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Analysis of the effects of COVID-19 restriction policies on drinking water consumption by smart water network data filtering

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ABSTRACT

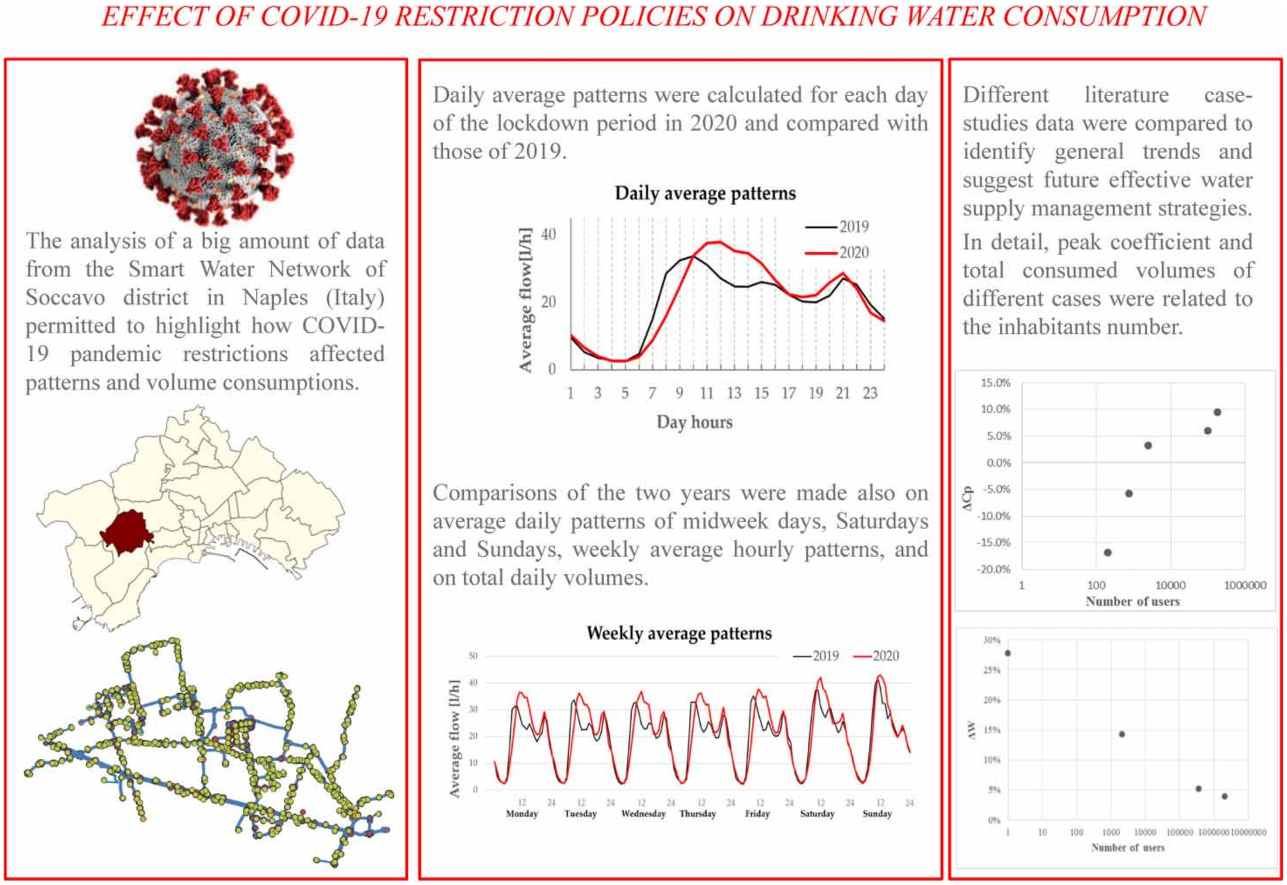
People's habits changed during the COVID-19 pandemic and the consequent containment policies, with numerous implications in all fields. In particular, restrictions had important consequences for drinking water consumption. The present work analyses this influence in the Soccavo district of Naples (Campania), in Italy, during the two periods of strongest restrictions in 2020: the national Lockdown (March 11–May 3) and the autumn Red Zone (November 16–December 6). A large amount of data, referred to single-household flowmeters connected to a Smart Water Grid acquisition system, was collected for the years 2019 (considered the average reference year) and 2020. The first step was the preliminary filtering of the data, by identification and elimination of anomalies and outliers, as well as anomalous annual patterns, through clustering and classification. The second step consisted of the comparison of the same meters in two consecutive years considering the daily and weekly average hourly patterns, the average daily patterns of midweek days, Saturdays, and Sundays, respectively, and the total daily volumes. The results are consistent with those in the literature. Some general trends in literature data were sought and pointed out in the present paper.

Key words: COVID-19, residential water consumption, Smart Water Grid, time series, water demand, water system management

HIGHLIGHTS

- The work focuses on the consequences of COVID-19 containment policies on drinking water consumption.
- Analysis of Soccavo district (Naples, Italy) data showed how restrictions affected patterns and increased volume consumption.
- Literature data comparison revealed that the peak coefficient increased more for big cities and volume consumption more for small cities.
- Results provide counsels to manage future critical situations.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The COVID-19 pandemic and the consequent containment policies have changed people's habits. On March 11, 2020, the WHO (World Health Organization) defined COVID-19 as a pandemic. Starting from this date, most of the world's countries implemented lockdown policies such as limiting all non-essential activities and forcing the population, as far as possible, to stay at home. In particular, in Italy, starting on March 11, 2020, and for 54 days, a national lockdown came into effect, which imposed the closure of all retail commercial activities and catering services, the suspension of all educational activities at all levels, the ban on leaving one's own municipality except for proven work reasons of absolute urgency or health needs.

For the Campania region, the worsening of the epidemiological situation in the autumn also led to further tightening of the measures with respect to the national easing, setting the so-called 'red zone' for three weeks in the period from November 15 to December 6, 2020, with some changes in the restrictions compared with the first lockdown, but with the substantial closure of the main activities considered non-essential (commercial, educational, and leisure), the prohibition of travel outside the municipality of residence if not necessary and a curfew from 10 pm to 5 am.

In general, during periods of restrictions implemented by governments to prevent the spread of the infection, activities that were previously carried out outside, including work, physical activity, or recreation, were relocated indoors or suspended.

COVID-19 and the impact of restriction policies have been widely studied in various disciplines. According to Ji *et al.* (2021), more than 200,000 articles on aspects of COVID-19 were published in 2020.

This research work aims to understand the impact in terms of water consumption caused by the pandemic, tracking the effect of the different restriction levels imposed during 2020.

Water demand in an urban context, which includes domestic and collective consumption, is influenced by multiple causes, such as socio-economic factors, water cost, geographical conditions, air temperature, rainfall, and other climate-related variables. It changes from user to user, in accordance with lifestyle habits, conditions of the water distribution system, and house composition; for the individual user it can change during the days, weeks, seasons, differently according to weekdays, holidays, day and night hours, and hot and cold seasons.

In recent decades, European policies and directives had water demand as the central topic, with the aim of guaranteeing to the population safe access to drinking water and the use of basic sanitation. In an urban context, the modeling of drinking water demand is crucial for efficient water management. It helps water companies to correctly plan water supply, to estimate losses in the distribution network and to develop criteria, innovative approaches, and attractive plans for users (Padulano & Del Giudice 2018). This interest in drinking water management has led to the implementation of Smart Water Networks (SWNs), which allows for the smart-meter recording and storage of data about water flows for significant portions of consumers. The raw data permit other information to be easily obtained, such as total daily volume, minimum hourly flow, and monthly and average daily flow rates. This also helps planning for the future as it is possible to forecast the water demand in distribution systems in the short, medium, and long terms.

