Deliverable 1.3.2

Demonstration of a planning instrument for integrated and impact based CSO control under climate change conditions in Berlin

SEVENTH FRAMEWORK PROGRAMME

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Demonstration of a planning instrument for integrated and impact based CSO control under climate change conditions in Berlin

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Summary (English)

Combined sewer overflows (CSO) after heavy rainfall can cause acute depletions of dissolved oxygen (DO) in the Berlin River Spree. Further aggravation of ecological deficits can be expected from global climate change. A planning instrument for CSO impact assessment under different sewer management and climate conditions has been developed at Kompetenzzentrum Wasser Berlin. It couples the sewer model InfoWorks CS, the river water quality model Hydrax/QSim and an impact assessment tool.

The planning instrument was validated for the years 2010 and 2011. Simulation results for the critical parameters discharge and DO concentrations in the Berlin River Spree agree well with measurements. Although not all observed DO deficits can be simulated accurately, the very good representation of processes related to the oxygen budget allows assessing relative changes in boundary conditions, e.g. from climate change or different CSO control strategies.

The conducted scenario analysis indicates that the coupled sewer-river-model reacts sensitively to changes in boundary conditions (temperature, rainfall, storage volume and other CSO control strategies, etc.). Based on the simulation year 2007 – representing an extreme year with regards to CSO volume and critical conditions in the river – sewer rehabilitation measures planned to be implemented until 2020 are predicted to reduce total CSO volumes by 17% and discharged pollutant loads by 21 - 31%. The frequency of critical DO conditions for the most sensitive local fish species will decrease by one third.

For a further improvement of water quality after the year 2020, the reduction of impervious surfaces emerges as a very effective management strategy where feasible. A reduction of the impervious connected area by 20% results in a decrease in the frequency of critical DO conditions by another third.

The studied increase in surface air and water temperature as part of the climate change scenarios leads to a significant aggravation of DO stress due to background pollution in the Berlin River Spree, while acute DO depletions after CSO are barely affected. However, changes in rain intensity have a considerable effect on CSO volumes, pollutant loads and the frequency of critical DO concentrations.

A general reduction of discharged pollutant loads by 60% based on the sewer status 2020 can prevent critical DO conditions in the Berlin River Spree, even for the exceptionally rain intense year 2007.

A detailed analysis of river processes after CSO, has shown that the biodegradation of organic carbon compounds is the most important contributor to acute DO depletions in the Berlin River Spree. An additional impairment of DO conditions is caused by the inflow of oxygen free CSO spill water and suspended solids into the Berlin River Spree.

In this report, CSO impacts under different management strategies or climate change conditions are assessed only for a part of the Berlin combined sewer

system (although the main part) and for one exemplary year. An extension of the planning instrument to the entire combined sewer system would enable to evaluate the full impact of measures. For a robust prediction of future CSO impacts it is also recommended to test different simulation periods or conduct long-term simulations.

Summary (German)

Nach Starkregen auftretende Mischwasserüberläufe können in der Berliner Stadtspree zu akuten Abfällen der Sauerstoffkonzentration führen, die sich durch mögliche Klimaveränderungen noch verstärken können. Um die Auswirkung von Mischwasserüberläufen bewerten zu können, wurde am Kompetenzzentrum Wasser Berlin ein Planungsinstrument entwickelt. Es basiert auf der Kopplung des Kanalnetzmodells InfoWorks CS, des Gewässergütemodells Hydrax/QSim und eines Immissionsbewertungsansatzes und wurde für verschiedene Mischwasserbewirtschaftungs- und Klimaszenarien getestet.

Das Planungsinstrument wurde für die Jahre 2010 und 2011 validiert, wobei insbesondere für die zentralen Bewertungsgrößen Durchfluss und Sauerstoffkonzentration in der Stadtspree eine gute bis sehr gute Übereinstimmung mit Messwerten festgestellt wurde. Zwar können nicht alle beobachteten Sauerstoffabfälle exakt abgebildet werden, dennoch erlaubt die sehr gute Prozessabbildung des Sauerstoffhaushalts eine Beurteilung relativer Veränderungen, zum Beispiel durch unterschiedliche Bewirtschaftungsmaßnahmen.

Die durchgeführte Szenarienanalyse zeigt, dass die Modelle sensitiv auf verschiedene Randbedingungen (Temperatur, Regenintensität, vorhandenes Stauraumvolumen, usw.) reagieren. Die bis 2020 geplanten Maßnahmen zur Stauraumerweiterung bewirken für das Testjahr 2007 – welches bezüglich Entlastungsvolumen und Auftreten fischkritischer Zustände ein Extremjahr darstellt – eine Reduzierung des Überlaufvolumens um 17%, eine Frachtreduzierung um 21 - 31% sowie eine deutliche Reduzierung der Häufigkeit kritischer Sauerstoffbedingungen hinsichtlich der empfindlichsten Fischart um ein Drittel.

Über den Sanierungszustand 2020 hinaus stellt sich die Entsiegelung befestigter Flächen als wirksame Maßnahme zur weitergehenden Mischwasserbewirtschaftung heraus. Durch eine Reduzierung der befestigten angeschlossenen Fläche um 20% kann die Häufigkeit fischkritischer Sauerstoffbedingungen um ein weiteres Drittel reduziert werden.

Die im Rahmen der Klimaszenarien untersuchte Erhöhung der Luft- und Wassertemperatur führt zu einer deutlichen Erhöhung der Hintergrundbelastung in der Stadtspree, während der akute Sauerstoffabfall nach Mischwassereinleitung kaum dadurch beeinflusst wird. Eine Änderung der Regenintensität wirkt sich neben den Überlaufvolumina und -frachten hingegen deutlich auf die Häufigkeit fischkritischer Sauerstoffbedingungen aus.

Eine erweiterte Sensitivitätsanalyse führt zu dem Schluss, dass durch eine allgemeine Reduktion der Überlauffrachten um 60% - ausgehend vom Sanierungszustand 2020 - selbst für das regenintensive Jahr 2007 kritische Sauerstoffbedingungen in der Stadtspree vermieden werden können. Des Weiteren konnte gezeigt werden, dass der Eintrag bzw. Abbau organischer Kohlenstoffverbindungen hauptverantwortlich für das Auftreten

fischkritischer Sauerstoffkonzentrationen nach Mischwasserüberläufen ist. Dennoch können auch die Einmischung von sauerstofffreiem Mischwasser und der Eintrag von Feststoffen zu einer Beeinträchtigung des Sauerstoffhaushalts im Gewässer beitragen.

Im Rahmen dieser Arbeit konnte der Effekt unterschiedlicher Bewirtschaftungsmaßnahmen und Klimaveränderungen nur für ein Teilgebiet des Berliner Mischwassersystems und ein Beispieljahr untersucht werden. Um das vorgestellte Modellwerkzeug für die Planung konkreter Maßnahmen einsetzen zu können, sollte eine Erweiterung des Modellgebietes in Erwägung gezogen und verschiedene Simulationszeiträume getestet werden.

Acknowledgements

The KWB part of the EU-FP7 project PREPARED was co-funded by Veolia Water and Berliner Wasserbetriebe. We would also like to thank Veolia Water, Berliner Wasserbetriebe and the Berlin Senate Department for Urban Development and the Environment for funding and supporting the development of the impact-based planning instrument for CSO control within the KWB project MIA-CSO.

Contents

1 Introduction

Combined sewer systems (CSS), such as in the city centre of Berlin, can be a significant source of pollution for urban surface waters. One of the main impairments for the Berlin River Spree is the depletion of dissolved oxygen (DO), mainly due to the degradation of organic pollutants entering the water body after intense rainfalls. According to nine years of continuous monitoring, critical DO conditions for fish are observed on up to 59 days per year at a river stretch highly impacted by combined sewer overflows (CSO).

Further aggravation of ecological deficits can be expected from global climate change (changes in rainfall intensity, temperature increase) which may not only lead to more frequent CSO events but also increase the vulnerability of the ecosystem. To reduce negative impacts and meet environmental objectives derived from the European Water Framework Directive (EC, 2000), extensive sewer rehabilitation measures will be implemented until the year 2020.

To support decision makers in planning further CSO control measures and assessing the impact of climate change, a planning instrument has been developed in the framework of the research project MIA-CSO, following the methodology described in PREPARED D 5.4.2 (Matzinger et al., 2012). The planning instrument consists of:

1. The sewer model InfoWorks CS (WSL, 2004),
2. The river water quality model Hydrax/QSim (Kirchesch and Schöl, 1999) and
3. An impact assessment tool.

Figure 1 shows the schematic structure of the planning instrument.

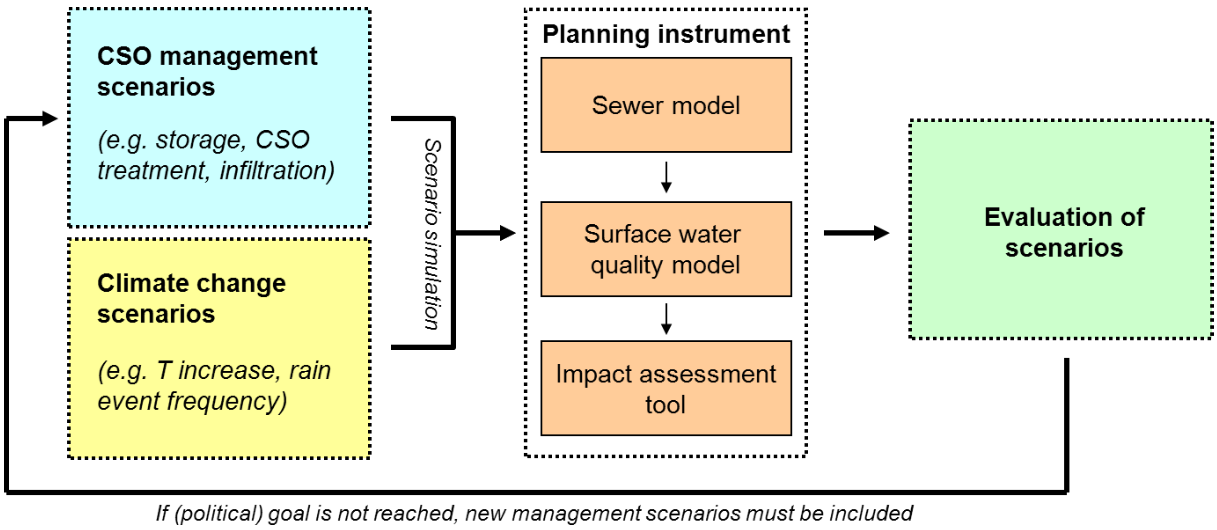

Figure 1: Schematic structure of the planning instrument and its application. External boundary conditions (such as global warming or changed water use) are yellow, CSO management scenarios are blue, the planning instrument is orange and the actual output of the instrument is green (adapted from Matzinger et al., 2012).

CSO management and climate change scenarios first have to be translated into model boundary conditions. Then, the sewer model InfoWorks CS is run to calculate discharges and pollutant loads of the 67 CSO outlets located in the modelled area. The sewer model results are used as boundary conditions for the river water quality model Hydrax/QSim, which simulates the nutrient and oxygen budget of the Berlin River Spree. Lastly, results of the coupled sewer-river-model are analysed with the impact assessment tool quantifying environmental impacts on the water body. Costs of management scenarios are not considered.

Aim of this work is the demonstration of the developed planning instrument for different CSO management and climate change scenarios. Specifically the following questions will be answered:

- Does the planning instrument sufficiently reproduce reality to be used for scenario analysis?
- Is the tool sensitive on CSO control strategies or climate change scenarios?
- What is the expected effect of mitigation measures or climate change effects on CSO emissions and river impacts?
- Which processes lead to critical DO concentrations for fish after CSO?

The report is organised in the following structure: After introducing the demonstration site (chapter 2) and the used model tools (chapter 3), methodological aspects and results of model validation are presented in chapter 4. The first subchapter of chapter 5 contains a detailed description of the studied scenarios (subchapter 5.1). Results of the scenario analysis can be found in the following subchapters 5.2 (planned sewer rehabilitation measures), 5.3 (possible management strategies after sewer rehabilitation) and 5.4 (future climate change effects), followed by a comparative summary in subchapter 5.5. The scenario analysis is complemented with an extended sensitivity analysis on selected CSO boundary conditions (chapter 6). Conclusions drawn from the presented results can be found in chapter 7. Tables and graphs which are not part of the main text can be found in the appendix in chapter 8. The report closes with a list of references in chapter 9.

2 Demonstration site

The following chapter contains a brief characterisation of the Berlin combined sewer system (subchapter 2.1) and its receiving water body, the Berlin River Spree (subchapter 2.2).

2.1 The combined sewer system of Berlin

From 1873 to 1909 the combined sewer system (CSS) of Berlin was built according to plans of James Hobrecht. He designed 12 independent gravity sewer systems with storm water outlets into the River Spree and its side channels. From the lowest point of each drainage area, water was pumped out of the city where it was spread for subsoil infiltration. Over the years this system was expanded and adjusted to the needs of a growing city (Bärthel, 2003).

Today, there are 18 subcatchments (total area: 102.5 km², impervious connected area: 66 km²) of the CSS with a sewer network of about 2,000 km length (Figure 2). Waste water of 1.2 million inhabitants connected to the CSS and storm water are collected and transported to waste water treatment plants (WWTP, Pawlowsky-Reusing and Schroeder, 2006).

Figure 2: Map of the combined sewer system of Berlin with its subcatchments and CSO outlets (red circles) into the Berlin River Spree and its side channels

About 6.5 million m³ per year are flowing into the Berlin urban water system during CSO events (pers. comm. Pawlowsky-Reusing, 2013). Table 1 shows that of all anthropogenic effluents to the urban water system, CSO have a portion of only 2% of CSO volume but between 9% and 23% regarding discharged pollutant loads for TSS, BOD_5, COD, NH_4-N and TP.

Table 1: Discharged volumes and pollutant loads for waste water treatment plants (WWTP), untreated rain water effluents from separate sewer system (SSS_{rain}) and untreated combined sewer overflows (CSO) into Berlin surface waters. References for annual volume and pollutant loads are indicated with letters a-e. Note that indicated pollutant loads for SSS_{rain} are partly eliminated by surface water processing plants Tegel and Beelitzhof.

	Volume		TSS		BOD_5		COD		NH_4-N		TP	
	Abs.	Rel.	Abs.	Rel.	Abs.	Rel.	Abs.	Rel.	Abs.	Rel.	Abs.	Rel.
	[10^6 m³]	[%]	[t]	[%]	[t]	[%]	[t]	[%]	[t]	[%]	[t]	[%]
WWTP	239.4[a]	82	1,224[a]	12	835[a]	31	9,873[a]	61	170[a]	64	88[a]	68
SSS_{rain}	48.2[b]	16	7,712[c]	79	1,229[d]	46	4,820[c]	30	67[c]	26	29[c]	22
CSO	6.5[e]	2	893[e]	9	603[e]	23	1,494[e]	9	26[e]	10	13[e]	10
Total	294.1	100	9,829	100	2,667	100	16,187	100	263	100	130	100

[a] mean annual volume and loads measured between 2007 and 2012 under consideration of post-treatment at surface water processing plant Tegel, unpublished data by BWB (pers. comm. Pawlowsky-Reusing, 2013)
[b] mean annual volume simulated with ABIMO for years 1961 to 1990 (SenStadtUm, 2012)
[c] mean annual loads calculated from [b] and mean concentrations measured between 2003 and 2008 (BWB, 2010)
[d] mean annual loads calculated from [b] and mean concentrations measured in 1989 and 1990 (Heinzmann, 1994)
[e] mean annual volume and loads simulated with InfoWorks CS (WSL 2004) for the the sewer status 2009 based on the rainfall time series of the years 1964 to 1983, unpublished data by BWB (pers. comm. Pawlowsky-Reusing, 2013)

To reduce CSO impacts and to achieve the good ecological potential and chemical status of the Berlin River Spree according to the Water Framework Dircetive, WFD (EC, 2000), a program to increase the storage capacity of the sewer system has been initiated in 2001. In the year 2010 – which was defined as the status quo for the presented work - the combined sewer system already disposed of a storage volume of 210,060 m³ which will be further extended to 307,060 m³ in 2020 (pers. comm. Pawlowsky-Reusing, 2012). The average specific storage volume is going to increase from 3,200 m³ to 4,600 m³ per km² connected impervious area in the mentioned ten-year time-period. Because of low slopes and historically large sewers, the Berlin CSS itself provides a fixed storage volume of 109,100 m³, which is already included in the mentioned data. Table 2 lists the storage volume for each subcatchment installed in 2010 and planned for the year 2020.

Table 2: Storage volume of the Berlin combined sewer system installed in 2010 and planned for 2020 (pers. comm. Erika Pawlowsky-Reusing, 2012). Subcatchments that are not part of the coupled sewer-river-model system are tagged with an asterisk.

Subcatchment	Impervious connected area (status 2007) [km²]	Total storage volume [m³]		Increase from 2010 to 2020	
		Installed in 2010	Planned for 2020	Absolute [m³]	Relative [%]
Bln I	2.44	8,800	12,000	3,200	36
Bln II	4.83	17,100	23,500	6,400	37
Bln III	3.03	11,850	21,850	10,000	84
Bln IV	5.66	7,100	24,100	17,000	239
Bln V	5.07	28,950	28,950	0	0
Bln VII	2.42	14,400	14,400	0	0
...	...	...	...	...	...

Subcatchment	Impervious connected area (status 2007) [km²]	Total storage volume [m³] Installed in 2010	Planned for 2020	Increase from 2010 to 2020 Absolute [m³]	Relative [%]
...	...	...	...	...	...
Bln VIII	3.88	8,700	8,700	0	0
Bln IX	3.12	15,900	15,900	0	0
Bln X	2.90	2,600	13,340	10,740	413
Bln XI	2.75	3,500	11,550	8,050	230
Bln XII	3.36	12,150	17,050	4,900	40
Chb I	8.06	16,400	34,200	17,800	109
Chb III	1.52	15,500	15,500	0	0
Nkn I*	3.94	8,700	16,150	7,450	86
Nkn II*	1.17	900	2,260	1,360	151
Ruh*	0.31	1,260	1,260	0	0
Sp I*	1.70	7,300	7,300	0	0
Wil	9.96	28,950	39,050	10,100	35
Total	66.12	210,060	307,060	97,000	46

2.2 The Berlin River Spree

From the Lusatian Highlands (Lausitzer Bergland) the River Spree flows for a length of about 382 km through Saxony, Brandenburg and the city of Berlin and joins the River Havel in Berlin-Spandau. In turn the Havel is a tributary of the River Elbe which flows into the North Sea. The catchment area of the Spree is about 10,105 km² and lies mostly in the northern German lowlands.

The Berlin section of the River Spree can be characterized as a regulated lowland river with an average slope of 0.009% (Driescher, 2002). According to data provided by the Senate Department for Urban Development and the Environment (SenStadtUm), the mean annual discharge is 29.9 m³/s (time-period 2000 to 2011 at Sophienwerder), with lowest monthly averages observed in June (11.7 m³/s).

The Berlin River Spree shows an approximate box profile with vertical banks made of sheet pile or brickwork walls on its watersides. The river bed lies at a depth of up to 3 m and is composed of fine-grained sand and fine particulate organic matter containing shells of the mussel *Dreissena polymorpha* (Leszinski, 2007).

The heavily modified Berlin River Spree is influenced by a system of hydraulic in- and outflows from the artificial water bodies Kupfergraben, Landwehrkanal (LWK), Berlin-Spandauer Schifffahrtskanal (BSSK), Charlottenburger Verbindungskanal (CVK), Westhafenkanal (WHK) and the River Panke. Moreover, the Berlin River Spree is influenced by approximately 180 CSO outlets located along the side channels and 16 kilometres of the Spree (Leszinski and Schumacher, 2009).

Between 1992 and 2001, Wolter et al. (2003) studied the local fish life of Berlin River Spree and the side channels. Most common species are fish of the family *Cyprinidae* which are relatively tolerant to oxygen deficits. The roach (*Rutilus rutilus*) and the European perch (*Perca fluviatilis*) are the dominant species representing more than 70% of the local fish abundance.

Local fish fauna is limited to relatively tolerant species since the Berlin rivers and channels are highly influenced by anthropogenic changes, such as artificial banks (sheet pile walls) and shipping traffic as well as flow regulation (lack of longitudinal connectivity). Natural reproduction in the Berlin section of the River Spree is limited to few locations in the upper section (close to Müggelsee) (Leszinski and Schumacher, 2009).

Table 3 lists the indigenous fish species that are most sensitive towards low concentrations of DO, the most critical water quality parameter related to combined sewer overflows in Berlin. The presented minimum oxygen demand is the DO concentration where 50% of the organisms died in experiments or observations (LC_{50}). According to Leszinski et al. (2007), an exposure of the DO minimum for 30 minutes or longer can cause death to the organism. The most sensitive indigenous fish is the asp (*Aspius aspius*), not tolerating DO concentrations below 2 mg/L.

Table 3: Most sensitive fish regarding low concentrations of dissolved oxygen observed in the Berlin water streams between 1992 and 2001 (adapted from Wolter et al., 2003).

Organism		Family	Oxygen demand in mg/L at T=20°C	
			Minimum	Normal
Asp	*Aspius aspius*	*Cyprinidae*	2.0	7.0 – 8.0
Gudgeon	*Gobio gobio*	*Cyprinidae*	1.6 – 2.0	7.0 – 8.0
Burbot	*Lota lota*	*Gapidae*	1.4 – 2.0	7.0 – 9.0
Common dace	*Leuciscus leuciscus*	*Cyprinidae*	1.6	7.0 – 8.0

3 Model setup

In the following chapter the different components of the planning instrument for CSO control will be presented, beginning with the sewer model InfoWorks CS (subschapter 3.1), continuing with the river water quality model Hydrax/Qsim (subchapter 3.2) and closing with the tool for CSO impact assessment (subchapter 3.3).

3.1 The sewer model InfoWorks CS

The urban drainage and storm water model InfoWorks CS (collection system) (WSL, 2004) was developed by Wallingford Software Limited and is currently distributed by Innovyze.

It is used to calculate discharge and pollutant loads of the combined sewer system (CSS) following rainfall events. By using a hydrodynamic model based on the equations of Saint-Venant, backwater effects and reverse flows, often occurring in complex CSS, can be simulated. Initial losses of storm water runoff due to wetting of the surfaces, infiltration, evapotranspiration, etc. are also taken into account.

InfoWorks CS simulates the advective transport of the main pollutants such as TSS (total suspended solids), BOD_5 (biochemical oxygen demand in 5 days, particulate and dissolved), COD (chemical oxygen demand, particulate and dissolved), NH_4-N (ammonia-nitrogen, dissolved), TKN (total Kjeldahl-nitrogen, particulate and dissolved), P_{dis} (dissolved phosphorus) and TP (total phosphorus, particulate and dissolved). Transformation and dispersion processes are neglected (WSL, 2004).

InfoWorks CS takes into account three pathways of pollutants potentially entering the water bodies via combined sewer outlets:

1. Waste water from domestic and trade/industrial sources,
2. Dissolved and particulate pollutants from surface runoff and
3. Resuspension of sediments in sewers.

(1) Dry-weather inflow and pollutants from domestic and trade waste water are defined via hydrographs and pollutographs, which describe the daily distribution of water flow and pollutant loads per inhabitant or trade/industrial area. Each model node of the sewer network is assigned a number of inhabitants and trade/industries, which define the dry-weather flow. In the Berlin model application measured hydrographs and pollutographs were generally related to inhabitants, since no information on average waste water production of trades were available.

(2) Dissolved and particulate pollutants on the surface of the catchment, defining the water quality of storm water runoff, are simulated with two independent submodels. For particles a build-up/wash-off model is used, simulating the accumulation of solids during dry-weather and the erosion and wash-off during storm events which is assumed to be proportional to the rainfall intensity. Dissolved matter originating from the surface is simulated with a so-called gully-pot-model, i.e. a fictive completely filled reservoir, in which pollutant concentrations increase linearly until wash-off during storm events (WSL, 2004). Each model node of the sewer network is assigned an impervious connected area, which defines inflow and pollutant loads during storm water (which is then mixed with dry weather flow from (1)). Runoff from pervious surfaces is not taken into account.

(3) The simulation of erosion and deposition processes in the sewer is based on selectable models: Ackers-White (Ackers, 1991), Velikanov (Velikanov, 1954) and KUL (Bouteligier et al., 2002). Due to positive experiences in previous research projects of modelling pollutant

loads in combined sewer systems, the Velikanov-model is used for the Berlin model application. It is based on threshold concentrations, C_{min} and C_{max}, defining the state of erosion (if $C_{TSS}<C_{min}$) or deposition (if $C_{TSS}>C_{max}$) of TSS and particulate fraction of other pollutants. If particle concentrations in waste water are in the range between both threshold concentrations they are kept in suspension.

The base flow caused by sewer infiltration is also taken into account. However, pollutant concentrations associated to the base flow are assumed to be zero.

The Berlin model application of InfoWorks CS was initially set up and calibrated within the research project ISM ("Integrated Sewage Management") (Schumacher et al., 2007). It represents all subcatchments that are listed in Table 2. However, the subcatchments Nkn I, Nkn II, Ruh and Sp I are located outside the studied river stretch and hence are not considered for coupled sewer-river modelling. The 14 considered subcatchments cover 89% of the impervious connected area and 91% of the storage volume (both in 2010 and 2020, see Table 2).

For the work described in this report, model parameters which influence pollutant build-up and wash-off on surfaces have been further adapted and validated for several CSO events monitored in the subcatchment Chb I within the project MIA-CSO (Caradot et al., 2011). As a result of model adaptations, total discharged volume and pollutant loads (TSS, COD, BOD_5, NH_4-N) simulated for five CSO events in 2010 and 2011, differed from measurements by less than 10%.

Rainfall data used as model input are collected by 9 to 10 pluviographs within the CSS of Berlin at a time step of 5 minutes. The pluviographs were assigned to model nodes based on Thiessen polygons. The model is run at a 30-second time step. Flow and pollutant loads for TSS, BOD_5, COD, TKN, NH_4-N, P_{dis} and TP at all CSO outlets are exported in a 5 minute time step. For calculating initial losses of storm water runoff the depression storage model is used. It defines the initial loss storage depending on surface type and slope of a subcatchment.

All sewer simulations are conducted by the water supply and waste water utility Berliner Wasserbetriebe (BWB). Model results are provided in the form of text-files and – with the help of a data transfer tool developed at KWB – aggregated to a 15 minute time step before being used as input data for the river water quality model Hydrax/QSim.

3.2 The river water quality model Hydrax/QSim

The coupled model Hydrax/QSim (Kirchesch and Schöl, 1999) has been developed and used since 1979 at the Federal Institute of Hydrology (Bundesanstalt für Gewässerkunde) in Germany. It can simulate the water quality of simple channels, complex river networks and water bodies with variable flow directions (Kirchesch, 2004). According to Matzinger (2009), it is one of the most complex and detailed river water quality model regarding biological parameters at present.

For the simulation of discharge and water levels the hydrodynamic module Hydrax, which solves the Saint-Venant equations, is used. The simulation of substance transport and biogeochemical processes is realized with the water quality module QSim. It calculates longitudinal, advective transport and dispersion of dissolved and particulate matter including sedimentation to the river bed during low flow periods. An ecological module simulates biogeochemical processes including the oxygen and nutrient budget as well as the development of phyto- and zooplankton and processes at the river bottom (Kirchesch, 2004). In the following the entire river modelling framework including hydraulics and water quality is referred to as Hydrax/QSim. The modular structure and functionality of Hydrax/QSim is shown in Figure 3.

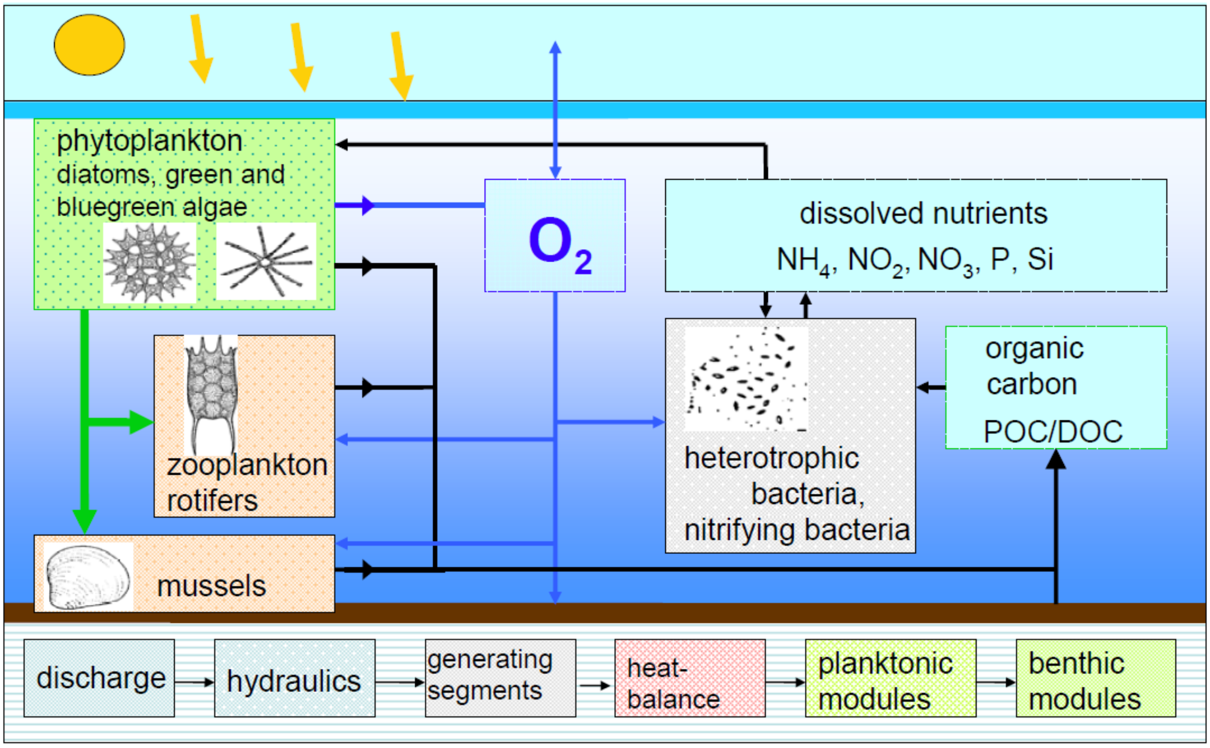

Figure 3: Modules and functionality of the river water quality model Hydrax/QSim (Kirchesch, 2004). POC=particulate organic carbon, DOC=dissolved organic carbon.

