

Application of stormwater impact assessment guidelines for urban lowland rivers – the challenge of distinction between background pollution and impacts of combined sewer overflows (CSO)

Application de directives concernant l'impact des eaux pluviales sur les rivières urbaines – le challenge de la distinction entre les impacts des rejets du réseau d'assainissement unitaire par temps de pluie (CSO) et la contamination de fond

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RÉSUMÉ

Ce travail présente l'application de guides techniques de gestion des impacts des eaux pluviales sur le taux d'oxygène dissous (OD) dans la rivière Spree de Berlin. Celle-ci reçoit d'une part les surverses de plus d'une centaine de déversoirs d'orages du réseau unitaire (DO), elle est exposée d'autre part à une forte pollution urbaine (impacts physiques, chimiques et morphologiques).

Afin d'analyser les causes de diminution de la teneur en OD de la Spree, l'application des guides techniques a été réalisée en complément avec l'analyse des données disponibles pour plusieurs paramètres : (i) des événements pluvieux ayant eu lieu avant que le taux critique de concentration en OD ne soit atteint, (ii) de la température et de la conductivité de l'eau, paramètres indicateurs de l'influence des rejets de DO sur la rivière, et enfin (iii) de la température et de l'OD avant l'atteinte de taux critiques en OD, afin d'analyser l'influence de la pollution urbaine globale. Cette approche a permis de mettre en évidence des diminutions des taux en OD dues à des rejets de DO et d'autres, indépendantes des surverses.

Les résultats indiquent que la rivière Spree est dans un état critique concernant l'OD. En amont du tronçon étudié, les impacts étaient dus principalement à la pollution urbaine globale. En aval du tronçon, les impacts étaient causés par des rejets de DO dans le tronçon étudié. Cependant, les concentrations les plus critiques, correspondant à des taux en OD < 2 mg L⁻¹, ont seulement eu lieu sous l'effet de rejets des DO. Ce travail souligne l'importance des mesures à prendre afin de réduire conjointement les impacts des déversoirs d'orages et des activités urbaines sur les cours d'eaux.

ABSTRACT

Stormwater impact guidelines for dissolved oxygen (DO) were applied to the Berlin River Spree, which (a) receives the effluents of more than 100 combined sewer discharge points and (b) is subject to significant anthropogenic background pollution. Discrimination of DO depressions, which are the direct result of combined sewer overflows (CSO) from DO depressions which are not related to CSO was achieved by combining stormwater impact guidelines with the analysis of data for: (i) rain events before critical DO depressions, (ii) water temperature (T) and conductivity as indicators for CSO impact in the river and (iii) T and DO before critical DO depressions to assess the effect of background pollution. Results indicate that the River Spree is in a critical state regarding DO for two main reasons: (a) upstream of the stretch with CSO discharge points because of background pollution and (b) downstream of the stretch because of CSO. Highly critical situations with DO < 2 mg L⁻¹ only occurred under CSO influence. Nevertheless, the analysis underlines the importance of measures to reduce both CSO and background pollution in urban rivers.

KEYWORDS

Background pollution, CSO, stormwater impact guidelines, lowland river

1 INTRODUCTION

Combined sewer overflows can lead to acute hydraulic, ammonia or oxygen stress for aquatic organisms in receiving rivers (Harremoës et al. 1996; Krejci et al. 2004b; Seidl et al. 1998). For large lowland rivers, where hydraulic impact is limited, ammonia and low dissolved oxygen (DO) are dominant stressors for aquatic organisms (Borchardt et al. 2001; Krejci et al. 2004a).

Several guidelines have been developed to assess the impact of CSO and stormwater inflows on receiving rivers and judge whether improvements in urban drainage systems are necessary to protect aquatic ecosystems (Borchardt et al. 2007; EPA 1995; FWR 1998; VSA 2007). Typically, these stormwater impact assessment guidelines are outlined for simple urban drainage systems with one or only few CSO outlets, which impact small rivers with high to moderate flow speeds. In such systems, acute CSO impacts in the river are limited to the duration of the CSO and can be directly linked to CSO occurrence. The application of the guidelines to complex urban drainage systems with numerous CSO outlets and large lowland rivers is not straight forward, since observed impacts in the river may divert in timing, duration and space from the CSO that triggered the impacts. Moreover, urban rivers are often under numerous anthropogenic pressures (Kaye et al. 2006), which render identification of the cause of critical situations in the river difficult.

