Effect of lockdown on wastewater characteristics: a comparison of two large urban areas

Marie-Noëlle Pons, Pauline Louis and Davide Vignati

ABSTRACT

The effect of the lockdown imposed to limit the spread of SARS-CoV-2 in France between March 14 and May 11, 2020 on the wastewater characteristics of two large urban areas (with between 250,000 and 300,000 inhabitants) was studied. The number of outward and inward daily commuters was extracted from national census databases related to the population and their commuting habits. For urban area A, with the larger number of daily inward commuters (110,000, compared to 53,000 for B), lockdown was observed to have an effect on the monthly load averages of chemical oxygen demand, biochemical oxygen demand, total Kjeldahl nitrogen, total suspended solids and total phosphorus, all of which decreased (confidence level of 95%). This decrease, which varied between 20% and 40% and reached 45% for COD, can be related to the cessation of catering and activities such as hairdressing, which generate large amounts of graywater. The ammonium loads, due to the use of toilets before leaving for work and after returning from work, remained constant. In the case of urban area B, lockdown had no noticeable effect. More data would be necessary in the long term to analyze the effect of changes in the balance between ammonia and carbon sources on the operation of wastewater treatment plants.

Key words | ammonium load, commuting, lockdown, SARS-CoV-2, wastewater-based epidemiology

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HIGHLIGHTS

- Wastewater characteristics have been related to commuting for work in two urban areas.
- Lockdown decreases carbon pollution loads where a large proportion of the population commutes for work.
- Ammonium load related to toilet use remained unchanged.

INTRODUCTION

Wastewater characteristics reflect a population's way of life and activity in a sewage catchment. In recent years, wastewater-based epidemiology (WBE), which uses various human biomarkers, has been widely developed to assess the lifestyle, dietary habits, well-being and health of populations (Gracia-Lor *et al.* 2017). The assessment (González-Mariño *et al.* 2019; Rice *et al.* 2020) of the spatiotemporal consumption of illicit drugs (such as cocaine and cannabis) and the development (Bade *et al.* 2020) of new illicit drugs have been the main focus of WBE in recent literature (from Karolak *et al.* (2010) in Paris to Benaglia *et al.* (2020) and Bijlsma *et al.* (2020) for festivals in Europe, to name a few specific studies). Alcohol (Ryu *et al.* 2016), nicotine (Driver *et al.* (2020), caffeine (Driver *et al.* 2020) and authorized pharmaceuticals (such as antibiotics (Plósz *et al.* 2010; Zhang *et al.* 2019), hormones (Plósz *et al.* 2010), antidepressants and antihypertensives (Riva *et al.* 2020) have also received attention. In addition, exposure to micropollutants such as phthalate plasticizers (González-Mariño *et al.* 2017), surfactants (Camacho-Muñoz *et al.* 2014) and pesticides

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(Rousis *et al.* 2017) has been investigated through WBE. Health issues are monitored by metformin for diabetes mellitus (Xiao *et al.* 2019) and lamivudine for hepatitis B (Hou *et al.* 2020). Pathogenic viruses can be directly analyzed in wastewater samples to monitor epidemic outbreaks, such as hepatitis E in Italy (Iaconelli *et al.* 2020), the Saffold cardiovirus in Italy (Bonanno Ferraro *et al.* 2019) and the human JC polyomavirus in Chile (Levican *et al.* 2019).

Regardless of research objectives, interpretation of the data depends on the number of people in the catchment. For Gao *et al.* (2016), this is one of the main sources of uncertainty in their study of pharmaceuticals and personal-care products (PPCPs) in 17 cities in China. The effect of season on WBE outcome was simulated by Hart & Halden (2020a): the number of inhabitants present in the catchment, their socioeconomic status and the temperature, all of which alter the degradation rate of biomarkers in sewers, are among the important factors to consider. Van Nuijs *et al.* (2011) and Zheng *et al.* (2019) normalized their data with respect to classical pollution parameters, such as phosphorus, nitrogen, chemical oxygen demand (COD) and biochemical oxygen demand (BOD_5), despite their potentially mixed origin (e.g., human or industrial). Zhang *et al.* (2019) used ammonia nitrogen, which is almost exclusively of human origin (Gray & Becker 2002), for normalization. O'Brien *et al.* (2014) used a census day for a near real-time population estimation to investigate the consumption of PPCPs; the approach worked better in large catchments than in small ones. Specific biomarkers, such as creatinine (a urinary metabolite) and coprostanol (a fecal metabolite), were proposed by Brewer *et al.* (2012) and Daughton (2012) for assessing diurnal and between-day changes in population, especially in small catchments.

