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Modelling the impacts of Combined Sewer Overflows on the river Seine water quality

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Abstract

To achieve the objectives of the European Water Framework Directive (EWFD), the Seine basin Water Authority has constructed a number of prospective scenarios forecasting the impact of planned investments in water quality. Paris and its suburbs were given special attention because of their impact on the river Seine. Paris sewer system and overflow control is of major concern in future management plans. The composition and fate of the urban effluents have been characterized through numerous *in situ* samplings, laboratory experiments and modelling studies. The PROSE model was especially designed to simulate the impact on the river of both permanent dry-weather effluents and of highly transient Combined Sewer Overflow (CSO). It was also used to represent the impact of Paris at large spatial and temporal scales. In addition to immediate effects on oxygen levels, heavy particulate organic matter loads that settle downstream of the outlets contribute to permanent oxygen consumption. Until the late 90s, the 50 km long reach of the Seine inside Paris was permanently affected by high oxygen consumption accounting for 112% of the flux upstream of the city. 20% of this demand resulted from CSO. However, the oxygenation of the system is strong due to high phytoplankton activity. As expected, the model results predict a reduction of both permanent dry-weather effluents and CSOs in the future that will greatly improve the oxygen levels (concentrations higher than 7.3 $mgO_2\ L^{-1}$, 90% of the time instead of 4.0 $mgO_2\ L^{-1}$ in the late 90s). The main conclusion is that, given the spatial and temporal extent of the impact of many CSOs, water quality models should take into account the CSOs in order to be reliable.

Keywords: Combined Sewer Overflow; Water quality modelling; Water quality; Oxygen; River Seine; European Framework Directive on Water

1. Introduction

Many old urban areas are drained by combined sewer networks. Combined Sewer Overflow (CSO) water, composed of a mixture of urban runoff and municipal wastewater, is discharged into the natural environment during rain events when the transport capacity of the sewer system is insufficient. In the Paris area, during rainy periods the daily flux of organic pollution dominates the fluxes from the wastewater treatment plants (WWTPs) (Even et al., 2004). Annually they are comparable to the pollution load of the WWTPs after treatment (Mouchel et al., 1998).

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The first evidence of CSO impacts on the receiving water bodies came to light in the 1960s but it was not until the 1990s that reducing the CSOs became a concern (Marsalek and Kok, 1997), because the most visible dry-weather pollution had been reduced by a systematic construction of WWTPs. Among the major problems caused by the CSOs is the acute short-term impact due to dissolved contaminants, bacteria and viruses, causing fish death (Boët et al., 1994) and health risks (US-EPA, 2001). Harremoes (1982) was the first to point out the additional delayed impact of CSOs on oxygen concentrations and the long-term ecological damage linked to the discharge of many pollutants by CSOs which is now well known (Brelot and Chocat, 1996; Chen et al., 2004). Impacts on the receiving system are generally studied in the vicinity of one CSO (Schaarup-Jensen and Hvitved-Jacobsen, 1990; Dégardin and Bujon, 1994; Chen et al., 2004; Even et al., 2004). However, it appears more and more important to acquire an overall vision of the system. Regarding great urban centers, it is also important to be able to estimate the spatial and temporal extent of the impacts of a group of CSOs. However, the processes involving both dissolved and particulate contaminants and different time scales are extremely complex.

The CSOs of the Paris sewer network have been widely studied within the PIREN SEINE program. The characterization of the sewer water and the impact on the receiving media have been studied both in laboratory experiments and by *in situ* measurements (Seidl et al., 1998a,b,c; Servais et al., 1999b). A complete ecological model describing the functioning of the river Seine, the PROSE model (Even et al., 1996, 2004, 2007-this volume; Flipo et al., 2004) was used to assess the biochemical processes developing downstream of a main CSO. It is used here to estimate the predictable effects of a reduction in both permanent and transient polluted discharges from the Paris sewer system into the Seine, resulting from planned equipment and management strategies discussed with the managers and decision-makers, co-funders of the program.

An international challenge is related to CSOs: the U. S. Clean Water Act requires cities and states to reduce the CSOs pollution; the EWFD implies that European countries should promote plan to suppress most obvious sources of pollution, including CSOs, to restore the "good ecological status" of their aquatic systems. Given the extremely expensive cost for CSOs treatment, and the wide range of solutions that can be mitigated, modelling the impact of CSOs remains a challenge for

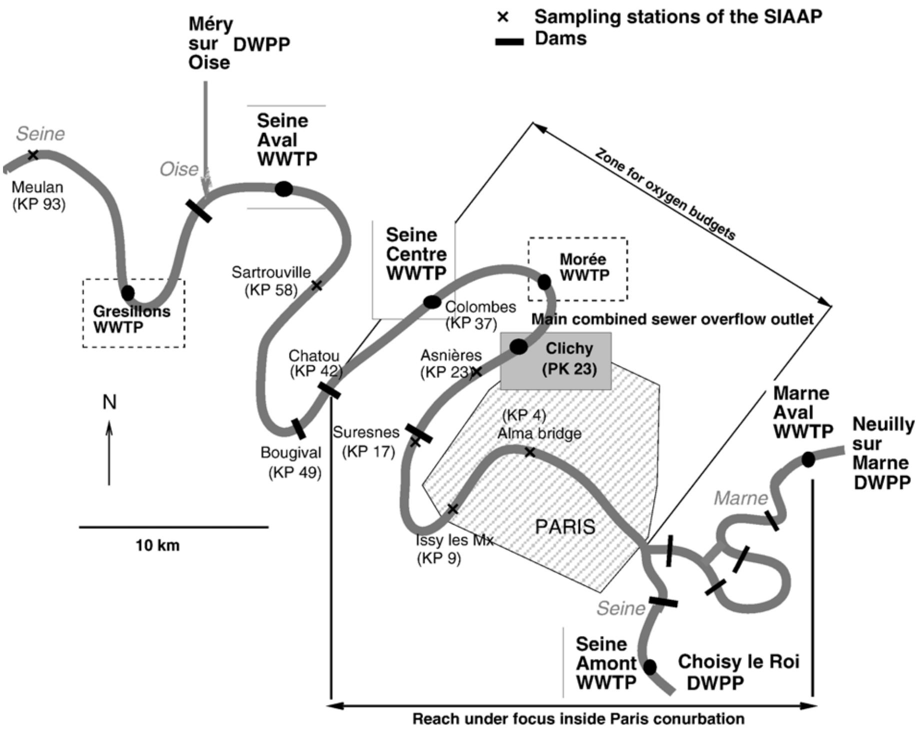

Fig. 1. Modelled reach of the river Seine between upstream Paris and Poses, at the entrance of the Seine estuary (left) and zoom on the Paris plants (right). DWPP: Drinking Water Production Plant; WWTP: Wastewater Treatment Plant.

the implementation of environmental policies in large urban areas. Because CSOs are highly transient and imply many pathways for contaminations, quantifying the relations source-impacts is very difficult. Simulating CSOs is also highly demanding to models that must be able to simulate precisely both seasonal trends in oxygen concentrations and additional short-term deficits due to CSOs. We also aimed here to validate the effectiveness of the concepts underlying the PROSE model and its potential for transfer to other rivers in large urban areas.

