# Influence of local calibration on the quality of online wet weather discharge monitoring: feedback from five international case studies

Nicolas Caradot, Hauke Sonnenberg, Pascale Rouault, Günter Gruber, Thomas Hofer, Andres Torres, Maria Pesci and Jean-Luc Bertrand-Krajewski

## ABSTRACT

This paper reports about experiences gathered from five online monitoring campaigns in the sewer systems of Berlin (Germany), Graz (Austria), Lyon (France) and Bogota (Colombia) using ultraviolet–visible (UV–VIS) spectrometers and turbidimeters. Online probes are useful for the measurement of highly dynamic processes, e.g. combined sewer overflows (CSO), storm events, and river impacts. The influence of local calibration on the quality of online chemical oxygen demand (COD) measurements of wet weather discharges has been assessed. Results underline the need to establish local calibration functions for both UV–VIS spectrometers and turbidimeters. It is suggested that practitioners calibrate locally their probes using at least 15–20 samples. However, these samples should be collected over several events and cover most of the natural variability of the measured concentration. For this reason, the use of automatic peristaltic samplers in parallel to online monitoring is recommended with short representative sampling campaigns during wet weather discharges. Using reliable calibration functions, COD loads of CSO and storm events can be estimated with a relative uncertainty of approximately 20%. If no local calibration is established, concentrations and loads are estimated with a high error rate, questioning the reliability and meaning of the online measurement. Similar results have been obtained for total suspended solids measurements.

**Key words** | calibration, CSO, turbidity, uncertainty, UV–VIS spectrometer, water quality

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## INTRODUCTION

Availability of online probes such as ultraviolet–visible (UV–VIS) spectrometers or turbidimeters allows *in situ* surrogate measurements of usual water quality indicators, such as chemical oxygen demand (COD) or total suspended solids (TSS) at high temporal resolution. The possibility of quasi-continuous measurements of these parameters is of particular interest for the description, understanding and modeling of highly dynamic processes, such as combined sewer overflows (CSO) or stormwater events (Gruber *et al.* 2006) and for the estimation of pollutant emissions into receiving waters.

However, online probes need to be calibrated and adjusted to local conditions to increase measurement quality and reduce systematic errors (Gamerith *et al.* 2011). For this purpose, laboratory measurements are correlated with *in situ* raw measurements (e.g. concentrations provided by the global calibration of the manufacturer for UV–VIS or turbidity values for turbidimeters). The obtained regression function is applied to correct the raw measurements (Rieger *et al.* 2005).

The calibration procedure can only be validated if samples cover the entire measurement range (at least the locally expected range of values) and are equally distributed (Langergraber *et al.* 2003). The measurement range of dry weather pollutant concentrations is relatively easy to cover with routine grab sampling campaigns (e.g. one sample collected each hour during 24 h). The variability of pollutant concentrations in sewer systems during rain events is more

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difficult and expensive to match. In the case of manual grab sampling, the operator must be on site during rain events to collect samples over the event duration, which is normally not easily known in advance. This task is particularly tricky considering logistic constraints (e.g. sampling during the day only) and the high uncertainties of flow and concentration forecasts. The limitations of manual grab sampling can be overcome using automatic samplers. In this case, samples are automatically collected when the flow or concentration measured by an additional probe (e.g. flow meter) exceeds a given threshold.

Purchase, installation and maintenance of online probes are significant expenses. The required local calibration increases strongly these expenses with additional sampling demand and laboratory costs. As a result, it is critical for an operator to determine the optimal calibration effort in order to gain reliable online measurements and minimize calibration expenses. This paper reports about experiences gathered from five online wet weather discharges (CSO or storm events) monitoring campaigns in the sewer systems of Berlin (Germany), Graz (Austria), Lyon (France) and Bogota (Colombia). The influence of local calibration on the quality of online COD measurements of wet weather discharges has been assessed.

## MATERIAL AND METHODS

### Study sites and sampling approach

Detailed descriptions of the monitoring sites, sensors and calibration procedures can be found in Caradot *et al.* (2013) and Sandoval *et al.* (2013) for Berlin; Gruber *et al.* (2006) and Hochedlinger *et al.* (2006) for Graz; Métadier & Bertrand-Krajewski (2011) for Lyon; Torres *et al.* (2013) and Sandoval (2013) for Bogota.

