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Effect of confinement on wastewater characteristics: A comparison of two large urban areas

Short title: Confinement and wastewater characteristics

Marie-Noëlle PONS^{1,2}, Pauline LOUIS¹, Davide VIGNATI³

¹ Université de Lorraine, CNRS, Laboratoire Réactions et Génie des Procédés, 1 rue Grandville, BP 20451, F-54001 Nancy cedex, France

² LTSER-Zone Atelier du Bassin de la Moselle, Laboratoire Réactions et Génie des Procédés, 1 rue Grandville, BP 20451, F-54001 Nancy cedex, France

³ Université de Lorraine, CNRS, Laboratoire Interdisciplinaire des Environnements Continentaux, Campus Bridoux, Rue du Général Delestraint, F-57070 Metz, France

Abstract

The effect of confinement implemented to limit the spreading of SARS-CoV-2 in France between March 14 and May 11, 2020, on the wastewater characteristics of two large urban areas (between 250,000 and 300,000 inhabitants) has been studied. The number of outward and inward daily commuters has been extracted from national census databases related to the population and commuting habits. For urban area A, with the larger number of daily inward commuters (110,000 for A and 53,000 for B), confinement was observed to have an effect on the monthly load averages of chemical oxygen demand (COD), 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 work, remained constant. In the case of urban area B, no effect of confinement was noticeable. 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.

Keywords: Ammonium load; Commuting; Confinement; SARS-CoV-2; Wastewater-based epidemiology

Highlights

- Wastewater characteristics has been confronted to work commuting in two urban areas
- Confinement decreases carbon pollution loads in case of large work commuting
- 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). Although 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. Exposure to micropollutants such as phthalate plasticizers (González-Mariño et al. 2017), surfactants (Camacho-Muñoz et al. 2014) or pesticides (Rousis et al. 2017) has been investigated through WBE. Health issues are approached by the monitoring of metformin for diabetes mellitus (Xiao et al., 2019) and lamivudine for hepatitis B virus (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 spread of the Saffold coronavirus in Italy (Bonanno Ferraro et al. 2019) or the human JC polyomavirus in Chile (Levican et al. 2019).

Regardless of research objectives, the data interpretation depends on the number of people present 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 has been simulated by Hart and Halden (2020a): the number of inhabitants present in the catchment, their socioeconomic status and the temperature that alters the degradation rate of biomarkers in the 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 (BOD₅), despite their potential mixed origin (e.g., human or industrial). Zhang et al. (2019) used ammonia nitrogen, which is quasi exclusively of human origin (Gray and Becker, 2012), 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 (urinary metabolite) and coprostanol (fecal metabolite), were proposed by Brewer et al. (2012) and Daughton (2012) to consider diurnal and between-day changes in population, especially in small catchments.

One factor that largely 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 an increase in the urban population during the day is expected. For example, the number of commuter workers increases the population of Washington, DC, by 78% (Laughlin et al., 2015) during the day. The relation between the spreading of influenza and mobility patterns at the metropolitan scale has been evaluated by Moss et al. (2019) using census data and Global Positioning System journey data, and the derived model was able to reproduce some of the characteristics of the influenza infection. 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 population confinement imposed to limit the spreading of SARS-CoV-2 also modified the human activity pattern: for example, travel bans, the development of telework, and the closure of nonessential stores were among the rules applied during the spring confinement 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 until the next academic year.

The question arises whether these drastic changes in habits affected the wastewater characteristics in urban areas, where they can be used to monitor further outbreaks of SARS-CoV-2 (Daughton, 2020; Hart and Halden, 2020b). To test this hypothesis, wastewater characteristics of two urban

areas have been compared at the urban area scale before and during/after the confinement period. The results are discussed with respect to the population dynamics in terms of travel i) between home and workplace and ii) between home and study place.

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, A is slightly more populated than B (20% more inhabitants), and each hosts a large university. Each urban area is 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 population travel from home to workplaces (FD_MOBPRO, version 2015) and from home to study places (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 persons are working in the community, how many are commuting to work in another community, and how many are commuting from another community to work there. 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 work commuting, the distances between the communities and the WWTP were evaluated; for that purpose, all communities from a single department were assigned to the geographic position of the department government seat. For the sake of simplification, all commuters residing in the same department as the urban area were considered to live 0 km from the WWTP.

For urban area A, historical data on the loads and concentrations of pollution (namely, COD, BOD₅, Kjeldahl nitrogen (TKN), ammonium (NH₄), 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 2020 (until May 31, 2020), the data on

the WWTP influent flow rate and concentrations of pollution 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, loads and concentrations of pollution (COD, BOD₅, TKN, NH₄, 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 (until 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 the urban area A WWTP in 2018 and 2019 (pre-confinement period). Samples were collected under dry weather conditions every hour over 24-hour periods on different days using a SIGMA 9000 autosampler (Hach, Loveland, Colorado). 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 by means of an electromagnetic flowmeter (Proline Promag 50P from Endress+Hauser, Huningue, France). The total COD (by potassium-dichromate oxidation at 150°C, using the Hach micromethod 8000 with spectrophotometric detection at 620 nm for the 0-1500 mgO₂/L range) and ammonium (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) were measured in these samples.