2. Studied system

The wastewater from Greater Paris (10 million inhabitants) is collected mostly by a combined sewer system and treated in four WWTPs (Fig. 1). The largest one is the Seine Aval plant, located 30 km downstream from Paris (2 $Mm^3\ d^{-1}$). At present, during rain events, runoff water that can't transit through the drainage system or be treated in a treatment plant, overflows at more than 200 outlets distributed throughout Paris and its suburbs. The largest one is located at Clichy (Fig. 1) where instantaneous overflows of more than 40 $m^3\ s^{-1}$ are frequently observed (on average, five events per year), while most discharges exceed 20 $m^3\ s^{-1}$ (Fig. 2). In summer, the flow of the Seine can be less than 100 $m^3\ s^{-1}$ in Paris (Fig. 2), which illustrates the potentially very severe impacts of CSOs on the river. Before the construction and full operation of the more recent equipment in the years 2000, CSOs regularly caused strong dissolved oxygen depletion in the river, endangering the fish population (Boët et al., 1994).

Two main reaches are impacted by the Paris conurbation (i) the zone down to the Chatou dam with three WWTPs, namely the Marne Aval, Seine Amont and Seine Centre WWTPs and all the storm sewer outlets; (ii) the reach downstream of the Seine Aval WWTP (Fig. 1). While the impact of the Seine Aval WWTP has been extensively studied and modelled (Garnier et al., 1992b; Servais and Garnier, 1993; Chesterikoff et al., 1998; Even et al., 1998; Brion et al., 2000), few studies have concentrated on the functioning of the River Seine inside Paris, which is the focus of this paper.

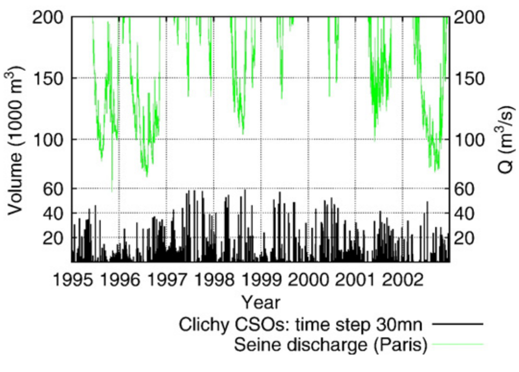

Fig. 2. Discharges of the Seine in Paris between 1995 and 2002 (upper curve, green) and CSO discharges at the main outlet at Clichy measured with a time step of 30 mn (lower curve, dark).

3. Definition of the scenarios and available data bases

3.1. The river system

Two contrasted years were selected in order to investigate the influence of the hydrological conditions. The year 1996 was particularly dry (annual average 214 $m^3\ s^{-1}$ inside Paris versus 354 $m^3\ s^{-1}$ on average during the last ten years). The year 2001 (annual average discharge: 526 $m^3\ s^{-1}$) characterizes a wet condition. The dry conditions, which are the most problematic for the water quality, are analyzed preferentially here.

Simulations were carried out from upstream of Paris to the Chatou dam (Fig. 1). The majority of the Paris sewer discharges occur in the modeled area. The upstream boundaries conditions (BCs) on the Marne and Seine rivers were set at the locations of drinking water production plants (Fig. 1). Because the river water is carefully monitored at these stations, a large data set is available to define model inputs: daily to weekly measurements of total suspended solids (SS), oxygen, nitrogen (NH_4^+, NO_3^-), orthophosphate (PO_4^{3-}), silica (Si), total organic carbon (TOC), dissolved organic carbon (DOC) and its biodegradable fraction (BDOC). This information was completed by weekly measurements of chl *a* carried out by the Interdistrict Federation for Sewage of Greater Paris (SIAAP) in the upstream Seine. River discharges measured by the Seine Navigation Service (SNS) at upstream BCs were used. Other upstream BCs were estimated by SENEQUE simulations on the main upstream sub-basins (Even et al., 2007-this volume).

The SIAAP and the SNS provided high-frequency (10 min) measurements of turbidity and oxygen and weekly chl *a*, NH_4^+, NO_3^- and PO_4^{3-} measurements. In the reach of interest, seven sites were surveyed (Fig. 1). Bacterial biomasses in the river Seine were provided by PIREN SEINE measurements (Garnier et al., 1992a; Servais and Garnier, 1993; Seidl et al., 1998c). This data set was used for the validation of the PROSE model.

3.1.1. Urban effluents

A consultation process including the major stakeholders in the basin was initiated in order to define the

Table 1
Past (1996), present (2001) and future (2015) point sources of BOD_5 (t d^{-1}) for the dry and wet hydrological context in the Parisian area

	Past-Dry	Present-Dry	Present-Wet	Future-Dry	Future-Wet
WWTP	11.15	2.8	5.7	10.9	16.2
Other permanent	39.7	26.5	26.5	14.0	14.0
CSO	27.7	29.1	74.1	3.3	5.7
Total	78.6	54.8	106.3	28.2	36.0

Human pressure Past-dry (1996) and Present-wet (2001) are real human pressures, used for the validation step (in dark). The other scenarios are hypothetical (in gray).

human pressure scenarios (AESN, 2003). They were defined for the present situation and the situation in 2015 (Table 1) for both dry (1996) and wet (2001) periods.

