The use of continuous sewer and river monitoring data for CSO characterization and impact assessment

L’utilisation de la mesure en continu pour caractériser les rejets du système d’assainissement et leurs impacts

Nicolas Caradot [1], Andreas Matzinger [1], Mathias Riechel [1], Hauke Sonnenberg [1], Erika Pawlowsky-Reusing [2], Bernd Heinzmann [3], Dörthe von Seggern [4], Pascale Rouault [1]

[1] Kompetenzzentrum Wasser Berlin gGmbH, Cicerostrasse 24, 10709 Berlin, Germany
[2] Berliner Wasserbetriebe, Netz- und Anlagenbau, Neue Jüdenstrasse 1, 10864 Berlin, Germany
[3] Berliner Wasserbetriebe, Research and Development, Cicerostrasse 24, 10709 Berlin, Germany
[4] Berlin Senate Department for Urban Development and the Environment, Brückenstrasse 6, 10179 Berlin, Germany

RÉSUMÉ

Cet article souligne l’intérêt d’utiliser la mesure en continu pour caractériser la dynamique des rejets et des impacts sur le milieu naturel. Une campagne de mesure en continu des rejets du système d’assainissement et de leurs impacts a été mise en place à Berlin en 2010. Les déversements par temps de pluie et les impacts sur le milieu naturel sont mesurés en aval de l’un des principaux rejets de la ville et à cinq différentes stations le long de la rivière Spree. La demande chimique en oxygène DCO est mesurée par des spectromètres UV-VIS avec de faibles incertitudes (10-30%). L’expérience montre cependant que ces sondes ne sont pas capables de mesurer avec précision sans avoir été étalonnées au préalable avec des échantillons locaux. L’article présente plusieurs méthodes d’évaluation des données ainsi que leurs applications à titre d’exemple pour un événement pluvial. Les analyses de la charge polluante, de la proportion d’eaux usées dans les rejets, de la contribution des eaux usées à la charge polluante et de la dynamique de la charge en fonction du volume (first flush) ont été réalisées tout en considérant les incertitudes. Les résultats soulignent l’intérêt d’utiliser la mesure en continu pour comprendre les rejets urbains par temps de pluie et pour soutenir la définition d’aménagement visant à réduire leurs impacts.

ABSTRACT

The present study aims at demonstrating the possibilities of on-line sensors for describing CSO emissions and river impacts. A continuous integrated monitoring, using state-of-the-art on-line sensors, was started in Berlin in 2010. It combines (i) continuous measurements of water quality and flow rates of combined sewer overflows (CSO) at one main CSO outlet and (ii) continuous measurements of water quality parameters at four sites within the urban stretch of the receiving river. UV-VIS probes provide continuous measurements of parameters such as chemical oxygen demand (COD) with relatively low uncertainties (10-30%). However, experience shows that on-line UV-VIS probes are not able to provide accurate measurements of water quality without being calibrated to local conditions. Several methodologies to analyze on-line CSO and river measurements are presented and illustrated with an exemplary event. Results show that reliable information such as the CSO load, the proportion of wastewater in CSO, the contribution of wastewater to CSO load, the first flush effect and the intensity of river impacts can be gained at high precision and temporal resolution. Given the broad range of high quality information from CSO impacts in the river to the characterization of CSO emissions, the study suggests the use of continuous integrated monitoring programs to support decisions on CSO management.

KEYWORDS

Combined sewer overflows, Integrated on-line monitoring, River impacts, UV-VIS spectrometer

1 INTRODUCTION

The EU Water Framework Directive (2000) requires the achievement of good ecological and chemical status of European water bodies especially by the prevention of point and non-point source pollution. Since significant efforts have been achieved in the past decades to reduce impacts from waste water treatment plants (WWTP), the attention of municipalities in most urban areas focuses more and more on impacts of combined sewer overflows (CSO) (Zabel et al., 2001).

However, efficient immission based management and reduction of CSO impacts requires detailed information on both CSO emissions and river impacts. CSO dynamics have to be known, since they strongly influence the extent and timing of impacts in receiving surface waters (Krebs et al., 1999). Model studies show the importance of an integrated view to understand the observed dynamics (Even et al., 2007, Holzer and Krebs, 1998). This is underlined by Passerat et al. (2011) who analyzed both CSO and receiving river samples for one single rain event, gaining valuable information on sewage composition, reaction times and extent of impacts.