One factor that significantly affects the quantification of the population in a given catchment is mobility related to work and education. Large urban areas attract workers and students, and therefore cause an increase in the urban population during the day. For example, the number of workers commuting in increase the population of Washington, DC, by 78% (Laughlin *et al.* 2015) during the day. The relationship between the spread of influenza and mobility patterns at the metropolitan scale has been evaluated by Moss *et al.* (2019) using census data and GPS journey data, and the derived model was able to reproduce some of the characteristics of the spread of influenza. Commuting has already been recognized as a key factor in the spatial and temporal spreading of SARS-CoV-2 in Italy (Savini *et al.* 2020).

The lockdown imposed to limit the spread of SARS-CoV-2 modified human activity patterns: for example, travel bans, the increase in working from home, and the closure of nonessential stores were among the rules applied during the spring lockdown in France, from March 17, 2020, to May 11, 2020. Schools and universities were closed on March 14, 2020. Schools reopened partially in May and June, but universities remained closed.

The question arises as to whether these drastic changes in daily life affected the wastewater characteristics in urban areas, where they can be used to monitor further outbreaks of SARS-CoV-2 (Daughton 2020; Hart & Halden 2020b). To test this hypothesis, we compared the wastewater characteristics of two urban areas before and during/after the lockdown. The results are discussed with respect to the population dynamics in terms of travel (i) between home and place of work and (ii) between home and place of study.

MATERIALS AND METHODS

Two urban areas, A and B, located in the Grand Est region of France, were selected for the test. Both have more than 250,000 inhabitants, (although A has 20% more inhabitants than B), and each has a large university. Both are composed of approximately 20 communities connected to a single wastewater treatment plant (WWTP).

The INSEE (National Institute for Statistics and Economic Studies) (http://www.insee.fr) provides different databases related to population (2017 data were used) and to travel between home and place of work (FD_MOBPRO, version 2015) and between home and place of study (FD_MOBSCO, version 2015). The FD_MOBSCO covers individuals between 2 and 35 years old. FORTRAN software was specifically developed to extract the relevant information from these databases, i.e., for each community, how many people work in the community, how many commute to work in another community, and how many travel in for work from another community. The same procedure was applied to study school enrollment for the three older age classes (individuals between 18 and 35 years old, who are mainly enrolled in universities). Furthermore, for commuting for work, the distances between the communities and the WWTP were evaluated; for that, all communities from a single *département* (administrative region) were assigned the geographic position of the *département's* central office. For simplicity, all commuters living in the same *département* as the urban area were considered to live 0 km from the WWTP.

For urban area A, historical data on pollution loads and concentrations for COD, BOD_5, Kjeldahl nitrogen (TKN), ammonium (NH_4), suspended solids (SS) and total phosphorus (TP) at the inlet of the WWTP were retrieved from the Rhin-Meuse Water Information System (http://rhin-meuse.eaufrance.fr) for the period 2011–2018. For 2019 and up to May 31, 2020, the data on the WWTP's influent flow rate and pollution concentrations were provided by the urban area authorities. To distinguish between dry and rainy days, daily rainfall data were collected from the Meteo-France website (https://publitheque.meteo.fr) for the period 2011–2020.

For urban area B, historical data on the flow rate, pollution loads and concentrations (COD, BOD_5, TKN, NH_4, SS, TP) at the inlet of the WWTP, as well as on the daily rainfall, were provided by the urban area authorities for the period 2017–2020 (up to June 30, 2020).

Monthly load and concentration averages were calculated for all wastewater characteristics without considering the weather conditions (e.g., rainfall). Daily load and concentration averages and their standard deviations were also calculated for each day of the week, excluding rainy days (i.e., days with rainfall amounts greater than zero).

Sampling campaigns were carried out at the inlet of urban area A's WWTP in 2018 and 2019 (pre-lockdown). Samples were collected under dry weather conditions every hour over 24-hour periods on different days using a SIGMA 9000 autosampler (Hach, Loveland, Colorado, USA). The samples were stored at 4 °C in polyethylene bottles for transport to the laboratory, where they were analyzed within 24 hours. The wastewater flow rate was measured using an electromagnetic flowmeter (Proline Promag 50P from Endress + Hauser, Huningue, France). The total COD was measured by potassium-dichromate oxidation at 150 °C, using the Hach micromethod 8000 with spectrophotometric detection at 620 nm for the 0–1,500 mgO_2/L range, and ammonium was measured by Nessler's micromethod adapted from the Hach method 8038 after filtration on 0.45-μm glass fiber filters after dilution by 20 using ultrapure water.

