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Quantification and qualification of the urban domestic pollution discharged per household and per resident

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ABSTRACT

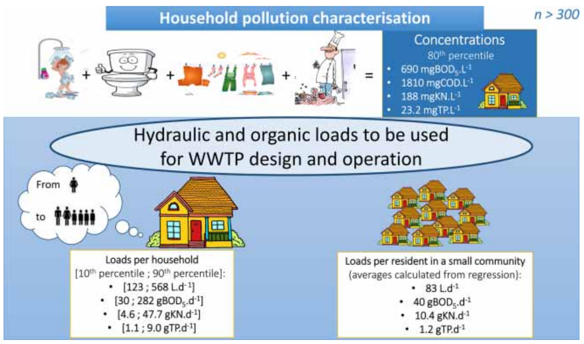
The research study aims to analyze the discharges of solely domestic wastewater from 15 single-family dwellings. This sizable dataset, containing over 300 unique and insightful data points, makes it possible to accurately qualify the raw wastewater in terms of concentrations, volumes and pollutant loads). Findings quantify the extremely wide data variability. As such, for single-family households of fewer than six residents, it is suggested not to use the standard P.E. pollution value as the design load, but rather a load range defined by the interval [10th percentile, 90th percentile] of the data distribution, i.e. [123;568 L·d^{-1}] and [30; 281 g BOD_5·d^{-1}] respectively for the daily hydraulic and organic loads. Also, an analysis of the hydraulic peak factor would tend to lobby in favor of a collective sewer solution. For subdivisions and residential zones with little economic activity and similar French lifestyle, the daily domestic pollution per resident is now determined with the values: 40 g SS, 94 g COD, 40 g BOD_5, 6.7 g NH_4^+-N, 10.4 g KN, and 1.2 g TP for a volume of 83 L. Those data could be used to optimize design and operation of decentralized or small-scale wastewater treatment plant.

Key words: capita, concentration, hydraulic load, onsite treatment, pollutant load, population equivalent

HIGHLIGHTS

- The household wastewater loads are defined by an interval based on percentiles.
- The ratio between the two bounds defining the organic load lies near 10.
- The average hydraulic peak factor equals approximately 8.
- The hydraulic peak factor drops with the number of aggregated houses.
- The average daily domestic pollution per resident is set at 40 g BOD5·d^{-1}.

GRAPHICAL ABSTRACT



INTRODUCTION

The quantification and qualification of pollution contained in wastewater are among the basic technical data inherent in a facility design adapted to effluent collection and treatment. This principle is valid for all types of pollution, regardless of its origin, whether domestic or industrial. At the scale of individual homes, data are scarce; yet such data are necessary to protect environment and human health and meet regulatory discharge standards.

As regards domestic wastewater, which is the topic of the present paper, the chemical measurement used to characterize the concentrations have been in effect for a long time. National regulations, applied in many countries for at least a half-century, have promoted a widespread reliance on analyses to verify the quality of the treated wastewater as well as to learn more about influents, in the aim of optimizing both treatment plants design and operation. These influent concentrations are variable and mainly depend on the kind of network and degree of dilution, by rainwater and/or the seepage of clean water (water table drainage, runoff connected to a separate network …). The amount of scientific data available decreases substantially with the size of the metropolitan area. At the individual dwelling scale, as characterized by a very short network and the complete absence of dilution due to external sources, wastewater characteristics remain relatively unknown, with the notable exception of recent works by Lowe *et al.* (2007, 2009) and Pishgar *et al.* (2021).

On the other hand, scientific knowledge of the 'domestic' nature of wastewater running through a collective network is sufficiently robust, now codified and integrated into modeling tools in the form of validated parameters (Rieger *et al.* 2012) applied to facility design.

The definition of population equivalent (P.E.) as 'the organic biodegradable load having a five-day biochemical oxygen demand (BOD_5) of 60 g of oxygen per day' was established by the European Directive dated May 21, 1991 (Article 2). Since then, this definition has been adopted by the profession and is now used as the reference organic load to be treated when designing wastewater treatment facilities. It was impossible however to retrace the intellectual path that led to selecting this particular value. The data used to define the domestic pollution load per person are derived most often from an aggregate measurement of the daily pollution load, based on the most accurate estimation possible of the population connected to the collection network (Alexander & Stevens 1979; Mesdaghinia *et al.* 2015).

At the dwelling unit scale, studies focusing on the complete water cycle that are intended to evaluate quality (by means of chemical measurements) and quantity (from corresponding volume measurements) are indeed rare. They are complicated to set up due to the technical difficulty of deriving a representative sample of this kind of pollution, composed of suspended solids potentially very coarse in size, compounded by the administrative difficulty of performing these measurements on private property. Such studies would however accurately assess the per-inhabitant pollution loads of domestic origin. Zanoni & Rutkowski (1972) had evaluated the domestic pollution of 270 single-family dwellings in California. The study conducted and synthesized by Lowe *et al.* (2009) focused on the discharges from 17 residences spread across three American states: Colorado, Florida, and Minnesota. No published study with this kind of scope has been identified in Europe.

In addition, identifying domestic pollution by its source is more recent, dating back ten or so years. Bibliographic summaries describe in specific terms the household water via its production source: (i) cooking water, (ii) washing and laundry water, (iii) bathing water plus black water, with a breakdown between urine, fecal matter and toilet paper (Jönsson *et al.* 2005; Meinzinger & Oldenburg 2009; Boutin & Eme 2016). Reconstituting the dataset to specify the entire array of domestic pollution entails summing individual contributions, since an aggregate measurement remains impossible; this sum can then be theoretically compared to the pollution unit, i.e. the population equivalent.

The present study focuses on raw wastewater discharges from 15 individual dwellings that have undergone simultaneous quantitative and qualitative monitorings, with a known number of residents. The term 'resident' refers to any individual who typically occupies, as a primary place of residence, the dwelling unit. Hence, a child attending boarding school during the week is a 'resident' despite not being systematically present when pollution measurements are performed. Conversely, guests staying at the unit are not counted as 'residents' even though the additional onsite activity generated by their stay and/or presence may be included in measurements. Therefore, the 'resident' unit is different from the 'capita' unit which doesn't integrate the social activities in an individual house.

The dataset is available in a data paper (Dubois *et al.* submitted).

The main two objectives of this study were to:

- define the ranges of variations of wastewater produced by individual homes and to deduce, for onsite treatment systems, the scope of their application in terms of flow, concentration and pollutant loads;

- enhance the technical knowledge dedicated to strictly domestic pollution, by defining the per 'resident' pollutant and hydraulic loads and comparing them to the few other available data and benchmarks set forth in national and local regulations.

This paper provides the main results relative to the concentrations and timelines of the raw domestic wastewater volumes to be treated for individual homes. The ensuing discussion focusses on the handling of pollution loads, first at the unit scale used for decentralized sanitation, then extrapolated to recommended per 'resident' pollutant estimates that can be used for dimensioning and operating future small scale centralized sanitation.

MATERIALS AND METHODS

Materials

Data

The data analyzed herein correspond to the discharges of raw wastewater from 15 single-family dwellings, as obtained by means of two distinct and complementary monitoring campaigns:

- monitoring campaign (i) focused on the continuous measurement of volumes discharged from three of the 15 dwelling units under study, and
- monitoring campaign (ii) characterizing, in both quality and quantity terms, the raw wastewater over a consecutive 24-hour period by all 15 units.

The acquisition and validation methods are detailed in Appendix 1. The data are described in Appendix 2 and available in a data paper (Dubois *et al.* submitted).

The household composition differs from one studied unit to the next: from a person living alone to families composed of several adults (2 or 3) and a variable number of children (0–4). The maximum number of unit residents is six. Residents' ages are not known, only the distinction between adults and children (i.e. under 18 years of age) is available. The composition of the 15 families therefore varies in number, in both adults and children. Despite the absence of a social survey, families answered to informal questions about work rhythm of parents and children's schooling; their lifestyles are different. The sample of these 15 houses chosen at random according to technical criteria (Appendix 1) reflects the diversity of the French individual habitat. Because of the similarity of lifestyles, it seems possible to extend the analysis to situations in other European countries.

