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Evaluating the impact of COVID-19 countermeasures on alcohol consumption through wastewater-based epidemiology: A case study in Belgium

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ABSTRACT

Wastewater-based epidemiology (WBE) is a complementary approach to monitor alcohol consumption in the general population. This method measures concentrations of xenobiotic biomarkers (e.g., ethyl sulphate) in influent wastewater (IWW) and converts these to population-normalized mass loads (PNML, in g/day/1000 inhabitants) by multiplying with the flow rate and dividing by the catchment population. The aims of this case study were to: (i) investigate temporal trends in alcohol use during the COVID-19 pandemic; and (ii) measure the effect of policy measures on alcohol consumption. Daily 24-h composite IWW samples (n = 735) were collected in the wastewater treatment plant of the university city of Leuven (Belgium) starting from September 2019 to September 2021. This is the first study that investigates alcohol use through WBE for a continuous period of two years on a daily basis. Mobile phone data was used to accurately capture population fluxes in the catchment area. Data was evaluated using a time series based statistical framework to graphically and quantitatively assess temporal differences in the measured PNML. Different WBE studies observed temporal changes in alcohol use during the COVID-19 pandemic. In this study, the PNML of ethyl sulphate decreased during the first lockdown phase, potentially indicating that less alcohol was consumed at the Leuven area during home confinement. Contrastingly, alcohol use increased after the re-opening of the catering industry. Additionally, a decrease in alcohol use was observed during the exam periods at the University of Leuven and an increase during the holiday periods. The present study shows the potential of WBE to rapidly assess the impact of some policy measures on alcohol consumption in Belgium. This study also indicates that WBE could be employed as a complementary data source to fill in some of the current knowledge gaps linked to lifestyle behavior.

1. Introduction

There has been growing concern that the coronavirus disease (COVID-19) pandemic and associated social isolation led to an increase in alcohol consumption and abuse (Andreasson et al., 2021; Ramalho, 2020; Calina et al., 2021). Trends in alcohol consumption at the general population level depend on several factors that differ among drinking cultures, policies and countries (Andreasson et al., 2021). For instance, changes in alcohol availability could affect the context in which alcohol

is consumed (e.g., drinking at home instead of public places such as bars) and, in turn, this could also result in differences in alcohol-related harms (e.g., less public violence but more domestic violence) (Andreasson et al., 2021). Additionally, the extent to which the COVID-19 crisis exacerbates mental health problems could potentially have considerable interactions on a population's alcohol consumption patterns (World Health Organization (WHO), 2020). Therefore, alcohol availability as well as mental health concerns have been considered as determining factors in the pandemic's consequences on population-level alcohol

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Received 11 July 2022; Received in revised form 29 September 2022; Accepted 30 September 2022 Available online 2 October 2022 0160-4120/© 2022 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). consumption (Andreasson et al., 2021). Similarly, different studies identified psychological distress, drinking motives, price changes, access to alcoholic drinks, and level of income as key predictors of alcohol consumption during past economic (e.g., recessions) and public health crises (de Goeij et al., 2015; Rehm et al., 2020; Bollen et al., 2021). However, it should be noted that local variations in demographics and other factors (e.g., the extent to which COVID-19 has impacted socio-economic functioning) should also be taken into consideration when evaluating changes in alcohol use at the societal level.

To curb the spread of COVID-19, countries have progressively introduced community-wide lockdowns and periods of quarantine resulting in an unprecedented number of people staying at home. COVID-19 countermeasures in different countries also directly affected alcohol consumption through several alcohol-linked measures (Andreasson et al., 2021; Vlaams expertisecentrum voor alcohol en andere drugs, 2021). Inter-country differences in alcohol measures ranged from a temporary alcohol ban (e.g., South Africa) to restrictions in alcohol sales at restaurants, pubs and bars (e.g., the Netherlands). In Belgium, a wide range of interventions resulted in changes in alcohol availability and context of use (FPS Public Health, 2022). This mainly included the closing of bars and nightlife during the lockdown phase, curfews, and restrictions in overnight alcohol sales. A detailed overview of Belgian COVID-19 countermeasures potentially impacting the social opportunities to consume alcohol can be found in Table 1.

On a European level, the state of play with respect to the impact of COVID-19 countermeasures on alcohol use appears to be heterogeneous across different countries. This is also reflected by the conflicting results between different epidemiological data sources (Ammar et al., 2020; Pišot et al., 2020; Global Drug Survey (GDS), 2020; Steffen et al., 2021; Chodkiewicz et al., 2020; Grossman et al., 2020). In Belgium, there appears to be more consensus between the findings of different information sources. According to the annual report 2020 of a multinational brewery annual consolidated alcohol volumes (in 1000 hL) decreased with 5.7 % in Belgium in the COVID-19 pandemic period (Vlaams expertisecentrum voor alcohol en andere drugs, 2020) compared to 2019 (Inbev, 2020; Leifman et al., 2022). This decrease was even more profound during the first six months of 2020 for which a 13 % decrease in alcohol volumes sold was reported compared to the same period in 2019 (potentially also because bars did not replenish their stocks during this period). However, it should be noted that alcohol users may pivot to cheaper or unrecorded forms of alcohol and sales-based declines may vary between regions. During home confinement, local in-house stocks may also be consumed first. According to the online Health Interview Survey COVID-19 of Sciensano (Belgian Scientific Institute of Public

Health), 23.1 % of known alcohol users (aged 18+) communicated an increase in alcohol consumption during the first wave of the pandemic, while 23.7 % of known users reported a decrease (Sciensano, 2020). These figures were in line with survey data from the Flemish expertise centre for alcohol and other drugs (VAD) (Vlaams expertisecentrum voor alcohol en andere drugs, 2020). It is worth mentioning that the interview method from Sciensano changed from computer-assisted personal interviews to online surveys, potentially excluding certain population groups (e.g., individuals with limited internet access). In addition, the subset of individuals with known alcohol use might not be representative for the entire population.