RESULTS AND DISCUSSION

Monthly pollution characteristics of urban area A

Figures 1 and 2 summarize the monthly load and concentration averages for A. In normal months (i.e., those pre-lockdown), the WWTP influent flow rate is lowest in July and August. The lowest TKN and NH_4 loads are registered in August, when a large part of the population is away on vacation and there is no teaching at the university. There is no definite trend for pollution concentration, which is rather constant throughout the year. During lockdown, the COD, BOD_5, TKN, SS and TP loads appear lower than the loads observed in normal months. This trend is not observed for the NH_4 load.

To statistically validate the differences between the types of loads, a control card was built. The lower and upper limits of flow rate, pollution load and concentration observed prior to lockdown were calculated according to Equations (1) and (2):

$$\text{Lower limit} = X_{\text{mean}} - t_{\frac{\alpha}{2},n-1} \cdot \sigma/\sqrt{n} \quad (1)$$

$$\text{Upper limit} = X_{\text{mean}} + t_{\frac{\alpha}{2},n-1} \cdot \sigma/\sqrt{n} \quad (2)$$

where X_{mean} is the average monthly value over n years of pollution flow, load or concentration, σ is the standard deviation, and $t_{\alpha/2,n-1}$ is the percentile of the Student distribution for $\alpha = 0.05$ (i.e., for a confidence level of 95%). Then a normalization procedure was applied based on Equations (3)–(5):

$$X_{\text{norm}} = \frac{(X - X_{\text{mean}})}{X_{\text{mean}}} \quad (3)$$

$$\text{Upper limit}_{\text{norm}} = \frac{(\text{Upper limit} - X_{\text{mean}})}{X_{\text{mean}}} \quad (4)$$

$$X_{\text{control}} = \frac{X_{\text{norm}}}{\text{Upper limit}_{\text{norm}}} \quad (5)$$

The normalized X_{control} values are plotted in Figure 3 for urban area A, together with the lines for the normalized upper and lower limits. It is confirmed that, except for ammonium, the loads during lockdown are significantly different from the loads prior to lockdown. The decrease was as much as 40% in the case of the COD load. For ammonium, the load was lower only in March, and it returned to the normal range in April and May.

In normal months, 32% of the total population of A works within the urban area, and 7% of the population commutes to work outside it (in 750 different communities) (Figure 4). It is difficult to differentiate a long-distance commuter from a short-distance commuter (likely to commute every day) as it depends upon the transport network (road, train). However, a distance of 200 km was selected as a limit for short-distance commuting. Above this value, the

