal and perfect).

(b) If the successive repeated measurements of the pipe diameter are close to each other but not close to the true or reference value, the measurements are precise, not true and inaccurate. There are significant systematic errors and no significant random errors. The significant bias should be detected and corrected in order to estimate the true value of the diameter. An increasing number of repeated measurements will not be sufficient to improve the estimation if systematic errors are simultaneously neither detected nor corrected.

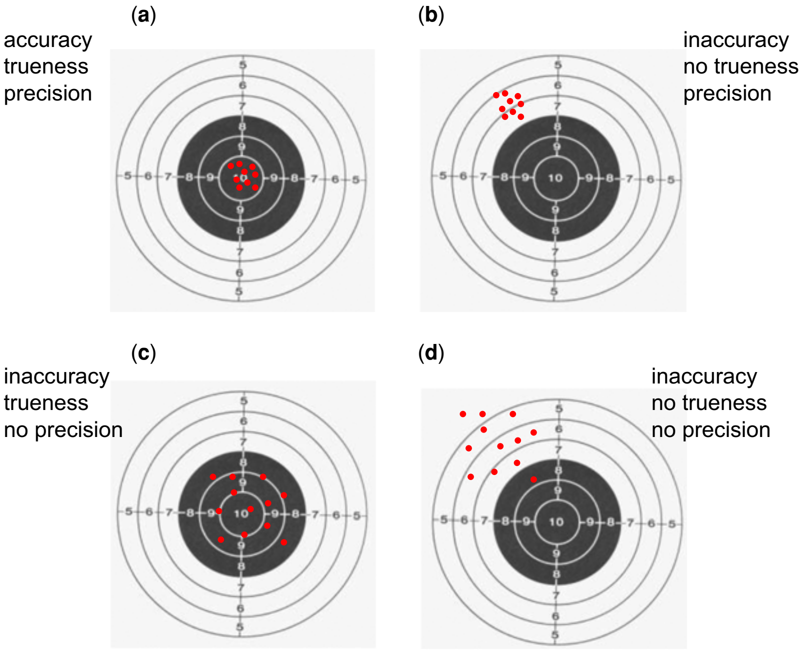

Figure 12.3 Conceptual representation of measurement precision, trueness and accuracy. The true value is equal to 10 and is represented by the centre of the target. Repeated measurements are represented by arrow impacts. Systematic errors in measurements are negligible if the impacts are in the central dark area with scores ranging from 8 to 10. Random errors are represented by the dispersion of the impacts. *Source*: Jean-Luc Bertrand-Krajewski (INSA Lyon).

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(c) If the successive repeated measurements of the pipe diameter are not very close to each other but remain close to the true or reference value, the measurements are imprecise but rather true and accurate. Systematic errors are not significant and random errors are predominant. In this case, increasing the number of repeated measurements will lead to a mean value of the diameter very close to the true value. Repeated measurements provide an accurate mean value of the pipe diameter.

(d) If the successive repeated measurements of the pipe diameter are not close to each other and not close to the true or reference value, the measurements are imprecise, not true and inaccurate. This is the worst case in practice, with high systematic and random errors. Improving the quality of the estimation of the pipe diameter would require (i) estimating and correcting the bias and (ii) increasing the number of repeated measurements and applying the bias correction to the mean value of the diameter.

In cases b and c, detecting systematic errors is the most challenging task and requires reference values. The above elements indicate two main topics in metrology:

- Estimation of random errors.
- Detection, estimation and correction of systematic errors.

The latter is the most difficult.

If the quality of the *measurement result* is lower than the quality either required (by law, regulation, standards, contract, etc.) or set as acceptable (by the user of the measurement result for further calculation, modelling, decision making, etc.), the operator has to explore and find, if possible, means to improve it.

measurement result (result of measurement)

Set of quantity values being attributed to a measurand together with any other available relevant information.

Such means may include changes and/or adaptations of the measuring system, the *measuring chain*, the measuring instruments, the measurement procedure, etc.

measuring chain

Series of elements of a measuring system constituting a single path of the signal from a sensor to an output element.

For example, if the discharge measurement in a sewer pipe does not comply with the required or acceptable level of precision, the operator may repair or replace the sensor (Chapter 7), change the sensor technology (Chapter 3) or any other element of the measuring chain (transmitter, logger, etc.), the sensor location in the sewer (Chapters 3, 4 and 6), the operation and maintenance conditions (Chapter 7), the measurement procedure, protocols and conditions, etc.

In order to evaluate the quality of any measurement result, it is of crucial importance to quantify the *measurement uncertainty* (Chapter 8).