#### Berlin site

The monitoring station was installed from 2010 to 2012 in a major overflow sewer in the city center of Berlin, Germany. Flow was measured directly in the overflow sewer and water quality was measured continuously (1 minute time step) in a bypass fed by a peristaltic pump, using a UV–VIS spectrometer (spectro::lyser 5 mm, s::can). Grab samples (2 L) were collected in the bypass flume every 5 minutes during CSO events by a refrigerated automatic sampler (Hydreka Company, Lyon, France) when the flow exceeded a given threshold. Seventy-five samples were collected during 15 CSO events between 2011 and 2012 (Figure 1), covering the entire concentration range of each event.

#### Graz site

The monitoring station was installed from 2002 to 2013 in the chamber of a main CSO outlet in Graz, Austria. Flow was measured in the inflow and overflow channels. Water quality was measured continuously (3 minute time step during dry weather and 1 minute time step during wet weather conditions triggered by a water level sensor in the chamber) using a UV–VIS spectrometer (spectro::lyser 5 mm, s::can). The device was fixed in a floating pontoon installed in the chamber. Grab sampling was performed during CSO events using a refrigerated automatic sampler (peristaltic system, American Sigma, Lovelend, CO, USA) triggered by an operator (83 samples between 2003 and 2009 over 13 events).

#### Lyon Ecully site

The site is located at the outlet of a residential combined sewer catchment in Ecully, France. Flow was measured directly in the sewer whereas water quality was measured continuously (2 minute time step) using two turbidimeters (Endress + Hauser and Hach Lange) on a by-pass fed by a peristaltic pump. Grab samples were collected during rain events using an automatic sampler (111 samples between 2003 and 2011 over 19 events).

#### Lyon Chassieu site

The station is situated at the outlet of a separate storm sewer catchment in Chassieu, France. Sensors were installed in a monitoring station situated at the inlet of a retention tank. Two turbidimeters (Endress + Hauser and Hach Lange, 2 minute time step) are located in a flume fed by a peristaltic pump. Grab samples were collected during rain events using an automatic sampler (177 samples between 2004 and 2010 over 48 events).

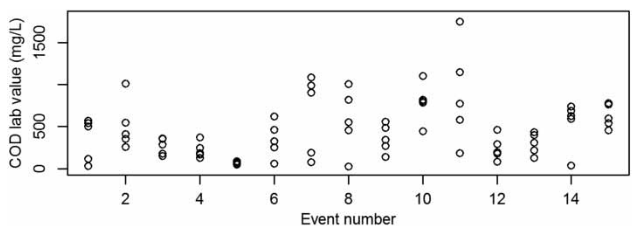


**Figure 1** | COD laboratory values obtained from the analysis of 75 grab samples over 15 CSO events at the Berlin site.

### Bogota site

The monitoring station is located at the outlet of the urban catchment Gibraltar in Bogota, Colombia, at the inflow of a main pumping station discharging to the Bogota River. Although the Gibraltar catchment was designed mainly as a separate system, it is considered as combined due to the presence of misconnections and the inappropriate separation of storm and wastewater in houses' facilities (Sandoval 2013). A UV-VIS spectrometer (spectro::lyser 5 mm, s::can) was installed on a stainless steel boat at the inlet of the station. Samples were collected manually during rain events (40 samples in 2011 over eight events).

### Sensor calibration

Using UV–VIS spectrometers, COD (or TSS, respectively) concentrations are calculated with multivariate regression techniques from absorbance spectra measurements. 'Global calibrations' for typical municipal wastewater (INFLUENTV120) and river water (EFFLUENTV120), which are provided as default configuration of the UV–VIS spectrometer by the manufacturer, can lead to a systematic error of up to 50% for COD measurements (Gamerith *et al.* 2011). To reduce uncertainties, laboratory measurements can be correlated with corresponding *in situ* measurements gained from the 'global calibration' to establish an improved 'local calibration' function

$$y = a \cdot x + b$$

with $a = \text{slope}$, $b = \text{offset}$, $x = \text{probe value}$ and $y = \text{new prediction}$, i.e. the correction of the raw measurements. If correlation is not satisfactory, laboratory measurements can be related directly to UV–VIS spectra using multivariate regression methods (e.g. partial least square method (Torres & Bertrand-Krajewski 2008)).

