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RESEARCH REPORT

ADDICTION SSA

Mapping consumptions and market size of cocaine, amphetamine and MDMA through wastewater analysis: A Dutch case study

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Abstract

Background and Aims: Illicit drug consumption is associated with public health effects and criminal activities. This study aimed to estimate Illicit drug consumption and annual market in the Netherlands from wastewater analysis of drug residues.

Methods: Residues of cocaine, amphetamine and 3,4-methylene dioxymethamphetamine (MDMA) were measured between 2015 and 2022 in 30 Dutch wastewater treatment plants serving both rural and urban populations. These wastewater treatment plants covered 20% of the total Dutch population. The Dutch annual retail market was estimated by extrapolating consumption to the total Dutch population, back-calculating consumption volume, correcting for drug purity and street price collected in voluntary checking services, and accounting for the correlation of consumption and urbanity.

Results: The per capita MDMA and cocaine consumption correlated positively with the urbanity of the wastewater treatment plant catchments with r^2 of 31% and 64%, respectively. Amphetamine did not show a significant correlation with urbanity. The three studied drugs were conservatively estimated to cover an average annual market value of 903 (95% prediction interval 829 to 987) million Euro for the studied period. Market estimations from prevalence figures and interceptions of international trade were similar.

Conclusions: Illicit drug consumption in the Netherlands appears to correlate positively with urban (in contrast to rural) areas. Wastewater analysis can be used to estimate the volume and monetary value of illicit drug markets as a proof of concept.

KEYWORDS

amphetamine, cocaine, Dutch drug consumption estimate, Dutch drug market estimate, environmental forensics, illicit drugs, illicit stimulants, MDMA, rural vs. urban stimulant consumption, wastewater-based epidemiology (WBE)

INTRODUCTION

Illicit drug consumption is of societal relevance because of its potential impact on public health and criminal activities linked to procurement, production and trade [1]. Collecting data on consumption and the drug market is of value for governments and law enforcement because it can direct or evaluate policy measures.

Various approaches are being applied to characterize the illicit drug production, supply and demand. For plant based illicit drugs, the land surface used to grow the crop is indicative for the production volume [2]. For synthetic illicit drugs production volume is more difficult to estimate because indicators such as numbers and size of dismantled laboratories and interceptions of precursors or products are more difficult to interpret [3, 4]. Statistics on use prevalence, drug related crimes and medical incidents related to drug consumption also indicate trade and consumption. Consumer behaviour is mostly monitored through surveys and qualitative interviews with experts [5]. The drug characteristics can be tested from samples of voluntary drug testing services or seized drugs, providing information on purity and pricing of drugs on the local market [6–8]. Although these sources provide valuable information, they are not suitable to determine local consumption volumes and markets.

Since 2005, wastewater-based epidemiology (WBE) has been applied to evaluate drug consumption for a defined population [9, 10]. WBE can provide information on the illicit drug consumption on local, regional, national and international scales [11–13]. Studies illustrate that drug residues can be determined rather accurately with appropriate monitoring of wastewater [14]. Wastewater-based epidemiology is often used for relative comparison of cities or regions [11]. Its use to back-calculate actual consumption volumes and market shares is less common because of uncertain excretion rates of the drugs and metabolites linked to the application route (e.g. ingestion, snorting, inhalation and injection) and the conditions under which the consumption takes place (e.g. poly drug use) [15, 16]. Although various studies mentioned the potential of WBE to estimate drug market sizes, only a few actually explored this [12, 17–19].

Loads of pharmaceuticals (licit drugs) in wastewater and surface waters can be predicted from prescription data within a factor two to three when accounting for metabolism and removal during wastewater treatment [20–22]. With frequent monitoring and extended knowledge on sewer hydrology, loads of some pharmaceuticals can even be predicted within an accuracy of a factor ∼1.5 in untreated wastewater [23]. The comparison of forward and back calculation for pharmaceuticals suggests that illicit drug residues in wastewater enable to back calculate consumed volumes with a similar accuracy [13, 24–26]. With additional information on street prices, these back calculated consumed volumes can be used to estimate the local financial market size [19].