The average number of residents per unit equals 3.5, while the average weighted by the number of measurement samples per household rises slightly to 3.6 residents. The 15-house sample was sorted by increasing number of adults and, within each given number of adults, by increasing number of children; this classification serves to explain the data numbering system employed.

These data were most often analyzed at the household level, except when an aggregation step is specifically mentioned.

Data aggregation

- Aggregation of data from monitoring campaign (i)

The wastewater volumes from three selected houses (H_1, H_{10} and H_{11}) were monitored on a continuous basis during three distinct sequences, which nonetheless overlapped during the same consecutive 90-day period. For this period, four datasets were created in the aim of simulating the volumes generated by two or three families sharing the same sewer collector. For each time interval, the hourly volumes were aggregated two by two, i.e. (H_1 and H_{10}), (H_1 and H_{11}) and (H_{10} and H_{11}), or else compiled all at once (H_1, H_{10} and H_{11}).

- Aggregation of data from monitoring campaign (ii)

Residents are either adults or children, with the distinction solely based on being older or younger than 18. To analyze the effect of these two types of residents on the daily hydraulic or pollutant loads to be treated, the households composed of adults only were aggregated. Hence, the group of households H_1 through H_5 can be compared with households H_6 through H_{15}, which comprise both adults and children.

The number of residents varies from 1 to 6 adults and children combined. To analyze the scale effect of this number of residents, households containing the same number of residents were aggregated, with the breakdown being: houses H_2,

H_3, H_4 and H_5 composed of two residents; H_6 and H_7 three residents; H_8, H_9, H_{13} and H_{14} four residents; H_{10} and H_{15} five residents; and lastly H_{11} and H_{12} six residents each. House H_1 remains an isolated case, as the lone household to be occupied by just one person.

Data validation step

The data had previously been validated according to a methodology described in Appendix 1.

A faucet inadvertently left open can explain the exceptionally high value of 4,517 $m^3 \cdot d^{-1}$ measured for household H_{11} on July 8, 2016; this data point was discarded from the subsequent analysis given its accidental nature.

Methodology

Statistical tools

- Descriptive statistics

The majority of data are presented in tabular form using conventional descriptive statistics: average, median, minimum and maximum values, standard deviation, coefficient of variation (CV: ratio of the standard deviation to the average, expressed in percentage), as well as the number of available values. The calculation of weighted averages relative to the number of available data points for each dwelling served to mitigate the impact of differences in the number of measurement points analyzed.

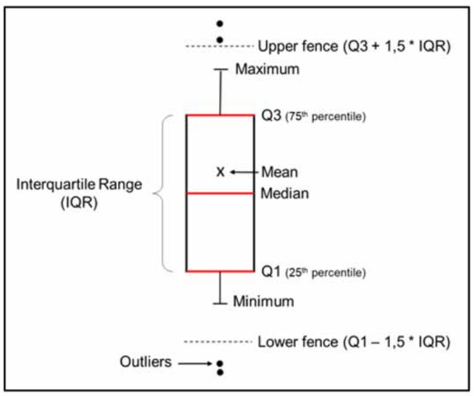
A graphical view has also been depicted in the form of box plots (Figure 1), offering the possibility to visualize the dispersion of the data distribution.

- Regression

The search for a correlation between two parameters by means of a simple model using linear regression constitutes part of the basic toolbox. As a reminder, when two parameters are correlated by a linear equation passing through the origin, the defining slope of the straight line corresponds exactly to the ratio between these two parameters. Moreover, the analyses of regression coefficient R^2 (Seber & Lee 2003) in conjunction with the straight-line slope serve to evaluate the stability of this relationship.

- Comparison of two datasets

In order to compare two datasets, various statistical tests are employed. The Shapiro-Wilk test is applied first to assess the normality of a distribution, with the null hypothesis being: 'The sample follows a normal law'. When the probability (p-value) associated with this test lies below the threshold of significance, commonly set at 5%, then the null hypothesis is rejected. Next, the comparison tools introduced vary depending on the response to this initial test: (i) if the distribution is Gaussian, the Student's t-test is then run to compare the averages of both samples and determine whether or not they differ; (ii) if the distribution is not Gaussian, the Wilcoxon-Mann-Whitney test compares the distributions of the two samples. The null hypothesis of this test is: 'Both samples belong to the same population'. Again, if the probability (p-value) for this test lies below 5%, the two samples are significantly different.



- *Mean*: represented by a cross
- *Median:* 50th percentile
- *Q1:* 25th percentile
- *Q3:* 75th percentile
- *Interquartile range*: IQR = Q3 - Q1 (encompassing 50% of the data points)
- *Lower fence*: Q1 - 1.5 × IQR, and *Upper fence*: Q3 + 1.5 × IQR. If the distribution follows a "normal law", then 99.3% of the data lie inside the two fences.
- *Outliers*: Qualification ascribed in statistics to data points lying outside the fences.

Figure 1 | Box plot representation of a given data distribution.

Hydraulic peak factor

Equation (1) defines the hydraulic peak factor (Cp):

$$C_p = \frac{Q_p}{Q_m} \tag{1}$$

where Q_p is the maximum daily flow rate and Q_m the average daily flow rate, both expressed in $L{\cdot}h^{-1}$.

Without knowing the maximum daily flow rate, the empirical formula (Equation (2)) is used within a collective wastewater treatment range for average flow rate greater than or equal to 2.8 $L{\cdot}s^{-1}$ (ASTEE Working Group 2017).

$$C_p = 1,5 + \frac{2,5}{\sqrt{Q_m}} \tag{2}$$

where Q_m is the average daily flow rate expressed in $L{\cdot}s^{-1}$.

For flow rates less than 2.8 $L{\cdot}s^{-1}$, C_p becomes fixed; a value of 3, or ultimately 4, is then proposed.

RESULTS

Concentrations

The concentrations of the six target parameters, (i) Suspended Solids (SS), (ii) Carbon oxygen demand (COD), (iii) Biochemical oxygen demand (BOD_5), (iv) Ammonium (NH_4^+-N), v) Kjeldhal Nitrogen (KN) and Total phosphorus (TP) characterizing the wastewater of the 15 studied dwellings are available in Appendix 2. It lists the average, median, minimum and maximum values, standard deviation, coefficient of variation, plus the number of data values available for each household. The nitrogen oxide forms (NO_2^--N and NO_3^--N), not present in the raw wastewater, have deliberately not been analyzed. The magnitudes of concentration variations are quite high; as an example, the magnitudes of parameters SS, COD and KN lie respectively within the intervals [54; 3,200 $mg{\cdot}L^{-1}$], [126; 5,817 $mg{\cdot}L^{-1}$] and [15; 555 $mg{\cdot}L^{-1}$]. A box plot graphical representation, deliberately limited to the two chemical parameters SS and KN for an illustration (Figure 2), shows the very high dispersion in concentration values at a given site. The magnitude of the average coefficients of variation calculated for each household support this observation. For all six concentrations, these averages vary between 25 and 70%.