Using turbidimeters, COD (or TSS, respectively) concentrations can be estimated by means of empirical equations relating turbidity values to COD laboratory measurements (Bertrand-Krajewski 2004; Lepot *et al.* 2013).

### Load calculation and uncertainty

Pollutant loads $M$ are calculated by sequential summation of loads at time step $i$, over the duration of the event:

$$M = \sum_i (Q_i \cdot c_i \cdot \Delta t)$$

with $Q_i = \text{flow}$ and $c_i = \text{concentration}$ corrected with the local calibration at time step $i$. The load standard uncertainty $u(M)$ can be estimated using the law of propagation of uncertainty (JCGM 104 2009) considering uncertainty in flow and concentration measurements.

### Analysis of the influence of sampling on calibration quality

For each study site, a set of local linear calibration functions was built by adding samples chronologically. The aim is to observe how calibration functions, established for wet weather conditions, may evolve with time when the number of samples used for its determination increases. The first calibration function was built with the two first samples collected at the beginning of the sampling campaign. The subsequent functions were built by adding the subsequent samples one at a time in their chronological order. Samples used for the analysis were collected during rain events only (Figure 2).

The influence of the number of samples used to build the local calibration functions was assessed using four indicators:

- The linear calibration parameters: slope $a$ and offset $b$.
- The root mean squared error (RMSE) of the residuals. The RMSE is the prediction error from the calibration function (Willmott *et al.* 1985). The RMSE is a good estimator of the load standard uncertainty $u(M)$ since it may contribute to more than 70% of the total measurement uncertainty (Caradot *et al.* 2013).
- The coefficient of variation (CV) of the residuals, i.e. the RMSE normalized to the mean of the laboratory values.

## RESULTS AND DISCUSSION

Graphical analysis of the results indicates that approximately 20 samples were needed in each case study to reach relatively stable calibration parameters (Figure 3(a) and 3(b)). The effort to collect more samples was thus not really necessary. It is crucial to reach the stability of the parameters to ensure the robustness of the calibration function and reduce measurement errors. If not enough samples are available, measured concentrations may strongly differ from real concentrations. It is important to notice that for each site the first 20 samples were collected over several storm events: four events in Berlin and Graz; five events in Ecully; eight events in Chassieu and five events in