The literature offers different studies on the relationship between COVID-19 and water demand. Most of them show an increase of the total volumes of domestic water consumption with the pandemic restrictions. A comprehensive review about water consumption during the pandemic was published by Cahill *et al.* (2022). In Bangladesh, a quantitative study was conducted which showed an increase in water volumes of individual users compared with the pre-pandemic period of about 14.9 l per capita (Sayeed *et al.* 2021). Dzimińska *et al.* (2021) analyzed data from three buildings in Poland by clustering to identify daily patterns of water needs, which showed, in the period of the pandemic compared with the previous period, an increased use of water between 2 and 4 pm, a decrease in evening consumption, a shift in the morning peak from 7 to 9 am during working days, and an increase in the consumed water volumes. Abu-Bakar *et al.* (2021) examined the water consumption of 11,528 households located in the south and east of England, during 20 weeks from January 2020, and identified four patterns of daily hourly consumption that did not vary with the lockdown, whereas the percentage of homes present in clusters and the average daily consumption changed (+46%). Kalbusch *et al.* (2020) examined consumption data from the city of Joinville in southern Brazil for residential, commercial, public, industrial uses. Analyses revealed a sharp decrease in consumption in the industrial (−53%), commercial (−42%), and public (−30%) sectors, linked to the suspension of all non-essential activities, an increase of 11% for residential consumption, and a 17% decrease in total city consumption during the COVID-19 lockdown period. Lüdtke *et al.* (2021) found for the metropolitan city of Hamburg in Germany, during the restrictions imposed by COVID-19, an increase (+14.3%) in water consumption compared with the one recorded in the same period in previous years, and on weekdays a shift of the morning peak from 7 to 9 am. The article also investigates, through the results produced by a previous study (Alda-Vidal *et al.* 2020), the possible causes of this increase in consumption, identifying five factors plus a sixth that encompasses them: time (the use of services has undergone a change by modifying the daily patterns), place (the use of services, located exclusively in the home, has led to an increase in consumption), intensity (the fear of contagion has led to greater care for personal and home hygiene, as well as the increase in recreational activities having generated an increase in water demand), efficiency (the consumption of water in the workplace is lower than at home, as it is spread over more people), new activities (during the lockdown, people's habits changed and new activities were introduced, e.g. gardening), and persistence (incorporates the other factors and identifies the permanence of the new habits, once the emergency is over). The same work showed a 35% increase in water consumption in England and Wales in May 2020, compared with the period before the lockdown. An analysis carried out on a complex of 280 houses in Cornwall, England (Menneer *et al.* 2021), revealed a total increase of 17% in water consumption. Other research (Bich-Ngoc & Teller 2020) conducted for the city of Liège dealt with the relationship between tourism and water demand, considering the significant reduction in travel (80%) between July 2019 and July 2020. The analysis revealed that cities with more outbound than inbound tourists, such as Liège, experienced an increase in demand in 2020 compared with 2019, unlike cities with strong inbound tourism, which showed a decrease in water demand. Balacco *et al.* (2020) analyzed the data of five cities in the region of Puglia, in Italy (Bari, Cellamare, Lizzano, Molfetta, Trani), referring to the periods between January 1 and April 30 of the years 2019 and 2020. In addition to the shift of 2 h in the peak, it was shown that, while for small cities the lockdown had little impact, in terms of daily volume reduction during the lockdown period, for large cities like Bari and Molfetta it was stronger. Another Italian study (Alvisi *et al.* 2021), analyzed the data from Rovigo city, showing an 18% increase in domestic consumption, and a delay in the morning peak of about 2–3 h. Rizvi *et al.* (2020) highlighted for the city of Dubai, in the United Arab Emirates, that the type of user affects the demand: daily consumption during lockdown periods increased in all apartment complexes except those with predominantly foreign residents. A Serbian study (Cvetković *et al.* 2021) analyzed domestic drinking consumption according to the age of the inhabitants, noting that in the houses where elderly people lived there was greater water consumption. Similarly, a study conducted in California (Zanocco *et al.* 2021) highlighted that the greatest increase in water consumption was observed in houses with children.

Buurman *et al.* (2022) analyzed the effects of the safe-distancing measures on water use patterns in different countries and cities (Belgium, Cyprus, Germany, Japan, Switzerland, Portugal, Romania, the Netherlands. and Singapore). They distinguished between temporal, spatial/sectoral and volume changes, and as common trends highlighted, respectively, a delay in the morning peak, a significant change in commercial water use pattern, and an increase in the volume of domestic water use (3%–8%). Cominato *et al.* (2022) compared water consumption profiles between pre-pandemic and pandemic for 14 social-housing buildings located in Joinville, southern Brazil. A shift of 2 h in the daily peak consumption was observed at night, as well as a small increase (about 4.5%) in demand in the first quarter of the pandemic period. Kim *et al.* (2021) investigated the relationship between active COVID-19 cases and domestic hot water demands, through a machine learning model with an artificial neural network, noticing that the COVID-19 outbreak affected the daily peak time, which shifted and lowered (with patterns of weekdays and weekends which could be assimilated) and increased the amount of domestic hot water usage. Ortiz *et al.* (2022) assessed the impact of the pandemic on the water consumption patterns and location in four Colombian cities known for their important commercial, industrial, academic, and touristic features. Results exhibited diverse diminishing water consumption trends alongside COVID-19 because of different attributes of the cities (e.g., size, environmental, socioeconomic, and sociocultural characteristics). For instance, the touristic case study was the most affected because of travel restrictions, with an average commercial demand drop of 32%.

Different authors focused on impacts of the pandemic on utilities water management, to provide suggestions for future interventions in the post-COVID era. For example, Feizizadeh *et al.* (2021) investigated the impacts of COVID-19 on multi-dimensional Urban Water Consumption Patterns (UWCPs) in the Tabriz metropolitan area, with the aim of forecasting the water demand and using the findings to develop evidence-informed strategies for sustainable water resource management in the post-COVID era, finding an increase in domestic water consumption of 17.6% during the pandemic and consequent difficulties in providing water resources. Similarly, Fritsche *et al.* (2022) underlined that the pandemic changes in water consumptions have important implications for water management and utility planning. They quantified regional water demand changes across 75 utilities in southeast Michigan throughout 2020. They observed that deviations were not uniform: the morning peak shifted and lowered, depending on community characteristics of income, population density, job density, and daytime population as well as altered movement trends in response to shutdowns. Di Mauro *et al.* (2021) monitored residential water end-use consumption and computed consumption statistics, hourly patterns, and daily and weekly use frequency before and after the COVID-19 lockdown, to understand how a change in social and economic factors can affect users' behavior and may represent a challenge for a water utility to understand features of increased water demand, adopt a novel model for demand forecasting, and improve the provided service. Berglund *et al.* (2022) analyzed how the operations of 27 water utilities worldwide were affected by the COVID-19 pandemic in terms of water system operation, demand, revenues, system vulnerabilities, and the use and development of emergency response plans (ERPs). Utilities varied in population size, location, and customer composition (e.g., residential, industrial, commercial, institutional, and university customers). A total of 23 of 27 utilities reported small changes in demand volumes and patterns, which could lead to some changes in water infrastructure operations and water quality. The pandemic revealed new system vulnerabilities and suggested that lessons learned would be used in future ERPs. Finally, some studies have analyzed the influence of anomalous phenomena. In particular, Li *et al.* (2021) compared urban water consumption data from southern and northern California: in the north, in agreement with the literature, the maximum residential water consumption and its peak increased during the lockdown. In southern California, on the other hand, April 2020 presented a 267% increase in precipitation compared with the previous 30-year average, which resulted in an overall decrease in water consumption.

In conclusion, most of the articles concerning the relationship between COVID-19 and drinking water consumption show an increase in residential consumptions, a decrease in industrial, commercial and public consumption, as well as a shift in the morning peak of 2–2.5 h on weekdays and a decrease in the evening peak.

