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Profiling wastewater characteristics in intra-urban catchments using online monitoring stations

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ABSTRACT

This study aims to investigate the differences in intra-urban catchments with different characteristics through real-time wastewater monitoring. Monitoring stations were installed in three neighbourhoods of Barcelona to measure flow, total chemical oxygen demand (COD), pH, conductivity, temperature, and bisulfide (HS^-) for 1 year. Typical wastewater profiles were obtained for weekdays, weekends, and holidays in the summer and winter seasons. The results reveal differences in waking up times and evening routines, commuting behaviour during weekends and holidays, and water consumption. The pollutant profiles contribute to a better understanding of pollution generation in households and catchment activities. Flows and COD correlate well at all stations, but there are differences in conductivity and HS^- at the station level. The article concludes by discussing the operational experience of the monitoring stations.

Key words: digitalization, real-time, sewage, sewer, smart cities

HIGHLIGHTS

- Wastewater monitoring stations were deployed in residential catchments.
- Flow, chemical oxygen demand, pH, conductivity, temperature, and bisulfide (HS^-) were monitored.
- Wastewater flow patterns are linked to socioeconomic status.
- Catchment characteristics and activities influence loads and concentrations.

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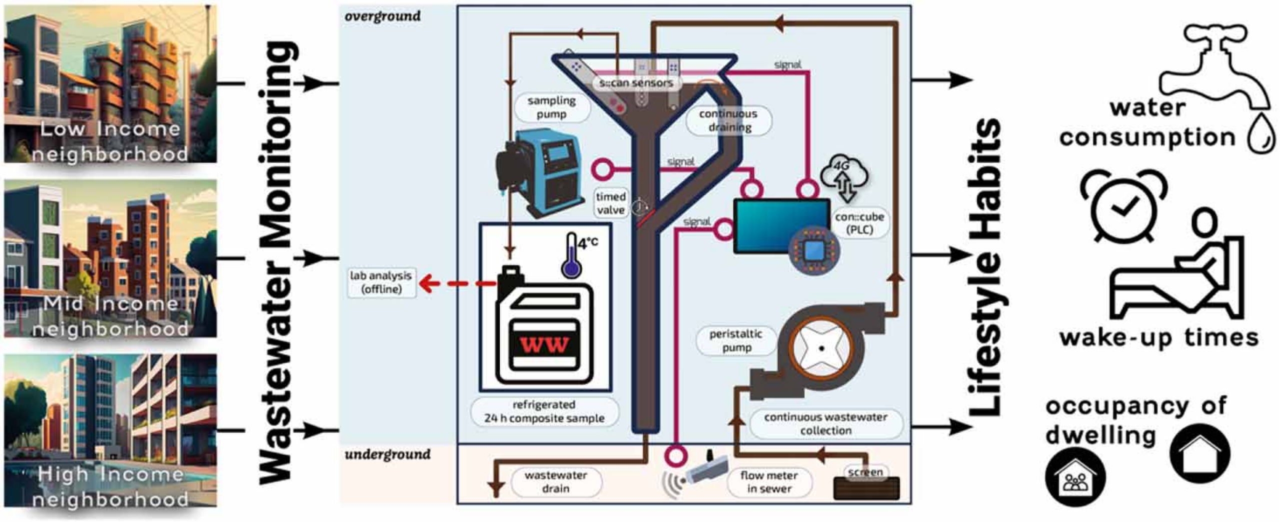
GRAPHICAL ABSTRACT



ABBREVIATIONS

Acronym	Definition
WD	wastewater discharged expressed as litre per inhabitant per day (L/inh/d)
COD	chemical oxygen demand
BOD	biochemical oxygen demand
BCASA	Barcelona Cicle de l'Aigua, S.A.
GIS	geographical information system
HS	bisulfide
INE	National Statistics Institute
S-low	low socioeconomic status subcatchment
S-med	medium socioeconomic status subcatchment
S-high	high socioeconomic status subcatchment
TSS	total suspended solids
CSO	combined sewer overflow
SES	socioeconomic status

1. INTRODUCTION

Wastewater is a byproduct of human activity, and its proper management is crucial for protecting public health and the environment. Communities generate wastewater through various applications such as toilet flushing, showering, cooking, and washing. The volume and chemical and microbiological composition of wastewater depend greatly on the habits of these communities. Moreover, during the transport of wastewater to treatment plants, issues such as sewer infiltration/exfiltration or non-residential discharges can further alter their composition. Traditionally, wastewater flows and their physicochemical characteristics (chemical oxygen demand (COD), biochemical oxygen demand, total suspended solids, nitrogen, phosphorus, pH, and conductivity, amongst others) have been monitored to ensure the effective management of urban wastewater systems. Understanding the dynamics of flows and physicochemical characteristics is crucial for the design and control of wastewater treatment plants (WWTPs) (Yuan *et al.* 2019). This is particularly important for maximizing the amount of treated wastewater while minimizing the costs involved. However, the benefits of understanding these dynamics extend beyond process optimization. Profiling wastewater from urban catchments can also provide valuable insights into the pollution habits of communities. By examining the composition of wastewater from different locations and at different times, we can gain a better understanding of the types of pollutants that are generated and their sources. In addition, such information can aid in understanding the lifestyle habits of communities, e.g. drug consumption (Daughton 2011; Escolà Casas *et al.* 2021), and their health status using chemical (Daughton 2018) and microbiological biomarkers (Medema *et al.* 2020).