The present paper exemplifies the assessment of critical situations in complex urban river systems for DO based on eight years of measurements for the River Spree in Berlin, Germany. In a first step, critical DO situations are identified using three existing guidelines. In a second step, critical DO situations due to CSO impacts are distinguished. Finally, the contribution of background river pollution is assessed.

2 STUDY SITE

The combined sewer system in the centre of Berlin, Germany, drains an area of 100 km² with 1.4 million inhabitants. This corresponds to about 20 % of the total drained area of Berlin, but almost 40 % of the city's population. The remainder of the area is drained mostly by a separated sewer system (Figure 1). In the combined sewer area, wastewater is collected together with stormwater and pumped to the waste water treatment plants, which are mostly located at the edge or beyond the city limits.

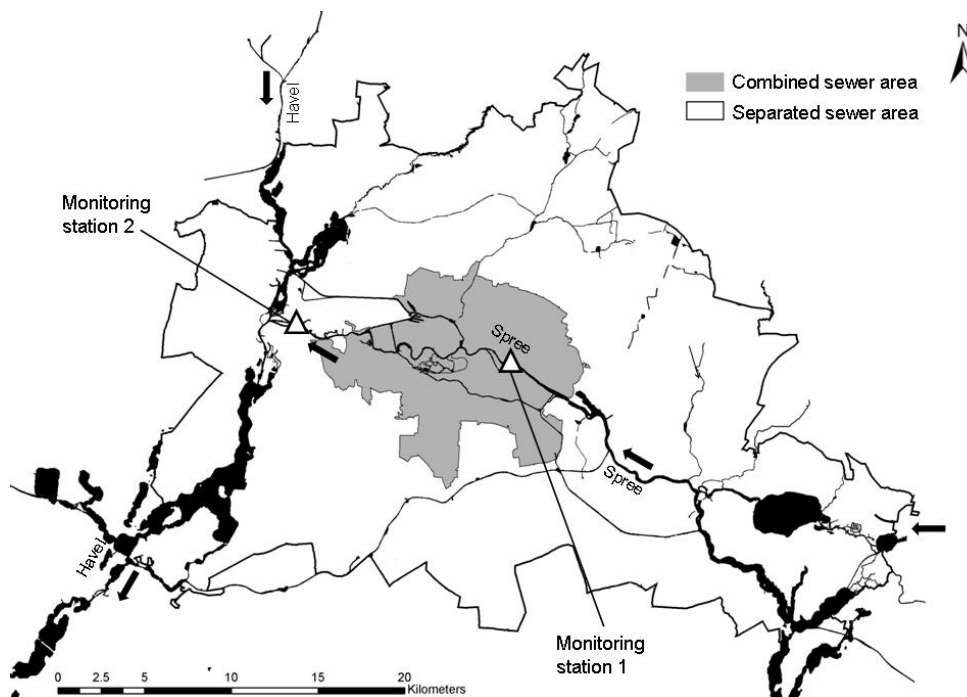


Figure 1: River and urban drainage system of Berlin, Germany. Triangles indicate monitoring stations 1 and 2. Arrows indicate flow direction of the rivers. Note that small, local combined sewer areas, which have no impact on the River Spree, are omitted.

If the storage volume of the combined sewer system is exceeded during storm events, combined sewage will overflow to the River Spree and its side channels via more than 150 CSO discharge points over a stretch of ~18 km. The receiving River Spree flows through the combined sewer area before it joins the River Havel, which leaves Berlin in the South-West (Figure 1). Average monthly flow rates before the confluence (at the monitoring station 2 in Figure 1) vary between $12 \text{ m}^3 \text{ s}^{-1}$ in summer and $42 \text{ m}^3 \text{ s}^{-1}$ in spring (long-time averages published by the Senate of Berlin). Given the significant cross-section of the river (average width ~50 m, average depth ~3 m), flow speeds are very low between 0.02 and 0.15 m s^{-1} . As a result it takes several days for the water to pass the combined sewer area. Monitoring station 1 is situated at the beginning of the combined sewer area, with low CSO influence, whereas monitoring station 2 is downstream of all CSO discharge points.