The interactions of the ecological processes shown in Figure 3 indicate that almost all biogeochemical processes in Hydrax/QSim have a direct or indirect influence on the concentration of dissolved oxygen (DO) in the studied water body. Next to the oxygen demand by degradation of organic compounds and the sediments, the oxygen concentration in the water column also depends on production and respiration by phytoplankton and macrophytes, respiration by zooplankton and benthic filter feeders and finally exchange with the atmosphere. Equation 1 adopted from Kirchesch and Schöl (1999) describes the simulation of the oxygen budget in a simplified way. However, each single process is described by a variety of differential equations.

$$\frac{dO_2}{dt} = k_{2,O} * (O_{2,S} - O_2) + k_{2,W} * (O_{2,S} - O_2) - O_{2,BOD} - O_{2,N} - \frac{O_{2,diff}}{H} + O_{2,A} + O_{2,M} - O_{2,ZOO} - O_{2,BFF} \qquad (1)$$

O_2	Oxygen concentration	[mg/L]
$k_{2,O}$	Oxygen entry rate at water surface	[1/d]
$O_{2,S}$	Oxygen saturation concentration	[mg/L]
$k_{2,W}$	Oxygen entry rate at weirs	[1/d]
$O_{2,BOD}$	Oxygen demand by degradation of BOD	[mg/(L*d)]
$O_{2,N}$	Oxygen demand by degradation of NH_4-N	[mg/(L*d)]
$O_{2,diff}$	Oxygen demand by sediments	[g/(m²*d)]
H	Average water depth	[m]
$O_{2,A}$	Oxygen change by algae	[mg/(L*d)]
$O_{2,M}$	Oxygen change by macrophytes	[mg/(L*d)]
$O_{2,ZOO}$	Oxygen demand by zooplankton	[mg/(L*d)]
$O_{2,BFF}$	Oxygen change by benthic filter feeders	[mg/(L*d)]

Covering many processes in the water column and the sediments Hydrax/QSim requires a large number of input state variables (see Table 4) and model parameters (see Table 12 and Table 13 in the Appendix) described in more detail in Schöl et al. (2002). Additionally to physical, chemical and biological conditions at the model boundaries, river geometry (cross section, spur dikes, weirs, etc.), river bed roughness and meteorological data are required. By using a one-dimensional approach, the distribution of these state variables across the river cross section is assumed to be homogeneous (turbulent flow regime).

For water quality simulation a highly CSO affected stretch of the Berlin River Spree and its side channels with a total length of 27 km was chosen. Figure 4 shows a map of the modelled water system including 11 km of the Berlin River Spree and its side channels Kupfergraben, Berlin-Spandauer Schifffahrtskanal (BSSK), Landwehrkanal (LWK), Charlottenburger Verbindungskanal (CVK) and Westhafenkanal (WHK). Moreover, the model boundaries and the measurement stations used as input data or for validation of the model are displayed.

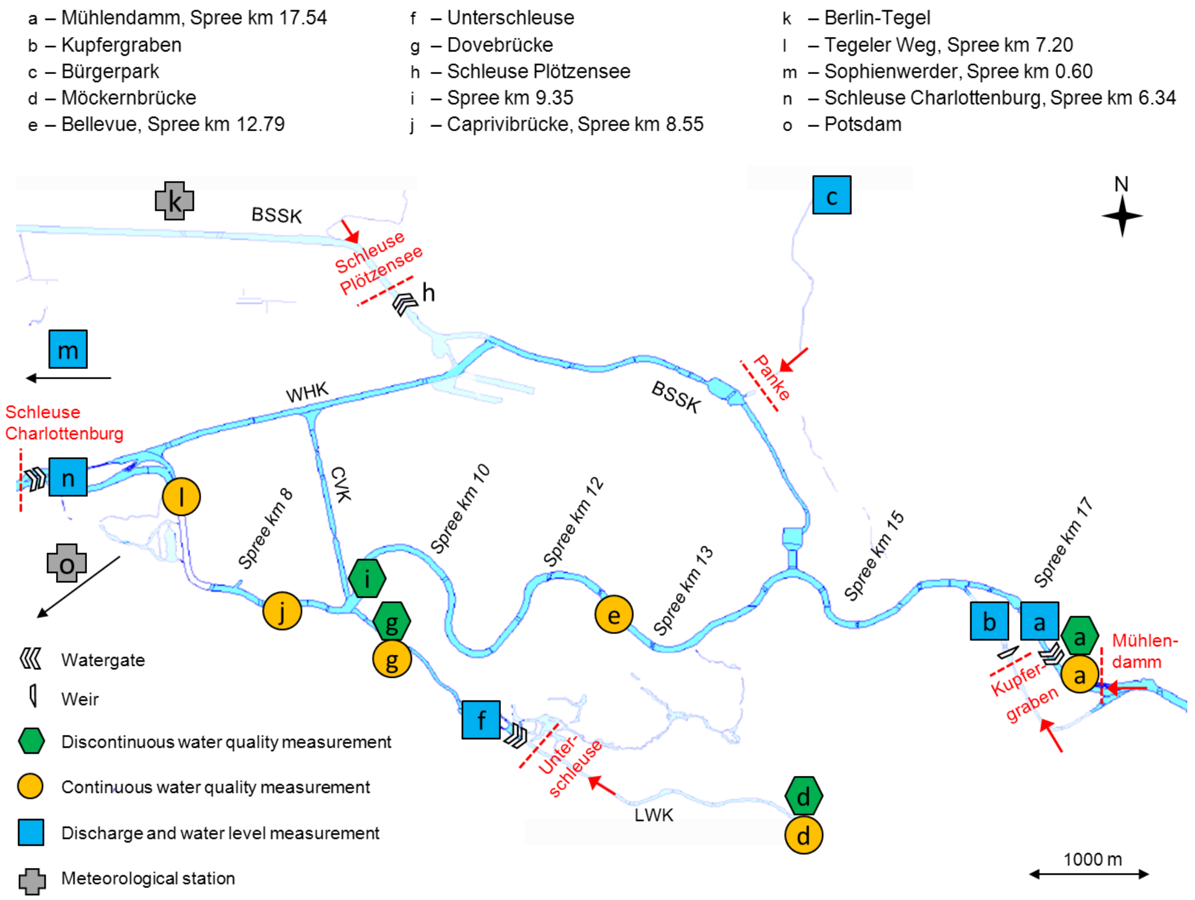

Figure 4: Map of modelled water system (blue), model boundaries (red) and measurement stations (green, yellow and blue symbols, adapted from SenStadt, 2004 and WSV, 2012). According to conventions of the Water Shipping Authority, the merging point of Havel and Spree in Berlin-Spandau is defined as Spree km 0. Abbreviations indicate BSSK: Berlin-Spandauer Schifffahrtskanal, CVK: Charlottenburger Verbindungskanal, LWK: Landwehrkanal and WHK: Westhafenkanal.

The studied water system is located between Spree km 17.54 – Schleuse Mühlendamm (a) and Spree km 6.34 – Schleuse Charlottenburg (n) with 67 CSO outlets discharging into the River Spree and its side channels. In the model system each of the 67 CSO outlets simulated with InfoWorks CS (see subchapter 3.2) is represented by an own inflow to the urban water system.

Simulations for the year 2010 show that 67% of the total CSO volume entering the studied water system is discharged via only three CSO outlets. These are located at Spree km 16.65 (29%), at BSSK 1.5 km downstream of the Spree outflow (21%) and in LWK downstream of the model boundary at Unterschleuse (17%). Another important CSO outlet is located at Spree km 10.28 contributing 4% to the CSO volume simulated for 2010.

Meteorological conditions, discharge and water quality at the upper boundary Mühlendamm (a), the main tributaries Kupfergraben (b), River Panke (c), Schleuse Plötzensee (h), Unterschleuse (f), the 67 CSO outlets and the water level at the lower model boundary Schleuse Charlottenburg (n) are the driving forces of Hydrax/QSim. Regarding model parameterisation, Hydrax/QSim was used in its default configuration as provided by BfG (see Table 12 and Table 13 in the Appendix for model parameterisation), since representation of CSO impacts was already optimised through calibration of the coupled sewer model InfoWorks CS (see subchapter 3.1).

To cover the temporal dynamics of CSO, Hydrax/QSim simulates flow conditions and water quality at a time step of 15 minutes, equal to the time step of the post-processed sewer model results serving as CSO input data. In contrast input data for hydraulics and water quality at the upper boundaries of the simulated streams are provided at a time step of 1 hour. Aggregation is realized through averaging or linear interpolation, depending if data are available at higher or lower temporal resolution, respectively. Data that are not provided by InfoWorks CS but needed as boundary condition in Hydrax/QSim are derived from literature values. Table 4 shows input data of hydraulics and water quality for Hydrax/QSim considering measurement stations and assumptions in detail.

Table 4: Hydraulic and water quality input data for Hydrax/QSim derived from measurement stations a=Mühlendamm, b=Kupfergraben, c=Bürgerpark, d=Möckernbrücke, f=Unterschleuse, g=Dovebrücke, n=Schleuse Charlottenburg and own assumptions.

Boundary	Hydraulics	Water quality
Mühlendamm, Kupfergraben	Daily averages of discharge at monitoring station (a).	<u>EC, DO, pH, T:</u> Continuous measurements at station (a), 15-minute-values aggregated to 1- hour-averages. <u>Blue-green algae, BOD_5, Chla, COD, diatoms, NH_4-N, NO_2-N, NO_3-N, TN, Si, P_{dis}, TP, TSS:</u> Monthly grab samples at station (a). <u>Assumptions:</u> Ca=89.9 mg/L, Nitrosomonas=0.008 mg/L, Nitrobacter=0.008 mg/L. For acid capacity monthly averages of the measurement period 1995-2006 at monitoring station (a) are taken. Rotifer data are derived from data on phytoplankton dynamics in the river at monitoring station (a) and (m).
Unterschleuse	Continuous measurements of discharge at monitoring station (f), 5-min-values aggregated to 1-hour-averages.	<u>EC, DO, pH, T:</u> Continuous measurements at station (g) for the validation years and (d) for the scenario analysis, 15-minute-values aggregated to 1-hour-averages. <u>COD, NH_4-N, NO_2-N, NO_3-N, TN, P_{dis} TP, TSS:</u> Monthly grab samples at station (g).

Boundary	Hydraulics	Water quality
		BOD$_5$: Monthly grab samples at station (d). Blue-green algae, Chla, diatoms, Si: Monthly grab samples at station (a). Assumptions: Ca=89.9 mg/L, Nitrosomonas=0.008 mg/L, Nitrobacter=0.008 mg/L, For acid capacity monthly averages of the measurement period 1995-2006 at monitoring station (a) are taken. Rotifer data are derived from data on phytoplankton dynamics in the river at monitoring station (a) and (m).
Panke	Continuous measurements of discharge at monitoring station (c), 5-min-values aggregated to 1-hour-averages.	Water quality of receiving river at point of inflow is assumed.
Schleuse Plötzensee	Assumed constant discharge of 0.2 m³/s.	Water quality of receiving river at point of inflow is assumed.
Schleuse Charlottenburg	Continuous measurements of water level at monitoring station (n), 15-min-values aggregated to 1 hour averages.	No water quality input data required for lower boundary.
CSO outlets	Simulated discharges at 67 CSO outlets, 5-min-values aggregated to 15-minute-averages.	BOD$_5$, COD, NH$_4$-N, TKN, P$_{dis}$, TP, TSS: Simulated for all 67 CSO outlets, 5-min-values aggregated to 15-minute-averages. Assumptions for Hydrax/QSim state variables that are not simulated by InfoWorks CS: NO$_2$-N=0.21 mg/L, NO$_3$-N=1.10 mg/L (Heinzmann, 1994), TN=TKN+NO$_2$-N+NO$_3$-N, fractions of diatoms=0.33, fractions of blue-green algae=0.33. Water temperature at point of inflow is assumed. Nitrosomonas, Nitrobacter, Si, Chla, rotifers and DO are set to zero. According to average inflow measurements of the storm water overflow tank Berlin Urbanstraße by Heinzmann (1996): pH=7.44, AC=1.39 mmol/L, Ca=36.04 mg/L, EC=293.33 µS/cm.

Daily averages of minimum and maximum surface air temperature [°C], humidity [%], wind velocity [m/s] and cloud cover [okta] are measured by the German Meteorological Service (Deutscher Wetterdienst) in Berlin-Tegel (k) which is located about 3 km to the north of the model boundary (WHK). Daily averages of global radiation [J/cm²] are taken from measurements at the meteorological observatory of the German Meteorological Service in Potsdam (o), about 25 km south-west of the studied river stretch.

3.3 CSO impact assessment

Based on the findings of Riechel (2009) and Matzinger et al. (2011) dissolved oxygen can be considered the most relevant water quality parameter for CSO impact assessment in the Berlin River Spree. In warm summer month, periods with very low DO concentrations can be observed even in the abscence of CSO, representing an additonal stress factor for fish and invertebrates. To distinguish between i) DO stress situations that can lead to any kind of impairment and that are often due to an elevated background pollution and ii) those that are potentially lethal for the most sensitive Spree fish only occuring after CSO, two different impact assessment approaches are applied as part of the planning instrument.

The Lammersen-approach (1997) allows quantifying the impact of CSO on aquatic organisms in receiving water bodies ranging from behavioural changes to death. For two different types of ecosystems, cyprinid and salmonid waters, concentration-duration-relationships for suboptimal DO concentrations are provided for a tolerable return period of 7 years. Thresholds are defined for three different temperatures (T=10, 15 and 20°C) to consider that oxygen demand of fish and invertebrates increases with higher water temperatures.

As suggested by local fish experts, the Lammersen-thresholds defined for cyprinid ecosystems, such as the Berlin River Spree, have been linearly inter- and extrapolated for any water temperature between 10 and 30°C for a more graduated assessment of DO stress situations. Throughout this report DO conditions in the River Spree are described as "suboptimal" whenever at least one of the temperature-dependent Lammersen thresholds is violated for the assigned critical duration.

Apart from the Lammersen-approach, a "critical" DO concentration of 2 mg/L is derived from the lethal concentration LC_{50} of the asp, the most sensitive indigenous fish species (see Table 3 in subchapter 2.2). If DO concentrations below 2 mg/L could be ruled out completely in the future the water quality of the River Spree would allow populations of the asp and the common barbell (*Barbus barbus*), the two key species expected in this type of lowland rivers (pers. comm. C. Wolter, 2011). Accordingly, an exposure of DO < 2 mg/L for at least 30 minutes is denominated as a critical condition. Figure 5 visualises the adapted concentration-duration-thresholds for suboptimal DO concentrations for different temperatures as well as the critical DO concentration (LC_{50}) for the asp.

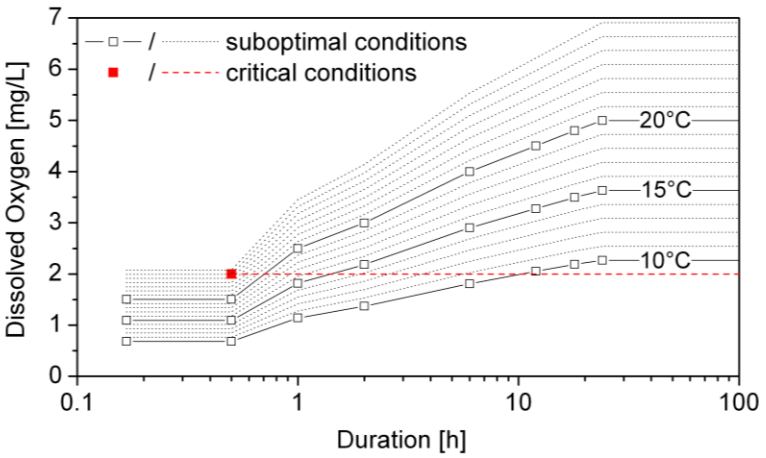

Figure 5: Applied thresholds for suboptimal and critical dissolved oxygen concentrations considering water temperature and duration. Black solid lines with eight boxes each represent thresholds provided by Lammersen for T = 10, 15 and 20°C. Black dotted lines give examples for the inter- and extrapolated thresholds for suboptimal conditions for any other temperature above 10°C. The red box represents the lethal DO concentration for the asp. It is used as the threshold for critical DO conditions in the Spree for all durations ≥ 0.5 h (red dotted line).

Assessment protocols for both suboptimal and critical DO conditions are implemented in a database application developed at KWB and can be automatically applied to simulated and measured data. CSO impacts for a given time series can be quantified regarding the number of events and/or calendar days with suboptimal or critical conditions.

4 Model Validation

Goal of the presented model application is the simulation of CSO impacts for different sewer management and climate change scenarios. However, before using models for the prediction of unknown situations in the future (scenario analysis) or in the past (due to lack of data), model results must be validated, i.e. compared to measured data. The following chapter contains an explanation of the applied methodology (subchapter 4.1) and results of model validation (subchapter 4.2).

4.1 Methodology

The coupled sewer-river-model based on InfoWorks CS and Hydrax/QSim is validated with monitoring data for the two independent simulation periods, April to November 2010 and 2011. The eight-month-summer time period April to November was chosen since it covers the entire time period in which suboptimal or critical DO conditions can be expected in the Berlin River Spree. As Riechel (2009) showed for continuous measurements of the years 2000 to 2007, suboptimal DO conditions in the Berlin River Spree are only observed during the summer months from May to September. For the purpose of model validation and scenario analysis, this time period has been extended by three month (April, October, November) in case that changes in rain intensity or atmospheric temperature lead to an prolongation of the affected time period.

For validation of the hydrodynamic module Hydrax, simulated discharge at Spree km 6.34 ("n" in Figure 4) is compared to the measured discharge at Spree km 0.60 ("m" in Figure 4, about 6 km downstream of "n"), since discharges are not measured within the simulated river stretch. It is assumed that these discharges are comparable, as there are no tributaries in between apart from the effluent from the WWTP Ruhleben of 0.2 to 0.7 m^3/s in 2011 (pers. comm. Ulf Miehe, 2012). However, the WWTP effluent or other minor sources are negligible compared to daily averages between 8.4 and 134.2 m^3/s measured by the Shipping Authority Berlin at Spree km 0.60 (monitoring station Sophienwerder).

For validation of the water quality module QSim, simulated DO, pH, water temperature (T) and electrical conductivity (EC) data are compared to continuous monitoring stations of SenStadtUm at Spree km 12.79, 8.55 and 7.20 ("e", "j" and "l" in Figure 4). Discontinuous measurements for the assessment of simulated state variables NH_4-N, NO_3-N, TN, P_{dis}, TP, TSS, Chlorophyll-a (Chla) and BOD_5 are derived from monthly samples at Spree km 9.35 ("i" in Figure 4) also provided by SenStadtUm. Within this report BOD_5 refers to the oxygen demand caused by biodegradation of organic carbon compounds and does not include oxygen demand by nitrification.

Model validation is done in different ways. First, CSO emission characteristics simulated with the sewer model, such as the number of CSO events, CSO volumes and pollutant loads, are briefly presented to give an overview on the studied time periods. CSO events are counted as single events if separated by more than 6 h and if total simulated CSO volume is greater than 1,000 m^3. For all state variables of interest model results are visually validated by plotting simulated against measured data. Since DO is the key variable for CSO impact assessment in the Berlin River Spree, DO concentrations are assessed in more detail with the help of time series plots, scatter plots and plots of residuals. In addition to visual validation, objective validation is done by calculating the goodness-of-fit indicator *NSE* (equation 2, Nash and Sutcliffe, 1970) and the error indicator *RMSE* (equation 3) where O_i and S_i are the observed and the simulated values for each time step and $\bar{O}$ is the average of all observed values.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2} \quad (2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - S_i)^2}{n}} \quad (3)$$

Lastly, model performance is evaluated with the help of the two approaches for CSO impact assessment presented in subchapter 3.3. For both simulations and measurements the occurrence of i) suboptimal DO conditions according to the Lammersen-approach (1997) and ii) critical DO conditions for the most sensitive indigenous fish, the asp (*Aspius aspius*), are quantified and compared at Spree km 12.79, 8.55 and 7.20.

4.2 Results and Discussion

4.2.1 CSO emissions for validation periods

Before the results of coupled sewer-river-modelling are validated in detail, emission characteristics simulated with the sewer model are briefly presented to give an overview on the number of CSO events, CSO volumes and pollutant loads for validation periods (Table 5). Note, that the model system consists only of parts of the Berlin combined sewer system (CSS), so that overall CSO volumes and pollutant loads in the Berlin River Spree and its side channels are higher (see subchapter 3.1).

Table 5: Simulated number of CSO events >1,000 m³, CSO volumes and pollutant loads of all 67 CSO outlets within the model system for the simulated time period April to November 2010 and 2011.

		2010	2011
Events	[-]	49	53
V	[$10^6 m^3$]	2.9	3.2
BOD_5	[t]	172.4	246.9
COD	[t]	483.5	663.3
TSS	[t]	389.0	548.4
NH_4-N	[t]	6.6	10.1
TKN	[t]	13.8	21.0
P_{dis}	[t]	1.3	1.8
TP	[t]	2.2	3.2

Most CSO events are simulated in May, August and November in 2010 and in June, July, August and September in 2011. However, major CSO events with discharged volumes >200,000 m³ only occur between July and August of both years. According to simulations, the CSO volume of July and August contribute 52% and 67%, whereas the greatest single CSO event contributes 19% and 26% to the total discharge of the simulation periods in 2010 and 2011, respectively. The results underline the importance of summer rainstorms for the total discharged volume of CSO. Figure 6 shows daily CSO volumes and rain intensities for the two simulated periods.

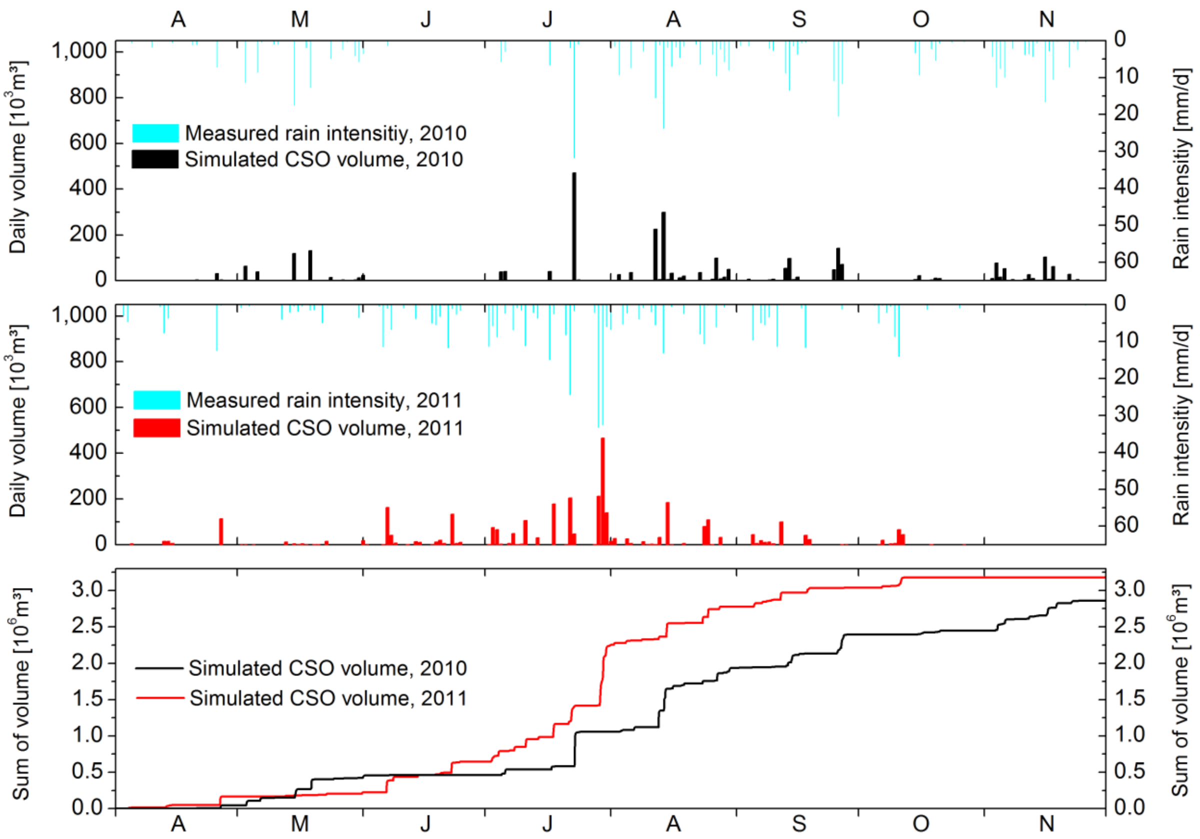

Figure 6: Temporal distribution of simulated CSO volumes and measured rain intensity for the time periods April to November of the years 2010 and 2011 (two upper panels). The lower panel shows the cumulative volume of all simulated CSO outlets for both simulation periods.

4.2.2 *Graphical and objective model validation*

<u>Hydraulics</u>

For both simulation periods discharges simulated at Spree km 6.34 are compared to measurements at Sophienwerder (Spree km 0.60). As it is shown in Figure 7, the simulation fits very well with measured data for both years yielding Nash-Sutcliff efficiencies (*NSE*) of 0.96 (2010) and 0.85 (2011) and root mean square errors (*RMSE*) of 6.1 and 7.2 m^3/s (about 20% of average flow). The comparably high *RMSE* stems from fluctuations in measurements at short temporal intervals, which are probably the result of wind, ship traffic and sluice activity (see plots of residuals in Figure 7). On the other hand, both peak flows during CSO and discharges during low flow periods can be well predicted. This is particularly remarkable since for the two upper model boundaries only daily discharge values are available as input data.

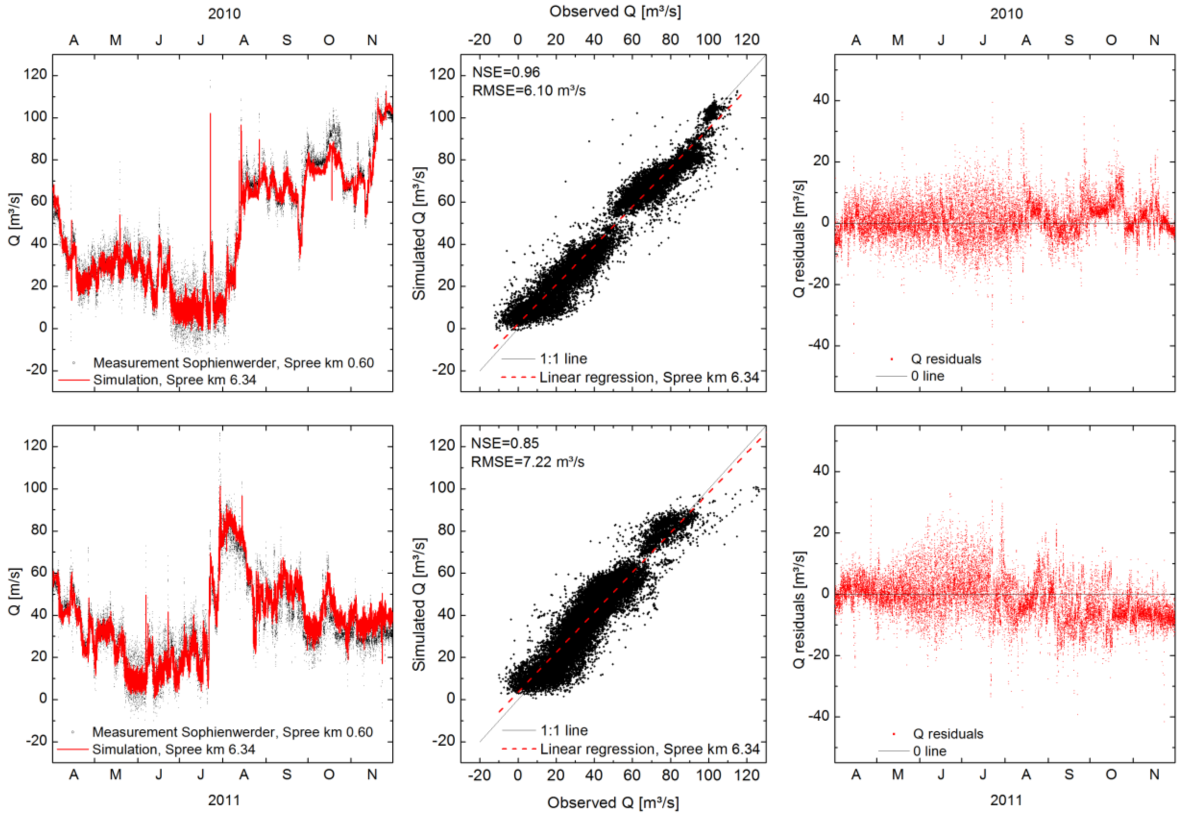

Figure 7: Time series plots, scatter plots and plots of residuals for discharge for 2010 (upper panels) and 2011 (lower panels), simulated at Spree km 6.34 and measured at Sophienwerder (Spree km 0.60).

Water quality

Overall, DO – the key parameter for CSO impact assessment in Berlin – is well represented by simulations (Figure 8 and Figure 9). In 2010 simulated DO concentrations range from 1.7 to 13.4 mg/L while observed concentrations range between 0 and 11.5 mg/L. The mean *RMSE* for all considered monitoring stations is 0.90 mg/L while *NSE* varies between 0.59 and 0.77. In 2011 simulated DO is between 0 and 12.6 mg/L. Continuously measured DO ranges from 0 to 11.6 mg/L. The mean value of *RMSE* is 1.02 mg/L and *NSE* varies between 0.58 and 0.64.

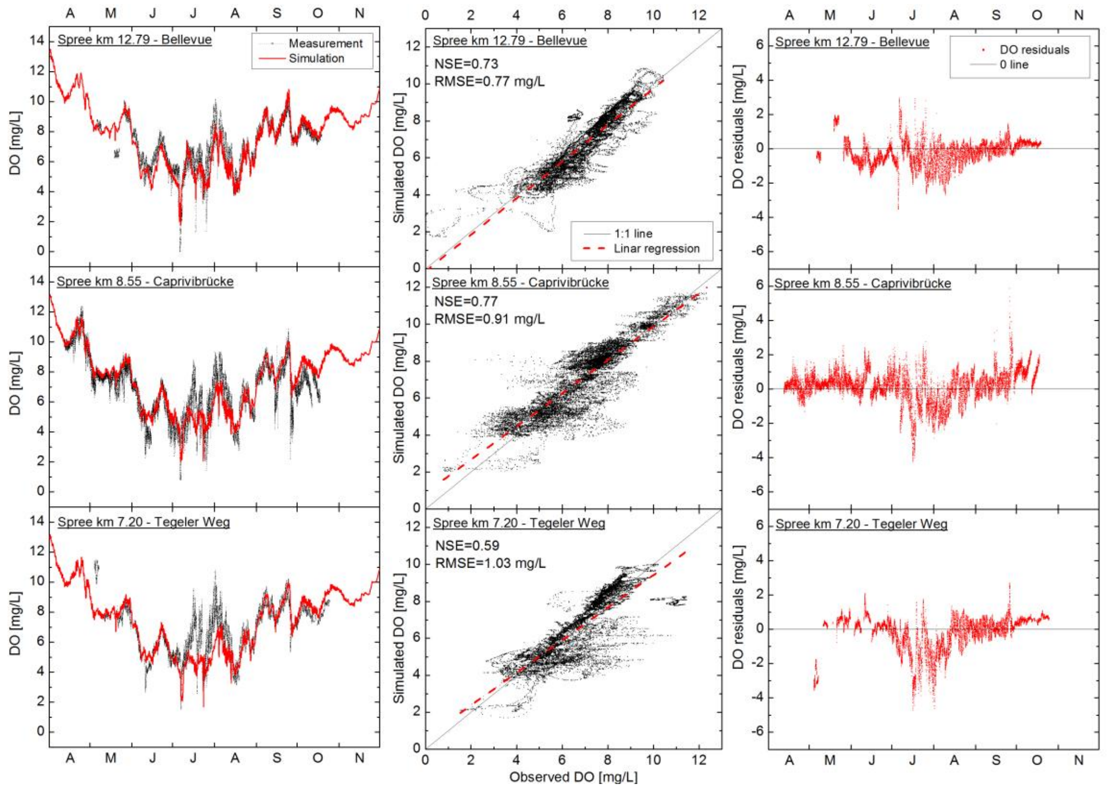

Figure 8: Time series plots, scatter plots and plots of residuals for simulated and measured DO concentrations at the monitoring stations Spree km 12.79 (Bellevue), Spree km 8.55 (Caprivibrücke) and Spree km 7.20 (Tegeler Weg) for 2010.