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The aim of this article is to investigate differences in wastewater characteristics (flows and concentrations) from intra-urban catchments differing in socioeconomic statuses and commercial activities using monitoring stations that collect data in real time. A few studies have investigated flow dynamics at the intra-urban level. It is worth mentioning the grey literature study from Enfinger & Stevens (2013) which provides daily flow patterns from various land-use areas (residential, business, hotel, and industrial) and the study from Cipolla & Maglionico (2014) which describes flow data in five urban areas collected over 6 months and discusses the results in the frame of heat recovery solutions. Physicochemical dynamics at the intra-urban level have been studied by Penn *et al.* (2013), Rodríguez *et al.* (2013), Sharma *et al.* (2013), Atinkpahoun *et al.* (2018), all of them using grab sampling followed by laboratory analyses. Consequently, a small number of days is included in these studies (from 0.4 to 11 days) and the time resolution is rather low (from 0.33 to 1 samples per hour), which makes it difficult to extract sound and typical daily, weekly, and seasonal patterns. An online monitoring approach would be preferred instead. Advances in instrumentation over the past two decades have enabled online monitoring of flows and physicochemical characteristics, pushing forward the digitalization of the water sector (Duffy & Regan 2017; Zhang *et al.* 2020). Online monitoring has the advantage of capturing wastewater composition dynamics at reduced costs compared to grab sampling for long-term studies. While there are many online physicochemical monitoring experiences at the WWTP level (Yuan *et al.* 2019), there are just a few in sewers due to the lack of infrastructure in place. Previous studies have deployed sewer monitoring stations to estimate pollutant concentrations and loads in combined sewer overflow (CSO) structures during wet weather conditions (Gruber *et al.* 2005; Caradot *et al.* 2013; Bersinger *et al.* 2018; Maruéjouls & Binet 2018), but none have explored the full potential of characterizing wastewater under dry weather conditions and relating it to the behaviour of communities.

In this study, we installed monitoring stations in three neighbourhoods of Barcelona to measure flow, total COD, pH, conductivity, temperature, and bisulfide (HS^-) over 1 year. Well-established parameters in sewage were selected which are simple to deploy, require little maintenance, and can withstand small periods of time outside a water matrix. Dynamic profiles were gathered for these parameters from each station during weekdays, weekends, and holidays. Specifically, this article describes (1) the rationale for the three stations' site selection, (2) the components used and the station configuration, (3) results dealing with daily patterns of flows, COD, conductivity, pH, and HS^-, and (4) some insights into the operation of these stations over a year.

2. MATERIALS AND METHODS

2.1. Site selection

Three sites for wastewater monitoring were chosen from the Barcelona sewer system, which is managed by *Barcelona Cicle de l'Aigua* (BCASA), a public entity of Barcelona's City Council. The primary criterion for site selection was to cover a gradient in socioeconomic status (SES) of the sub-catchments' residents, including low-, middle-, and high-SES areas. Site selection was based on essential requirements and thresholds established for each SES category, using a geographical information system (GIS)-based socioeconomic indicator database (SI Table 1) created to characterize the entire municipality of Barcelona. The requirements included selecting residential areas with populations ranging from 5,000 to 20,000 people and minimal contributions from industrial or commercial activities and hospitals. Thresholds were also set for the number of restaurants and food services (less than 15 units per 1,000 inhabitants) and hotels (limited to 8 hotels per km^2) to minimize the influence of transitory visitors and focus on the residents. A spatial analysis was performed to eliminate areas that did not meet the requirements. The remaining potential locations were then analysed using a cluster analysis using the squared Euclidean distance measure and the Ward's criterion to identify the six areas that best met the project requirements. The sewer network infrastructure of these six potential locations was then consulted within BCASA's pre-existing GIS database and hydraulic model to identify a closed basin design and a suitable location for the sampling stations. Other practical considerations included an accessible sewer well, access to electricity, no impact on citizen mobility, and likelihood of approval from the municipal planning service. SI Table 2 presents additional information about the chosen locations. The selected stations are identified as S-low, S-med, and S-high (low, medium, and high SES, respectively). A summary of the main socioeconomic indicators of sub-catchments' residents is presented in Table 1.

2.2. Catchments and sewer network description

A description of the three catchments' characteristics is provided in Table 1. Data on the residents were obtained from the Spanish National Statistics Institute (INE) for the year 2019 (Instituto Nacional de Estadística 2019), and data on commercial activities were obtained from the census of economic activities from the municipality of Barcelona (Ajuntament de Barcelona

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Table 1 | Characteristics of the sampled areas

	S-low	S-med	S-high
Number of inhabitants[a]	18,042	8,914	5,090
Household yearly income (€/yr)[a]	25,849	38,430	78,476
Number of bars and restaurants[b]	53	89	25
Catchment area (m^2)	719,334	252,195	183,617
Pipes length (m)	11,126	6,921	3,103
Number of origin sewerholes	500	409	128
Distance from origin manholes to sampling point (m) (Q1/Q2/Q3)	484/724/894	363/583/846	190/356/459
Residence time origin manholes to sampling point (h) (Q1/Q2/Q3)	0.9/1.4/2.3	0.8/1.8/2.9	0.7/1.6/4.3
Slope of pipes (m/m) (Q1/Q2/Q3)	0.006/0.020/0.065	0.002/0.005/0.012	0.006/0.012/0.025

Note: Q, quartiles (Q1 marks the point below which 25% of the data falls, Q2 is the median, and Q3 marks the point below which 75% of the data falls); S-low, low socioeconomic status subcatchment; S-med, medium socioeconomic status subcatchment; S-high, high socioeconomic status subcatchment.
[a]INE 2019.
[b]Using commercial census from Ajuntament de Barcelona (2019).

2019). Sewer network indicators, including pipe dimensions and velocity, were obtained from BCASA. The InfoWorks hydraulic model (Innovyze) used by BCASA was utilized to calculate the distance and residence time from all potential origin manholes in each catchment to its sampling point. This was accomplished by converting the sewer network from the InfoWorks model into a graph and using graph theory algorithms to automatically generate all potential routes from sewer origins to sampling sites and estimate the required metrics. Further details on this methodology can be found in the supplemental information. Data on domestic and commercial drinking water consumption from 2019, aggregated by postal code, was provided by Aigües de Barcelona.

2.3. Monitoring stations' components and setup

Each of the three stations was set up nearly identically. All equipment was housed in a stainless cabin measuring $2 \times 1.4 \times 2$ m and installed at street level near a sewerhole. Figure 1 depicts a graphical representation of the stations, while SI Figure 1 depicts a photograph of one of the actual setups and SI Table 3 lists all the station components. Following there is a description of the hydraulic circuit, the water quality sensors, the sampling system, the controller, and the flowmeters.