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 without confinement), the WWTP influent flow rate is the lowest in July and August. The lowest TKN and NH₄ loads are registered in August, when a large part of the urban area population is on vacation and when there is no class at the university. There is no definite trend for pollution concentration, which is rather constant throughout the year. During confinement, the COD, BOD₅, TKN, SS and TP loads appear lower than the loads observed in normal months. This trend is not observed for the NH₄ 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 loads and concentrations observed prior to confinement 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 to 5:

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

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

$$X_{\text{control}} = X_{\text{norm}} / \text{Upper Limit}_{\text{norm}} \quad (5)$$

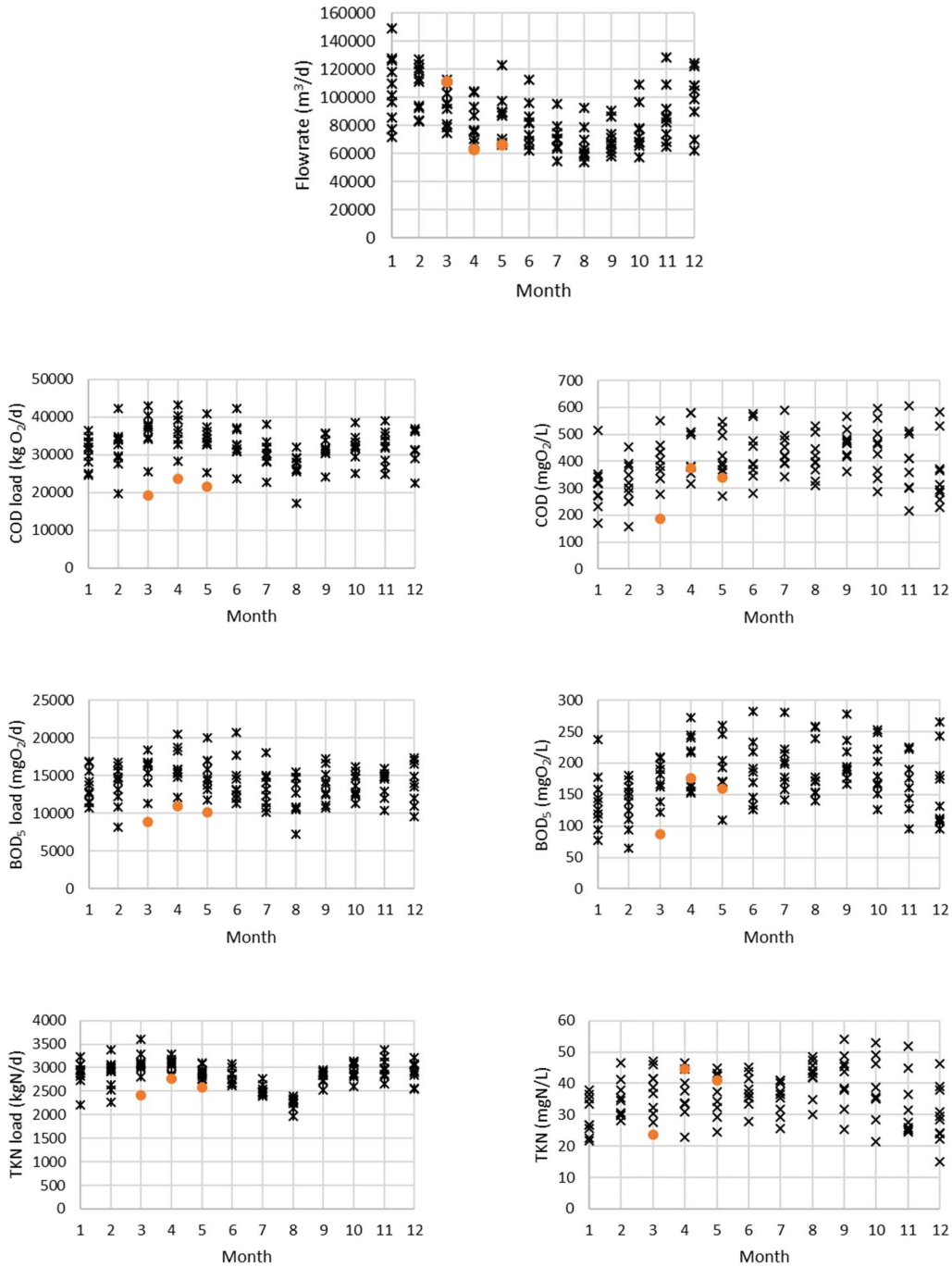


Figure 1: Wastewater flowrate and monthly load (left column) and concentration (right column) averages for COD, BOD₅ and TKN in the pre-confinement period (January 2011 to February 2020) (*) and during the confinement period (March to May 2020) (closed symbols) for A. Months are ranked between January (1) and December (12).