Figure 2 also exposes the great dispersion across sites. The bounds of the median SS concentration variation interval for each of the 15 households were obtained for H_{12}, with a minimum at 185 $mg{\cdot}L^{-1}$, and H_{11} featuring a maximum of 1,070 $mg{\cdot}L^{-1}$. Both these households were composed of 6 residents (2 adults, 4 children). For nitrogen pollution, expressed

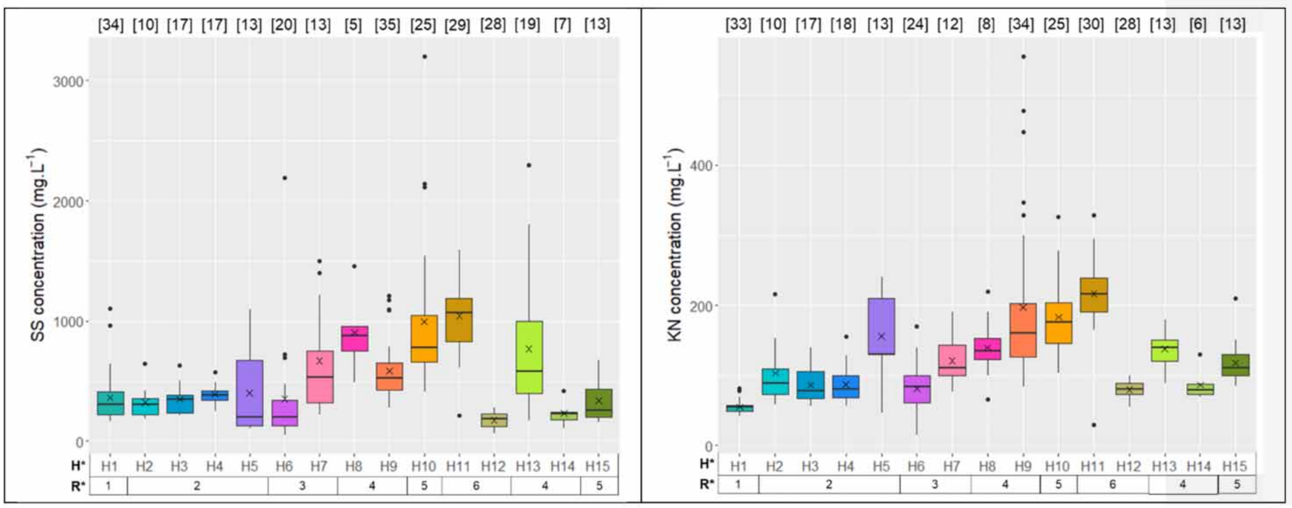


Figure 2 | Concentrations, in $mg{\cdot}L^{-1}$, of the raw wastewater from 15 dwellings – left: SS, right: KN. *Note:* **H***=Household, **R***=No. of residents. The number of data points in each dataset is in brackets.

in KN, these bounds are positioned at 55 mg·L^{-1} for H_1 (one resident) and 216 mg·L^{-1} for H_{11} (six residents). For phosphorus pollution, expressed in TP, these bounds stand at 6.9 mg·L^{-1} and 29.4 mg·L^{-1} respectively for the same households (H_1 and H_{11}) identified at the nitrogen pollution bounds. The raw wastewater concentration distributions of a unit housing 1–6 residents are listed in Table 1 for all parameters studied herein.

Comparisons of the concentrations measured during weekdays or weekends (Olivier *et al.* 2019b) do not reveal significant differences. A comparison of these datasets was further refined by applying the statistical tool dedicated to distributions that do not necessarily follow a normal law (i.e. the Wilcoxon-Mann-Whitney test); this exercise did not find any difference between the two distributions.

The median values of the concentrations in SS, BOD_5, KN and TP, i.e. 415 mg·L^{-1}, 412 mg·L^{-1}, 110 mg·L^{-1} and 12.5 mg·L^{-1} respectively, can now be compared (Figure 3) with the equivalent data available for single-family dwellings, as established by the University of Colorado (Lowe *et al.* 2009). These median values of the SS, BOD_5, KN and TP concentrations, i.e. 232 mg·L^{-1}, 420 mg·L^{-1}, 57 mg·L^{-1} and 10.4 mg·L^{-1} respectively, had already been deemed comparable to widespread North American references (Lowe *et al.* 2007). It can thus be stated that the BOD_5 concentrations stemming from a French dwelling are equivalent to those recorded in the United States. On the other hand, for parameters SS, KN and (to a lesser extent) phosphorus pollution, differences do appear, with higher concentrations in France. These deviations are difficult to explain; it is likely that they stem, in part, directly from the composition of products consumed across households. However, without precise data on the composition of these products, such an assumption cannot be confirmed. From a technical standpoint, the hypothesis of bias present in the mode chosen to sample the raw wastewater generated in the American study, which would fail to collect all SS despite every precaution taken, is also a possibility.

The distribution of the entire dataset is provided on the same graph (Figure 3) as the distribution of wastewater quality from municipalities with fewer than 2000 P.E. (Mercoiret 2010), whose typically short networks may be separate. The 'concentrated' nature of onsite systems compared to a collective sewer collector is obvious. The concentration factor of carbon-containing matter reaches 1.6 if the comparison pertains to medians and 1.9 if it focuses on averages. For the nitrogen and phosphorus parameters, the concentration factors are less but still reach 1.2, or even 1.9, depending on which modes of comparison have been chosen.

The domestic nature of the pollution (Table 2) is evaluated by analyzing the ratios of the chemical substances contained in the wastewater. Henze *et al.* (2010) defined three levels of wastewater characterization ratios, namely: (i) low, (ii) typical, and (iii) high.

The ratios of wastewater generated directly from American residences (Lowe *et al.* 2009), compared to values obtained within the scope of this study, are surprisingly different; they tend to be high, except for the COD/BOD_5 ratio, which is 'typical' according to Henze (2010) and NH_4^+-N/KN, which is lower. The overall organic matter can be quantified by the COD parameter and the nitrogen organic fraction, expressed by the difference between KN and NH_4^+-N. It is compared with suspended solids, yielding ratios of 3.8 and 30.9 respectively, both of which are above the French benchmark values of 2.6 and 7.1. This observation could serves to validate the hypothesis stated previously, namely of a bias in the sample leading to underestimating suspended solids in the American study. Based on these criteria, it becomes impossible to establish the 'domestic' nature of American wastewater. Consequently, in the following and especially for pollutant loads calculation, the values obtained within the scope of this study will be compared with great prudence to the lone bibliographic reference characterizing single-family dwellings.

The concentration ratios of raw wastewater directly discharged from French homes are quite comparable to those of wastewater collected via sewer networks in rural France. The balance of the nitrogen forms shows, for an individual dwelling, a

Table 1 | Concentrations, in mg·L^{-1}, of the raw wastewater from 15 dwellings: average values and the 10th, 50th 80th and 90th percentiles

Concentrations, in mg·L^{-1}		SS	COD	BOD_5	KN	NH_4^+-N	TP
Average		543	1,209	514	127	81	15.3
Percentiles	10th	162	467	200	56	29	6.5
	50th (median)	415	962	412	110	69	12.5
	80th	789	1,810	690	188	124	23.2
	90th	1,100	2,199	931	220	153	30.0
No. of data points		285	296	226	290	284	279