CSO were found to occur typically for rain events beyond a total height of 4.7 mm for the most sensitive areas (Riechel 2009). On average this comparably low threshold is exceeded 36 times per year between 2000 and 2007 (at a rain gauge to the north of the River Spree), with large interannual variability. For instance, 55 rain events above 4.7 mm occurred in the exceptionally wet year 2007 compared to 25 events in dry 2006. In terms of volume, currently about seven million m^3 of combined sewage enter the River Spree each year, with an average sewage to stormwater ratio of 1:11 (unpublished data, Berliner Wasserbetriebe).

Figure 2 shows a typical signal recorded at monitoring station 2 following a major rain event with a total height of 18 mm. Shortly after the rain event, a drop in specific conductivity κ_{20} can be observed, as a result of dilution with stormwater. Concurrently with the drop in κ_{20} , DO starts to decrease, reaching a minimum about 12 hours later. Two to three days after the rain event, a second drop in κ_{20} can be seen, again accompanied by a DO depression. Such a second, delayed DO depression was observed regularly for single rain events in eight years of observation (Riechel 2009). The second signal is most probably the result of the same rain event, but from CSO discharge points further upstream in the city on the River Spree and its side channels. However, an influence of local rain events cannot be fully excluded.

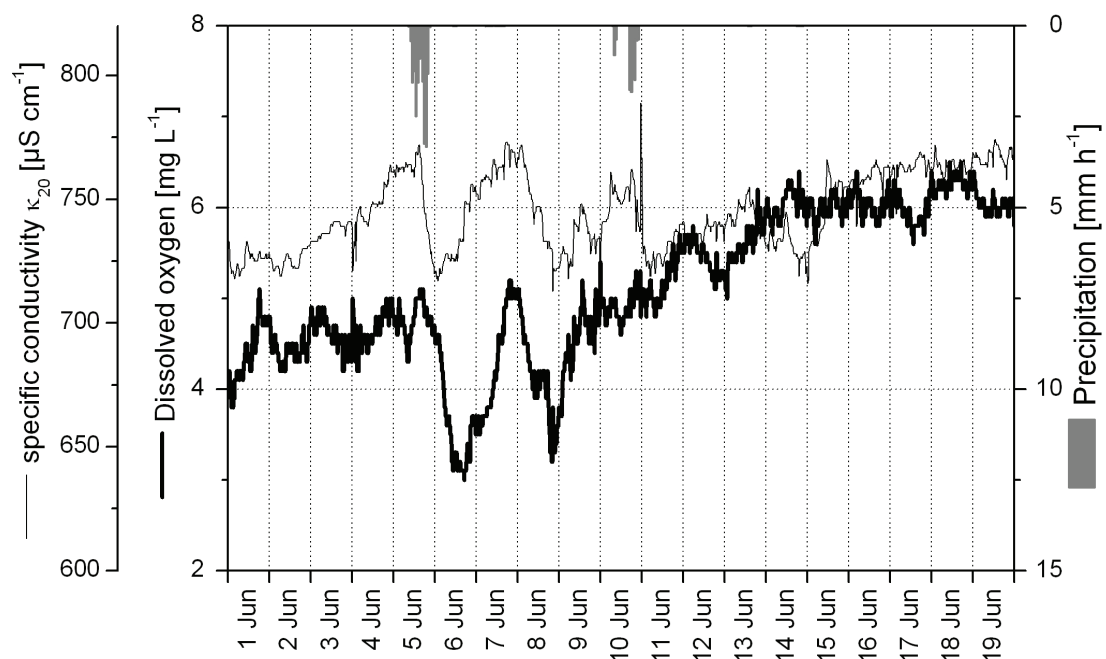


Figure 2: Dissolved oxygen and specific conductivity at monitoring station 2 following a rain event with a total height of 18 mm on June 5th 2005.

3 MATERIAL AND METHODS

3.1 River monitoring data

Eight years (2000-2007) of river monitoring data were collected at monitoring station 2 and seven years at monitoring station 1 (DO sensor was out of service in 2002) by the Senate of Berlin (see map in Figure 1). At both stations quasi continuous measurements of water temperature (T), DO and κ_{20} were performed via online sensors (WTW TechnoLine sensors) on a bypass and stored at a 15 min-interval. Online sensors were calibrated at a weekly interval.