Most existing monitoring studies are based on autosampling and therefore often focus on loads rather than dynamics. However, on-line sensors allow suitable dynamic measurements of critical parameters like COD or NH_4-N (Langergraber et al., 2003). The present study aims at demonstrating the possibilities of on-line sensors for describing CSO emissions and river impacts. Firstly, the paper presents the integrated monitoring started in Berlin in 2010 and gives details about calibration and measurement uncertainties. Secondly, several methodologies to analyze on-line CSO and river measurements are proposed and illustrated with an exemplary event. The CSO load, the proportion of wastewater in CSO, the contribution of wastewater to CSO load, the first flush effect and the river impacts are analyzed. Through an exemplary event, the proposed methodologies underline the interest of continuous monitoring to understand the dynamic and composition of CSO and impacts.

2 MATERIAL AND METHODS

2.1 Study site

The combined sewer system in the centre of Berlin, Germany, drains an area of ~100 km^2 with ~1.4 million inhabitants. If the storage volume of the combined sewer system is exceeded during storm events, combined sewage overflows at ~450 CSO structures into ~180 collecting overflow sewers with outlets along an ~18 km stretch of the River Spree and its side channels.

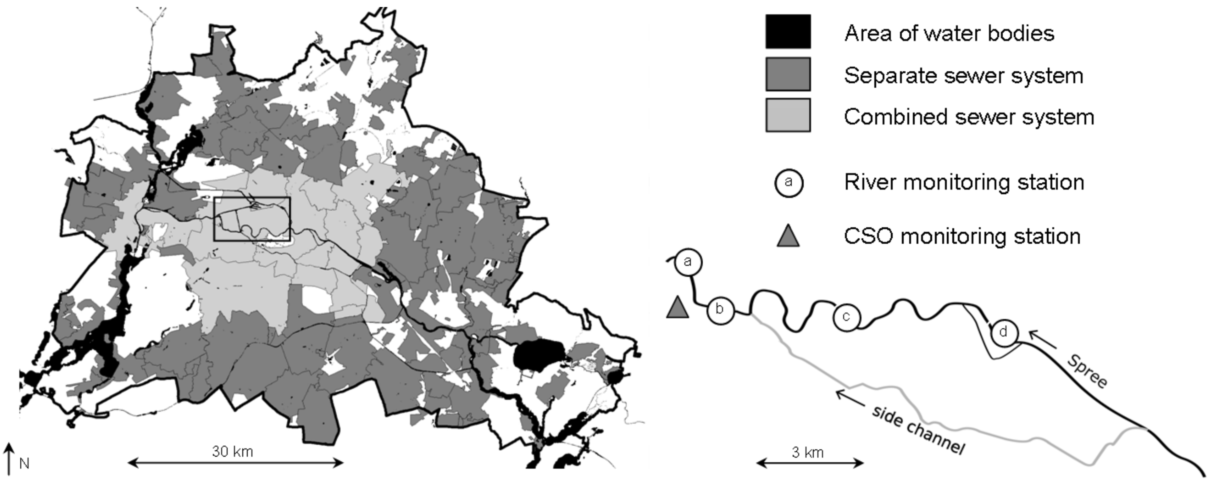

Figure 1. Map of the Berlin urban drainage area. The box in the left-hand panel shows the location of the monitored section of Berlin which is shown in larger scale in the right panel.

The receiving River Spree is a large and regulated lowland river with average monthly flow rates between 12 $m^3 s^{-1}$ in summer and 42 $m^3 s^{-1}$ in spring, which translates into very low flow speeds of few cm s^{-1}. As a result, it can take several days for water to pass through the CSO-impacted river stretch in the centre of Berlin (Figure 1).

In the River Spree CSO lead to critical DO concentrations every year and to occasional larger fish kills. Riechel et al. (2010) found that critical states regarding DO are due to both (i) CSO in the urban centre of Berlin and (ii) background pollution upstream of the city. However they showed that highly critical situations with DO < 2 mg l^{-1} only occurred under CSO influence. Given this significant pressure from CSO, the presented monitoring is part of an initiative from both water utility and local authority to better understand and simulate CSO emissions and impacts for an immission based planning of countermeasures.

2.2 Integrated monitoring approach

The integrated monitoring includes one monitoring point within an overflow sewer (triangle in Figure 1) and four monitoring stations along the CSO-impacted stretch of the River Spree (stations “a”, “b”, “c” and “d” in Figure 1). More information on site and instrument selection as well as on the implementation of the monitoring stations are given in Caradot et al. (2011).

The CSO monitoring was installed in a major overflow sewer about 230 m downstream of the main overflow structures and 500 m upstream of the outlet to the river. During dry weather, the overflow sewer is filled up to a water level of about 1.3 m with backwater from the River Spree; during CSO events, combined sewage from CSO structures is discharged through the overflow sewer into the River Spree. Flow is measured each minute directly in the overflow sewer, based on water level (air-ultrasound, Nivus company) and flow velocity (two ultrasound sensors, Nivus company). Water quality is measured each minute on a bypass fed by a peristaltic pump, using (i) a UV-VIS spectrometer (spectro::lyser, s::can company) for the measurement of absorption water spectra which enable calculating equivalents of chemical oxygen demand (CODeq), dissolved COD (CODdeq) and total suspended solids (TSSeq) and (ii) a conductivity sensor (condu::lyser, s::can company) for measurements of electrical conductivity (EC) and temperature (T).