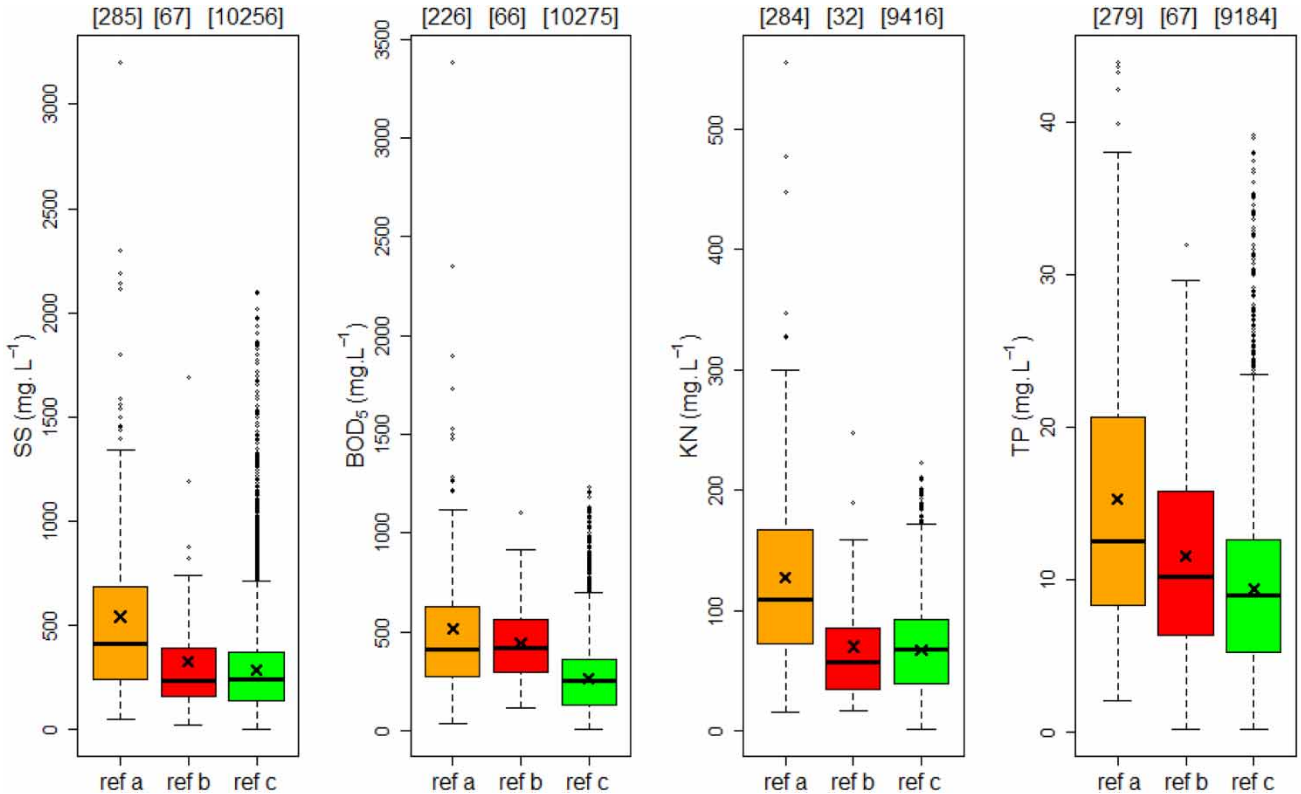


Figure 3 | Comparative distributions of raw wastewater concentrations, in mg·L^{-1}, from three datasets: [ref a] output by the present study, [ref b] reported by Lowe *et al.* (2009), and [ref c] reported by Mercoiret (2010). *Note:* The number of data points in each dataset is in brackets.

Table 2 | Average ratio values used to qualify 'domestic' wastewater, and comparison with a few bibliographic references

Bibliographic references		COD/BOD$_5$	COD/KN	COD/TP	COD/SS	BOD$_5$/KN	BOD$_5$/TP	NH_4^+-N/KN
This study		2.3	9.8	85	2.6	4.0	37.4	0.64
Lowe *et al.* (2009)		2.3	17.9	102	3.8	9.4	58.4	0.26
Mercoiret (2010)		2.6	9.7	71	2.6	3.9	28.5	0.74
Henze (2010)	low ratio	1.5–2.0	6–8[a]	20–35		3–4[a]	10–15	
	typical	2.0–2.5	8–12[a]	35–45		4–6[a]	15–20	
	high ratio	2.5–3.5	12–16[a]	45–60		6–8[a]	20–30	

[a]The ratio employed compares the target substances with total nitrogen.

slight deficit in the ammonia fraction or a predominant organic form (ratio: 0.64), as explained by the freshness of effluent circulating in a very short network. In France, phosphate elimination in washing detergents partially explains the high values of ratios involving phosphorus (Stricker & Héduit 2010). The chemical characteristics obtained from those data, i.e. raw wastewaters originating from a single-family dwelling, define exactly the 'domestic' nature of wastewater. Except for ratios involving total phosphorus, which lie well above the 'high' benchmark values selected, the other ratios satisfy the same classification: 'typical' defined by Henze (2010).

Wastewater volumes

Daily volumes

The daily volumes of wastewater, as measured during the sampling campaigns for physicochemical analyses (campaign ii)) are presented in Figure 4 for each dwelling. This display underscores the variations within a given site, as exhibited by coefficients of variation ranging from a minimum of 23% (H_{13}) to a maximum of 69% (H_2). It also points out the disparities across

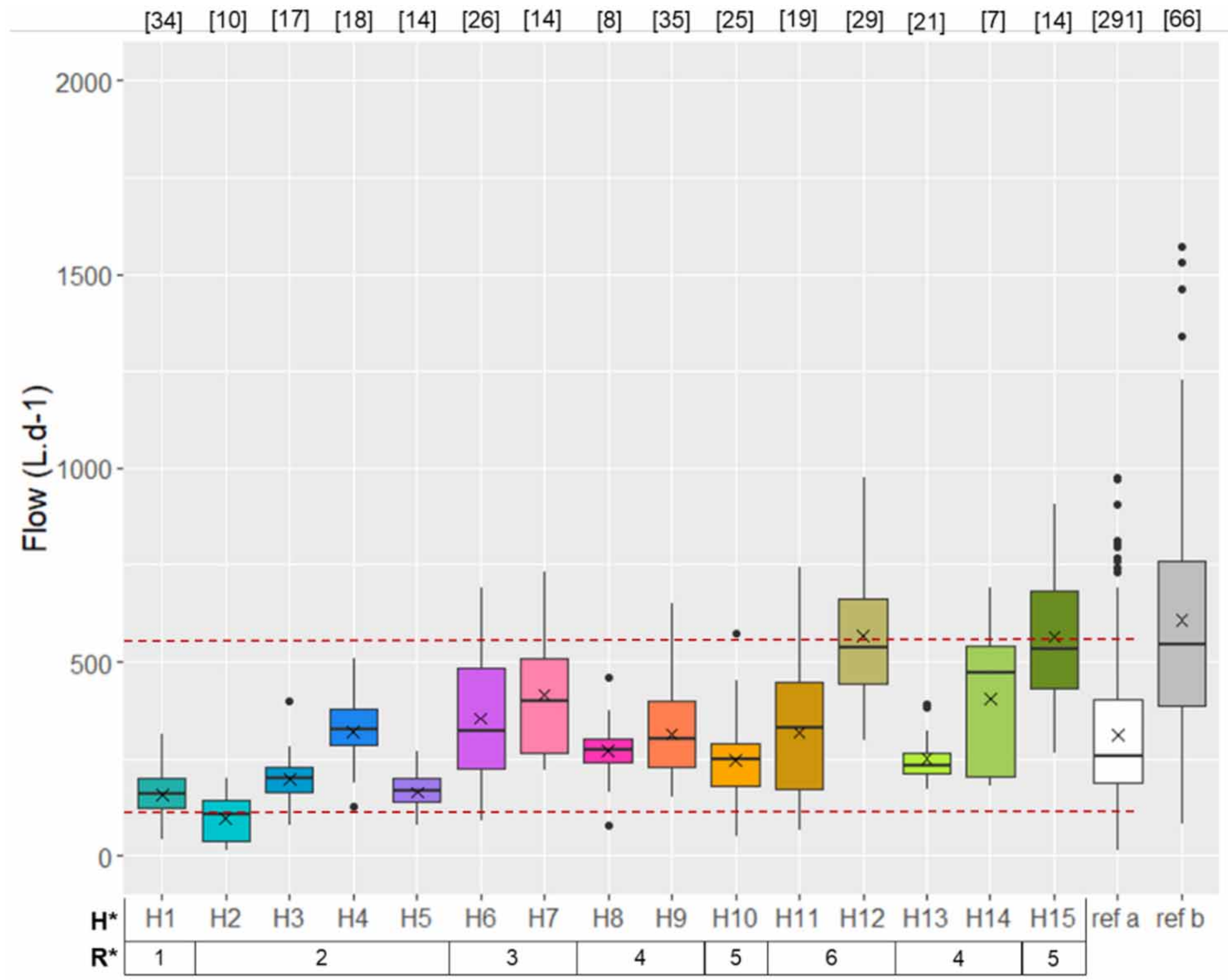


Figure 4 | Distribution of the daily volumes of 15 French households sorted by increasing number of adult residents and complete data for French (ref a) and American (ref b as per Lowe *et al.* 2009) datasets, in L.d^{-1}. *Note:* H* = Household, R* = No. of residents. The number of data points in each dataset is in brackets; red dashes correspond to the 10th and 90th percentiles of the complete French data distribution.

sites, which can be very significant even when occupied by the same number of residents (e.g. H_{11} and H_{12} both contain 2 adults and 4 children). The daily volume is lowest in H_2, which houses two residents, whereas only one person resides in H_1; similarly, it is surprising to note that the distributions of volumes generated by dwellings H_1, H_3 and H_5 are nearly identical, although the number of residents differs (just a single occupant in H_1 *versus* two in H_3 and H_5). These assessments highlight the impact of lifestyle on water consumption.

