ICA2025OSLO
14th IWA Specialised Conference on
Instrumentation, Control and Automation

# Use of long-term continuous dissolved oxygen to describe the effects of combined sewer overflows.

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**Abstract**: Freshwater ecosystems provide fundamental services to human societies (e.g., drinking water, flood regulation, waste assimilation). A proper management of their integrity is thus essential, particularly where urban areas are served by combined sewer systems (CSS). During high rainfall events, a mixture of urban runoff and municipal waters can be discharged to receiving waters through the activation of combined sewer overflows (CSOs). CSO events can cause a sudden dissolved oxygen (DO) depletion and contribute additional pollutant (metals, organics, trace elements), pathogens and nutrient loads to receiving water bodies. However, efforts to mitigate punctual CSOs effects suffer from a lack of high resolution and long term monitoring data. Based on continuous DO signals, functional indicators such as aquatic metabolism have been proposed by researchers to assess water quality. In this study, we analyse the impact of CSOs on the Seine River in the Paris region using twenty years of hourly DO data collected at 8 sites. Daily metabolic rates (i.e., gross primary production (GPP), ecosystem respiration (ER), net ecosystem production (NEP)) were estimated along the Seine River, and their dynamics confronted to environmental variables (flow, temperature, nutrients). First results show a strong seasonal and hydroclimatic influence on the metabolic balance. However, the river metabolism is also impacted by the urban area both at the seasonal scale and after short term hydrological events. While GPP and ER show similar patterns, their trajectories are decoupled from NEP, which mainly follows the river water quality.

**Keywords**: Dissolved oxygen; high resolution data; combined sewer overflow; aquatic metabolism.

## Introduction

Combined sewer overflows (CSOs) represent one of the most significant sources of intermittent pollution in urbanized watersheds. During heavy rainfall, combined sewer systems designed to collect both sewage and stormwater may exceed their capacity and discharge untreated effluent directly into rivers and streams. These events release high loads of organic matter, nutrients, and pathogens, which can rapidly and drastically alter aquatic ecosystem functioning (Rodriguez-Castillo et al., 2017). DO is a critical indicator of water quality, reflecting both physical processes (i.e reaeration, temperature) and biological activity (i.e, photosynthesis, respiration, organic matter decomposition) (Jankowski et al., 2021). CSO events often cause abrupt drops in DO concentrations, leading to hypoxic or even anoxic conditions that can impair aquatic life and ecosystem services (Even et al, 2007). However, quantifying the magnitude and duration of these impacts has historically been limited by the availability of high-resolution and long-term data (Riechel et al., 2016). Recent advancements in continuous monitoring technologies now allow for the collection of DO data at fine temporal scales (i.e less than one hour intervals) over extended periods. These long-term continuous datasets offer a unique opportunity to characterize both acute responses to CSOs and longer-term trends in ecosystem metabolism (Arroita et al., 2019). In this study, we analyze over 26 years of continuous DO records from multiple riverine stations, some affected by CSOs and others not. Our objectives are to (1) detect and characterize the influence of CSO events on DO dynamics, (2) assess the short-term and seasonal impacts of CSOs on river metabolism (gross primary production( GPP), ecosystem respiration (ER), and net ecosystem production(NEP)), and (3) evaluate the utility of long-term DO monitoring for water quality management in urban river systems.

1. Study area

The Seine River watershed, covering approximately 78,600 km², is primarily situated within the Paris Basin (Fig. 1) with a pluvio-oceanic as hydrological regime. The mean annual precipitation is about 680 mm evenly distributed throughout the year (Romero et al., 2016). Over the past two decades, annual flow at Paris Austerlitz has ranged between 182 m³/s and over 527 m³/s, with peak discharges typically occurring in mid-February and low-flow periods during August (Flipo et al., 2020). These summer low flows are sustained around 100 m³/s through releases from upstream reservoirs (Garnier & Billen, 2007).