The river monitoring stations are equipped with probes to measure standard water quality parameters pH, DO, T, and EC (MS5, OTT Messtechnik, time step 15 min). In addition, TSSeq, CODeq and CODdeq are monitored each minute at the beginning and the end of the river stretch (stations “a” and “d” in Figure 1) using a UV-VIS spectrometer (spectro::lyser, s::can company). Probes at the river monitoring stations are fixed with metal supports and immersed directly in the river, with the exception of station “d” at which probes are operated on a bypass situated in a small house close to the river bank.

In order to calibrate locally the spectrometers, samples are taken during rain events to gain laboratory measurements over the whole concentration range (high concentrations for the parameter of interest are expected only during CSO events). Due to the short duration of overflows, it is very difficult to gain manual samples of impacts or CSO events. Therefore autosamplers have been used to ensure sufficient samples during CSO events for calibration. For the sewer monitoring, samples are taken during CSO events by an automatic sampler (Hydreka company) if the flow exceeds a given threshold. For the river monitoring, samples are taken during CSO by an automatic sampler (Hydreka company), but also on a regular basis during dry weather, in order to identify seasonal variation of water quality as it is expected in natural waters. Samples are analyzed for COD and CODd on site (cuvette tests by Hach Lange company), thus reducing errors due to time delay and transport. The analysis of TSS requires transport of samples to a certified laboratory.

2.3 Calibration of spectrometer with consideration of uncertainties

UV-VIS spectrometers are in-situ probes. Concentrations are calculated with multivariate regression techniques from absorbance measurements. Calculation is based on global calibrations for typical municipal wastewater (INFLUENTV120) and river (EFFLUENTV120) provided as default configuration of the UV-VIS spectrometer. However, due to the different composition of waste and river water a second calibration step (local calibration) is required to enhance the measurement quality. On-line probes are not able to provide accurate measurements of water quality without being locally calibrated with laboratory measurement (Caradot, 2012). Manufacturer global calibration can lead to systematic error up to 50% for COD measurements (Gamerith *et al.*, 2011). The efforts of the monitoring operator should focus on this calibration step, as the precision of the measurement depends mostly on the quality of the regression. For this purpose, laboratory measurements are correlated with in-situ measurements from the global calibration. If results are not satisfying, advanced methods can correlate directly UV-VIS spectra with laboratory measurements (e.g. Partial Least Square method (Torres and Bertrand-Krajewski, 2008)). Using appropriate local calibration, measurement error can be reduced to an order of magnitude of 10 to 30%.

Local calibration for sewer monitoring

In order to consider both errors on spectrometer and lab measurement, the Monte-Carlo (MC) method has been used to perform local linear regressions between raw spectrometer measurement from the global calibration and lab values (Figure 2). For the CSO monitoring, 156 lab measurements from 25 CSO events have been analyzed and correlated with *in-situ* probe measurements from the global calibration. Lab values cover a very large measurement range from 23 mg l^{-1} to 1965 mg l^{-1}. Considering the high slope of the calibration function (a = 2.032), the use of the global calibration would lead to a very high underestimation of the COD concentrations, especially in the upper range.

Total uncertainty on concentrations has been calculated using the law of propagation of uncertainty, considering the errors of measurement, laboratory, MC regression and field conditions. Field uncertainties derive from the representativeness of the in-situ measurements regarding the observed phenomena. For example, the position of the pump intake in the overflow sewer can influence the representativeness of TSS measured in the monitoring by-pass. Field uncertainties were estimated equal to 5% of the measured value, following the suggestion of Métadier and Bertrand-Krajewski (2011). As a result, total uncertainty on concentration is about 30% for COD at 400 mg l^{-1} and decreases when the concentration increases to about 10% for COD at 1000 mg l^{-1}. Details of uncertainty calculation can be found in Caradot (2012).

Local calibration for river monitoring

For the river monitoring, 73 lab measurements from 15 events in 2012 have been used to correlate spectrometer with lab values. However, even with a wide range of laboratory values (from 23 to 107 mg l^{-1}), no reliable local linear calibration can be set up with the Monte Carlo method ($r^2 = 0.3$). The global calibration provided by the manufacturer is not sensitive enough to the COD variations observed in the river during CSO impacts. In order to gain accurate values of COD in the river, a Partial Least Square regression (PLS) method has been used to correlate directly the UV-visible spectra and the lab measurements, without considering the global calibration provided by the manufacturer. Details of the methodology can be found in (Torres and Bertrand-Krajewski, 2008). The then calculated correlation coefficient r^2 is 0.86 and the root mean square error RMSE is 5 mg l^{-1}. Considering field uncertainties, total uncertainty on concentration is estimated to about 30% for COD at 30 mg l^{-1}.