The current study aims to estimate Dutch national drug consumption and financial market size of amphetamine (also known as speed), 3,4-methylene dioxymethamphetamine (abbreviated as MDMA and also known as ecstasy or molly) and cocaine, from drug residues in wastewater. Methamphetamine was analysed, but not often detected, therefore, data were not included in this study. Subsequently, obtained results are compared to national and international estimates of trade [2, 3, 27] and use that are based on prevalence and law enforcement data [5, 28–30].

METHODS

From wastewater sampling to illicit drug market size

Figure 1 illustrates seven relevant steps to use wastewater in estimating per capita drug consumption [31] and market size. Below the methods are described step by step. Details can be found in the Supporting Information. The analysis was not pre-registered on a public platform, and the results should be considered exploratory.

Wastewater sampling (step 1)

Sampling was performed according to protocols defined by the Sewage Epidemiology Core group [32]. Representative 24 hour composite wastewater influent samples were for at least seven consecutive days per sampling location [31]. Sampling weeks were planned outside public holidays, school holidays and large events to prevent deviations from 'baseline' consumption [33].

Chemical analysis and quantification (step 2)

Drug residues were quantified using liquid chromatography coupled to high resolution mass spectrometry (LC-HRMS). Analytical methods were validated by annual interlaboratory testing throughout the monitoring period [34].

Calculating loads per 1000 inhabitants (step 3)

The measured levels of the three analytes in each 24 hour composite sample were divided by the corresponding daily wastewater flow provided by the water authorities to obtain the load. The load was normalized to the connected population and expressed per 1000 inhabitants.

Correlating loads to urbanity (step 4)

The urbanity of the catchment of the wastewater treatment plants (WWTP) was expressed in an urbanisation score (U_{wwtp}) that ranged from 0 (not urban) to 1 (extremely urban). The scores were derived from the urbanity classification of the Dutch National Statistics

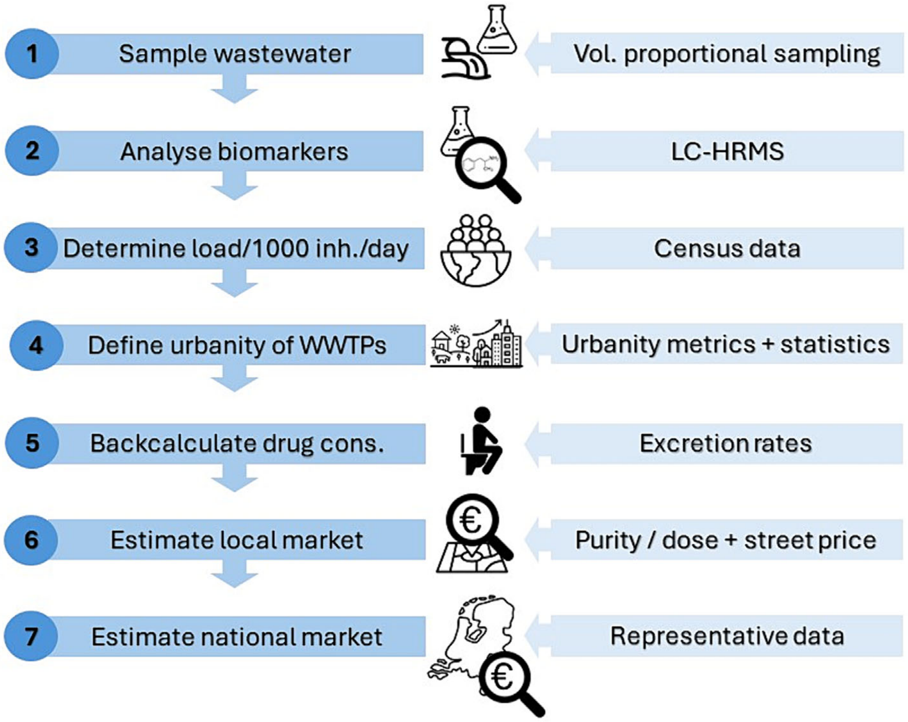

FIGURE 1 Seven steps and quality criteria in calculating illicit drug consumption and market size from wastewater analysis. LC-HRMS, liquid chromatography-high resolution mass spectrometry; WWTPs, wastewater treatment plants.

