Carbon budget in a large river subject to high human pressure: the Seine River downstream from the Paris urban area

Bilan carbone d'un fleuve soumis à une forte pression anthropique : la Seine à l'aval de l'agglomération parisienne

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RÉSUMÉ

Les réseaux hydrographiques jouent un rôle significatif dans le bilan carbone (C) aux échelles locales à globales. Le tronçon de Seine entre l'agglomération parisienne et l'estuaire (220 km) est étudié ici comme exemple de fleuve soumis à une forte pression anthropique. Nous estimons, avec un modèle hydro-biogéochimique mécaniste, les taux des différents processus contrôlant le cycle du C organique (CO) en amont et en aval de l'une des stations d'épuration ayant la plus forte capacité au monde, pour une période de 6 ans. Nos résultats soulignent l'importance des dynamiques benthiques, et donc de processus hydro-sédimentaires, dans le cycle du C dans les fleuves ou grandes rivières, où l'effet des processus benthiques sur le métabolisme écosystémique est généralement considéré comme négligeable. Le tronçon étudié a un fonctionnement moyen hétérotrophique, *i.e.* avec une production nette de CO_2, la respiration benthique représentant un tiers de la respiration totale (0.27 sur 0.86 $gC.m^{-2}.j^{-1}$). Les transferts de CO sont largement influencés par les dynamiques benthiques pendant les périodes sèches, où 25% des apports sont transformés ou accumulés dans la couche sédimentaire. Pendant les périodes de basses eaux avec des conditions favorables au développement phytoplanctonique, les rejets urbains peuvent localement/temporairement modifier le métabolisme du fleuve.

ABSTRACT

Fluvial networks play an important role in regional and global carbon (C) budgets. The Seine River, from the Paris urban area to the entrance of its estuary (220 km), is studied here as an example of a large human-impacted river system. We assess, with a process-based hydro-biogeochemical model, the rates of the different processes affecting organic C (OC) cycling, upstream and downstream from one of the world's largest wastewater treatment plants, over a 6-year period. It is generally assumed that the contribution of benthic processes to the total stream metabolism decreases with higher stream orders. However, our results stress the major influence of benthic dynamics, and thus of physical processes such as sedimentation and resuspension, on C cycling in downstream river systems. The whole studied stretch is on average heterotrophic, *i.e.* with net CO_2 production. On average, benthic respiration accounts for one third of the total river respiration (0.27 out of 0.86 $gC.m^{-2}.d^{-1}$). OC export is significantly affected by benthic dynamics during the driest periods, when 25% of the inputs to the system is transformed or stored in the sediment layer. In periods of low flow and favorable conditions for phytoplankton growth, the river metabolism can be locally/temporarily altered downstream from large urban effluents.

KEYWORDS

Benthic/pelagic compartments, ecosystem metabolism, organic carbon, Seine River, urban emissions

INTRODUCTION

Fluvial networks represent only a small fraction of the Earth's surface; however, they are active players in the carbon (C) cycle, and can affect regional and global C budgets (Cole et al., 2007). They don't only constitute pathways for terrestrial organic C (OC) from land to oceans: significant amounts of this OC can be transformed on the way or stored within these systems. In order to mitigate human induced alterations of the C cycle, it is therefore important to understand and quantify the different rates of processes controlling OC fate in fluvial systems, especially in highly anthropized areas.

Ecosystem metabolism, *i.e.*, the balance between the total ecosystem's primary production and respiration rates, is an integrative indicator of the processes affecting OC cycling in streams. OC dynamics can also be significantly affected by hydro-sedimentary processes. These processes directly govern the transport of particulate forms, but can also affect photosynthesis by impacting light radiation, and control sediment accumulation in the benthic layer, where important biogeochemical processes take place. The significant role of the benthic compartment in stream metabolism has been extensively acknowledged for small streams, but has rarely been studied for large rivers.

Here, we investigate OC cycling along a stretch of the Seine River receiving large urban effluents. We are particularly interested in the influence of hydro-sedimentary and benthic processes. To assess the effect of major effluents on OC cycling, we calculate OC fluxes up- and downstream from one of the world's largest wastewater treatment plants (WWTPs), for low and high flow conditions. These are selected results from a recently published study (Vilmin et al., 2016).

1 METHODS

The hydro-biogeochemical functioning of the Seine River is simulated with the ProSe model (Even et al., 1998), along a 220 km stretch, from the Paris urban area to the entrance of the estuary, and for a 6-year period (2007-2012). Major tributaries, WWTP emissions and combined sewer overflows are accounted for as lateral boundary conditions. The largest WWTP, Seine Aval (SAV), treats the effluents of 5 million equivalent inhabitants.

The ProSe model mechanistically simulates hydrodynamics, solid and dissolved transport, biogeochemical processes in the water column and in the benthic layer (major nutrients, C and O_2 cycling), and exchanges between these two compartments (sedimentation, erosion and diffusion).

In the present work, we focus on the fate of OC compounds. Two types of detrital OC (dissolved and particulate, noted DOC and POC) are represented, as well as primary producers (PP) and heterotrophic bacteria (HB). The model was recently validated for the simulation of OC (Vilmin et al., 2016).

Since river functioning and the effects of human pressure may differ depending on flow characteristics, all OC amounts and fluxes are: i) integrated along two distinct stretches (up- and downstream from SAV), and ii) averaged over the whole 6-year period, and for low and high flows periods (*i.e.*, 30 consecutive driest/wettest days of each year). In the present proceeding, only results for low flows are plotted (Fig. 1), since they show the strongest influence of SAV.