Leveraging these results, the present work analyzes the influence that restrictions had on residential drinking water consumption in the Soccavo district of Naples (Campania), in Italy. The data acquisition has been carried out through a SWN system for years 2019 (considered the average reference year) and 2020. After excluding anomalous annual patterns and filtering the data, identifying and eliminating anomalies and outliers by clustering and classification, the large amount of data from the same meters were compared between years. According to the existing literature, to verify user behavior during lockdown periods, the average daily and weekly hourly patterns were obtained, identifying, in addition to the average daily pattern over the entire period, also the average daily patterns of midweek days, Saturdays and Sundays. Also, with the aim of verifying the eventual variation in water consumption during restriction times, the total daily volumes were analyzed. Then, data referring to the different literature case-studies were compared in order to identify general trends or evidence. Specifically, the peak coefficient and the total consumed volumes of different situations were related with the number of inhabitants and general trends were pointed out with the aim of suggesting to water companies effective strategies to manage water supply in the post-COVID era.

2. MATERIALS AND METHODS

The data processed in this work were collected from the Smart Water Network (SWN) located in the Soccavo district of the City of Naples (Italy). This network was implemented as part of a larger project, called 'waterGRID', developed in collaboration by the Special Company ABC – Acqua Bene Comune di Napoli, DICEA (Department of Civil, Architectural and Environmental Engineering) of the University 'Federico II' of Naples, and IBM – International Business Machines Corporation Italy.

The SWN was implemented in a macro-area of about 3.7 km^2 in the western peripheral area of the municipality of Naples, where 5,380 flowmeters were installed. Details of the administrative, technical and hydraulic features of the district are well described by Padulano & Del Giudice (2018, 2019).

In order to evaluate the COVID-19 impact and also the evolution of the system over time, the annual flow data of 1,122 meters, corresponding to about 2,500 users (Padulano & Del Giudice 2019), from January 1, 2019, to December 31, 2020, were provided by the smart metering system, collected on an hourly basis. The huge amount of data was processed with the help of MATLAB. Data were then filtered to prevent analyses from being invalidated by database inconsistencies, determined by (Lamberti *et al*. 1994):

- technological problems: e.g., data transmission interruptions or meter malfunctions,
- user behavior problems: e.g., determined either by changes in consumers or by apartments, houses, premises, etc., permanently or temporarily uninhabited,
- hydraulic problems: e.g., due to leaks that cause strong increases in consumption, especially at night,
- anomalous data: e.g., the outliers, namely data that significantly differ from the others (Barnett & Lewis 1994) generated by random user behaviors.

The data filtering was carried out using the technique described in Padulano & Del Giudice (2021) through three successive steps: a preliminary analysis, consisting of the visual inspection of a consumption map, in order to detect critical issues (e.g., concentrated null values), the detection of anomalies, through the use of two indicators of completeness and continuity (Braca *et al.* 2013), and the identification of outliers. The anomaly/outlier detection procedure enabled the identification of 637 meters considered as reliable for further analysis.

After cleaning the data, the significant annual behavior of the meters was identified, using a clustering and classification procedure. Clustering is a technique which consists in dividing an initial multidimensional dataset into various fields containing objects that have similar characteristics with the aim of finding recurring patterns (Zhou *et al.* 2013; Sancho-Asensio *et al.* 2014). In the present work a mixed strategy was used, where at the first level a SOM (Self Organizing Map) of variable size was applied and at the second level the *K*-means algorithm was applied to the centroids of the clusters defined in the first stage (Padulano & Del Giudice 2018). Classification is a technique that divides data into predetermined sets and consists of two phases: the construction of a model capable of identifying the intrinsic characteristics of each cluster, and the association of unclassified data in each modeled cluster. In the present work, the decision tree model was used, and three final clusters were chosen for 2019 and three for 2020, representing typical annual trends.

To evaluate the COVID effect on drinking water demand, the 637 meters remaining after data cleaning were analyzed for the year 2019, considered as reference, and for two time-windows in the year 2020: the period of the first national Lockdown in Italy, from March 11 to May 3, 2020, and the autumn Red Zone (when similar, but less strict, measures with respect to the national March Lockdown were adopted), from November 15 to December 6, 2020. For the reference year, the same windows were considered (11/3 to 3/5 and 15/11 to 6/12). For all periods, the variations in the weekly and daily consumption patterns were first evaluated and then a volumetric analysis was performed.

For the above defined time windows, Table 1 reports the daily average flow, the standard deviation of hourly consumption daily pattern, and the peak coefficient, estimated as the ratio between the maximum hourly value Q_{max} in the daily pattern

Table 1 | General information for the dataset

Water consumption data

Period	**Mar–May 2019**	**Nov–Dec 2019**	**Mar–May 2020 (Lockdown)**	**Nov–Dec 2020 (Red Zone)**
Q_{av}, daily average flow [l/h]	19.54	17.78	20.55	18.03
Cp, peak coefficient [–]	1.72	1.69	1.78	1.79
Standard deviation of daily average flow [l/h]	9.72	8.35	11.52	9.63

and the daily average flow Q_{av}:

$$Cp = \frac{Q_{max}}{Q_{av}} \tag{1}$$

The analysis of data in Table 1 shows that:

- the daily average consumption during the Lockdown period is higher compared with 2019; a slightly higher value can be observed also during the Red Zone;
- the peak coefficient is also higher, compared with 2019, during Lockdown, while during Red Zone the peak value is almost the same;
- the standard deviation is higher both during Lockdown and Red Zone, compared with the same period of the previous year. This is because the peaks during the day are higher than in 2019.

In presenting the results, daily patterns from different literature studies (Alvisi *et al.* 2021; Di Mauro *et al.* 2021; Feizizadeh *et al.* 2021; Kim *et al.* 2021; Li *et al.* 2021; Lüdtke *et al.* 2021; Buurman *et al.* 2022; Cominato *et al.* 2022; Fritsche *et al.* 2022; Ortiz *et al.* 2022) have been compared between each other and against those of the present study in order to find some general trend. Specifically, for each case the peak coefficient percentage variation in 2020 compared with the value in 2019 and the increase in volume consumption during Lockdown compared with the same period of 2019 for the different literature studies were compared among each other and against the values of the present research and related to the number of users of each specific situation.

3. RESULTS

3.1. National Lockdown

With the aim of evaluating the COVID-19 effect on drinking water consumption during the first national Lockdown, an additional filtering was performed as the 2019 data presented an anomaly in April, leaving only 218 meters for comparison between the two years.

As Figure 1 shows, the average flow rates in the Lockdown period and in the corresponding weeks of 2019 do not show any abnormal days or data, and the same weeks show similar trends in 2019 and 2020.

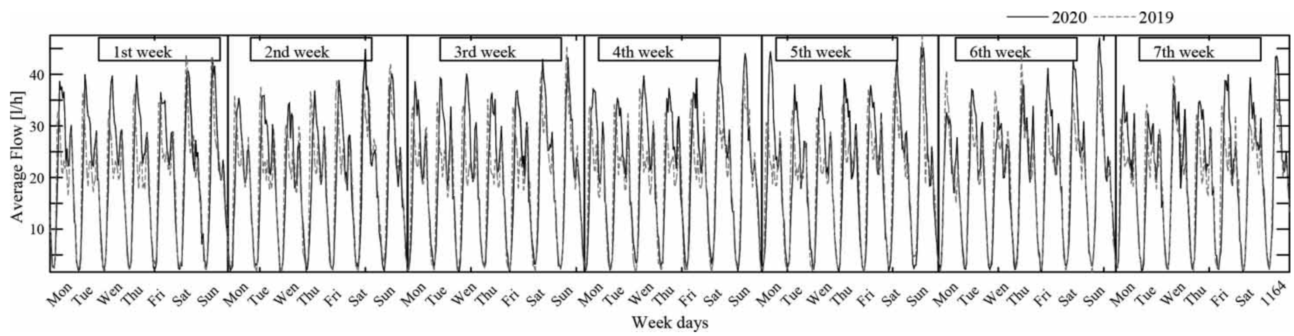


Figure 1 | Average flow rate trend in the seven weeks of the Lockdown and in the respective weeks of 2019.