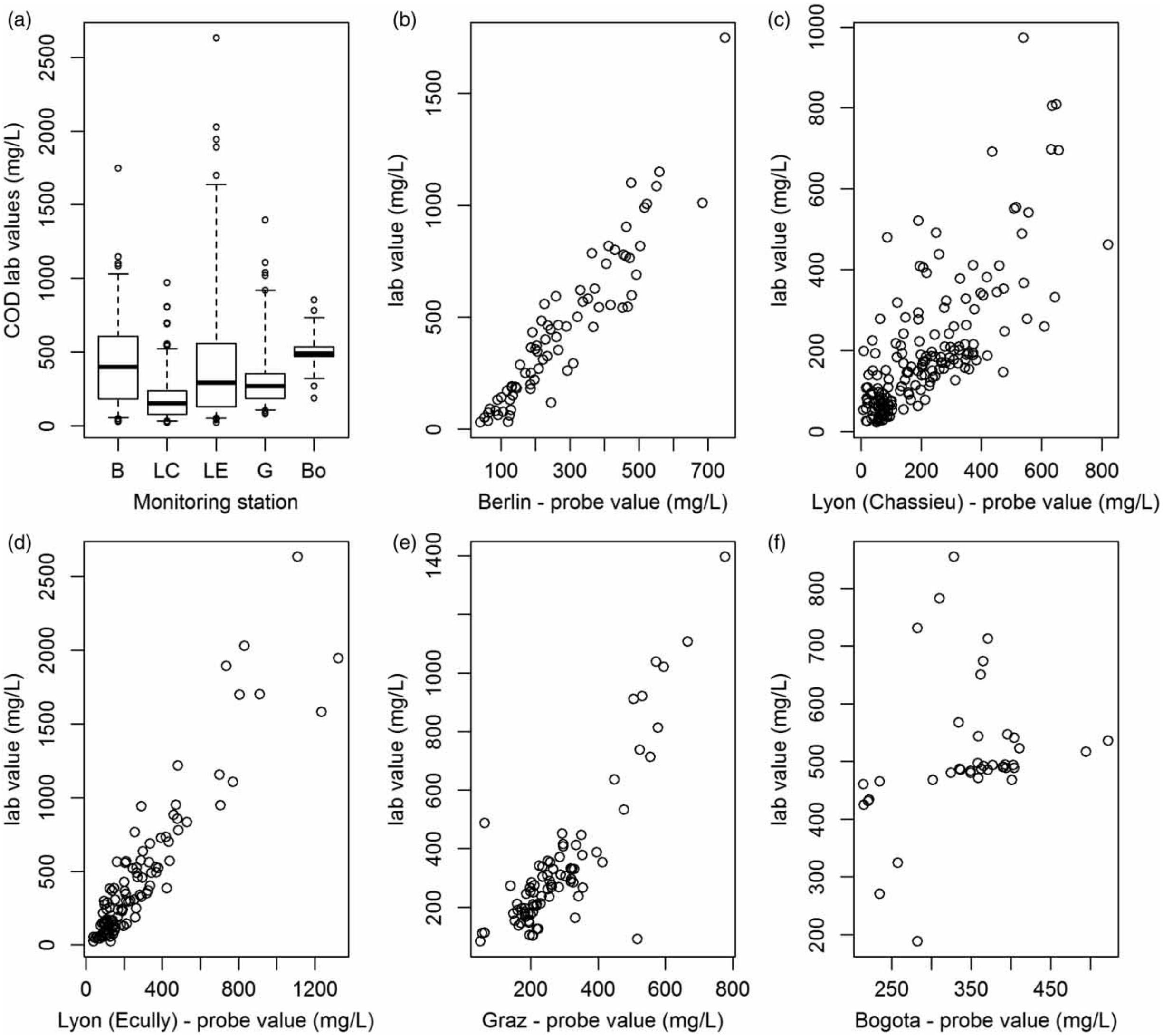


**Figure 2** | (a) The box plots of laboratory values obtained during rain events in each case study: B for Berlin, LC for Lyon Chassieu, LE for Lyon Ecully, G for Graz and Bo for Bogota. (b)–(f) The pairs of probe values and related COD laboratory values of samples collected at the times of the probe measurements.

Bogota. The stability of the parameters would probably not have been reached if all samples were taken over the same event and over a very tight concentration range, since most of the natural variability of the concentration would not have been analyzed.

On the other hand, 20 samples seems to be not sufficient to reliably estimate uncertainties in the calibration function. For each case study, RMSE varies strongly by adding the first samples to the calibration (Figure 3(c)). RMSE is less stable than slopes and offset: even with more than 20 samples, significant variations are observed at some sites (Ecully, Graz).

CV (normalized RMSE) shows an intermediate behavior between function parameters and RMSE, with a relative stability with at least 20 samples in some cases. This indicates that 20 samples is not really a sufficient number to estimate the measurement uncertainty, if the entire measurement range has not been covered by the laboratory measurements. For example in the case of Lyon Chassieu, the RMSE calculated with the first 20 samples is 86 mg/L whereas the RMSE calculated with 80 samples is 108 mg/L. The measurement uncertainty increases by increasing the number of samples from 20 to 80 even if the coefficients $a$ and $b$ remain stable. In this case, the use of only 20 samples would lead to relatively accurate measurement ($a$ and $b$ are stable) but the calculated uncertainty would underestimate the real uncertainty. It means that at the stage of 20 samples, not enough information was available to assess accurately the measurement uncertainty.