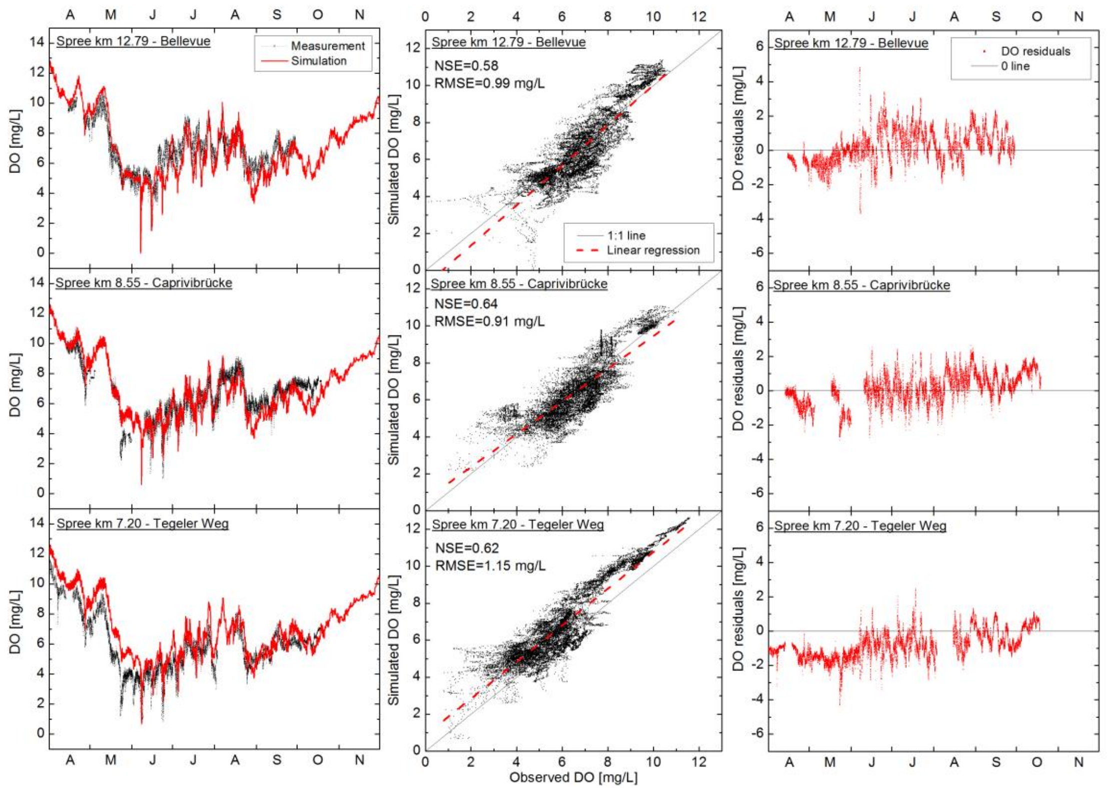

Figure 9: Time series plots, scatter plots and plots of residuals for simulated and measured DO concentrations at the monitoring stations Spree km 12.79 (Bellevue), Spree km 8.55 (Caprivibrücke) and Spree km 7.20 (Tegeler Weg) for 2011.

The extent and duration of DO depressions after CSO are also in general agreement with measured concentrations (with certain limitations), as exemplified for single events in Figure 10 and Figure 11 for 2010 and 2011, respectively.

Figure 10 shows two particular CSO events in July 2010, which lead to significant DO deficits in the Berlin River Spree. Although the overflow event on 2010-07-23 (Figure 10, right panel) leads to the biggest CSO volume simulated for 2010 (475,000 m³), the worst impacts on DO occurring in the River Spree is observed for a comparably small CSO event on 2010-07-06 (Figure 10, left panel). For both events a significant decrease in DO is simulated. However, a slight overestimation of measured DO is observed for the CSO event on 2010-07-06, in particular for Spree km 12.79 (Bellevue), which might have different reasons. On the one hand, the preceding CSO was caused by a rain event with a very heterogeneous spatial distribution, which cannot be fully represented by the installed rain gauges. On the other hand, high water temperature of 26°C (see Figure 12), low flow velocity of approximately 8 cm/s and a long antecedent dry weather period (see Figure 6) could be the reason for acute measured DO decrease from 6 to 0 mg/L observed at Spree km 12.79. Thus, the coupled sewer-river-model is not able to accurately simulate the observed DO drop for this particular event.

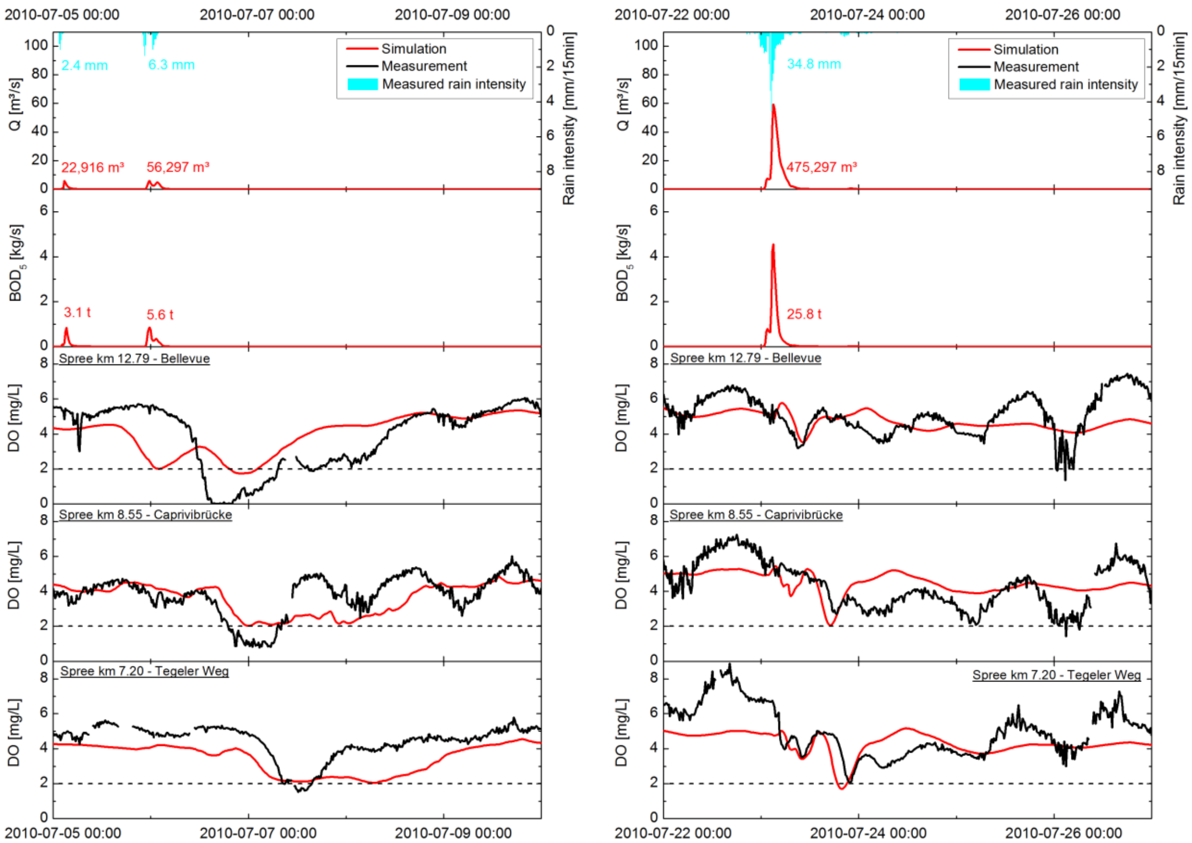

Figure 10: Simulated discharge and BOD₅ mass flow for all simulated CSO outlets and measured rain intensity within the investigation area as well as simulated and measured DO concentrations for two particular CSO events in July 2010 at Spree km 12.79 (Bellevue), Spree km 8.55 (Caprivibrücke) and Spree km 7.20 (Tegeler Weg). Dotted line marks the critical concentration for the asp (Aspius aspius).

Figure 11 shows simulated and observed DO concentrations for two particular CSO events in June 2011. During the event from 2011-06-07 to 2011-06-08 (left panel) simulations and measurements both reach a value of 0 mg/L for several hours at Spree km 12.79. Simulated and measured DO concentration and impact duration at Spree km 12.79 agree well except for a time shift of 8 h. Moreover, an almost perfect model performance can be observed at Spree km 8.55 during the time period from 2011-06-21 to 2011-06-25 (Figure 11, right panel).

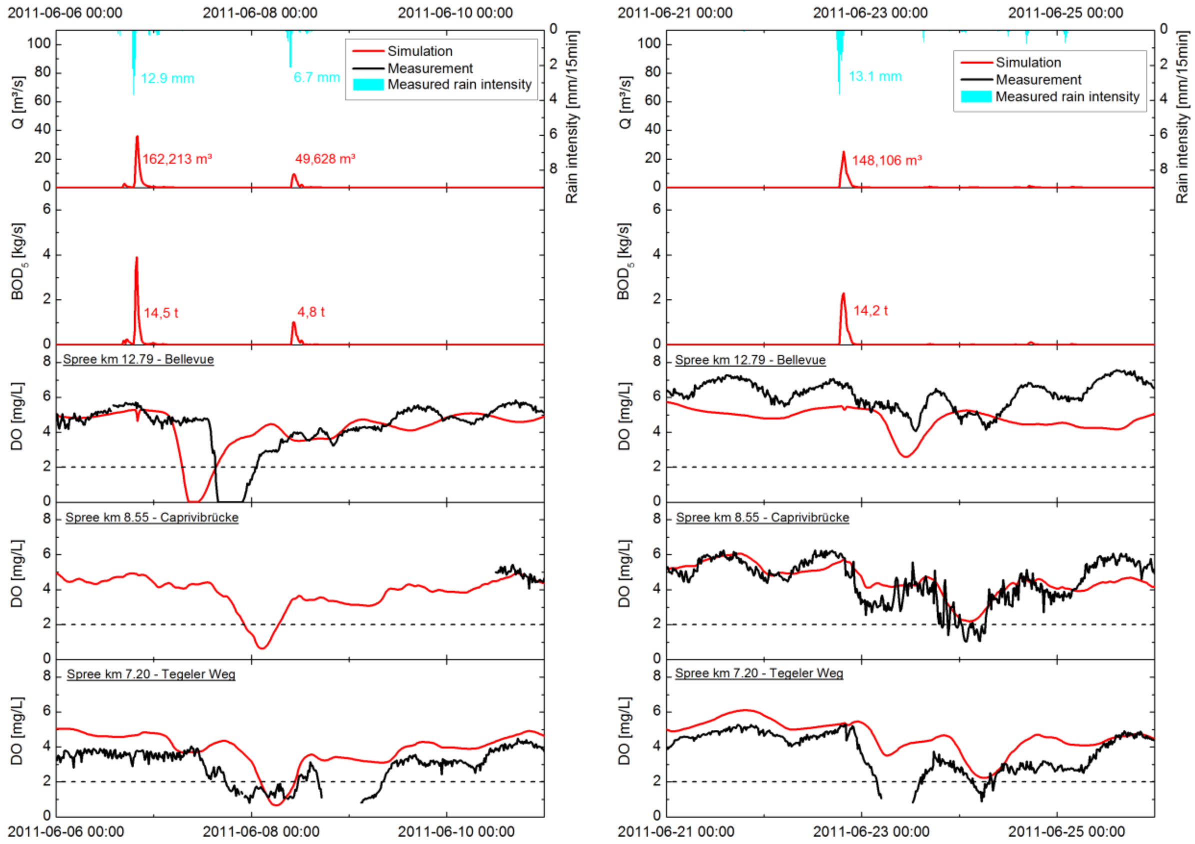

Figure 11: Simulated discharge and BOD_5 mass for all simulated CSO outlets and measured rain intensity within the modelled investigation area as well as simulated and measured DO concentrations of two particular CSO events in June 2011 at Spree km 12.79 (Bellevue), Spree km 8.55 (Caprivibrücke) and Spree km 7.20 (Tegeler Weg). Dotted line marks the critical concentration for the asp (Aspius aspius).

The generally good representation of DO is remarkable, considering that DO is depending on most physical, geochemical or biological processes. This is underlined by the findings in a model study with Hydrax/QSim for the River Elbe, where high *NSE* were found for various state variables, but DO showed negative annual *NSE* for two of three validation years (Quiel et al., 2011).

The examples from Figure 10 and Figure 11 show that not all CSO events can be predicted with the same quality. Both an over- and underestimation of measured DO concentrations can be observed due to uncertainties in model input data and process description. Besides, the low resolution of input data for river hydraulics (see subchapter 3.2, Table 4) can lead to an advanced or delayed simulation of effects in comparison to measurements. These effects occur throughout the simulation period, as indicated by continuous lines in the scatter plots in Figure 8 and Figure 9, which are the result of systematic deviations for entire DO peaks/depressions. However, as pointed out above, DO deficits from CSO impacts can be generally predicted at good quality for both validation years. This allows using the coupled model for the comparison of different CSO control strategies.

Next to DO concentrations the state variables water temperature (T), pH and electrical conductivity (EC) are measured continuously at Spree km 12.79, 8.55 and 7.20. Their comparison with model results is show in Figure 12 (2010) and Figure 13 (2011).

Simulated water temperature for both years fit very well with measured data at all three monitoring stations (*NSE*≥0.97) indicating properly predicted heat exchange processes by Hydrax/QSim.

For pH, visual comparison of measured and simulated data looks very satisfying. Nevertheless, model performance regarding the *NSE* is relatively low due to the typically low variance of measured pH. For state variables, which hardly deviate from their average value, it is relatively difficult to obtain high *NSE* values (see Equation 2, subchapter 4.1). However, the maximum *RMSE* for the two simulation periods and three monitoring stations is below 3% of the measured average.

The electrical conductivity (EC) is very well simulated for both years indicated by high *NSE* values ranging from 0.65 to 0.93. However, during large CSO events, measured EC decrease is typically more pronounced than for the simulation, since EC of CSO spill water is assumed to be constant (293.3 µS/cm) in Hydrax/QSim. Data from a three-year CSO monitoring in Berlin (pers. comm. Caradot, 2012) show that EC in CSO spill water varies strongly depending on the rain water to sewage ratio and can reach average values below 200 µS/cm for big storm events.

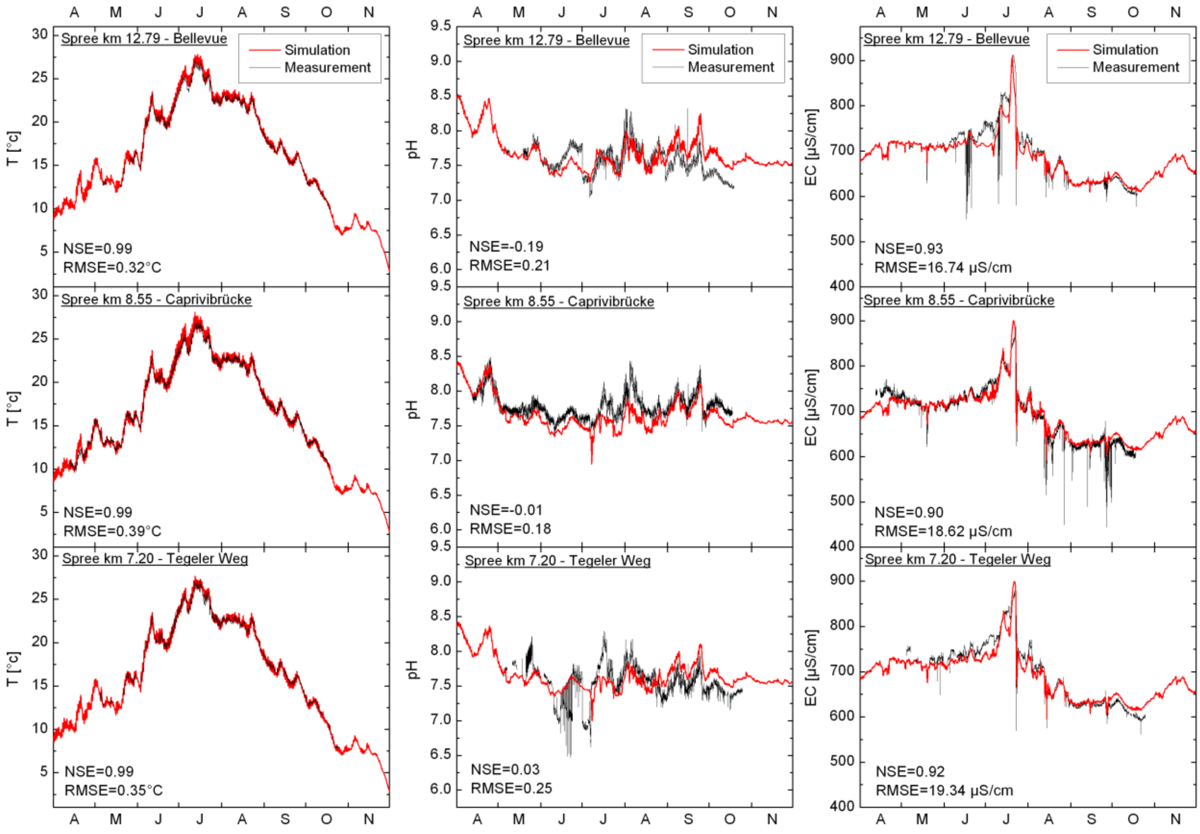

Figure 12: Time series plots for simulated and measured T (left), pH (central) and EC (right) at the monitoring stations Spree km 12.79 (Bellevue), Spree km 8.55 (Caprivibrücke) and Spree km 7.20 (Tegeler Weg) for 2010.

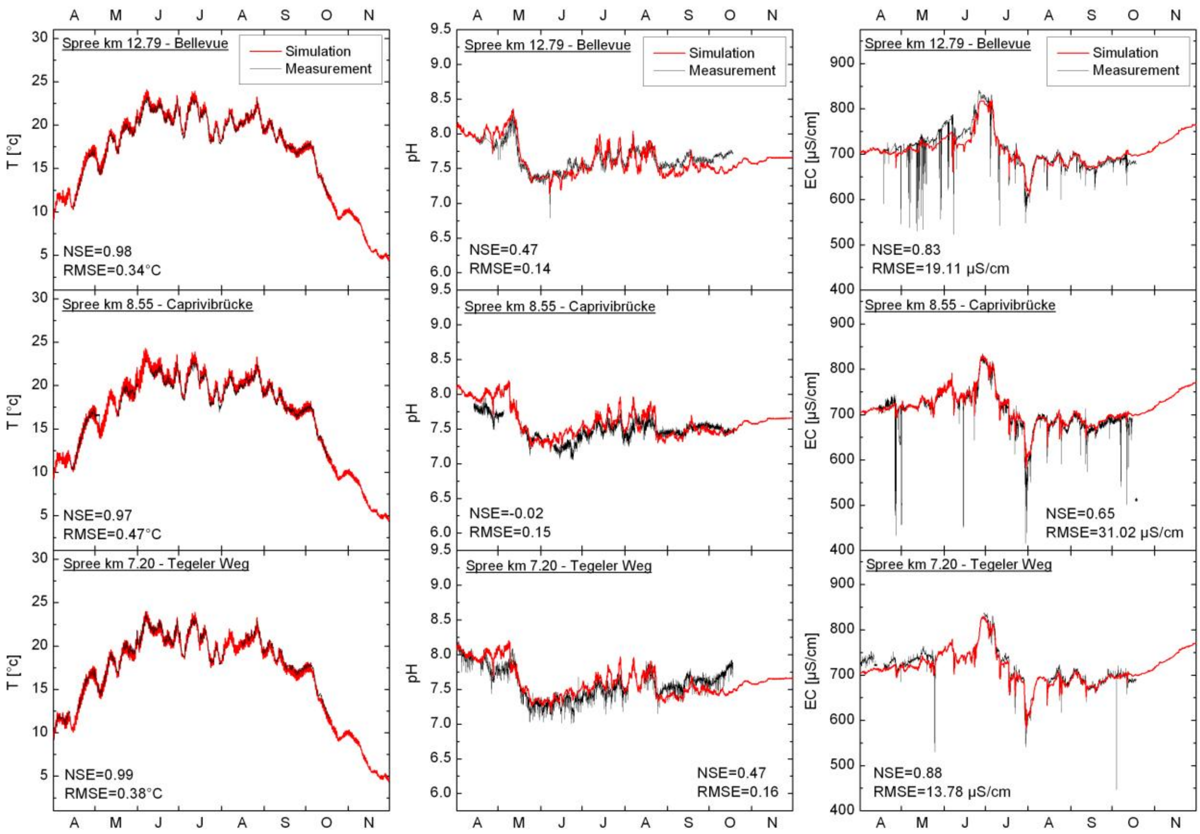

Figure 13: Time series plots for simulated and measured T (left), pH (central) and EC (right) at the monitoring stations Spree km 12.79 (Bellevue), Spree km 8.55 (Caprivibrücke) and Spree km 7.20 (Tegeler Weg) for 2011.

Monthly grab samples are not suitable to evaluate the model performance regarding the sensitivity towards CSO. However, they still can be useful for the assessment of simulated background levels and seasonal fluctuations of water quality state variables. Figure 14 (2010) and Figure 15 (2011) show time series plots for the state variables TSS, BOD_5, Chla, NH_4-N, NO_3-N, TN, P_{dis} and TP simulated and discontinuously measured at Spree km 9.35, upstream of Landwehrkanal (see map in Figure 4).

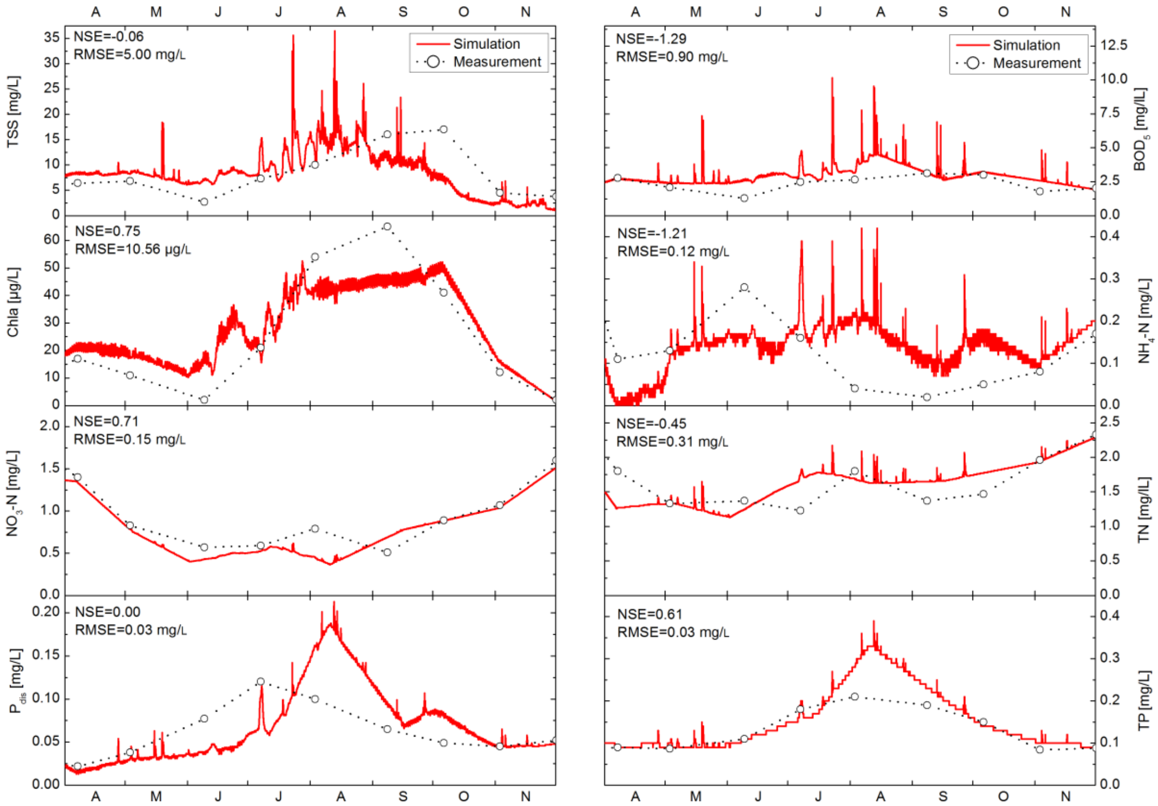

Figure 14: Time series plots for simulated and measured TSS, BOD_5, Chla, NH4-N, NO3-N, TN, P_{dis} and TP for 2010 at Spree km 9.35, upstream of Landwehrkanal (see map in Figure 4).

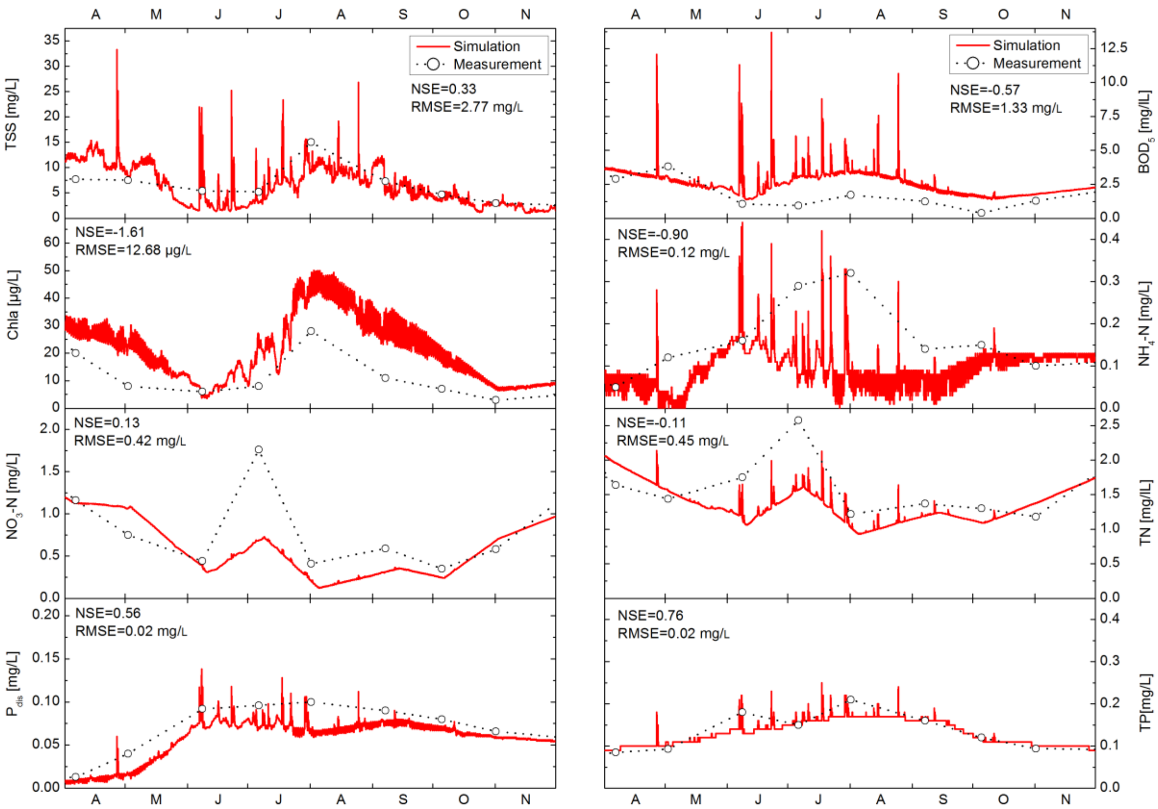

Figure 15: Time series plots for simulated and measured TSS, BOD_5, Chla, NH_4-N, NO_3-N, TN, P_{dis} and TP for 2011 at Spree km 9.35, upstream of Landwehrkanal, upstream of Landwehrkanal (see map in Figure 4).

Annual patterns of simulated TSS, BOD_5, Chla, NO_3-N, TN, P_{dis} and TP for both years show a good agreement with discontinuous measurements. Only for NH_4-N, the simulated and measured patterns differ clearly. However NH_4-N simulations are in the correct range, given that measured annual fluctuations of 0.2 mg/L are very low. Clearly distinguishable peaks of simulated TSS, BOD_5 and NH_4-N concentrations indicate CSO events that are typically not covered by discontinuous measurements based on grab samples.

The approximately steady section of simulated Chla concentrations of 45 µg/L between August and October 2010 points to limitation of algae growth. Since concentrations of NH_4-N, NO_3-N and P_{dis} are comparably high, nutrients do not seem to limit algae growth. Other limitation factors can be light, temperature, Si and zooplankton.

Peaks of P_{dis} and TP in August 2010 are simulated due to exceptionally high concentrations in input data derived from monthly measurements at Mühlendamm. Remarkably good model performances for the state variables P_{dis} and TP are found for the year 2011.

4.2.3 *Model validation based on impact assessment*

For three river stretches - Spree km 12.79 (Bellevue), Spree km 8.55 (Caprivibrücke) and Spree km 7.20 (Tegeler Weg) - measured and simulated data of the years 2010 and 2011 are compared regarding the occurrence of suboptimal and critical DO conditions. Figure 16 and Figure 17 visualize the frequency of suboptimal and critical DO conditions according to measurements and simulations expressed as the number of concerned calendar days.

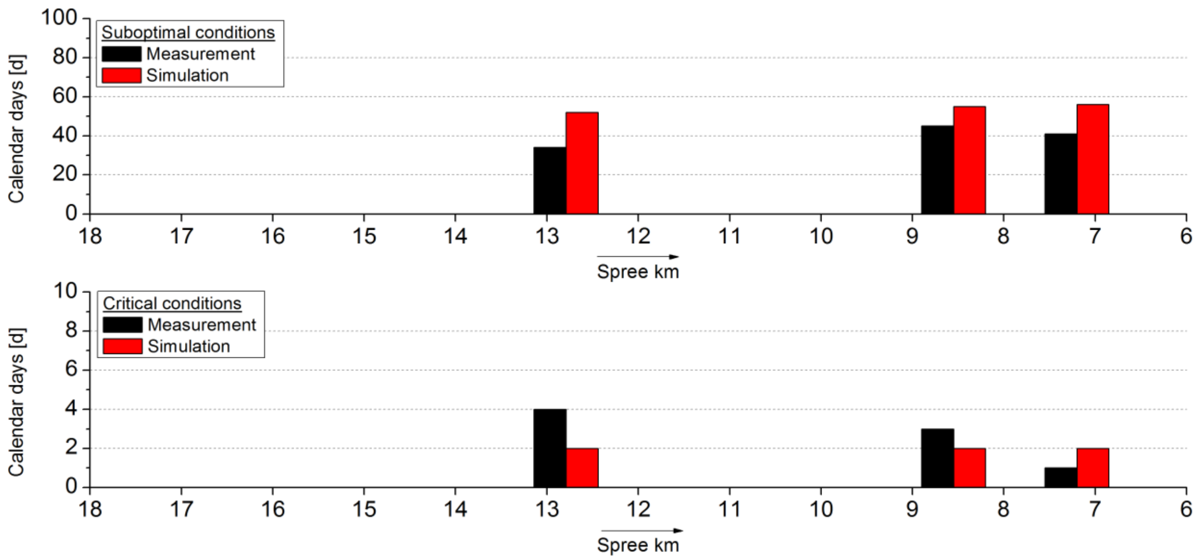

Figure 16: Number of calendar days with suboptimal (upper panel) and critical DO conditions (lower panel) according to measurements and simulations for the year 2010. The arrow indicates the flow direction of the River Spree.

Results of impact assessment for both years show that the coupled model InfoWorks-Hydrax/QSim can simulate both suboptimal DO conditions based on the Lammersen-approach (1997) as well as critical DO conditions typically caused by CSO.