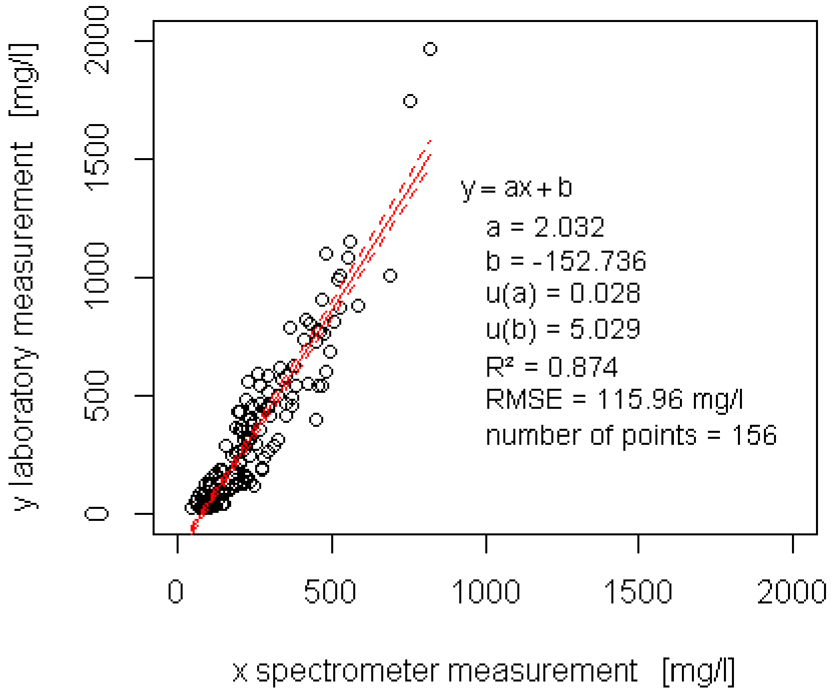

Figure 2. Calibration plot for COD measurement at the sewer monitoring station. The dashed curves are the 95% confidence interval of the regression.

2.4 What can be learnt from online CSO and river impact measurements?

Event load calculation (CSO and river impacts)

CSO load calculation informs about the extent and the intensity of the expected impacts in the river. Event loads M are calculated by adding the load at each time step i over the duration of the event.

$$M_i = \sum (Qi \cdot Ci \cdot \Delta \mathrm{t}) \qquad [1]$$

with Q_i = flow at time step i [m³ s^{-1}] and C_i = concentration at time step i [mg l^{-1}]

Total uncertainty u of load M is calculated for each time step i based on flow and concentration uncertainties (see 2.3), applying the law of error propagation:

$$u(M_i)^2 = (u(Q_i)^2 \cdot C_i{}^2 + Q_i{}^2 \cdot u(C_i)^2) \cdot \Delta \mathrm{t}^2 \qquad [2]$$

Proportion of wastewater in the CSO

The proportion of wastewater in the CSO informs about the volume ratios of wastewater (r_{waste}) and rain runoff (r_{rain}) in the CSO. In order to estimate r_{waste}, we assume the mixing of dry weather wastewater and rain runoff water, with average electrical conductivities EC_{rain} and EC_{waste}. Using EC as a conservative tracer (Passerat et al., 2011), the proportion of rain and wastewater can be calculated in a simple mixing calculation:

$$r_{rain} = \frac{EC_{waste} - EC_{CSO}}{EC_{waste} - EC_{rain}}; \quad r_{waste} = 1 - r_{rain} \qquad [3]$$

In order to calculate $r_{rain,}$ EC_{waste} and EC_{rain} have to be estimated based on local measurements. Since conductivity in both rain and sewage may vary, average and extreme values of the 95% confidence interval have been considered for the calculation. Average electrical conductivity in wastewater $EC_{waste,average}$ has been set to 1368 µS cm^{-1} based on several 24-hour dry weather measurement campaigns in the combined sewer system close to the CSO structure. Extreme values of the 95% confidence interval for EC_{waste} have been estimated as $EC_{waste,average}$ ± 2 x standard deviation (sd) with 2 x sd = 137 µS cm^{-1}. Thus, $EC_{waste,min}$ is 1231 µS cm^{-1} and $EC_{waste,max}$ is 1505 µS cm^{-1}.Using the same approach, average and extreme values of EC_{rain} have been set to 120 ± 97 µS cm^{-1} according to a one-year monitoring campaign in a similar catchment of Berlin (Heinzmann, 1993).