The values recorded serve to qualify the daily hydraulic loads of wastewater to be treated for a French household containing 1–6 residents and an American household of between 2 and 6. Table 3 summarizes these values.

Table 3 | Daily volume of wastewater for a house occupied by at most six residents in two distinct geographic settings, in L.d^{-1}

	Daily volume, in L.d^{-1}						
		Percentiles					
Geographic setting	**Average**	**10th**	**50th (median)**	**90th**	**min**	**max**	**Number of values**
15 French households	311	123	257	569	14	977	291
16 American households (according to Lowe *et al.* 2009)	631	288	549	1,056	83	2,025	63

A strong variation magnitude is apparent, as exhibited by the deviations between median and average, with the average being greater than the median due to some very high values, in addition to coefficients of variation near 60% in both settings. It comes as no surprise then that the North American daily volume exceeds that measured in France, by a factor of roughly 2 for all distribution values cited, except for the minimum value, which is five times higher.

The average daily value of 311 L/household is far from either interval bound [123; 569 L/household], as defined by eliminating 10% of the highest and lowest values, thus corresponding to 80% of the household situations encountered. Generally, a wastewater treatment plant functions correctly when it is regularly under loaded, indicating a hydraulic residence time longer than the design value. However, it is useful to ensure that the plant copes with large variations in hydraulic loads with an alternation from one day to the next, between net under load or overload.

Hourly volumes

Over a period beyond one year, an additional continuous data collection effort (Dubois 2021) was undertaken for the three households H_1, H_{10} and H_{11}, whose number of residents varies from 1 person living alone to 2 adults and 4 children.

Table 4 compares daily volumes according to the two monitoring campaign modes. For household H_1, the daily volume measurements were equivalent for both modes (i.e. continuous or over a 24-hour collection period). For H_{10} and H_{11}, the volumes measured during the 24-hour sampling period were 12% to 18% greater than those calculated in the continuous campaign (after deleting all zero daily flow rates). Without both types of measurements on a larger number of households, it is impossible to derive an overall corrective factor for the values subsequently chosen to calculate hydraulic and pollutant loads; it is likely that these values have been slightly overestimated.

As an additional piece of information, daily volumes producing a zero value (Table 4) occurred between 3 and 8% of the time for houses H_{10} and H_{11} and were never encountered for H_1. They correspond to periods when the house was unoccupied. The analysis of the hourly volumes of the different days of the week are available (Dubois *et al.* submitted). For example, H_{10} showed different hydrographs for each day of the week, confirming the impact of a household's lifestyle on wastewater production.

This additional monitoring campaign allowed conducting a finer temporal analysis, at the hourly scale, of daily volumes. As such, it was possible to determine the hydraulic peak factors (Equation (1)). The average C_p (Table 4) are equivalent for the three households and lie between 7.2 and 8.3. The high values recorded in the case of single-family dwellings effectively illustrate the lack of smoothing wastewater flow rates for such units, since lengths of collection pipes are so short. Note as well that the three maximum coefficients all exceed 22, which means that all wastewater discharged in a given day is sometimes generated over a very brief time period, i.e. barely one hour. The lifestyles and patterns of households explain why wastewater discharges are quite staggered over time.

To complete this analysis, datasets combining the households either two by two or with all three together were created, along with new C_p, calculated over the common data collection period limited to 90 days. Once two distinct lifestyles overlap, a smoothing of the volumes to be treated appears, as detected by smaller magnitudes in C_p variation. More specifically, ranging from 7.2 to 8.3 for the three families taken on their own, the average values decrease and lie within the interval [5.4–5.6] for the three combinations of two families and equal 4.5 when aggregating the three families (Figure 5). The aggregation of

Table 4 | Daily volume ($L \cdot d^{-1}$) of wastewater for households H_1, H_{10} and H_{11}, according to the two measurement modes employed and their corresponding hydraulic peak factor (C_p)

Household	H_1			H_{10}			H_{11}		
Parameter	Daily volume		C_p	Daily volume		C_p	Daily volume		C_p
Units	$L.d^{-1}$		–	$L.d^{-1}$		–	$L.d^{-1}$		–
Campaign	(ii)	(i)		(ii)	(i)		(ii)	(i)	
Average	158	162	7.9	248	203	8.3	317	278	7.2
Median	160	143	7.4	250	186	7.0	331	256	6.2
No. data points[a]	34/34	611/611		25/25	490/533		19/19	415/431	

[a]Number of nonzero data entries/total number of data points.

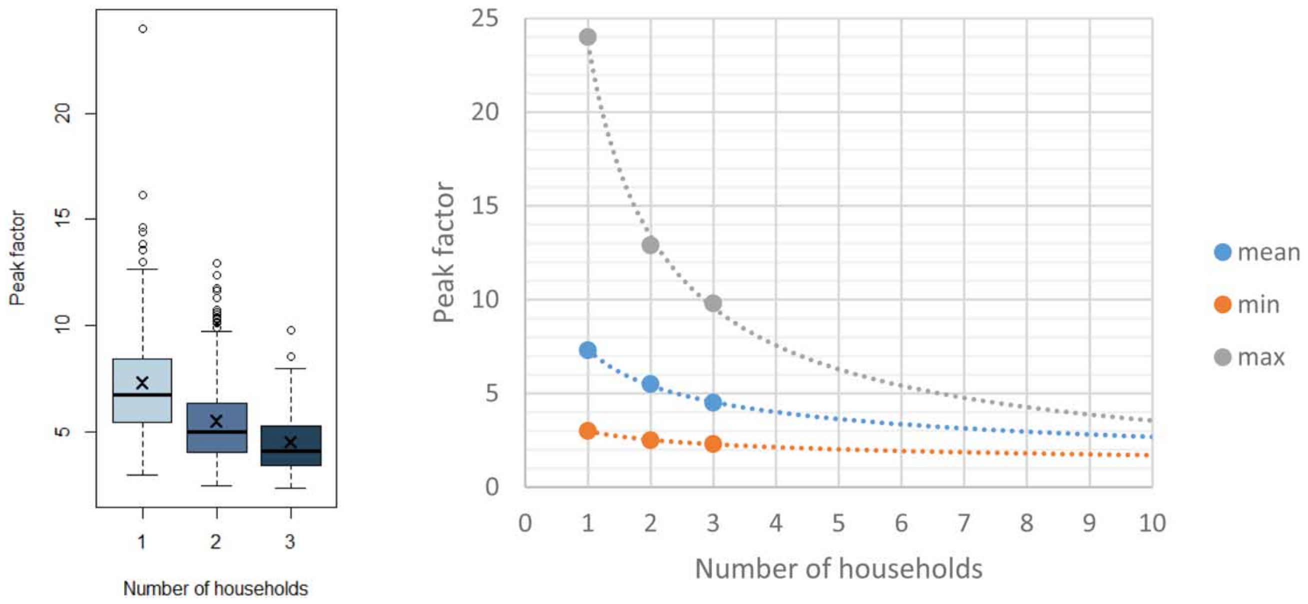


Figure 5 | Distribution of peak factor values vs. aggregated number of dwellings (left) and forecast of their evolution in average, minimum and maximum values (right).

several families serves to smooth the individual contributions of each family thanks to an overlap of several distinct lifestyle patterns; the model (*Figure* shows the average C_p reaching the symbolic value of 4 once aggregation exceeds 4 households. Similarly, the maximum C_p value would no longer exceed 4 once aggregation exceeds 8.7 households.