In 2010 suboptimal DO conditions are simulated at higher frequency than they are measured. The average frequency of suboptimal DO conditions for the considered river stretches Spree km 12.79, 8.55 and 7.20 is 40 calendar days measured and 54 calendar days simulated. Average frequencies of critical DO conditions for simulation (2.0 calendar days) and measurements (2.7 calendar days) agree well for the validation year 2010.

When assessing model performance regarding the occurrence of critical DO conditions by using the sharp threshold of 2 mg/L it has to be noted that slight deviations between simulated and measured DO can strongly affect the resulting frequency of critical DO conditions. For instance on 2010-07-06 (Figure 10, left panel), the critical threshold of 2 mg/L is violated by measured DO, which drops to the value of 1.5 mg/L at Spree km 7.20, but not by the simulated minimum of 2.1 mg/L. The opposite happens at Spree km 7.20 on 2010-07-23 (Figure 10, right panel), where the lowest measured DO concentration is 2.1 mg/L, while the simulated value drops to the critical value of 1.7 mg/L. For both events model performance based on impact assessment is of poor quality, although time series of measured and simulated DO agree relatively well.

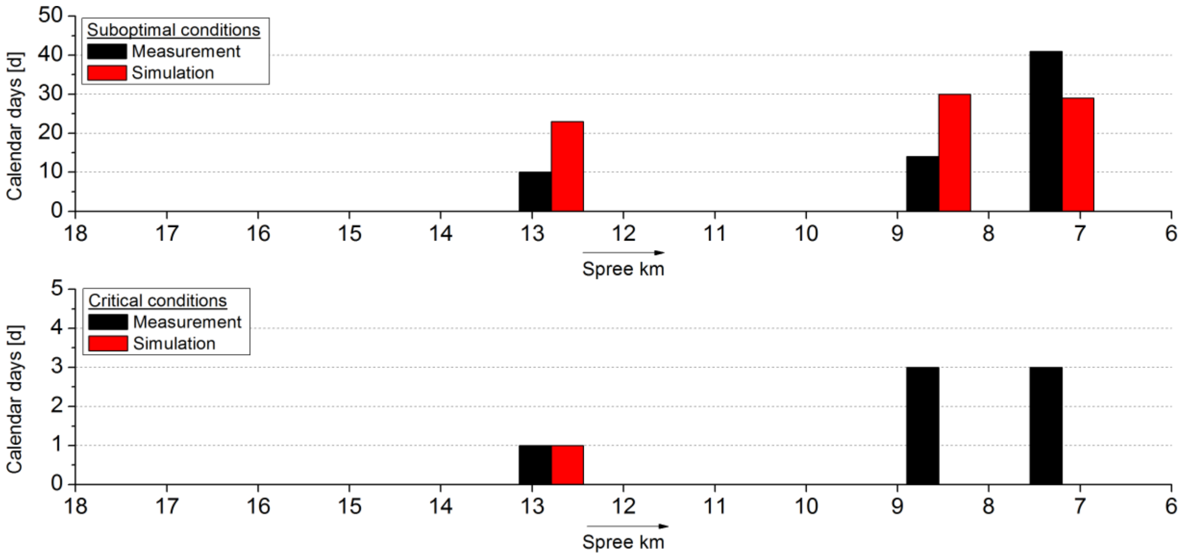

Figure 17: Number of calendar days with suboptimal (upper panel) and critical DO conditions (lower panel) according to measurements and simulations for the year 2011. Because of a lack in measurement data at one monitoring station, the impact assessment starts on 2011-06-11. The arrow indicates the flow direction of the River Spree.

In 2011 impact assessment starts from 2011-06-11, since no measured data are available at some of the stations before that date (see Figure 11). For the evaluated time period the simulated average frequency of suboptimal DO condition is 27 calendar days, while 22 calendar days are measured. Despite this overall agreement both over- and underestimation of frequencies of suboptimal conditions is observed when looking at specific monitoring stations.

Regarding critical DO conditions the average value for the simulation is 0.3 calendar days while 2.3 calendar days are measured. At Spree km 12.79 the occurrence of critical DO conditions fit very well with measured data. However, no critical DO conditions are simulated at Spree km 8.55 and 7.20. To explain this, the following example is given.

After the CSO event on 2011-06-22 (Figure 11, right panel), measured DO concentration at Spree km 8.55 and 7.20 drops below the critical value of 2 mg/L during 2 calendar days, whereas simulated DO is overestimated with a minimum value of 2.2 mg/L at both stations. Thus, 2 of 3 measured calendar days with critical DO conditions are not simulated at Spree km 8.55 and 7.20 for that particular event, although time series show a very good agreement of simulated DO concentrations with measurements at Spree km 8.55 (Figure 11, right panel).

The validation shows that the planning instrument for CSO control is able to predict both the annual DO pattern at dry-weather conditions and water quality changes after CSO.

Biogeochemical processes relevant for the oxygen budget in the Berlin River Spree are well represented. Simulated DO concentrations can even reach very low values of 0 mg/L after CSO indicating that the coupled model reacts sensitively to CSO pollutant loads of different extents. However, these simulated critical DO conditions cannot be used for absolute predictions, but for comparing different sewer status.

5 Scenario analysis

As shown in the previous chapter, the coupled sewer-river model developed for CSO impact assessment in Berlin allows for a good representation of hydraulics and water quality for both background conditions and under the influence of CSO. In the following chapter the model tool is demonstrated for selected management and climate change scenarios. Focus of this scenario analysis is the assessment of model sensitivity to different CSO mitigation measures, which is an important precondition for the future use of the instrument in concrete planning of CSO management.

5.1 Definition of scenarios

In this subchapter, scenarios are described for which the planning instrument for CSO control has been tested. There are three categories of scenarios:

1. Planned sewer rehabilitation measures (scenarios S1 and S2),
2. Possible management strategies after sewer rehabilitation (scenarios S3 and S4),
3. Climate change effects (scenarios S5a, S5b and S5c).

Table 6 summarizes scenarios and respective model implementation.

Table 6: Scenario definitions and their model implementation in InfoWorks CS and Hydrax/QSim

		Scenario description	**Model implementation**
Planned sewer rehabilitation measures	S1	Sewer status 2010	A model of the Berlin CSS that represents the sewer status 2010 was already available (total storage volume: 191,900 m^3).
	S2	Sewer status 2020	Implementation of the rehabilitation measures planned until 2020 (total storage volume: 280,090 m^3).
Possible management strategies after sewer rehabilitation	S3	Sewer status 2020 (S2) with additionally increased storage volume	Based on the sewer status 2020 (S2) the storage volume of each subcatchment is increased by 20% of the storage volume already provided by storm water tanks, storage sewer, CSO barriers, movable weirs and real time control. The additional storage volume (in total 36,598 m^3) is mainly implemented in form of storm water tanks near the pumping stations (total storage volume: 316,688 m^3).
	S4	Sewer status 2020 (S2) with additionally reduced impervious connected area	Based on the sewer status 2020 (S2) the impervious connected area of each subcatchment is reduced by 20%. Runoff from pervious areas is not considered.

		Scenario description	Model implementation
Climate change effects	S5a	Sewer status 2020 (S2) with increased temperature	Based on the sewer status 2020 (S2) surface air and water temperature is increased by 1.9 K.
	S5b	Sewer status 2020 (S2) with increased temperature and higher rain intensity	Additionally to increased temperatures (see S5a) rain intensity of all considered rain gauges is multiplied by a factor of 1.2.
	S5c	Sewer status 2020 (S2) with increased temperature and lower rain intensity	Additionally to increased temperatures (see S5a) rain intensity of all considered rain gauges is multiplied by a factor of 0.8.

All scenarios were developed in close cooperation with stakeholders from Berliner Wasserbetriebe (BWB) and the Senate Department for Urban Development and the Environment (SenStadtUm). Scenarios S1 and S2 describe the sewer status quo 2010 and the planned configuration of the combined sewer system for the year 2020, respectively. For all other scenarios, the common objective was not to describe future changes in full detail, but to test overall model sensititvity to different boundary conditions. In this context, the management scenarios S3 and S4 roughly indicate to which extent future CSO control measues could be implemented, but do not necessarily describe technically and economically feasible configurations of the sewer system or the catchment. Likewise, the climate change scenarios S5a, S5b and S5c consider expected changes in temperature and rainfall intensity but do not take into account hydrological or biogeochemical side effects outside the model boundaries. Nonetheless, climate change scenarios are based on a literature study which can be summarised as follows:

For Berlin and the time period 2046-2055, an average surface air temperature increase of 1.9 K is predicted in summer months (April to September) compared to the time period 1951-2006 (Lotze-Campen et al., 2009). Considering low depth and flow velocity of the flow-regulated Berlin River Spree and its side channels, it is expected that water temperature will rise by the same value as surface air temperature, as indicated by studies on rivers (Kaushal et al., 2010) or lake surface temperatures (Livingstone and Lotter, 1998). This can be confirmed for the Berlin River Spree by monthly averages of measured water and surface air temperatures, which show an almost 1:1 relationship. Consequently, both water and surface air temperature are increased by 1.9 K for the climate change scenarios S5a, S5b and S5c. Regarding the future occurrence of extreme rain events contradictory views can be found in literature (Matzinger et al., 2012). To reflect these uncertainties both an increase and decrease in rain intensity is analysed in scenario S5b and S5c by modifying the rain fall input data (2007) by ±20%.

For each scenario the model run covers the time period April to November (8 months) of the test year 2007 since all adverse CSO impacts are expected to occur in that period (see subchapter 4.1). All model input data (rain data, hydraulic river data, water quality data and meteorological data) are taken from the year 2007, which was the most intense year of its decade regarding the occurrence of extreme rainfall events and critical DO conditions in the studied water system of Berlin.

All three model components of the planning instrument are run for each of the scenarios in Table 6, with the exception of scenario S5a, for which temperatures are adapted only in Hydrax/QSim boundary conditions and no new InfoWorks CS run is necessary.

Scenario analysis is done in three ways. First, CSO emissions and the number of events with volumes > 1,000 m³ as simulated by InfoWorks CS are evaluated. Then, simulated CSO volumes, BOD_5 loads and resulting DO concentrations in the Berlin River Spree are visually analysed for two particular CSO events and the three following river stations: Spree km 14.60 (upstream of most CSO outlets), km 10.28 (with several CSO outlets up- and downstream) and km 7.20 (downstream of most CSO outlets). See Figure 18 for a simplified map of the modelled river stretch and the three studied river stations.

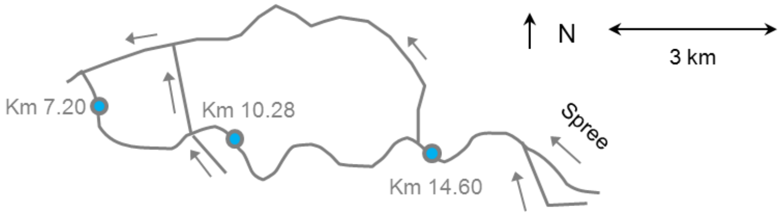

Figure 18: The modelled river stretch and the three studied river stations. Arrows indicate flow direction.

Finally, the frequencies of suboptimal and critical DO conditions are quantified for eight points along the Berlin River Spree (km 17.54, 16.30, 14.60, 12.79, 10.28, 8.55, 7.20 and 6.34, see map in Figure 4) to give a detailed picture on the spatial distribution of DO stress and identify possible hotspots. The following three subchapters are organised along that structure.

5.2 Planned sewer rehabilitation measures

In this subchapter the effect of planned sewer rehabilitation measures on CSO emissions and impacts is studied based on two simulations for the sewer status 2010 (S1) and 2020 (S2), respectively (see Table 6 in subchapter 5.1), both driven with input data from the scenario year 2007. Results show that for the eight-month time period of the scenario year the planned increase of storage volume by 88,190 m³ (+46%) leads to a reduction of CSO volumes by 1 million m³ (-17%). The absolute and relative reduction of volume and pollutant loads is presented in Table 7.

Table 7: Simulated number of CSO events >1,000 m³, CSO volumes and pollutant loads for the sewer status 2010 (S1) and the sewer status 2020 (S2) for the studied time period April to November 2007. Number of events, volumes and pollutant loads refer to the sum of all 67 CSO outlets within the model system.

		S1 Sewer status 2010	S2 Sewer status 2020
Events	[-]	52	52 (±0%)
V	[10^6 m³]	5.9	4.9 (-17%)
BOD_5	[t]	353.7	273.0 (-23%)
COD	[t]	960.2	744.7 (-22%)
TSS	[t]	839.5	663.3 (-21%)
NH_4-N	[t]	12.2	8.4 (-31%)
TKN	[t]	25.6	18.2 (-29%)
P_{dis}	[t]	2.3	1.7 (-29%)
TP	[t]	4.1	3.0 (-27%)

Table 7 indicates that the reduction of mainly wastewater related pollutants such as NH_4-N, TKN, P_{dis} or TP is greater than the reduction in volume or mainly storm water associated pollutants. This points to the existence of a first flush effect as reported by many authors (Gupta and Saul, 1996; Bertrand-Krajewski et al., 1998; Krebs et al., 1999). Due to the implementation of storm water tanks, storage sewers and movable weirs, a greater part of the highly concentrated initial volume of a CSO event can be captured.

For both scenarios (S1 and S2) the same number of CSO events with a discharged volume greater than 1,000 m³ has been simulated (Figure 19, left panel). Since planned sewer rehabilitation measures aim at diminishing overall CSO impacts and do not target on every single CSO outlet, it is possible that overflow frequency as defined in subchapter 4.1 does not decrease. However, classification of CSO events regarding their overflow volume points to a slight decrease in occurrence of medium-sized CSO events (10,000 to 100,000 m³) and an increase in occurrence of small events (<10,000 m³).

The right panel in Figure 19 indicates that the effectiveness of the available new storage volume regarding CSO volume reduction varies strongly between rain events depending on their extent, duration, timing and spatial distribution. Only few events, typically characterised by a uniform rainfall distribution and represented by the range between the dashed black and the red line, can use the extra storage volume to full capacity. The maximum reduction in discharged volume (87,000 m³, 98% of the additional storage volume) is simulated for the CSO event on 2007-08-21 following an uniformly distributed eight-hour rain event of an average rainfall depth of 25.5 mm. For a list of CSO volumes, pollutant loads and other characteristics of all CSO events simulated for both scenarios, see Table 14 and Table 15 in the Appendix.

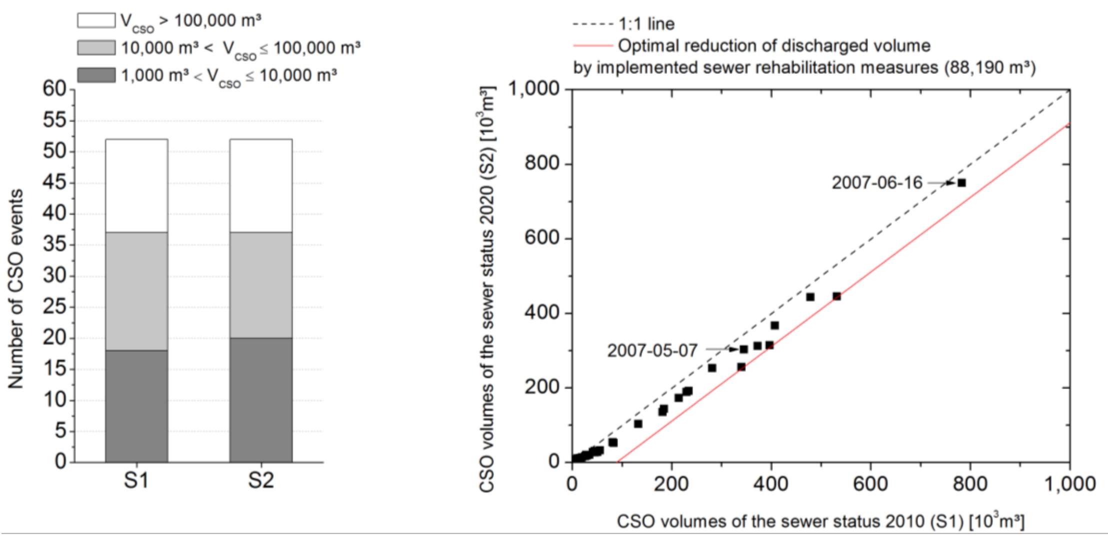

Figure 19: Left panel: Number of CSO events >1,000 m³ for i) the sewer status 2010 (S1) and ii) the sewer status 2020 with implemented sewer rehabilitation measures (S2). Right panel: Discharged volumes for all 52 CSO events >1,000 m³ simulated for the sewer status 2020 (S2) plotted against the corresponding volumes simulated for the sewer status 2010 (S1). The red line indicates the reduction that could be achieved if the entire additional storage volume of 88,190 m³ is used. The two exemplary events in Figure 20 on 2007-06-16 and 2007-05-07 are marked.

For the illustration of the effect of different CSO emission scenarios on the impacts in the receiving water body, time series for discharge and BOD_5 mass flow originating from CSO as well as DO concentrations in the River Spree are plotted for two exemplary events on

2007-06-16 and 2007-05-07, the largest and the seventh largest event regarding CSO volume of the eight-month period, respectively (Figure 20).

For both events, sharp drops in DO concentrations can be observed at Spree km 10.28 immediately after the CSO flow peak. They are caused by the inflow of oxygen free CSO spill water at one or several CSO outlets located at short distance upstream the observed river stretch. That first DO drop is typically followed by a second larger DO depression, which is the result of oxygen-depleting organic material entering the water body at different locations, above all via a CSO outlet at Spree km 16.65 (see subchapter 3.2).

Regarding the effect of the planned sewer rehabilitation measures, there are significant differences between both events exemplified in Figure 20. For the 7th largest CSO event on 2007-05-07, 12% of discharged volume and 15% of BOD_5 load is reduced compared to the sewer status 2010 (S1). As a result, DO concentration in the Berlin River Spree increases significantly and critical DO conditions at Spree km 7.20 can be prevented. For the largest CSO event on 2007-06-16 only 4% of volume and 10% of BOD_5 load can be reduced. Even for the sewer status 2020 (S2) overall BOD_5 mass flow reaches values up to 5.6 kg/s indicating a massive potential for DO consumption. Hence, only slight changes in DO can be observed. The example supports the hypothesis that the larger a rain event, the smaller the relative effect of installed storage volume on CSO emissions and impacts in the river.

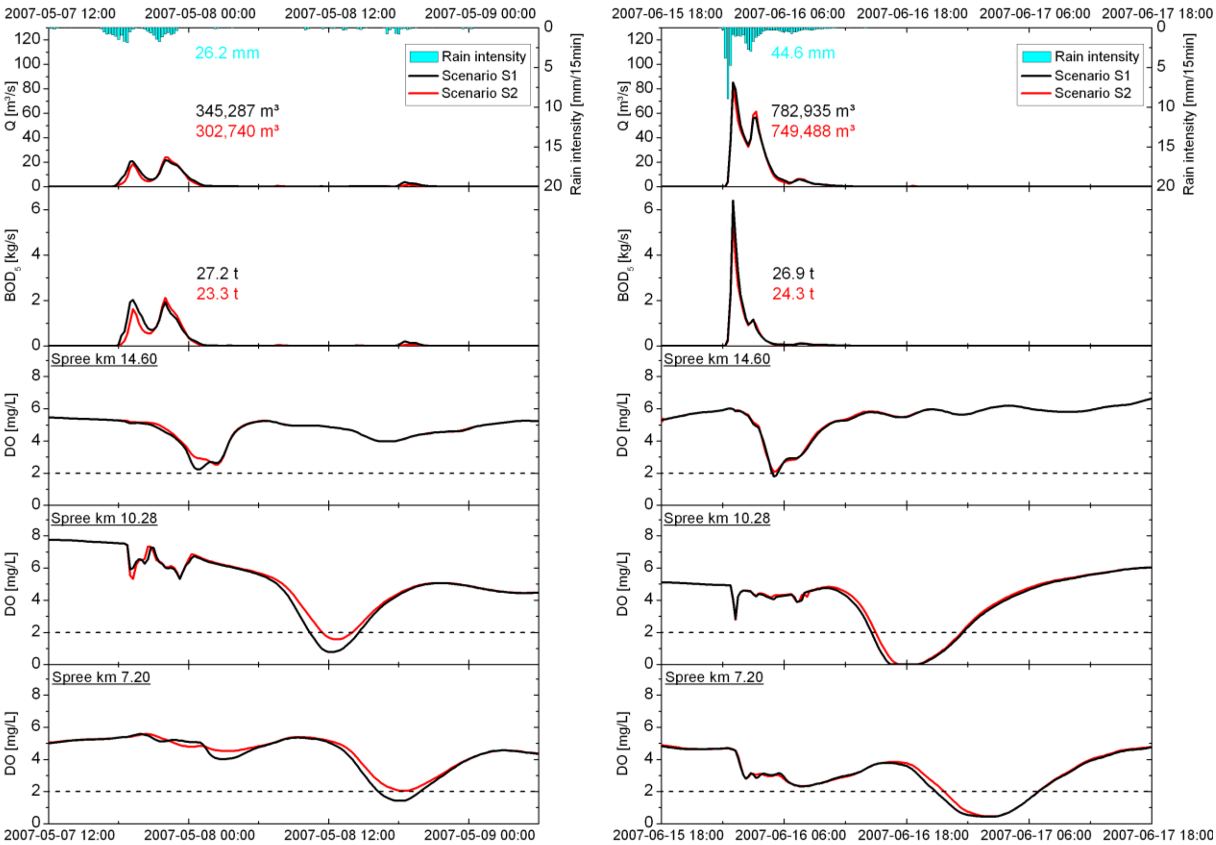

Figure 20: CSO emissions and impacts for two CSO events of the studied time period simulated for i) the sewer status 2010 (S1) and ii) the sewer status 2020 with implemented sewer rehabilitation measures (S2). The upper two panels of each plot show the simulated discharge and BOD_5 mass flow for all simulated CSO outlets as well as measured rain intensity averaged over nine rain gauges within the investigation area. The lower three panels show the simulated DO concentrations at Spree km 14.60, 10.28 and 7.20 (in flow direction). Numbers in the figure indicate total rainfall, CSO volume and BOD_5 load. The dotted line marks the critical concentration for the asp (Aspius aspius).

Impact assessment results in Figure 21 indicate that the frequency of suboptimal DO conditions, averaged for the eight considered river stretches, is only slightly reduced from 27.5 calendar days for the sewer status 2010 (S1) to 26.9 calendar days for the sewer status 2020 including implemented sewer rehabilitation measures (S2). The effect of CSO control measures on the occurence of suboptimal DO conditions is negligible, since they are primarily caused by low background levels of DO in combination with high temperatures, in line with findings by Riechel (2009). However, frequency of suboptimal DO conditions varies along the River Spree with a significant increase from Spree km 10.28 to 8.55. The observed increase is the result of the inflow of the channel Landwehrkanal (LWK) (see subchapter 3.2 , Figure 4) at Spree km 8.95, containing very low DO concentrations with an annual average of 3.4 mg/L measured for the scenario year 2007.

The result is different regarding critical DO conditions, which are primarily caused by CSO. While for the sewer status 2010 (S1) an average of 3.9 calendar days with critical DO conditions is simulated, such low DO concentrations are predicted only for 2.6 calendar days for the sewer status 2020 (S2), averaged for eight stations of the Berlin River Spree. The greatest reduction from 5 to 2 calendar days with critical DO conditions is observed at Spree km 6.34, being the result of an increase in storage volume in subcatchment Bln IV by 17,000 m³ (+239%), affecting a major CSO outlet in BSSK.

As the two exemplary CSO events in Figure 20 indicate, reduction in calendar days with critical DO conditions is both due to mainly shortening of critical CSO events as well as the prevention of critical DO conditions for some events.

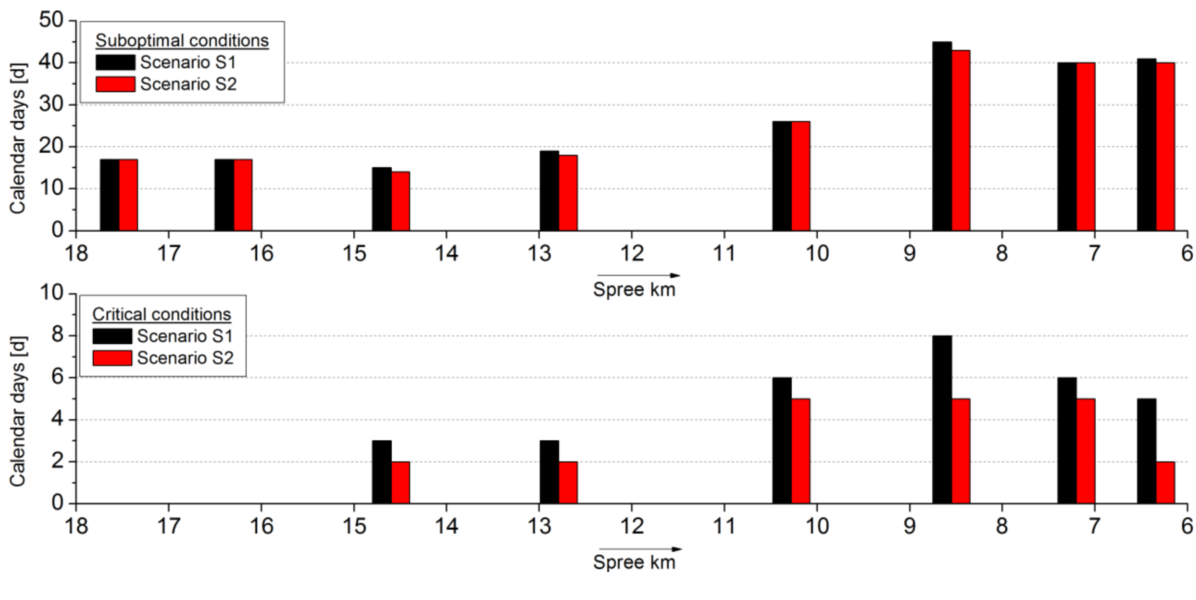

Figure 21: Simulated number of calendar days with suboptimal (upper panel) and critical DO conditions (lower panel) for i) the sewer status 2010 (S1) and ii) the sewer status 2020 with implemented sewer rehabilitation measures (S2).The arrow indicates the flow direction of the River Spree.

In consideration of water quality and weather input data of 2007, it can be summarised that planned sewer rehabilitation measures until 2020 are capable of reducing the frequency of critical DO concentrations by about one third and partly preventing them, but incapable of significantly decreasing suboptimal DO conditions, since they are mostly influenced by boundary conditions upstream the combined sewer system. As described in subchapter 3.1, some outlets of the combined sewer system are located outside the river model boundaries (e.g. upstream LWK km 1.6). For that reason, not all planned CSO control measures can be properly simulated, resulting in an underestimation of positive effects in the River Spree.

5.3 Possible management strategies after sewer rehabilitation

In the following subchapter the sewer status 2020 (S2) - based on the test year 2007 - is used as a reference scenario to estimate how CSO emissions and impacts would change in case of an additional increase of the storage volume by 20% (S3) and a reduction of the impervious area by 20% (S4) (see subchapter 5.1 for a detailed explanation of scenarios). Simulated CSO emissions (Table 8 and Figure 22) for the studied time period show that further management strategies would lead to pronounced effects on CSO volume and discharged pollutant loads, described in more detail below.

Table 8: Simulated number of CSO events >1,000 m³, CSO volumes and pollutant loads for the sewer status 2020 (S2), the sewer status 2020 with increased storage volume (S3) and the sewer status 2020 with reduced impervious connected area (S4) for the studied time period April to November 2007. All number of events, volumes and pollutant loads refer to the sum of all 67 CSO outlets within the model system. Relative changes shown for scenario S3 and S4 refer to the sewer status 2020 (S2).

		S2 Sewer status 2020	S3 Sewer status 2020 with storage volume increased by 20%	S4 Sewer status 2020 with impervious connected area reduced by 20%
Events	[-]	52	52 (±0%)	51 (-2%)
V	[$10^6 m^3$]	4.9	4.6 (-6%)	3.3 (-32%)
BOD_5	[t]	273.0	247.3 (-9%)	181.9 (-33%)
COD	[t]	744.7	676.2 (-9%)	497.5 (-32%)
TSS	[t]	663.3	605.1 (-9%)	441.6 (-33%)
NH_4-N	[t]	8.4	7.3 (-14%)	5.7 (-32%)
TKN	[t]	18.2	16.0 (-12%)	12.3 (-33%)
P_{dis}	[t]	1.7	1.5 (-12%)	1.1 (-32%)
TP	[t]	3.0	2.7 (-11%)	2.0 (-33%)

For scenario S3, for which - compared to the sewer status 2020 (S2) - the storage volume of each subcatchment has been increased by 20% (total increase: 36,598 m³), 6% of CSO volume (310,000 m³) and 9 to 14% of pollutant loads can be reduced for the eight-month simulation period. As outlined for scenario S2 in subchapter 5.2, the reduction of sewage-based pollutants, e.g. NH_4-N, is particularly pronounced, indicating a more effective retention of the highly concentrated, waste water dominated initial volume of a CSO event. However, no changes in CSO frequency are observed compared to the reference scenario S2.

With the reduction of the impervious connected area by 20% (S4), total CSO volume for the eight-month simulation period is significantly reduced by 1,600,000 m³ (-32%). Relative decrease of pollutant loads is in the same range as volume reduction. However, large variance in pollutant load reduction is found when single CSO events are looked at. This phenomenon can be explained by the varying contribution of storm and wastewater to discharged CSO volumes. In this context, the reduction in NH_4-N is particularly high for CSO events with a relatively small discharged volume, assuming that wastewater ratio for such events is comparably high. Regarding CSO frequency, one CSO event >1,000 m³ can be prevented by reducing the impervious connected area by 20% (S4). When classifying CSO events according to their total discharged volume, a significant reduction of large CSO events (>100,000 m³) can be observed whereas the number of medium-sized and small events (<100,000 m³) is increased (Figure 22, left panel).

In Figure 22 (right panel) discharged volumes of single CSO events simulated for the change scenarios S3 and S4 are plotted against the discharged volumes simulated for the reference scenario S2. In general, changes in CSO volumes are less pronounced for scenario S3 with an increased storage volume than for scenario S4 with a reduced impervious connected area. As shown in subchapter 5.2 for the planned sewer rehabilitation measures (S2), absolute event-based reduction in CSO volume for scenario S3 is limited to the extent of increased storage volume. The maximum reduction of discharged volume is 32,000 m³ (88% of the additional storage volume), simulated for the CSO event on 2007-08-21, for which antecedent rainfall distribution is comparably uniform. In contrast, the absolute reduction in discharged volume for scenario S4 is only limited by the rainfall and reaches a value of 190,000 m³ for the largest CSO event on 2007-06-16 with a mean rainfall depth of 44.6 mm. For more detailed data, see Table 16 and Table 17 in the Appendix.