Contribution of wastewater to CSO load

The contribution of wastewater to total CSO load (c_{waste}) represents the fraction of CSO load that comes from dry weather wastewater. Other fractions of the total CSO load originates from the rain runoff and the resuspension of sediments accumulated in the sewer. The analysis of the three load contributions informs about the major pollutant sources and enables to identify efficient measures to reduce CSO emissions and impacts.

Metadier and Bertrand-Krajewski (2011) proposed an advanced methodology to estimate the dry weather (DW) contribution to total COD event loads using on-line turbidity measurement. Since no on-line measurement is available in the sewer system close to the monitored CSO outlet, the contribution of wastewater to total COD load in the CSO (c_{waste}) has been estimated as follows:

$$c_{waste} = \frac{COD_{waste} \cdot V_{waste}}{COD_{CSO} \cdot V_{CSO}} \qquad [4]$$

$$\text{with} \quad V_{waste} = r_{waste} \cdot V_{CSO} \qquad [5]$$

CSO volume (V_{CSO}) and COD concentrations (COD_{cso}) are measured directly and V_{waste} is calculated in equation [5], based on the proportion of wastewater in the CSO (r_{waste}, equation [3]). In order to calculate c_{waste}, COD_{waste} has to be estimated based on local measurements. Since COD concentration of wastewater may follow daily variations, average and extreme values of the 95% confidence interval have been considered for the calculation. Average $COD_{waste,average}$ has been set to 748 mg l^{-1}, based on dry weather measurements at the WWTP inflow in 2010. Extreme values of the 95% confidence interval have been estimated as $COD_{waste,average}$ ± 2 x standard deviation (sd) with 2 x sd = 468 mg l^{-1}). Thus, $COD_{waste,min}$ is 280 mg l^{-1} and $COD_{waste,max}$ is 1216 mg l^{-1}.

First flush effect: pollutant VS volume repartition

Information about the temporal repartition of pollutant loads during CSO is essential to develop strategies aiming at reducing adverse effects on the receiving water body. If the main proportion of the pollutant mass is contained in the volume at the beginning of a CSO, the interception of this early volume could reduce the impacts significantly. Numerous authors have proposed more or less strict definitions of the so-called first flush phenomenon as summarized in Diaz-Fierros et al. (2002). To assess the phenomenon the cumulated COD load is plotted versus the cumulated flow, as suggested by Bertrand-Krajewski et al. (1998).

Advective transport of CSO in the river

In order (i) to identify impacts from the monitored CSO and (ii) to assess their intensity, the advective transport of measured CSO loads in the river has been calculated using three different model tools. River flows upstream the monitored CSO outlet were calculated using the one-dimensional hydrodynamic flow model Hydrax, which solves the full Saint-Venant equations to calculate water levels, discharges and flow velocities in rivers (Kirchesch and Schöl, 1999). Driving forces of the model are the discharges at the upper boundary (station “d” in Figure 1), the discharges at the main tributaries and the water level at the lower boundary (at the confluence downstream of station “a” in Figure 1). Additionally, the hydraulic influence of CSO discharges along the river stretch was estimated by sewer system simulation with the model “Infoworks CS” (WSL, 2004). Lastly, conservative transport of pollutants from the monitored CSO sewer was simulated using an advective box model in the software package Aquasim (Reichert, 1994). The simulation is based on river flow upstream of the measured CSO outlet predicted with the coupled Infoworks/Hydrax simulation, flow and concentration measurements from the CSO monitoring station as well as river geometry. The displacement of the discharged CSO loads towards the river monitoring station “a” was modeled under the simplification that no degradation and sedimentation but only advective transport occurs.

3 RESULTS AND DISCUSSION

In the next paragraphs, the application of the methodologies presented in 2.4 is illustrated with an exemplary event on 2011-08-24 (Figure 3).

Event load calculation (CSO and river impacts)

An overflow was recorded in the overflow sewer for a duration of 1h and 30min. Flow increases at the beginning of the event with a peak flow of 1.1 $m^3\ s^{-1}$ and increases a second time at the end of the event to a value of 1 $m^3\ s^{-1}$ (Figure 3a).Total volume of the CSO event is 3759 ± 422 m^3 (11%), with a total COD load of 1037 ± 215 kg (20%) and a volume averaged COD concentration of 276 mg l^{-1}.