This study focuses on the lower Seine downstream of the Paris conurbation, from Port-à-l'Anglais (PAA) (upstream of Paris) to the Méricourt dam, spanning approximately 127 km (see Figure 1.1). This stretch crossing the Greater Paris metropolitan area, hosting more than 10 million inhabitants. Urban wastewater from Paris is managed by the Syndicat Interdépartemental de l'Assainissement pour l'Agglomération Parisienne (SIAAP), a public agency operating 5 main WWTPs along this stretch, whose treatment capacities and technologies have been significantly upgraded over the past two decades. During intense rainfall events, combined sewer overflows (CSOs) discharge untreated effluent directly into the Seine through two major outlets of Clichy and La Briche (Figure 1.1), contributing up to 30–60% of the total annual stormwater discharge (Escoffier et al., 2018).

Since 1995, the SIAAP through the MeSeine Observatory, also monitored DO and water temperature every 15 minutes, from upstream to downstream of Paris at 8 stations (Figure 1.1). Water samples are also collected fortnightly along this river stretch to perform the mandatory physico-chemical analyses. Water quality is monitored daily at the main WWTP outfalls and at major CSO outlets. Discharge data from Austerlitz and hydroclimatic information from national databases provide additional insights. These discharge records allowed us to contextualize the impact of CSOs relative to the river's flow dynamics.

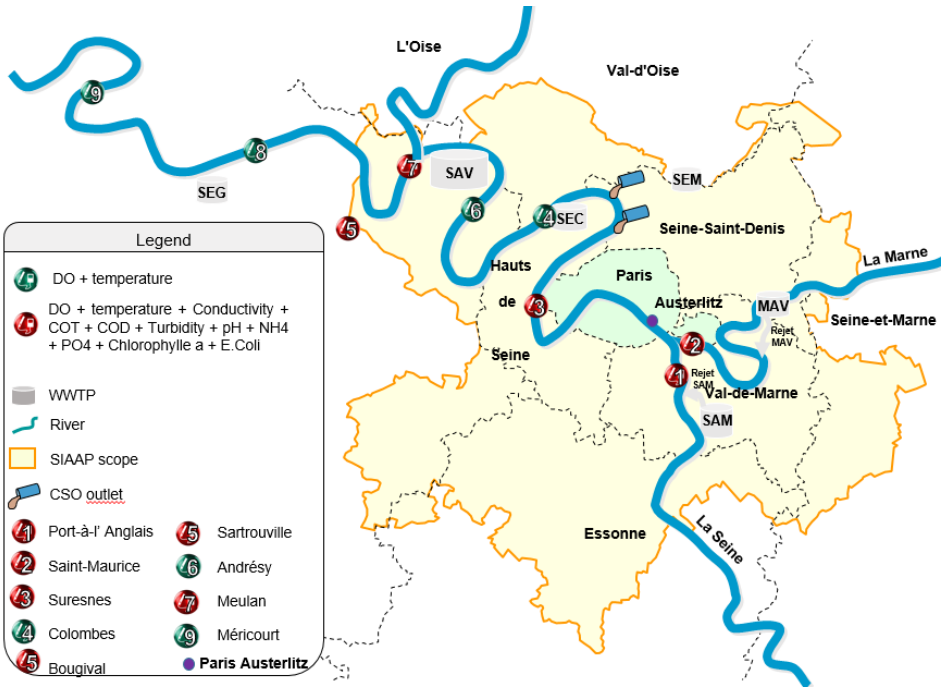


**Figure 1.1** Study area showing the 8 sites of the MeSeine Observatory, major WWTP and CSOs.

## 2. Methodology

Based on the analysis of metabolic rates (GPP, ER and NEP), the aim of this study is to identify long-term trends and key environmental stressors affecting the river, then distinguish random events and establish clear patterns between metabolic rates and CSO characteristics.