To fill in some of the current knowledge gaps on the effects of the COVID-19 pandemic on population-wide alcohol consumption, there is a need for complementary data. Over the past decade, wastewater-based epidemiology (WBE) has become a well-established tool for providing epidemiological information on alcohol use among populations with the possibility to obtain data at high spatio-temporal resolutions (Boogaerts et al., 2021: Boogaerts et al., 2016 Mar: Baz-Lomba et al., 2016: Gao et al., 2020; Chen et al., 2019; van Wel et al., 2016; Asicioglu et al., 2021; Thai et al., 2021). Within this approach, concentrations of ethyl sulphate, a Phase-II metabolite of ethanol, in daily raw influent wastewater samples are converted to population-normalized mass loads (PNML, g/day/1000 inhabitants) by multiplying with the daily wastewater flow rates (L/day) and dividing by the estimated daily catchment population served by the wastewater treatment plant (WWTP) at a given day (Baker et al., 2014). Earlier studies have shown the applicability of WBE to monitor spatio-temporal changes in legal and illegal drug use during the COVID-19 pandemic (Been et al., 2021; Boogaerts et al., 2022; Bade et al., 2021; Bade et al., 2021; Alygizakis et al., 2021; Galani et al., 2021; Montgomery et al., 2021; Wang et al., 2020; Estévez-Danta et al., 2022; Reinstadler et al., 2021). In this light, WBE is the only methodology that can capture data at high spatial and temporal resolutions. For this reason, the WBE approach may be particularly useful as a complementary monitoring tool to measure the effect of different policy measures on alcohol consumption during this public health crisis in Belgium (Bade et al., 2021; Bade et al., 2021).

The aim of this study was to investigate alcohol use before and during the pandemic through WBE to evaluate the effect of the different countermeasures on consumption in the catchment of WWTP Leuven (Belgium). For this purpose, a two-year wastewater monitoring campaign with daily wastewater sample collection was initiated in the city of Leuven to investigate whether temporal changes in alcohol consumption occurred after the implementation of the different policy changes summarized in Table 1. Furthermore, this study provides a

Table 1

Restricting and easing of COVID-19 measures in Belgium during the sampling horizon (September 2019-September 2021) (Ammar et al., 2020).

Code	Date	Туре	Measure	
А	14-Mar-2020	Restriction	Closing of the catering industry	
			Recreative, sportive and cultural activities suspended	
			Non-essential stores closed	
			Stay-at-home measures: non-essential travel/commuting prohibited	
В	4-May-2020	Relaxation	Expansion of the number of close contacts to four persons	
			More persons allowed to work	
С	8-Jun-2020	Relaxation	Re-opening of catering industry with a curfew at 1 am	
			Expansion of the number of close contacts to ten persons	
			Culture sector re-opened	
D	1-Jul-2020	Relaxation	Re-opening of amusement parks, casinos, wellness and pools	
			Expansion of the number of close contacts to fifteen persons	
Е	29-Jul-2020	Restriction	Restriction of the number of close contacts to five persons	
			Limiting the number of persons allowed to sport events	
F	9-Oct-2020	Restriction	Restriction of the number of close contacts to three persons	
			Curfew for the catering industry at 11 pm	
G	19-Oct-2020	Restriction	Closing of the catering industry	
н	8-May-2021	Relaxation	Re-opening of outside terraces of catering industry	
I	9-Jun-2021	Relaxation	Complete re-opening of the catering industry (also indoor) with a curfew at 10 pm and only four persons allowed per table	
J	20-Aug-2021	Relaxation	Omission of all restrictions for the catering industry (curfew, service, number of seats per table,)	

statistical framework based on time series analysis that can be applied to other WBE applications to monitor the effect of policy changes on legal and illegal substance use.

2. Materials and methods

2.1. Sampling

Daily 24-h composite influent wastewater samples (IWW) were collected in the catchment area served by the WWTP of Leuven in a timeproportional manner from September 2nd, 2019 through September 4th, 2021. The autosampler device operated at a high frequency (10 min) and at 4 °C to compile daily representative IWW samples to ensure accurate average biomarker concentrations over a 24-h period (Ort et al., 2010). After collection, IWW aliquots were stored immediately at -20 °C to guarantee high in-sample stability during storage (Banks et al., 2018; Gao et al., 2018). IWW samples were analyzed within four months after collection at the WWTP. The average residence time in the sewer network was less than 24-h, and the wastewater temperature ranged from 11 to 24 °C. Fig. S1 overlays the daily wastewater flow rates with the population size estimates during the sampling horizon.