The 2015 scenario forecasts a drop in industrial and permanent discharges of raw wastewater in the Paris area from 26.5 tBOD_5 d^{-1} to 14 tBOD_5 d^{-1} (Table 1). The BOD_5 load from the WWTPs inside Paris is currently between 2 and 6 t$BOD_5 d^{-1}$ and will increase to between 11 and 16 tBOD_5 d^{-1} (Table 1), due to the doubling of the Seine Amont treatment capacity and the construction of la Morée WWTP (Fig. 1). The purpose of these extensions, in addition to the building of the Grésillon plant, is to reduce the permanent discharge at the Seine Aval WWTP (−25%). In the future, the latter and the Grésillon plant will be dedicated to the treatment of runoff water, providing a 90% reduction of the CSOs (Table 1).

While at present, nitrogen is not treated at the Seine Aval WWTP and total N treatment at other sites is less than 70%, overall elimination will reach 70% in the future. The treatment of the total P will be increased to 80%.

3.1.2. Permanent dry-weather effluents

WWTP discharges generally show a daily period, with a maximum flow during the day. As WWTPs are dimensioned to support the daily maximum discharge, a hypothesis of 80% of the nominal capacity for the mean daily dry-weather discharge at each WWTP was adopted.

Total SS, Biological Oxygen Demand (BOD_5), NH_4 or Total Kjedal Nitrogen (TKN), nitrates and total phosphorus (P_{tot}) concentrations were used as basic information to describe the WWTP effluent quality. In addition, in the framework of the PIREN SEINE, numerous samples of effluents from the main Paris WWTPs were collected to determine their quality in terms of organic matter and bacteria biomass loads (Servais et al., 1998). Correlations were established between BOD_5 and the various fractions of organic carbon used as variables in the PROSE model (Billen et al., 1994; Garnier et al., 1995). The mean load of refractory dissolved organic carbon per inhabitant was estimated. Specific physiological characteristics such as the growth rate of bacteria in the effluents were also determined (Garnier et al., 1992a).

3.1.3. Transient wet-weather effluents

The annual volume discharged at each WWTP or storm sewer outlet provided the spatial pattern of overflow discharges. Discharges measured with a time step of 30 min at the outlet of Clichy were used to redraw overflow patterns in time. Various series of measurements at outflows have shown that the fractionation of the carbon and physiological characteristics of the bacteria during wet weather were not very different from those of dry-weather periods (Seidl et al., 1998b; Servais et al., 1999b). Given the lack of information on the quality of the water at the outlets, its composition was set to that of the known average wastewater composition at the entrance of the WWTPs. In the WWTPs, rules define the distribution between (treated water) / (partially treated water) / (raw water) at the outlets were established according to the management rules used at the plants.

4. The PROSE model

The PROSE model is a river water-quality model, designed to simulate the impact of urban effluents (permanent dry-weather effluents and CSOs) on receiving freshwater. Highly transient events were also represented with time scale of a few minutes.

The hydrodynamic module is a longitudinal one-dimensional model based on the Saint–Venant equations solved by a finite difference method, the Preissmann scheme. Fixed and mobile sills are taken into account. The bottom friction is calculated by a Strickler formulation.

The transport module simulates the advection and mixing of constituents in the water. Since a significant proportion of biochemical constituents of the ecosystem is linked to particles, special care was taken to describe the particle transport model. Sedimentation and erosion are both explicitly simulated (Even et al., 2004) as well as a single well-mixed benthic mud layer (see Discussion). Fluxes of dissolved components at the water–sediment interface are based on the mass-transfer formulation according to Boudreau (1997).

The biochemical model RIVE (Billen et al., 1994; Garnier et al., 1995), was used to represent the biological processes in the water column. The conceptual scheme is based on a macro-scale representation of the microorganism dynamics that govern the transformation of many constituents. The philosophy behind RIVE is that a good description of the microbial (bacterial and algal) processes should be robust enough to work efficiently in many situations created by varying environmental conditions (Billen et al., 1994; Reichert et al., 2001). Two groups of algae are represented: siliceous diatoms and non-siliceous chlorophyceae (Garnier et al., 1995) and two types of heterotrophic bacteria: " small-sized " (<1 μm) and " large-sized " (>1 μm) (Garnier et al., 1992a; Servais and Garnier, 1993). The latter dominate in the wastewater (more than 80% of the bacterial biomass) (Garnier et al., 1992a; Servais et al., 1999a). The physiological characteristics of the two types of bacteria have been defined (Garnier et al., 1992a). Three classes of degradability are considered for both dissolved and particulate carbon.

No specific calibration of the model was performed for this study. For more details see Garnier et al. (1995), Even et al. (1998, 2004), Flipo et al. (2004).

5. Results

Oxygen is a synthetic variable and a good indicator of the health of an aquatic environment. This discussion will therefore be based on this variable. Many other variables (organic matter, suspended matter, nutrients,…) have been simulated and validated. Detailed results can be seen in Even et al. (2003, 2007-this volume).

5.1. Model validation

Simulations fit well measurements at each sampling station (Fig. 3). The mean relative errors vary between 10 and 31% for the dry year 1996 (discrepancies of between 0.5 and 1.3 mg L^{-1}) and are below 10% in 2001 (Table 2). The large discrepancies for oxygen in 1996 are mainly due to the poor simulation of the phytoplanktonic bloom in May and June (chl *a* concentrations higher than 100 μg L^{-1} and average error between 20% and 40%). Large discrepancies in some periods may be due to a lack of knowledge of the Marne chl *a* concentrations, which were supposed to be the same as in upstream Seine. If this period is omitted, the relative errors on oxygen are lower than 18% in 1996 (Table 2).

In 1996, differences between the daily oxygen variation amplitudes calculated by the model and the measurements vary between 20 and 50%. The discrepancies are greater at the downstream sites. This is partly due to the vertical daily stratification previously observed