From a strictly technical perspective, the complexity of designing wastewater treatment installations increases with temporal variations in hydraulic (and pollutant) loads. The aggregated sewer solution, with more regular flow inputs, thus becomes a relevant solution, on technical grounds. In addition, this solution could lead to a better functioning of the treatment systems compared to wastewater treatment for individual dwellings.

DISCUSSION

This discussion takes place at two distinct scales, first at the household scale (to be applied to decentralized sanitation), then at the resident scale (to be applied to the context of small communities).

Households' hydraulic and pollutant loads

In the case of onsite treatment for individual dwellings, the design of treatment facilities is not based on a specific number of residents, but instead on the potential of the dwelling to accommodate a given number of residents. This treatment capacity expressed in P.E. closely mirrors the average size of single-family houses, i.e. 5 rooms, a figure that has remained stable for some 20 years. As such, installations are more likely to offer capacity for 5 P.E. (Olivier *et al.* 2019a). In contrast, the number of individuals per household has decreased, from 3.2 in 1968 to just 2.2 in 2017 (INSEE Statistics Office 2017). For this reason, the majority of French houses occupied by one to five residents are all equipped with the same size treatment system, designed solely on a theoretical pollution of five P.E., i.e. 300 g $BOD_5 \cdot d^{-1}$.

In this study, reference to the 'resident' (see definition in the Introduction) has been deliberate since it incorporates a social dimension that corresponds either to accommodating individuals beyond the typical household or, conversely, to an absence of household members. Without a users' survey describing the various activities of each household, it proves impossible to draw a direct correlation between their respective levels of activity and the ultimate results.

The daily hydraulic and pollutant loads of wastewater from the 15 dwellings for all six parameters (SS, COD, BOD_5, NH_4^+-N, KN and TP) are listed in Appendix 3 by average, median, minimum and maximum values, standard deviation, coefficient of variation and number of values available for each household.

As regards hydraulic aspects, facilities are designed based on a single daily flow rate standard of 750 L per household (5 P.E. * 150 L/P.E.). With respect to the daily flow rates measured *in situ* (campaign *ii)*), the vast majority of facilities (97%)

operate under conditions of smaller hydraulic loads. The average daily hydraulic load to be treated (311 L) represents barely 40% of the rated load.

The loads in BOD_5 and total phosphorus are shown in *Figure* The magnitudes of variations across sites, already indicated for both concentrations and daily volumes, are even more pronounced. The pollutant loads were expected to be relatively stable over time: hence, if the water consumption was greater, thus diluting the pollution, then the pollutant concentrations decrease. However, such is not systematically the case: high daily volumes may be associated with high concentrations and, *vice versa*, smaller volumes with lower concentrations. The average coefficient of variation calculated in each household, for these six pollution loads, varies between 33 and 97%; keep in mind that when calculated for concentrations, the average coefficient of variation interval extended from 25% to 70%.

The magnitudes of variations in the daily pollutant loads across the various sites are especially high and correspond, e.g. for the three parameters SS, COD and KN, to the respective intervals of [4; 1,128 g d^{-1}], [7; 2,058 g d^{-1}] and [1; 110 g d^{-1}].

Table 5 summarizes the average and median values, along with the 10th and 90th percentiles of each daily load distribution.

Calculations have focused on the hydraulic and pollutant loads to be treated by means of distinguishing weekdays from the weekend (Olivier *et al.* 2019b); they output values systematically higher on the weekend than during the week. A statistical comparison of the two datasets, conducted in the same manner as for the concentrations, concluded however that there is no difference between the two distributions. In case of household aggregation, it is likely that these differences are more pronounced, yet the dataset is unable to reflect this.

The 90th percentile of the BOD_5 load distribution (282 g d^{-1}) lies close to the standard design of 300 g $BOD_5 \cdot d^{-1}$. Currently, facilities are therefore designed to treat sizable loads. Nonetheless, it is still necessary to also ensure effective system operations for smaller pollution loads. i.e.

To enable 80% of households to benefit from an efficient facility, while mitigating the impact of extremely low or high situations, it would be useful to select a treatment range encompassing the load interval defined by the 10th and 90th percentiles of the distribution of values obtained during this study. The systems dedicated to the treatment of wastewater generated by a single family should all be equipped with a facility capable of acting as a hydraulic buffer tank, thereby attenuating the hydraulic variations not only daily but also hourly. For example, a septic tank can buffer the hydraulic variations.

The magnitudes of these ranges [30: 282 g $BOD_5 \cdot d^{-1}$].and [123: 568 $L \cdot d^{-1}$], with a factor lying near 10 for organic load and 5 for hydraulic load between the two bounds, constitute a strong technical requirement for onsite treatment.

Residents' hydraulic and pollutant loads

The loads calculated above are all individually related to the number of residents[1] and then analyzed together in order to define the hydraulic and pollutant loads of a resident.

Table 5 | Daily hydraulic loads, in $L.d^{-1}$, and pollutant loads, in $g.d^{-1}$, of a household's raw wastewater: the values listed are averages, 10th, 50th and 90th percentiles, standard deviations, coefficients of variation and number of data points

Daily loads of a household		Hydraulic, in $L.d^{-1}$ Volume	Pollutant, in $g.d^{-1}$ SS	COD	BOD_5	NH_4^+-N	KN	TP
Average		311	150	354	155	24	38	4.6
Percentile	**10th**	**123**	**27**	**76**	**30**	**4.6**	**8.6**	**1.1**
	50th (median)	257	113	281	140	20	33	3.7
	90th	**568**	**305**	**676**	**282**	**47.7**	**73.3**	**9.0**
Standard deviation		183	140	289	123	19	31	3.5
Coefficient of variation		59%	94%	82%	79%	79%	80%	77%
No. of data points		291	274	285	223	279	273	268

[1] The term of a 'resident' is defined above, in the introduction section.

Initial comparisons have sought to separate the loads produced by the two types of residents, i.e. adults and children younger than 18. The values obtained are quite similar between the two groups, when distinguishing the presence or absence of children; the most pronounced differences appear for parameter BOD_5, with an average of 42 $g{\cdot}d^{-1}$.resident^{-1} for the 'adults' group and 46 $g{\cdot}d^{-1}$.resident^{-1} for the 'adults+children' group. This comparison of the two datasets was further refined using the statistical tool dedicated to non-normal distributions which concluded that the two distributions exhibited no differences. In the following, no distinction will be made between adults and children categories.

Table 6 presents the descriptive statistics corresponding to the hydraulic and pollutant loads of a single resident. Accordingly, the average daily hydraulic load is slightly below 100 L/resident. The coefficient of variation for this parameter (56%) is among the lowest for all coefficients of variation applicable to the analyzed loads. The average daily loads in SS, COD, BOD_5, NH_4^+-N, KN and TP for a single resident amount to: 45 $g{\cdot}d^{-1}$, 105 $g{\cdot}d^{-1}$, 45 $g{\cdot}d^{-1}$, 6.5 $g{\cdot}d^{-1}$, 10.6 $g{\cdot}d^{-1}$ and 1.3 $g{\cdot}d^{-1}$, respectively. Let us note here that the medians are systematically lower than the averages, thus demonstrating a distribution that contains some high values. Even if all wastewater being analyzed followed strictly 'domestic' criterion, the magnitudes of parameter variation would all remain high, with coefficients lying between 56% (parameter NH_4^+-N) and 87% (SS). The calculation of weighted averages by each household's number of residents yields values very close to the averages, thereby reflecting the negligible impact of heterogeneity in each household's number of residents.

Compared to the daily P.E. load set at 60 $g{\cdot}d^{-1}$, corresponding to the 79th percentile of the distribution analyzed here, the average daily load in BOD_5, evaluated at 45 $g{\cdot}d^{-1}$, is 25% less. Wastewater from dwelling does not include activities associated with day-to-day social life, e.g. schools or consumer goods shops. Excluding industrial activities, which as such are not counted within the daily P.E. load, it follows logically that the value determined here, at the dwelling scale, is less than the reference unit.