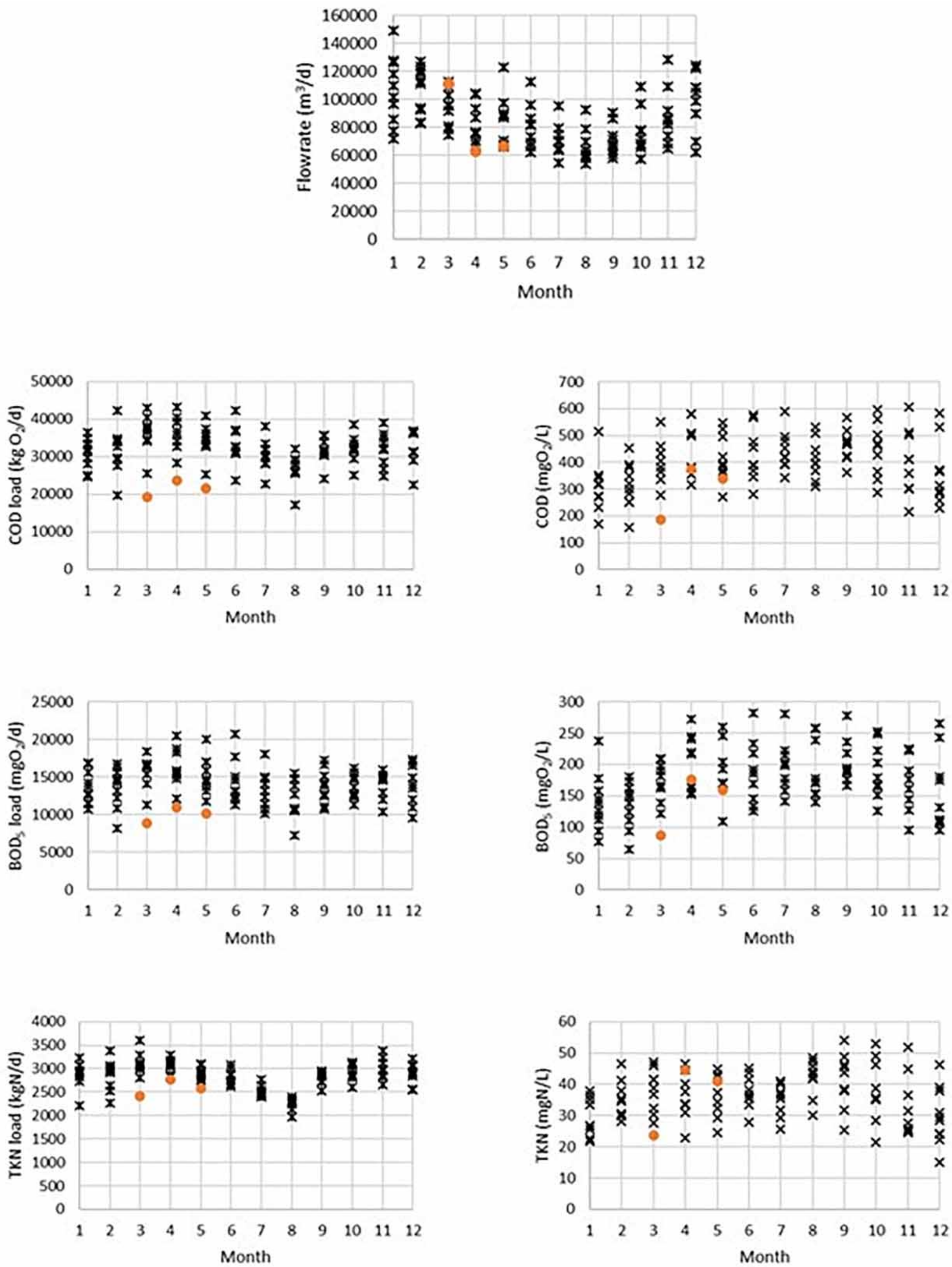

Figure 1 | Wastewater flowrate and monthly load (left-hand column) and concentration (right-hand column) averages for COD, BOD_5 and TKN in the pre-lockdown period (January 2011 to February 2020; asterisks) and during the lockdown period (March to May 2020) (dots) for A. The months are numbered from 1 for January to 12 for December.

number of commuters decreases sharply. Approximately 17,200 commuters working outside urban area A travel less than 200 km and might be considered daily commuters. These daily commuters, as well as the rest of the population that stays in the urban area all day, contribute to the morning peak of ammonium concentration: according to