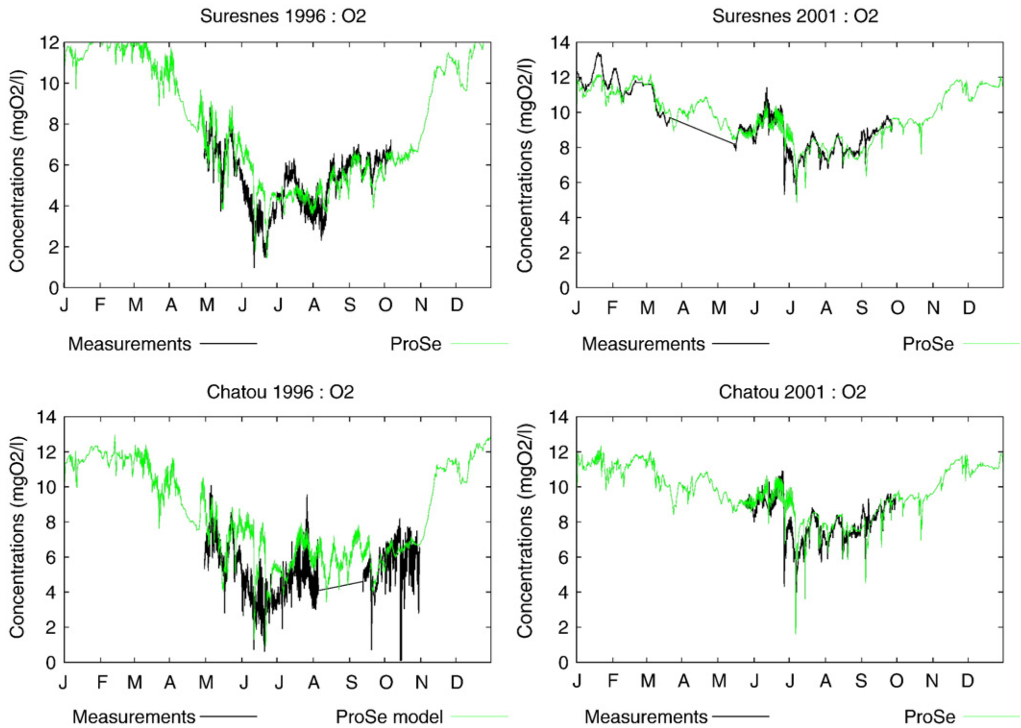

Fig. 3. Dissolved oxygen concentrations at Suresnes and Chatou, for the validation years 1996 and 2001 calculated with the PROSE model and measurements from the SIAAP.

Table 2
Errors calculations on the mean daily oxygen concentrations for the two reference year 1996 and 2001 at five sites sampled within Paris

Year	Site	N1	ΔC_{moy} (mg L^{-1})	$\left(\frac{\Delta C}{C}\right)_{moy}$ (%)	N2	ΔC_{moy} (mg L^{-1})	$\left(\frac{\Delta C}{C}\right)_{moy}$ (%)
1996	Suresnes	158	0.71	16.9	–	–	–
	Asnieres	169	1.2	23.2	148	0.92	15.2
	Colombes	183	1.2	25.5	164	0.87	16.7
	Chatou	146	1.3	31	126	0.85	17.8
2001	Suresnes	205	0.5	5.3	–	–	–
	Asnieres	102	0.52	6.5	–	–	–
	Colombes	105	0.64	8.7	100	0.56	6.9
	Chatou	126	0.52	7	123	0.47	6.4

N1: number of sampled days; N2: number of samples with discards less than 2.0 mg L^{-1}.

during low flow and hot periods. This phenomenon contributes to high oxygen concentrations in the upper layer, where data were collected (+2 to 4 mg L^{-1}), which are not representative of the whole water column as simulated by PROSE (Mouchel et al., 1994).

Ammonia concentrations in Paris are low (between 0.2 and 0.7 mgN L^{-1}) and nitrification is low (Brion et al., 2000). The model errors fall within the measurements uncertainty (±0.1 mgN L^{-1}).

Total heterotrophic bacteria biomass was measured by four series of measurements in July and August 1996 in Paris. It ranges from 0.09 to 0.2 mgC L^{-1} at Colombes and from 0.07 to 0.15 mgC L^{-1} at Chatou. During the same period, estimates by the model, between 0.07 and 0.24 mgC L^{-1} at Colombes, 0.05 and 0.18 mgC L^{-1} at Chatou, are coherent with the biomass fluctuations.

Many processes influence the oxygen dynamics in the river Seine inside the Paris conurbation and downstream of it. The modelling of the involved processes has been validated previously in certain reaches: 1) heterotrophic bacteria activity downstream of the Seine Aval WWTP (Garnier et al., 1992a; Servais and Garnier, 1993; Even et al., 1998), 2) downstream of the Clichy CSO (Even et al., 2004); 3) nitrification downstream of the Seine Aval WWTP (Even et al., 1998; Brion et al., 2000), 4) in the estuary (Billen et al., 1999), 5) reaeration in the navigated part of the Seine (Thibodeaux et al., 1994); 6) phytoplanktonic activity was validated at the scale of the complete hydrographic network (Garnier et al., 1995). This work includes the previous studies which are extended over the whole year. Moreover, inside the Paris conurbation the PROSE model is able to reproduce the balance involving many processes (Fig. 6). This is the first application of the PROSE model at such a large scale including all types of urban effluents. The satisfying validation of the model illustrates its potential to adapt to complex situations, which is an important criterion as long as forecasting is considered.

Because discharge and water quality data are available for only a few CSO outlets, the scenarios are also based on a theoretical reconstruction, as described in Section 3.1.3. This is an obvious source of error in the simulation and validation of detailed water quality data after the overflows have occurred. This point deserves further study and much needs still to be learned about the functioning of the combined sewer network during rainy periods. The ability of the PROSE model to simulate water quality after CSO events has already been verified in previous studies (Even et al., 2004) including a specific data collection to precisely characterize the quality of the discharged water. For simulation purposes, one must understand that CSOs and rain events are basically random and that the situations simulated in this study are only intended for comparison, mostly to predict future situations.

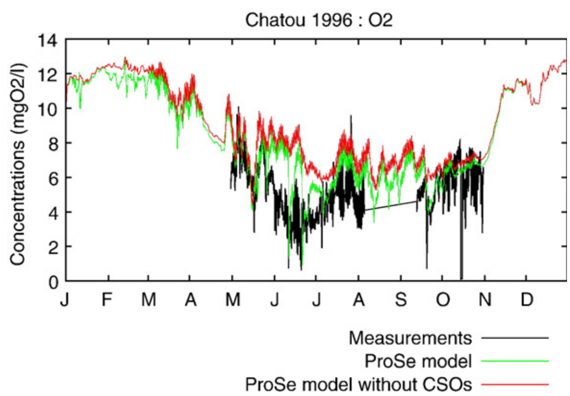

Fig. 4. Comparison of the dissolved oxygen concentrations at Chatou for the dry year 1996 calculated with the PROSE model with and without CSOs; measurements from the SIAAP.