TABLE 1 Back calculation factors to convert loads of drug biomarkers to consumption.

Drug residue	Factor applied for consumption estimation[a] (coefficient of variance %, *n* subjects, standard error of mean)	Ingestion route applied for calculations of consumption	Excretion route applied for calculations of consumption
Benzoylecgonine (to estimate consumption of cocaine)	3.59 (26%, >500, 1%)	Nasal	Renal excretion (urine)
Amphetamine	2.77 (23%, 9, 8%)	Oral	Renal excretion (urine)
MDMA	4.40 (41)[b]	Oral	Renal excretion (urine)

Abbreviation: MDMA, 3,4-methylene dioxymethamphetamine.
[a]Data obtained from Gracia-Lor *et al*. [25] and references therein.
[b]Coefficient of variance not given.

Bureau [35] that defines extremely urban as >2500 addresses per km^2 (score 1) very urban as 1500 to 2500 addresses per km^2 (Score 0.75), moderately urban as 1000 to 1500 addresses per km^2 (score 0.5), lightly urban as 500 to 1000 addresses per km^2 (score 0.25) and not urban as <500 addresses per km^2 (score 0). These scores were multiplied by the number of inhabitants per urbanity class ($N_{urbanity\ class}$) and subsequently divided by the total number of inhabitants in the catchment of the WWTP catchment (N_{wwtp}) to obtain the overall urbanity score (U_{wwtp}) as shown in Equation (1).

$$U_{wwtp} = \frac{1 * N_{extr.\,urban} + 0.75 * N_{very\,urban} + 0.5 * N_{mod.urban} + 0.25 * N_{light.\,urban} + 0 * N_{not\,urban}}{N_{wwtp}} \tag{1}$$

Back calculating drug consumption (step 5)

Per capita consumption was calculated by converting the per capita loads with factors correcting for excretion (Table 1) [25].

Estimating local drug market (step 6)

Market size per drug was estimated by multiplying the calculated consumption within a WWTP catchment (*Consumption [WWTP]*) with street prices of the drugs after correcting for purity or dose and the consumers price index [36] (Table 2) of the respective year as shown in Equation (2).

TABLE 2 Consumer price indices, purities or doses and street quality of 'real' voluntary provided drugs[a] from test services.

Year	Consumers price index[b] (2022 = 100%)	Cocaine		Amphetamine		MDMA	
		Purity %[c]	Street price €/g	Purity %[d]	Street price €/g	Dose mg/pill[e]	Street price €/pill
2015	82.4%	64.0	51	46.0	7.2	146.9	4.5
2016	82.6%	66.8	49	44.5	8.6	156.5	5.6
2017	83.8%	68.3	49	46.0	7.4	164.1	4.9
2018	85.2%	65.4	49	48.1	7.3	171.0	4.1
2019	87.4%	68.8	50	49.5	7.4	172.0	4.1
2020	88.5%	68.9	50	50.8	8.1	166.0	4.3
2021	90.9%	71.3	52	51.7	7.9	147.8	4.2
2022	100.0%	74.3	52	47.9	8.5	136.0	4.4
Average (2015–2022)		68.5	50.3	47.7	7.8	157.5	4.5