3.2 Application of CSO guidelines to river monitoring data

Two national stormwater guidelines, one from the UK (FWR 1998) and one from Germany (Borchardt et al. 2007), as well as one scientific approach (Lammersen 1997) were used for the identification of critical DO conditions in the river. The three approaches define maximum allowable DO thresholds, depending on exposure time and frequency of occurrence. A detailed description of the three approaches is given by Schindler et al. (2008).

The question whether DO situation is critical in the River Spree was answered in three steps:

1. Data falling below any DO thresholds were identified for the two monitoring stations and grouped into DO depression events. If two events followed each other with a gap of less than six hours they were considered as one combined event, following the recommendations of FWR (1998).
2. In a second step, events that exceeded tolerable exposure time were identified. For combined events (see above), exposure time was calculated excluding short interim periods with DO above thresholds.
3. Finally, critical events were counted for each exposure-threshold combination to evaluate frequency over the years of observation.

For the further analysis of single events, only the approach by Lammersen (1997) was used, since it defines only one occurrence frequency and has a more scientific basis than the two guidelines.

3.3 Identification of CSO-triggered critical oxygen conditions in the river

In an urban river, it is important to evaluate whether critical DO depressions are actually the result of CSO. For each critical DO depression the following questions were answered:

1. Has a rain event exceeding the critical height of 4.7 mm occurred within three days before the observed DO depression?
2. Is there a drop in specific conductivity during (or shortly before) the DO depression?
3. Is there a drop in water temperature during (or shortly before) the DO depression?

If point (1) and at least one of points (2) or (3) were answered positively the DO depression was assumed to be likely the result of CSO.

3.4 Influence of background pollution of the river

It is expected that background pollution and hydrological factors influence the severity of CSO impacts in a receiving river. To judge the importance of background effects, averages of the river parameters T, DO and river flow, as well as standard deviation of DO were calculated for 48 hours before each critical DO depression, and compared to monthly averages of the four parameters over the seven/eight years of observation. Based on a two-sample t-test it was judged if the value of a parameter before critical DO depressions (sample 1) differs significantly from monthly averages (sample 2) and consequently influences the severity of the CSO impacts.

In a first step, F-test was used to decide whether samples 1 and 2 have the same variance. Depending on the results, two-sample t-test was applied either for equal or unequal variance. Results

of the t-test were judged based on p value, i.e. the probability that the two samples are equal. If $p < 0.05$ we assumed that sample 1 and 2 are significantly different.

4 RESULTS AND DISCUSSION

4.1 Application of CSO guidelines to river monitoring data

Application of the three stormwater assessment methods revealed that the River Spree is in a critical, non-tolerable state regarding DO at both monitoring stations. DO measurements at monitoring station 1 violate criteria in two of nine frequency-exposure classes of the UK guideline, three of nine classes of the German guideline and six of eight exposure classes of the Lammersen approach. Similarly, DO concentrations at monitoring station 2 were critical for two of nine frequency-exposure classes in both of the national guidelines and for all the eight classes by Lammersen. Figure 3 shows frequency of critical situations for the different exposure time classes by Lammersen at the two monitoring stations. Critical events of long duration with DO between 3 and 5 mg L⁻¹ occurred more frequently at monitoring station 1 (upstream of the combined sewer area), whereas DO concentrations below 1.5 mg L⁻¹ were only recorded at monitoring station 2 (downstream).

Since number of violations of the Lammersen approach were individually counted for each class (Figure 3), one DO depression can appear in several classes. For instance, if DO drops below 1.5 mg L⁻¹ for 4 hours, it violates criteria of four classes in Figure 3 (from “< 1.5 mg L⁻¹; > 10 min” to “< 3.0 mg L⁻¹; > 120 min”). Thus, the results from the different classes were filtered to count each event only once (in the example the event would be considered as one event of 4 hours duration). In total 21 critical DO depressions were recorded at monitoring station 1 in seven years (excluding 2002) and 17 critical DO depressions at monitoring station 2 in eight years of observation. It is surprising that the river at monitoring station 2, which is heavily impacted by CSO, experiences fewer critical events than at monitoring station 1, where CSO impact is expected to be low to moderate. On the other hand, events with DO < 2 mg L⁻¹, which are expected to be particularly problematic for aquatic organisms (Wolter et al. 2003), do only occur at monitoring station 2. On one of these particularly severe events, more than 15,000 dead fish were collected in the River Spree and its side channels (Kalk 2005).