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measurement uncertainty (uncertainty of measurement, uncertainty)

Non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used.

The uncertainty is expressed in practice as an interval or range of values, named the *coverage interval*, containing the true value of the measurand with a given level of probability, named *coverage probability*.

coverage interval

Interval containing the set of true quantity values of a measurand with a stated probability, based on the information available.

coverage probability

Probability that the set of true quantity values of a measurand is contained within a specified coverage interval.

Chapter 8 presents in detail the methods the operator may apply to evaluate measurement uncertainties. Three methods are available, depending on the context of each measurement:

- The Type A evaluation is based on replicate measurements of the quantity of interest and applies statistical inference to evaluate its uncertainty.
- The Type B evaluation, also named the law of propagation of uncertainties (LPU), is based on a mathematical relation, named the measurement model, allowing evaluation of both the quantity of interest and its uncertainty from other known quantities and their respective uncertainties.
- The Monte Carlo evaluation is based on stochastic simulations of the measurement model followed by statistical analysis of their results.

Type A evaluation of measurement uncertainty (Type A evaluation)

Evaluation of a component of measurement uncertainty by a statistical analysis of measured quantity values obtained under defined measurement conditions.

Type B evaluation of measurement uncertainty (Type B evaluation)

Evaluation of a component of measurement uncertainty determined by means other than a Type A evaluation of measurement uncertainty.

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measurement model (model of measurement, model)

Mathematical relation among all quantities known to be involved in a measurement.

A global description of the uncertainty and its components is given in the *uncertainty budget*.

uncertainty budget

Statement of a measurement uncertainty, of the components of that measurement uncertainty, and of their calculation and combination.

With the Type A evaluation, the operator first calculates the *standard uncertainty* of the quantity of interest, which, in first approximation, is equivalent to the standard deviation.

standard uncertainty (standard uncertainty of measurement, standard measurement uncertainty)

Measurement uncertainty expressed as a standard deviation.

With the Type B evaluation, the standard uncertainty is obtained by applying the measurement model and the LPU, which provides a *combined standard measurement uncertainty*.

combined standard measurement uncertainty (combined standard uncertainty)

Standard measurement uncertainty that is obtained using the individual standard measurement uncertainties associated with the input quantities in a measurement model.

The operator then sets the coverage probability. Most frequently, a 95% probability is used. The last step consists of calculating the coverage interval by multiplying the standard uncertainty u by a coefficient k, named the *coverage factor*, corresponding to the chosen coverage probability. The result is the *expanded measurement uncertainty* $U = ku$. The final result is then expressed as $y \pm U$, or $[y - U, y + U]$.

coverage factor (standard uncertainty of measurement, standard measurement uncertainty)

Measurement uncertainty expressed as a standard deviation.

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expanded measurement uncertainty (expanded uncertainty)

Product of a combined standard measurement uncertainty and a factor larger than the number one.

For example, if the discharge in a circular pipe is $Q = 0.45$ m^3/s, the combined standard uncertainty is $u(Q) = 0.02$ m^3/s and the coverage factor is $k = 2$ for a 95% probability, then the coverage interval is expressed as $Q = 0.45 \pm 0.04$ m^3/s. For the sake of simplicity, this is interpreted as 'the true value has 95% probability to be between 0.41 and 0.49 m^3/s'. It may also be convenient to express the result as a fraction or a percentage of the measured value. In this case, the *relative standard uncertainty* is 0.044 or 4.4% and the *expanded relative uncertainty* is 0.089 or 8.9%.

A note on reporting digits: when presenting the outcome of some measurement, care has to be taken that this is communicated in the right manner. Suppose in the previous example the average value for the discharge is $Q = 0.4536541$ m^3/s (being a typical result as presented in the double precision computer outcome) with a combined standard uncertainty of $u(Q) = 0.02$ m^3/s, the last five digits in the average result should not be reported as they would suggest an accuracy that is not there. In this case only the last two digits have meaning and are to be reported accordingly. Another example: 45700 ± 300 should be reported as $(4.57 \pm 0.03) \times 10^4$.

relative standard measurement uncertainty

Standard measurement uncertainty divided by the absolute value of the measured quantity value.

With the Monte Carlo evaluation, the stochastic simulations of the measurement model result in (i) the mean value of the quantity of interest, and (ii) the boundaries of the shortest interval containing a given percentage of the simulated values. The percentage corresponds to the coverage probability.

In the previous discharge example, the Monte Carlo evaluation gives the mean discharge $\bar{Q} = 0.45$ m^3/s and the 95% coverage interval [0.41, 0.19].