The average daily BOD_5 load value determined here corresponds precisely to the value adopted by Zanoni & Rutkowski in 1972. The medians found (37 g $BOD_5{\cdot}d^{-1}$, 9.4 g $N{\cdot}d^{-1}$ and 1.1 g $P{\cdot}d^{-1}$) are all less than those identified by Lowe *et al.* (2009), which were 68 g $BOD_5{\cdot}d^{-1}$, 10 g $N{\cdot}d^{-1}$ and 1.5 g $P{\cdot}d^{-1}$ per occupant. The deviation with respect to parameter BOD_5 is truly significant, whereas the deviations with respect to the set of nutrient characteristic parameters are quite small. This comparison is to be viewed somewhat cautiously since the American wastewater does not fit the 'domestic' criterion (Table 2). Moreover, the loads are related to the number of actual occupants and not residents. Another approach, based on a bibliographic search (Boutin & Eme 2016), including the contributions of grey water and black water, also led to selecting a high BOD_5 value (65 g $O_2{\cdot}d^{-1}$) and an equivalent nitrogen value (10.4 g $N{\cdot}d^{-1}$). As regards phosphorus, the average daily load of 1.3 g $P{\cdot}d^{-1}$ per resident is less than the 1.8 g $P{\cdot}d^{-1}$ per capita defined by Alexander & Stevens (1979); it more closely resembles the 1.5 g $P{\cdot}d^{-1}$ per capita adopted by Stricker & Héduit (2010) based on an analysis of loads measured at a treatment plant servicing the target population.

In the aim of evaluating the scale factor associated with the number of residents, a more fine-tuned analysis was conducted by collating data with an identical number of residents and then seeking a correlation between the number of residents varying from 1 to 6 and the 6 corresponding average (hydraulic and pollutant) loads. Table 7 provides the averages calculated using these regressions; they are relatively stable for all parameters analyzed, with coefficients of variation at 5% for nitrogen parameters and overall less than 13%.

Table 6 | Daily hydraulic loads, in $L.d^{-1}$, and pollutant loads, in $g.d^{-1}$, of raw wastewater ascribed to a resident: averages, 10th, 50th and 90th percentile values, standard deviations, coefficients of variation, number of sample data points and weighted averages

Daily loads per resident		Hydraulic ($L.d^{-1}$) Volume	Pollutant ($g.d^{-1}$) SS	COD	BOD_5	NH_4^+-N	KN	TP
Average		98	45	105	45	6.5	10.6	1.3
Percentiles	10th	41	11	32	12	2.3	4.4	0.4
	50th (median)	84	35	85	37	5.9	9.4	1.1
	90th	175	89	193	80	11.7	17.3	2.4
Standard deviation		55	39	82	37	3.6	6.5	0.9
Coefficient of variation		56%	87%	78%	82%	56%	61%	69%
No. of data points		291	274	285	223	279	273	268
Weighted average		95	44	106	43	6.6	10.4	1.3

Table 7 | Average daily hydraulic loads, in $L.d^{-1}$, and pollutant loads, in $g.d^{-1}$, of raw wastewater ascribed to a resident, as determined by means of linear regression

Average daily loads per resident		Hydraulic ($L.d^{-1}$) Volume	Pollutant ($g.d^{-1}$) SS	COD	BOD_5	NH_4^+-N	KN	TP
Average, determined by linear regression		**83**	**40**	**94**	**40**	**6.7**	**10.4**	**1.2**
Standard deviation		7.91	4.39	11.85	5.04	0.28	0.52	0.13
Bound	Lower	67	32	70	30	6.1	9.4	1.0
	Upper	98	49	118	50	7.2	11.5	1.5

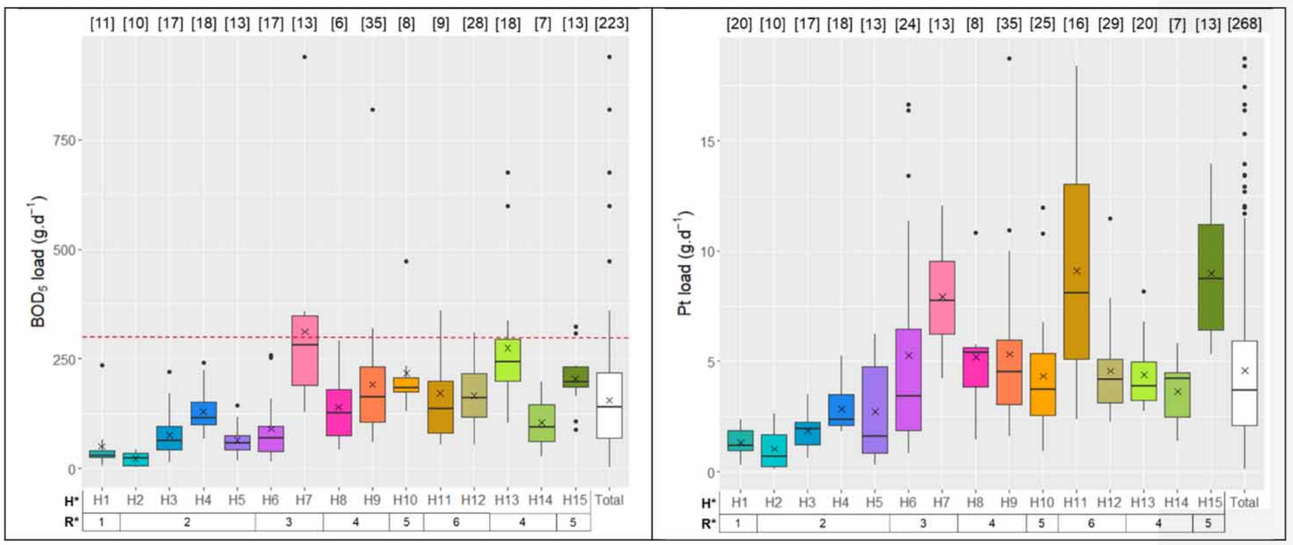


Figure 6 | Distribution of raw wastewater loads, in $g.d^{-1}$, for 15 dwellings classified by increasing number of adult residents – left: BOD_5; right: TP. *Note*: **H***=Household, **R***=No. of residents. The number of data points in each dataset is in brackets; red dashes correspond to the rated load value of a household containing five occupants.

This calculation mode has thus established the average daily domestic pollution of a resident equal to: 40 g $SS{\cdot}d^{-1}$, 94 g $COD{\cdot}d^{-1}$, 40 g $BOD_5{\cdot}d^{-1}$, 6.7 g NH_4^+-$N{\cdot}d^{-1}$, 10.4 g $KN{\cdot}d^{-1}$, and 1.2 g $TP{\cdot}d^{-1}$ for a volume of 83 $L{\cdot}d^{-1}$. Table 7 indicates the bounds of the variation interval for these loads, as conventionally defined by the average values plus or minus two standard deviations. Using linear regression based on the number of residents reduce the average values by 19% for the daily volumes and by 12–13% for the carbon parameters. The nitrogen loads are least sensitive to this scale factor, and the new values only differ by 2–3% from the initial ones. Overall, it would seem that the strictly domestic pollution is: (i) overestimated on the carbon parameters, (ii) accurate on the nitrogen parameters, and (iii) slightly overestimated on the phosphorus parameter. These results characterize the strictly domestic daily pollution and are especially applicable to subdivisions and residential zones with little economic activity. The values of 40 g $BOD_5{\cdot}d^{-1}$ and 83 $L{\cdot}d^{-1}$ are lower, by respectively 33 and 45%, than the typical benchmarks of 60 g $BOD_5{\cdot}d^{-1}$ and 150 $L{\cdot}d^{-1}$ and will contribute to a better design of new wastewater treatment plants, as well as the renovation or extension of current facilities.

Figure 7 illustrates, for parameters BOD_5 and NH_4^+-N, the magnitudes of variations for each number of household residents. Let us note the similarity in this magnitude for 3, 4 or 6 residents with regard to carbon parameters, as revealed by the BOD_5 parameter.