Proportion of wastewater in the CSO

Application of equation [3] on average and extreme values of electrical conductivities EC_{waste} and EC_{rain} results in a range of wastewater fraction over the duration of the CSO event. Figure 3d shows the proportion of wastewater in the CSO based on $EC_{waste,average}$ and $EC_{rain,average}$ as well as the corresponding extreme values of the 95% confidence interval. Considering $EC_{waste,average}$ and $EC_{rain,average}$, sewage content in CSO decreases from ~26% at the beginning of the event to ~16% within 10 minutes, increases again to ~27% and finally decreases to 1% at the end of the CSO event (solid line in Figure 3d). The average proportion of wastewater over the entire CSO is 13 ± 8%. It means that the true value of r_{rain} lies between 5 and 21% around an average value of 13% with a 95% probability. The corresponding rain ratio underlines that about 87 ± 8% of the CSO volume is composed of rain runoff.

Contribution of wastewater to CSO load

Since uncertainty on the proportion of wastewater in the CSO r_{waste} is pretty low (± 8%), calculation of the contribution of wastewater to COD load c_{waste} has been performed assuming an average proportion of wastewater r_{waste} = 13% (equation (5]). Application of equation [4] on the average and extreme values of COD_{waste} shows the high variability of the contribution of wastewater to CSO load during the exemplary event (Figure 3e). The average contribution c_{waste} over the entire CSO event is 35 ± 22%. It means that the true value of c_{waste} lies between 13 and 57% around an average value of 35% with a 95% probability.

Results indicate that about 35% of the discharged COD comes from wastewater. Thus, about 65% of the COD carried in the CSO originate from two other major sources: wash-off by stormwater runoff and resuspension of sewer sediments. However, the significant uncertainty on c_{waste} underlines the need to consider local daily variations of COD in wastewater to gain more accurate results.