To assess the change in demand over the week, the 2019 and 2020 weekly average patterns were generated (Figure 2). For the 2020 data, compared with the 2019 data, an increase in the morning peak and its postponement for all the days of the week (of about 2 h on midweek days) can be observed. The afternoon peak is considerably reduced until it disappears in the Sunday pattern. The evening peak is not very different on all days of the week.

In order to understand the hourly variations during the day, the daily average pattern calculated on all the days of the window from March 11 to May 3, 2019 and 2020 and the daily average patterns on weekdays, Saturdays and Sundays were generated (Figure 3).

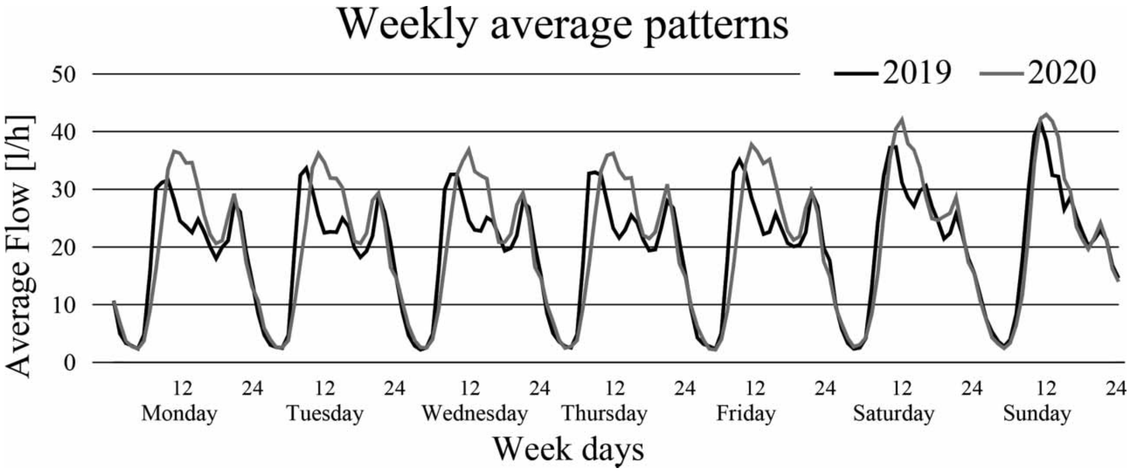


Figure 2 | Weekly average patterns for 2019 and 2020.

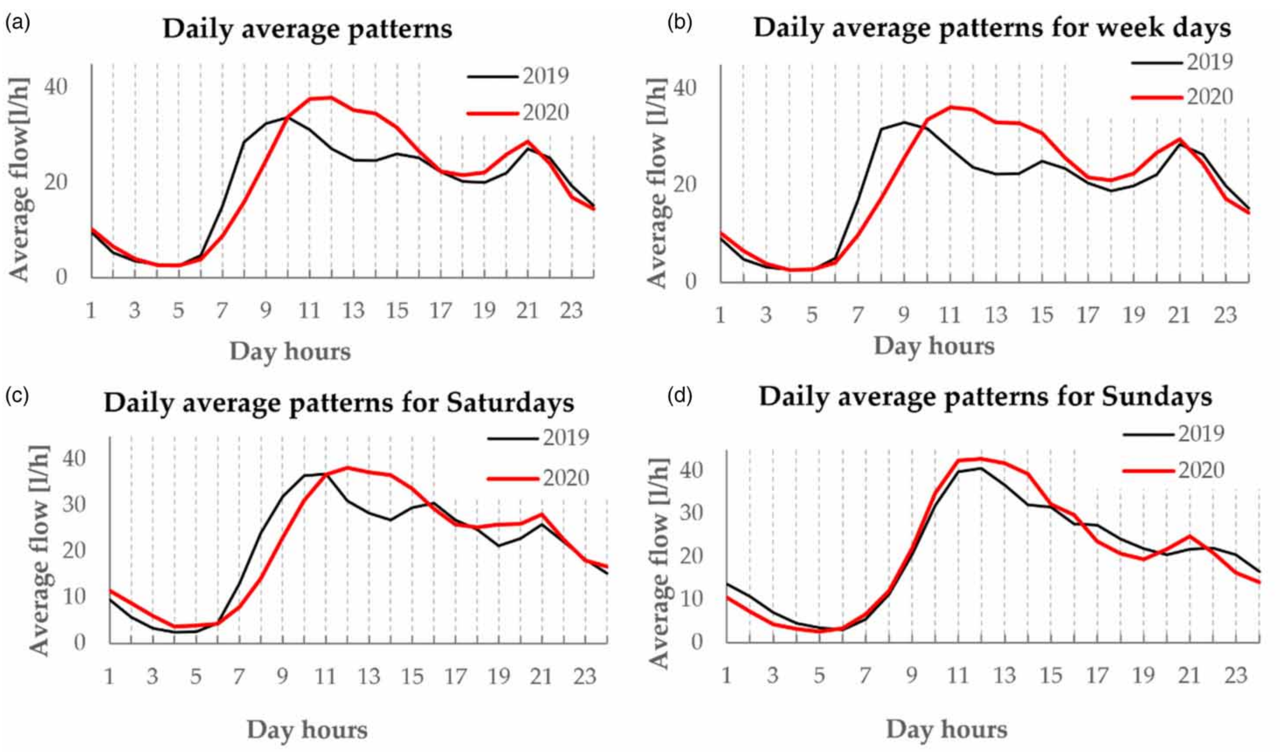


Figure 3 | General daily average patterns for 2019 and 2020 (a) and, specifically, only for: (b) weekdays, (c) Saturdays; and (d) Sundays.

Finally, for the 218 meters analyzed, the total daily volume for 2019 and 2020 was calculated as the sum of all the daily meter volumes (Figure 4). The average daily volume was also calculated, averaging the total daily volumes from 11 March to 3 May and the total volume, adding the total daily values of the entire period under consideration.

3.2. Autumn Red Zone

In Campania, the region in which the Soccavo neighborhood in Naples is located, the worsening epidemiological situation led to the establishment of the so-called Red Zone for three weeks from November 16 to December 6, 2020. During this period measures similar to the national Lockdown were adopted.

The same analyses as those of the first Lockdown were performed. Of the 637 meters present in 2019 and 2020 it was necessary to carry out further filtering due to the anomalies present in November 2019, so that a final number of 458 meters was considered.

Figure 5 shows the graph of average flow rates during the Red Zone period and corresponding days in 2019. The graph shows no abnormal days or consumption data, and the weeks in 2019 and 2020 show similar trends.

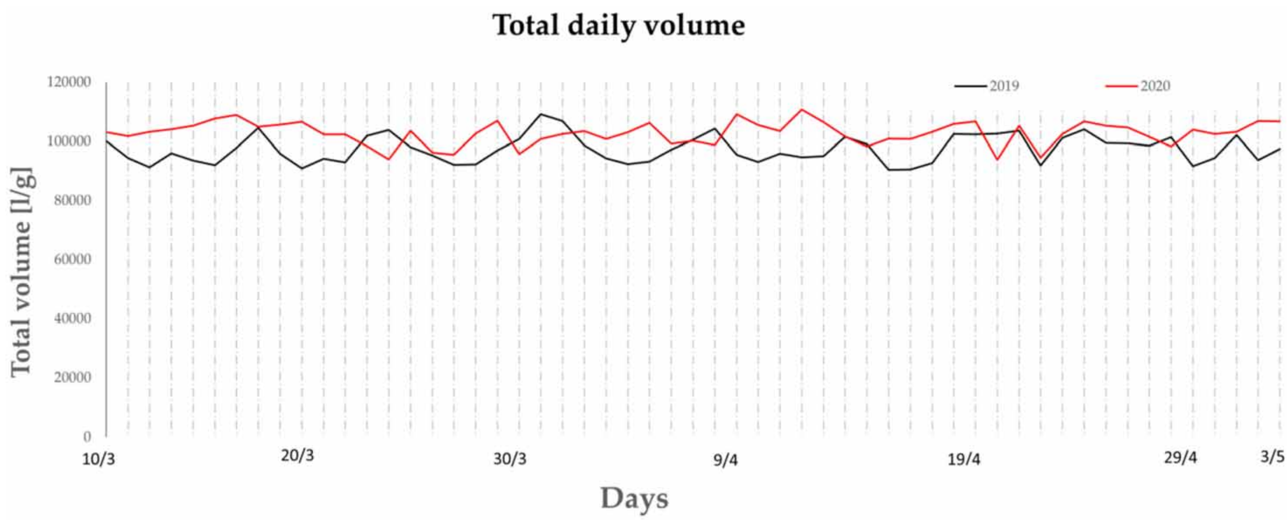


Figure 4 | Total daily volumes in the Lockdown period.