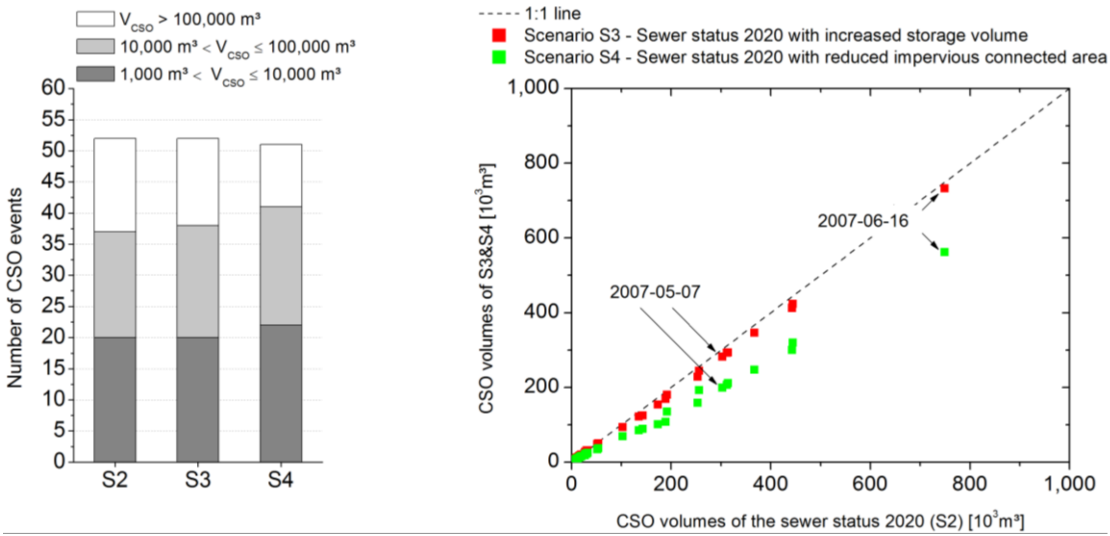

Figure 22: Left panel: Number of CSO events >1,000 m³ for i) the sewer status 2020 (S2), ii) the sewer status 2020 with increased storage volume (S3) and iii) the sewer status 2020 with reduced impervious connected area (S4). Right panel: Discharged volumes for all 52 CSO events >1,000 m³ simulated for the sewer status 2020 (S2) plotted against the corresponding volumes simulated for i) the sewer status 2020 with increased storage volume (S3) and ii) the sewer status 2020 with reduced impervious connected area (S4). The two exemplary events in Figure 23 on 2007-06-16 and 2007-05-07 are marked.

Regarding single CSO events, an installation of 20% more storage volume (S3) compared to the sewer status 2020 (S2) enables to reduce 7% of discharged volume and 10% of BOD_5 loads for the 7th largest CSO event on 2007-05-07. For the largest CSO event on 2007-06-16, only 2% of CSO volume and 3% of BOD_5 loads can be reduced. Hence, only slight effects on DO concentrations can be observed at the three considered river stretches in Figure 23 for this scenario.

For the same event, the reduction of the impervious connected area by 20% (S4) leads to a significant decrease in CSO volume and pollutant loads, in both cases improving the water quality of the Berlin River Spree. On 2007-05-07, 35% of discharged volume and 37% of BOD_5 loads are hold back so that critical DO conditions are prevented at all observed points within the affected river stretch (Figure 23, left panel). For the major CSO event on 2007-06-16 (Figure 23, right panel) 25% of CSO volume and 22% of BOD_5 loads can be reduced resulting in a significantly shorter duration of critical DO conditions and in an increase in the minimum DO concentration by about 1 mg/L. The largest relative reduction of BOD_5 loads (87%) for scenario S4 is simulated for the comparably small CSO event on 2007-07-17 with a discharged volume of 8,503 m³.

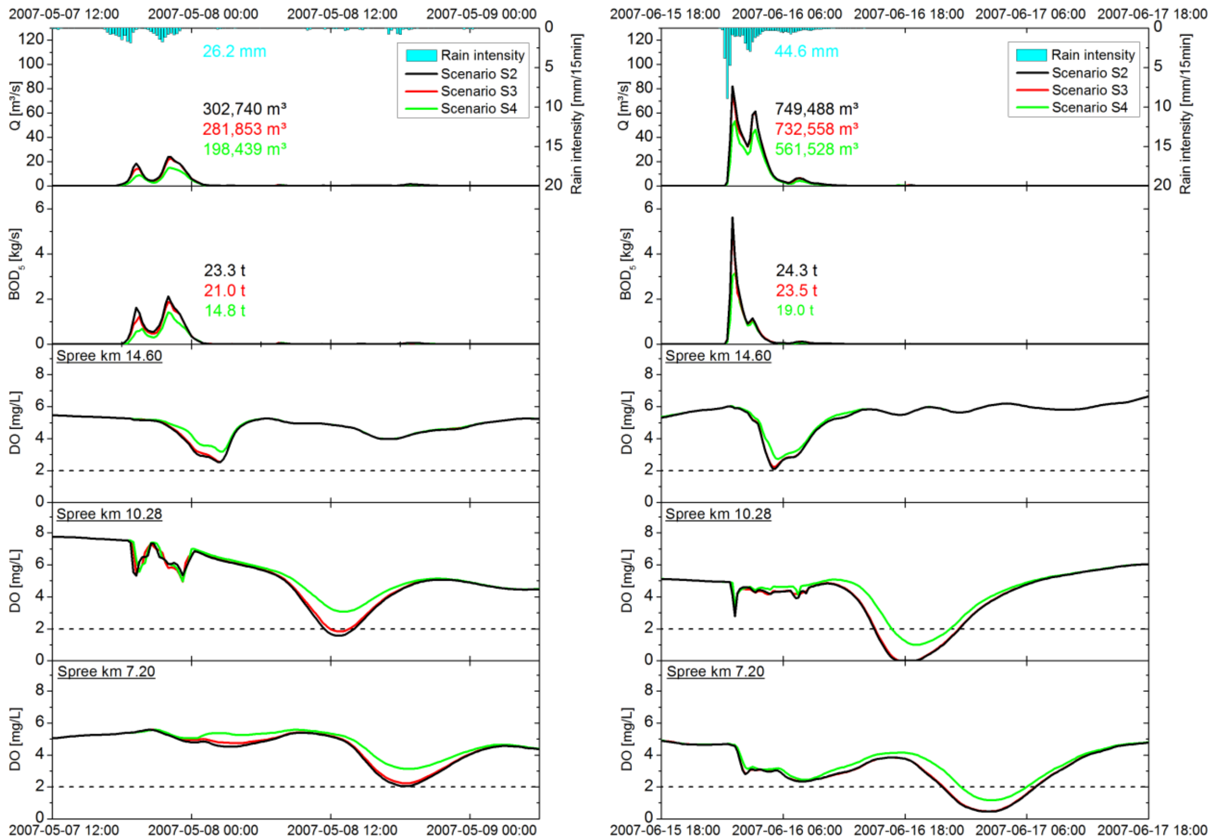

Figure 23: CSO emissions and impacts for two CSO events of the studied time period simulated for i) the sewer status 2020 (S2), ii) the sewer status 2020 with increased storage volume (S3) and iii) the sewer status 2020 with reduced impervious connected area (S4). The upper two panels of each plot show the simulated discharge and BOD_5 mass flow for all simulated CSO outlets as well as measured rain intensity averaged over nine rain gauges within the investigation area. The lower three panels show the simulated DO concentrations at Spree km 14.60, 10.28 and 7.20 (in flow direction). Numbers in the figure indicate total rainfall, CSO volume and BOD_5 load. The dotted line marks the critical concentration for the asp (Aspius aspius).

CSO impact assessment for eight stations of the Berlin River Spree shows that the frequency of suboptimal DO conditions only decreases slightly when further management strategies are implemented (see upper panel in Figure 24). The average value for the eight considered river points is 26.5 calendar days for scenario S3 (-1%) and 25.0 calendar days for scenario S4 (-7%). At the upper model boundary (Spree km 17.54), the occurrence of suboptimal DO conditions for the scenarios S2, S3 and S4 is identical due to constant water quality input data, measured at Mühlendamm for the test year 2007 (see subchapter 3.2; Figure 4).

Primarily CSO influenced critical DO conditions can be prevented and shortened to a larger extent by reducing the impervious connected area by 20% (S4) than by an increase of storage volume by 20% (S3), see lower panel in Figure 24. For scenario S3 the average frequency of critical DO conditions is reduced by 20% to 2.1 calendar days, whereas the average frequency of such conditions for scenario S4 is only 1.3 calendar days, representing a reduction by 50% compared to the sewer status 2020 (S2). Critical DO conditions previously occurring at Spree km 14.60, 12.79 and 6.34 can be prevented completely for this scenario. However, it has to be taken into account that scenarios have not been compared regarding costs and feasibility of implementation.

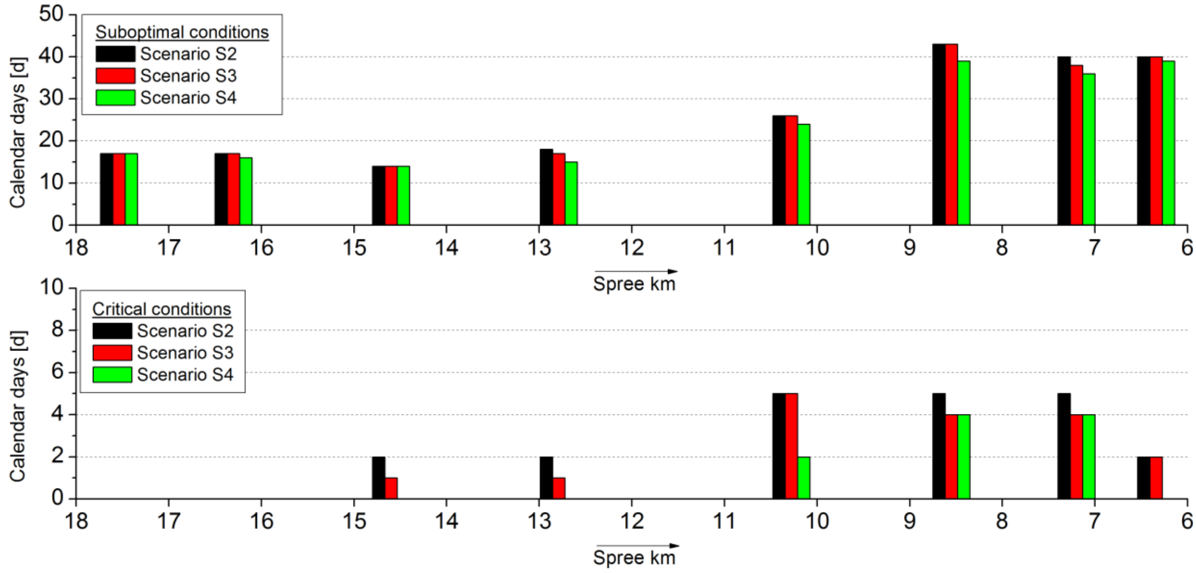

Figure 24: Simulated number of calendar days with suboptimal (upper panel) and critical DO conditions (lower panel) for i) the sewer status 2020 (S2), ii) the sewer status 2020 with increased storage volume (S3) and iii) the sewer status 2020 with reduced impervious connected area (S4).The arrow indicates the flow direction of the River Spree.

5.4 Future climate change effects

Based on the sewer status 2020 (S2) and the test year 2007 the effect of an increase in surface air and water temperature (S5a) and changes in rainfall intensity (S5b, S5c) are analysed regarding the expected CSO emissions and river impacts. Table 9 shows CSO emission results for the considered scenarios (see subchapter 5.1 for details on scenario definition). Since the representation of temperature increase only requires changes in river model boundary conditions, CSO emissions are adopted from scenario S2.

Table 9: Simulated number of CSO events >1,000 m³, CSO volumes and pollutant loads for the sewer status 2020 (S2), the sewer status 2020 with increased temperature (+1.9 K) (S5a), the sewer status 2020 with increased temperature (+1.9 K) and higher rain intensity (+20%) (S5b) and the sewer status 2020 with increased temperature (+1.9 K) and lower rain intensity (-20%) (S5c) for the studied time period April to November 2007. All number of events, volumes and pollutant loads refer to the sum of all 67 CSO outlets within the model system.

		S2 Sewer status 2020	S5a Sewer status 2020 with increased temperature	S5b Sewer status 2020 with increased temperature and higher rain intensity	S5c Sewer status 2020 with increased temperature and lower rain intensity
Events	[-]	52	52	58 (+12%)	47 (-10%)
V	[10^6m³]	4.9	4.9	6.6 (+35%)	3.3 (-33%)
BOD_5	[t]	273.0	273.0	330.7 (+21%)	206.0 (-25%)
COD	[t]	744.7	744.7	890.6 (+20%)	572.6 (-23%)
TSS	[t]	663.3	663.3	800.9 (+21%)	503.3 (-24%)
NH_4-N	[t]	8.4	8.4	10.9 (+30%)	5.7 (-33%)
TKN	[t]	18.2	18.2	23.0 (+26%)	13.0 (-29%)
P_{dis}	[t]	1.7	1.7	2.1 (+24%)	1.2 (-27%)
TP	[t]	3.0	3.0	3.7 (+22%)	2.2 (-26%)

For the scenarios with increased (S5b) and reduced (S5c) rain intensities, the change in CSO volume is slightly different (+35% versus -33%), which is confirmed by the number of CSO events (Figure 27, left panel: +6 versus -5 CSO events). Changes in pollutant loads are more expressed for scenario S5c (e.g. -33% versus +30% for NH_4-N), which can be explained by the lower number of very large, strongly diluted CSO events >100,000 m³ compared to scenario S5b (Figure 25, left panel). For both scenarios, changes in waste water associated pollutants, such as NH_4-N and P_{dis}, are more significant than for storm water associated pollutants. This indicates that at lower and higher rain intensities, first flush effects are reduced and intensified, respectively. Regarding single CSO events, the absolute change in discharged volumes increases with greater CSO events for both scenarios S5b and S5c (Figure 25, right panel). For more detailed data, see Table 18 and Table 19 in the Appendix.

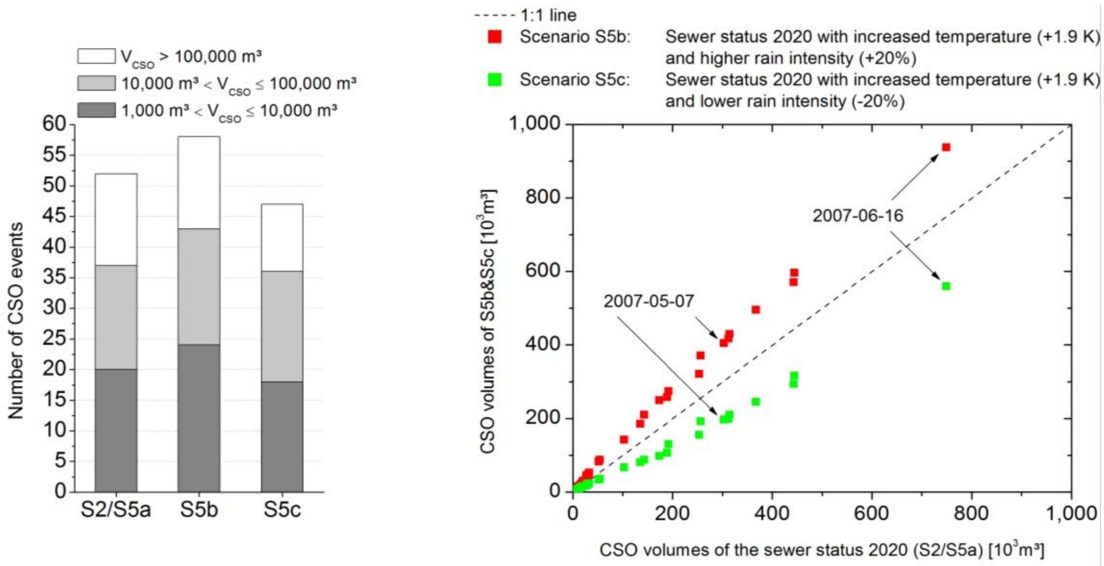

Figure 25: Left panel: Number of CSO events >1,000 m³ for i) the sewer status 2020 (S2), ii) the sewer status 2020 with increased temperature (+1.9 K), iii) the sewer status 2020 with increased temperature (+1.9 K) and higher rain intensity (+20%) and iv) the sewer status 2020 with increased temperature (+1.9 K) and lower rain intensity (-20%). Right panel: Discharged volumes for all 52 CSO events >1,000 m³ simulated for the sewer status 2020 (S2) plotted against the corresponding volumes simulated for i) the sewer status 2020 with increased temperature (+1.9 K) and higher rain intensity (+20%) and ii) the sewer status 2020 with increased temperature (+1.9 K) and lower rain intensity (-20%). The two exemplary events in Figure 26 and Figure 29 on 2007-06-16 and 2007-05-07 are marked.

In the following, increased temperature (scenario S5a) and additionally changed rain intensity (scenarios S5b and S5c) are evaluated separately regarding their impact on DO in the Berlin River Spree. First, the influence of an increase in surface air and water temperatures by 1.9 K (S5a) on suboptimal and critical DO conditions is assessed by comparing results to scenario S2. Subsequently, the effect of increased (S5b) and reduced rain intensity (S5c) is evaluated and compared to the reference scenario S5a, all basing on the same surface air and water temperature.

_Acute CSO impacts, as exemplified for the events on 2007-05-07 and 2007-06-16 in Figure 26, are not notably influenced by an increase in surface air and water temperature. However, a general slight decrease in DO is observed, independent of the occurence of CSO.

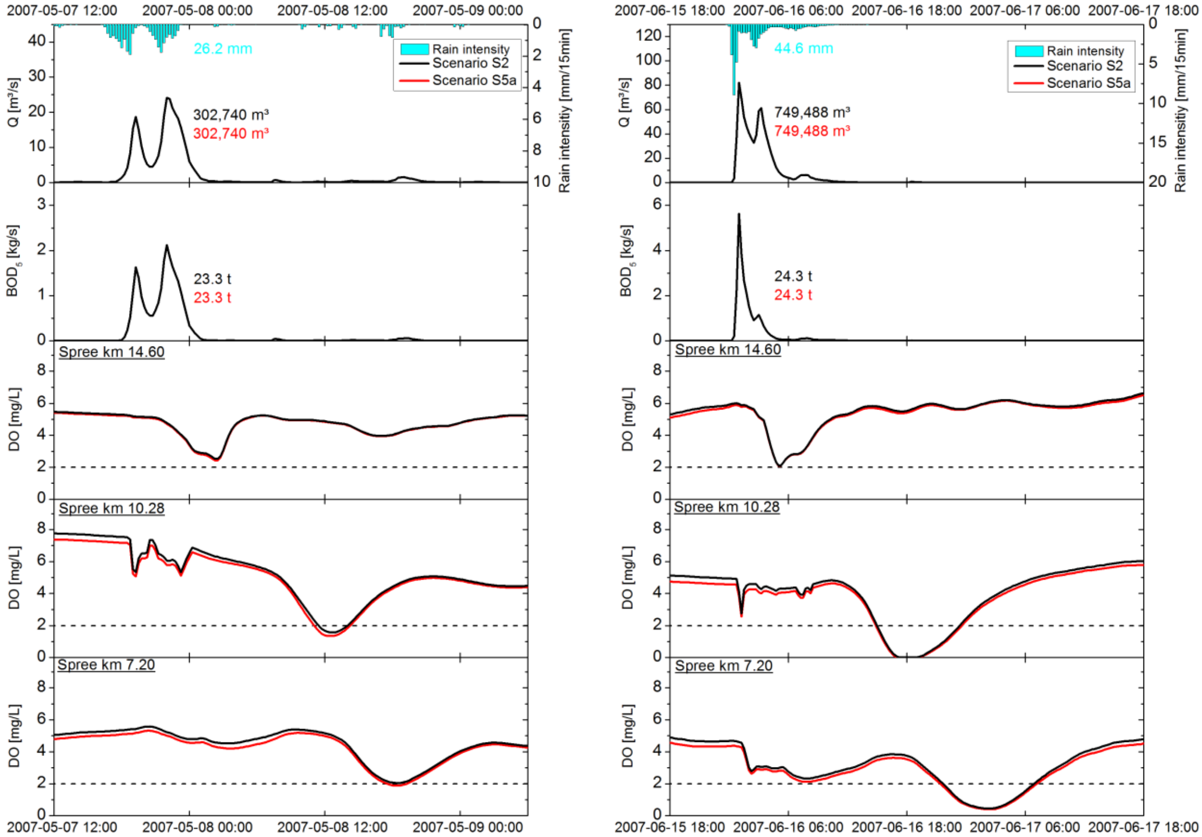

Figure 26: CSO emissions and impacts for two CSO events of the studied time period simulated for i) the sewer status 2020 (S2) and ii) the sewer status 2020 with increased temperature (+1.9 K) (S5a). The upper two panels of each plot show the simulated discharge and BOD_5 mass flow for all simulated CSO outlets as well as measured rain intensity averaged over nine rain gauges within the investigation area. The lower three panels show the simulated DO concentrations at Spree km 14.60, 10.28 and 7.20 (in flow direction). Numbers in the figure indicate total rainfall, CSO volume and BOD_5 load. The dotted line marks the critical concentration for the asp (Aspius aspius).

A temperature increase of 1.9 K influences most processes relevant for the oxygen budget in the Berlin River Spree. Typically, processes leading to oxygen consumption, such as the oxygen flux into the sediment, are intensified whereas oxygen production processes, such as oxygen production by algae or physical oxygen transfer are diminished. As a result, the average DO concentration decreases from 7.5 mg/L to 7.2 mg/L (-3%) at Spree km 7.20. For upstream river stations, the effect is less prononced, since the period with temperature influence on simulated DO is shorter and changes in DO beyond the model boundaries are not considered. Eight-month averages of DO process rates simulated for scenario S2 and S5a are displayed for Spree km 7.20 in Table 10.

Table 10: Oxygen relevant process rates and their relative changes in the Berlin River Spree for sewer status 2020 (S2) and the sewer status 2020 with increased temperature (+1.9 K) (S5a). All processes are averaged for the studied time period at Spree km 7.20 and ordered by their significance for the oxygen budget for scenario S2.

		S2 Sewer status 2020	S5a Sewer status 2020 with increased temperature	
Oxygen flux into the sediments	[mg/(L*d)]	-0.5732	-0.6158	(+7%)
Oxygen production by algae	[mg/(L*d)]	0.1815	0.1699	(-6%)
Physical oxygen transfer	[mg/(L*d)]	0.1094	0.0984	(-10%)
Oxygen demand by BOD degradation	[mg/(L*d)]	-0.0961	-0.1010	(+5%)
Oxygen demand by algae respiration	[mg/(L*d)]	-0.0727	-0.0705	(-3%)
Oxygen demand by zooplankton	[mg/(L*d)]	-0.0273	-0.0313	(+15%)
Oxygen demand by nitrifiers	[mg/(L*d)]	-0.0079	-0.0084	(+6%)

Results of the impact assessment for scenario S5a compared to scenario S2, as shown in Figure 27, indicate that the average frequency of critical DO conditions is slightly increased from 2.6 to 2.9 calendar days due to the temperature increase. No additional events with critical DO concentrations are observed, but duration of occurring deficits is slightly longer, sometimes covering an extra calendar day. For instance at Spree km 6.34 both events of critical DO conditions (2007-06-17 and 2007-06-22) shift into a new calendar day leading to a higher frequency of 2 calendar days, although there is no additional event.

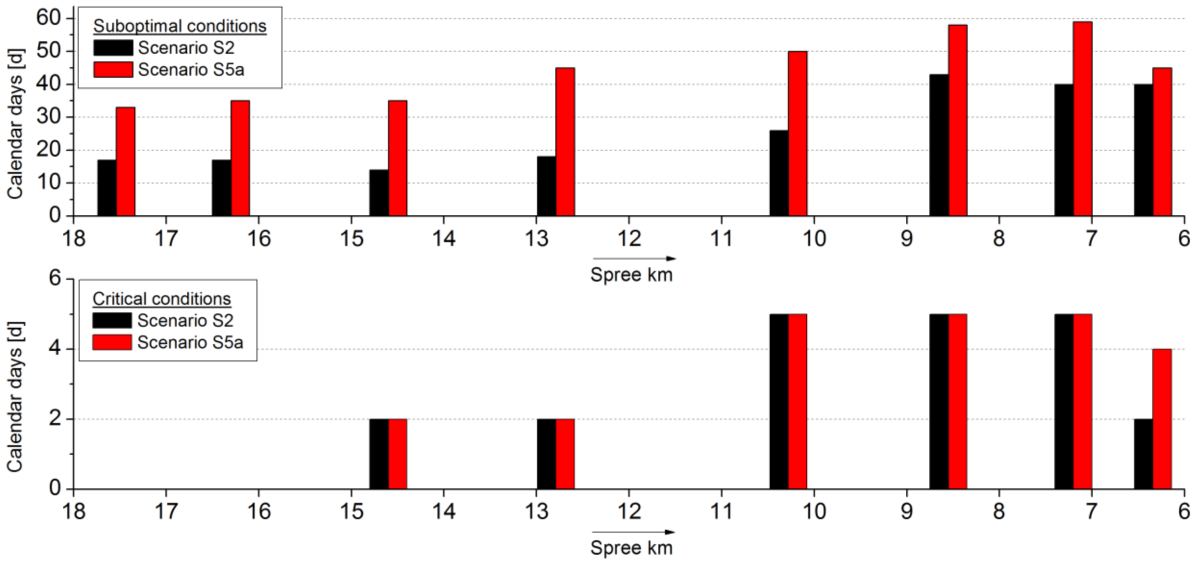

Figure 27: Simulated number of calendar days with suboptimal (upper panel) and critical DO conditions (lower panel) for i) the sewer status 2020 (S2) and ii) the sewer status 2020 with increased temperature (+1.9 K) (S5a). The arrow indicates the flow direction of the River Spree.

While the influence of temperature on the occurrence of critical DO conditions is negligible, the frequency of suboptimal DO conditions is increased by 67% from an average value of 26.9 to 45.0 calendar days for the eight considered river stretches. This aggravation of overall DO stress is due to the combination of the change in processes (Table 10) and an increased oxygen demand by fish and invertebrates. As a consequence of higher temperatures, concentration-duration-thresholds for suboptimal DO conditions as proposed by Lammersen become more stringent (see subchapter 3.3). For instance, the 24h-Lammersen-threshold is not breached in the beginning of June (2007-06-05 to 2007-06-09) for scenario S2, but violated on every day for scenario S5a at Spree km 10.28 (see Figure 28). The related average DO concentration decreases from 5.8 mg/L (S2) to 5.5 mg/L (S5a) while the 24h-Lammersen-threshold increases from an average of 5.4 mg/L (S2) to 5.9 mg/L (S5a).

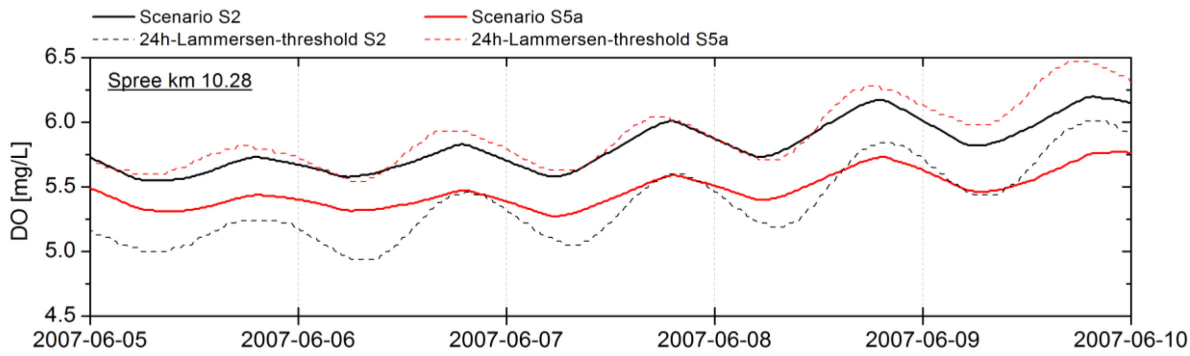

Figure 28: Simulated DO concentrations and 24h-Lammersen-thresholds for the sewer status 2020 (S2) and the sewer status 2020 with increased temperature (+1.9 K) (S5a) at Spree km 10.28.

In the following, the effect of changed rain intensity in combination with increased temperature on DO is evaluated.

During the CSO event on 2007-05-07, 20% higher rain intensity (S5b) leads to 34% more CSO volume containing 24% more BOD_5 load (Figure 29). The larger volumes of oxygen free CSO spill water and higher pollutant loads entering the Berlin River Spree, lead to lower DO concentrations under CSO influence. For the major CSO event on 2007-06-16, the discharged volume increases by 26% while BOD_5 load is almost constant. Due to the intense rainfall, most solids from the surface of the catchment are already washed off for the reference scenario S5a, thus no additional loads can be acquired from this source. However, with increased rain intensity (scenario S5b) DO depressions at all considered river stretches are slightly extended in length, beginning earlier but ending at the same time as for the reference scenario S5a. This effect is due to CSO induced greater flow velocities of the Berlin River Spree, leading to faster transport of pollutant loads (e.g. oxygen consuming BOD_5) that are discharged in the beginning of a CSO event.

Generally, the contrary effect is found for scenario S5c with 20% lower rain intensities, for which impact duration is typically shorter due to lower flow velocities at time of overflow. For the CSO event on 2007-05-07, 35% of CSO volume and BOD_5 load are hold back. While for the major CSO event on 2007-06-16 discharged volume is reduced by 25%, BOD_5 load remains constant, since lowered rain intensity is still strong enough to wash off all solids built-up on the surface of the catchment.

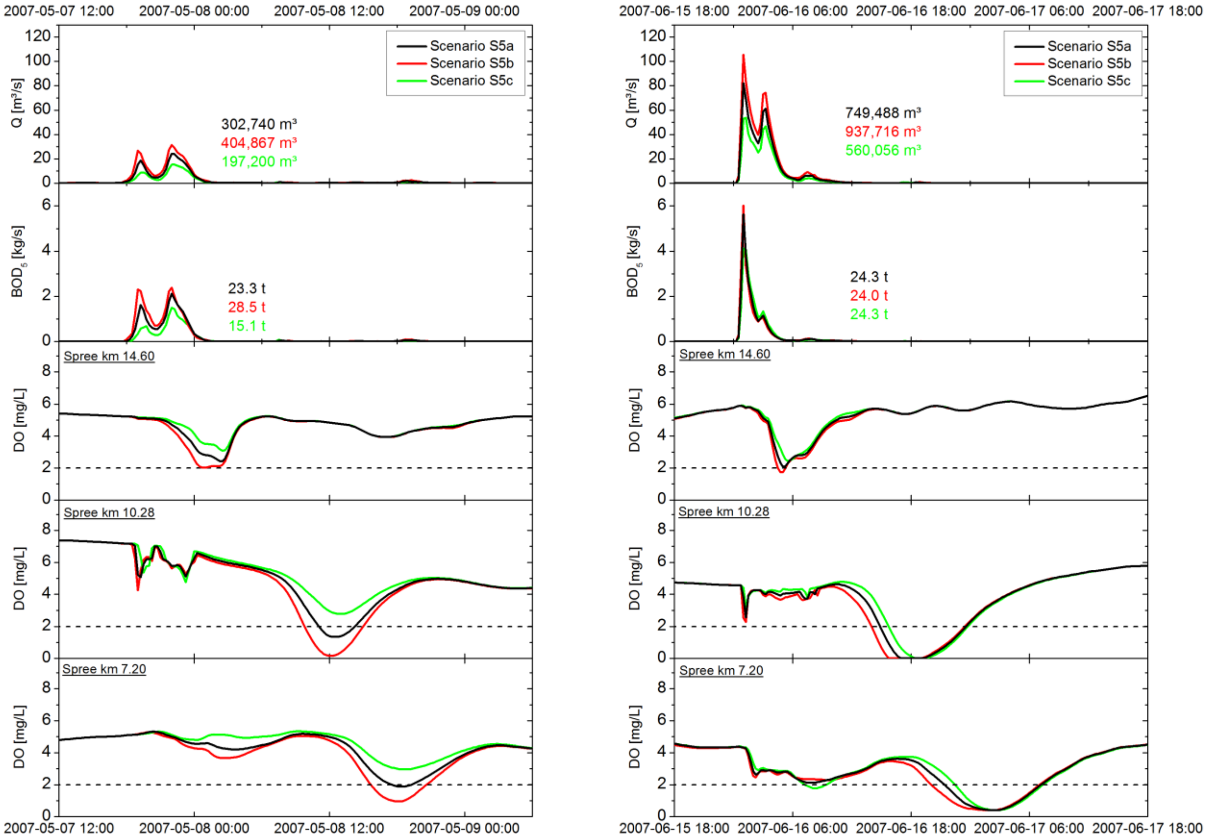

Figure 29: CSO emissions and impacts for two CSO events of the studied time period simulated for i) the sewer status 2020 with increased temperature (+1.9 K) (S5a), ii) the sewer status 2020 with increased temperature (+1.9 K) and rain intensity (+20%) (S5b) and iii) the sewer status 2020 with increased temperature (+1.9 K) and reduced rain intensity (-20%) (S5c). The upper two panels of each plot show the simulated discharge and BOD_5 mass flow for all simulated CSO outlets within the investigation area. The lower three panels show the simulated DO concentrations at Spree km 14.60, 10.28 and 7.20 (in flow direction). Numbers in the figure indicate CSO volume and BOD_5 load. The dotted line marks the critical concentration for the asp (Aspius aspius).

