The impact of reservoirs on water quality and greenhouse gas in downstream rivers: a case study in the Seine Basin (France)

L'impact des réservoirs sur la qualité de l'eau et les gaz à effet de serre des cours d'eau aval: exemple du bassin de la Seine (France)

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RÉSUMÉ

Les réservoirs impactent de manière hétérogène la rétention des nutriments et les émissions de gaz à effet de serre (GES), ce qui prévient d'extrapoler leur impact à grande échelle, et souligne la nécessité de réaliser de nouvelles mesures pour une plus large variété de réservoirs. Dans cette étude, des campagnes de terrain ont été menées d'avril 2019 à novembre 2020, dans trois réservoirs en dérivation et leurs rivières associées dans le bassin de la Seine. Les mesures effectuées concernent les concentrations des variables clés de qualité de l'eau (par exemple, l'oxygène dissous, le nitrate, la silice dissoute, la matière organique dissoute, l'alcalinité totale, etc.) ainsi que les GES (dont le méthane: CH_4, le dioxyde de carbone: CO_2 et le protoxyde d'azote: N_2O). Les résultats indiquent que les caractéristiques hydrologiques et les processus biogéochimiques régissent ensemble la qualité de l'eau et les concentrations de GES dans les trois réservoirs. Les concentrations de CH_4 sont élevées en été et en automne, et faibles en hiver et au printemps, à l'opposé des variations saisonnières du CO_2. Aucune tendance saisonnière n'a été trouvée pour les concentrations de N_2O. Les trois réservoirs sont de faibles sources de GES par rapport aux flux moyens de GES des réservoirs mondiaux. Les trois réservoirs modifient considérablement les concentrations en nutriments et les concentrations de CO_2 dans les rivières en aval pendant la période de vidange. Nos résultats mettent en évidence l'importance d'analyser les caractéristiques biogéochimiques et hydrologiques de manière combinée pour comprendre le fonctionnement biogéochimique des réservoirs et leurs impacts sur les cours d'eau en aval.

ABSTRACT

The heterogeneity of the impacts of reservoirs on nutrient retention rates and greenhouse gas emissions (GHG) constrains the large-scale extrapolation and emphasize the necessity of additional measurements in regional reservoirs. In this study, field campaigns were conducted in the three diverted reservoirs of the Seine Basin and their related rivers from April 2019 to November 2020. Concentrations of the key water quality variables (e.g., dissolved oxygen, nitrate, dissolved silica, dissolved organic matter, total alkalinity, etc.) and GHG (including methane: CH_4, carbon dioxide: CO_2, and nitrous oxide: N_2O) were analysed. Results indicated that both the hydrological characteristics and biogeochemical processes were the dominant drivers of water quality and GHG concentrations in the three reservoirs. CH_4 concentrations were high in summer and autumn, and low in winter and spring, which were opposite to the seasonal patterns of CO_2, while no obvious seasonal patterns were found for N_2O concentrations. The three reservoirs were slight sources of GHG compared to the average GHG fluxes from global reservoirs. Interestingly, the three reservoirs significantly changed downstream nutrient and CO_2 concentrations during the emptying period. Our results highlight the importance of the combination of biogeochemical and hydrological characteristics to understand the biogeochemical functioning of reservoirs, and their impacts on downstream rivers.

KEYWORDS

Downstream river, Greenhouse gas, Reservoir, Seine Basin, Water quality

1 INTRODUCTION

The construction of reservoirs alters hydrological characteristics (e.g., increases water residence time), and influences multiple biogeochemical processes (see Maavara et al. 2020). The biogeochemical impacts of reservoir construction have been well discussed, especially the greenhouse gas (GHG) emission and nutrient retention, which are their two related issues (Deemer et al. 2016; Maavara et al. 2020). Although many studies have been conducted to investigate the role of reservoirs on GHG emissions and nutrient retentions, the high variations of GHG emissions and nutrient retentions in different reservoirs still emphasized the importance of increasing measurements in future research.

In this study, monthly field campaigns were conducted in three reservoirs and their up- and dowstream rivers in the Seine Basin, with the objectives of (1) understanding the dynamics of water quality changes and the responsible processes (hydrological and biogeochemical); (2) evaluating the impact of these reservoirs on downstream nutrients and GHG concentrations.

2 MATERIALS AND METHODS

2.1 Study sites

The three diverted reservoirs, Marne, Aube, and Seine reservoirs, are located in the upstream of the Seine Basin. They were built mainly for preventing flooding in winter and early spring, and supporting downstream low water flows in summer and autumn. These three reservoirs showed similar hydrological characteristics, and two specific periods were defined: the filling period (December–June) and the emptying period (July–November), representing water entering and leaving reservoirs, respectively. A 20-year analysis showed a high stability in their hydrological and biogeochemical functioning (Yan et al. 2021).

2.2 Sampling strategy

The concentrations of key water parameters and GHG were measured in three reservoirs and their related rivers (upstream and downstream) from April 2019 to November 2020, covering almost two hydrological cycles. The key water parameters include dissolved oxygen (DO), nitrate (NO_3^-), dissolved silica (DSi), dissolved organic carbon (DOC), and biodegradable dissolved organic carbon (BDOC), total alkalinity (TA). GHG includes methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O). Additionally, Vratio (daily volume: maximum volume of reservoir) was used to reveal the hydrological characteristics of the reservoirs.