It is worth noting that both Type A and Type B methods give symmetric coverage intervals, with the measurement result expressed as $y \pm U$. This is correct if some hypotheses are verified, especially with the Type B evaluation. The Monte Carlo evaluation is more general and may give non-symmetric coverage intervals defined by their boundaries.

Two aspects of uncertainty assessment shall be distinguished. The first one consists of estimating uncertainties of measured values, as just briefly presented above. The second aspect consists of comparing the obtained uncertainties with the *target measurement uncertainty* either required by law, regulation, standards, contracts, etc., or set as acceptable by the operator according to the use of the measurement results for design, control, modelling, decision making, etc.

target measurement uncertainty (target uncertainty)

Measurement uncertainty specified as an upper limit and decided on the basis of the intended use of measurement results.

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If the target uncertainty is not reached, the measurement system, chain and process shall be improved or revised.

It is of crucial importance to ensure that measurements are free of systematic errors or that systematic errors are detected and corrected. This includes two steps: (i) ensuring under controlled conditions that the sensor itself has no systematic error by means of a comparison with a reference value, and (ii) ensuring that the *in situ* use of the sensor in field conditions is free of systematic error by means of a comparison with reference values.

In the first step, the operator compares the values given by the sensor to *measurement standards*. This is the sensor *calibration* (see Chapter 7). No sensor shall be used without initial calibration, followed by periodic *verifications* and a new calibration if a verification fails.

measurement standard

Realization of the definition of a given quantity, with stated quantity value and associated measurement uncertainty, used as a reference.

calibration

Operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication.

verification

Provision of objective evidence that a given item fulfils specified requirements.

For the example of discharge measurement in a circular pipe, the water level sensor shall be calibrated. The measurement standards depend on the sensor technology (piezo-resistive sensor, ultrasonic sensor, radar sensor, etc.).

In the case where the calibration shows that sensor outputs are not as close to standards values as required or set as acceptable, the operator may proceed to the *adjustment* of the sensor or of the measuring system. It is also possible to establish a mathematical relation (calibration function) to correct the sensor outputs without adjusting the sensor. In the simplest cases, the adjustment includes two steps: *zero adjustment* and span (or gain) adjustment.

adjustment of a measuring system (adjustment)

Set of operations carried out on a measuring system so that it provides prescribed indications corresponding to given values of a quantity to be measured.

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zero adjustment of a measuring system (zero adjustment)

Adjustment of a measuring system so that it provides a null indication corresponding to a zero value of a quantity to be measured.

In the second step, the operator compares the values given by the calibrated sensor to *in situ* reference values. For example, checking that the position of the sensor in the sewer pipe corresponds to its theoretical position, that there is no offset, etc. This may require a sequence of calibrations, defined as *calibration hierarchy*. This is necessary to ensure a full *metrological traceability*.

calibration hierarchy

Sequence of calibrations from a reference to the final measuring system, where the outcome of each calibration depends on the outcome of the previous calibration.

metrological traceability

Property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.

Measurement results shall be systematically submitted to verification and *validation* before any further use (see Chapter 9).

validation

Verification, where the specified requirements are adequate for an intended use.

When a measured value is zero, what does it mean? Here we touch upon definitions regarding the Detection Limit (also referred to as LoD, Limit of Detection) and Quantification Limit (also referred to as LoQ, Limit of Quantification). These terms have a close relation with *nominal indication interval*, *sensitivity* and *resolution* as discussed earlier and are mostly used and applied in e.g. analytical chemistry, but they can have meaning as well in the field of UDSM.

For example, in some countries, the number of CSO events has to be reported for which a range of definitions is applied, all have one thing in common: namely the number of times a spill has occurred in a certain time window. Now, suppose the operator applies a water level measuring device to check whether or not the water level has risen above the crest level of the weir. When the measured water level h is smaller or equal to the crest level, no spill occurs; when h is larger than the crest level, a spill has occurred. Here the operator has to deal with the Detection Limit. In Figure 12.4, the blue curve