2.3.1. Hydraulic circuit

To prevent clogging, a PVC cylindrical screen (1 m long and 110 mm diameter) with 25 mm diameter holes was installed in the sewer. The screen was connected to a 32 mm diameter plastic tube (with 8 mm holes in the last 1 m) and the AMP-22 peristaltic pump (Boyser, Spain) in the cabin, which continuously fed wastewater to a 12 L acrylic glass reservoir. The reservoir was constantly emptied via a drain at the top. The hydraulic retention time of the circuit, including the reservoir, was approximately 2 min. An automatic maintenance routine was performed twice a day, which involved emptying the reservoir to remove accumulated large particles. The peristaltic pump was then run in the opposite direction (reservoir to sewer) for 5 min to flush the sampling tube before refilling.

2.3.2. Water quality sensors

Online sensors from *scan GmbH* (Austria) were installed within this reservoir to measure well-established parameters in sewage: (i) conductivity and temperature (condu::lyser), (ii) CODeq and bisulfide (HS^-) (spectro::lyser, an optical spectrophotometric probe, active in the UV-visible range), and (iii) pH (pH::lyser). The measuring frequency was set at 3 min for all sensors. While all sensors were subject to automated cleaning using compressed air, the spectro::lyser received additional mechanical cleaning using the s::can ruck::sack, which is a submersible automatic brush cleaner.

2.3.3. Sampling system

A stainless-steel cylindrical screen with 2 mm diameter holes and pressurized air cleaning was placed in the reservoir and connected to a qdos30 peristaltic pump (Watson Marlow S.L.U., Spain) to collect samples and store them in a small fridge installed in the cabin. The prefilter was cleaned automatically with compressed air.

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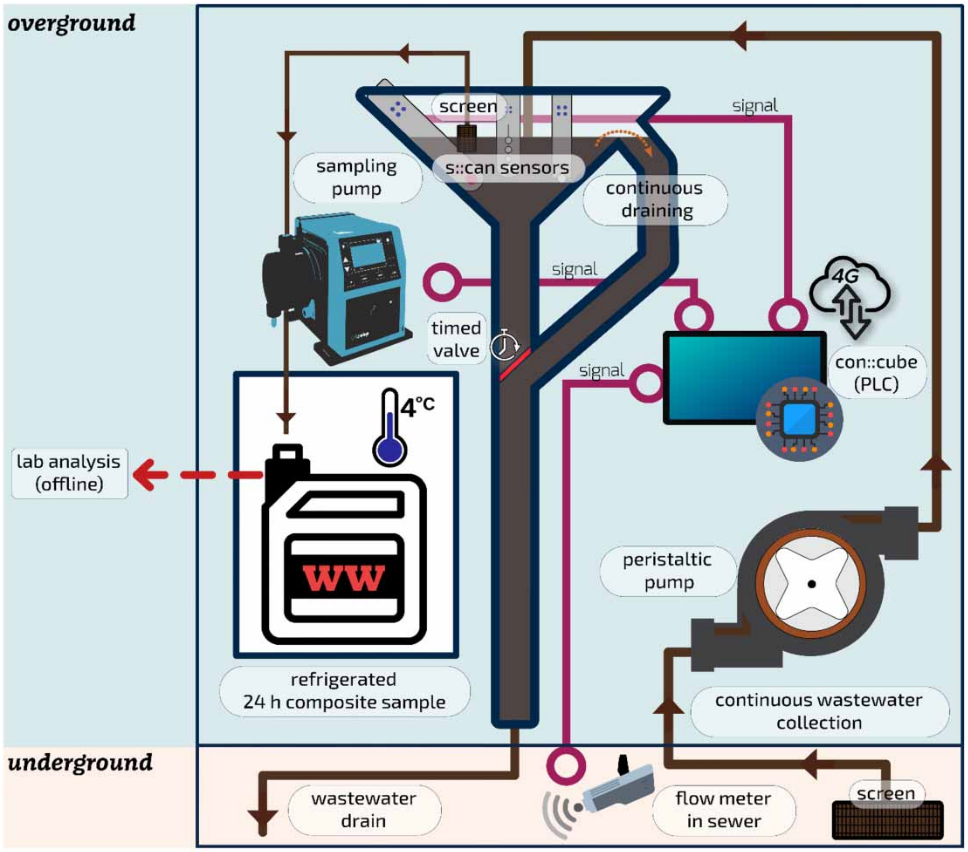

Figure 1 | Overview of the components making up the stations (the hydraulic circuit starts from the bottom right).

2.3.4. Controller

The con::cube PLC unit (*scan GmbH*, Austria) controlled these sensors as well as the actuators for emptying-filling cleaning cycles, allowed remote connection using a 4G modem, uploaded data via ftp to the SCOREwater data storage platform (https://tst-scorewater.dataplatform.eu/#/home), and managed other equipment such as the sampling pump and activated compressed air cleaning cycles.

2.3.5. Flowmeters

Flowmeters were installed into the sewer system at each of the stations to measure the flowrate. A Nivus PCM4 (Eppingen GmbH, Germany) with a submerged ultrasonic combi sensor was installed at station S-low. The FLO-DAR AV (Hach, Colorado, USA), equipped with a contactless radar-based sensor for velocity and a contactless ultrasonic sensor for level, was used at S-med. Initially, station S-high utilized the SIGMA 950AV (Hach, Colorado, USA) with a submerged Doppler sensor (from March 2021 until October 2021). On 20 October 2021, it was replaced with a Nivus NFM-550 (Eppingen GmbH, Germany) which uses contactless velocity and level (Nivus OFR) sensors, increasing the quality of the obtained velocity and level signals by avoiding sensor clogging and drifting.

The S-mid station was deployed in November 2020 and the other two in February 2021. The study period is from March 2021 to March 2022.

2.4. Sampling stations maintenance

Weekly maintenance was conducted at each of the three stations, involving accessing the sewer to clean the prefilter and remove any solids that may clog the hydraulic system. Operators manually cleaned the wastewater reservoir within the cabin and the sensors. Maintenance required a team of four people as stated in the health and safety measures from BCASA and lasted approximately 90 min per station. Following the collection of each offline sample onsite, the sampling

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pumps were cleaned by reverse pumping tap water, and the clear silicone tubing was mechanically cleaned as needed. The number of maintenance visits per station can be found in SI Table 4 and the maintenance log file in SI.