Calculating averages using regressions conceals these variations, and results are not applicable to a single-family dwelling. When the number of residents varies from 1 to 6, this set of analyses thus confirms the justification of adopting a load range within a 10th-to-90th percentile interval of magnitudes, without having to take the number of actual residents into account.

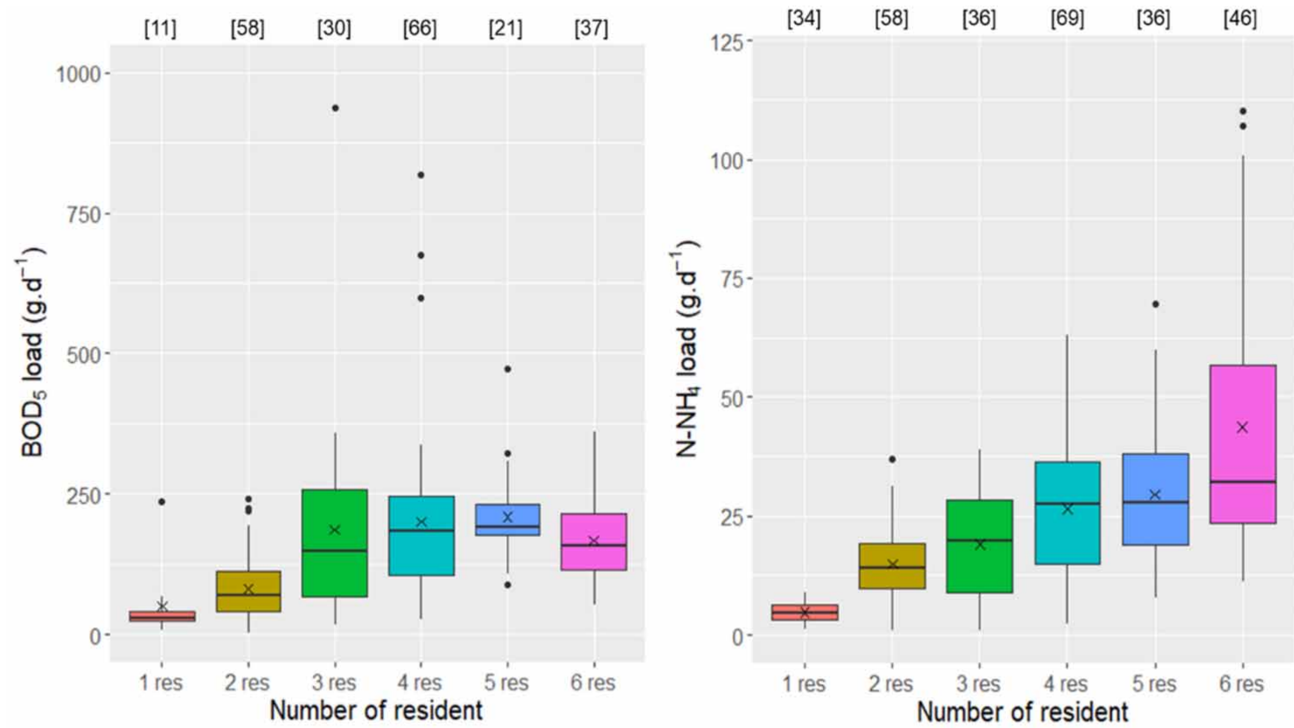


Figure 7 | Distributions of daily loads by number of residents, in BOD_5 (left) and NH_4^+-N (right).

CONCLUSION

The quantification and qualification of pollution are among the basic technical data inherent in a facility design adapted to effluent collection and treatment. At the scale of individual homes, data are scarce; yet such data are necessary to protect environment and human health and meet regulatory discharge standards. This paper has analyzed 302 composites samples of strictly raw domestic wastewater from 15 single-family dwellings with known numbers of residents. The parameters studied herein were the three carbon parameters: SS, COD and BOD_5, the two nitrogen parameters: NH_4^+-N and KN, and total phosphorus TP. The daily volumes were measured simultaneously, and an hourly hydraulic monitoring campaign served to complete the dataset for three of the 15 homes. Such a dataset is rare by virtue of both the technical difficulty involved in conducting a sampling program representative of actual pollution, i.e. composed of suspended solids that may be very coarse, and the administrative difficulty of performing these measurements on private property. Such data however are essential, in terms of not only providing solid bases for designing domestic wastewater treatment facilities, but also accurately quantifying the strictly domestic pollution at the scale of a single day for a single resident. Given the lack of an adequate survey describing the various activities taking place within each household, it was impossible to establish a direct correlation between these results and the level of household activity.

As regards onsite treatment at the individual dwelling level, the keyword to remember is 'variability', as it pertains to the entire set of results presented herein. More specifically, variability applies not only across sites, even when they contain the same number of residents, but within a given site, for daily volumes as well as concentrations. Variability further increases when calculating the daily pollutant loads to be treated. Within a given household, the volumes of wastewater generated during the day vary depending on residents' lifestyle. The average hydraulic peak factor, as computed for three differently sized households, is determined with a floor value of 7. A small sewer connecting a few houses becomes a relevant solution on technical grounds with more regular flow inputs. As regards concentrations, the 15 variation coefficients averages for the six chemical parameters all lie within the interval [25%, 70%]. Besides the lifestyle specific to each dwelling, the variable number of residents occupying each house contributes to heightening the variability of the hydraulic and pollutant loads to be treated. In fact, the wastewater treatment design for a dwelling is based on the building's occupancy potential; for this reason, two houses, one occupied by a single person and the other by a family composed of 2 adults and 3 children, feature treatment facilities both designed on the same basis of 5 P.E., i.e. 300 $BOD_5 \cdot d^{-1}$. To take this wide variability into account, it is suggested to select as reference values not the averages or medians, but rather the 80th percentile when defining the concentrations of each parameter, and the 10th-to-90th percentile load interval as the single-family dwelling treatment range.

This study has revealed that the wastewater concentrations stemming from single-family homes are 1.2–1.9 times more heavily concentrated than the wastewater collected through France's sanitation networks designed for fewer than 2000 P.E.. Without any dilution in a very short network due to external water inflows, the 80th percentile values of parameters SS, COD, BOD_5, KN, NH_4^+-N and TP amount respectively to: 789 $mg \cdot L^{-1}$, 1,810 $mg \cdot L^{-1}$, 690 $mg \cdot L^{-1}$, 188 mg $N \cdot L^{-1}$, 124 $mg \cdot L^{-1}$, and 23.2 $mg \cdot L^{-1}$. It was not possible to distinguish the quality and quantity of wastewater to be treated according to its generation on weekdays versus the weekend. The design bases currently in use are representative of a high load intake. In contrast, they do not integrate the weak loads that happen to correspond to a conventional single-family living situation. As such, the daily hydraulic load range is defined by the 10th-to-90th percentile interval, i.e. [123; 568 $L \cdot d^{-1}$]. As for the daily organic load range, it is defined on the same theoretical bases by the interval [30; 281 g $BOD_5 \cdot d^{-1}$]. The treatment range magnitudes constitute a demanding technical requirement, and the presence of a facility capable of acting as a hydraulic buffer tank, as advised in order to attenuate hydraulic variations, should be beneficial to treating pollutant pollution.

It is possible to determine the average daily domestic pollution of a typical resident, which has been established at 40 g SS, 94 g COD, 40 g BOD_5, 6.7 g NH_4^+-N, 10.4 g KN and 1.2 g TP for a volume of 83 L, by taking into consideration the number of residents housed in each dwelling. These values serve to characterize the strictly domestic daily pollution and are especially applicable to subdivisions and residential zones with relatively little economic activity.

At the single-family dwelling scale, when the number of residents varies between 1 and 6, the set of analyses conducted herein has confirmed the justification of selecting the range of loads to be treated as a function of magnitude, without acknowledging the number of actual residents.

All data could be used to optimize design and operation of decentralized or small-scale wastewater treatment plant.

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DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories.

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