Note: National data for cocaine, amphetamine, MDMA are obtained from Van Laar *et al.* [5] (2015–2020) or online reporting after 2020 [28–30]. Annual sample sizes range from 2221 to 11 654 for MDMA pills, 541 to 1540 samples for cocaine powder and 598 to 1088 samples for amphetamine powder.
Abbreviation: MDMA, 3,4-methylene dioxymethamphetamine.
[a]Data are based on real samples that consist exclusively or mainly of the presumed substance. Fake drugs, consisting (mainly) of other substances (e.g. caffeine) and dubious samples with unidentified/quantified compounds are excluded from the market calculation.
[b]Consumers price index is calculated based on annual mutation of consumer prices, 2022 is set as 100% [36].
[c]A total of 99%–100% of the cocaine is presented as powder.
[d]A total of 95%–100% of amphetamine is presented as powder/crystal.
[e]A total of 83%–93% of the MDMA samples are presented to the test service as pill, the rest is presented as powder and not included in the calculation.

$$Market\ size\,(WWTP) = \frac{Consumption(WWTP)}{purity\ or\ dose} * \frac{street\ price\,(year)}{consumption\ price\ index\,(year)} \tag{2}$$

Estimating national drug market size (step 7)

A total of 20% of the Dutch population was studied by sampling the wastewater influents during 1 week between 2015 and 2022. Some WWTPs were studied for multiple weeks within or over multiple years. The relationship between drugs residues in wastewater and urbanity were used as a proof of concept to illustrate the use of demographic information to refine the consumption and market estimates. Subsequently, the national consumption and total drug market size was extrapolated.

Statistical evaluation

The observed overall loads of the three substances were described by means, range and quantiles and were modelled by a generalized linear model (GLM) with day of week and urbanity score as additive predictors and applying a 0.05 significance level. The predictor r^2 was used to characterize the effect size of the model. A case-based bootstrap procedure (bootstrap size of 1000) was used to establish 95% prediction intervals when applying the models. All statistical calculations were done in the *R* programming environment [37].

RESULTS

Descriptive statistics of the dataset

In total 392, 364 and 357 unique 24 hour composite wastewater samples were selected for analysis of benzoylecgonine, amphetamine and MDMA, respectively. More than 3.6 million Dutch inhabitants were monitored for one or more weeks. Table 3 and Figure 2 provide descriptive statistics of the data and Table A1 and A2 in the Supporting Information provides an overview of sampling dates. In all cases seven consecutive 24 hour composite samples were collected per WWTP. For MDMA and amphetamine several monitoring weeks were excluded because of suspected or identified residues of drug production waste in the wastewater [38]. Drug production waste can contain non-consumed MDMA or amphetamine leading to overestimation of consumption.

Samples were taken at the influent of the WWTP except for two locations where samples were collected at a strategic location in the sewer system to isolate a specific municipality. Furthermore, one municipality was covered by five small WWTPs, two of which served less than 5000 inhabitants. The WWTPs were sampled individually, but the results were pooled to prevent small sample size bias. All other WWTPs served at least 7867 inhabitants, which is almost in agreement with the 10 000 inhabitant threshold for robust and ethically acceptable estimations of per capita loads [39]. The week averages of the daily per capita loads of the studied WWTPs vary a factor 9.3, 21 and 19 for benzoylecgonine, amphetamine and MDMA, respectively. The loads were log normally distributed. Amphetamine data were not corrected for medical use of dexamphetamine, because its contribution was negligible (3.1% or less, see Supporting Information).

TABLE 3 Descriptive statistics of the data.

	Benzoylecgonine	Amphetamine	MDMA
No. of unique WWTP	30	30	30
Range of inhabitants per WWTP	2613–607 195	2613–670 195	2613–670 195
Total no. of inhabitants covered	3 653 599	3 653 599	3 653 599
Sampling years	2015–2022	2015–2022	2015–2022
No. of sampling days and full weeks	392; 56	357; 51	364; 52
Average daily load in mg per 1000 inhabitants per day	497	240	105

Abbreviations: MDMA, 3,4-methylene dioxymethamphetamine; WWTP, wastewater treatment plants.