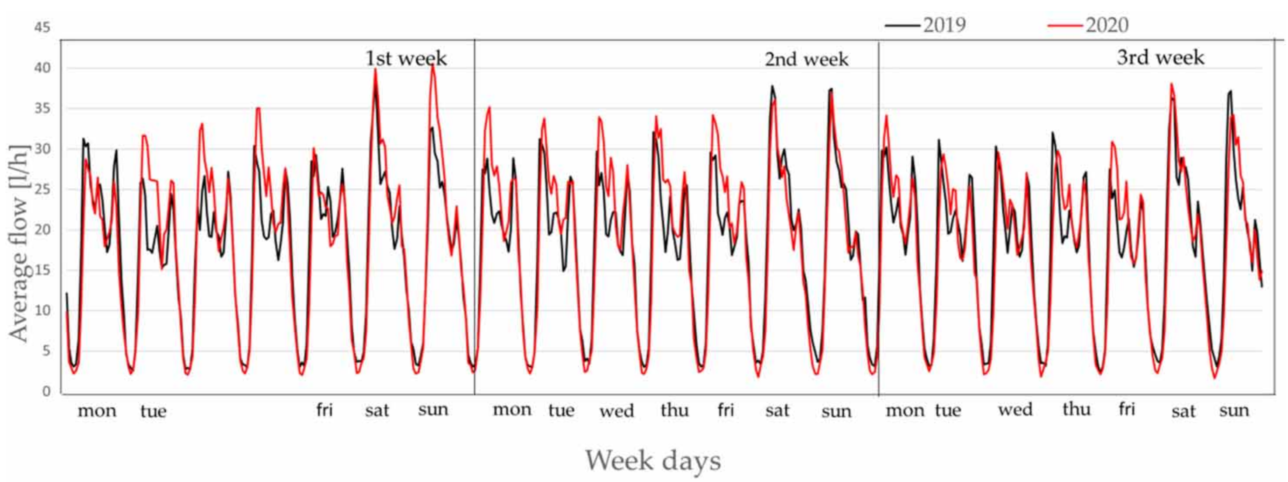


Figure 5 | Average flow rate trend in the three weeks of the Red Zone and in the respective weeks of 2019.

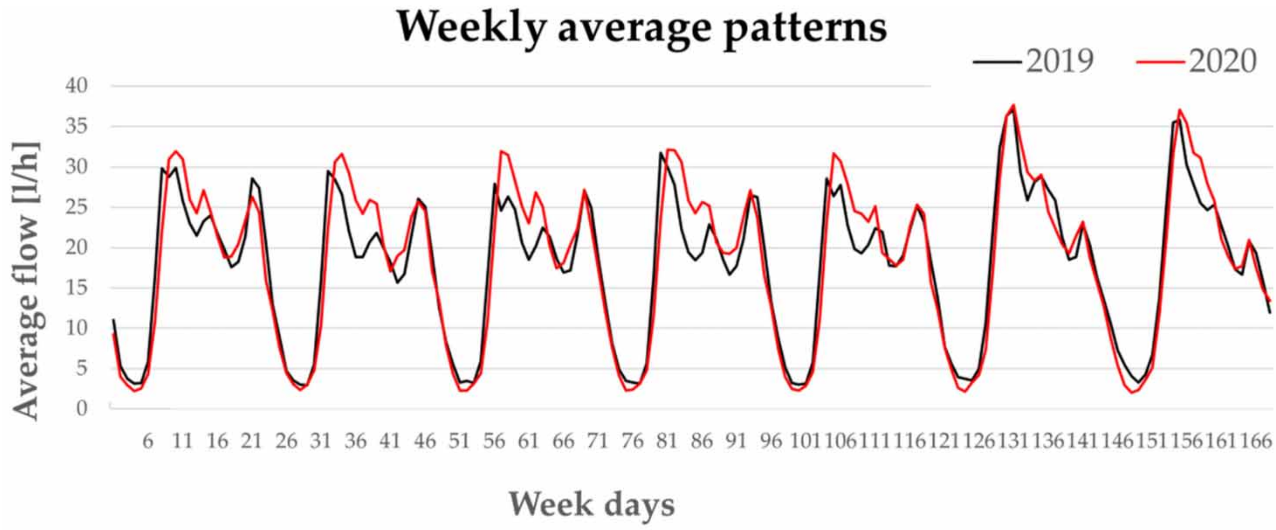


Figure 6 | Weekly average patterns for 2019 and 2020.

To assess the change in demand over the week, the 2019 and 2020 weekly average patterns were generated (Figure 6).

In order to understand the hourly variations during the day, the daily average pattern calculated on all the days of the period in question, from November 16 to December 6, 2019 and 2020 and the daily average patterns on weekdays, Saturdays, and Sundays were generated (Figure 7).

Finally, total daily volumes were analyzed for changes in user consumption in the restriction phase (Figure 8).

3.3. Literature data comparison

After analyzing data for the present case study and evaluating the daily, weekly and total patterns, a comparison was performed with the same patterns available in the different literature studies (Alvisi *et al.* 2021; Di Mauro *et al.* 2021;

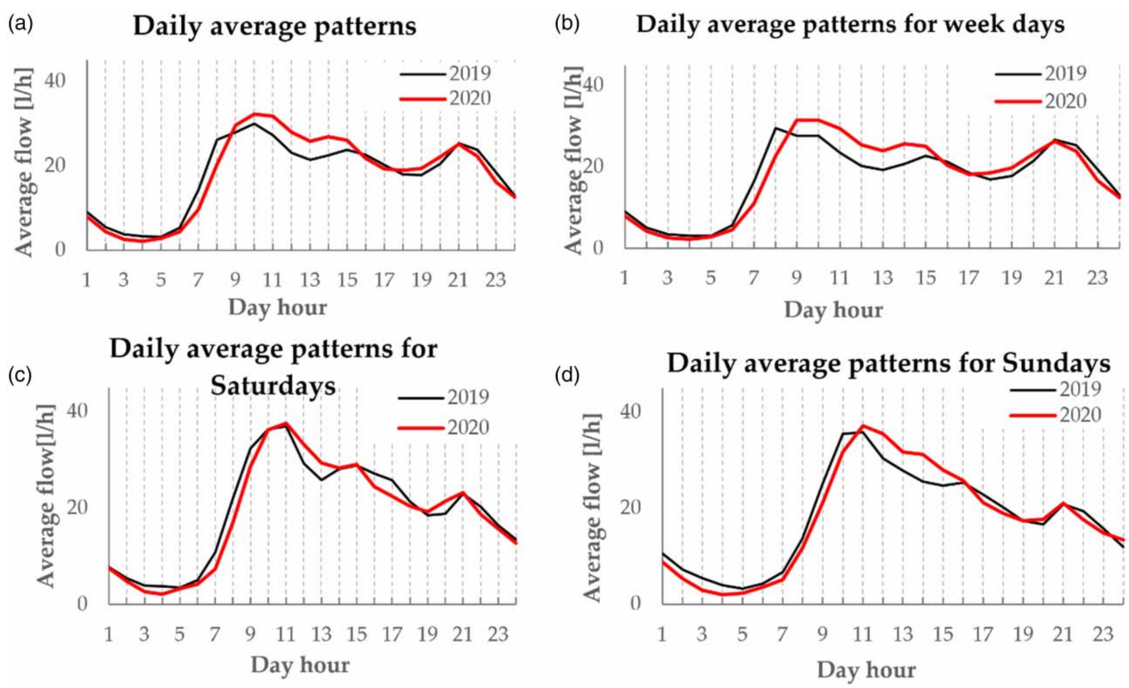


Figure 7 | Daily average patterns for 2019 and 2020 (a) and specifically for: (b) weekdays; (c) Saturdays; and (d) Sundays.