2 OC BUDGET: IMPORTANCE OF HYDRO-SEDIMENTARY PROCESSES

On average for 2007-2012, the Seine River is a heterotrophic system, with a net production of CO_2 of 0.23 $gC.m^{-2}.d^{-1}$ upstream from SAV, and of 0.37 downstream. Whatever the hydrological conditions, benthic respiration is a significant term of the system's total metabolism, accounting for around 1/3 of the total respiration, both up- and downstream from SAV.

At low flow, the system locally becomes autotrophic downstream from SAV (Fig. 1). Primary producers have a significant influence on river metabolism. The system is then a sink of detrital organic matter, with large amounts of POC accumulating in the benthic layer, where it is degraded. 25% of the total OC inputs are then stored or removed in the benthic layer.

At high flow, the system is heterotrophic, with net CO_2 production rates of 0.20 and 0.84 $gC.m^{-2}.d^{-1}$ up- and downstream from SAV, respectively. POC tends to be eroded from the benthic layer, and DOC is transferred from the water column to the bottom sediments, where it is consumed by heterotrophic bacteria for growth and respiration needs.

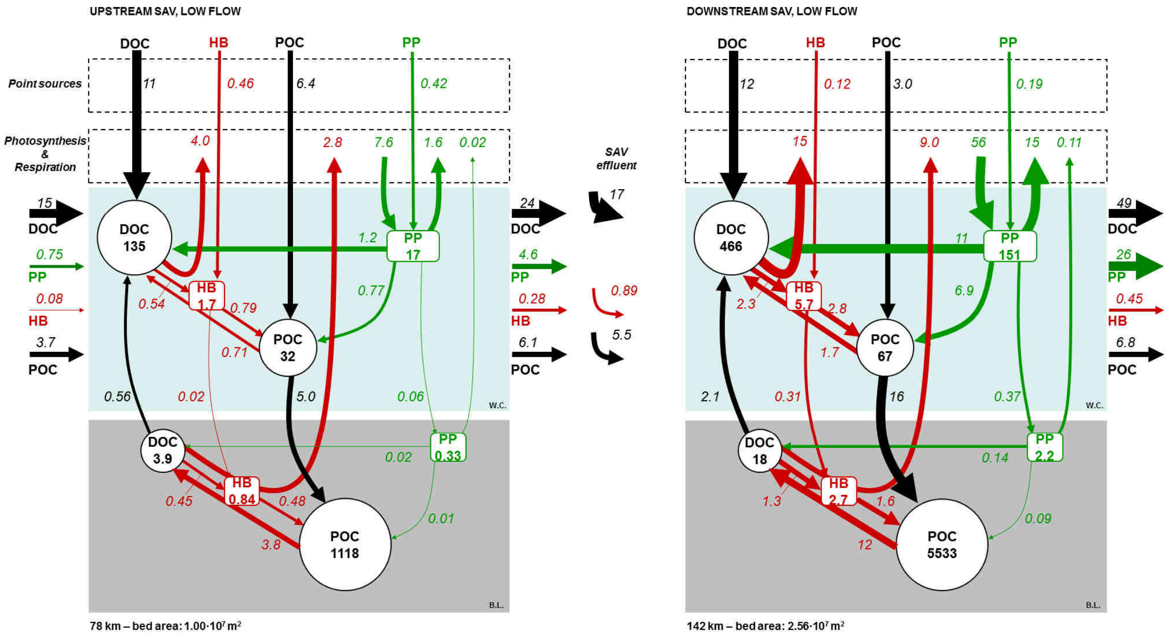

Figure 1: OC weights (tC) and fluxes (tC.day^{-1}) in the water column and sediment layer, up- and downstream from SAV, during low flow periods, from Vilmin et al. (2016).

3 IMPACT OF THE MAIN WWTP EFFLUENT OF THE PARIS URBAN AREA

SAV constitutes 18% of the total OC inputs to the studied system for 2007-2012, and has therefore a strong direct influence on OC exports by the Seine River. During low flow periods, its contribution reaches 31%, with most of the POC being accumulated in the benthic layer before it reaches the estuary. The OC content of bed sediments is *ca* 10% higher downstream from SAV than in the upstream section. Significant amounts of heterotrophic biomass originating from the effluent settles in the benthic layer downstream SAV as well, which contributes to increasing the total ecosystem respiration.

Large inputs of particulate and dissolved compounds from effluents can alter downstream biogeochemical functioning. In the case of the Seine River, during low flow periods, the system shifts from heterotrophic upstream to autotrophic downstream from SAV (Fig. 1). This is most likely the result of a combination of favorable climatic conditions, low residence times, and large nutrient inputs from the effluent itself and upstream river basins, which promotes the growth of primary producers.

4 CONCLUSIONS

It is generally assumed that benthic dynamics have little impact on total stream metabolism in large lowland rivers (high Strahler orders). However, our results show that they can have a significant impact in such systems on both OC export to estuaries and CO_2 production. POC exports are indeed controlled by successive benthic accumulation and re-mobilization processes, and the benthic layer contributes all year round to around 1/3 of the total ecosystem respiration of the Seine River along the studied stretch. In areas of high human pressure, effluents can induce changes in the flow and quality of the water column and bed sediments, leading to discontinuities in the biogeochemical functioning along the river continuum.

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