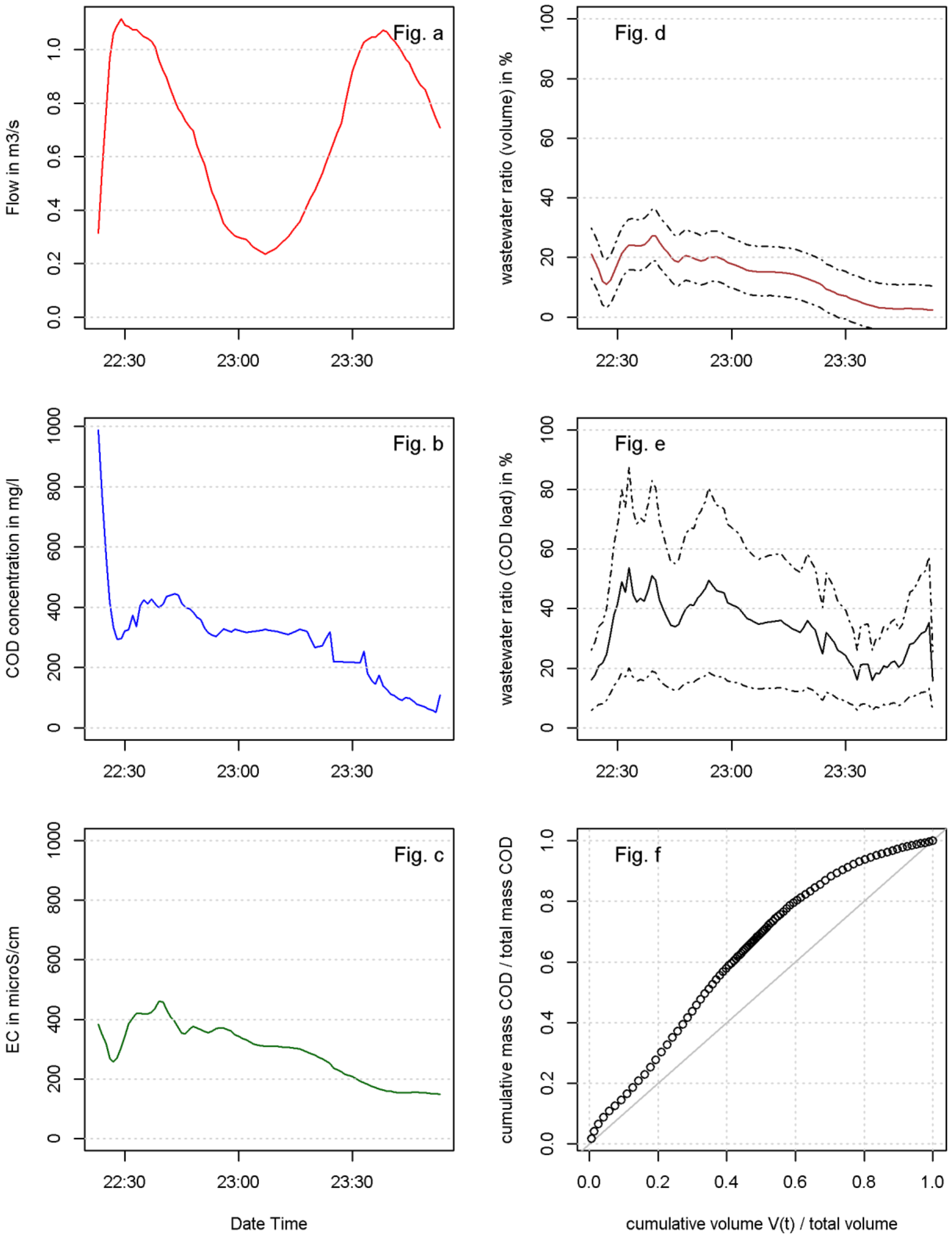

Figure 3. Dynamic of CSO for an event on 2011-08-24. From Fig. a to f : flow, COD concentration, EC, proportion of wastewater in the CSO, contribution of wastewater to CSO load and pollutant VS volume repartition. Dotted-dashed lines in Fig. d and e show the extreme values of the 95% confidence intervals.

First flush effect: pollutant VS volume repartition

The cumulated COD mass has been plotted versus the cumulated flow (Figure 3f). A light first flush effect is observed during the event: the whole M=f(V) curve is above the bisector y = x, where the pollutant mass M is proportional to the volume V. About 60% of the mass is contained in the first 40% of the CSO volume.

Advective transport of CSO in the river

Figure 4 shows CSO impacts in the river at station “a”, downstream to the monitored CSO outlet. About one hour after the first flow peak in the overflow sewer (Figure 4b), the downstream river monitoring station “a” records a clear augmentation in COD concentration (Figure 4d). Parallel to this COD augmentation, DO starts to decrease slowly (Figure 4d).