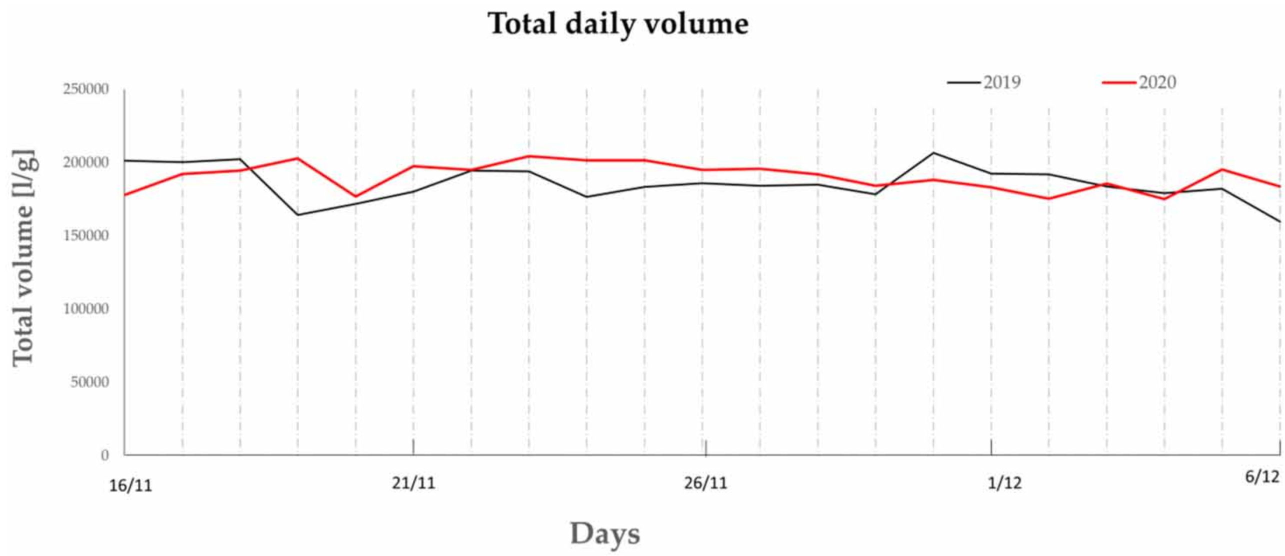


Figure 8 | Total daily volumes in the Red Zone period.

Feizizadeh *et al.* 2021; Kim *et al.* 2021; Li *et al.* 2021; Lüdtke *et al.* 2021; Buurman *et al.* 2022; Cominato *et al.* 2022; Fritsche *et al.* 2022; Ortiz *et al.* 2022). The objective was to seek general remarks to provide useful information for water companies to target their operational response during eventual future pandemics or similar lockdown situations due to unpredictable events. Specifically, for the literature case-studies showing daily consumption patterns (Alvisi *et al.* 2021; Lüdtke *et al.* 2021; Buurman *et al.* 2022; Cominato *et al.* 2022) it was possible to evaluate (see Table 2) the peak coefficient (Equation (1)) for 2019 and 2020. Then, the variation in 2020 with respect to the value in 2019 of the peak coefficient Cp (normalized with respect to daily average flow in order to compare the different works) was calculated according to Equation (2):

$$\Delta Cp = \frac{Cp_{2020} - Cp_{2019}}{Cp_{2019}} \tag{2}$$

Similarly, the increase in volume consumption during the Lockdown, compared with the same period of 2019, for the different literature studies was evaluated according to Equation (3):

$$\Delta W = \frac{W_{2020} - W_{2019}}{W_{2019}} \tag{3}$$

Table 2 reports the values of the peak coefficient Cp, and their variation during the Lockdown, as well as the volume consumption increase, calculated as above described, together with the number of users of each analyzed case.

Figure 9 illustrates the peak coefficient variation plotted against the number of users in a semi-logarithmic scale.

Table 2 | Values and variation of volume and peak coefficient, with related number of users in literature case-studies

References	Cp_{2019}	Cp_{2020}	ΔCp [%]	W_{2019}	W_{2020}	ΔW [%]	No. of users
This work	1.724565	1.724565	3.1	469.1	493.2	5.8	2,548
Alvisi *et al.* (2021)	2.16395	1.8	−16.8	1,400.8	1,712.6	19.2	208
Cominato *et al.* (2022)	1.70694	1.607628	−5.8	147.9	154.3	4.5	762
Lüdtke *et al.* (2021)	1.466937	1.605676	9.5	307,026.6	342,066.1	11.4	184,000
Buurman *et al.* (2022)	1.716456	1.817844	6	13.9	13.2	−5.6	101,000

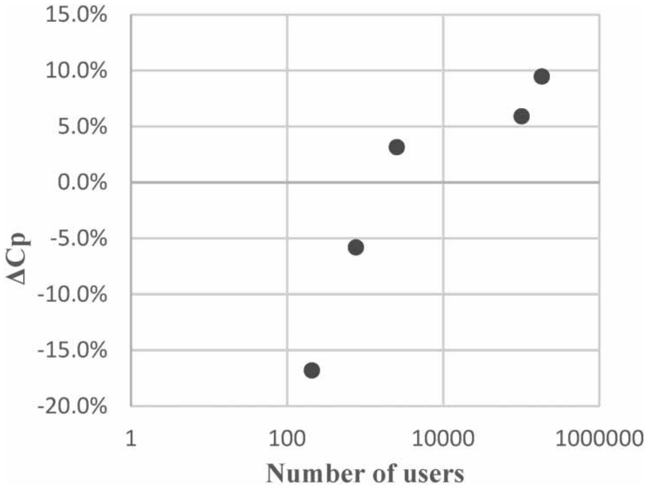


Figure 9 | Peak coefficient variation in 2020 with respect to 2019 against number of users.

The volume variations were also provided for other works (Di Mauro *et al.* 2021; Feizizadeh *et al.* 2021; Kim *et al.* 2021; Li *et al.* 2021; Fritsche *et al.* 2022; Ortiz *et al.* 2022). The volume variations for all studies are reported and compared in Table 3. Then, the data were aggregated for classes of number of users, and for each of them an average volume

Table 3 | Variation of volume and related number of users in the different case-studies

Authors	City/region	Δ*W* [%]	No. of users
Di Mauro *et al.* (2021)	Naples, Italy	27.8	1
Alvisi *et al.* (2021)	Rovigo, Italy	19.2	208
Cominato *et al.* (2022)	Joinville, Brazil	4.5	762
This work	Naples, Italy	5.8	2,548
Kim *et al.* (2021)	Seoul, South Korea	37.7	2,754
Buurman *et al.* (2022)	Singapore	9.5	4,383
Buurman *et al.* (2022)	Cipro	−5.6	101,000
Ortiz *et al.* (2022)	City D[a]	3.0	104,694
Lüdtke *et al.* (2021)	Seevetal, Germany	11.4	184,000
Li *et al.* (2021)	Modesto, CA, USA	−4.0	216,810
Ortiz *et al.* (2022)	City C[a]	7.0	220,822
Li *et al.* (2021)	Bakersfield, CA, USA	−4.0	416,539
Li *et al.* (2021)	Oakland, CA, USA	4.5	440,981
Li *et al.* (2021)	Sacramento, CA, USA	12.0	513,625
Buurman *et al.* (2022)	Belgium	19.2	564,000
Li *et al.* (2021)	San Francisco, CA, USA	8.0	815,200
Li *et al.* (2021)	Fresno, CA, USA	2.0	1,100,000
Fritsche *et al.* (2022)	Michigan	−6.0	1,136,270
Ortiz *et al.* (2022)	City B[a]	3.0	1,150,104
Li *et al.* (2021)	San Jose, CA, USA	7.0	1,995,105
Feizizadeh *et al.* (2021)	Tabriz, Iran	17.6	2,000,000
Li *et al.* (2021)	Orange County, CA, USA	1.0	3,198,000
Li *et al.* (2021)	Los Angeles, CA, USA	2.7	3,899,000

[a]Unspecified city in Colombia.

variation was calculated (Table 4). The aggregated volume variation values are plotted as a function of the user numbers in Figure 10.