The frequency of suboptimal DO conditions is only slightly affected by changed rain intensity (Figure 30, upper panel). The average value for the eight considered river stretches for scenario S5b is 46.1 calendar days (+3%) and 44.0 calendar days (-2%) for scenario S5c. At the upper model boundary (Spree km 17.54), the occurrence of suboptimal DO conditions for the scenarios S5a, S5b and S5c is identical due to constant water quality input data, measured at Mühlendamm for the test year 2007 (see subchapter 3.2, Figure 4) and modified systematically regarding surface air and water temperature.

The average frequency of critical DO conditions for scenario S5b with 20% higher rain intensity is 4.3 calendar days, +48% more than for the reference scenario S5a. For scenario S5c with 20% lower rain intensity the average frequency of critical DO conditions is reduced by 38% to 1.8 calendar days, compared to the reference scenario S5a. Critical DO conditions at Spree km 14.60 are prevented completely.

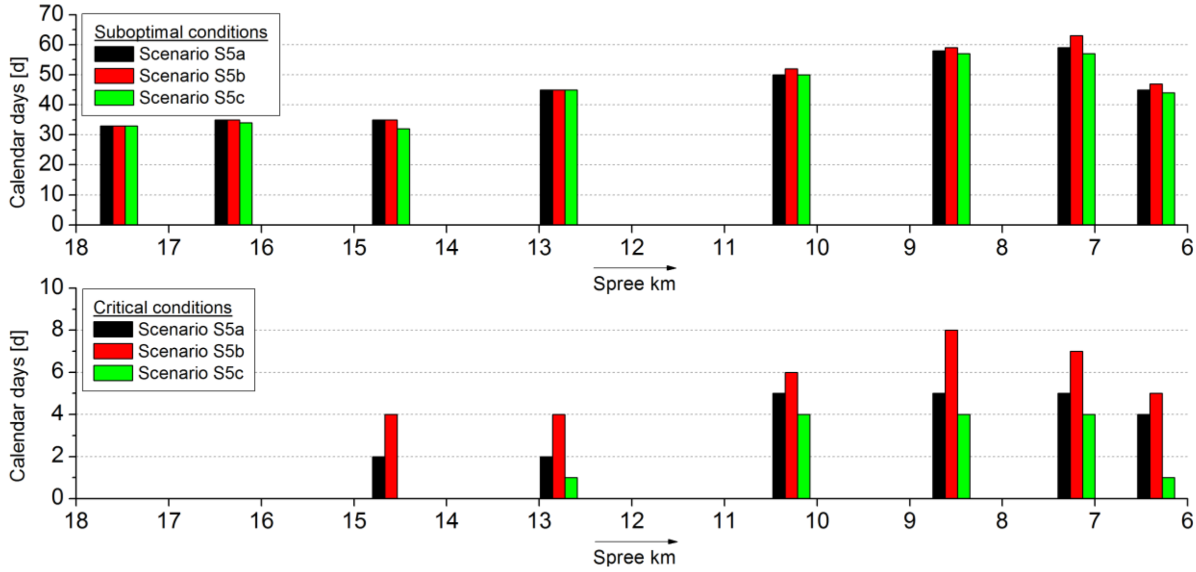

Figure 30: Simulated number of calendar days with suboptimal (upper panel) and critical DO conditions (lower panel) for i) the sewer status 2020 with increased temperature (+1.9 K) (S5a), ii) the sewer status 2020 with increased temperature (+1.9 K) and rain intensity (+20%) (S5b) and iii) the sewer status 2020 with increased temperature (+1.9 K) and reduced rain intensity (-20%) (S5c). The arrow indicates the flow direction of the River Spree.

5.5 Comparative summary of scenarios

For the four CSO management scenarios S1-S4 and the scenario year 2007, a linear correlation between discharged pollutant loads, in particular BOD_5 and COD, and the average frequency of critical DO conditions was found (R^2=0.99). Under consideration of that linear relationship critical DO concentrations could be prevented if discharged BOD_5 loads were reduced to 102.1 t. A comparable but slightly weaker correlation ($R^2=0.95$) was found between discharged CSO volume and the frequency of critical conditions.

The reduction of the impervious connected area (S4) is the most effective studied CSO control measure regarding the reduction in CSO volume, pollutant loads and frequency of critical DO conditions. However, scenario S5c with increased temperature and decreased rain intensity is the only scenario distinctly reducing the number of CSO events.

For scenario S4 (reduction of the impervious connected area by 20%) and scenario S5c (reduction of rainfall intensity by 20%) a comparable CSO volume is expected. However, absolute reduction in CSO volume for scenario S5c (1,589,000 m³) is slightly greater (~3%) than for scenario S4 (1,537,000 m³). This can be explained by rainfall losses on the surface of the catchment, e.g. by depression storage at the beginning of a rainfall event, which in total are smaller for scenario S4 with reduced impervious area. In contrast, pollutant loads, in particular those originating from storm water, are reduced more effectively for scenario S4 where pollutants are built up and washed off only on 80% of the initial area.

None of the studied CSO control measures (S1-S4) can significantly reduce overall DO stress for aquatic organisms, which is mostly related to background pollution effects. Likewise, changes in rainfall intensity (S5b, S5c) do not result in less frequent suboptimal DO conditions. In contrast, increase in surface air and water temperature by 1.9 K (S5a) leads to 67% more frequent suboptimal DO conditions in the Berlin River Spree.

Results obtained with the coupled model tool for four CSO management scenarios (S1-S4) and three climate change scenarios (S5a-S5c) are summarized in Table 11.

Table 11: Summary of scenario results for the simulation period April to November 2007.

		Planned sewer rehabilitation measures		Further management strategies		Climate Change effects		
		S1	**S2**	**S3**	**S4**	**S5a**	**S5b**	**S5c**
		Sewer status 2010	Sewer status 2020 (with implemented sewer rehabilitation measures)	Sewer status 2020 with increased storage volume	Sewer status 2020 with reduced impervious connected area	Sewer status 2020 with increased temperature	Sewer status 2020 with increased temperature and higher rain intensity	Sewer status 2020 with increased temperature and lower rain intensity
Storage volume within investigation area	[$10^3 m^3$]	191.9	280.1	316.7	280.1	280.1	280.1	280.1
Discharged volume	[$10^6 m^3$]	5.9	4.9	4.6	3.3	4.9	6.6	3.3
Discharged load of - BOD_5	[t]	353.7	273.0	247.3	181.9	273.0	330.7	206.0
- COD	[t]	960.2	744.7	676.2	497.5	744.7	890.6	572.6
- TSS	[t]	839.5	663.3	605.1	441.6	663.3	800.9	503.3
- NH_4-N	[t]	12.2	8.4	7.3	5.7	8.4	10.9	5.7
- TKN	[t]	25.6	18.2	16.0	12.3	18.2	23.0	13.0
- P_{dis}	[t]	2.3	1.7	1.5	1.1	1.7	2.1	1.2
- TP	[t]	4.1	3.0	2.7	2.0	3.0	3.7	2.2
CSO events >1,000 m^3	[n]	52	52	52	51	52	58	47
CSO events >1,000 and ≤10,000 m^3	[n]	18	20	20	22	20	24	18
CSO events >10,000 and ≤1000,000 m^3	[n]	19	17	18	19	17	19	18
CSO events >100,000 m^3	[n]	15	15	14	10	15	15	11
Average number of								
- Suboptimal DO conditions	[d]	27.5	26.9	26.5	25.0	45.0	46.1	44.0
- Critical DO conditions	[d]	3.9	2.6	2.1	1.3	2.9	4.3	1.8

6 Extended sensitivity analysis

Theoretically, CSO control measures can i) reduce CSO volume (e.g. by increasing the storage volume), ii) reduce CSO pollutant concentrations (e.g. by end-of-pipe treatment) and iii) increase DO levels in CSO spill water (e.g. by oxygen-diffusers in overflow sewers) or lead to a combination of the above. With the aim to i) detect measures that allow an overall prevention of critical DO conditions and ii) distinguish and better understand CSO related river processes, CSO boundary conditions are changed systematically within an extended sensitivity analysis.

6.1 Methodology

In addition to the scenarios described in subchapter 5.1, the effect of different CSO boundary conditions (discharge, pollutant concentrations and DO in CSO spill water) on the quality of the receiving water body is analysed in more detail. By that, boundary conditions can be derived at which critical DO conditions are unlikely to occur or at least can be significantly diminished.

The analysis is based on the simulation for the sewer status 2020 and the scenario year 2007 (scenario S2 as described in subchapter 5.1). It focuses on a CSO event on 2007-06-16, which led to the most intense and longest-lasting critical DO condition of the simulation period April to November 2007. Time series for simulated CSO discharge and pollutant concentrations for all 67 CSO outlets are modified systematically by multiplication with a factor before being used as boundary conditions for river water quality modelling in Hydrax/QSim. The following, modifications in CSO boundary conditions are considered:

1. Reduction of CSO discharge by 10, 20, 30, 40 and 50%,
2. Reduction of all pollutant concentrations in CSO by 10, 20, 30, 40 and 50%,
3. Increase of DO concentration in CSO spill water to 1, 2, 3, 4 and 5 mg/L.

First, the listed modifications are done one-at-a-time. Then, all possible combinations of reducing the discharge and pollutant concentrations of CSO are considered. By these modifications, the implementation of further measures such as an additional increase of the storage volume, the installation of CSO treatment technologies or the aeration of the CSO spill water at the outlet is taken into account. Even though the simulations require a rough simplification of possible measures they can indicate to which extent CSO discharges or concentrations have to be reduced to prevent the most intense DO drop within the simulation period.

Apart from the information on breached concentration-duration-thresholds, different processes responsible for the observed DO drop are analysed by modifying simulated CSO boundary conditions. Based on the simulation for the sewer status 2020 (S2), the model Hydrax/QSim is run several times, each time neglecting one CSO state variable entirely. By that, the influence of different CSO boundary conditions on the simulated DO drop can be evaluated. The following processes, which are expected to have a major impact on DO concentrations in receiving water bodies, have been analysed:

1. Biodegradation of organic carbon compounds (via BOD5 and COD, combined),
2. Mixing of oxygen free CSO spill water (via DO),
3. Inhibition of photosynthesis due to increased turbidity (via TSS),
4. Nitrification and other processes (via NH4-N and other state variables).

For instance, if no input data of CSO boundary conditions for TSS are provided, TSS in CSO spill water will be assumed to be equal to the river concentration. For that particular state variable, river water quality will not be influenced by CSO. In comparison with the original simulation of scenario S2, the effect of TSS on DO in the river can be assessed.

The analysis is done for the DO deficit following the major CSO event on 2007-06-16. To cover the development of studied processes along the Berlin River Spree, results are shown for six stations in distances of approx. 2 km. In contrast to impact assessment in chapter 1, Spree km 17.54 and 6.34 are not considered for the following reasons. Spree km 17.54 represents the upper model boundary and is therefore not affected by changes in CSO emissions. At Spree km 6.34 CSO induced DO depression lasts very long and cannot be clearly distinguished from the impacts of the following event.

6.2 Results and discussion

As shown in chapter 5 (scenario analysis), a reduction of CSO pollutant loads can significantly reduce acute DO stress after intense storm events. Anyway, with the limited number of studied scenarios not the entire range of expected river impacts can be covered. To overcome these limitations, the following subchapter discusses the systematic variation of CSO discharges and concentrations for the most severe CSO event of the simulation period.

By reducing 50% of CSO discharges over the entire duration of the chosen event (see subchapter 6.1), critical DO conditions in the Berlin River Spree can be fully prevented, even under the extreme conditions of the scenario year 2007. The same reduction of CSO pollutant concentrations has a comparable but slightly smaller effect on DO (Figure 31, Panel a-c). Likewise, the absolute duration of critical DO conditions for all studied reductions of CSO discharges (-10, 20, 30, 40 and 50%) is marginally shorter than for reduced pollutant concentrations (Figure 31, panel e and f).

Even though both measures account for the same reduction in pollutant loads, the effect is slightly different for the following reason. Based on the assumption that DO concentration in CSO spill water is 0 mg/L (anaerobic conditions), the inflow of large CSO volume can impair the oxygen budget of the river even without taking into account any degradation processes. In contrast to an only decrease of pollutant concentrations, the reduction in discharges does not only reduce pollutant loads but also implies a volume reduction of oxygen free CSO spill water, additionally improving the oxygen budget of the river.

In this context, an increase of the DO concentration in CSO spill water to 5 mg/L can temporarily improve the water quality downstream of big CSO outlets (Figure 31, panel a to c). The duration of critical DO conditions seems to decrease linearly when increasing the DO concentration in CSO spill water from 0 to 5 mg/L (Figure 31, panel h and i). However, it is less effective regarding the prevention of critical DO concentrations below 2 mg/L. Such conditions typically occur at some spatial and temporal distance to big CSO outlets when biodegradation had already led to significant oxygen consumption.

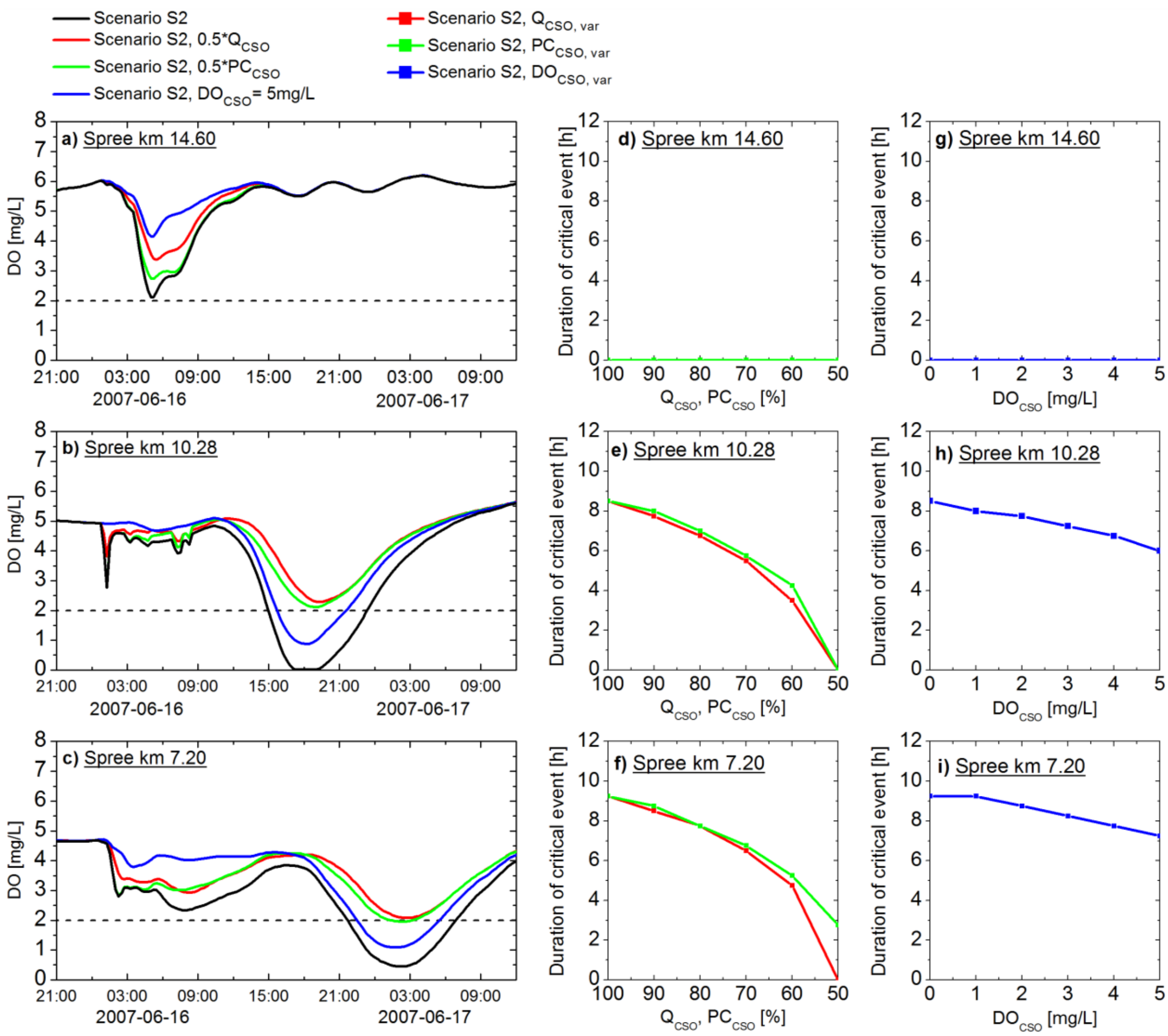

Figure 31: Panel a-c: Time series plots for dissolved oxygen for i) the sewer status 2020 (S2, black line), ii) the sewer status 2020 with CSO discharges reduced by 50% (red line), iii) the sewer status 2020 with CSO pollutant concentrations reduced by 50% (green line) and iv) sewer status 2020 with 5 mg/L dissolved oxygen in CSO spill water (blue line) for the major CSO event on 2007-06-16 and three river stations (Spree km 14.60, 10.28 and 7.20). Dotted line marks the critical concentration for the asp (Aspius aspius). Panel d-f: Absolute duration of critical DO conditions due to this CSO event for sewer status simulation 2020 and progressively reduced CSO discharges ($Q_{CSO,var}$) and pollutant concentrations ($PC_{CSO,var}$). Panel g-i: Absolute duration of critical DO conditions due to this CSO event for sewer status simulation 2020 and progressively increased dissolved oxygen concentrations in CSO spill water ($DO_{CSO,var}$).

For time series plots of reduced CSO discharges and pollutant concentrations by 10, 20, 30 and 40% as well as increased DO concentrations in CSO spill water to 1, 2, 3 and 4 mg/L, see Figure 34, Figure 35, Figure 36, Figure 37 in the Appendix.

Figure 32 displays minima of occurred DO concentrations during the major CSO event on 2007-06-16 at three river stretches concerning various combinations of these potential measures. Due to the relatively high significance of oxygen free CSO spill water (see Figure 33), the reduction of discharged volume increases DO concentrations at Spree km 14.60 more effectively than a decrease in pollutant concentrations. For instance, CSO volume has to be reduced only by 20% (at constant pollutant concentrations) to reach a DO concentration of 2.5 mg/L (point A in Figure 32). In contrast, 30% lower pollutant concentrations (at constant CSO volume) is necessary for the same effect (point B in Figure 32).

At the stations Spree km 10.28 and 7.20 the reduction of CSO pollutant loads by implementing additional storage volume or end-of-pipe filters have comparable effects on the DO concentration, as indicated by parallel DO-isolines in Figure 32. However, at Spree km 10.28 absolute changes in DO at a given variation of boundary conditions are more significant with a possible increase of the lowest DO concentration from 0 to 3 mg/L if CSO volume and pollutant concentrations are both reduced by 40% (point C in Figure 32).

For Spree km 7.20 comparably larger variations of simulated CSO volume and pollutant concentrations are required for the same relative effect on DO. This can be explained by the fact that this river stretch is significantly impaired by CSO outlets upstream of the model boundaries (see subchapter 3.2, Figure 4), which cannot be considered for sensitivity analysis.

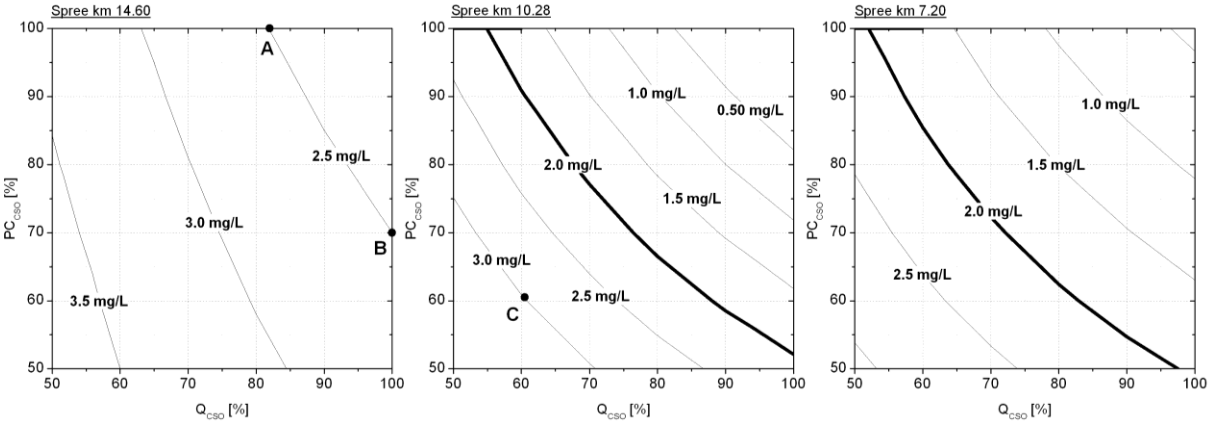

Figure 32: Minima of dissolved oxygen concentrations at Spree km 14.60 (upstream of most CSO outlets), 10.28 and 7.20 (downstream of most CSO outlets) occurring due to the major CSO event on 2007-06-16 for combinations of progressively reduced discharges Q_{CSO} and pollutant concentrations PC_{CSO} based on the sewer status 2020 (S2). Thick line marks the critical concentration for the asp (Aspius aspius). Points A, B and C represent examplary sets of boundary conditions explained in more detail in the text.

In consideration of the major CSO event in 2007 and roughly simplified model implementation of possible measures, combinations of reduced CSO discharges and concentrations can be derived. For instance, a reduction of CSO volume by 20% in combination with 40% lowered CSO pollutant concentrations can prevent critical DO conditions after CSO at the three considered river stretches (Spree km 14.60, 10.28 and 7.20).

The above studied scenarios aim at testing model sensitivity to CSO boundary conditions and represent CSO control measures in a very simplified way. For instance, it has been assumed that the relative reduction of CSO volume is the same for small and large events and is equally distributed over the entire duration of each event. Regarding the reduction of CSO pollutant concentrations it is assumed that both particulate and dissolved pollutants can be hold back to the same extent.

Following the hypothesis that there are three main processes that lead to the observed DO drop after CSO in the Berlin River Spree – biodegradation of organic compounds, inflow of oxygen free CSO spill water and turbidity-induced reduction in algae growth – additional model runs have been conducted to quantify the relative effect of these processes. They are based on the simulation for the sewer status 2020 (S2) and imply the neglect of i) BOD_5 and COD concentrations in CSO (combined), ii) oxygen free CSO spill water and iii) TSS concentrations in CSO. This is realised by assuming that the respective state variable in CSO is equal to that of the receiving river. Results are shown in Figure 33.

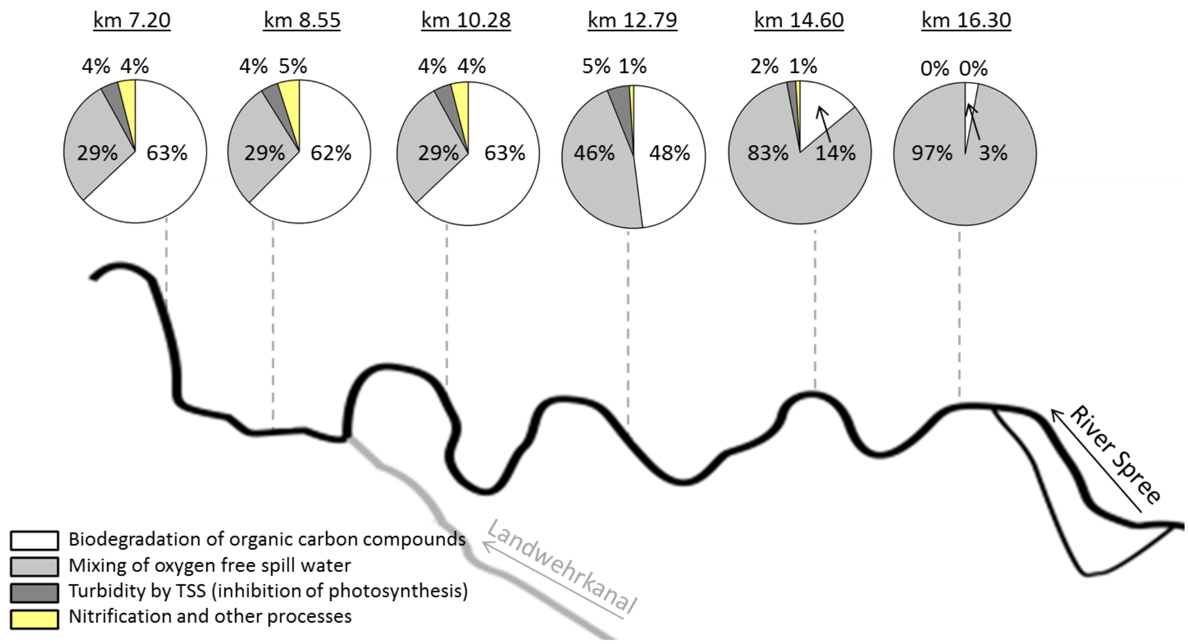

Figure 33: Simulated significance of the state variables i) BOD_5 and COD (combined), ii) DO and iii) TSS on the DO deficit following the CSO event on 2007-06-16 for the sewer status 2020 with implemented sewer rehabilitation measures (S2). The arrows indicate the flow direction of the River Spree and the side channel Landwehrkanal.

At Spree km 16.30, which is mainly influenced by a CSO outlet at Spree km 16.65, which contributes 14% of the total CSO volume discharged on 2007-06-16, oxygen free CSO spill water causes 97% of the occurring DO deficit. Due to the short distance (350 m) and associated travel time (45 min), degradation processes are still of minor importance. At longer distance to the major upstream CSO outlets, biodegradation of organic compounds (expressed via BOD_5 and COD) gets more important. The highest contribution of this process to the overall DO deficit (63%) is observed at Spree km 10.28.

The decrease in DO concentrations due to TSS induced processes, such as the inhibition of photosynthesis by turbidity, ranges from 0 to 5% reaching a maximum at Spree km 12.79. It has been observed that all other processes, such as nitrification, affect DO deficits after CSO by less than 5%.

7 Conclusion

A planning instrument for integrated and impact based CSO control under climate change conditions has been developed and demonstrated in Berlin. After a detailed validation, the planning instrument was tested for different management and climate change scenarios followed by an extended sensitivity analysis on selected CSO boundary conditions.

Model validation shows that results of the coupled sewer-river-model applied for CSO impact assessment in the Berlin River Spree fit well with measurements, both at dry weather as well as under the influence of CSO. Although not all observed DO deficits can be simulated accurately, the very good representation of processes influencing the oxygen budget allows assessing relative changes in boundary conditions, e.g. from different CSO control measures.

The performed scenario and extended sensitivity analysis indicate that the coupled sewer-river-model reacts sensitively to changes in boundary conditions such as temperature, rainfall, storage volume or other CSO control strategies. Further, the observed reactions for the different scenarios are reasonable and follow the expected tendency. Site-specific measures within the model boundaries can be assessed regarding relative changes in emissions (CSO volume and discharged pollutant loads) and impacts (suboptimal and critical DO conditions). Hot spots in the Berlin water system and related CSO outlets can be detected and studied to locate cost-efficient measures.

By applying the planning instrument on various CSO control strategies and climate change effects in the framework of the scenario analysis and extended sensitivity analysis the following conclusions can be drawn:

- The frequency of critical DO concentrations in the Berlin River Spree correlates with CSO volumes and discharged pollutant loads.
- Planned sewer rehabilitation measures until 2020 significantly reduce discharged pollutant loads and CSO impacts on the Berlin River Spree.
- An additionally reduction of the impervious connected area is a very effective measure to further reduce CSO volume, discharged pollutant loads and the frequency of critical DO concentrations in the Berlin River Spree.
- For the extreme conditions of the scenario year 2007 and the sewer status 2020, a complete prevention of critical DO conditions can be achieved with the reduction of CSO pollutant loads by 60%.
- Despite the reduction in CSO volume, the studied management scenarios do not lead to a change in overflow frequency, which in contrast is the case for the studied rainfall scenarios.
- A higher temperature due to climate change significantly increases overall DO stress for aquatic organisms in the Berlin River Spree but has no significant effect on acute impacts after CSO.
- The primary cause for critical DO concentrations for fish after CSO is the inflow and biodegradation of organic carbon compounds.
- Mixing of oxygen free CSO spill water into the Berlin River Spree is the second most important process and immediately impairs its oxygen budget after CSO.

Although the coupled model – consisting of InfoWorks CS, Hydrax/QSim as well as the impact assessment tool – provides a reliable picture of relative changes of CSO impacts on the Berlin River Spree under different CSO control strategies, the following uncertainties and assumptions have to be taken into account:

- The sewer model InfoWorks CS was calibrated and validated for only one sewer subcatchment. Parameter values for the description of build-up/wash-off on impervious connected surfaces were then transferred to all other subcatchments of the combined sewer system.
- Sedimentation and transformation processes in the sewer are largely neglected.
- The model considers one pluviograph per 10 km^2, which does not allow to fully capture local rainfall dynamics.
- CSO state variables that are not simulated are assumed to be constant. However, certain variables, such as electrical conductivity which is related to the highly variable storm water ratio, can vary considerably.
- Input data for Hydrax/QSim are partly based on daily averages regarding hydraulics and monthly grab samples regarding water quality. In consequence, dynamics of some state variables, such as Chlorophyll-a, cannot be fully reflected.
- Model boundaries don't cover all CSO outlets affecting the studied water system. As a consequence, measures or changes beyond model boundaries are neglected.

In respect of these uncertainties the following steps are proposed for future application of the presented planning instrument.

- It is suggested to validate the sewer model InfoWorks CS for a second subcatchment, which is currently done in the framework of the research project MIME carried out by Berliner Wasserbetriebe (BWB).
- The expansion of the model boundaries is recommended to represent all water bodies affected by CSO impacts and fully quantify the potential benefit from CSO control measures.
- Further, a critical discussion of the simulation time period (e.g. long term simulations, use of one standard year, averaging of long-term input data to a mean scenario period) should be started.
- If the model tool is used by decision-makers for detailed planning, not only environmental impacts but also costs for the implementation of measures should be included.
- Finally, an extension of measurements for rainfall, river hydraulics and water quality can lead to an improvement of overall model performance and to a more accurate prediction of CSO impacts.