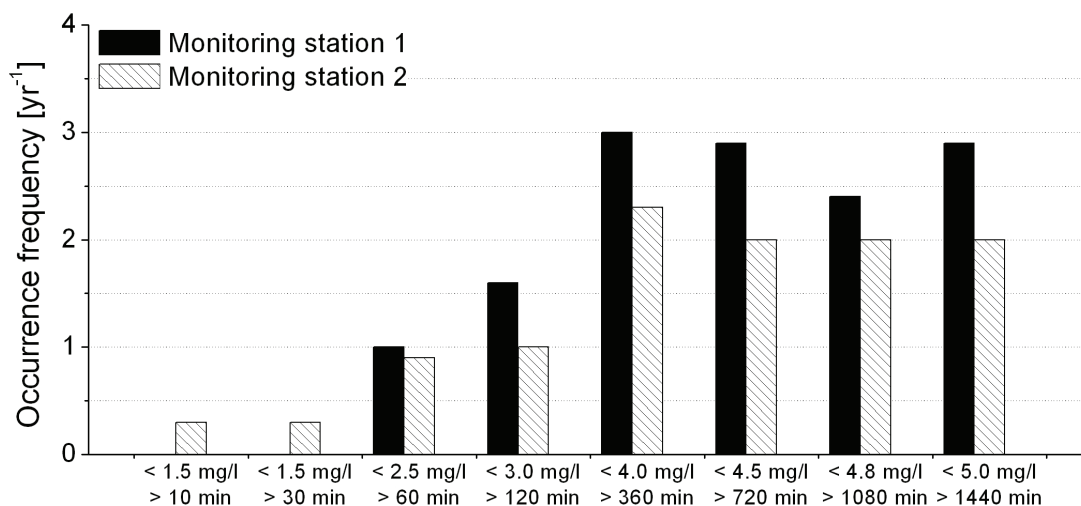


Figure 3: Occurrence of critical DO events in seven threshold-exposure classes after Lammersen (1997) for the two monitoring stations on the River Spree (Figure 1) over seven/eight years of observation.

4.2 Identification of CSO-triggered critical oxygen conditions in the river

Application of the qualitative method described under 3.3 revealed that only 6 of the 21 critical DO depressions at monitoring station 1 were the result of CSO. In contrast, only 2 of 17 critical DO depressions at monitoring station 2 could not be explained by CSO. The results are exemplarily shown for 2007, a year with a high frequency of strong rain events in summer (Figure 4). Even rain events beyond 20 mm did not lead to problematic situations in the River Spree at monitoring station 1

(Figure 4a). As expected, the situation is different for monitoring station 2, where all the critical DO depressions in 2007 were the result of strong rain events (Figure 4b). However, even at monitoring station 2, not all strong rain events lead to critical conditions in the river. Considering the entire observed eight-year period, ~50 % of rain events > 20 mm and five out of six rain events > 40 mm resulted in critical DO depressions at monitoring station 2.

4.3 Influence of background pollution of the river

The situation in the river has a clear effect on DO depressions from a seasonal perspective. Critical DO depressions were only detected between May and September, when temperature is high, which leads to faster degradation of organic matter and lower oxygen transfer from atmosphere, because of T-dependency of DO saturation (Weiss 1970). However, results in 4.2 showed that even in summer, impacts of CSO on the river vary. The question is what makes one CSO critical for the river, while another one has only minor effects.