2.5. Costs

The station design, construction, and component procurement occurred between late 2019 and early 2020. Each fully equipped cabin incurred a cost of €51,527. Stations were built off-site in a mechanical workshop and transported fully assembled. After minor construction work to connect electricity and plumbing, they were installed at their designated locations. Installation costs comprised station placement, electrical wiring, hydraulic tubing, and onsite construction work (such as constructing a concrete base for the station and drilling to access the sewer and electrical connections). The first year of operation required a yearly cost of €15,057 per station. Cost details are presented in SI Table 5.

2.6. Sensors calibration and verification

Wastewater grab samples were collected at the stations and analysed in the laboratory (lab) using WTW WT 252,070 kits to calibrate three COD sensors. Spectro::lyser readings were compared to lab values, and a calibration curve for each station was generated and applied (SI Table 6); r^2 of the curves were 0.83, 0.89, and 0.80 for S-low, S-med, and S-high, respectively. The s::can pH and conductivity sensors were calibrated on-demand with monthly checks with hand-held sensors from Hanna Instruments (UK). The maximum accepted deviation tolerance was ± 0.1 for pH and 3% for conductivity. HS^- was factory calibrated.

The flow sensors were adjusted after sewer operators measured the sewer level just after installation, with an offset. Regular level measurements were taken during maintenance activities to ensure that the deviation was less than 25% (generally accepted errors for flowmeters measuring in sewers). The median deviation between sensor level and manually measured levels was 25% in S-low, 6% in S-med, and 23% in S-high. For velocity validation, the hand-held sensor SonTek FlowTracker (YSI, US) Doppler flowmeter was used shortly after installation. The measuring focal point of this device is 10 cm from the sensor limiting its use to only S-med because the two other stations had a narrower cross-section. In the other two stations, a more rudimentary validation was performed by using a floating object and measuring the time it took to travel a known distance, which was repeated six times. The measurement deviation between flowmeter velocity and *in situ* test was less than 30% in S-low and S-med (the standard deviation was 66% of the mean value for the six replicates of the manual verification, so not the most accurate validation but the best available). The deviation of velocity in S-high was smaller than 5%.

2.7. Data treatment and reconciliation

The data from each station were regularly exported as a CSV file from the station's con::cube. The CSV files contained individual measurements taken every 3 min and were processed using custom Python V3.9.1 code and libraries including *pandas*, *matplotlib*, *seaborn*, *numpy*, *numba*, *scipy*, *itertools*, and *functools*. The Python code was used to merge the data series over a specified period, check for irregularities, compute flow and loads, and generate dynamic plots. The COD loads were estimated by multiplying the COD concentrations by flows and dividing the values by the number of inhabitants of each neighbourhood; these load calculations were carried out for winter time to avoid variations due to holiday periods. Manual data labelling was conducted on daily profiles of flows and the water quality monitoring setup; the latter was based on the analysis of COD daily profiles only on dry weather days, with rainy days excluded. Three independent experts conducted labelling of the data quality into three categories: very good (typical daily profile), acceptable (daily typical profile with slight deviations, lasting less than an hour or occurring during low flow periods or at night with increased noise), and not acceptable (profiles with values outside the typical range, with drift, shift, or significant noise). Daily COD profiles labelled as not acceptable can indicate issues with the hydraulic system affecting sensor readings, such as an empty reservoir. The results of data labelling are provided in SI Table 7. Metadata on the maintenance actions executed on the stations, including start and end times, are provided as supplementary material, along with the data labelling for flows and water quality setups. Any posterior results analysis was based only on the data from the good and acceptable days.

A thorough data analysis was conducted, including the detection and elimination of irregularities such as missing data points, drift and shift, intercepted data points, and outliers. Rainy days were excluded from the analysis. Outliers were removed using the interquartile range (IQR) method, by defining the normal data range with a lower limit as $Q1-1.5 \times IQR$ and the upper limit as $Q3 + 1.5 \times IQR$. The relevant drifts were identified and eliminated using trend and fast Fourier transform analysis, resulting in a reconciled homogenous dataset from which plots were generated and other parameters were computed. Flow was calculated using the velocity of the wastewater, column height, and cross-sectional area of each measuring point. Typical daily

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patterns for flows and water quality parameters were extracted from the time series. The main functions employed in the process were pandas' 'apply', 'resample', 'mean', and 'map', along with seaborn's 'lineplot' for visualization purposes. Correlations were estimated between flow, COD, pH, and conductivity observations for the entire study period and using the Pearson method in the 'cor' function in R. Additional information about data processing can be found in the SI section *Additional details on data processing*. Furthermore, part of the data analysis was conducted on summer and winter data, which respectively spanned from 21 June 2021 to 23 September 2021, and from 21 December 2021 to 20 March 2022.

3. RESULTS

3.1. Flow dynamics and variation between different days

Figure 2 illustrates the flow dynamics obtained from the three stations. The results reveal interesting patterns related to the behaviour of the inhabitants. For example, the morning peak of wastewater discharge occurs earlier on weekdays than on weekends (Figure 2, Column 1). While the peak on weekends is around 12:00 PM in all three neighbourhoods, the peak on weekdays is at 07:30 AM in S-low, 09:00 AM in S-med, and 10:00 AM in S-high. In addition, the evening peak is much less pronounced in S-high than in S-low and S-med. In S-low and S-med, the evening peak reaches values similar to the morning peak, but not in S-high where the evening peak flow is approximately half of the morning peak. The weekend afternoon flow peak is slightly higher than weekday afternoons at the same time.

Regarding seasonal differences, winter flows are higher than summer flows in S-low (0.024 versus 0.019 m^3/s on average) and S-high (0.00860 vs 0.00864 m^3/s) (Figure 2, Column 2), but not in S-med (0.018 versus 0.023 m^3/s). The summer peaks in S-low and S-high are less intense than the winter ones, while in S-med, the summer peak (at 11:40 AM) occurs 1 h and 10 min later than the winter peak (at 10:30 AM). Although the number of inhabitants connected to S-low (18,042) is higher than that of S-med (8,914), flow rates are similar in both stations, ranging between 0.01 and 0.032 m^3/s. Conversely, flow rates in S-high are about half of those in S-low and S-med, ranging between 0.004 and 0.016 m^3/s.