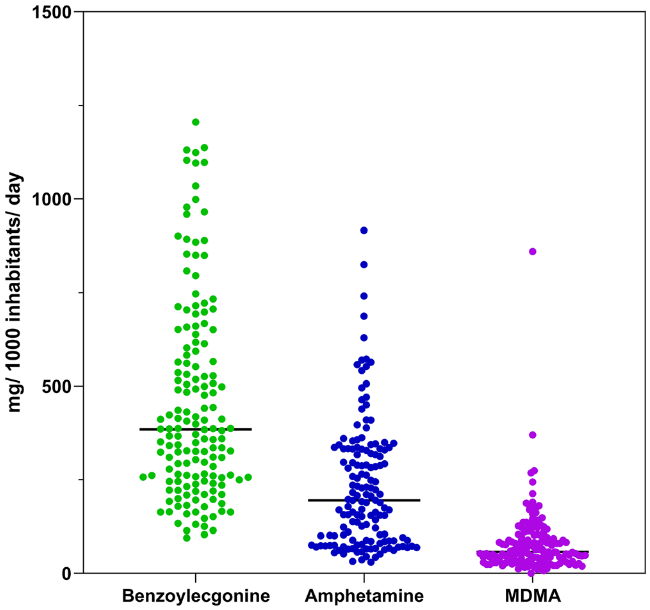

FIGURE 2 The distribution of the load of the substances per 1000 inhabitants per day of all individual 24 hour composite samples.

Urbanity

Figure 3 shows the relationship between the load per 1000 inhabitants per day ($L_{1000/inh./d}$) and the urbanity (U_{wwtp}) as defined in Equation (1). The $L_{1000/inh./d}$ is fitted with a logarithmic relation as shown in Equation (3).

$$L_{1000\,inh./d}(U_{wwtp}) = L_{1000\,inh./d}(U_0) * \exp(k * U_{wwtp}) \qquad (3)$$

Where $L_{1000/inh./d}$ (U_{wwtp}) at any given urbanity score (U_{wwtp}) is a function of the consumption at an urbanity score of 0 ($L_{1000/inh./d}$ [U_0]) and an exponential function with a rate constant k with the unit (U^{-1}).

The log transformed per capita loads of amphetamine show no significant correlation with urbanity, whereas MDMA and benzoylecgonine are positively correlated with urbanity. This means that the average per capita consumption of the latter drugs is higher in more urbanized WWTP catchments. The obtained slopes indicate the magnitude of the variation with urbanity. The loads vary approximately a factor 3 for MDMA and 5 for benzoylecgonine over the range of studied urbanity scores (0.09 to 0.95). The r^2 of the fitted curves are 31% for MDMA and 64% for benzoylecgonine, so a relevant part of the variation of MDMA and cocaine consumption can be explained by urbanity. The GLM analysis corrects for weekly variations such as week-weekend trends that are often observed for the consumption of stimulants like MDMA and cocaine [13, 40].

Calculating consumption and extrapolating to market size

The loads of the drugs or their metabolites per 1000 inhabitants can be used to estimate the consumption [25]. It was assumed that the cocaine consumption is dominated by snorting cocaine, whereas MDMA (pill) and amphetamine (powder) is predominantly taken orally [28]. The observed correlation between consumption and urbanity was used to extrapolate the consumption to all 314 WWTP covering 345 Dutch municipalities with urbanity scores ranging from 0.00 to 0.95. Subsequently, these figures were added up to estimate the annual consumption and market size of the total Dutch population between 2015 and 2022. The monetary value was corrected for inflation using 2022 price levels. The annual Dutch market size of the three drugs is estimated on €903 million with a 95% prediction interval of €829 to €987 million (Figure 4, Supporting Information, Table A3 and A4).