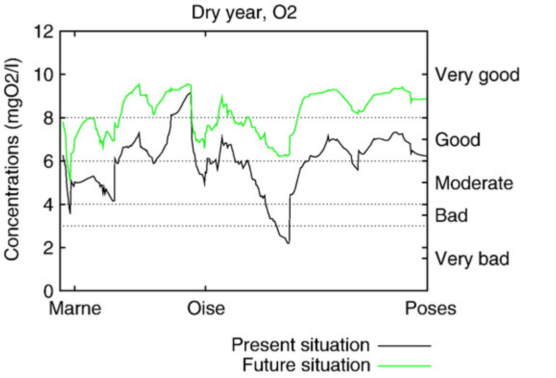

Fig. 5. Longitudinal evolution of the oxygen between Marne (KP −6) down to the estuary (limit at the dam of Poses, KP 202). Comparison between the past (1996) and the future (2015) situations.

5.2. Impact of the Paris CSOs

The simulation results for the past situation with and without CSOs are compared at Chatou (Fig. 4). In the nineties, the CSO contribution to the BOD load inside Paris was 40%. As shown in Fig. 4, this load had noticeable impact on the system during the whole summer, from the end of May to November and especially in June and July, where the difference between the simulations with and without CSO varies between 0.5 and 5 mg L^{-1} (mean of 1.3 mg L^{-1}).

In 1996, the general trend was toward a dissolved oxygen level decrease all along the 50 km inside the Paris conurbation (Fig. 5). The oxygen deficits at Chatou varied between 2 and 7 mgO_2 L^{-1}, with an average of 4.35 mgO_2 L^{-1} between May and October. The reoxygenation at the Chatou dam and the lack of heavy urban effluents before the Seine Aval WWTP improved the oxygen levels downstream (Fig. 5).

After rain events, at Colombes and Chatou, oxygen minima below 2 mgO_2 L^{-1} and lasting from one hour to nine days were observed on several occasions during the summer of 1996 (Fig. 3). The D90 (such that 90% of the concentrations are higher than the D90 limit) calculated from the measurements varied from 3.3 mgO_2 L^{-1} to 4.7 mgO_2 L^{-1} in all sampled sites inside the Paris conurbation. Although the measurements cover the summer period only, the model can be used to provide an estimate for the D90s at the annual scale, which are 5% to 15% higher. The annual D90 for a situation without CSO is 6.3 mg L^{-1} (+19%) at Chatou.

Budgets representative of July 1996 (fluxes cumulated over the whole month) were calculated with the PROSE model (Fig. 6) from the Marne/Seine junction (KP −6) to upstream of the Chatou dam (KP 44) (Fig. 1). The benthic consumption accounts for 56% of the oxygen losses inside this reach. The equivalent of 112% of the upstream oxygen flux is respired due to phytoplanktonic activity and the reaeration at the air–water interface that compensates for large oxygen consumption. The budget of the biological processes is equilibrated. The CSOs have an effect only on the benthic demand, which is reduced by 32% (20% reduction of the total oxygen consumption) when they are not taken into account (Fig. 6).

5.3. The present and future situations

The present situation is that of a 40% reduction in the permanent dry-weather discharges inside Paris while the CSOs remain of the same order and in predicted situation

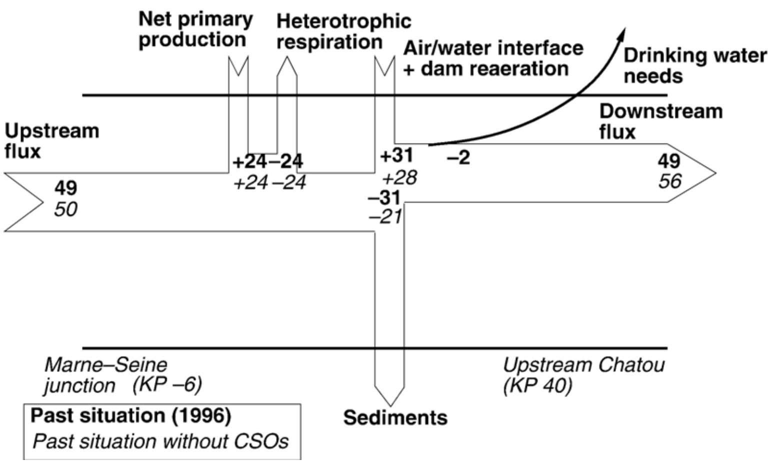

Fig. 6. Oxygen budgets (t d^{-1}) in July 1996 (average calculated for the cumulated fluxes over 30 days), calculated with the PROSE model for past human pressure (1996), between the Marne/Seine junction (KP −6) and upstream of the Chatou dam (KP 40). Storm events in July: 116 tBOD (mean of 3.7 tBOD d^{-1}, 2% of the annual load); one event on the 5th of July: 112 tBOD in a day; permanent dry-weather load: 27.4 tBOD d^{-1}.

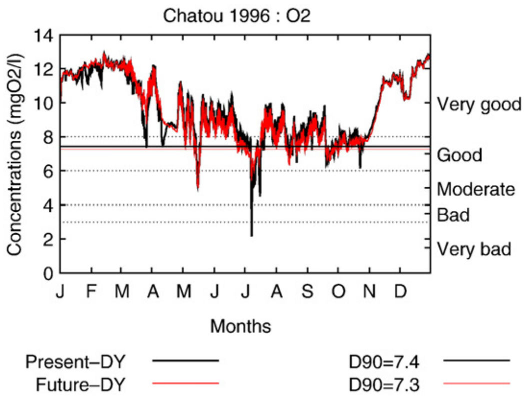

Fig. 7. Simulation of the dissolved oxygen at Chatou for the dry year (1996); comparison of the present (2001) situation and the future (2015) scenario.

both permanent and transient effluents are reduced (Table 1). The evolution of the water quality inside Paris is similar in the present and predicted situations and it is far better than the situation in the nineties, with D90 around 7.4 $mgO_2\ L^{-1}$ at Chatou (Fig. 7).

For the present situation the oxygen consumption in the water column and at the sediment–water interface is reduced by 15% and 52% respectively (21 $tO_2\ d^{-1}$ and 15 $tO_2\ d^{-1}$). The oxygen budgets for the predicted situation show a net oxygen production (+14 $tO_2\ d^{-1}$) (Fig. 8). A 58% drop of the benthic demand is forecast. 68% of the upstream flux is respired. The air–water reaeration is lowered by 16% while the phytoplanktonic activity remains the same.