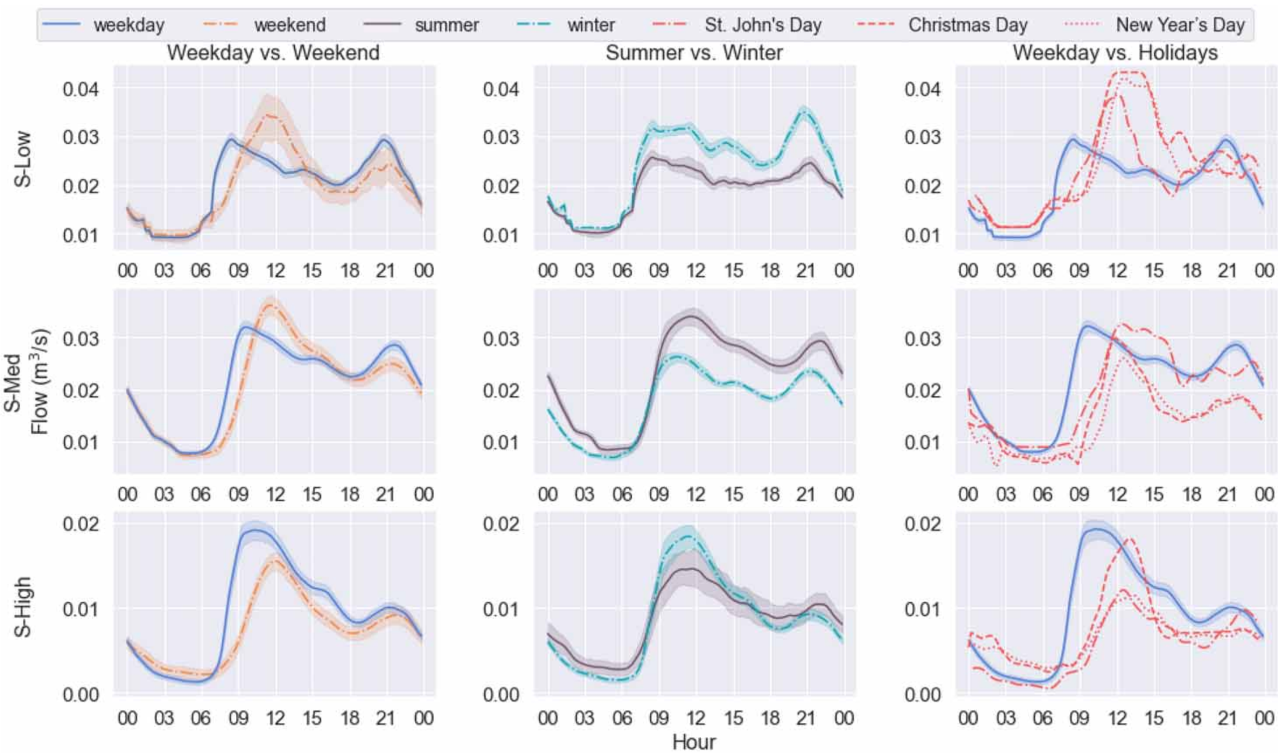

Figure 2 | Flow daily dynamics – each line shows averaged flows of multiple days over 24 h. *Column 1* shows differences in dynamics between weekdays and weekends. *Column 2* shows differences in dynamics between summer and winter days. *Column 3* shows differences between the average of a weekday and holidays (Christmas Day 25 December 2021, New Year's Day January 2022 and St John's Day ('Dia de Sant Joan' 24 June 2021, a very popular holiday in Barcelona).

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Column 3 of Figure 2 shows the flow patterns during three different holidays, which differ significantly from a typical day. The peaks for Christmas Day and New Year's Day in S-low were also larger than those for any other day, but not for St. John's Day. During the holidays, different dynamics were observed in S-med and S-high. In S-med, the flow on Christmas Day and New Year's Day was lower than on any other day, and the flow on St. John's Day was similar to a typical weekend day. In S-high, the peak of Christmas Day was larger than St. John's and New Year's days.

Figure 3 shows the differences in daily wastewater discharged volumes between the three neighbourhoods, excluding rainy days with more than 1 mm precipitation from the analysis. The means of the three neighbourhoods were statistically different (p-value 2e-16). S-low had the lowest wastewater discharge per capita at 109 L/d/Inhabitant, while S-med had the highest volume discharge at 183 L/d/Inh. S-high had an intermediate wastewater discharge of 141 L/d/Inh. We observed statistically significant differences in the average weekday and weekend volumes in S-high (p-value 0.01) and in the average volumes of working days and holidays in S-med and S-high (p-values of 0.01 and 0.03, respectively).

3.2. Conductivity, COD, and HS^-

Figure 4 shows conductivity, COD, and HS^- dynamics in the three stations. The conductivity patterns differ greatly between stations. S-low and S-high have the smallest intra-diurnal variation, with minimum-maximum ranges of approximately 500 μS/cm. S-med has much greater intra-diurnal variation, with peaks around 4,500 μS/cm at 6 AM (coinciding with the low flow periods). COD concentrations are largest in S-low ranging between 500 and 1,100 mg/L, followed by S-med and S-high ranging between 400 and 800 mg/L. COD patterns mimic those observed for the flows; interestingly, there is no difference between summer and winter. While the morning COD peak in S-low is at around 9 AM, it is a bit later (around 11 AM) in S-med and S-high. HS^- concentrations range between 1 and 4 mg/L in all stations during winter time. However, in summer at S-med, HS^- concentrations are much higher ranging between 4 and 7.5 mg/L. In all stations, the temperature daily profiles show a decrease during night hours; higher temperatures are observed during the summer relative to winter by approximately 8–9 °C. Temperatures in S-low are about three degrees lower than in the other two stations (this station is more inland and at a slight elevation). pH patterns are similar across stations with a peak in the morning, on average an hour earlier than the COD. pH is about 0.5 units lower in S-low than in the other two stations. The estimated COD per capita loads were found to be 106 g COD/Inh/d in S-low, 111 g COD/Inh/d in S-med, and 101 g COD/Inh/d in S-high. SI Table 8 presents a summary of the data for winter and summer as well as weekdays and weekends.