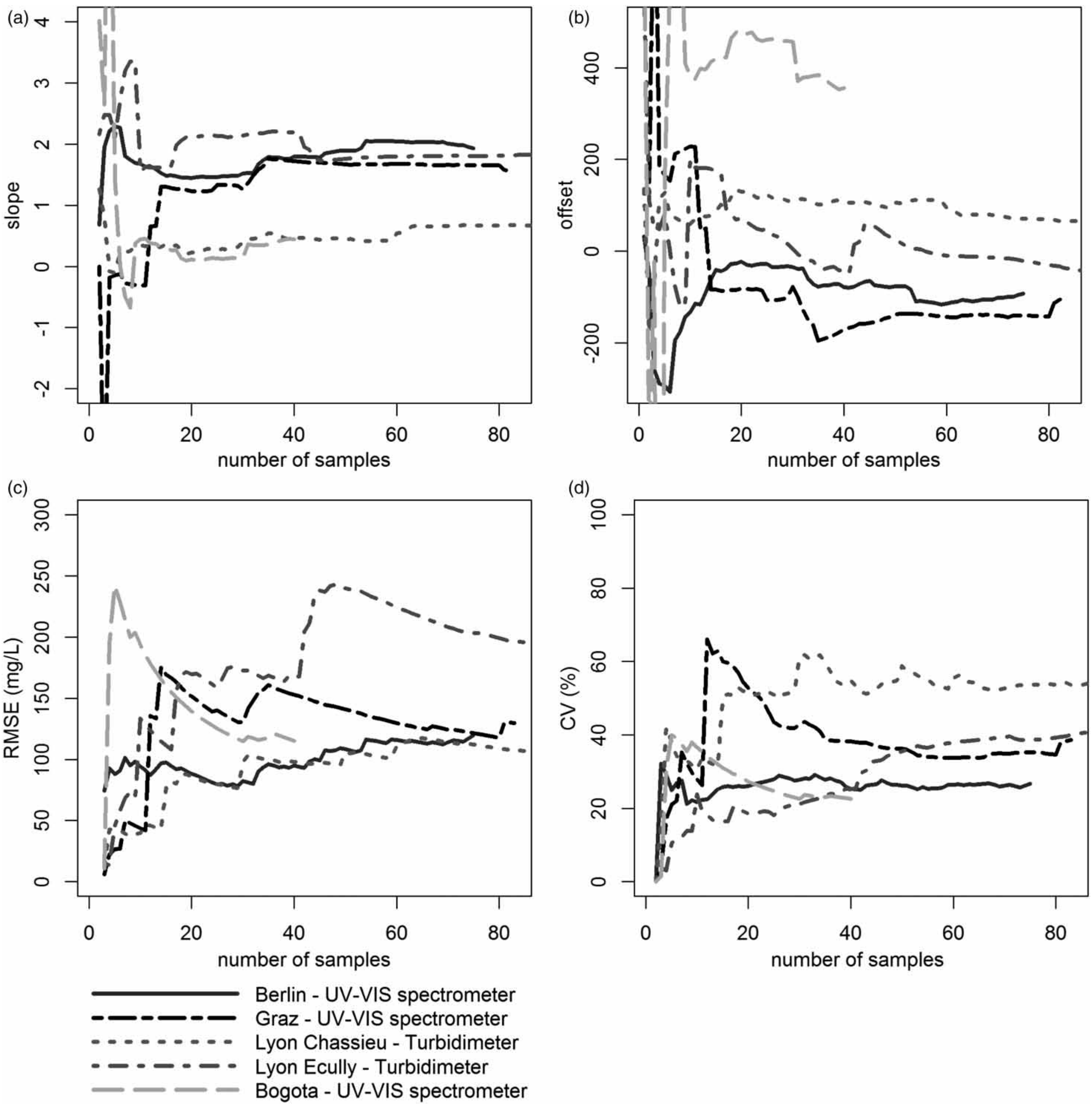


**Figure 3** | Influence of the number of samples used to establish calibration functions in each study site.

Increasing the number of samples leads to more of the natural variability of storm event concentrations being included (with increased RMSE and CV) without modifying substantially the calibration function (*a* and *b* remain stable).