As illustrated by Fig. S2, the catchment area of the WWTP Leuven does not only include the mid-size university city of Leuven, but also twelve surrounding municipalities (e.g., Kessel-Lo, Heverlee, Oud-Heverlee). The student population in the catchment is substantial and changes in alcohol use might be related to the behavior and movements of university students in and out the catchment area. In 2019, 47 252 students were enrolled at the university campus in Leuven, which concerns approximately 45 % of the catchment population. However, all enrolled students will potentially not be present in the catchment area each day and the de facto number of students out and in the catchment area respectively, as reflected by the weekly changes in population

numbers (see Section 3.1. and Fig. 1). A 2019 survey at the KU Leuven indicated that 90 % of students return homeward during the weekends (Leuven, 2019). For this reason, the contribution of students is less pronounced during the weekends compared to the work week.

2.2. Sample preparation and analysis

Direct injection and sample analysis were executed according to a previously validated analytical method from Boogaerts et al. (Boogaerts et al., 2016). More information on the materials can be found in the Supplementary Information. The suitability of ethyl sulphate as a biomarker for alcohol consumption has already been established in numerous WBE studies (Bade et al., 2021; Boogaerts et al., 2016; Baz-Lomba et al., 2016; Gao et al., 2020). A multi-level calibration curve ranging between 1.5 and 100 $\mu g/L$ was constructed using different working standard solutions and a fixed amount of the internal standard ethyl sulphate-D5 (50 µg/L). For analyte confirmation, the quantifier/ qualifier (Q/q) ratio must not differ more than \pm 15 % from the Q/q ratios observed in the calibrators and the relative retention time should be lower than 2.5 % (European Commission, 2002). Concentrations in all samples were above the lower limit of quantification (1.5 μ g/L). Quality control was applied by in-house QA/QC measures (e.g., quality control samples, inclusion of replicates, ...) and through participation in an inter-laboratory exercise provided by the Sewage Analysis Core group Europe (SCORE) (van Nuijs et al., 2018).

3. Calculations and statistical analysis

3.1. Back-calculations

The PNML of ethyl sulphate can be considered as a proxy for the use of alcohol in the WWTP catchment area (Boogaerts et al., 2016; Gao et al., 2020; van Wel et al., 2016). The PNML of ethyl sulphate were



Fig. 1. Population number estimated based on daily mobile network data in the catchment area served by WWTP Leuven. Green dashed lines represent COVID-19 related relaxations. Red dashed lines show COVID-19 related restrictions. The encoding of the letters corresponding with the COVID-19 interventions can be found in Table 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

back-calculated based on Equation 1. Within this formula, c_{EtS} is the concentration of ethyl sulphate measured in the 24-h composite IWW sample (µg/L), Q is the total daily wastewater flow measured in the wastewater treatment plant (L/day) and P_{Leuven} is the population number in the catchment area of the wastewater treatment plant of Leuven at a given day.

Equation 1 WBE back-calculations to population-normalized mass loads (PNML).

$$PNML = \frac{c_{EtS} \bullet Q}{P_{Leuven}}$$

Mobile network data was used to estimate the *de facto* population (PLeuven) contributing to the wastewater system to refine the backcalculation of the PNML (Boogaerts et al., 2022; Thomas et al., 2017; Baz-Lomba et al., 2019). The use of an anthropogenic population proxy was necessary to account for fluctuations in population numbers during the COVID-19 pandemic. A detailed description of this methodology can be found in Boogaerts and Quireyns et al. (Boogaerts et al., 2022). Anonymized aggregated data from mobile network operator Orange Belgium (Cropland, Antwerp, Belgium) was acquired to temporally estimate the population in the catchment area. For this purpose, all signalization records of mobile devices with cell phone masts overlaying the catchment area were compiled. Machine-to-machine (i.e., direct communication between devices) and Internet of Things communications were excluded. For population estimation only mobile device signals present for more than two hours in the catchment area were considered, and a visit was terminated when the signal was absent for more than three hours. Extrapolation of the population size was done based on several factors, including zone probability, contact probability and market share (for more details, see Table S1). Population data based on mobile network-based analytics were obtained for the entire sampling period (September 2019 through September 2021) and radio cell coverage (i.e., transmission antennas) were matched with the boundaries of the WWTP catchment area. Fig. 1 shows the fluctuations in the population number served by the WWTP of Leuven. This figure clearly shows the temporal differences in population estimates during the sampling period. For example, a decrease of approximately 50 % in the amount of people present in the catchment area of Leuven was observed during the lockdown phase (starting mid-March 2020), due to the COVID-19 countermeasures such as social distancing and self-isolation and/or related student efflux from the WWTP catchment area. This further indicates the importance of refinement of WBE back-calculations with dynamic population numbers.

No further back-calculation to estimate consumed alcohol doses was performed since this would also increase the overall uncertainty associated with excretion factors derived from pharmacokinetic studies (Gao et al., 2020). In recent years, suitable correction factors have been proposed for the refinement of back-calculations to alcohol doses. The application of these factors resulted in good agreement between official alcohol sales and WBE data (López-García et al., 2020; Ryu et al., 2016; Reid et al., 2011). However, the primary focus of this study was to monitor temporal changes in alcohol use. For this purpose, a viable approach would be to use the PNML of ethyl sulphate as a proxy for alcohol use. This is appropriate because the main goal of this study was to analyze relative trends, and no comparison between WBE and official sales statistics was performed.