### 2.1 Estimating metabolism from DO time series

GPP and ER volumetric estimates ($gO_2.m^{-3}.d^{-1}$) were calculated using Odum's (1956) single-station diel oxygen method, based on a DO mass-balance between GPP, ER and atmospheric exchange (F(t)). Hourly DO were used for Metabolism estimates.

$$\frac{dC}{dt} = GPP(t) + F(t) + ER(t)$$

For each time interval, the instantaneous DO rate of change corrected for F is equal to the instantaneous net DO production rate, called Net Primary Production (NPP). ER is calculated from the average net DO consumption during the night and extrapolated as constant over 24 h. Instantaneous GPP is calculated as the sum of NPP and ER integrated over the light period. NEP is the balance between GPP and ER (positive and negative during standard diel cycles, respectively) and indicates the autotrophic or heterotrophic status of the ecosystem, when positive or negative, respectively.

## 3. Results

From 1997 to 2022, DO concentrations average 5 to 14 $mg.L^{-1}$ at all sites. DO were generally low (mean = 7 - 5 $mg.L^{-1}$) between May and October across all sites, coinciding with elevated water temperatures and increased biological activity. Interannual variability was evident, with some years exhibiting more pronounced summer declines, often associated with warm and/or dry conditions and periods of frequent sewage overflows. For instance, the summers of 2003, 2011, and 2019 experienced multiple DO depletion episodes, with concentrations dropping below 4 $mg.L^{-1}$ for more than 6 consecutive hours at all monitoring sites downstream of Paris city. Those levels are considered harmful to sensitive aquatic species. DO depletion was typically less severe at the upstream site PAA (see Figure 1.1) compared to downstream ones, possibly reflecting increased thermal stress and cumulative urban impacts in the lower reaches. More concerning, DO levels occasionally fell below $mg.L^{-1}$ (hypoxic conditions), particularly downstream of major sewer overflow outfalls or during heatwave events. These hypoxic episodes were usually short-lived (lasting from a few hours), and have become less frequent in recent years, likely due to improvements in the urban sanitation infrastructure.

DO depletion tends to be more severe in summer due to heightened metabolic activity, we then compared the sites specifically over the summer period define between May to October. To account for the different start dates of monitoring stations, the comparison was restricted to the common period between 2008 and 2022. Years with insufficient DO data were also excluded from the analysis. Filtering out positive ER or negative GPP (non-physical estimates), and the sum of the previous, NEP showed in Figure 3.1, metabolic fluxes ranged between ~-4.7 to ~2.5 $gO_2.m^{-3}.d^{-1}$. Metabolic variability seems to increased downstream, likely due to urban organic matter inputs, aligning with the river continuum concept (Vannote et al., 1980), as extended by Garnier et al. (2020). ER consistently exceeded GPP, indicating heterotrophy, except upstream at PAA (green box). NEP stabilized in recent years, reflecting nutrient reduction in the River due to

wastewater treatment improvements. Notably. the implementation of nitrification in WWTPs since 2007, have significantly reduced ammonium loads downstream of SAV and improved overall water quality (Garnier et al., 2020). As preliminary results, seasonal and hydroclimatic factors, especially high temperatures and low discharge strongly influenced metabolic rates, notably during 2011, 2019, and 2020 summers.