4. DISCUSSION

From the analysis of Figures 1–4, the following observations can be made concerning the effect of the COVID-19 pandemic on water consumption and the consequent containment measures, in the period from March 11 to May 3, 2020, compared with the same period in 2019:

- an increase in the total water volume consumption of 5.8%;
- an increase in the average daily volume from 101.55 to 107.37 m^3;
- a higher morning peak on midweek days shifted by 2 h later;
- higher morning consumptions between 10 am and 2 pm for all days of the week;
- a second relative peak in the morning between 12 and 2 pm and disappearance of the afternoon peak;
- lower afternoon consumption compared with 2019 data on weekends and higher on midweek days;
- a higher evening peak on all days of the week;
- lower evening consumptions for all days of the week;
- a shift of the morning peak on Saturdays by 1 h compared with 2019;
- a 2020 Sunday trend similar to the 2019 Sunday trend.

From the analysis of Figures 5–8 it can be said that during the Red Zone, convened in Campania between November 16 and December 6, 2020, the pandemic of COVID-19 and the measures for its management, compared with the same period in 2019, caused:

- an increase in the total volume of 1.33%;
- an increase in the average daily volume from 194.98 to 197.58 m^3;
- a morning peak on midweek days, between 8 and 9 am, higher and shifted compared with 7 am in 2019;
- higher consumption throughout the week in the 10 am–2 pm range;
- an afternoon peak during the week and on Saturdays;

Table 4 | Aggregated classes of volume variation and related number of users in the different case-studies

Range of users	Average ΔW [%]
1–100	27.8
100–10,000	14
10,000–10,000,000	5
>10,000,000	4

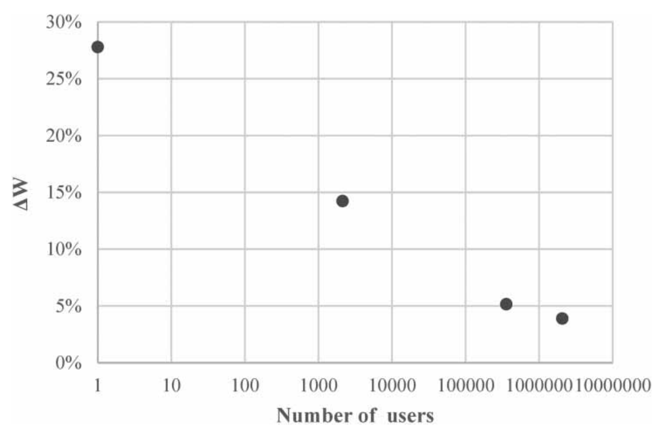


Figure 10 | Volume consumption increase in 2020 with respect to 2019 against number of users.

• an evening peak of the same height on all days of the week;
• a lower night-time consumption on all days of the week;
• a 2020 Sunday trend similar to the 2019 Sunday trend.

From the analyses of Figure 9 it is possible to notice an increasing trend of variation in the peak coefficient as the number of users increases. This can be explained by the fact that the peak coefficient is usually lower where the number of users is higher, because there is a more uniform distribution of consumption, due to the more varied habits of inhabitants who may use water any time, compared with small cities, where all the users have more or less the same habits and mainly use water at the same times. During the pandemic lockdown, when all the inhabitants stayed home according to the spread-prevention restrictions, the variation in peak coefficient was more evident for big cities, where, before, consumptions were more uniformly distributed, than for small cities, where users' habits did not change much with the pandemic.

The plot in Figure 10, where data have been aggregated in ranges of inhabitants (1–100; 100–10,000; 10,000–10,000,000; greater than 10,000,000) and an average value has been considered in each range, shows in a semi-logarithmic plan a decreasing trend of water volume variation with increasing number of users. The reason may be ascribed again to the fact that in big cities, consumptions were more uniformly distributed than in small towns, whereas the fact that during COVID-19 lockdown people who usually spend the day at work changed to staying at home all day long produced a more sensitive variation of habits and, consequently, of consumption in small cities.

5. CONCLUSIONS

The aim of the present work is the analysis of the effect of the COVID-19 pandemic and related restriction policies on drinking water consumption through the study of data from a Smart Water Grid located in the Soccavo district of Naples (Italy).

After data filtering, the 2 h data matrices per meter of 2019 and 2020 were intersected to have the same meters in both analyses. The period of the national Lockdown (from March 11 to May 3) and of the Red Zone (November 16–December 6) in 2020 were analyzed separately, comparing them with the corresponding periods of 2019. In general, in agreement with the trends found in the literature, in the two periods characterized by strong restrictions for the containment of the pandemic, the analysis of patterns and daily volumes showed:

• an increase in the total consumption volume (5.8% and 1.33%, respectively);
• an increase in the average daily volume;
• a morning peak on midweek days higher and shifted by 1–2 h compared with that of 2019;
• higher morning consumptions between 10 am and 2 pm for all days of the week;
• a higher evening peak on all days of the week;
• lower evening consumptions for all days of the week;
• a 2020 Sunday trend similar to the 2019 Sunday trend.

The present results confirm that the containment measures of the COVID-19 pandemic generated an increase in residential drinking water consumption and a change in usage patterns.

The comparison between the different case-studies shows, as a general trend, that during the pandemic the peak coefficient increased more for water systems with a larger number of users. In fact, in these cases, compared with small cities, the consumption was already more uniformly distributed, and then the variation in peak coefficient in Lockdown was more evident than for small cities, where user's habits did not change much with the pandemic. On the other side, the volume consumption variation during lockdown was higher for small cities, where consumption was less homogeneous before and, consequently, more significantly affected by users' change of habits produced by the COVID-19 containment policies, compared with big cities.

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AUTHOR CONTRIBUTIONS

G.D.G. and R.P. conceptualized the study; G.D.G. and R.P. prepared the methodology; M.N. and R.P. performed software analysis; C.D.C., G.D.G, S.E., M.N., and R.P. performed validation, formal analysis, and investigation; G.D.G. collected the resources; R.P. performed data curation; M.N. and S.E. wrote the original draft preparation; M.N. and S.E. wrote, reviewed, and edited the article; M.N. and S.E. visualized the study; G.D.G. supervised the study. All authors have read and agreed to the published version of the manuscript.

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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.

REFERENCES

Abu-Bakar, H., Williams, L. & Hallett, S. H. 2021 Quantifying the impact of the COVID-19 lockdown on household water consumption patterns in England. *npj Clean Water* **4**, 13.

Alda-Vidal, C., Smith, R., Lawson, R. & Browne, A. L. 2020 *Understanding Changes in Domestic Water Consumption Associated with COVID-19*. Artesia Consulting, Bristol, UK.