3.2. Statistical analysis

3.2.1. Graphical analyses

Seasonal and Trend decomposition using Loess (STL) was applied to additively decompose the time series of the measured PNML of ethyl sulphate in (i) a trend component describing the longitudinal trends in alcohol consumption; (ii) a seasonal component accounting for periodic changes in alcohol use, and (iii) an error term consisting of the remaining variability across the time series (Hyndman and Athanasopoulos, 2021). Firstly, seasonality was observed in the PNML of ethyl sulphate on a weekly scale. Secondly, missing data (n = 69, n% = 9%) was imputed by interpolating a seasonally adjusted time series (frequency = 7 days), following computation of a robust STL decomposition. The interpolated time series was then additively decomposed in its different components as a final step. Finally, a 28-day weighted moving average was applied to the longitudinal trend component to capture the average temporal change in the PNML. Although the raw data and its high temporal resolution is particularly useful to highlight specific dates, a weighted moving average was applied to better visualize the overall trend over the two year period. Within this framework, linear interpolation could be applied since the missing values were randomly distributed across the entire sampling campaign, and the different days of the week.

A similar method was applied by *Tscharke et al.* to investigate longterm temporal trends in opioid use through WBE (Tscharke et al., 2016). Time series decomposition was performed with R version 4.1.3 (R, Vienna, Austria) with the forecast package (Hyndman et al., 2022). In contrast to other decomposition methods, STL can handle any type of seasonality and could therefore be applied to extract the weekly trends in alcohol use. Additionally, this additive decomposition method was suitable for decomposing the time series since seasonal variation did not change over time (Hyndman and Athanasopoulos, 2021). For STL decomposition to work effectively, a minimum of two observations of each season should be measured. For this reason, it was also possible to use this method to extract other types of time patterns (e.g. monthly, quarterly, seasonally,...).

3.2.2. Quantitative analysis

Multiple regression with seasonal autoregressive integrated moving average (SARIMA) modelled errors were applied to test whether the different policy changes resulted in a significant effect on the PNML of ethyl sulphate (Hyndman and Athanasopoulos, 2021). These dynamic regression models were used instead of traditional linear regression models since time series are prone to phenomena such as nonstationarity and seasonality, and its observations are typically autocorrelated. Adjustment for these phenomena is necessary to obtain independent and uncorrelated residuals, a key assumption of regression models. The SARIMA model part consists of a non-seasonal (p,d,q) and seasonal (P,D,Q)_m component, each consisting of three parameters: i) p, the order of the autoregressive part (i.e., a linear combination of lagged values of the time series); ii) d, the degree of first differencing involved to remove non-stationarity; and iii) q, the order of the moving average part (i.e., a linear combination of lagged model error terms). In the seasonal component, m represents the seasonal period used in this model. A detailed description of this modelling approach is provided by Hyndman et al. (Hyndman and Athanasopoulos, 2021). Regression models with SARIMA errors were computed in R with the ARIMA function (from the fable package) and different models were tested (i.e., by varying the SARIMA parameters) (O'Hara-Wild et al., 2021). The order of differencing was determined using repeated Kwiatkowski--Phillips-Schmidt-Shin (KPSS) tests. Minimization of the corrected Akaike Information Criteria (AICc) was used to optimize SARIMA parameters.

In a next step, different external regressors (e.g., effect of study and exam periods, and holiday periods, COVID-19 restrictions, and relaxations,...) were tested to predict the PNML of ethyl sulphate. The effect size and significance of each independent variable was determined individually. This way, the SARIMA modelling approach combined with linear regression provides a quantitative way to determine the effect of certain policy changes and was used in addition to the graphical investigation. Each external regressor (see Equation 2 and 3) was defined as a dichotomous variable (e.g., no restriction and restriction at a specific time). Different scenarios were tested in which (i) COVID-19 restrictions were assessed individually or combined and (ii) different effect durations (one week, two weeks and one month) were evaluated.



STL decomposition of the population-normalized mass load of ethyl sulphate PNML interp = trend + season 7 + remainder

Fig. 2. Seasonal and Trend decomposition using LOESS of the imputated population-normalized mass load (PNML_interp, expressed in g/day/1000 inhabitants). The latter (top graph) is the sum of the longitudinal trend (trend, second graph), the weekly trend (season_7, third graph) and the residuals (remainder, bottom graph).

This resulted in six different scenarios as illustrated in Table S2.

4. Results

4.1. Graphical analysis: Time series decomposition

Fig. 2 visualizes the results of the STL decomposition. The data and R scripts that were used for the statistical analyses are provided in the Supplementary Files. In this study, the seasonal component of the time series consisted of the weekly changes in alcohol consumption, with the highest use observed during the weekends (see Fig. S3). Similar periodic changes in alcohol use were also found by others in this research field (Boogaerts et al., 2021; Baz-Lomba et al., 2016; Gao et al., 2020). No other significant seasonal patterns (e.g., monthly, seasonally, yearly, ...) were observed within this time series with the autocorrelation function. However, only two years of sampling were included and, at the time of the study period, a large socio-demographic disruption occurred which might influence specific periodic changes.

The trend component in Fig. 2 captured the longitudinal pattern of the PNML of ethyl sulphate over the sampling campaign. This visualization also clearly highlights the high temporal resolution obtained with the WBE approach and its ability to pinpoint certain specific days during the sampling campaign (e.g., holidays, start of academic year at University of Leuven at the end of September).

