Water Research 39 (2005) 5162–5174

WATER RESEARCH

www.elsevier.com/locate/watres

Quantifying the uncertainty of on-line sensors at WWTPs during field operation

Leiv Rieger[a], Michael Thomann[b], Willi Gujer[a], Hansruedi Siegrist[a,*]

[a]*Swiss Federal Institute for Environmental Science and Technology (EAWAG) and Swiss Federal Institute of Technology (ETH), Ueberlandstrasse 133, CH-8600 Dübendorf, Switzerland*

[b]*BMG Engineering AG, Grammetstrasse 14, CH-4410 Liestal, Switzerland*

Received 24 August 2004; received in revised form 25 July 2005; accepted 27 September 2005

Abstract

It remains an ongoing task to quantify the uncertainty of continuous measuring systems at WWTPs during field operation. The commonly used methods are based on lab experiments under standardized conditions and are only suitable for characterizing the measuring device itself. For measuring devices under field conditions, a knowledge of the response time, trueness and precision is equally important.

A method is proposed which can be used to characterize newly installed on-line sensors or to evaluate monitoring data which may contain systematic errors. The concept is based on comparative measurements between the sensor and a reference. A linear regression is used to differentiate between trueness and precision. Various statistical tests are conducted to validate the preconditions of linear regression. The information about the trueness and precision of the measuring system under field conditions helps to adapt control strategies more effectively to the relevant processes and permits sophisticated control concepts. Moreover, the concept can help to define guidelines for evaluating the uncertainties of effluent quality monitoring to overcome the concerns about on-line sensors, improve the trust in these systems and to allow the use of continuously measuring systems for legislative purposes.

The approach is discussed in detail in this paper and all statistical tests and formulas are listed in the Appendix.

Keywords: Uncertainty; Response time; On-line sensor; Monitoring; Trueness; Precision

1. Introduction

The use of on-line sensors increased significantly during the last 10 years but in most countries they are still not allowed as references for legislative purposes (the common method is to monitor the effluent quality based on grab or 24-h composite samples). The main reason is the lack of trust in continuously measuring devices. Although the reliability and availability of on-line sensors could be improved significantly and the results are comparable or even better than to analyse samples in the plant lab using test kits (as commonly done at WWTPs) there is still a need to evaluate the accuracy of on-line sensors during field operation.

Depending on the goal of the measurement setup, different sources of uncertainty are relevant. When monitoring the effluent concentration—e.g. in order to calculate an effluent quality tax—no systematic error (deviation from trueness) is allowed. For control

*Corresponding author. Tel.: +41 1 823 5054; fax: +41 1 823 5389.

E-mail addresses: leiv.rieger@modeleau.org (L. Rieger), hansruedi.siegrist@eawag.ch (H. Siegrist).

0043-1354/$ - see front matter
doi:10.1016/j.watres.2005.09.040

Nomenclature

α	estimated intercept of regression function
β	estimated slope of regression function
Accuracy	the closeness of agreement between a test result and the accepted reference value (ISO 5725-1, qualitative term)
Bias	total systematic error (quantitative term)
f	degrees of freedom
$F_{(f1,f2,0.99)}$	F-distribution at 1% significance level
In-line	measurement directly in the media
n	number of measurements
On-line	measurement in a side stream. On-line sensor is also used as the generic term for continuously measuring probes (on- and in-line) to facilitate the reading
Precision	term for random errors: the measure of precision is usually expressed in terms of imprecision
Prediction interval	confidence interval for a predicted value
s_y	residual standard deviation
SE_α	standard error of α
SE_β	standard error of β
$t_{(f,0.95)}$	t-distribution at a 5% significance level
Trueness	term for systematic errors: the closeness of agreement between a measurement and an accepted reference value. The measure of trueness is usually expressed in terms of bias
TS	test statistic
Uncertainty	precision + trueness
Variability	in the present case, measuring deviations due to changing matrices
x_i	conc. of the ith reference sample (from lab)
$\bar{x}$	average over x_i
x_0	auxiliary value for calculating the intervals in direction of y
y_i	conc. of the ith value of the measuring device
$\bar{y}$	average over y_i
$\hat{y}_i$	estimated measuring device value corresponding to x_i, predicted from a regression function
y_0	auxiliary value for calculating the intervals in direction of x

applications on the other hand, a knowledge of the random error (precision) and the 'error' caused by the response time are most important (Rieger et al., 2003).

To evaluate the uncertainty of an on-line sensor during field operation, an approach is needed which reflects the specific measuring chain and is applicable to WWTPs. Various approaches are described in the literature for detecting, locating or even quantifying the uncertainties of measuring devices. The following list is incomplete but gives a sufficient impression of the main directions:

- Estimated total uncertainty (ISO, 1993): A theoretical approach in which the total error is calculated on the basis of the potential uncertainty of the individual sources of error using an error propagation approach. The total uncertainty of the measuring chain is expressed as a confidence interval.
- Comparison with a reference method (e.g. ISO, 2003): The device under evaluation is compared with a reference measurement or a standard solution. The precision is usually tested with repeated measurements at the same concentration.
- Mass balances (Thomann, 2003; Meijer et al., 2002; Nowak et al., 1999): Mass balances using redundant information with overlapping boundaries for several fluxes of wastewater, sludge or gas compounds as well as energy flow are used to locate and quantify measuring errors.
- Stochastic evaluation of typical/untypical states (Rosen and Lennox, 2001; Yoo et al., 2004): Stochastic approaches (e.g. with principal component analysis PCA or independent component analysis ICA) allow any deviations of the measuring signal from normal conditions to be detected.

The advantage of a stochastic evaluation is that each measuring value is evaluated, whereas the other methods are off-line evaluations. A disadvantage is that only significant deviations from a defined state are detected and no absolute values of the uncertainty can be given. Mass balances give information about the trueness of several measurements of concentrations and flows, but tell us nothing about the precision of a single instrument. The total uncertainty concept differentiates the sources of the errors. This is very interesting for specialists but is not usually required for regular plant operation. We selected the second approach of taking independent measurements but had to make some adaptations in order to apply these methods to on-line sensors during field operation.

Most specifications for measuring devices are based on repeated measurements of standard solutions under standard conditions (ISO, 1990, 1994, 2003). This is important and is suitable for characterizing the measuring method or comparing different devices. In contrast, the goal of this work is to define procedures for