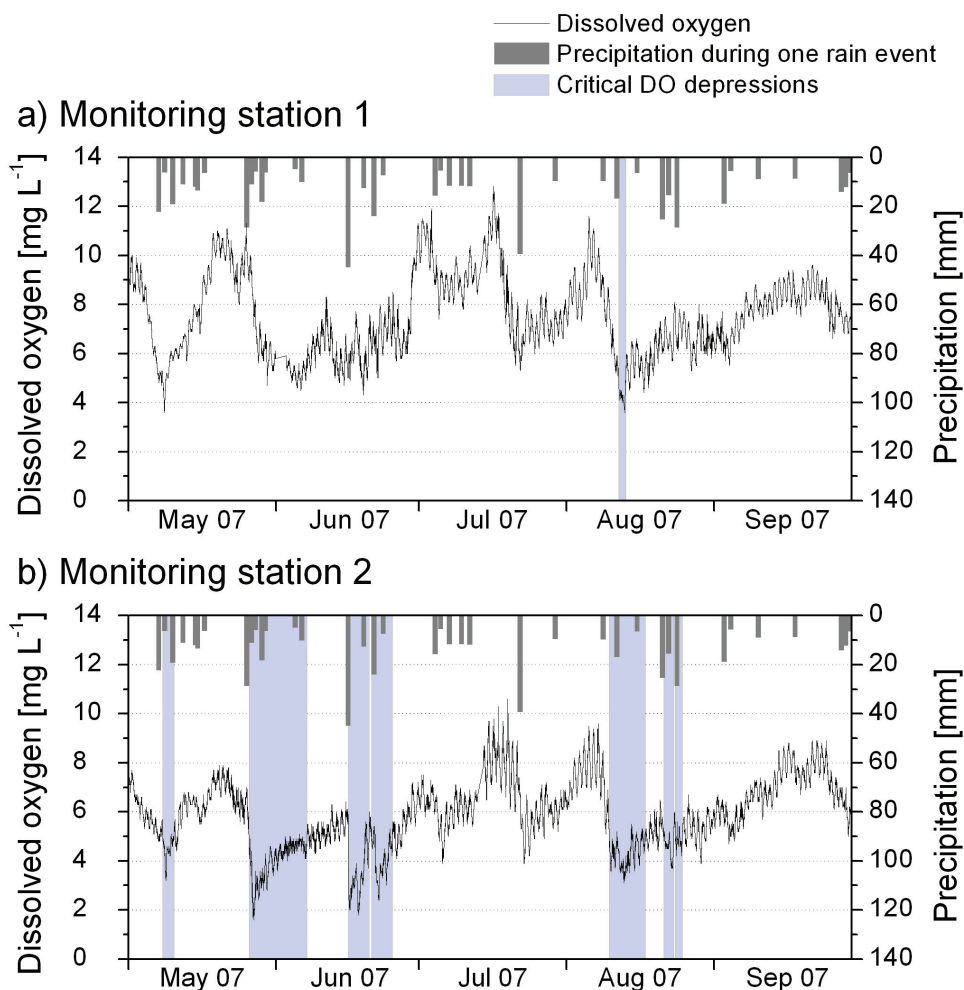


Figure 4: Dissolved oxygen, precipitation events > 4.7 mm and identified critical DO situations in the River Spree in summer 2007 at (a) monitoring station 1 and (b) monitoring station 2.

Beside variable composition of CSO, e.g. due to varying surface washoff load, a straight-forward explanation would be that the extent of DO depression after CSO depends on the conditions in the river directly before the rain event.

The hypothesis was tested for both monitoring stations as described in section 3.4. It was shown that flow in the river has no significant influence on critical DO depressions for either monitoring station ($p = 0.27$ to 0.78). Similarly, the DO standard deviation, a measure for day-night DO amplitude, was found to have no effect on occurrence of critical DO situations ($p = 0.13$ to 0.82). However, T was

significantly higher ($p = 0$ to 0.04) and DO significantly lower ($p = 2 \cdot 10^{-7}$ to 0.04) before DO depressions from May to July at monitoring station 1, with few upstream CSO discharge points. Surprisingly, for monitoring station 2, which is located downstream of the entire combined sewer system, again no significant influence of background parameters (with the exception of DO in month of June) on occurrence of critical DO depressions was found. Results are exemplified in Figure 5. General seasonal DO changes were very similar at the two monitoring stations. However, DO before critical situations is mostly below median at monitoring station 1, whereas DO is more equally distributed around median at monitoring station 2.

The results confirm the dominance of background pollution (without CSO influence) for DO depressions at monitoring station 1. They underline that CSO are the cause of DO depressions at monitoring station 2, with minor effects from background pollution. Here, other factors than background river pollution seem decisive whether a CSO leads to critical DO depressions in the river or not. The most likely explanation would be variable composition of CSO.