To accurately capture the average temporal change in alcohol consumption, Fig. 3 plots the 28-day weighted average of the trend component. Some of the COVID-19 interventions had a profound effect on the use of alcohol in the catchment area served by WWTP Leuven. During the first lockdown phase (A-B) (Vlaams expertisecentrum voor alcohol en andere drugs, 2020), alcohol consumption was lower compared to the pre-pandemic period. In contrast to these highly restrictive measures, alcohol use increased after the re-opening of the catering industry (Vlaams expertisecentrum voor alcohol en andere drugs, 2020) (C) and 2021 (H). Minor expansions (B) and reductions (E) in the number of contacts per household did not result in major changes in alcohol consumption. The implementation of a curfew at 11 pm (F) could potentially have halted the on-going increase in alcohol use at the beginning of October 2020, but more information is needed to confirm this hypothesis.

Another observation of the obtained high-resolution dataset was that alcohol use consistently declined during the exam periods (i.e., in January, June and end of August) at the University of Leuven, with the exception of the finals in June 2020. However, at this time, the catering industry re-opened and the number of contacts per household increased to 15. In contrast to the exams, holiday periods resulted in an increase in alcohol use.

4.2. Quantitative analysis: Dynamic regression models with SARIMA errors

Dynamic regression was performed to verify and quantify the effects of the policy changes observed in the previous section. Equation 2 and 3 describe the multiple regression models with SARIMA error models that were constructed to fit the logarithm of the PNML of ethyl sulphate. The distinction between both models is that Equation 2 considers the effect of all restrictions or relaxations combined and that Equation 3 determines the effect of each intervention individually. The estimated SARIMA errors resembled a white noise series and were normally distributed in both cases (see Figs. S4 and S5).

Equation 2 Dynamic regression model with SARIMA errors, all restrictions and relaxations were combined as separate external regressors.



Fig. 3. Temporal changes in the 28-day weighted moving average of the trend component (expressed in g/day/1000 inhabitants). The latter was obtained by decomposing the population-normalized mass load of ethyl sulphate with STL decomposition. Green dashed lines represent COVID-19 related relaxations. Red dashed lines show COVID-19 related restrictions. The encoding of the letters corresponding with the COVID-19 interventions can be found in Table 1. Blue areas overlay with exam periods during the academic year. The green plotted lines on the chart visualize the temporal changes during general holiday periods. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

log(PNML) Combined restrictions + Combined relaxations + Exampleriod + Holiday period + ε

where ε is modelled using ARIMA(0,1,2)(3,0,0)₇.

Equation 3 Dynamic regression model with SARIMA errors that considered each policy change individually. The encoding of the letters corresponding with the COVID-19 interventions can be found in Table 1.

improve the predictive accuracy. For this reason, the direction of the effect size of the predictors should not be neglected as they could be valuable to forecast the PNML.

In addition, Table 2 shows that some of the governmental interventions had a significant effect on the consumption of alcohol. For

 $\log(PNML)$ RestrictionA + RelaxationB + ... + RelaxationJ + Examplied + Holidayperiod + ε

where ε is modelled using ARIMA(0,1,2)(3,0,0)₇.

Table 2 summarizes the p-values obtained with the different scenarios described in Section 3.2.2. Holiday periods resulted in increased alcohol consumption in all scenarios, while exam periods resulted in significant decreases in alcohol use in most cases. For both categorical variables (i.e., holiday and exam periods), the same period was considered for all scenarios, but small differences might originate because of the influence of the other external regressors (e.g., specific interventions) within the dynamic regression model and different effect durations (i.e., 7, 14 or 30 days, see Table S2). Importantly, for forecasting purposes, predictors with insignificant p-values may still example, re-opening of the catering industry in June 2020 (C) resulted in significantly increased alcohol consumption (i.e., a 75.8 % increase when considering a period of 30 days after the implementation of this restriction). The combined effect of the COVID-19 relaxations when considering 14 days after re-lifting of each measure also resulted in a significant increase in alcohol use. The analysis also showed that the restrictive measures (A, E, F and G) did not result in significant changes in the consumption of alcohol in any of the tested scenarios (i.e. as combined external regressor or as separate external regressors, different effect periods,...).

However, the difficulty with the quantitative approach is that the

Table 2

Multiple regression with SARIMA errors results: effect sizes and p-values obtained with the different scenarios that assessed effect duration and combination of policy changes. The significance level alpha was set at 0.05. (*): for some interventions a period of less than 30 days was considered because the following intervention started in less than a month. The encoding of the letters corresponding with the COVID-19 interventions can be found in Table 1.

		7 days Effect size (%) [p-value]	14 days Effect size (%) [p-value]	30 days Effect size (%) [p-value]				
i) Interventions as separate external regressors								
Exam period		-4.27 [0.46]	- 10.9 [3.3e ⁻ 2]	- 13.3 [6.3e ⁻ ³]				
Holiday period		16.1 [5.5e ⁻⁴]	13.3 [1.6e ⁻³]	15.5 [3.5e ⁻⁴]				
Intervention	Α	3.2 [0.85]	0.3 [0.97]	-5.54 [0.58]				
	(Restriction)							
	В	1.8 [0.91]	34.3 [1.6e ⁻²]	-6.2 [0.62]				
	(Relaxation)							
	С	-15.1 [0.33]	43.2 [5.9e ⁻³]	75.8 [1.0e ⁻³]				
	(Relaxation)							
	D	-1.9 [0.90]	32.3 [2.7e ⁻²]	24.5 [0.22]*				
	(Relaxation)							
	E	-16.1 [0.28]	-5.2 [0.66]	5.48 [0.71]				
	(Restriction)		0 6 50 403					
	F	-26.1 [7.4e	-9.6 [0.49]	-7.3 [0.61]*				
	(Restriction)	-]	16 8 50 151	0 5 50 401				
	G (Destaintion)	-15.9 [0.30]	-16.7 [0.15]	-9.5 [0.40]				
	(Restriction)	1 1 [0 04]		24.0 [5.26-2]				
	П (Bolovetion)	1.1 [0.94]	7.4 [0.55]	24.9 [5.2e]				
	(Relaxation)	19.6 [0.49]	0.0 [0.49]	2 4 [0 77]				
	I(Relaxation)	2 1 [0 00]	9.2 [0.46] 5 7 [0 70]	5.4 [0.77] 6 28 [0.68]				
	(Relavation)	2.1 [0.90]	-3.7 [0.70]	-0.28 [0.08]				
ii) Combination of all restrictions and relavations								
Exam period		-5.2 [0.37]	-9.3 [8.8e ⁻²]	-5.9 [0.29]				
Holiday period		16.4 [4.4e ⁻⁴]	14.6 [1.2e ⁻³]	16.7 [2.7e ⁻⁴]				
Restrictions		-13.1 [0.14]	-7.8 [0.27]	-5.5 [0.48]				
Relaxations		-4.4 [0.53]	17.8 [5.3e ⁻³]	8.8 [0.28]				