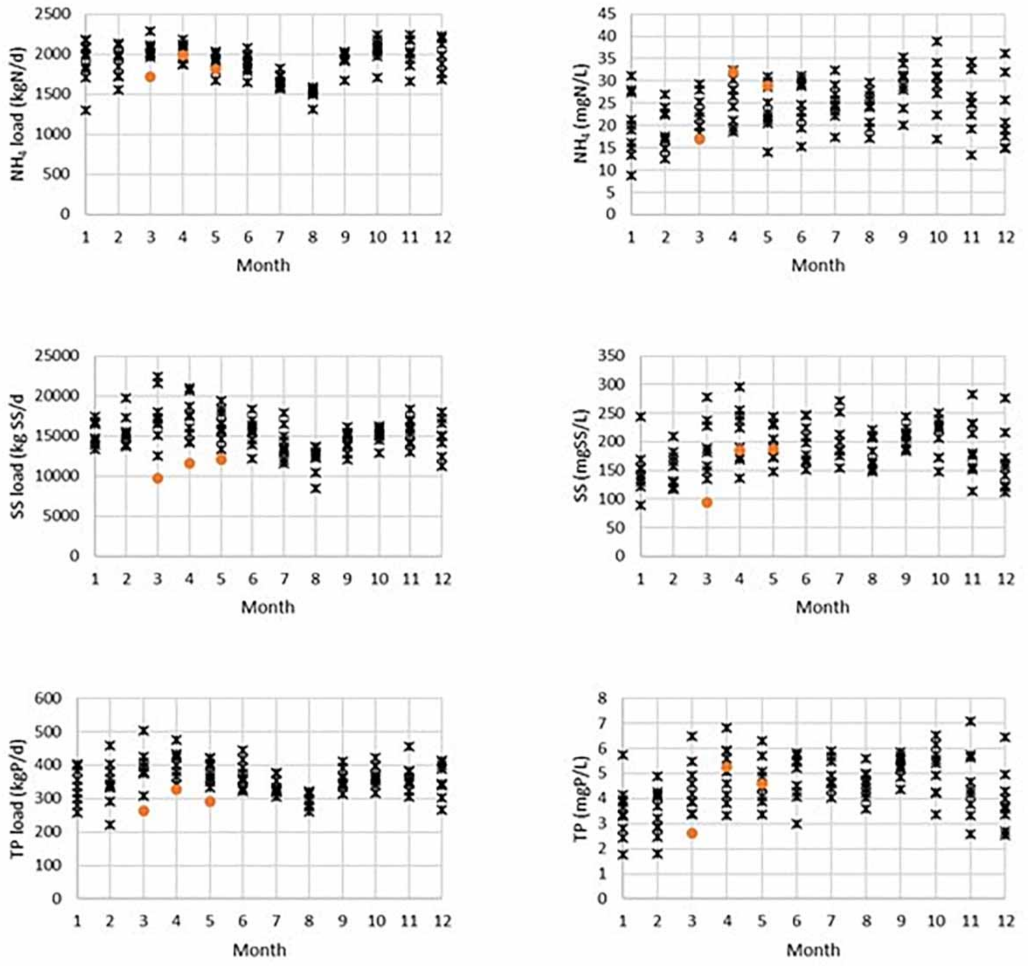

Figure 2 | Monthly load (left column) and concentration (right column) averages of NH_4, SS and TP in the pre-lockdown period (January 2011 to February 2020; asterisks) and during the lockdown period (March to May 2020) (dots) for A. The months are numbered from 1 for January (1) to 12 for December.

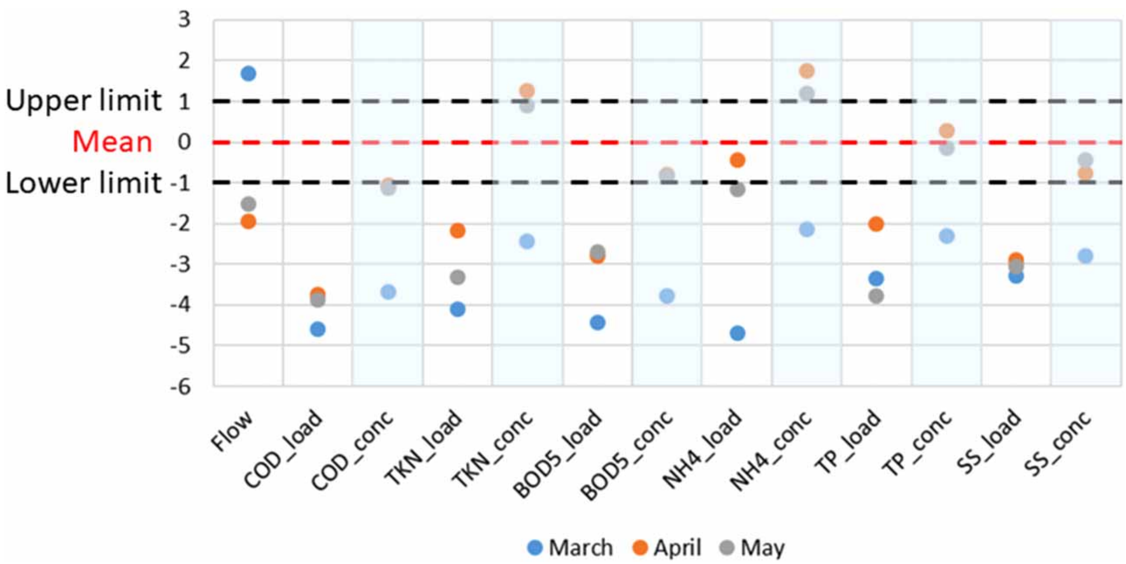

Figure 3 | Normalized control card for urban area A.