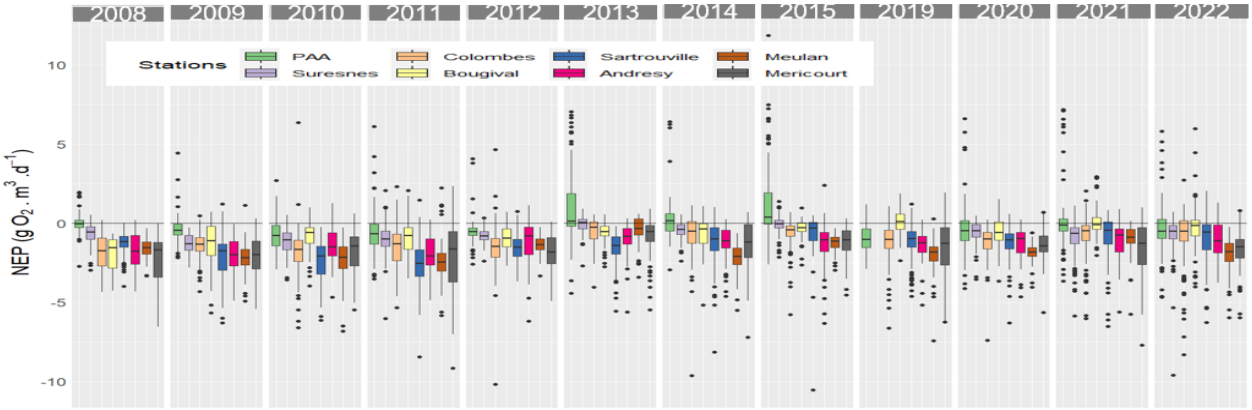


**Figure 3.1** Boxplots showing the distribution of daily NEP values over the years for the 8 MeSeine Observatory stations.

CSO events affect the river metabolism, by enhancing or reducing GPP and ER, depending on the season and oxygen saturation levels. Figure 3.2 highlights two periods impacted by discharges from the Clichy and La Briche CSOs, showing variations in metabolic rates (increases, reductions or both).This complex interplay involves oxygen deficits, prior CSO overflows and phytoplankton activity. Metabolic indicators are also valuable for classifying recovery times and build predictive models, providing insights into CSO impacts and supporting improved ecosystem management strategies.

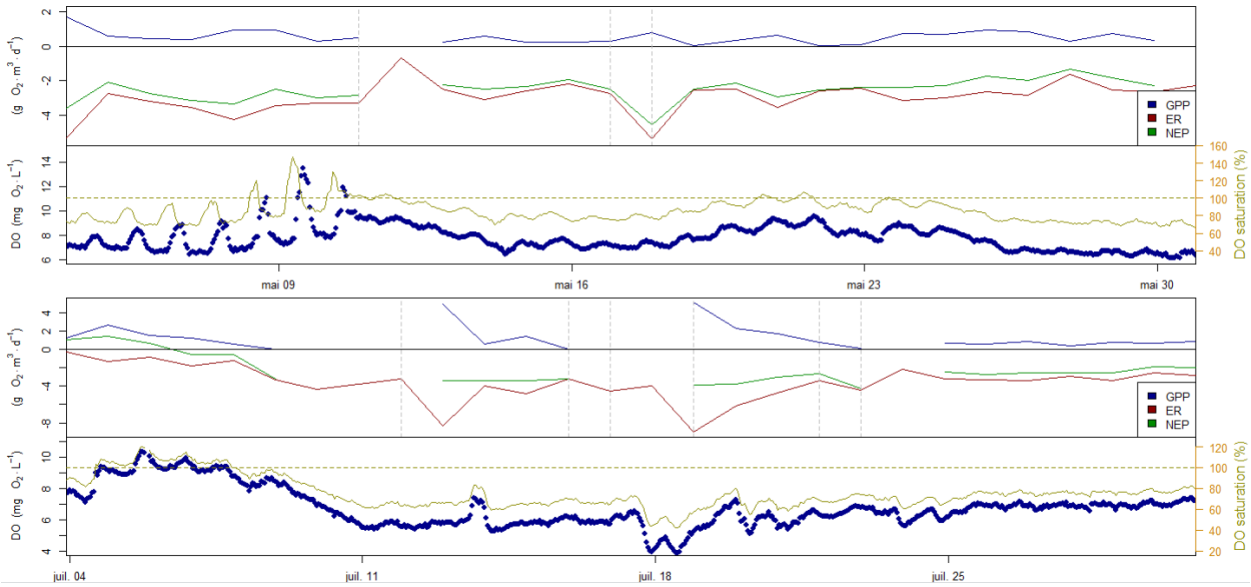


**Figure 3.2** Metabolic rates (GPP, ER & NEP) and DO curves from 05/05/2011 to 30/05/2011 and from 05/07/2011 to 30/07/2011 at Bougival station. Vertical lines are Clichy and La Briche discharge dates.