6. Discussion

6.1. The spatial and temporal scale of the CSO impact

Many studies have considered the effect of one CSO (Hvitved-Jacobsen, 1982; Schaarup-Jensen and Hvitved-Jacobsen, 1990; Dégardin and Bujon, 1994; Even et al., 2004) and the acute short-term impact due to dissolved contaminants. Harremoes (1982) was the first author to mention the delayed impact of CSOs due to settled organic matter. However this delayed impact was studied at the daily scale (Hvitved-Jacobsen, 1982).

The results obtained for a situation without CSOs show a quasi-permanent impact of the ones in Paris. Inside the Paris conurbation, the main result of the planned new installations would be to strongly reduce the CSOs, while the discharged volume of wastewater after treatment would increase because of significant extensions of the WWTPs in the upstream part of the Paris conurbation. According to the modelling results presented here the improvement of the oxygen levels during dry-weather in the predicted situation is due to a strong reduction of the inputs from both CSOs and permanent untreated discharges. However, the results show a weak effect on the heterotrophic activity in the water column relative to the benthic demand. This is explained by the magnitude of the upstream BDOC flux (1.5 times the Paris zone contribution by effluents and phytoplanktonic lysis), that probably comes from upstream algae lysis (Flipo et al., 2004). The phytoplankton lysis in the reach itself represents 70% of the effluent load. The bacterial activity is also only slightly

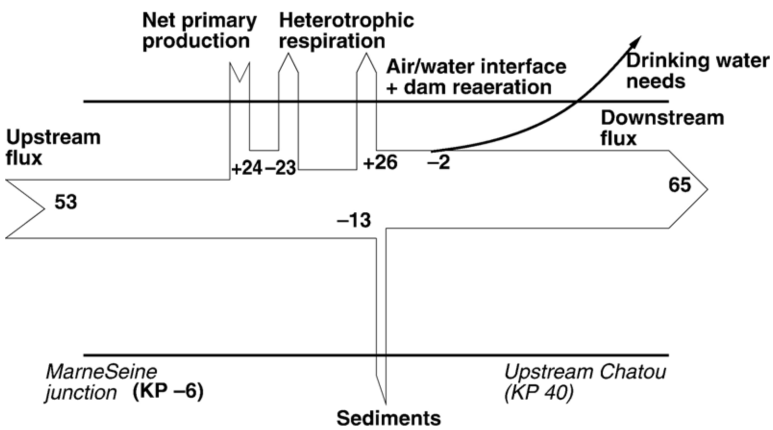

Fig. 8. Oxygen budgets (t d^{-1}) in DY-July (average calculated for the cumulated fluxes over 30 days) calculated with the PROSE model for the future human pressure, between the Marne/Seine junction (KP −6) and upstream of the Chatou dam (KP 40). Total load of storm events in July: 106 tBOD (mean of 3.5 tBOD d^{-1}; 12.3% of the annual load); two main events on the 7th and 14th of July: 53 tBOD and 35 tBOD respectively; permanent dry-weather load: 5.2 tBOD d^{-1}.

lowered. The system appears to be driven mainly by the phytoplankton, whose photosynthetic activity directly prevents severe oxygen depletion in the system and indirectly provides BDOC stocks high enough to sustain the heterotrophic bacteria respiration. As a result, the most obvious effect of the CSOs is on the benthic demand. Note, however, that when similar annual amounts of BOD are eliminated from the CSOs or from permanent dry-weather discharges (comparison of the past without CSOs and the present situations), the effect on benthic demand is weaker in the first case (−32% and −52% respectively). As most CSOs occur in winter and spring (in July 1996 they accounted for only 13% of the permanent dry-weather BOD load), this feature shows the strong remanent effect of CSOs.

It should be mentioned that the significant oxygen depletion inside Paris observed in the past has not been thoroughly studied until now; even the more pessimistic hypotheses regarding known dry-weather wastewater discharges from a possibly leaking sewer system were unable to reproduce the periodically observed sharp oxygen depletion. This gave rise to controversies among the major stakeholders regarding the existence of unknown or even hidden wastewater discharges inside Paris or its near suburbs, during dry-weather. According to our results, the CSOs were the known but not well understood causes of these deficits.

Two factors enhance the impact of CSOs. The first one is the presence of large amounts of particulate organic matter in the wastewater discharged during rain events. Experimental evidence shows that it settles rapidly (mean settling velocity of 1 m h^{-1}) (Maldiney, 1994; Tangerino, 1994) and modelling has confirmed the strength of this process for a single CSO (Even et al., 2004). The second one is the diffuse character of the CSOs, due to the large number of outlets, which cause a wide geographical dispersion of the settled sediments. Because of the large stock of benthic degradable matter, oxygen levels were permanently lowered along the 50 km long reach inside Paris. However a hypothesis that considers an average wastewater composition at the entrance of the WWTPs may underestimate the SS load from CSOs because during rainy events the deposits accumulated inside the sewage system during dry periods are re-suspended due to the rapid flow increase (Ahyerre et al., 2001) and represent the main fraction of the particle load in the overflows (Gromaire et al., 2001).

When the impact of the CSO is considered over a large time scale the D90s should also be taken into account. Actually, many D90s calculated along the downstream part of the river Seine are mainly driven by the short- and long-term impacts of the CSOs.

6.2. Sediment transport

Given the amount and importance of particles in CSOs, special attention was paid to the conceptualization of the particle transport sub-model in PROSE. An explicit representation of the settling and erosion processes was necessary to describe spatial and temporal imbalances between the two fluxes in highly transient conditions. Specific settling velocities, as often as possible measured in the field (Maldiney, 1994; Tangerino, 1994), were used to simulate the settling of each particulate compartment (solids, organic matter, bacteria) (Even et al., 2004). Erosion was simulated according to an energy-based concept where a fixed fraction of the dissipated energy at the bottom is used to re-suspend the deposited layer; it includes the effect of natural turbulence and of the river barges, as it was shown that the latter could divide by two the total sediment storage in the river (Martin, 2001). The two erosion parameters were calibrated to represent observed SS concentrations in the water column at low flow (predominance of navigation) and SS increase during floods (predominance of river flow turbulence). The adopted conceptual scheme represents observed settling of high amounts of SS downstream of outlets. So far, this scheme has been validated on a wide range of situations (Even et al., 2004, 2007-this volume).