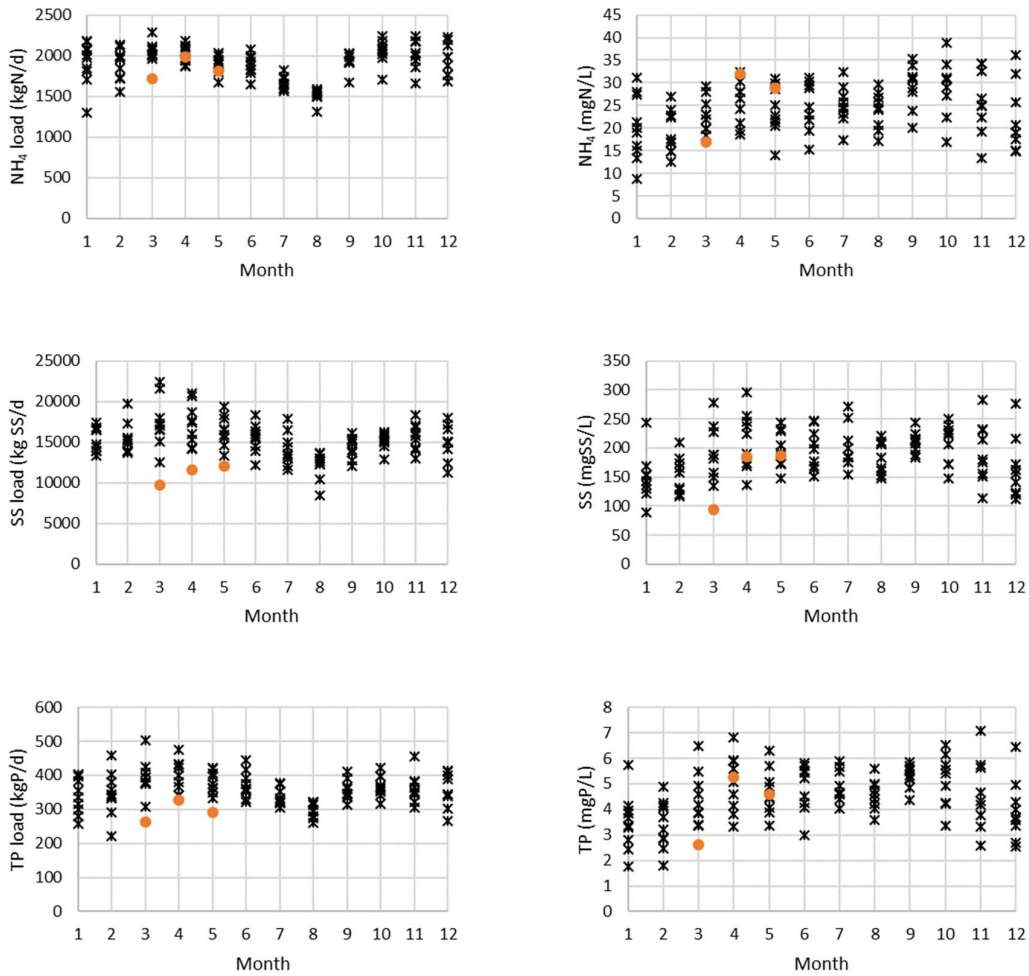


Figure 2: Monthly load (left column) and concentration (right column) averages of NH_4 , SS and TP in the pre-confinement period (January 2011 to February 2020) (*) and during the confinement period (March to May 2020) (closed symbols) for A. Months are ranked between January (1) and December (12).

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 confinement are significantly different from the loads prior to confinement. The decrease reached 40% in the case of the COD load. For ammonium, its load was lower only in March, while it returned to the normal range in April and May.

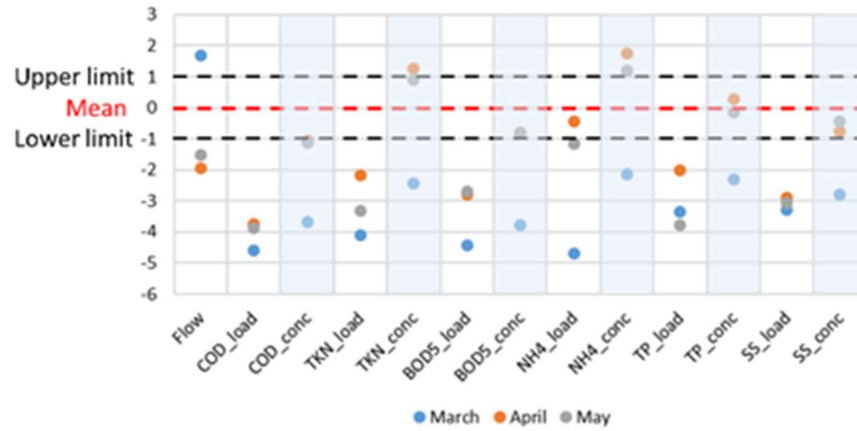


Figure 3: Normalized control card for urban area A

In normal months, 32% of the total population of A is working within the urban area, and 7% of the population commutes to work outside the urban area (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 transportation network (road, train) linking the urban area to the rest of the territory. However, a distance of 200 km has been selected as a limit for short-distance commuting. Above this value, the 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 Gray and Becker (2002), 98% of the ammonium load comes from toilets. During weekdays (i.e., from Monday to Friday), the morning peak (due to bladder voiding at the end of the night) is detected at approximately 11:00 AM at the inlet of the urban area A WWTP; additionally, the ammonium concentration starts to increase at approximately 8:00 AM (Figure 5a). There is a delay 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 delayed until 14:00 on weekends.

Approximately 110,000 individuals residing in approximately 1450 communities commute toward urban area A for work: 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 done early morning and after work in their community of residence, i.e., not in urban area A. For urban area A's residents, morning and after-work bladder voiding will occur similarly under confinement. This similarity explains why the nitrogen load has been affected to a limited extent by confinement. TKN contains ammonia ($\approx 67\%$ with $\sigma = 3\%$) and organic nitrogen. Part of this organic nitrogen comes from human being excreta and urine, but also from food residues finding their way to the sewer during food preparation and dish washing. The part of ammonia in TKN increases to 71% during confinement. A part of the decrease in organic nitrogen can be related to the closing down of restaurants. It is difficult to discuss further the effect of confinement on TKN as the inhabitants' diet may have changed during confinement. The wastewater flow rate is rather stable by daytime (between 3,000 and 4,000 m³/h), decreasing to 2,000 m³/h at night (Figure 5c).

Approximately 27,000 students older than 18 years and studying in urban area A are registered as residents out of A. It is difficult to guess 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 confinement does not seem to have been sufficiently large to decrease the ammonium load.

The results are different for COD, BOD₅, TKN and TP loads. Some of them are related to visits to toilets, but catering (in restaurants and canteens) contributes to pollution by graywater production. These loads are more distributed throughout the day than the ammonia load, as shown for COD in Figure 5b; additionally, approximately 10% of the COD load can be attributed to kitchen activities (Gray and Becker, 2002). In normal months, the workers commuting toward the urban area contribute to the loads related to catering. Their absence during confinement contributes to the

decreases observed for the COD, BOD₅, TKN and TP loads. Other activities, such as hairdressing, have an effect on graywater production and were banned during confinement.