2.3 Calculations and analysis

The saturation of DO (S_{DO}) and GHG, and the GHG fluxes were calculated. The monthly dynamics of key water variables and the seasonal patterns of GHG concentrations were analysed. Wilcoxon–test and Spearman's rank correlation coefficient were used to respectively show the differences in water quality in the up- and downstream rivers (filling and emptying periods), and analyse the correlations between water parameters and GHG concentrations (emptying period).

3 RESULTS AND DISCUSSION

A prerequisite for GHG analysis is to understand the hydrological and biogeochemical processes that are related to the GHG production. The three reservoirs showed similar hydrological characteristics, with the highest Vratio (highest depth) in June–July, and the lowest Vratio (lowest depth) in the end of November. In addition, these three reservoirs also showed similar biogeochemical processes on the basis of the observed monthly dynamics of the water quality variables. We found that S_{DO} values were high during summer (with high water depth), indicating high primary productivity, and low during autumn (with low water depth), suggesting a high respiration rate. The variations of the Vratio of reservoirs were concomitant with water quality changes. We observed a decreased Vratio with an increase of DSi concentrations due to dissolution of the biogenic silica contained in the organic matter of diatoms, an increased NH_4^+ concentrations through the decomposition of organic matter, while NO_3^- concentrations declined by denitrification process, and decreased S_{DO} due to the increased respiration rate.

Biogeochemical processes, together with hydrology and gas exchange at the water–air interface, regulate the concentrations and emissions of GHG in these reservoirs, and influence their temporal patterns. High water temperature, water depth, and primary productivity were favourable for methanogenesis in the sediment, and may lead to high CH_4 concentrations in summer and early autumn. During winter and spring, the water entering reservoirs with low CH_4 affected CH_4 concentrations in reservoirs. In terms of the N_2O concentration, no obvious seasonal patterns were found in the three reservoirs. Although these reservoirs showed strong capacity in NO_3^- elimination mainly due to denitrification, we did not find high N_2O concentrations, as an intermediate product of the denitrification process. The seasonal patterns of CO_2 in three reservoirs were opposite to that of CH_4 and resulted from the combined effects of hydrological characteristics and biogeochemical processes occurring in reservoirs. Water entering the reservoirs from the upstream rivers that contain high concentrations of CO_2 and relatively low primary productivity are the main reasons for the observed high CO_2 concentrations in the reservoirs during winter and spring. But primary productivity, one of the important regulators of CO_2 in water, was low in the three reservoirs during winter and early spring (low S_{DO}), leading to the low assimilation rate of CO_2. In summer, the high S_{DO} corresponds to the low CO_2 concentrations, indicating the importance of primary productivity for CO_2 concentrations in the reservoirs, which was further supported by the negative correlation between S_{DO} and CO_2.

The saturation of GHG in the surface water is the reference for the potential of GHG exchange at the water–air interface (influx or efflux). The three reservoirs were generally oversaturated with CH_4 (in all seasons) and CO_2 (except a short period during summer/autumn), while were almost always equilibrated with N_2O. Furthermore, the GHG fluxes were calculated in C-CO_2 equivalent, and the results indicated that the three reservoirs were sources of CH_4, CO_2, hardly for N_2O, with the average values of 6.0 mg C m^{-2} d^{-1}, 132.7 mg C m^{-2} d^{-1}, and 0.03 mg C m^{-2} d^{-1}, respectively. These GHG fluxes were relatively lower than the average values from reservoirs at the global scale (Figure 1).

Finally, the impacts of the three reservoirs on water quality and GHG concentrations of downstream rivers showed that the three reservoirs significantly changed the downstream water quality and CO_2 concentrations during emptying period, including increase DOC and BDOC concentrations, while decrease DSi, TA, and CO_2 concentrations. Overall, our results highlight the importance of combining biogeochemical and hydrological characteristics to understand the biogeochemical functioning of reservoirs to downstream rivers.

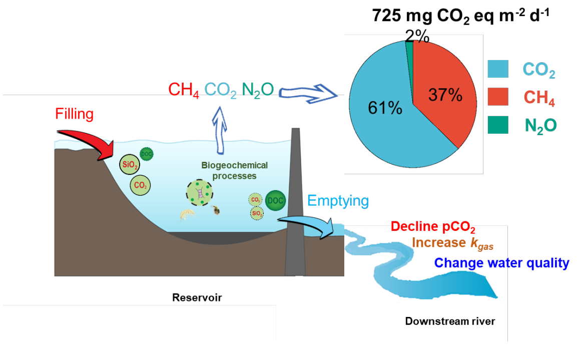

Figure 1: Schematic diagram of the functioning of the reservoirs.

4 SUMMARY

In this study, the dynamics of the key water quality variables and GHG concentrations were measured in the three diverted reservoirs of the Seine Basin. The hydrological characteristics and biogeochemical processes play important roles in regulating water quality changes and GHG concentrations in the reservoirs. The three reservoirs were GHG emitters, but the values were much lower than the average values of global reservoirs. Importantly, it was found that the three reservoirs significantly changed downstream water quality and CO_2 concentrations during emptying period.

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