effects of some of the COVID-19 interventions on alcohol use may be short-lived. This is also demonstrated by the longitudinal trend component in Fig. 3. This indicates that the scenarios considering only a short period of time after the implementation of a certain intervention (e.g., only 7 or 14 days) may be most appropriate to capture the effect. However, considering shorter effects periods increases uncertainty due to lower frequencies of independent categorical variables. Moreover, as illustrated in Fig. 3, not every COVID-19 countermeasure influenced alcohol consumption directly. Although combining multiple interventions (either restrictions or relaxations) increases the period of intervention under investigation, it could also potentially conceal the effects of certain policy changes that had the strongest individual effect. Nevertheless, the quantitative approach indicates that some of the COVID-19 measures resulted in short-term temporal changes in alcohol use, with the same direction of effect as compared to the graphical analysis, although not statistically significant. It is important to note that inclusion of COVID-19 countermeasures in the models still resulted in a lower AICc values, meaning that they had predictive value for determining the PNML of ethyl sulphate. This suggests that the direction of the effect size (i.e. positive or negative) could be used as verification of the graphical investigation in Section 4.1.

5. Discussion

5.1. WBE as an epidemiological tool to monitor temporal changes

To our knowledge, this is the first WBE study that investigates alcohol use during the COVID-19 crisis for a continuous period of two years. Daily IWW samples (n = 735) were analyzed to highlight specific days (e.g., start of the academic year at the University of Leuven, start of the holiday period, New Year, ...), but the collection of weekly composite IWW samples might be sufficient to capture the long-term trends in alcohol use (i.e., two year pattern). However, more research is needed to compare the different sampling strategies (i.e., continuous or stratified) and frequencies (i.e., daily, weekly, monthly, ...) to accurately capture long-term trends. The high temporal resolution in this study was particularly useful to evaluate the short-term temporal changes in alcohol use.

As indicated before, approximately 45 % of the catchment population served by WWTP Leuven consisted of university students in 2019. However, the total number of enrolled students will probably not be present each day. The contribution of the student population in Leuven is clearly visible in the decomposed trend in alcohol use. Decreases in alcohol consumption were observed during the exam periods (Fig. 3) of each academic year (except for of June 2020), which were followed by an increase in consumption at the start of each semester. In contrast to the exam periods, holiday periods resulted in increased alcohol use (i.e., summer vacation, Christmas holidays,...). During the exam periods, it is also likely that less students are present in the catchment area compared to the rest of the academic year. Higher alcohol consumption at the start of the summer vacation could potentially be explained by the end of the academic year that coincided with the vacation period of high school students. Additionally, summer times were often characterized by eased COVID-19 measures (e.g., re-opening of the catering industry in 2020 and 2021, expansion of the number of contacts, ...). In contrast to holiday periods, the exam periods only influence the student population in the catchment area. Even though the nightlife and fraternity parties were not allowed during the entire sampling period, the student population of Leuven still engaged socially to consume alcoholic beverages. Additionally, changes in alcohol consumption could also potentially be explained by changing demographic characteristics of the catchment population with a large proportion of university students being absent during certain phases of the different waves of the COVID-19 crisis. For example, during the lockdown phases, students were advised by the government to return home and no students were allowed on-site at the university. However, it was also possible that some students remained isolated in student housings within the catchment area. Yet, there was a 50 % decrease in the number of people present in the catchment area due to the stay-at-home measures and a reduction in commuting patterns in and out of the Leuven area was observed. A limitation of WBE is that it cannot tell if an increase or decrease in alcohol consumption is the result of changing socio-demographic features of the catchment area. It is important to keep this in mind when evaluating changes in the longitudinal trend of the PNML of ethyl sulphate. Furthermore, the European Championship of soccer began Mid-June 2021 and could also have a synergetic effect with the other factors that contributed to the increase in alcohol use during this period.