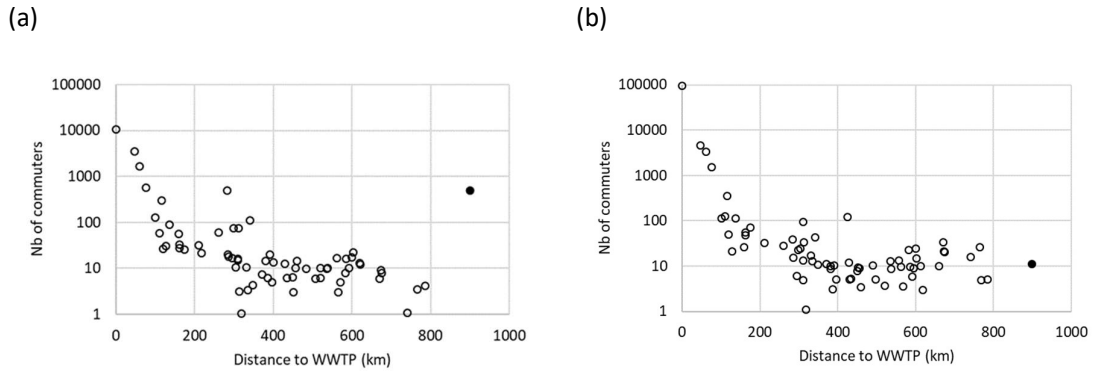


Figure 4: Outward and inward number of commuters versus the commuting distance for urban area

A: open symbols = commuting within metropolitan France, closed symbols: commuting overseas (France) or abroad (foreign countries).

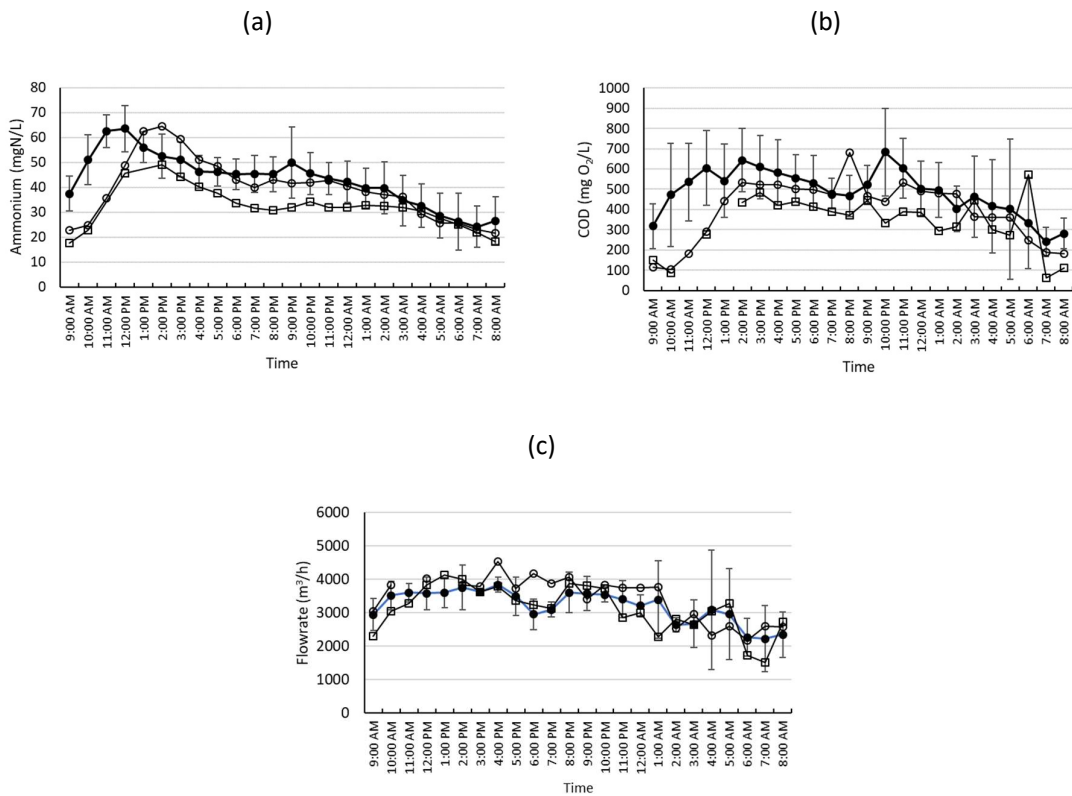


Figure 5: Daily variations in ammonium (a) and COD (b) concentrations at the inlet of the urban area

A WWTP. Closed symbols with error bars ($\pm \sigma$) are for weekdays, open symbols are for weekends (squares = Saturday-Sunday and circles = Sunday-Monday).

Comparison between the two urban areas

Although the time horizon is much shorter for urban area B (3 years only), the monthly load and concentration averages observed at the inlet of the urban area B WWTP do not show any differences between the pre-confinement and the confinement periods, as shown on the control card (Figure 6).

Detailed data are available in the Supplementary Information (Figure S1).

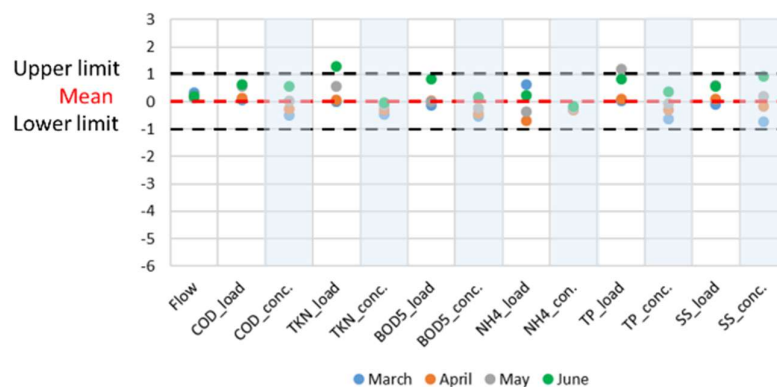


Figure 6: Normalized control card for urban area B

For urban area B, the total number of commuters leaving B to work outside is 75% of the total number of commuters leaving A to work outside, and 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 both urban areas is related to the number of daily commuters coming to work from outside the urban area: it is only 53,000 for B (against 110,000 for A). The number of students older than 18 years old who could potentially leave B during confinement is also much lower than those studying in A (11,000 against 27,000). These smaller numbers seem to have masked any drastic effect of confinement on the wastewater characteristics at the inlet of urban area B WWTP.