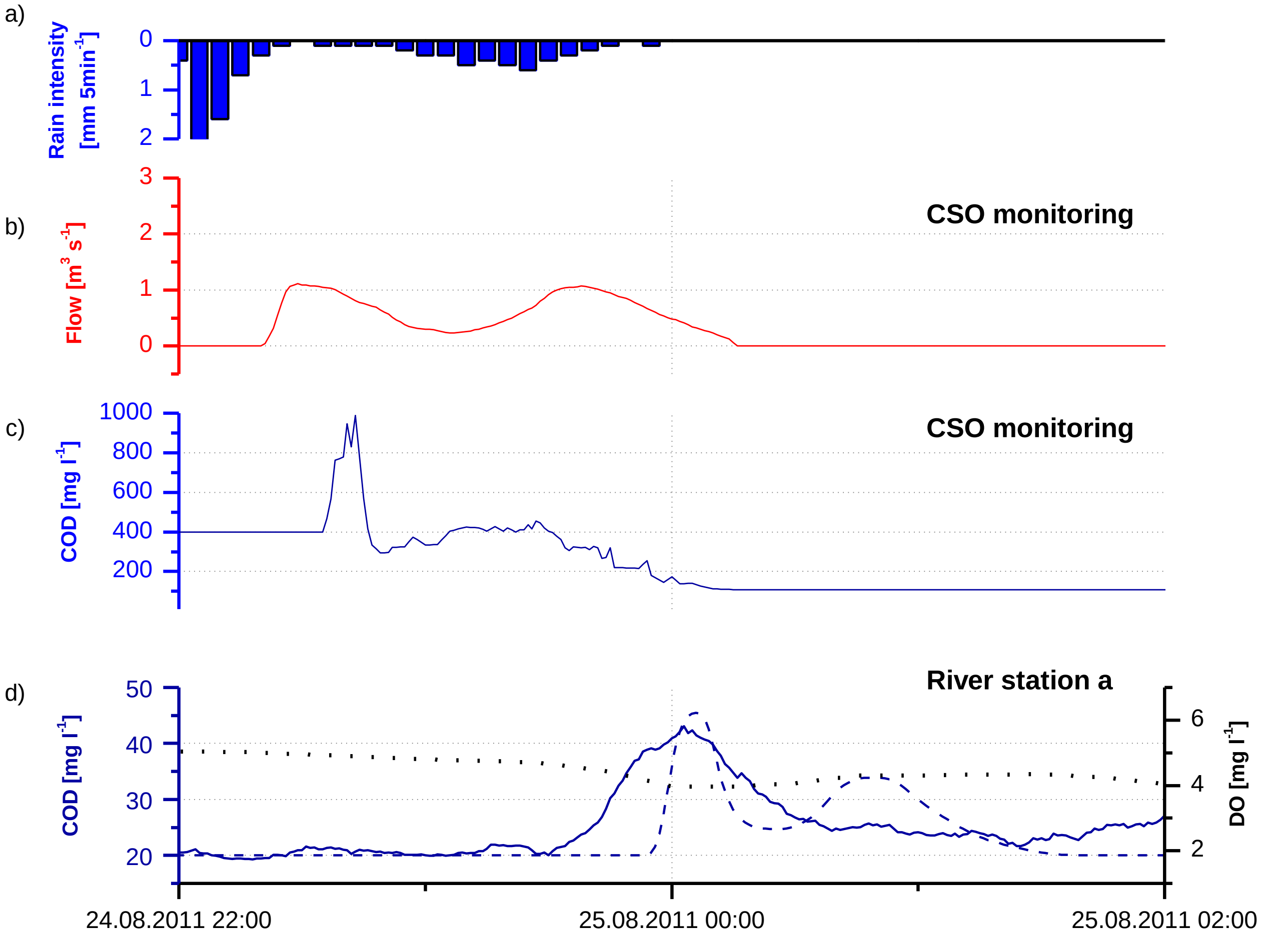

Figure 4. Continuous integrated measurements for a rain event on 2011-08-24 with CSO: (a) is local rain intensity, (b) is measured CSO flow, (c) is measured COD in CSO, (d) is measured COD (solid line) and DO (dotted line) in the downstream river station “a” (Fig. 1). Dashed line in (d) represents the simulation of expected COD under the assumption of conservative transport.

To assess the effect of the observed CSO on the river and distinguish its impact from other CSO outlets and river background, expected mixing and advective transport in the river were simulated for the observed CSO outlet as outlined in 2.4. The results of the simulation for COD are shown as dashed lines in Figure 4d and indicate that the peak of COD in the river can indeed be explained by the observed CSO. The conservative simulation results show two COD peaks whereas the measurements indicate only one main peak. Since the diffusion effect in the river is not considered by the simplified conservative model, it is expected that modelling results show higher COD variations than monitoring results. However, it is noteworthy that no apparent reduction in COD is visible when comparing conservative simulation results (without decay or sedimentation) with measurements. Assuming that COD from CSO is mostly well degradable, maximal decay after a flow time of ~1 h would be expected to be only ~1% according to Chapra (1997) or 4% to 6% according to findings by

Seidl et al. (1998). Sedimentation of COD seems also insignificant, since according to Chapra (1997) losses of particulate organic matter are < 1% for a flow time of ~1 h and observed river depths of 3 m. Accordingly, expected decrease of COD at river monitoring station “a” is in the range of estimated error of measured COD loads (see 2.3).

Since no measurement of river flow close to the outlet is available, the impact load has not been calculated. With flow data, river load could be calculated using equation [1]. Results may be compared to CSO load and help understanding river processes like sedimentation or pollutant degradation.

4 CONCLUSIONS

The presented integrated monitoring results underline through an exemplary event the interest of using parallel on-line sensors at CSO outlets and in the river for the characterization of CSO emissions and the assessment of CSO impacts in the river.

First results indicate that UV-VIS spectrometer probes allow continuous measurement of parameters such as COD with relative low expected uncertainties despite the changing matrices of CSO and river water. Pollutant dynamics and load calculations describe emissions of the sewer system with uncertainties between 10% and 30%. However, UV-VIS probes need to be calibrated to local conditions with laboratory measurement over the whole range of expected measurements in order to reach this precision. Further investigations are still necessary to specify the number of samples to reach a satisfactory calibration quality.

Secondly, the application of the presented methodologies shows that CSO load, proportion of wastewater in CSO, contribution of wastewater to CSO load, first flush effect and river impacts can be analyzed at high temporal resolution. For the exemplary event, the total CSO load has been calculated with a significant uncertainty of 20%, mainly due to the relatively low concentrations of the event (relative uncertainty increases with decreasing concentrations). The average contribution of wastewater to COD load is 35% while wastewater only contributes 13% to the CSO volume. It means that about 65% of the COD carried in the CSO originate from two other major sources: wash-off by stormwater runoff and resuspension of sewer sediments.

Aim of this paper is to present through an exemplary event a wide range of methodologies to analyze CSO and impacts. Further investigations with the monitoring data of Berlin will describe 22 CSO events measured between 2010 and 2012. CSO characteristics will be correlated to rain characteristics (rain intensity, dry weather duration before CSO event, etc.) in order to see if CSO features could be described using rain data. The statistical analysis of CSO and river data could also support the definition of counter measures to reduce CSO and river impacts.

Finally, integrated monitoring data allows calibration and validation of sewer and river models. Once established such models can be applied for a refined location of hot spots in the river, where impacts are most severe. Moreover they can be used as planning tools for an optimized implementation of CSO countermeasures. In the case of Berlin, monitoring results will be used for the calibration and validation of a coupled sewer-river water quality model to support future immission based management of CSO impacts.

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