It is interesting to note that the stability of the parameters is achieved for both UV–VIS spectrometers and turbidimeters using a similar number of samples. This result suggests that the amount of information needed to calibrate the probes is rather dependent on the water matrix and the expected range of concentrations than on the type of sensor.

Lastly, the influence of the number of samples on COD load estimations has been evaluated (Figure 4). The total CSO load over 3 years of monitoring (2010–2012) has been calculated for each calibration function obtained in the case study of Berlin (75 calibrations, from the two first samples to all samples). Load uncertainty is represented by

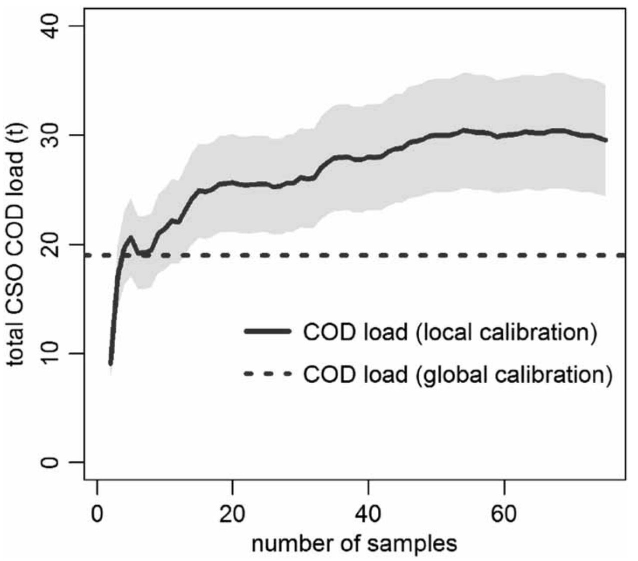


**Figure 4** | Influence of the number of samples on total COD load calculated using local and global calibration functions in Berlin.

its 95% confidence interval and has been estimated considering only the calibration prediction error (RMSE). The load standard uncertainty $u(M)$ is estimated using the law of propagation of uncertainty considering uncertainty in flow and concentration measurements. Uncertainty in flow is assumed negligible ($u(Q) = 0$) whereas uncertainty in concentration is estimated by the calibration prediction error only ($u(c) = \text{RMSE}$) (Caradot *et al.* 2013).

Using all 75 samples collected during the monitoring to calibrate the probe, the total CSO load is $30\,\text{t} \pm 20\%$. Approximately 20 samples are needed to reach stable load values: with more than 20 samples, the calculated load is already within the range of uncertainty of the load calculated with all 75 samples.

The effort to gain more than 20 samples is less efficient, since the load values remain relatively stable between 20 samples and 75 samples. The use of the global calibration provided by the manufacturer leads to a strong underestimation of the CSO load (−20%). The load calculated with the global calibration is outside the range of uncertainty of loads calculated with local calibration using a minimum of 15 samples.

## CONCLUSION

The results underline the need to establish local calibration functions for the online measurement of wet weather discharges using UV–VIS spectrometers or turbidimeters. From this experience, it is suggested that practitioners calibrate locally their probes using at least 15–20 samples. However, these samples should be collected over several events and should cover most of the natural variability of the measured concentration. For this reason, the use of automatic peristaltic samplers in parallel with online monitoring is recommended with short representative sampling campaigns during wet weather discharges. These conclusions have been drawn for COD measurements but similar results have been obtained for TSS measurements (results not shown here). It suggests that the stability of calibration parameters depends mainly on the amount of information on concentration variability obtained. Using reliable calibration functions, instantaneous COD concentrations can be estimated with CV of approximately 40%, and loads can be estimated with a relative uncertainty of approximately 20% for CSO and storm events. If no local calibration is established, COD concentrations and loads are estimated with strong errors, questioning the reliability and meaning of the online measurement. The expense and effort required for online monitoring (device, installation, maintenance and calibration) are justified only if high quality data are obtained.

These results are recommendations based on the experience of five online monitoring programs in the cities of Berlin, Graz, Lyon and Bogota. The conclusions can be used to find an appropriate balance between calibration expenses and expected measurement quality in the specific case of event-based monitoring.

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