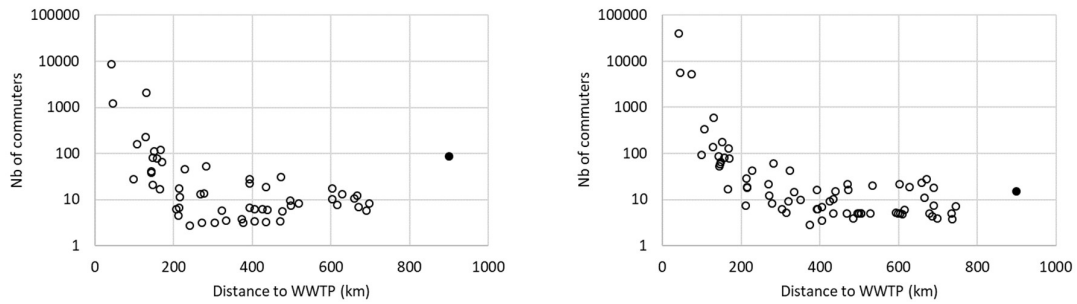


Figure 7: Outward and inward number of commuters versus the commuting distance for urban area

B: open symbols = commuting within metropolitan France, closed symbols: commuting overseas (France) or abroad (foreign countries).

Day effect in urban area A

In normal months, the daily pollution loads in dry weather conditions are the highest on Wednesdays and Thursdays and the lowest on Saturdays and Sundays (Figure S2 of Supplementary Information). A day effect was considered for urban area A. No real effect could be seen on weekdays; however, except for ammonium, the daily averages during the confinement were predominantly lower than the low limit defined for each weekday using Equation 1. The situation is more complex for ammonium, but this is in agreement with the monthly average results. The Saturday and Sunday characteristics prior to and during confinement 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 COD, BOD₅, NH₄, TKN and TP). By comparing the wastewater characteristics of two urban areas during the confinement induced by SARS-CoV-2, it could be shown that most of these characteristics, especially in terms of pollutant

loads, are changed during confinement when the urban area is strongly subject to daily commuting. However, the ammonium load, directly related to the use of toilets mostly in the community of residence in early mornings and after work, remains stable. Taking into account population travel and activity in an urban area can be useful to analyze the spread of SARS-CoV-2 through WBE in the next months, whereas re-confinement (total or partial) might be imposed and teleworking might expand. 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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Effect of confinement on wastewater characteristics. Comparison of two large urban areas

Short title: Confinement and wastewater characteristics

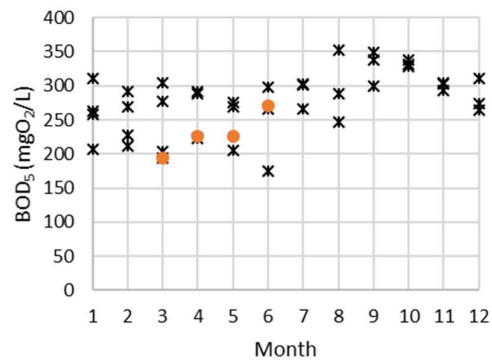
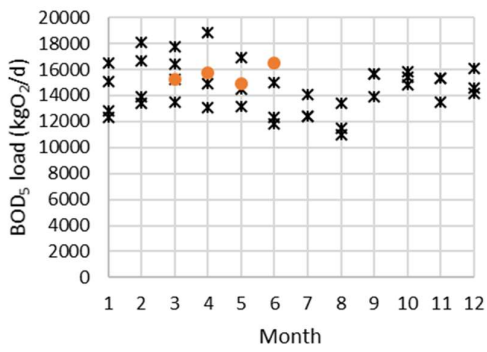
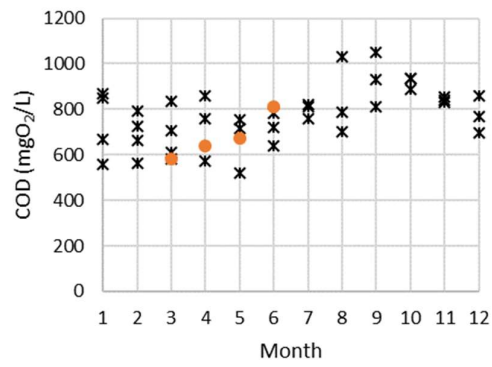
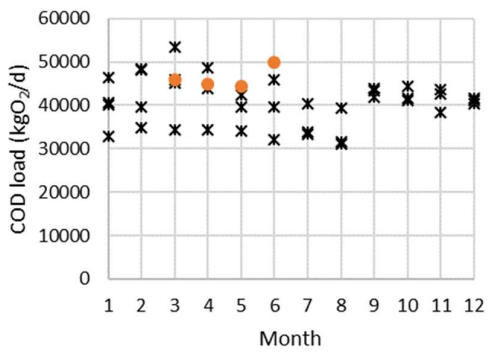
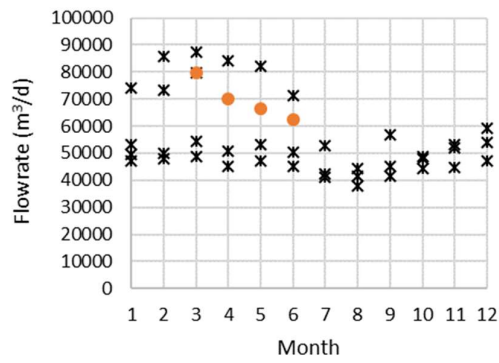
Marie-Noëlle PONS^{1,2}, Pauline LOUIS¹, Davide VIGNATI³

1 Université de Lorraine, CNRS, Laboratoire Réactions et Génie des Procédés, 1 rue Grandville, BP 20451, F-54001 Nancy cedex, France

2 LTSER-Zone Atelier du Bassin de la Moselle, Laboratoire Réactions et Génie des Procédés, 1 rue Grandville, BP 20451, F-54001 Nancy cedex, France