It is surprising that DO situation does not turn critical at monitoring station 2 during time periods when background pollution leads to a problematic situation at monitoring station 1, since the two stations experience very similar hydrological, climatic and water quality conditions. The reason for the "recovery" between the two monitoring stations may be reduction and progressive degradation of algal biomass, because of changed living conditions for phytoplankton in the River Spree compared to the lakes in the East (Figure 1). Riechel (2009) found higher chlorophyll a and BOD values at monitoring station 1, compared to monitoring station 2, which supports the hypothesis. An alternative explanation could be increase in DO at a weir, which is located ~ 5.5 km upstream of monitoring station 2. However, further research is needed to clarify the reason for the recovery.

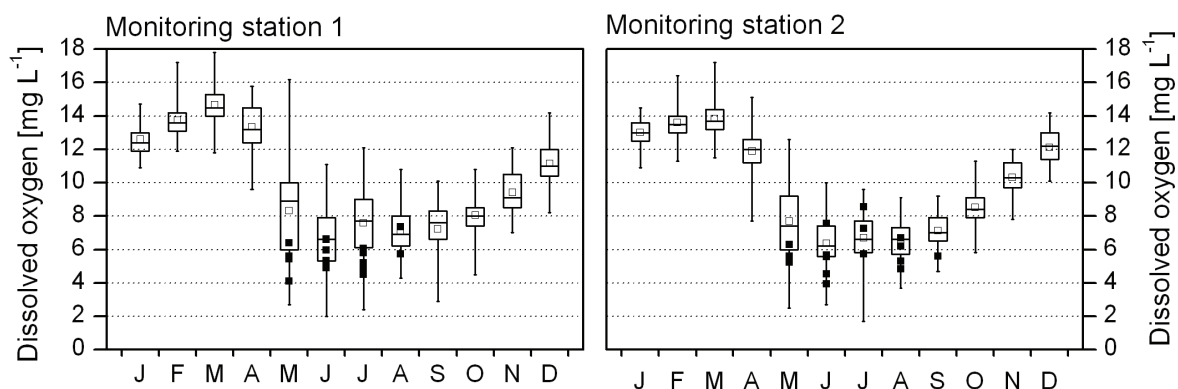


Figure 5: Range of average daily dissolved oxygen concentrations (box plots) compared to 48 h averages before critical dissolved oxygen depressions (filled black squares). Box plots show average (empty squares), median (line in box), 75 and 25 % quantiles (box) and minima/maxima (whiskers).

5 CONCLUSIONS

The analysis shows that stormwater guidelines, typically developed for small rivers with one or only few CSO discharge points, can be applied to more complex systems with large rivers and many CSO discharge points. However, additional complexity needs to be accounted for in the analysis:

- Depending on distribution of CSO discharge points, location and timing of rain event and flow speed of the receiving river, CSO impacts may (i) occur in several impact zones and (ii) can arrive at a monitoring station with a significant time lag after the rain event.
- Urban rivers may already be under significant pressure, independent of CSO.

As a result, the main challenge is (a) the identification, which critical conditions are actually the result of CSO and (b) the assessment of the role of background pollution. In the case of the River Spree (a) and (b) were exemplified for critical DO conditions. It was found that specific conductivity and water temperature often show a negative peak as a result of CSO. Thus, the two parameters were used in addition to the rain record to identify CSO-triggered DO depressions. The impact of background pollution was assessed successfully by comparing T and DO before critical DO depressions with average seasonal values of the two parameters.

Results showed that background pollution (not connected to rain storms) is responsible for critical DO depressions upstream of the main area of combined sewer system, whereas CSO are the reason for critical DO depressions at the end of the impacted river stretch. This signifies that DO in the River Spree recovers on the way through the area of combined sewer system in the absence of CSO. Surprisingly, two monitoring stations before and after the CSO impacted river stretch showed a similar number of critical DO depressions over the seven/eight years of observation. However, the most critical events with $\text{DO} < 2 \text{ mg L}^{-1}$, which are likely to lead to a significant wipe out of aquatic organisms, exclusively occur as a result of CSO. In terms of management measures, both reduction of CSO and improvement of background river condition are suggested.

ACKNOWLEDGEMENTS

This work was only possible thanks to the data on the River Spree, which was supplied by the Berlin Senate Department of Health, Environment and Consumer Protection and rain data supplied by Berliner Wasserbetriebe. The presented work was carried out in the frame of the KWB research project MIA-CSO, which is funded by Veolia Water and Berliner Wasserbetriebe.

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