Unlike the above approach, most water-quality models use simplified representations of sediment transport. A common hypothesis is to consider a permanent net loss from the water column (Billen et al., 1994; Brown and Barnwell, 1987). Such a representation leads to a very different prediction of the spatial distribution of the sediment stocks. Moreover settling velocities have to be adapted reach by reach to correctly simulate the impact of a polluted effluent. Site-specific parametrization generally prevents easy and extensive use of these models. Finally, the diagenetic model originally coupled to the RIVE model, *i.e.* VENICE, considers an analytical solution of stationary equations (Billen, 1982; Billen et al., 1994). This hypothesis avoids an explicit representation of the benthic layer because it can calculate the inorganic fluxes (oxygen, nutrients) at the sediment–water interface as a function of instantaneous carbon fluxes, that are assumed not to vary much in time. This approach was not able to reliably represent highly transient exchanges of sediment and delayed benthic effects. To describe these processes, an explicit representation of the benthic layer was introduced into the PROSE model. Conversely, the many field studies of sediment transport have seldom been coupled with complete biochemical processes. This was done in the PROSE model.

7. Conclusion

It was also shown that it was essential to take into account the CSOs to understand the hydro-system long-term behavior inside Paris and the ability of the PROSE model to represent the functioning of a system impacted by multiple human pressures is here demonstrated. According to the model, 56% of the oxygen consumption was due to the benthic oxygen demand; CSOs explained 32% of this demand for a typical summer month and the D90 increases by 1 $mgO_3\ L^{-1}$ when they are excluded. This is one of the research program main results, since it contributes to clarify the debate on the pollutions responsible for the oxygen depletions observed in the Seine. When classical and simplified modeling approaches applied in the Seine mainly used re-calibration to adjust models results to the observations and simply have miss the CSOs phenomena, the interest of a completely deterministic approach is here illustrated. This result was useful for managers and decision-makers in the river basin.

But, the source-impacts relations in natural ecosystems are complex and a significant part of the measurement and modelling efforts should be devoted to improve this knowledge. In many urban areas, high frequency measurements networks are currently installed to come up with requirements on evaluating the effect of the environmental policies. These data crossed with main evolutions of the pollution treatment, will be helpful to assess the source-impacts relations. This includes the becoming of highly polluted sediment stored in the system for long time, which is a main challenge for scientists. The PROSE model illustrates how models, by solving large spatial and time periods, can be helpful to cope with those issues.

At the same time, Real Time Control (RTC) of sewer systems has been developing during the last years in many cities in all parts of the world, in Québec (Pleau et al., 2005), in Tokyo (Maeda et al., 2005) or in parts of Paris sewer system. RTC enables an optimal operation of costly engineered systems and is one of the latest development regarding sewer systems. It requires huge modelling and data acquisition efforts to optimize the function of the sewer system (gates, pumping stations) for any rain event. But, although several scientists have claimed for the need of integrating the water quality in the receiving system in the objective function (Schütze et al., 2004), the practical implementation of RTC only minimizes discharged water volumes. Our modelling results demonstrate the complexity of the response of the receiving system. In the Seine, that is a highly eutrophicated system, the phytoplanktonic activity was shown to be the main factor controlling both oxygenation and bacteria activity. The focus was here on oxygen, but many other contaminants are discharged by CSOs, which behavior is determined by organic matter, suspended solids and oxygen. These considerations show that a good understanding of the response of the system to urban discharges remains a critical step in the design of improved sewer systems. This is where the main challenge is laying, before its introduction in RTC procedures.

Conversely, the contribution of CSOs to the global ecosystems functioning should be further explored. While the treatment capacity at the WWTPs will increase, the relative contribution of the CSOs to oxygenation, nutrient releases and eutrophication should be considered (Even et al., 2007-this volume). All those points highlight the complexity of the interactions within hydro-systems impacted by many human activities.

In addition many important changes should be taken into account in the future: urban areas still sprawling and new types of runoff treatment are created; new regulatory contexts linked to extended usage of water do appear, such as bathing directives; climate change, that may influence the hydrology, should be considered.

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References

AESN, DIREN de bassin. État des lieux du district Seine et côtiers normands; 2003. Version 2.

Ahyerre M, Chebbo G, Saad M. Nature and dynamics of water sediment interface in combined sewers. J Environ Eng 2001;127(3):233–9.

Billen G. Modelling the processes of organic matter degradation and nutrients recycling in sedimentary systems. Sediment microbiology. Academic Press; 1982. p. 15–52.

Billen G, Garnier J, Hanset P. Modelling phytoplankton development in whole drainage networks: The RIVERSTRAHLER model applied to the Seine river system. Hydrobiologia 1994;289:119–37.

Billen G, Garnier J, Servais P, Brion N, Ficht A, Even S, et al. Programme scientifique Seine Aval. L'oxygène: un témoin du fonctionnement microbiologique, vol. 5. IFREMER; 1999.

Boudreau BP. Diagenetic models and their implementation. Springer; 1997.

Boët P, Duvoux B, Allardi J, Belliard J. Incidence des orages estivaux sur le peuplement piscicole de la seine à l'aval de l'agglomération parisenne (bief andrésy-méricourt). La Houille Blanche 1994;1/2:141–7.

Brelot E, Chocat B. Impact des rejets sur les milieux récepteurs. La Houille Blanche 1996;1:16–21.

Brion N, Billen G, Guezennec L, Ficht A. Distribution of nitrifying bacteria in the Seine river (France) from Paris to the estuary. Estuaries 2000;23:669–82.

Brown, L.C., Barnwell, T.O., 1987. Enhanced stream water quality models, QUAL2E and QUAL2E UNCAS. Documentation and user's TechReport. Department of civil Engineering, Tufts University, Medford, MA 02155. Environmental research laboratory office of research and development. U.S. Environmental Protection Agency, rapport EPA/600/3-87/007.

Chen J-C, Chang N-B, Chen C-Y, Fen C-S. Minimizing the ecological risk of combined-sewer overflows in an urban river system by a system-based approach. J Environ Eng 2004;130(10):1154–69.

Chesterikoff A, Thévenot D, Mouchel J-M, Poulin M, Garban B, Ollivon D. La Seine en son bassin. Fonctionnement écologique d'un système fluvial anthropisé. Elsevier; 1998. p. 301–44. Ch. Le fleuve dans la ville.

Dégardin P, Bujon G. Appréciation de l'impact des déversements de temps de pluie en région parisienne à l'aide du modèle mathématique Kalplan. La Houille Blanche 1994;1:148–52.