3 Université de Lorraine, CNRS, Laboratoire Interdisciplinaire des Environnements Continentaux, Campus Bridoux, Rue du Général Delestraint, F-57070 Metz, France

Supplementary Information



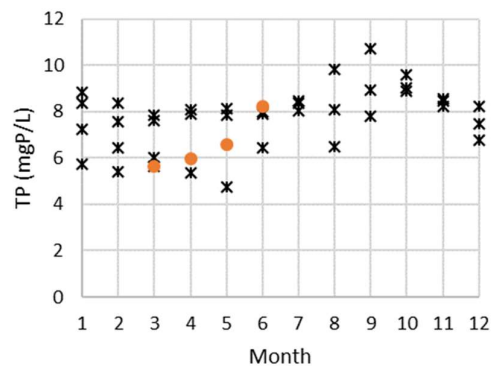
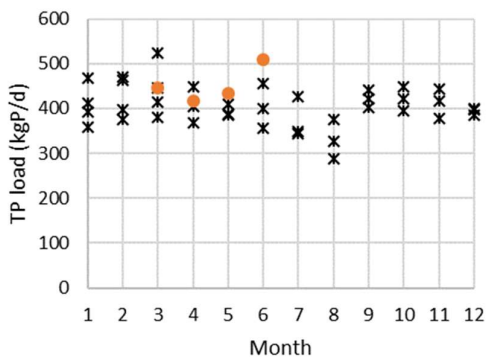
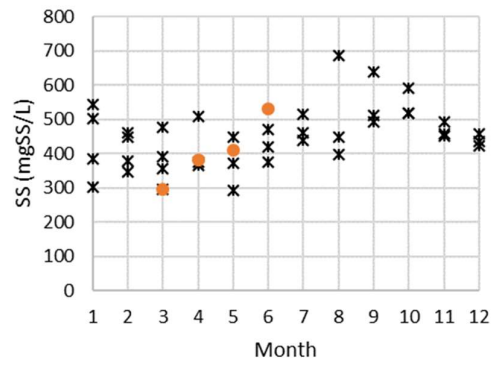
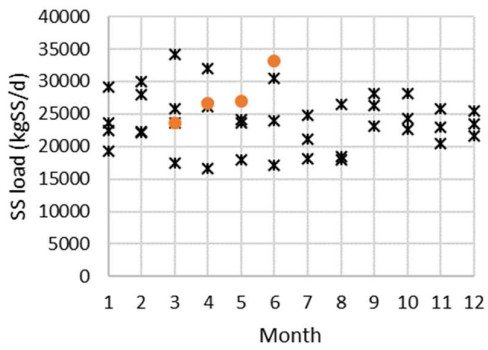
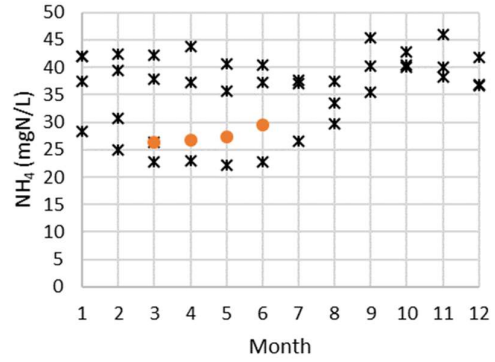