Alvisi, S., Franchini, M., Luciani, C., Marzola, I. & Mazzoni, F. 2021 Effects of the COVID-19 lockdown on water consumptions: northern Italy case study. *Journal of Water Resources Planning and Management* **147** (11), 05021021.

Balacco, G., Totaro, V., Iacobellis, V., Manni, A., Spagnoletta, M. & Piccinni, A. F. 2020 Influence of COVID-19 spread on water drinking demand: the case of Puglia region (southern Italy). *Sustainability* **12** (15), 5919.

Barnett, V. & Lewis, T. 1994 *Outliers in Statistical Data*, 3rd edn. J. Wiley & Sons, Chichester, UK.

Berglund, E. Z., Buchberger, S., Maria Cunha, M., Faust, K. M., Giacomoni, M., Goharian, E., Kleiner, Y., Lee, J., Ostfeld, A., Pasha, F., Pesantez, J. E., Saldarriaga, J., Shafiee, E., Spearing, L., van Zyl, J. E. & Yang, Y. C. E. 2022 Effects of the COVID-19 pandemic on water utility operations and vulnerability. *Water Resources Planning and Management* **148** (6), 04022027.

Bich-Ngoc, N. & Teller, J. 2020 Potential effects of the COVID-19 pandemic through changes in outbound tourism on water demand: the case of Liège (Belgium). *Water* **12** (10), 2820.

Braca, G., Bussettini, M., Lastoria, B. & Mariani, S. 2013 *Linee guida per l'analisi e l'elaborazione statistica di base delle serie storiche di dati idrologici (Guidelines for the Analysis and Basic Statistical Processing of Hydrological Time Series)*. Manuals and Guidelines 84, Istituto Superiore per la Protezione e la Ricerca Ambientale, Rome, Italy.

Buurman, J., Freiburghaus, M. & Castellet-Viciano, L. 2022 The impact of COVID-19 on urban water use: a review. *Water Supply* **22** (10), 7590–7602. doi:10.2166/ws.2022.300.

Cahill, J., Hoolohan, C., Lawson, R. & Browne, A. L. 2022 COVID-19 and water demand: a review of literature and research evidence. *Wiley Interdisciplinary Reviews: Water* **9** (1), e1570.

Cominato, C., Sborz, J., Kalbusch, A. & Henning, E. 2022 Water demand profile before and during COVID-19 pandemic in a Brazilian social housing complex. *Heliyon* **8**, e10307. https://doi.org/10.1016/j.heliyon.2022.e10307.

Cvetković, D., Nešović, A. & Terzić, I. 2021 Impact of people's behaviour on the energy sustainability of the residential sector in emergency situations caused by COVID-19. *Energy and Buildings* **230**, 110532.

Di Mauro, A., Santonastaso, G. F., Venticinque, S. & Di Nardo, A. 2021 Impact of COVID-19 emergency on residential water end-use consumption measured with a high-resolution IoT system. *AQUA – Water Infrastructure, Ecosystems and Society* **70** (8), 1248–1256. doi:10.2166/aqua.2021.088.

Dzimińska, P., Drzewiecki, S., Ruman, M., Kosek, K., Mikołajewski, K. & Licznar, P. 2021 The use of cluster analysis to evaluate the impact of COVID-19 pandemic on daily water demand patterns. *Sustainability* **13** (11), 5772.

Feizizadeh, B., Omarzadeh, D., Ronagh, Z., Sharifi, A., Blaschke, T. & Lakes, T. 2021 A scenario-based approach for urban water management in the context of the COVID-19 pandemic and a case study for the Tabriz metropolitan area, Iran. *Science of the Total Environment* **790**, 148272. https://doi.org/10.1016/j.scitotenv.2021.148272.

Fritsche, J. R., Whitby, P., Griffin, E., Norton Jr., J. W., Alfahham, N., Kuhns, T. & Bell, K. Y. 2022 Changes in water demand resulting from pandemic mitigations in Southeast Michigan. *AWWA Water Science* **4**, e1286. doi:10.1002/aws2.1286.

Ji, B., Zhao, Y., Wei, T. & Kang, P. 2021 Water science under the global epidemic of COVID-19: bibliometric tracking on COVID-19 publication and further research needs. *Journal of Environmental Chemical Engineering* **9**, 105357.

Kalbusch, A., Henning, E., Brikalski, M. P., Vieira de Luca, F. & Konrath, C. A. 2020 Impact of coronavirus (COVID-19) spread-prevention actions on urban water consumption. *Resources, Conservation and Recycling* **163**, 105098.

Kim, D., Yim, T. & Lee, J. Y. 2021 Analytical study on changes in domestic hot water use caused by COVID-19 pandemic. *Energy* **231**, 120915. https://doi.org/10.1016/j.energy.2021.120915.

Lamberti, P., Maiolo, M., Mazzola, M. R. & Veltri, P. 1994 *Rapporto sui consumi idropotabili in Italia sul finire degli anni 80*. CUEN, Napoli, Italy.

Li, D., Engel, R. A., Ma, X., Porse, E., Kaplan, J. D., Margulis, S. A. & Lettenmaier, D. P. 2021 Stay-at-home orders during the COVID-19 pandemic reduced urban water use. *Environmental Science and Technology Letters* **8** (5), 431–436.

Lüdtke, D. U., Luetkemeier, R., Schneemann, M. & Liehr, S. 2021 Increase in daily household water demand during the first wave of the COVID-19 pandemic in Germany. *Water* **13** (3), 260.

Menneer, T., Qi, Z., Taylor, T., Paterson, C., Tu, G., Elliott, L. R., Morrissey, K. & Mueller, M. 2021 Changes in domestic energy and water usage during the UK COVID-19 lockdown using high-resolution temporal data. *International Journal of Environmental Research and Public Health* **18** (13), 6818.

Ortiz, C., Salcedo, C. & Saldarriaga, J. 2022 Assessment of the effects of COVID-19 pandemic stay-at-home measures on potable water consumption patterns, location, and financial impacts for water utilities in Colombian cities. *Water* **14** (19), 3004. https://doi.org/10.3390/w14193004.

Padulano, R. & Del Giudice, G. 2018 A mixed strategy based on self-organizing map for water demand pattern profiling of large-size smart water grid data. *Water Resources Management* **32**, 3671–3685.

Padulano, R. & Del Giudice, G. 2019 Pattern detection and scaling laws of daily water demand by SOM: an application to the WDN of Naples, Italy. *Water Resources Management* **33**, 739–755.

Padulano, R. & Del Giudice, G. 2021 A nonparametric framework for water consumption data cleansing: an application to a smart water network in Naples (Italy). *Journal of Hydroinformatics* **22** (4), 666–680.

Rizvi, S., Rustum, R., Deepak, M., Wright, G. B. & Arthur, S. 2020 Identifying and analysing residential water demand profile; including the impact of COVID-19 and month of Ramadan, for selected developments in Dubai, United Arab Emirates. *Water Supply* **21** (3), 1144–1156.

Sancho-Asensio, A., Orriols-Puig, A. & Golobardes, E. 2014 Robust on-line neural learning classifier system for data stream classification tasks. *Soft Computing* **18**, 1441–1461.

Sayeed, A., Rahman, M. H., Bundschuh, J., Herath, I., Ahmed, F., Bhattacharya, P., Tariq, M. R., Rahman, F., Joy, M. T. I., Abid, M. T., Saha, N. & Hasan, M. T. 2021 Handwashing with soap: a concern for overuse of water amidst the COVID-19 pandemic in Bangladesh. *Groundwater for Sustainable Development* **13**, 100561.

Zanocco, C., Flora, J., Rajagopal, R. & Boudet, H. 2021 Exploring the effects of California's COVID-19 shelter-in-place order on household energy practices and intention to adopt smart home technologies. *Renewable and Sustainable Energy Reviews* **139**, 110578.

Zhou, K., Yang, S. & Shen, C. 2013 A review of electric load classification in smart grid environment. *Renewable and Sustainable Energy Reviews* **24**, 103–110.

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