Even S, Poulin M, Mouchel JM, Billen G. Simulating the impact of CSO's from greater Paris on the Seine river using the model ProSe. In: Seventh International Congress on Urban Drainage Storm Water . IAWQ, EWPCA, IAHR and ATV, 1996.

Even S, Poulin M, Garnier J, Billen G, Servais P, Chesterikoff A, et al. River ecosystem modelling: application of the PROSE model to the Seine river (France). Hydrobiologia 1998;373:27–37.

Even S, Poulin M, Thouvenin B. Evolution prospective de la qualité des eaux de surface. scénario tendanciel de la Directive Cadre Européenne de l'agglomération parisienne à l'estuaire. Tech. rep., PIREN Seine; 2003. http://www.sisyphe.jussieu.fr/internet/piren/.

Even S, Mouchel J-M, Seidl M, Servais P, Poulin M. Oxygen deficits in the Seine river downstream of combined sewer overflows: importance of the suspended matter transport. Ecol Model 2004;173(2–3):177–96.

Even S, Billen G, Bacq N, Théry S, Ruelland D, Garnier J, Cugier P, Poulin M, Blanc S, Lamy F, Paffoni C. New tools for modelling water quality of hydro-systems: an application in the Seine River basin in the frame of the Water Framework Directive. Sci Total Environ 2007;375:274–91 (this volume). doi:10.1016/j.scitotenv.2006.12.019.

Flipo N, Even S, Poulin M, Tusseau-Vuillemin M-H, Améziane T, Dauta A. Biogeochemical modelling at the river scale: plankton and periphyton dynamics: Grand Morin case study, France. Ecol Model 2004;176:333–47.

Garnier J, Billen G, Servais P. Physiological characteristics and ecological role of small- and large-sized bacteria in a polluted river (Seine river, France). Arch Hydrobiol Beih 1992a;37:83–94.

Garnier J, Servais P, Billen G. Bacterioplankton in the Seine river (France): impact of the Parisian urban effluent. Can J Microbiol 1992b;38:56–64.

Garnier J, Billen G, Coste M. Seasonal succession of diatoms and chlorophycae in the drainage network of the river Seine: observations and modelling. Limnol Oceanogr 1995;40 (4):750–65.

Gromaire M-C, Garnaud S, Saad M, Chebbo G. Contribution of different sources to the pollution of wet weather flows in combined sewers. Water Res 2001;35(2):521–33.

Harremoes P. Immediate and delayed oxygen depletion in rivers. Water Res 1982;16:1093–8.

Hvitved-Jacobsen T. The impact of combined sewer overflows on the dissolved oxygen concentration of a river. Water Res 1982;16: 1099–105.

Maeda M, Mizushima H, Ito K. Development of the real-time control (rtc) system for tokyo sewage system. Water Sci Technol 2005;51 (2):213–20.

Maldiney, M.-A., 1994. Caractéristiques physiques des particules en suspension dans un fleuve canalisé, exemple de la Seine. Thèse de doctorat, École Nationale Supérieure des Ponts et Chaussées, CERGRENE.

Marsalek J, Kok S. Stormwater management and abatement of combined sewer overflow pollution. Water Qual Res J Can 1997;32(1):1–5.

Martin, L., 2001. Fonctionnement écologique de la Seine à l'aval de la station d'épuration d'Achères : données expérimentales et modélisation bidimensionnelle. Thèse de doctorat, ENSMP.

Mouchel J-M, Simon L, Maldiney M-A. Impacts en Seine des rejets urbains de temps de pluie sur les concentrations d'oxygène dissous. La Houille Blanche 1994;1:135–41.

Mouchel J-M, Boët P, Hubert G, Guerrini M-C. La Seine en son bassin. Fonctionnement écologique d'un système fluvial anthropisé. Ch. Un bassin et des hommes : une histoire tourmentée. Elsevier; 1998. p. 77-125.

Pleau M, Colas H, Lavallee P, Pelletier G, Bonin R. Global optimal real-time control of the Quebec urban drainage system. Environ Model Softw 2005;20(4):401–13.

Reichert P, Borchart D, henze M, Rauch W, Shanahan P, Somlyody L, et al. River water quality modelling no. 1: II. Biochemical process equations. Water Sci Technol 2001;43(5):11–30.

Schaarup-Jensen K, Hvitved-Jacobsen T. Dissolved oxygen stream model for combined sewer overflows. Water Sci Technol 1990;22(11):137–46.

Schütze M, Campiasano A, Colas H, Schilling W, Vanrolleghem P. Real time control of urban wasterwater systems — where do we stand today? J Hydrol 2004;299:335–48.

Seidl M, Huang W, Mouchel J. Toxicity of combined sewer overflows on river phytoplankton : the role of heavy metals. Environ Pollut 1998a;101:107–16.

Seidl M, Servais P, Martaud A, Gandouin C, Mouchel J. Organic carbon biodegradability and heterotrophic bacteria along a combined sewer catchment during rain events. Water Sci Technol 1998b;37:25–33.

Seidl M, Servais P, Mouchel J-M. Organic matter transport and degradation in the river Seine (France) after a Combined Sewer Overflow. Water Res 1998c;32:3569–80.

Servais P, Garnier J. Contribution of heterotrophic bacterial production to the carbon budget of the River Seine (France). Mar Ecol 1993;25:19–33.

Servais P, Billen G, Garnier J, Idlafikh Z, Mouchel J-M, Seidl M, et al. Carbone organique: origines et biodégradabilité. Elsevier; 1998. p. 483–525. Ch. 11.

Servais P, Garnier J, Demarteau N, Brion N, Billen G. Supply of organic matter and bacteria to aquatic ecosystems through waste water effluents. Water Res 1999a;35:3521–31.

Servais P, Seidl M, Mouchel J. Comparison of parameters characterising organic matter in a combined sewer during rain events and dry weather. Water Environ Res 1999b;71(4):408–17.

Tangerino C. Mesure de la vitesse de chute des matières en suspension, du carbone organique total et des bactéries en seine. Master, CERGRENE — ENPC, 1994.

Thibodeaux L, Poulin M, Even S. A model for enhanced aeration of streams by motor vessels with application to the River Seine. J Hazard Mater 1994;37:459–73.

UNITED STATE ENVIRONMENTAL PROTECTION AGENCY. Source Water Protection Practices Bulletin. Managing sanitary sewer overflows and combined sewer overflows to prevent contamination of drinking water. Tech. rep. Office of Water; 2001. http://www.epa.gov/.