5.2. Temporal changes in alcohol consumption during the COVID-19 pandemic

Fig. 3 showed that alcohol consumption decreased shortly after the implementation of COVID-19 restrictions, including the first lockdown phase (A-B). Contrastingly, there were no significant effect of the restrictions on alcohol use using the quantitative approach. This could potentially be the result of low levels of alcohol use observed right before the start of the lockdown measures. The results of the graphical approach were in line with data from other WBE applications (Bade et al., 2021; Bade et al., 2021). For instance, Bade et al. found that alcohol consumption decreased significantly during the lockdown when social venues (e.g., bars, nightclubs,...) were closed and social activities prohibited (Bade et al., 2021; Bade et al., 2021). In that study, 134 IWW samples were analyzed retrospectively from 20 sites in Australia (covering 47 % of the general population) (Vlaams expertisecentrum voor alcohol en andere drugs, 2020) from before the lockdown (February), during the lockdown (April) and after most restrictions were eased (June). In addition, samples were collected on seven consecutive days every two months in the same locations starting from April 2016 to

the end of 2019. These findings might suggest that alcohol use in the catchment population was impacted by the stay-at-home measures and self-isolation, potentially by limiting the social opportunities to consume alcohol. However, the decrease in alcohol use during the lockdown phase (A-B) might also be the result of changing demographics with a lot of university students moving out of the borders of the catchment area. In addition, Bade et al. observed that weekend use was especially affected by the stringent COVID-19 countermeasures, but this was not the case in the present study. Analysis of seasonality showed that weekly trends in alcohol use remained unaffected in WWTP Leuven during the lockdown phase compared to the 2019 period. In Leuven, people still consume more alcohol during the weekend compared during the week during the pandemic. This is an interesting observation as most students are not present in the catchment area of Leuven during the weekends before and during the pandemic. At the same time, it is hypothesized that the changes in availability (e.g., curfews, restrictions in overnight alcohol sales, closing of catering industry, ...) also affected the amounts of alcohol used during the periods associated with the majority of COVID-19 restrictions. It also appears that the consumption of alcoholic beverages in periods of home confinement was lower compared to the periods when the catering industry re-opened (C, H).

The present study also observed that the reduction in alcohol use was followed by an immediate increase in consumption after re-lifting of most restrictions, which was also in line with the results found by Bade et al (Bade et al., 2021). In contrast to the results on restrictions, the quantitative analysis confirmed that some of these relaxations resulted in a significant increase in alcohol use. Furthermore, this was also confirmed by the overall significant increase over a 14-day period when combining the effect of all relaxations (see Table 2). The elevation in consumption was especially the case for relaxations that influenced the availabilities of venues where you can drink. Particularly, relaxations directly linked with the re-opening of the catering industry (C, H) resulted in an increase in alcohol consumption in the first 1.5 years of the sampling period. Re-opening of the catering industry (only outdoors) in May 2021 (H) resulted in a profound short-term increase in alcohol consumption. Contrastingly, re-opening of the catering industry indoors (June 2021) (I) and the re-lifting of all remaining restrictions concerning the catering industry (e.g., curfew, limited number of seats,...) (J) in August 2021 did not result in an additional increase in alcohol consumption. We hypothesize that this could be related to the ambient temperature during these summer times. It is plausible that people who were used to go to pubs before the pandemic now exchanged their pub culture for outside facilities (e.g., terraces) since these were sooner available. Additionally, people might be less motivated to follow the stringent COVID-19 countermeasures after almost two years of the start of the COVID-19 crisis. It should also be noted that the impact of the first exit strategy (May 2020) (B) was less intense compared to other relaxations with only a small increase in alcohol consumption that was quickly followed by a further decrease. This short-lived increase in alcohol use could be the result of the nature of the policy change, that is, the intervention only allowed for people to expand their number of contacts and did not affect the availability of alcohol directly. Furthermore, the exam period coincided with the first exit strategy. During these times, it is possible that the student population contributed less to the measured PNML of ethyl sulphate in the sewage system.

As visualized by the longitudinal trend component, only a minor increase from baseline alcohol consumption was noted during the entire sampling period. The observed pattern was in line with the slightly increasing pattern in alcohol use in Belgium that was reported in the 2018 Global Status Report on alcohol and health (World Health Organization, 2019).

6. Study advantages and limitations

6.1. Study advantages

To our knowledge, this is the first WBE study that investigates alcohol use during the COVID-19 pandemic for a continuous period of two years. By analyzing daily 24-h composite samples, WBE is one of the few data sources that can measure the effects of policy changes with a very high temporal resolution. For this reason, WBE proved to be a valuable complementary information source to assess the (short-term) effects of the COVID-19 countermeasures in the catchment population.

This case study also proves that WBE is capable of measuring consumption patterns in very specific locations. Furthermore, this investigation is among the first WBE applications that provides a statistical evaluation based on time series analysis (i.e. time series decomposition and multiple regression with SARIMA errors) to investigate temporal changes in alcohol use and can be used as a framework for other researchers in the field to investigate similar datasets.

6.2. Study limitations

Important to note is that WBE provides consumption estimates at the general population level. It cannot provide information on the sociodemographics of specific individuals who consume alcohol, nor on the drivers for alcohol use during the COVID-19 disruption (Bollen et al., 2021). Additionally, this study considers only a sampling period of two consecutive years and is not conclusive with regards to the long-term effects of the COVID-19 crisis.

Additionally, it is possible that specific policy interventions and/or events could have a synergetic or antagonistic effect on alcohol consumption (Calina et al., 2021). The dynamic regression models with ARIMA errors only consider a selection of events to predict the PNML of ethyl sulphate, but other factors that were not included might also have an impact on alcohol use (e.g., weather conditions, other drinking motives, ...) and could potentially further increase the predictive accuracy of the models (Bollen et al., 2021).