DISCUSSION

Qualitative and semi quantitative assessment of uncertainties and inaccuracies of market size estimates from wastewater analysis of drug residues

Figure 1 illustrates the steps from sampling of wastewater to the Dutch market estimate. The calculations behind these steps are based on a series of assumptions. Below these assumptions and their uncertainties are discussed.

Not all consumed drugs might end up at the WWTP as not all excrements containing drug residues might end up in the sewer and part of the wastewater might be lost because of leaky sewers. Especially in a festival setting and for specific groups within a population such as homeless people, not all excrements might be collected by the

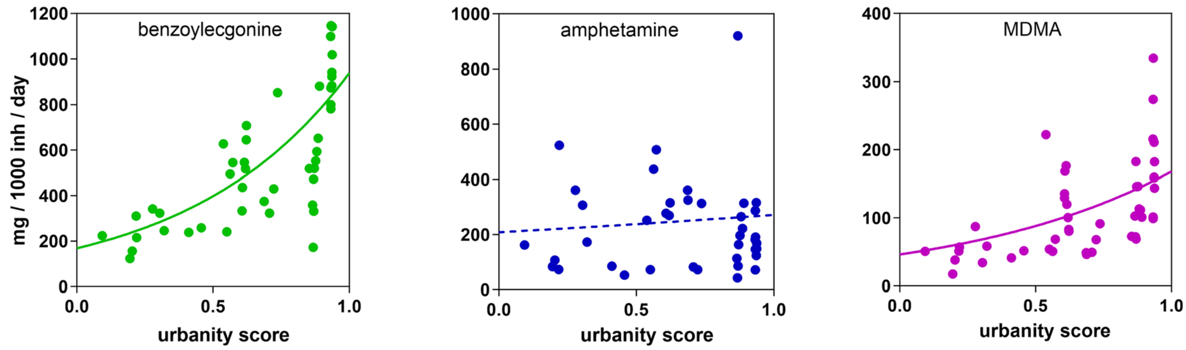

FIGURE 3 Drug residue loads of cocaine (left), amphetamine (middle) and 3,4-methylene dioxymethamphetamine (MDMA) (right) per 1000 inhabitants versus wastewater treatment plant specific urbanity scores. Dots represent the mean values of the wastewater treatment plants per sampling week, curves show the fits of the data, solid lines represent significant trends and dashed lines represent non-significant trends.

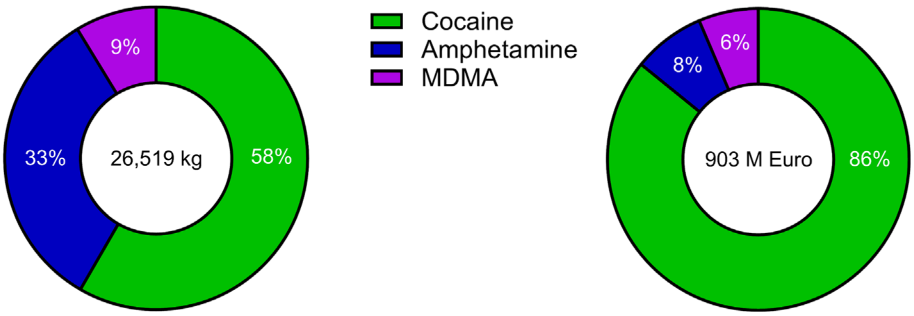

FIGURE 4 Projected Dutch annual drug consumption and market size.

sewer system. The fraction that is 'lost' is unknown. Sewer exfiltration is hard to quantify, but internationally listed losses range from 1% to 13% [41]. In the Netherlands wastewater exfiltration is expected to be at the lower end of this distribution as a significant part of Dutch sewers lies beneath the groundwater table, preventing exfiltration from natural flow sewers. Both the excrements not entering the sewer and sewerage that leaks from sewers lead to losses. Therefore, wastewater analysis at the WWTP is a conservative indicator.