3.3. Correlations

Table 2 presents the correlations among flow, COD, and pH. The results indicate the strongest correlations between COD and flow variables, with coefficients ranging from 0.47 to 0.69. The highest correlation is observed in S-med, with a lag time of 20 min (representing the delay of COD relative to flow). Conversely, pH demonstrates relatively weak correlations with both

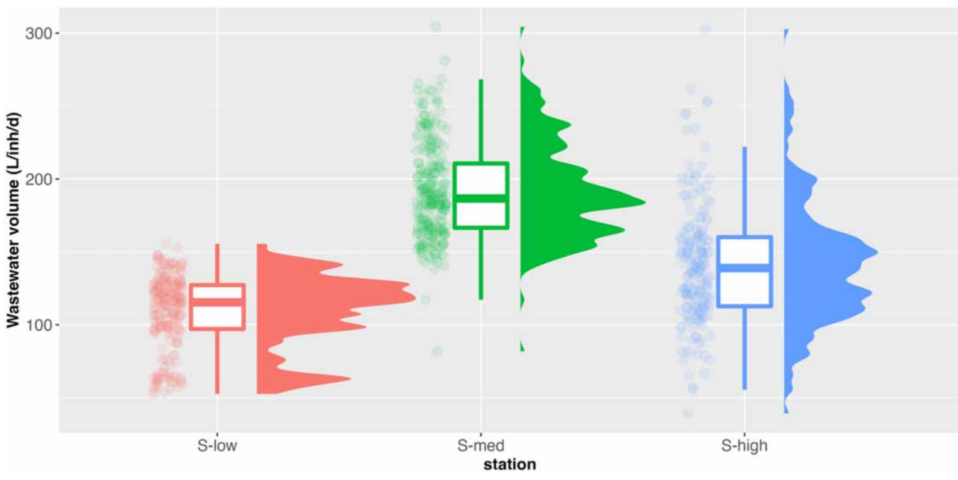

Figure 3 | Box plot with individual points in semi-transparent points to the left and a distribution plot to the right showing normalized wastewater discharge per capita in the three stations.

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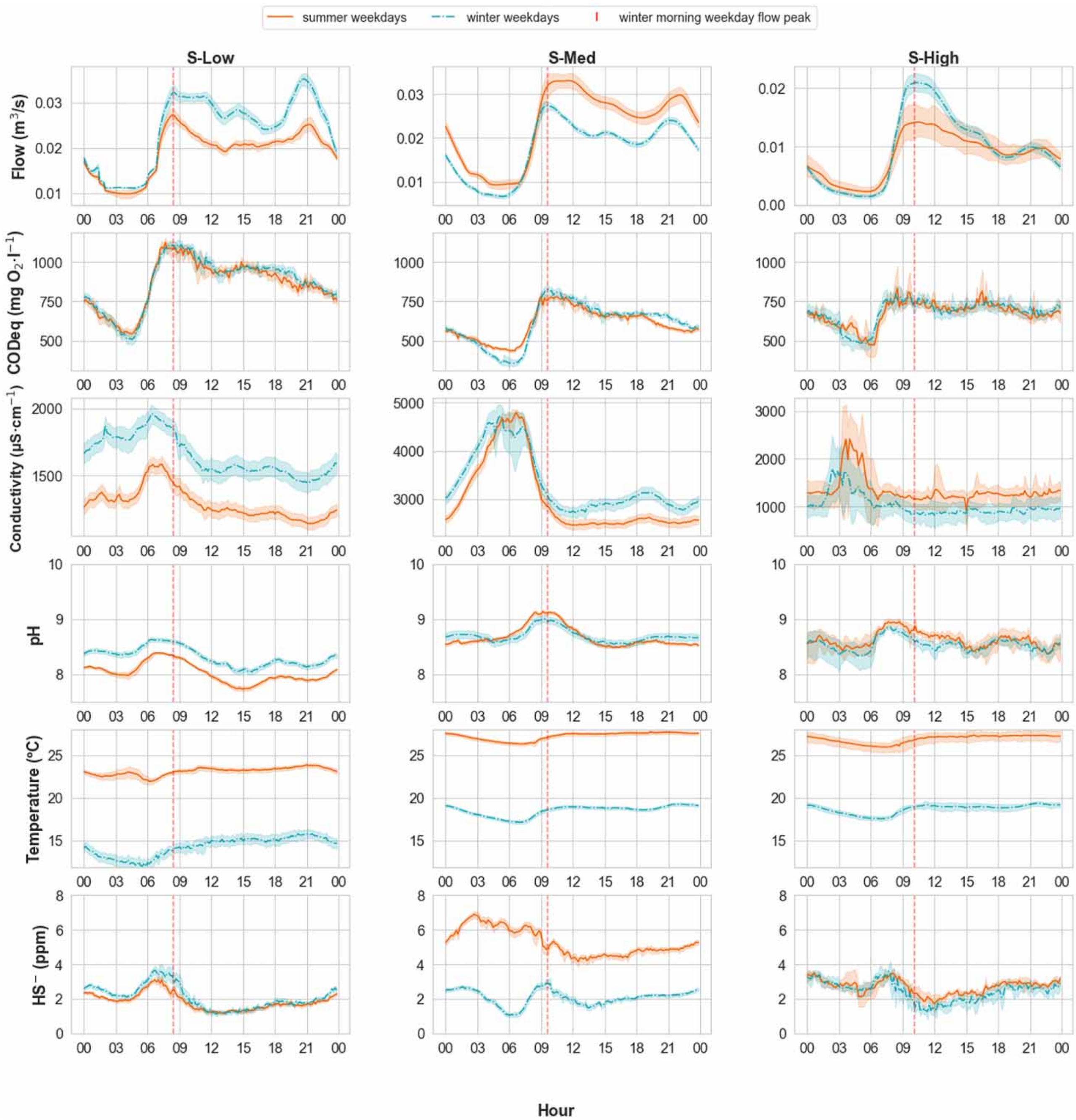

Figure 4 | Dynamics of chemical oxygen demand (CODeq), conductivity, pH, temperature, and HS^- measured at the three stations; each line shows averaged values of multiple days over 24 h.

Table 2 | Pearson correlation calculated at the lag time (in brackets) that yields the maximum correlation

Variables	S-low	S-med	S-high
COD versus flow	0.54 (40 min)	0.69 (20 min)	0.47 (90 min)
pH versus flow	0.18 (170 min)	0.32 (130 min)	0.29 (170 min)
pH versus COD	0.13 (90 min)	0.26 (90 min)	0.18 (50 min)

Correlation is between variables in the three neighbourhoods using all observations from the dataset. Positive lag times were evaluated (lag of left variable as compared to the right variable in the 'variables' column) ranging from 0 to 180 min at 10 min intervals.