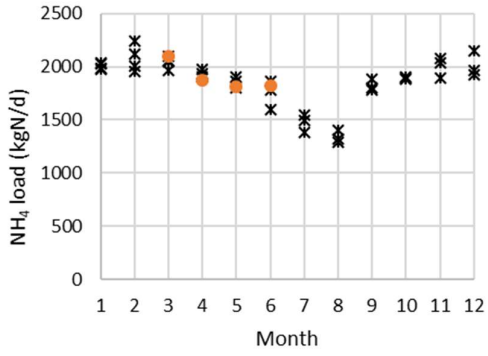
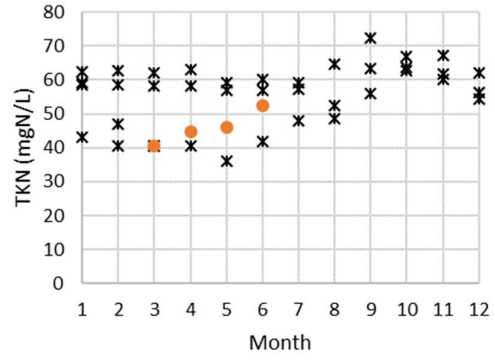
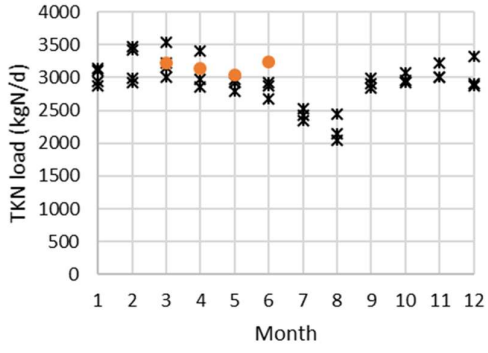
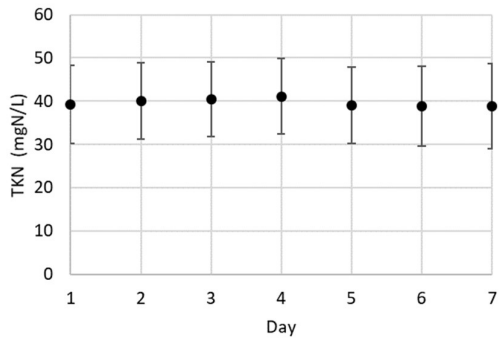
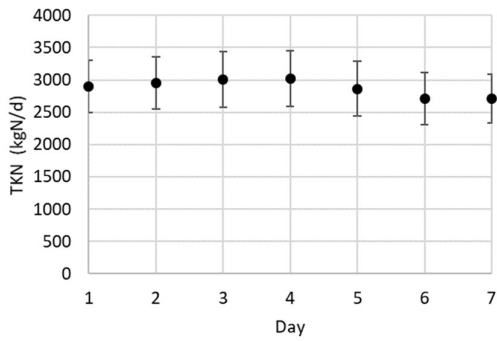
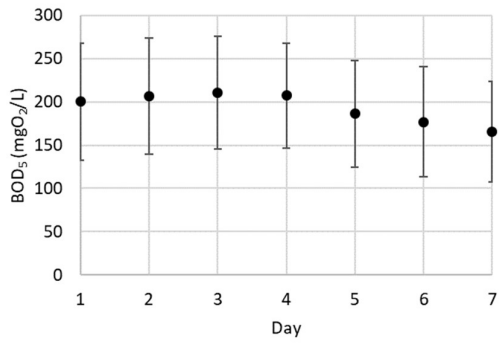
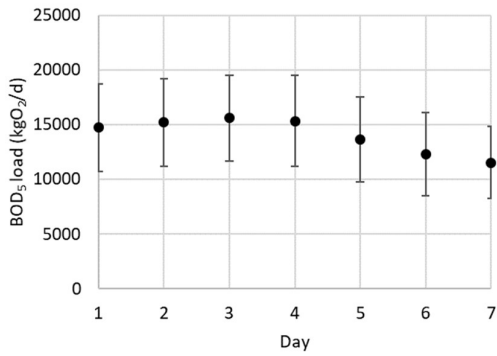
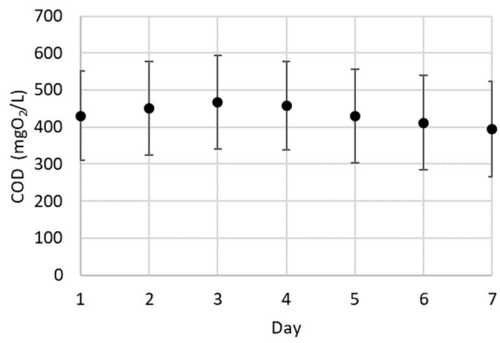
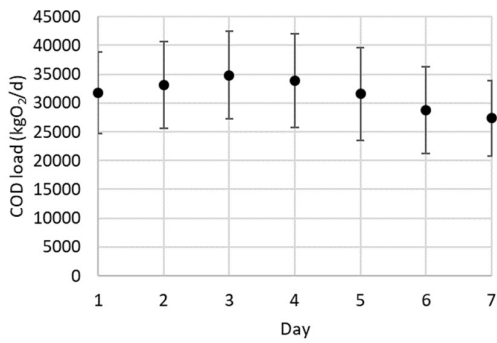
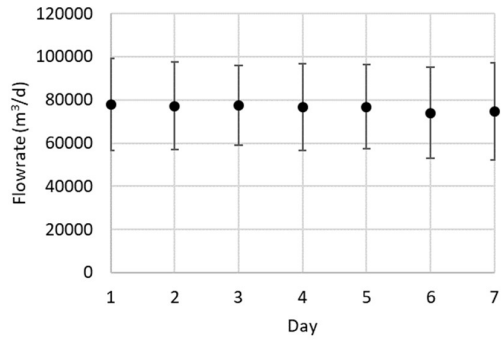