It should be noted that the results of the catchment under investigation are not generalizable to the entire Belgian population. The catchment area is urban, only corresponds to 1 % of the entire Belgian population, and is characterized by a large student population. Additionally, the heterogenic effects of COVID-19 countermeasures on alcohol consumption across different European countries may also be true on a national level, and spatial differences in response to the policy changes might be present in different Belgian locations. Nevertheless, these findings are valuable in the global picture of alcohol use during the COVID-19 pandemic.

Previous studies have found that ethyl sulphate degrades considerably in real rising main sewer and simulated rising main sewer, and less strongly in gravity sewer conditions over a 12-h period (Banks et al., 2018; Gao et al., 2019), which could lead to an underestimation of the alcohol consumption. However, it should be noted that sewer reactors tend to overestimate the degradation in pilot and actual sewers (Choi et al., 2020). Ethyl sulphate also has high in-sewer stability in biofilmfree (BFF) conditions (Banks et al., 2018), but BFF stability has no clear relationship to stability in pilot and actual sewers (Choi et al., 2020). Furthermore, ethyl sulphate has a high in-sample stability within 18 h (Rozhanets, et al., 2021). The contrasting results between these studies indicate that more research is needed to investigate the stability of ethyl sulphate during in-sewer transport. However, at this point, ethyl sulphate is considered the most appropriate WBE biomarker to measure alcohol use and is widely adopted in different WBE studies (Boogaerts et al., 2021; Baz-Lomba et al., 2016; Gao et al., 2020; Burgard et al., 2019). The objective is to establish temporal trends within one location rather than compare spatially. Degradation within one location will be relatively constant and likely not influence the underlying temporal trend in a meaningful way.

Although flow-proportional sampling is recommended for the collection of 24-h composite IWW samples, time-proportional sampling was applied for technical reasons in this study. However, as briefly mentioned, high sampling frequencies were applied to compile the daily IWW samples to ensure accurate average biomarker concentrations over the 24-h period (Ort et al., 2010).

Important to note is that WBE relies on the premise that the sociodemographic attributes of the catchment population remain fairly constant. In this sense, an increase of alcohol use observed with WBE can be due to three scenarios: i) a larger proportion of people consuming the same amounts of alcohol; ii) a smaller proportion of people consuming more; or iii) the combination of both. During the different phases of the COVID-19 pandemic, the demography of the catchment population may change significantly over time (see section 2.1. Sampling). Changes in socio-demographics also occur during the weekend with the majority of students leaving the catchment area. To minimize the uncertainty associated with changes in population size, mobile network data was implemented for the refinement of WBE back-calculations. In particular, the application of a dynamic population marker, such as mobile phone data, is necessary to account for the daily variations in the population present in the catchment area. Additionally, the use of this population proxy is needed to account for the major changes in population size during the COVID-19 pandemic. In particular, the first lockdown period (i.e. 14 March 2020 through 8 June 2020) was characterized by a 50 % decrease in population size. In these instances, the use of static population numbers would result in high uncertainty.

7. Conclusions

This case study shows that WBE can measure the effect of policy changes on alcohol use with a high temporal resolution. To our knowledge, this is the first study that investigates daily IWW samples on ethyl sulphate for a period of two years. In this light, WBE proved capable of monitoring the short-term temporal changes in alcohol use. Owing to its easily adjusted temporal frequencies, WBE can retrospectively provide aggregated consumption estimates, continuously, and with a shorter lag time to the policy changes compared to traditional information sources. Its unique feature to compile consecutive daily consumption estimates proves to be particularly useful to measure the direct effects of the COVID-19 countermeasures on alcohol use. In particular, the graphical approach was successful in visualizing shortterm changes in the consumption patterns of alcohol. This information can be used by governmental and health institutions for the optimization and management of prevention, harm-reduction, and treatment strategies to target alcohol consumption. The results of this study show that WBE is more sensitive compared to other epidemiological information sources to assess the direct effects of governmental interventions on alcohol use (Boogaerts et al., 2022; Bade et al., 2021; Reinstadler et al., 2021; Thomaidis et al., 2016). The quantitative statistical framework used in this study is useful for future WBE research to evaluate the effect of policy changes on exposure to different xenobiotics (e.g., illegal drugs, pharmaceuticals, ...).

CRediT authorship contribution statement

Tim Boogaerts: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Xander Bertels:** Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Bram Pussig:** Conceptualization, Resources, Methodology, Writing – original draft, Writing – review & editing. **Maarten Quireyns:** Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Louis Toebosch:** Investigation, Visualization, Writing – review & editing. **Natan Van Wichelen:** Investigation, Writing – review & editing. **Catalina Dumitrascu:** Investigation, Writing – review & editing. **Catherina Matheï:** Conceptualization, Funding acquisition, Methodology, Resources, Supervision. **Lies Lahousse:** Formal analysis, Methodology, Supervision, Writing – review & editing. **Bert Aertgeerts:** Resources, Supervision, Writing – review & editing. Hans De Loof: Formal analysis, Methodology, Supervision, Writing – original draft, Writing – review & editing. Adrian Covaci: Conceptualization, Methodology, Funding acquisition, Resources, Project administration, Supervision, Writing – original draft, Writing – review & editing. Alexander L.N. van Nuijs: Conceptualization, Methodology, Funding acquisition, Resources, Formal analysis, Project administration, Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have shared the link to my data in the "Attach Files" step.

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Appendix A. Supplementary data

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