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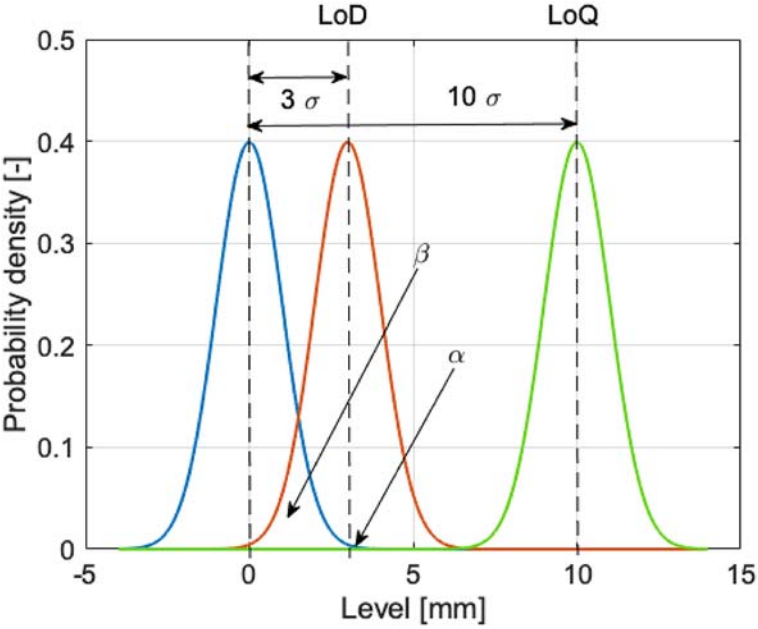

Figure 12.4 Schematic figure illustrating the concepts of LoD and LoQ. *Source*: Francois Clemens-Meyer (Deltares/TU Delft/NTNU).

symbolizes the probability density function of the crest level of the weir (the mean value is used as the estimate of 'the crest level'), the red curve symbolizes the probability density of the water level measurement. When the standard deviation of both the crest level and the water level measurement are equal, then a simple definition of the Detection Limit is that the mean values of crest level and water level should be three standard deviations apart to be sure that the water level is either under or above the crest level. A more advanced approach is to set a certain maximum to the probability β (in the example 0.1336), or set a value for the minimum difference of the measured value to zero, commonly 3 times the standard deviation is used for defining the LoD.

When the volume or the discharge of spilled CSO water is of importance, the operator has to deal with the Quantification Limit. In many cases a stage-discharge relation is used to determine the spilled discharge as a function of measured water level (see Section 3.4).

In Figure 12.4, the green curve depicts the uncertainty of the water level measurement. In this case, the Quantification Limit is defined as follows: the distance between the crest level and the measured water level is such that the probability that the values overlap is much less than 1% when the distance between the values is 10 standard deviations (overlap = $\sim 6 \times 10^{-7}$). In this case, when the green graph is valid, the measured value can be used to quantify the difference between the crest of the weir and the measured water level, and therefore the discharge can be quantified.

So, in the case where the red graph represents the measurement, one can only state that 'a CSO event has occurred' but the volume was less than the LoQ. Of course one is free to choose different (possibly more relaxed) values for α and β provided this is clearly documented along with reported results, see e.g. Armbruster & Pry (2008) for more details.

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12.2 LIST OF DATA AND MATLAB FILES

The following paragraphs list the Matlab® code files (.m files) and the data files (.csv or.mat files) which are used in Chapters 6 to 9 as examples of application of methods and algorithms explained in the main text. These files are available for download on the book companion webpage at https://doi.org/10.2166/9781789060102.

In Chapter 3:

- ap_1.txt
- av_1.txt
- Calculation steps for tracing experiments.xlsx
- D_10-100.txt
- D_10-1000.txt
- dilution.txt
- P.dat
- pic_1.txt
- pic_1_Ascending_part.fig
- pic_1_Descending_part.fig
- pic_1_result-tracer.dat
- pic_1_Start&End.fig
- regw123etalo.dat
- sans_dilution.txt
- tracer.m

In Chapter 6:

- IWA_hydro.mat
- IWA_Jacobian.m
- loc1loc2.mat
- meas_freq_exp.m
- v2_k15_C2.csv

In Chapter 7:

- ciaponi1.csv
- OLS123.m
- piezo1.csv
- turbi251.csv
- WLS123cal.m

In Chapter 8:

- eggshape1.csv
- hV1.csv
- manning1.csv
- raingauge1.csv
- uMCM.m
- uTypeA.m
- uTypeB.m
- uTypeBsum.m
- vol1.csv

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In Chapter 9:

- ARMA_SPACE.m
- lin_step_power.m
- linear_trend.m
- min_max_sample.m
- outlier_tests.m
- outliers_example.mat
- piece_lin_fit.m
- step_trend.m

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JCGM (2012). *JCGM 200:2012 – International vocabulary of metrology – Basic and general concepts and associated terms (VIM) (Vocabulaire international de métrologie – Concepts fondamentaux et généraux et termes associés (VIM)*. Joint Committee for Guides in Metrology, Geneva (Switzerland), 108 p. Available at https://www.bipm.org/documents/20126/2071204/JCGM_200_2012.pdf (accessed 26 April 2021).

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