Figure S1: Monthly load (left column) and concentration (right column) averages in the pre-confinement period (Jan 2017 to Feb 2020) (*) and during the confinement (March to May 2020) and post-confinement (June 2020) (closed symbols) for B. Months are ranked between January (1) and December (12).



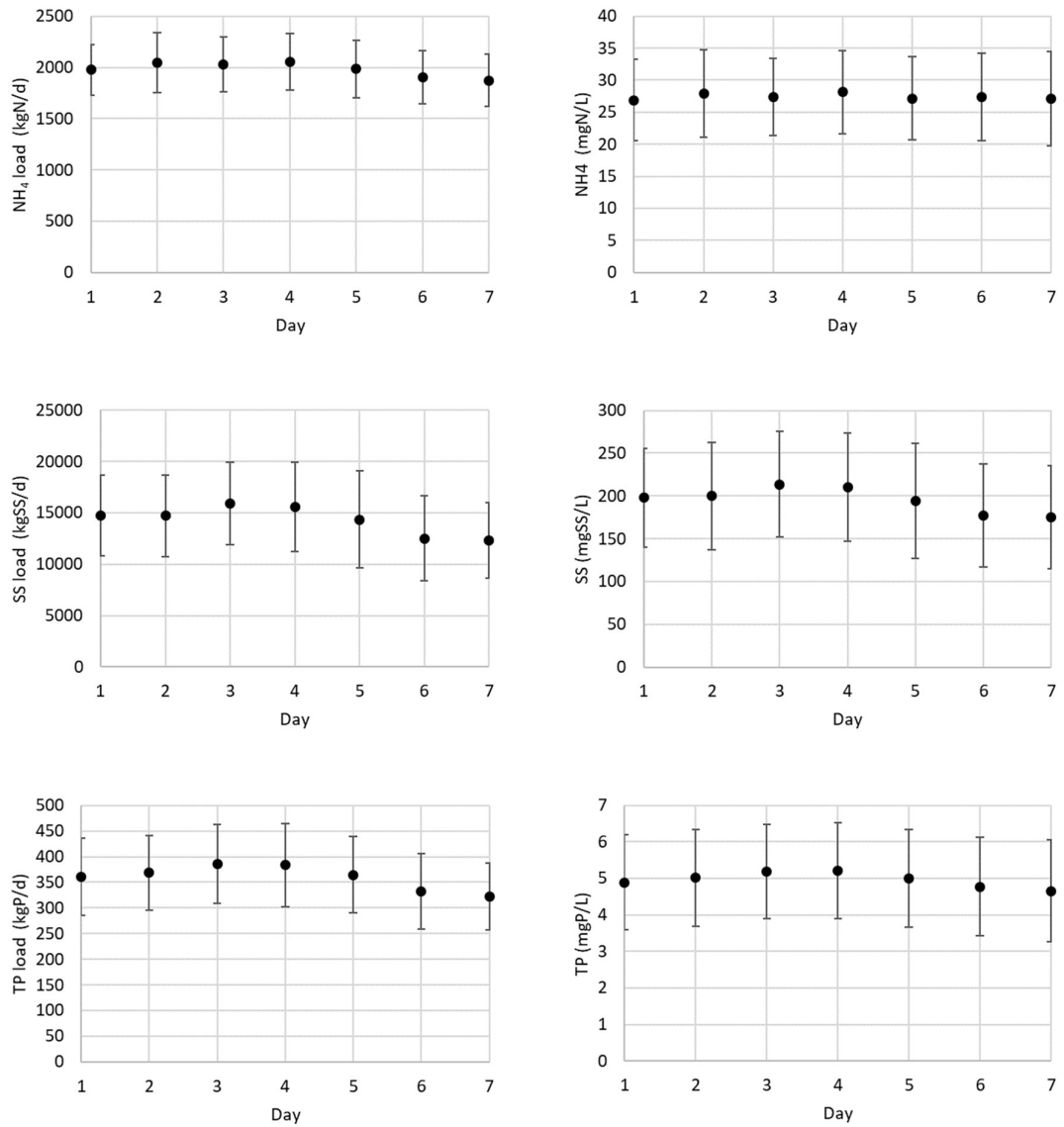


Figure S2: Load and concentrations averages, calculated between Jan 2011 and Feb 2020, for urban area A in function of the day of the week for dry days only: Monday (1), Tuesday (2), Wednesday (3), Thursday (4), Friday (5), Saturday (6), Sunday (7)

| Day | | Flowrate (m ³ /d) | COD load (kgO ₂ /d) | COD (mg/L) | TKN load (kg N/d) | TKN (mgN/d) | NH ₄ load (kgN/d) | NH ₄ (mgN/L) | BOD ₅ load (kgO ₂ /d) | BOD ₅ (mgO ₂ /L) | SS load (kgSS/d) | SS (mgSS/L) | TP load (kgP/d) | TP (mgP/L) |
|-----------|--------------|------------------------------|--------------------------------|------------|-------------------|-------------|------------------------------|-------------------------|---------------------------------------------|----------------------------------------|------------------|-------------|-----------------|------------|
| Monday | <Lower Limit | 78 | 100 | 100 | 100 | 89 | 67 | 33 | 100 | 89 | 100 | 78 | 89 | 67 |
| | >Upper limit | 22 | 0 | 0 | 0 | 0 | 33 | 67 | 0 | 11 | 0 | 0 | 11 | 33 |
| | Within limit | 0 | 0 | 0 | 0 | 11 | 0 | 0 | 0 | 0 | 0 | 22 | 0 | 0 |
| Tuesday | <Lower Limit | 67 | 100 | 83 | 75 | 33 | 67 | 33 | 100 | 100 | 92 | 83 | 100 | 42 |
| | >Upper limit | 33 | 0 | 8 | 0 | 58 | 33 | 58 | 0 | 0 | 8 | 17 | 0 | 42 |
| | Within limit | 0 | 0 | 8 | 25 | 8 | 0 | 8 | 0 | 0 | 0 | 0 | 0 | 17 |
| Wednesday | <Lower Limit | 80 | 100 | 100 | 100 | 40 | 80 | 10 | 100 | 90 | 100 | 80 | 90 | 70 |
| | >Upper limit | 20 | 0 | 0 | 0 | 60 | 20 | 60 | 0 | 0 | 0 | 10 | 10 | 30 |
| | Within limit | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 10 | 0 | 10 | 0 | 0 |
| Thursday | <Lower Limit | 80 | 100 | 90 | 90 | 40 | 70 | 30 | 100 | 90 | 100 | 60 | 100 | 60 |
| | >Upper limit | 20 | 0 | 0 | 0 | 60 | 30 | 60 | 0 | 0 | 0 | 30 | 0 | 30 |
| | Within limit | 10 | 0 | 10 | 10 | 0 | 0 | 10 | 0 | 10 | 0 | 10 | 0 | 10 |
| Friday | <Lower Limit | 70 | 100 | 100 | 90 | 40 | 80 | 30 | 100 | 100 | 90 | 70 | 100 | 50 |
| | >Upper limit | 30 | 0 | 0 | 0 | 40 | 20 | 60 | 0 | 0 | 10 | 30 | 0 | 30 |
| | Within limit | 0 | 0 | 0 | 10 | 10 | 0 | 10 | 0 | 0 | 0 | 10 | 0 | 20 |
| Saturday | <Lower Limit | 70 | 90 | 90 | 40 | 40 | 50 | 20 | 90 | 70 | 70 | 70 | 90 | 50 |
| | >Upper limit | 20 | 0 | 10 | 40 | 50 | 20 | 70 | 10 | 20 | 10 | 30 | 10 | 30 |
| | Within limit | 10 | 10 | 0 | 20 | 10 | 30 | 10 | 0 | 10 | 20 | 0 | 0 | 20 |
| Sunday | <Lower Limit | 80 | 80 | 60 | 40 | 30 | 20 | 20 | 50 | 50 | 70 | 60 | 70 | 40 |
| | >Upper limit | 20 | 10 | 20 | 30 | 70 | 40 | 70 | 40 | 40 | 10 | 30 | 0 | 40 |
| | Within limit | 0 | 10 | 20 | 30 | 0 | 40 | 10 | 10 | 10 | 10 | 10 | 30 | 20 |

Figure S3: Load and concentrations averages, calculated between January 2011 and February 2020, for urban area A in function of the day of the week for dry days only: Monday (1), Tuesday (2), Wednesday (3), Thursday (4), Friday (5), Saturday (6), Sunday (7)