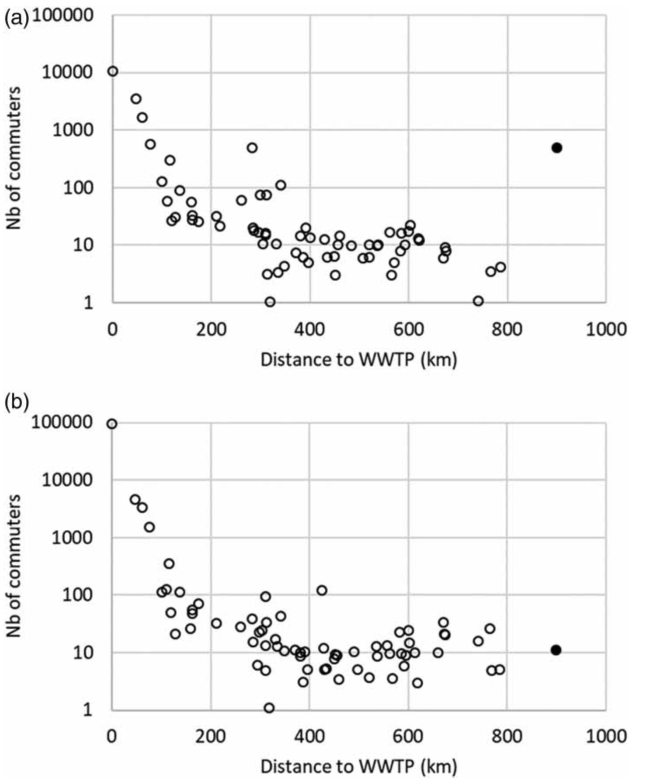

Figure 4 | Numbers of outward and inward commuters versus the commuting distance for urban area A: open symbols = commuting within metropolitan France, solid symbols = commuting within France or abroad.

Gray & Becker (2002), 98% of the ammonium load comes from toilets. On weekdays (i.e., from Monday to Friday), the morning peak (due to bladder voiding first thing in the morning) is detected at approximately 11:00 AM at the inlet of urban area A's WWTP; additionally, the ammonium concentration starts to increase at approximately 8:00 AM (Figure 5(a)). The delay is due to the transport time along the sewage network. In urban area A, the distance, as the crow flies, between the farthest community and the WWTP is 10 km. The peak is 2:00 PM on weekends. Approximately 110,000 individuals living in approximately 1,450 communities commute toward urban area A for work, and more than 95% of them are daily commuters. Although they can contribute to the ammonium load during the day, their main contribution related to ammonium will be in the early morning and after work in their community of residence, i.e., not in urban area A. For urban area A's residents, the pattern of morning and after-work bladder voiding will be the same as under lockdown. This similarity explains why the nitrogen load has been affected to a limited extent by lockdown. TKN contains ammonia ($\approx$ 67% with $\sigma = 3\%$) and organic nitrogen. Part of this organic nitrogen comes from human excreta and urine, and the rest is from food residues finding their way into the sewer during food preparation and dish washing. The proportion of ammonia in TKN increases to 71% during lockdown. A part of the decrease in organic nitrogen can be related to the restaurant closures. It is difficult to further discuss the effect of lockdown on TKN as the inhabitants' diet may have changed. The wastewater flow rate is rather stable in the daytime (between 3,000 and 4,000 m^3/h), decreasing to 2,000 m^3/h at night (Figure 5(c)).

Approximately 27,000 students over 18 and studying in urban area A are registered as being resident outside the area. It is difficult to assess how many of them went back home. For example, the medical students stayed and helped during the crisis. The decrease in the number of students present in urban area A during lockdown does not seem to have been sufficiently large to decrease the ammonium load.

The results are different for COD, BOD_5, TKN and TP loads. Some of them are related to toilet use, but catering (in restaurants and canteens) contributes to pollution by graywater production. These loads are more evenly distributed throughout the day than the ammonia load, as shown for COD in Figure 5(b); additionally, approximately 10% of the COD load can be attributed to kitchen activities (Gray & Becker 2002). In normal months, the workers commuting toward the urban area contribute to the loads related to catering. Their absence during lockdown contributes to the decreases observed for the COD, BOD_5, TKN and TP loads. Other activities, such as hairdressing, have an effect on graywater production and were also banned during lockdown.

Comparison between the two urban areas

Although the time horizon is much shorter for urban area B (only 3 years), the monthly load and concentration averages observed at the inlet of urban area B's WWTP do not show any differences between the pre-lockdown and the lockdown periods, as shown on the control card (Figure 6). Detailed data are available in Figure S1 (Supplementary Information).