8 Appendix

Table 12: Parameter values concerning phytoplankton dynamics in the river water quality model Hydrax/QSim

Parameter	Unit	Green algae	Diatoms	Blue-green algae
Chlorophyll/biomass ratio	µgChla/mgBio	21.5	21.5	21.5
Max. growth rate	1/d	1.8	1.6	1
Light saturation for photosynthesis	µE/(m²*s)	88	39	34
Half saturation constant for N	mg/L	0.048	0.018	0.02
Half saturation constant for P	mg/L	0.022	0.02	0.02
Half saturation constant for Si	mg/L	-	0.08	-
Basal respiration	1/d	0.085	0.085	0.085
Growth-dependent respiration (portion of growth-rate)	-	0.2	0.2	0.2
BOD_5-increase	mg/µgChla	0.004	0.021	0.004
COD-increase	mg/µgChla	0.073	0.105	0.073
Max. N-content of algae cell	mg/mgBio	0.049	0.1	0.085
Max. P-content of algae cell	mg/mgBio	0.012	0.009	0.007
Max. Si-content of algae cell	mg/mgBio	-	0.18	-
Min. N-content of algae cell	mg/mgBio	0.008	0.017	0.014
Min. P-content of algae cell	mg/mgBio	0.0016	0.0011	0.0009
Min. Si-content of algae cell	mg/mgBio	-	0.18	-
Max. N-uptake	1/d	0.09	0.31	0.31
Max. P-uptake	1/d	0.69	0.62	0.62
Max. Si-uptake	1/d	-	2.5	-
Min. DO-production	mg/mgBio	1.3	1.3	1.3
Max. DO-production	mg/mgBio	1.8	1.8	1.8
Sedimentation coefficient	0-1	0.5	0.5	0
Filterability	0-1	0.8	0.6	0.1

Table 13: Parameter values concerning rotifers, mussels, heterotrophic nanoflagellates, nitrogen, degradation of carbon and others applied in the river water quality model Hydrax/QSim

	Parameter	**Unit**	**Value**
Rotifers	Max. ingestion rate	µgC/(µgC$^{2/3}$*d)	2.9
	Half saturation constant for food ingestion	mg/L	0.43
	Rotifer weight	µg	0.3
	Basal respiration	1/d	0.03
Mussels	Optimal food concentration for Dreissena	mgC/L	1.2
Heterotrophic nanoflagellates	Max. uptake	1/d	1.61
	Half saturation constant for bacteria uptake	mgC/L	0.0143
Nitrogen	Max. growth rate of Nitrosomonas	1/d	1.08
	Half saturation constant of Nitrosomonas	mgNH_4-N/L	0.48
	Mortality rate of Nitrosomonas	1/d	0.1
	Max. turnover of Nitrosomonas	gNH_4-N/(m^2*L)	2.4
	Half saturation constant of sessile Nitrosomonas	mg/L	3.7
	Max. growth rate of Nitrobacter	1/d	1.1
	Half saturation constant of Nitrobacter	mgNO_2-N/L	1.3
	Mortality rate of Nitrobacter	1/d	0.1
	Max. turnover of Nitrobacter	gNO_2-N/(m^2*L)	4.9
	Half saturation constant of sessile Nitrobacter	mg/L	1.2
	NH_4-turnover rate in sediment	m/d	0.25
	Denitrification rate in sediment	m/d	0.32
Degradation of carbon	Hydrolysis rate of easily degradable particulate organic carbon	1/d	0.12
	Hydrolysis rate of easily degradable dissolved organic carbon	1/d	18
	Half saturation constant for hydrolysis of easily degradable dissolved organic carbon	mgC/L	0.25
	Half saturation constant for hydrolysis of refractory dissolved organic carbon	mgC/L	2.5
	Half saturation constant for degradation of monomeric carbon	mgC/L	0.1
	Max. uptake rate of monomeric carbon by bacteria	1/d	24.7
	Yield coefficient of bacteria biomass	-	0.25
	Basal respiration of heterotrophic bacteria	1/d	0.03
Others	Absorption coefficient of yellow substance at 440nm	-	0.75

Table 14: Simulated CSO volumes and pollutant loads for single CSO events >1,000 m³ of all 67 CSO outlets within the model system for the sewer status 2010 (S1), simulated time period April to November 2007.

Beginning	End	Duration	V	BOD_5	COD	TSS	NH_4-N	TKN	P_{dis}	TP
		[min]	[m³]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]
2007-05-07 11:45	2007-05-09 18:15	3,285	345,287	27,221	86,814	59,789	926	1,966	262	404
2007-05-10 04:15	2007-05-11 23:45	2,625	83,436	5,384	13,859	11,128	266	551	43	75
2007-05-12 08:00	2007-05-13 16:15	1,950	55,698	4,654	11,717	11,060	114	315	19	45
2007-05-14 01:45	2007-05-14 09:45	495	16,766	1,552	3,873	3,890	28	86	5	13
2007-05-14 19:30	2007-05-16 04:00	1,965	229,814	14,310	36,326	30,647	640	1,328	102	186
2007-05-16 20:00	2007-05-17 08:30	765	19,674	843	2,241	1,563	56	101	9	14
2007-05-25 18:30	2007-05-26 08:15	840	234,313	18,688	52,571	50,376	397	884	94	167
2007-05-26 16:30	2007-05-28 04:45	2,190	181,625	10,749	28,132	27,242	341	676	60	107
2007-05-28 18:00	2007-05-30 18:45	2,940	396,725	19,472	49,126	47,560	709	1,359	114	205
2007-06-05 03:30	2007-06-05 11:00	465	1,108	28	70	68	1	2	0	0
2007-06-12 19:00	2007-06-13 01:45	420	1,817	50	130	123	2	3	0	0
2007-06-15 01:00	2007-06-15 10:45	600	10,357	524	1,590	1,339	6	22	2	5
2007-06-16 00:30	2007-06-17 08:00	1,905	782,935	26,907	70,644	71,309	822	1,531	149	255
2007-06-21 11:15	2007-06-23 20:00	3,420	407,470	27,621	71,118	59,855	1,192	2,500	195	353
2007-06-25 18:30	2007-06-26 04:45	630	4,401	117	326	283	0	6	0	1
2007-06-26 12:15	2007-06-26 23:00	660	12,872	1,055	2,814	2,461	23	72	5	11
2007-06-27 13:45	2007-06-27 23:30	600	2,235	282	762	755	0	10	0	2
2007-06-28 13:00	2007-06-29 01:45	780	10,814	1,283	3,351	2,762	50	113	8	16
2007-06-29 17:45	2007-06-30 02:00	510	6,381	940	2,380	2,181	29	69	5	10
2007-06-30 08:45	2007-06-30 19:15	645	1,869	60	174	141	0	4	0	1
2007-07-04 09:30	2007-07-06 00:45	2,370	184,725	18,431	48,356	42,344	634	1,416	111	210
2007-07-06 17:30	2007-07-08 05:15	2,160	50,602	5,111	13,112	12,056	144	353	25	53
2007-07-09 21:00	2007-07-10 21:15	1,470	81,480	4,518	11,721	10,551	109	326	20	48
2007-07-11 15:30	2007-07-12 16:45	1,530	45,427	2,100	5,483	4,226	108	219	18	31
2007-07-17 05:00	2007-07-18 02:15	1,290	10,446	1,259	3,276	3,428	8	45	2	8
2007-07-20 07:45	2007-07-20 18:00	630	7,734	641	1,846	1,659	3	25	2	5
2007-07-22 06:15	2007-07-23 12:45	1,845	478,924	29,009	77,928	73,245	815	1,748	158	289
2007-07-24 14:30	2007-07-25 09:30	1,155	1,669	54	140	96	4	7	1	1

Beginning	End	Duration	V	BOD_5	COD	TSS	NH_4-N	TKN	P_{dis}	TP
		[min]	[m³]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]
2007-07-28 10:15	2007-07-28 21:45	705	2,782	98	257	153	9	16	1	2
2007-07-29 14:30	2007-07-30 20:30	1,815	46,072	2,257	7,284	3,907	149	275	30	44
2007-08-08 15:00	2007-08-09 06:00	915	281,283	11,278	32,531	28,902	338	667	75	121
2007-08-11 07:45	2007-08-12 15:00	1,890	133,139	12,404	32,901	32,002	251	648	51	108
2007-08-15 22:15	2007-08-16 16:15	1,095	15,255	1,244	3,609	2,960	23	73	6	13
2007-08-21 03:00	2007-08-23 10:45	3,360	531,512	35,350	92,980	90,726	1,094	2,191	198	348
2007-08-24 03:00	2007-08-25 09:15	1,830	372,546	14,328	36,596	36,611	436	887	74	138
2007-08-30 20:45	2007-08-31 08:30	720	1,197	43	111	96	2	4	0	0
2007-08-31 16:00	2007-09-01 10:15	1,110	1,477	47	122	104	2	4	0	1
2007-09-03 03:30	2007-09-04 23:45	2,670	213,904	18,989	50,159	39,477	1,064	1,958	177	280
2007-09-10 07:15	2007-09-10 23:15	975	50,658	3,767	11,010	7,723	148	355	31	55
2007-09-18 01:30	2007-09-18 19:00	1,065	29,439	1,498	4,958	2,532	100	193	21	31
2007-09-25 10:30	2007-09-25 16:45	390	1,292	29	120	51	1	3	0	1
2007-09-27 18:30	2007-09-30 01:45	3,330	340,151	23,786	63,697	53,055	829	1,898	151	287
2007-10-17 23:00	2007-10-18 06:30	465	3,126	141	366	365	0	6	0	1
2007-11-02 13:00	2007-11-03 01:15	750	1,847	37	123	85	0	2	0	0
2007-11-06 01:45	2007-11-06 21:00	1,170	25,921	1,031	7,906	1,291	55	88	34	39
2007-11-07 05:00	2007-11-07 20:15	930	34,382	1,513	5,558	2,086	145	242	30	39
2007-11-09 01:45	2007-11-10 01:00	1,410	27,782	914	2,645	1,724	47	106	9	15
2007-11-10 16:15	2007-11-12 00:45	1,965	41,398	1,301	3,724	2,097	104	195	18	27
2007-11-12 07:45	2007-11-12 22:45	915	1,267	22	55	49	0	2	0	0
2007-11-23 08:30	2007-11-23 22:15	840	5,521	148	395	275	7	19	1	2
2007-11-25 05:15	2007-11-25 22:30	1,050	8,929	173	1,166	236	8	16	5	6
2007-11-29 21:30	2007-11-30 16:15	1,140	6,398	130	1,279	156	2	6	5	5

Table 15: Simulated CSO volumes and pollutant loads for single CSO events >1,000 m³ of all 67 CSO outlets within the model system for the sewer status 2020 with implemented sewer rehabilitation measures (S2), simulated time period April to November 2007. These data are identical for the sewer status 2020 with increased temperature (S5a).

Beginning	End	Duration	V	BOD_5	COD	TSS	NH_4-N	TKN	P_{dis}	TP
		[min]	[m³]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]
2007-05-07 11:45	2007-05-09 18:30	3,300	302,740	23,268	73,594	51,915	747	1,620	213	333
2007-05-10 04:15	2007-05-11 23:30	2,610	51,932	2,114	5,609	4,959	34	138	7	21
2007-05-12 08:00	2007-05-13 16:15	1,950	32,699	2,265	5,761	5,718	21	114	4	18
2007-05-14 01:45	2007-05-14 09:45	495	10,913	1,133	2,782	3,048	5	42	1	7
2007-05-14 19:30	2007-05-16 04:00	1,965	189,127	11,165	28,372	23,985	488	1,027	78	144
2007-05-16 20:00	2007-05-17 08:30	765	13,412	564	1,484	1,209	21	50	4	7
2007-05-25 18:30	2007-05-26 08:15	840	192,039	14,078	39,457	38,034	303	671	71	125
2007-05-26 16:30	2007-05-28 04:45	2,190	135,117	8,832	23,519	22,572	255	524	48	86
2007-05-28 18:00	2007-05-30 18:45	2,940	314,528	14,632	36,936	36,439	484	954	79	146
2007-06-05 03:30	2007-06-05 11:00	465	1,101	24	60	62	0	1	0	0
2007-06-12 18:45	2007-06-13 01:45	435	1,830	59	154	138	2	4	0	1
2007-06-15 01:00	2007-06-15 10:45	600	10,255	467	1,389	1,166	9	24	2	5
2007-06-16 00:15	2007-06-17 08:00	1,920	749,488	24,276	64,087	64,735	731	1,351	134	229
2007-06-21 11:15	2007-06-23 20:00	3,420	367,022	23,977	61,701	52,272	1,036	2,140	169	304
2007-06-25 18:30	2007-06-26 04:45	630	4,391	115	323	277	0	6	0	1
2007-06-26 12:15	2007-06-26 23:00	660	10,407	674	1,834	1,702	2	31	1	5
2007-06-27 13:45	2007-06-27 23:30	600	2,251	273	742	731	0	9	0	2
2007-06-28 12:45	2007-06-29 01:45	795	5,153	480	1,293	1,209	2	22	1	4
2007-06-29 17:45	2007-06-30 02:00	510	2,917	317	806	778	5	19	1	3
2007-06-30 08:45	2007-06-30 19:15	645	1,883	53	159	124	0	3	0	1
2007-07-04 09:30	2007-07-06 00:45	2,370	143,207	12,921	34,140	30,032	417	954	75	144
2007-07-06 17:30	2007-07-08 05:15	2,160	30,866	2,472	6,522	6,191	29	127	7	21
2007-07-09 20:45	2007-07-10 21:15	1,485	53,655	3,230	8,396	7,986	41	180	9	28
2007-07-11 15:30	2007-07-12 16:45	1,530	30,876	1,160	3,071	2,867	8	60	2	9
2007-07-17 05:00	2007-07-18 02:15	1,290	8,503	864	2,214	2,372	4	30	1	5
2007-07-20 07:45	2007-07-20 18:00	630	6,987	640	1,808	1,690	3	24	2	5
2007-07-22 06:15	2007-07-23 12:45	1,845	442,810	25,359	67,958	64,132	723	1,536	138	253

Beginning	End	Duration	V	BOD_5	COD	TSS	NH_4-N	TKN	P_{dis}	TP
		[min]	[m³]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]
2007-07-24 14:30	2007-07-25 09:30	1,155	1,678	51	134	104	3	6	0	1
2007-07-28 10:15	2007-07-28 21:45	705	2,780	78	207	140	7	10	1	1
2007-07-29 14:30	2007-07-30 20:30	1,815	26,378	800	3,123	1,568	33	71	10	15
2007-08-08 15:00	2007-08-09 07:15	990	253,537	9,128	26,173	24,224	255	496	57	92
2007-08-11 07:45	2007-08-12 15:00	1,890	103,008	8,916	23,843	23,013	181	465	38	79
2007-08-15 22:15	2007-08-16 16:15	1,095	11,749	986	2,874	2,484	2	40	3	8
2007-08-21 03:00	2007-08-23 10:45	3,360	444,699	27,509	72,645	70,995	817	1,654	150	267
2007-08-24 03:00	2007-08-25 09:15	1,830	312,502	12,608	32,276	32,147	396	795	67	123
2007-08-30 20:45	2007-08-31 08:30	720	1,202	56	146	112	4	6	1	1
2007-08-31 16:00	2007-09-01 10:15	1,110	1,483	71	188	142	5	8	1	1
2007-09-03 03:30	2007-09-04 23:45	2,670	173,175	15,140	39,632	32,698	741	1,428	123	206
2007-09-10 07:15	2007-09-10 23:15	975	27,506	1,563	4,846	3,479	30	108	9	19
2007-09-18 01:45	2007-09-18 19:00	1,050	17,901	608	2,529	1,245	7	39	6	10
2007-09-25 10:30	2007-09-25 16:45	390	1,291	24	125	41	0	2	0	1
2007-09-27 18:15	2007-09-30 01:45	3,345	255,960	17,467	46,623	40,025	519	1,285	97	197
2007-10-17 23:00	2007-10-18 06:30	465	3,137	143	376	371	0	6	0	1
2007-11-02 13:00	2007-11-03 01:15	750	1,851	39	134	90	0	2	0	0
2007-11-06 01:45	2007-11-06 21:00	1,170	15,827	579	6,247	622	12	19	25	27
2007-11-07 05:00	2007-11-07 20:15	930	19,793	277	2,194	388	5	17	8	10
2007-11-09 01:45	2007-11-10 01:00	1,410	19,893	451	1,393	969	5	35	2	6
2007-11-10 15:15	2007-11-12 01:00	2,040	27,136	412	1,420	883	3	31	2	5
2007-11-12 07:15	2007-11-12 22:45	945	1,254	20	54	47	0	1	0	0
2007-11-23 09:30	2007-11-23 22:15	780	5,527	115	319	237	2	12	0	1
2007-11-25 05:00	2007-11-25 22:30	1,065	8,220	123	992	175	2	7	4	4
2007-11-29 21:30	2007-11-30 16:15	1,140	6,398	128	1,296	145	2	6	5	6

Table 16: Simulated CSO volumes and pollutant loads for single CSO events >1,000 m³ of all 67 CSO outlets within the model system for the sewer status 2020 with increased storage volume (S3), simulated time period April to November 2007.

Beginning	End	Duration	V	BOD_5	COD	TSS	NH_4-N	TKN	P_{dis}	TP
		[min]	[m³]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]
2007-05-07 11:45	2007-05-09 18:30	3,300	281,853	21,027	66,619	46,840	681	1,470	194	303
2007-05-10 04:15	2007-05-11 23:30	2,610	47,936	1,808	4,849	4,295	20	110	5	17
2007-05-12 08:00	2007-05-13 16:15	1,950	30,803	1,962	5,017	4,969	14	97	3	15
2007-05-14 01:45	2007-05-14 09:45	495	10,916	1,129	2,773	3,048	4	41	1	7
2007-05-14 19:30	2007-05-16 04:00	1,965	169,081	9,896	25,188	21,232	435	914	70	128
2007-05-16 20:00	2007-05-17 08:30	765	13,412	420	1,109	1,024	3	22	1	3
2007-05-25 18:30	2007-05-26 08:00	825	179,701	13,114	36,789	35,467	274	616	65	116
2007-05-26 16:30	2007-05-28 04:45	2,190	121,682	7,395	19,699	19,273	184	402	36	68
2007-05-28 18:00	2007-05-30 18:45	2,940	292,287	13,047	32,916	32,605	424	841	69	129
2007-06-05 03:30	2007-06-05 11:00	465	1,102	24	61	64	0	1	0	0
2007-06-12 18:45	2007-06-13 01:45	435	1,830	41	109	112	0	1	0	0
2007-06-15 01:00	2007-06-15 10:45	600	10,228	423	1,278	1,102	4	16	2	4
2007-06-16 00:15	2007-06-17 08:00	1,920	732,558	23,503	62,161	62,691	698	1,300	129	221
2007-06-21 11:15	2007-06-23 20:00	3,420	345,821	22,023	56,587	48,381	933	1,934	152	276
2007-06-25 18:30	2007-06-26 04:45	630	4,390	115	322	274	0	6	0	1
2007-06-26 12:15	2007-06-26 23:00	660	10,408	673	1,833	1,701	1	31	1	5
2007-06-27 13:45	2007-06-27 23:30	600	2,251	273	742	731	0	9	0	2
2007-06-28 12:45	2007-06-29 01:45	795	5,153	480	1,293	1,209	2	22	1	4
2007-06-29 17:45	2007-06-30 02:00	510	2,917	320	812	786	5	19	1	3
2007-06-30 08:45	2007-06-30 19:15	645	1,883	53	157	121	0	3	0	0
2007-07-04 09:30	2007-07-06 00:45	2,370	123,954	10,693	28,261	25,153	320	757	59	115
2007-07-06 17:30	2007-07-08 05:15	2,160	27,628	2,060	5,474	5,316	8	87	3	15
2007-07-09 20:45	2007-07-10 21:15	1,485	49,650	2,999	7,794	7,491	32	158	7	25
2007-07-11 15:30	2007-07-12 16:45	1,530	30,494	1,130	2,994	2,831	5	54	2	9
2007-07-17 05:00	2007-07-18 02:15	1,290	7,494	535	1,362	1,460	2	19	1	3
2007-07-20 07:45	2007-07-20 18:00	630	6,987	639	1,802	1,698	1	22	1	5
2007-07-22 06:15	2007-07-23 12:45	1,845	423,304	23,852	63,926	60,300	675	1,442	129	237
2007-07-24 14:30	2007-07-25 09:30	1,155	1,676	53	136	108	3	6	0	1

Beginning	End	Duration	V	BOD_5	COD	TSS	NH_4-N	TKN	P_{dis}	TP
		[min]	[m³]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]
2007-07-28 10:15	2007-07-28 21:45	705	2,783	94	250	195	6	10	1	1
2007-07-29 14:30	2007-07-30 20:30	1,815	22,911	647	2,723	1,383	15	42	8	11
2007-08-08 15:00	2007-08-09 07:15	990	244,184	8,408	24,195	22,456	226	444	52	84
2007-08-11 07:45	2007-08-12 15:00	1,890	93,292	7,953	21,272	20,581	160	412	33	70
2007-08-15 22:15	2007-08-16 16:15	1,095	11,750	990	2,885	2,495	2	40	3	8
2007-08-21 03:00	2007-08-23 10:45	3,360	412,434	25,060	66,275	64,686	743	1,504	137	243
2007-08-24 03:00	2007-08-25 09:15	1,830	293,175	11,447	29,282	29,406	337	696	58	108
2007-08-30 20:45	2007-08-31 08:30	720	1,199	51	133	112	3	5	0	1
2007-08-31 16:00	2007-09-01 10:15	1,110	1,482	65	174	143	4	6	1	1
2007-09-03 03:30	2007-09-04 23:45	2,670	153,388	13,167	34,507	29,119	573	1,158	97	169
2007-09-10 07:15	2007-09-10 23:15	975	22,973	1,257	4,011	2,923	11	70	6	14
2007-09-18 01:45	2007-09-18 19:00	1,050	17,640	582	2,453	1,209	5	35	6	10
2007-09-25 10:30	2007-09-25 16:45	390	1,291	22	127	37	0	2	0	1
2007-09-27 18:15	2007-09-30 01:45	3,345	227,792	15,292	40,692	35,493	419	1,082	79	166
2007-10-17 23:00	2007-10-18 06:30	465	3,136	147	388	380	1	6	0	1
2007-11-02 13:00	2007-11-03 01:15	750	1,851	40	137	92	0	2	0	0
2007-11-06 01:45	2007-11-06 21:00	1,170	15,578	559	6,110	583	12	19	24	26
2007-11-07 05:00	2007-11-07 20:15	930	19,531	278	2,281	389	5	15	8	10
2007-11-09 01:45	2007-11-10 01:00	1,410	19,897	445	1,378	970	4	33	2	5
2007-11-10 15:15	2007-11-12 00:45	2,025	26,809	420	1,432	914	2	30	2	5
2007-11-12 07:15	2007-11-12 22:45	945	1,254	22	56	50	0	2	0	0
2007-11-23 09:30	2007-11-23 22:15	780	5,529	110	306	229	1	10	0	1
2007-11-25 05:00	2007-11-25 22:30	1,065	8,221	123	1,007	174	2	7	4	4
2007-11-29 21:30	2007-11-30 16:15	1,140	6,400	130	1,299	148	2	6	5	6

Table 17: Simulated CSO volumes and pollutant loads for single CSO events >1,000 m³ of all 67 CSO outlets within the model system for the sewer status 2020 with reduced impervious area (S4), simulated time period April to November 2007.

Beginning	End	Duration	V	BOD_5	COD	TSS	NH_4-N	TKN	P_{dis}	TP
		[min]	[m³]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]
2007-05-07 12:00	2007-05-09 18:15	3,270	198,493	14,827	46,317	32,629	520	1,090	139	216
2007-05-10 04:15	2007-05-11 23:30	2,610	36,255	1,166	3,195	2,733	12	72	3	11
2007-05-12 08:00	2007-05-13 05:15	1,290	22,310	1,192	3,102	2,960	8	62	2	10
2007-05-14 01:45	2007-05-14 09:45	495	8,038	1,019	2,496	2,766	2	35	1	6
2007-05-14 19:30	2007-05-15 21:00	1,545	106,919	6,099	15,583	13,116	260	557	42	78
2007-05-16 20:00	2007-05-17 08:30	765	10,476	388	994	972	2	19	0	3
2007-05-25 18:30	2007-05-26 05:15	660	134,549	9,722	27,244	25,860	232	496	52	91
2007-05-26 16:30	2007-05-28 04:45	2,190	88,572	6,004	16,054	15,132	180	370	34	60
2007-05-28 18:00	2007-05-30 18:15	2,910	206,081	9,583	24,249	23,750	322	633	53	97
2007-06-12 19:00	2007-06-13 01:45	420	1,438	48	125	109	2	4	0	1
2007-06-15 01:15	2007-06-15 10:45	585	7,051	231	618	549	8	17	1	3
2007-06-16 00:15	2007-06-17 07:15	1,875	561,528	19,009	50,359	49,833	643	1,142	116	191
2007-06-21 11:15	2007-06-23 20:15	3,435	246,943	15,875	40,680	34,333	727	1,455	117	206
2007-06-25 18:30	2007-06-26 04:45	630	3,494	79	228	191	0	4	0	1
2007-06-26 12:15	2007-06-26 23:15	675	8,131	331	917	808	0	17	1	3
2007-06-27 13:45	2007-06-27 23:15	585	1,782	182	489	483	0	7	0	1
2007-06-28 12:45	2007-06-29 01:30	780	3,745	496	1,316	1,320	1	17	1	3
2007-06-29 17:45	2007-06-30 02:00	510	1,723	141	367	338	2	8	0	1
2007-06-30 08:45	2007-06-30 19:15	645	1,472	80	229	193	0	4	0	1
2007-07-04 09:30	2007-07-06 00:45	2,370	84,892	7,168	19,039	16,970	200	491	38	76
2007-07-06 17:30	2007-07-08 00:15	1,860	21,340	1,420	3,820	3,575	12	69	4	12
2007-07-09 21:00	2007-07-10 20:00	1,395	33,926	2,110	5,517	5,307	17	105	4	17
2007-07-11 15:30	2007-07-12 16:45	1,530	23,836	973	2,560	2,443	4	47	2	7
2007-07-17 05:00	2007-07-17 16:00	675	5,839	112	288	260	1	8	0	1
2007-07-20 07:45	2007-07-20 18:15	645	5,560	485	1,258	1,329	0	16	0	3
2007-07-22 06:15	2007-07-23 12:00	1,800	319,513	19,413	51,958	48,615	592	1,229	111	199
2007-07-24 14:30	2007-07-25 09:45	1,170	1,310	40	104	78	3	5	0	1
2007-07-28 10:15	2007-07-28 21:45	705	2,198	65	171	122	5	8	1	1

Beginning	End	Duration	V	BOD_5	COD	TSS	NH_4-N	TKN	P_{dis}	TP
		[min]	[m³]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]
2007-07-29 14:30	2007-07-30 20:15	1,800	17,689	516	2,098	1,101	15	36	6	9
2007-08-08 15:00	2007-08-09 07:00	975	192,428	6,664	19,088	17,595	202	380	44	69
2007-08-11 07:45	2007-08-12 09:30	1,560	68,723	5,776	15,487	14,576	146	338	29	56
2007-08-15 22:30	2007-08-16 16:15	1,080	9,269	874	2,505	2,206	3	36	2	7
2007-08-21 03:00	2007-08-23 02:45	2,880	299,444	18,472	48,858	46,966	610	1,188	110	189
2007-08-24 03:00	2007-08-25 08:45	1,800	210,884	8,825	22,616	22,178	306	593	51	91
2007-08-31 16:15	2007-09-01 10:15	1,095	1,165	59	156	124	3	6	1	1
2007-09-03 03:30	2007-09-04 03:30	1,455	91,756	7,691	20,373	17,092	324	660	56	98
2007-09-04 10:45	2007-09-04 23:45	795	8,579	533	1,320	1,247	16	40	2	5
2007-09-10 07:15	2007-09-10 23:15	975	17,544	828	2,651	1,949	6	44	4	9
2007-09-18 02:00	2007-09-18 19:15	1,050	13,758	537	1,963	1,159	5	34	4	8
2007-09-25 10:30	2007-09-25 16:45	390	1,015	16	154	19	0	1	1	1
2007-09-27 18:15	2007-09-28 09:30	930	65,498	4,702	13,609	10,339	142	361	32	60
2007-09-28 15:30	2007-09-30 01:45	2,070	92,886	6,145	15,456	14,491	183	440	30	64
2007-10-17 23:00	2007-10-18 06:45	480	2,490	96	244	239	1	5	0	1
2007-11-02 13:00	2007-11-03 01:00	735	1,441	61	165	156	0	3	0	0
2007-11-06 01:45	2007-11-06 21:00	1,170	12,177	403	3,898	514	7	14	15	16
2007-11-07 05:00	2007-11-07 20:30	945	15,271	260	2,750	278	5	11	11	12
2007-11-09 01:45	2007-11-10 01:00	1,410	15,618	282	928	614	2	20	1	4
2007-11-10 15:30	2007-11-12 01:00	2,025	21,174	329	1,140	729	1	22	2	4
2007-11-23 09:45	2007-11-23 22:15	765	4,369	77	227	161	1	7	0	1
2007-11-25 05:30	2007-11-25 22:45	1,050	6,532	104	366	213	1	9	1	2
2007-11-29 21:45	2007-11-30 16:15	1,125	5,089	89	1,204	57	2	2	5	5

Table 18: Simulated CSO volumes and pollutant loads for single CSO events >1,000 m³ of all 67 CSO outlets within the model system for the sewer status 2020 with increased temperature (+1.9 K) and higher rain intensity (+20%) (S5b), simulated time period April to November 2007.