In addition to the observed links between CSO discharges and DO levels, our results revealed that the impacts of overflows varied in nature and timing. First, CSO events often altered the typical diel DO curve, preventing accurate estimation NEP. Second, DO depletions were not always directly caused by CSOs, for instance, oxygen drops were observed at PAA the upstream site before the Clichy and La Briche outlets, likely due to WWTP (SAM on Figure 1.1) overflows during rainfall events. Moreover, the spatial and temporal propagation of impacts varied among stations. At the station closest to the discharge point, a DO drop could be observed within a few hours, with its magnitude influenced by the prior day's metabolic state. In some cases, no clear impact was detected, while in others, effects became apparent only after several days. For instance on figure 3.3, during a CSO event in July 2019, DO concentrations recorded at 3 stations PAA (upstream), Bougival (close to the outlet), and Méricourt (downstream) showed distinct responses: no change was observed at PAA (as expected), a DO drop occurred after 2 days at Bougival for more than 10 hours, and a more severe and prolonged depletion appeared at Méricourt after 4 days. This highlights how the spatial distance from the discharge point can modulate both the timing and severity of the DO response.

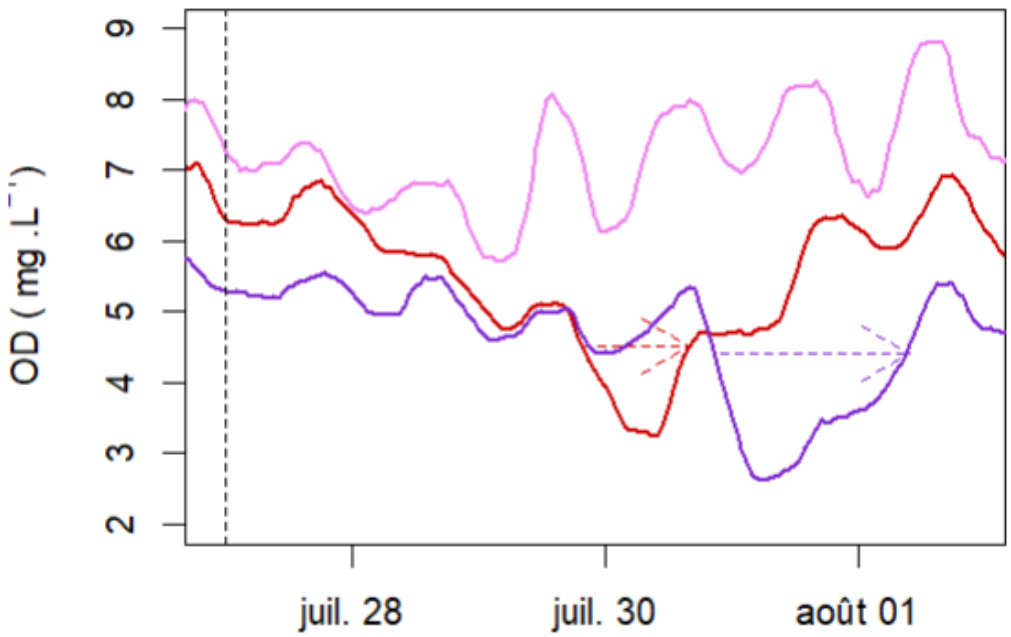


**Figure 3.3** DO curves from 2019/07/27 to 2019/08/02 at PAA (purple), Bougival (red) and Méricourt (blue) stations. The vertical line is a Clichy and La Briche discharge date. Arrows show the DO depletion length.

Conclusion and future work

The above analysis shows that the Seine River metabolism follows specific upstream to downstream trends between 2008 and 2022, influenced by urban impacts, seasonal changes and hydroclimatic conditions. Future work will refine the analysis of short-term impacts of CSO and other events on the metabolic regime of the river. Such analysis will be conducted using an extended 28 year long database including additional daily or hourly data regarding outflows of the urban sanitation system.

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