For urban area B, the total number of outward commuters is 75% of the total number of outward commuters from A. The number of short-distance commuters (17,200 for A and 13,000 for B) follows the same trend (Figure 7). The main difference between the areas is the number of daily commuters coming in from outside the area: it is only 53,000 for B (as against 110,000 for A). The number of

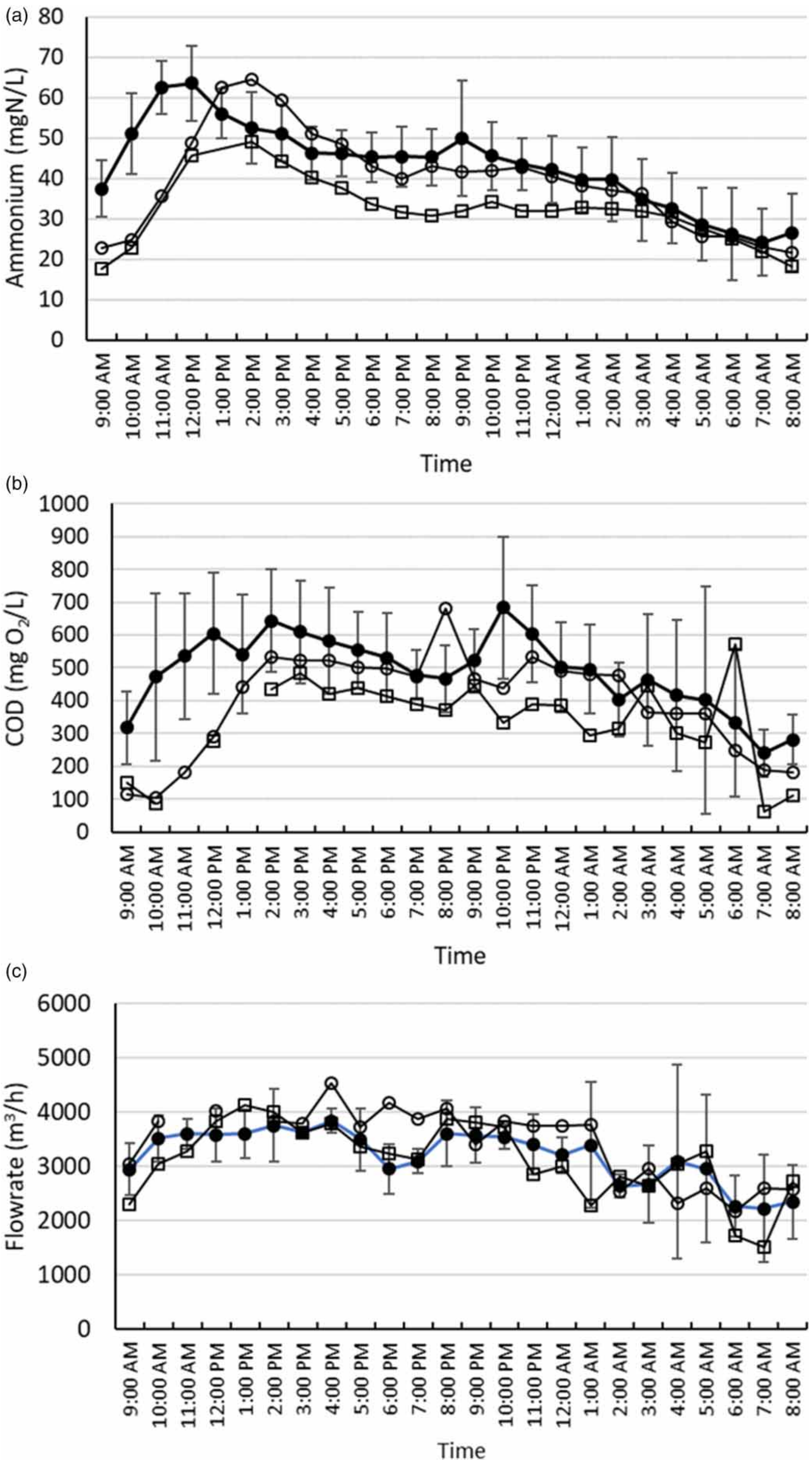

Figure 5 | Daily variations in ammonium (a) and COD (b) concentrations at the inlet of urban area A's WWTP. Solid symbols with error bars (± σ) are for weekdays, open symbols are for weekends (squares = Saturday–Sunday and circles = Sunday–Monday).