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COD and flow, exhibiting coefficients ranging from 0.13 to 0.32. Notably, there is a lag between pH and COD, spanning 50–90 min, while the lag between pH and flow is even more substantial, ranging from 130 to 170 min.

4. DISCUSSION

In this article, we demonstrate the utility of wastewater monitoring stations for profiling wastewater characteristics at the intra-urban level using online sensors. Hereby, we discuss the extraction of information on citizens' habits and the profiling of domestic sewage from different catchments in the same city.

4.1. Understanding flow patterns

Different flow patterns are observed between surveilled intra-urban catchments. S-low and S-med follow the typical flow pattern of residential areas, when comparing to the typical profiles shown by Enfinger & Stevens (2013) (provided in SI). Nevertheless, the S-high flow profile is a bit special for two reasons: (i) the evening peak is much less pronounced than in S-low and S-med and (ii) the weekend curve in S-high never crosses the weekday curve. The morning peak on weekdays is 1 h earlier in S-low when compared to S-med and 2 h when compared to S-high; note that the hydraulic residence times between point of wastewater generation and sampling points are similar across neighbourhoods (median of 1.4, 1.8, and 1.6 h in S-low, S-med, and S-high, respectively). The evening peak is as well earlier in S-low as compared to S-med and S-high. At all stations, a delay of the first daily peak is observed on weekends in comparison to weekdays, as previously documented in the literature (Butler 1993; Cipolla & Maglionico 2014; Atinkpahoun *et al.* 2018).

In S-low, it was found that wastewater discharge was similar during weekdays and weekends and during large family celebrations days, and wastewater discharge decreased only during the summer months. Probably such wastewater discharge patterns are associated with mobility patterns from the catchment residents. In S-med, it was observed that wastewater discharge is similar during weekdays and weekends, and during the celebration of St. John's Day, but during the summer months, there is more wastewater discharge happening in the neighbourhood. S-med is a beachfront neighbourhood that is likely to receive more visitors than S-low and S-high, which are predominantly residential. This is probably due to S-med's location nearby a popular tourist area, which attracts more people during the summer months. In S-high, it was observed that wastewater discharge is lower during weekends as compared to weekdays, probably indicating weekend mobility of their inhabitants. This pattern also applies during the summer months and all holidays, except for Christmas Day. The Ownership of second homes in Catalonia is closely linked to SES, with approximately 31% of residents earning a monthly net income higher than 5,000€ reported to possess a second home (Instituto Nacional de Estadística 2021). In the city of Barcelona, it was found that 33% of individuals belonging to a high SES own a second home located outside the city (Ajenjo & Alberich 2006). These properties serve as retreats for weekend getaways, holiday destinations, and summer retreats.

It is possible to contrast these wastewater discharge volumes against drinking water consumption volumes. Aigües de Barcelona S.A. provided drinking water consumption from 2018 aggregated per postal code from Barcelona. The median drinking water consumption (the sum of domestic and commercial activities) was estimated per postal codes related to each of the three sampling points. Wastewater discharge volumes per capita are the highest in S-med, followed by S-high and S-low (183, 141, and 109 L/inh/d, respectively). When contrasting against drinking water consumption this order remains; S-med is the neighbourhood with the largest drinking water consumption (165 L/inh/d) followed by S-high (146 L/inh/d) and S-low (125 L/inh/d). Moreover, the analysis of drinking water consumption exclusively from domestic sources reveals a correlation with SES, with S-low, S-med, and S-high recording values of 100, 114, and 119 L/inh/d, respectively. The higher overall drinking water consumption in S-med is primarily attributed to its greater number of commercial activities, which account for approximately 30% of the total water consumed in the neighbourhood. It is important to acknowledge that the correlation between drinking water and wastewater volumes can be influenced by other factors, including infiltration or phreatic drains. Within the scope of this study, BCASA informed us that phreatic drains occurred in short periods of time in S-med, resulting in an approximate daily impact of 400 m^3, which accounted for approximately 20% of the total daily flow.

4.2. Profiling domestic sewage from different catchments in the same city

Our analysis reveals that the flow and COD dynamics are similar across stations, but the magnitude of COD concentrations varies depending on the dilution of the domestic discharge with other sources. Station S-low had the highest COD concentrations, and it is also the one having the lowest wastewater discharge volumes. On the other hand, S-med had lower COD

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concentrations compared to S-low and coincided with the largest wastewater discharge volumes. This can be attributed to S-med having the largest drinking water consumption due to commercial activities which results in increased grey water discharge. It could as well be attributed to S-med being a beachfront neighbourhood that experiences phreatic infiltration of seawater through the bedrock, which is eventually pumped up from construction zones and garages and discharged into the sewer, raising conductivity. As an example, a construction zone in S-med had a permit from the City Council to discharge water to the sewer from April to May 2021. The permit allowed the construction company to discharge 400 m^3/d of water at a maximum conductivity of 20,000 μS/cm. Such discharges affect conductivity in S-med, which reaches values of up to 5,000 μS/cm when the flow is the lowest. In contrast, S-high had similar COD concentrations as S-med, had relatively higher wastewater discharge volumes, and did not receive phreatic drains or saline water discharges.

Our analysis reveals that the COD load per capita and per day fall within the ranges suggested in the literature is 25–200 g COD/inh/d (Lens *et al.* 2015), but are slightly lower than the default value of 130 gCOD/Inh/d as suggested by Volcke *et al.* (2020). It is worth noting that the sampling was conducted at the neighbourhood level with minimal industrial activity and in a city that is dedicated to public awareness of proper waste management habits, particularly those concerning oils discharge to the sink. The slightly higher loads observed in S-med may be attributed to the mass of oils and greases discharged from bars and restaurants. The values presented in SI Figure 2 indicate that S-low and S-med receive the discharge of 71 and 48 kg oils and greases per day, respectively, significantly higher than the value for S-high (26 kg/d); when normalizing per inhabitant, the loads per capita are 4, 5.4, and 5.1 g/person/day, respectively, in S-low, S-med, and S-high. By using the estimated COD per capita loads from winter, it was possible to estimate the change in population during summertime. Our analysis shows a decrease in population of 23 and 11% in S-low and S-high, respectively, and an increase of 28% in S-med.