Beginning	**End**	**Duration**	**V**	**BOD_5**	**COD**	**TSS**	**NH_4-N**	**TKN**	**P_{dis}**	**TP**
		[min]	**[m³]**	**[kg]**	**[kg]**	**[kg]**	**[kg]**	**[kg]**	**[kg]**	**[kg]**
2007-04-17 19:15	2007-04-18 01:00	360	1,401	0	1	0	0	0	0	0
2007-04-24 05:00	2007-04-24 09:00	255	1,187	12	47	13	2	2	0	0
2007-05-07 11:30	2007-05-09 18:30	3,315	404,867	28,543	85,876	65,758	880	1,911	229	372
2007-05-10 04:00	2007-05-11 23:45	2,640	82,854	4,304	11,015	9,719	133	339	22	48
2007-05-12 08:00	2007-05-13 19:45	2,160	52,399	3,594	9,012	8,995	58	200	10	30
2007-05-14 01:45	2007-05-14 12:00	630	14,319	1,056	2,619	2,857	5	39	1	6
2007-05-14 18:30	2007-05-16 09:00	2,325	273,906	14,842	37,626	31,263	762	1,465	120	204
2007-05-16 20:00	2007-05-17 08:45	780	17,186	598	1,611	1,301	20	50	4	7
2007-05-25 18:30	2007-05-26 09:00	885	257,922	16,570	46,574	45,013	390	812	88	151
2007-05-26 16:30	2007-05-28 05:00	2,205	186,009	9,725	25,598	25,020	297	588	54	95
2007-05-28 18:00	2007-05-30 19:15	2,970	429,793	16,389	41,373	40,532	616	1,138	99	172
2007-06-05 03:30	2007-06-05 11:15	480	1,733	34	86	88	1	2	0	0
2007-06-12 18:45	2007-06-13 02:00	450	2,654	82	219	198	3	6	0	1
2007-06-15 01:00	2007-06-15 12:45	720	14,534	780	2,891	1,860	11	35	6	10
2007-06-16 00:15	2007-06-17 08:45	1,965	937,716	24,029	62,324	64,347	782	1,396	136	228
2007-06-21 11:15	2007-06-23 20:15	3,435	495,808	28,641	73,736	62,325	1,267	2,581	207	367
2007-06-25 18:30	2007-06-26 05:00	645	5,718	240	625	599	1	11	0	2
2007-06-26 12:00	2007-06-26 23:15	690	12,976	1,135	3,033	2,985	3	45	2	8
2007-06-27 13:45	2007-06-27 23:30	600	2,940	230	629	602	0	9	0	2
2007-06-28 10:45	2007-06-29 01:45	915	7,051	534	1,394	1,328	4	27	1	4
2007-06-29 17:45	2007-06-30 02:00	510	4,258	495	1,244	1,257	8	27	1	4
2007-06-30 08:45	2007-06-30 19:30	660	2,416	48	150	108	0	3	0	0
2007-07-04 09:15	2007-07-06 01:00	2,400	210,368	17,811	46,473	41,445	613	1,347	106	199
2007-07-06 17:30	2007-07-08 12:45	2,610	47,754	3,945	10,163	9,640	85	241	15	37
2007-07-09 08:00	2007-07-09 13:30	345	1,297	140	346	376	1	5	0	1
2007-07-09 20:45	2007-07-11 05:00	1,950	87,709	4,929	12,629	11,601	124	348	22	51
2007-07-11 15:30	2007-07-12 16:45	1,530	45,434	1,912	4,959	4,257	64	157	11	23
2007-07-17 04:30	2007-07-18 06:00	1,545	11,405	1,518	3,924	4,252	9	49	3	9

Beginning	End	Duration	V	BOD_5	COD	TSS	NH_4-N	TKN	P_{dis}	TP
		[min]	[m³]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]
2007-07-20 07:45	2007-07-20 18:15	645	8,906	751	2,219	1,961	1	27	2	6
2007-07-22 06:15	2007-07-23 13:30	1,890	571,325	26,236	70,170	66,674	818	1,636	153	266
2007-07-24 14:15	2007-07-25 09:45	1,185	2,529	59	155	128	3	6	0	1
2007-07-28 09:45	2007-07-28 22:00	750	3,914	121	320	232	9	15	1	2
2007-07-29 14:30	2007-07-30 20:45	1,830	42,992	1,678	5,430	3,145	86	179	19	29
2007-08-08 15:00	2007-08-09 07:30	1,005	321,794	10,873	30,994	28,779	317	611	69	111
2007-08-11 07:45	2007-08-12 17:15	2,025	141,993	10,352	27,497	27,023	212	533	43	89
2007-08-13 16:15	2007-08-13 21:45	345	1,037	67	174	175	0	3	0	0
2007-08-15 22:00	2007-08-16 16:30	1,125	14,932	1,394	3,979	3,582	2	53	3	11
2007-08-21 03:00	2007-08-23 14:00	3,555	596,833	30,848	81,071	80,020	994	1,918	178	304
2007-08-24 03:00	2007-08-25 09:30	1,845	417,411	13,654	34,894	35,229	444	859	75	133
2007-08-30 20:15	2007-08-31 08:30	750	1,778	81	212	157	5	10	1	1
2007-08-31 16:00	2007-09-01 10:15	1,110	2,124	97	254	197	6	11	1	1
2007-09-03 03:30	2007-09-05 00:00	2,685	250,106	20,677	53,537	45,089	1,028	1,945	168	278
2007-09-10 07:00	2007-09-11 04:15	1,290	44,842	2,927	8,449	6,460	75	224	17	36
2007-09-18 01:15	2007-09-18 19:30	1,110	23,375	852	3,257	1,805	9	56	7	13
2007-09-25 10:15	2007-09-25 17:00	420	1,995	57	175	112	1	6	0	1
2007-09-27 18:15	2007-09-30 06:45	3,645	371,138	23,649	62,182	54,572	708	1,720	128	260
2007-10-02 02:30	2007-10-02 12:30	615	1,281	52	131	138	0	2	0	0
2007-10-17 23:00	2007-10-18 06:45	480	4,248	114	341	277	0	6	0	1
2007-11-02 10:00	2007-11-03 01:45	960	2,832	28	128	59	0	1	0	0
2007-11-03 09:30	2007-11-03 20:30	675	1,335	11	53	24	0	0	0	0
2007-11-06 01:45	2007-11-06 21:15	1,185	20,334	862	7,806	1,138	16	37	30	33
2007-11-07 05:00	2007-11-07 20:30	945	29,687	757	2,522	1,402	33	82	8	13
2007-11-09 01:45	2007-11-10 01:00	1,410	25,266	715	2,053	1,588	9	53	3	8
2007-11-10 15:30	2007-11-12 01:00	2,025	36,759	920	2,624	1,968	18	80	4	11
2007-11-12 07:15	2007-11-12 23:00	960	1,630	37	92	85	0	3	0	0
2007-11-23 08:15	2007-11-23 22:30	870	7,171	149	418	311	3	14	1	2
2007-11-25 05:00	2007-11-25 22:45	1,080	10,354	207	1,837	279	3	9	7	8
2007-11-29 21:30	2007-11-30 17:00	1,185	8,391	202	1,116	373	2	12	3	5

Table 19: Simulated CSO volumes and pollutant loads for single CSO events >1,000 m³ of all 67 CSO outlets within the model system for the sewer status 2020 with increased temperature (+1.9 K) and lower rain intensity (-20%) (S5c), simulated time period April to November 2007.

Beginning	End	Duration	V	BOD_5	COD	TSS	NH_4-N	TKN	P_{dis}	TP
		[min]	[m³]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]
2007-05-07 12:30	2007-05-09 18:15	3,240	197,200	15,097	51,251	32,008	528	1,124	166	247
2007-05-10 04:15	2007-05-11 23:15	2,595	35,834	1,150	3,249	2,633	13	76	4	12
2007-05-12 08:00	2007-05-13 07:30	1,425	22,425	1,232	3,247	3,026	8	67	3	10
2007-05-14 01:45	2007-05-14 09:15	465	7,842	1,116	2,749	2,964	3	43	1	7
2007-05-14 19:45	2007-05-15 20:45	1,515	106,023	6,635	17,085	14,256	258	596	43	84
2007-05-16 20:15	2007-05-17 08:15	735	10,130	429	1,099	1,062	1	22	0	3
2007-05-25 18:30	2007-05-26 07:15	780	130,018	11,180	31,438	29,881	219	520	53	99
2007-05-26 16:30	2007-05-28 04:30	2,175	87,915	7,152	19,238	18,285	178	399	35	68
2007-05-28 18:00	2007-05-30 18:15	2,910	199,197	11,925	30,221	29,972	317	709	54	111
2007-06-12 19:00	2007-06-13 01:45	420	1,019	33	88	78	1	3	0	0
2007-06-15 01:45	2007-06-15 10:30	540	6,819	278	738	664	9	19	2	3
2007-06-16 00:30	2007-06-17 07:15	1,860	560,056	24,261	65,121	64,306	645	1,276	126	224
2007-06-21 11:15	2007-06-23 05:45	2,565	233,289	16,904	43,480	37,172	701	1,473	115	210
2007-06-23 11:45	2007-06-23 19:45	495	11,523	612	1,594	1,527	5	32	1	5
2007-06-25 18:30	2007-06-26 04:30	615	3,062	71	209	170	0	4	0	1
2007-06-26 12:15	2007-06-26 23:00	660	8,005	281	803	668	0	16	1	3
2007-06-27 13:45	2007-06-27 20:00	390	1,570	97	283	245	0	4	0	1
2007-06-28 13:00	2007-06-29 01:00	735	3,555	460	1,238	1,199	1	17	1	3
2007-06-29 17:45	2007-06-30 02:00	510	1,508	126	337	296	2	8	0	1
2007-06-30 09:30	2007-06-30 19:00	585	1,324	73	230	173	0	4	0	1
2007-07-04 09:30	2007-07-06 00:30	2,355	81,082	7,241	19,717	17,020	186	486	38	77
2007-07-06 17:30	2007-07-08 00:00	1,845	21,028	1,481	4,054	3,692	12	73	4	13
2007-07-09 21:00	2007-07-10 19:45	1,380	33,830	2,224	5,926	5,505	18	115	5	19
2007-07-11 15:30	2007-07-12 16:30	1,515	23,402	910	2,465	2,233	5	47	2	8
2007-07-17 05:00	2007-07-17 17:00	735	5,628	80	217	175	1	7	0	1
2007-07-20 07:45	2007-07-20 18:00	630	5,167	353	922	945	0	13	0	2
2007-07-22 06:15	2007-07-23 12:00	1,800	316,778	23,873	64,233	60,172	588	1,378	118	231
2007-07-28 10:30	2007-07-28 21:15	660	1,670	55	146	110	4	6	1	1

Beginning	End	Duration	V	BOD_5	COD	TSS	NH_4-N	TKN	P_{dis}	TP
		[min]	[m^3]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]
2007-07-29 14:45	2007-07-30 05:15	885	16,942	536	2,227	1,138	18	37	7	10
2007-08-08 15:00	2007-08-09 07:00	975	192,037	7,895	22,913	20,982	201	405	48	78
2007-08-11 07:45	2007-08-12 08:45	1,515	66,818	6,780	18,276	17,205	145	370	30	63
2007-08-16 03:45	2007-08-16 16:00	750	8,657	779	2,394	1,899	3	35	3	8
2007-08-21 03:15	2007-08-23 03:30	2,910	294,007	21,941	58,480	56,084	604	1,291	115	212
2007-08-24 03:00	2007-08-25 08:45	1,800	210,506	10,983	28,144	27,822	316	677	54	105
2007-09-03 03:45	2007-09-04 04:30	1,500	89,470	7,424	20,215	16,198	311	647	57	98
2007-09-04 10:45	2007-09-04 23:30	780	8,351	542	1,350	1,249	16	42	3	6
2007-09-10 07:45	2007-09-10 23:15	945	17,151	760	2,552	1,740	6	43	4	9
2007-09-18 02:15	2007-09-18 19:00	1,020	13,254	416	1,779	834	5	28	4	7
2007-09-27 18:30	2007-09-30 06:15	3,600	155,250	10,909	30,357	24,815	318	800	66	128
2007-10-17 23:00	2007-10-18 06:30	465	2,055	119	300	289	1	6	0	1
2007-11-06 01:45	2007-11-06 21:00	1,170	11,680	370	3,530	498	6	12	13	15
2007-11-07 05:00	2007-11-07 20:15	930	15,035	281	4,249	113	8	5	18	19
2007-11-09 02:00	2007-11-10 00:45	1,380	15,157	183	828	357	2	13	2	3
2007-11-10 15:30	2007-11-12 00:45	2,010	20,746	213	972	441	1	13	2	4
2007-11-23 09:45	2007-11-23 22:15	765	3,872	37	148	71	0	3	0	1
2007-11-25 05:30	2007-11-25 22:15	1,020	6,178	76	255	157	1	7	1	1
2007-11-29 21:45	2007-11-30 16:00	1,110	4,568	79	1,126	47	2	1	5	5

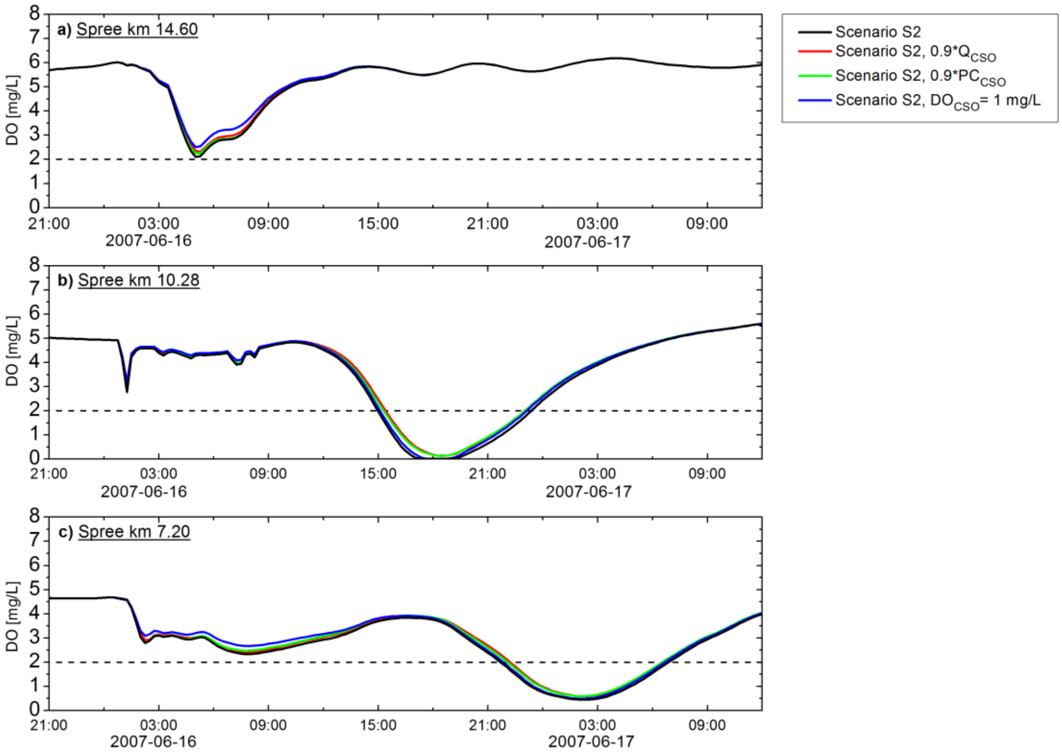

Figure 34: Time series plots for dissolved oxygen for i) the sewer status 2020 with implemented sewer rehabilitation measures (S2, black line), ii) the sewer status 2020 with CSO discharges reduced by 10% (red line), iii) the sewer status 2020 with CSO pollutant concentrations reduced by 10% (green line) and iv) sewer status 2020 with 1 mg/L dissolved oxygen in CSO spill water (blue line) for the major CSO event on 2007-06-16 and three river stations (Spree km 14.60, 10.28 and 7.20). Dotted line marks the critical concentration for the asp (Aspius aspius).

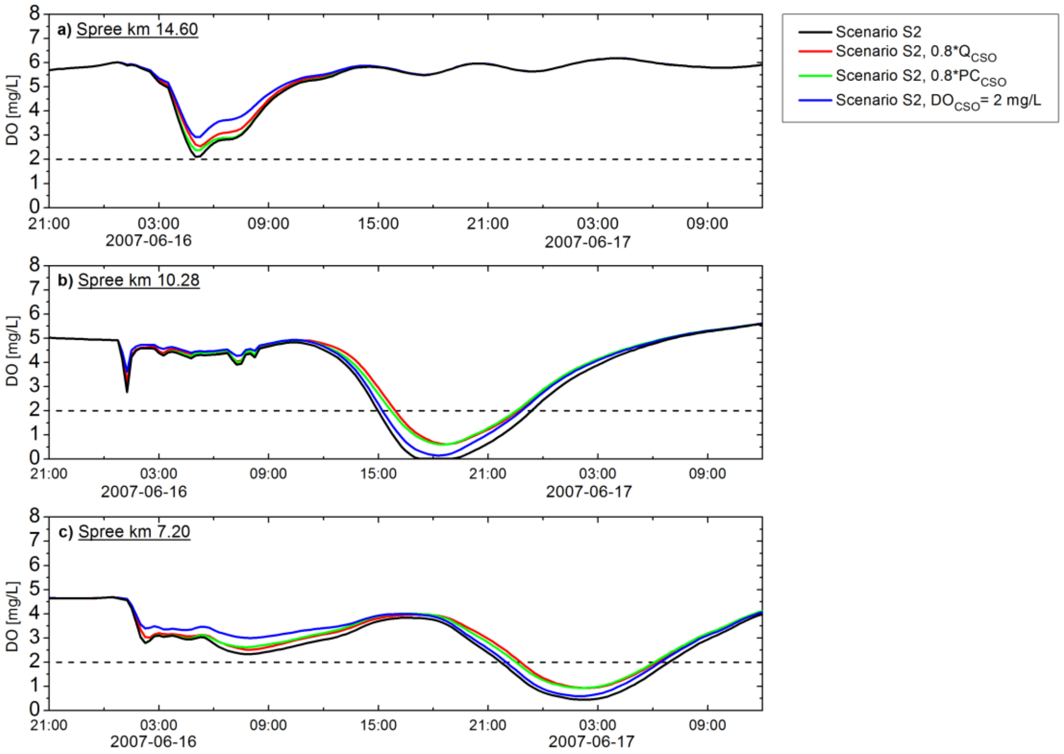

Figure 35: Time series plots for dissolved oxygen for i) the sewer status 2020 with implemented sewer rehabilitation measures (S2, black line), ii) the sewer status 2020 with CSO discharges reduced by 20% (red line), iii) the sewer status 2020 with CSO pollutant concentrations reduced by 20% (green line) and iv) sewer status 2020 with 2 mg/L dissolved oxygen in CSO spill water (blue line) for the major CSO event on 2007-06-16 and three river stations (Spree km 14.60, 10.28 and 7.20). Dotted line marks the critical concentration for the asp (Aspius aspius).

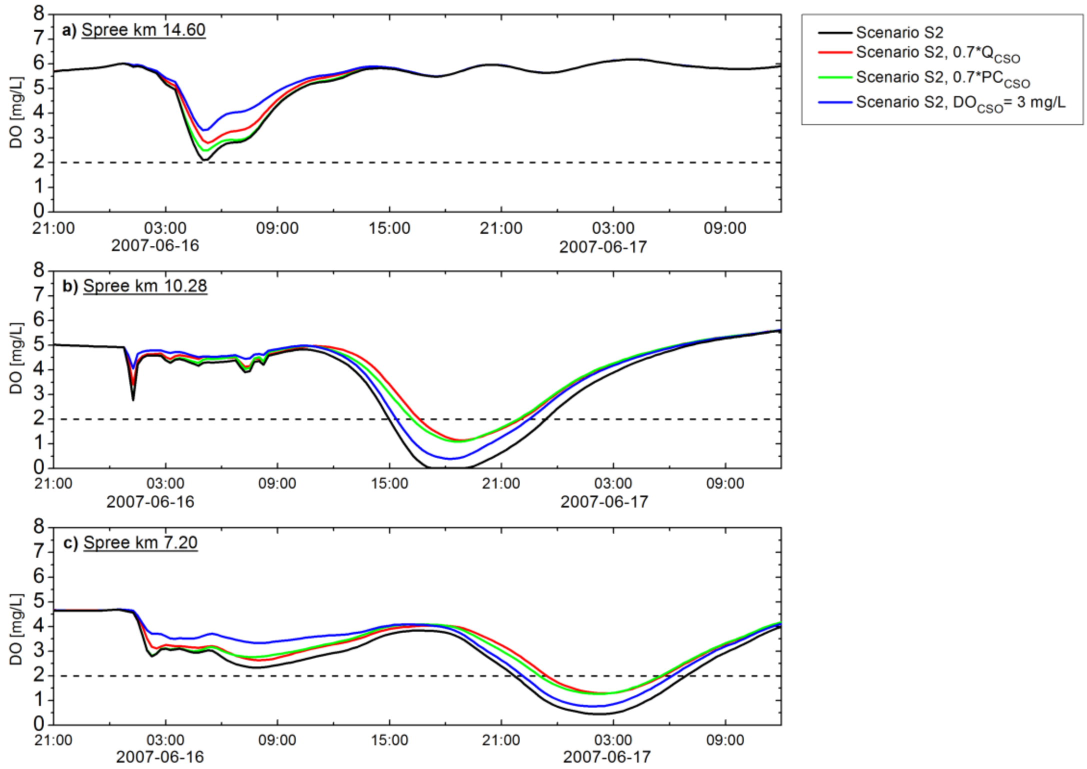

Figure 36: Time series plots for dissolved oxygen for i) the sewer status 2020 with implemented sewer rehabilitation measures (S2, black line), ii) the sewer status 2020 with CSO discharges reduced by 30% (red line), iii) the sewer status 2020 with CSO pollutant concentrations reduced by 30% (green line) and iv) sewer status 2020 with 3 mg/L dissolved oxygen in CSO spill water (blue line) for the major CSO event on 2007-06-16 and three river stations (Spree km 14.60, 10.28 and 7.20). Dotted line marks the critical concentration for the asp (Aspius aspius).

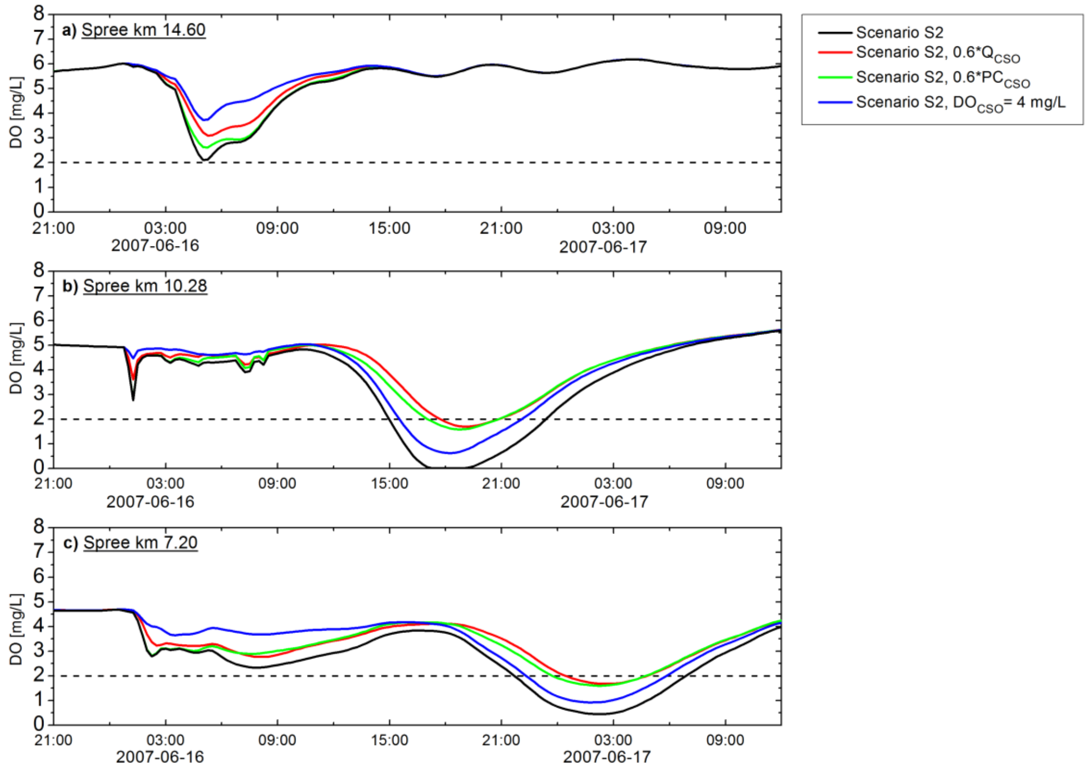

Figure 37: Time series plots for dissolved oxygen for i) the sewer status 2020 with implemented sewer rehabilitation measures (S2, black line), ii) the sewer status 2020 with CSO discharges reduced by 40% (red line), iii) the sewer status 2020 with CSO pollutant concentrations reduced by 40% (green line) and iv) sewer status 2020 with 4 mg/L dissolved oxygen in CSO spill water (blue line) for the major CSO event on 2007-06-16 and three river stations (Spree km 14.60, 10.28 and 7.20). Dotted line marks the critical concentration for the asp (Aspius aspius).

9 References

Ackers, P. (1991). Sediment aspects of drainage and outfall design. International Symposium on Environmental Hydraulics, Hong Kong, edited by A. A. Balkema.

Bärthel, H. (2003). GEKLÄRT! 125 Jahre Berliner Stadtentwässerung. Berliner Wasserbetriebe. Berlin.

Bertrand-Krajewski, J.L., Chebbo, G. and Saget, A. (1998). Distribution of pollutant mass vs volume in stormwater discharges and the first flush phenomenon. Water Research 32(8): 2341-2356.

Bouteligier, R, Vaes, G. and Berlamont, J. (2002). Deposition-Erosion Criterion for Sediment Transport in Sewers based on Shear Stress Calculations. Katholieke Universiteit Leuven.

BWB (2010). Effizienz von Maßnahmen der Regenwasserbehandlung in Berlin. Studie von BIOPLAN, ifs Ingenieurgesellschaft f. Stadthydrologie mbH und IWG Institut für Wasser und Gewässerentwicklung Karlsruhe, im Auftrag der Berliner Wasserbetriebe.

Caradot, N., Sonnenberg, H., Riechel, M., Heinzmann, B., von Seggern, D., Matzinger, A. and Rouault, P. (2011). Application of online water quality sensors for integrated CSO impact assessment in Berlin (Germany). 12th International Conference on Urban Drainage. Porto Alegre/Brazil. 11-16 September 2011.

Driescher, E. (2002). Naturräumliche Gegebenheiten und Landschaftsentwicklung. In Köhler, J., Gelbrecht, J. and Pusch, M. (eds). Die Spree – Zustand, Probleme, Entwicklungsmöglichkeiten. Limnologie aktuell. Band 10. E. Schweizerbart´sche Verlagsbuchhandlung. Stuttgart.

EC (2000). Water Framework Directive. Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy.

Gupta, K. and Saul, A.J. (1996). Specific relationships for the first flush load in combined sewer flows. Water Research 30 (5): 1244-1252.

Heinzmann, B. (1994). Beschaffenheit und Bedeutung städtischer Regenabflüsse im Trennsystem. Gwf Wasser-Abwasser Vol. 135. No. 7. 381-390.

Heinzmann, B. (1996). Mittlere Zu- und Ablaufkonzentrationen am Urbanbecken in Berlin Kreuzberg 1993. Berliner Wasserbetriebe. Kurzbericht.

Kaushal, S.S., Likens, G.E., Jaworski, N.A., Pace, M.L., Sides, A.M., Seekell, D., Belt, K.T., Secor, D.H., Wingate, R.L. (2010). Rising stream and river temperatures in the United States. Frontiers in Ecology and the Environment 8 (9): 461-466.

Kirchesch, V. (2004). QSim – The water quality model of the Federal Institute of Hydrology.

Kirchesch, V. and Schöl, A. (1999). Das Gewässergütemodell QSIM – Ein Instrument zur Simulation und Prognose des Stoffhaushalts und der Planktondynamik von Fliessgewässern. Hydrologie und Wasserbewirtschaftung 43: 302-309.

Krebs, P., Holzer, P., Huisman, J.L. and Rauch, W. (1999). First flush of dissolved compounds. Water Science and Technology 39 (9): 52-62.

Lammersen, R. (1997). Die Auswirkungen der Stadtentwässerung auf den Stoffhaushalt von Fließgewässern. Schriftenreihe der Stadtentwässerung und Gewässerschutz des Institutes für Wasserwirtschaft der Universität Hannover, Heft 15.

Leszinski, M. (2007). Bewertung des ökologischen Zustands der Berliner Spree anhand des Makrozoobenthos ausgewählter Flussabschnitte – mit Anmerkungen zum ökologischen Potenzial.

Leszinski, M., Schumacher, F., Schroeder, K., Pawlowsky-Reusing, E. and Heinzmann, B. (2007). ISM Studie: Immissionsorientierte Bewertung von Mischwasserentlastungen in Tieflandflüssen. Kompetenzzentrum Wasser Berlin gGmbH.

Leszinski, M. and Schumacher, F. (2009). SAM-CSO Studie: Möglichkeiten und Grenzen der Revitalisierung der Stadtspree als Lebensraum für die Fischfauna, p. 18. Kompetenzzentrum Wasser Berlin gGmbH.

Livingstone, D.M. and Lotter, A.F. (1998). The relationship between air and water temperatures in lakes of the Swiss Plateau: a case study with palaeolimnological imlications. J. Paleolimnology 19: 181-198.

Lotze-Campen, H., Claussen, L., Dosch, A., Noleppa, S., Rock, J., Schuler, J. and Uckert, G. (2009). PIK Report No. 113. Klimawandel und Kulturlandschaft Berlin. Potsdam Institute for Climate Impact Research.

Matzinger, A. (2009). River water quality modelling: Status quo. Kompetenzzentrum Wasser Berlin gGmbH.

Matzinger, A., Riechel, M., Caradot, N. (2011). Ammonia toxicity: Impact assessment of combined sewer overflows on the River Spree in Berlin. Kompetenzzentrum Wasser Berlin gGmbH.

Matzinger, A., Riechel, M., Petersen, S.O., Heinzmann, B. and Pawlowsky-Reusing, E. (2012). A planning instrument for an integrated and recipient/impact based CSO control under conditions of climate change. PREPARED report, p. 50.

Nash, H.E. and Sutcliffe, J.V. (1970). River flow forecasting through conceptual models, Part I – A discussion of principles. Journal of Hydrology. 10 (3): 282-290.

Pawlowsky-Reusing, E. and Schroeder, K. (2006). ISM – Integrated Sewage Management: Final Research Report. Kompetenzzentrum Wasser Berlin gGmbH.

Quiel, K., Becker, A., Kirschesch, V., Schöl, A., Fischer, H. (2011). Influence of global change on phytoplankton and nutrient cycling in the Elbe River. Regional Environmental Change 11: 405-421.

Riechel, M. (2009). Auswirkungen von Mischwassereinleitungen auf die Berliner Stadtspree, p. 88. Kompetenzzentrum Wasser Berlin.

Schöl, A., Kirchesch, V., Bergfeld, T., Schöll, F., Borcherding, J. and Müller, D. (2002). Modelling the Chlorophyll *a* Content of the River Rhine – Interrelation between Riverine Algal Production and Polulation Biomass of Grazers, Rotifers and the Zebra Mussel, *Dreisseina polymorpha*. International Review of Hydrobiology. 87: 295-317.

Schumacher, F., Gebauer, U., Pawlowsky-Reusing, E., Meier, I., Schroeder, K., Leszinski, M. and Heinzmann, B. (2007). Teilstudie: Gewässersimulation der Stauhaltung Charlottenburg (Spree und Kanäle) unter Berücksichtigung der Mischwasserentlastungen am Beispiel eines Starkregenereignisses im September 2005. Kompetenzzentrum Wasser Berlin gGmbH.

SenStadt (2001). Abwasserbeseitigungsplan Berlin, Senatsverwaltung für Gesundheit, Umwelt und Verbraucherschutz Berlin.

SenStadtUm (2012). Umweltatlas. Berlin, 02.09 Entsorgung von Regen und Abwasser, Tabelle 2 . http://www.stadtentwicklung.berlin.de/umwelt/umweltatlas/dc209_04.htm.

SenStadt (2004). Dokumentation der Umsetzung der EG-Wasserrahmenrichtlinie in Berlin (Länderbericht) – Phase: Bestandsaufnahme.

Sieker, F. (2004). Regen(ab)wasserbehandlung und –bewirtschaftung unter Berücksichtigung der Anforderungen nach § 7a WHG und einer möglichst ortsnahen Versickerung. Forschungsbericht 298 26 516. UBA-FB 000607.Umweltbundesamt. Berlin.

Velikanov, M. A. (1954). Principle of gravitational theory of the movement of sediments. USSR Academy of Sciences of Bulletin, Geophysical Series 4: 349-359.

Wolter, C., Arlinghaus, R., Grosch, U. A. and Vilcinskas, A. (2003). Fische & Fischerei in Berlin. Zeitschrift für Fischkunde Supplement 2, 1-156.

WSL (2004). InfoWorks CS User Manual. Copyright 1997. Wallingford Software Ltd.

WSV (2012). Karte der Berliner und Brandenburger Wasserstraßen. Wasser- und Schifffahrtsverwaltung des Bundes (WSV). http://www.wsa-berlin.wsv.de/wasserstrassen/images1/karte_mit_bildern..pdf (2012-08-02).