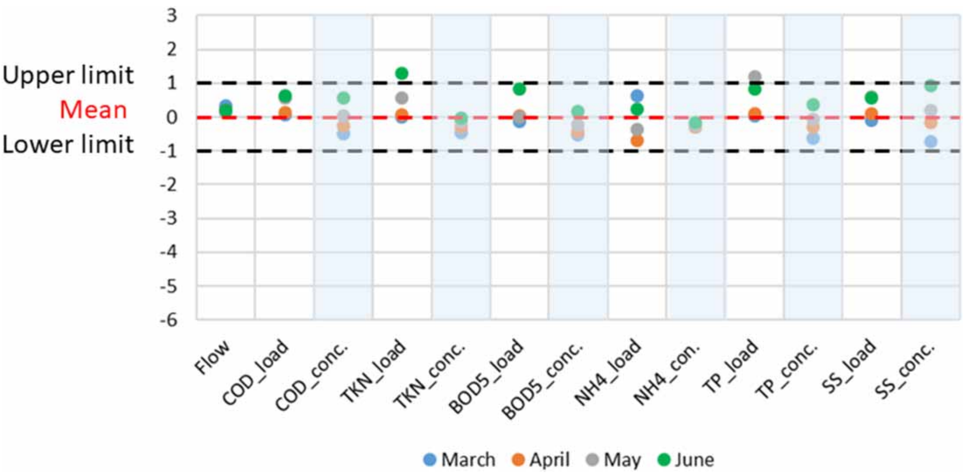

Figure 6 | Normalized control card for urban area B.

students over 18 who could potentially leave B during lockdown is also much lower than those studying in A (11,000 against 27,000). These smaller numbers seem to have masked any significant effect of lockdown on the wastewater characteristics at the inlet of urban area B's WWTP.

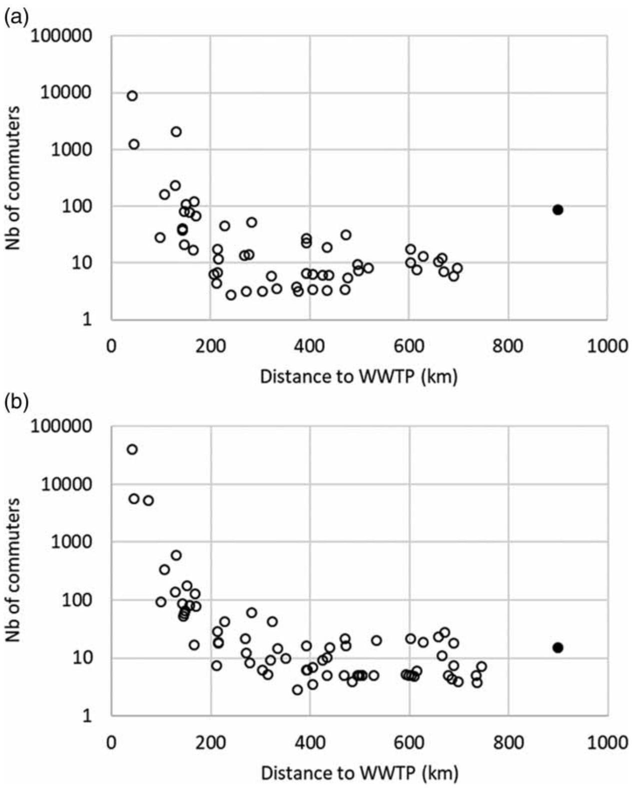

Figure 7 | Numbers of outward and inward commuters versus the commuting distance for urban area B: open symbols = commuting within metropolitan France, solid symbols = commuting within France or abroad.

Day effect in urban area A

In normal months, the daily pollution loads in dry weather conditions are highest on Wednesdays and Thursdays and lowest on Saturdays and Sundays (Figure S2 of the Supplementary Information). A daily effect was considered for urban area A. No real effect could be seen on weekdays; however, except for ammonium, the daily averages during the lockdown were predominantly lower than the lower limit defined for each weekday using Equation (1) (Figure S3 of the Supplementary Information). The situation is more complex for ammonium, but this is in agreement with the monthly average results. The characteristics of Saturdays and Sundays prior to and during lockdown are similar. This result confirms the effect of commuting on wastewater characteristics.

CONCLUSIONS

In any study, the outcome of WBE depends on a proper estimation of the population included in the investigation. It is even more important when WBE is used to track the spread of epidemics. An indirect assessment of the population in a catchment is often based on the wastewater characteristics related to classical pollution parameters (such as COD, BOD_5, NH_4, TKN and TP). By comparing the wastewater characteristics of two urban areas during the SARS-CoV-2 lockdown, it could be shown that most of these characteristics, especially in terms of pollutant loads, changed during lockdown when the urban area has many daily commuters. However, the ammonium load, which is directly related to the use of toilets mostly in the community of residence in the early mornings and after work, remains stable. Taking into account population travel and activity in an urban area could be useful for analyzing the spread of SARS-CoV-2 through WBE in the case of a re-imposition of lockdown and an increase in working from home. The effect of the balance between ammonia and carbon loads on the long-term operation of WWTPs remains to be investigated in the future, when more data will be available to monitor the variations in these loads as a function of commuting.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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