In terms of flow, COD, pH, and conductivity daily dynamics our findings are in agreement with those from Atinkpahoun *et al.* (2018), which analysed 11 daily profiles using grab samples and concluded that COD and ammonium exhibit diurnal variation, in contrast to pH and conductivity. In our study, COD and flow correlate reasonably well with lag times ranging from 20 to 90 min. pH and conductivity showed a weaker correlation with either flow and COD. In the study by Sharma *et al.* (2013), an in-depth analysis of a 10 h profile (from 4 AM to 2 PM) was conducted by collecting grab samples and observed a correlation (R^2 using linear regression, not Pearson) between pH and COD with a 1-h lag time of 0.52, and a correlation of 0.51 between pH and flow. Rodríguez *et al.* (2013) collected 29 daily profiles (using grab samples) and observed very similar dynamics for flows and COD, with a single morning peak. While the flow data exhibit a double peak – both in the morning and evening, the COD only aligns with the morning peak. This discrepancy, where the evening peak does not correspond, affects the overall correlation. Despite a strong correlation observed during the morning peak, the divergence in the evening peak limits the overall correlation between the two variables.

Flow, conductivity, and HS^- showed significant differences between the summer and winter seasons in our study. Discharged wastewater volumes were lower in the summer compared to winter at S-low and S-high, but higher at S-med. Conductivity in S-low was lower during the day in summer and higher at night, while in S-med, conductivity showed a higher peak at night and was slightly higher overall during summer. HS^- concentrations increased at S-med during summer, likely due to the effect of temperature on sewer-biological processes (Sharma *et al.* 2013), as evidenced by a correlation with sewage temperature (SI Figure 3). Sewage velocity was the slowest in S-med (median of 0.12 m/s) compared to S-high (0.19 m/s) and S-low (0.23 m/s). In contrast to our findings on conductivity and HS^-, we found no significant differences in COD concentrations between summer and winter seasons. Our study adds to the existing literature by generating continuous data over a 1-year period for three sub-catchments with different socioeconomic statuses.

4.3. Operational experience

During a 1-year operating period, wastewater quality monitoring in S-low and S-med stations demonstrated good performance on 61 and 71% of the days, respectively (see system performance and data quality sections in SI). However, the performance of S-high was relatively poor, with 71% of the daily profiles deemed unacceptable due to visually identified periods of malfunctioning during some parts of the daily profiles. These deviations included excessive noise or positive drift caused by increased sediment accumulation in the reservoir, negative drift during periods without wastewater renewal in the reservoir, and shift obtained when the tank was empty. Nevertheless, the good and acceptable days in S-high (29%) were sufficient to achieve the goal of the study and capture the daily dynamics during dry weather conditions. The problems in S-high were resolved as the study progressed, with positive drift due to solids accumulation minimized by emptying the tank twice a day. The remaining issues were addressed by improving the hydraulic circuit, including stronger fixation of the screen at

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the bottom of the sewer and increasing the amount of holes in the tubing. It may have been beneficial to install a platform downwards of the pumping point with a slope of less than 20%, as observed in the setup in Graz, Austria, by Gruber *et al.* (2005). This would have raised the wastewater level at the pumping point and improved the hydraulic circuit's performance during the night. Mechanical cleaning of spectrolyzers prevented drift caused by sensor fouling from occurring. In the first few months of operation in S-med (November 2020 to March 2021), pressurized air cleaning was utilized, but drift was frequently observed. Drift was eliminated by installing mechanical brush cleaners on the spectrolyzers and combined with pressurized air cleaning.

The importance of monitoring wastewater throughout the sewage network, rather than solely at the inflow of a WWTP, has been previously recognized, and various monitoring stations have been constructed for different purposes beyond the scope of this study. The most commonly studied application is the monitoring of pollution loads during CSOs (Gruber *et al.* 2005; Caradot *et al.* 2013; Bersinger *et al.* 2018; Maruéjouls & Binet 2018). Rieger & Vanrolleghem (2008) describe a versatile system for monitoring different water types. These previous studies seldom analyse dry weather pollution patterns, as their goal is to assess conditions during wet weather. The generated data can help make more accurate models to simulate flows, pollutants concentrations, and loads from urban areas, which are normally calibrated using grab or composite samples (Langergraber *et al.* 2008; Martin & Vanrolleghem 2014). The stations proposed in this study provide real-time profiling of domestic sewage from catchments and can be further used to detect anomalies in system performance, such as sudden increases in COD loads or conductivity. Water companies can use these stations combined with advanced data analysis tools to understand catchment activities and detect potential incidents and deviations from normal catchment behaviour. Furthermore, the monitoring of HS^- concentrations might anticipate odour problems. While we acknowledge that the design of the stations could be optimized to reduce operating and capital expenditures, it is difficult to envision a portable setup that can function at the intra-urban level without adequate infrastructure to support and protect it. It is worth noting that the proposed setup did not experience any instances of vandalism at any of the sampling points.

5. CONCLUSIONS

Real-time monitoring of flows and physical-chemical parameters has allowed us to profile wastewater from three intra-urban catchments in Barcelona. The following conclusion can be drawn on the wastewater discharges:

- Morning and evening flow peaks were earlier in S-low as compared to S-middle and S-high.
- S-low and S-middle communities behave purely as residential areas, while the high-SES community (S-high) has a smaller flow peak in the evenings.
- In S-high, wastewater discharge was significantly lower during weekends and holidays.

The pollutant profiles we have obtained contribute to a better characterization of pollution generation in residential catchments:

- Flows and COD signals correlated well in all stations.
- Low correlations were obtained for flows and pH or conductivity.
- The estimated COD per capita loads were similar across stations ranging from 101 and 111 g COD/Inh/d.
- At the beachfront station, S-med, conductivity values around 4,500 μS/cm were observed at 6 AM coinciding with the period of low wastewater flow, which resulted in seawater infiltration.
- HS^- concentration in S-med was highly correlated with temperature.

Finally, the wastewater monitoring stations operated well during the 1-year period with one maintenance action per week.

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CREDIT AUTHOR STATEMENT

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DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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