In all cases volume proportional sampling was applied to obtain representative 24 hour composite samples (step 1) and mass labelled internal standards were used to correct for losses during sample treatment and matrix effects (step 2). Population sizes of sewer catchments to calculate per capita loads were obtained from the Dutch Bureau of Statistics (CBS) that collected these data in collaboration with all Dutch Water Authorities (step 3). The current dataset was obtained at WWTP with calibrated wastewater flow meters (except two sampling locations at pumping stations). All analyses were performed by a single laboratory, and census data was validated by the Dutch National Statistics bureau and Water Authorities.

Samples are collected during seven consecutive days. The resulting data are used to estimate annual consumption and to estimate consumption of the Dutch population while correcting for urbanity (step 4). It is debatable to what extent the sampling week is representative for a full year. The sampling weeks were not homogenously spread over the year and intentionally planned outside large events or public holidays (Supporting Information, Table A1). Events and festivities can lead to temporal increases of drug consumption [33, 42]. Holidays might both lead to a temporal reduction of inhabitants and increased numbers of visitors that can affect consumption in both directions. However, a study in Oslo, the capital of Norway, showed that although summer holidays significantly reduced the number of inhabitants, it did not affect the absolute consumption of drugs [43]. Additionally, long term monitoring of drug consumption illustrated rather stable consumption over time in the Netherlands [44]. Therefore, the applied sampling outside large events or holidays presumably presents a conservative estimate of the annual average [13].

The conversion of loads in wastewater to actual consumption is based on the excretion rates of the selected biomarker (step 5). The used conversion factors are based on common application routes under controlled conditions, using volunteers in pharmacological studies [25]. Consumption in the field can also include polydrug use and different administration routes. This affects uptake, distribution, metabolism and excretion rates. For example, cocaine consumption is based on benzoylecgonine excretion of snorted cocaine, the main application route in the Netherlands [8]. However, the base form (crack cocaine) is smoked as well [45] and results in an almost twofold lower excretion of benzoylecgonine than snorting [46]. The applied excretion of benzoylecgonine from snorted cocaine, therefore, underestimates total consumption of cocaine consumed in both forms.

The conversion from pure active substance to street quality that is required to estimate monetary values is based on street prices and average purities (step 6) from 32 drug testing service locations in the

Netherlands and mobile testing services at festivals and events, where consumers can voluntarily test their drugs [8]. The purity and dosing of the drugs is very stable over the sampling period (Table 2). The price levels corrected for dose or purity and inflation show stable or slightly decreasing price levels for amphetamine, cocaine and MDMA over the sampling period. Potentially, these figures might not be representative for the whole market as the visitors of test services do not represent the total user community [47]. Occasional users might be more prone to test their drugs and might pay more for their drugs. In addition, recorded prices are not fully reliable for amphetamine and cocaine because 'advertised' weight might not fully correspond with the sold weight. MDMA dosing is less affected because it is mostly sold in tablet form for which average dosages are well studied [5]. These deviations can both lead to underestimations and overestimations of the market size.

Finally, the calculated local drug consumption and market for 20% of the Dutch population covered by 30 WWTP was used to predict the national consumption and financial market size (step 7). Because the correlation between urbanity and par capita consumption for cocaine and MDMA was significant and could explain a relevant part of the variation, this correlation was applied to predict the consumption of all non-studied WWTPs. The extrapolation from 20% of the population to national figures inevitably introduces uncertainty, but correcting for urbanity reduces this uncertainty for cocaine and MDMA.

Prediction accuracy

The derived 95% prediction interval takes variation as a result of wastewater sampling, chemical analysis, inaccurate census data [31] and the correlation with the urbanity score into account (step 1–4, Figure 1). It does not include the uncertainty of the back calculation factors for excretion (Figure 1, step 5), purity or dosing and pricing (Figure 1, step 6), nor does it account for deviating consumption during holidays and events. The standard errors of the mean for excretion, purity or dose and pricing are small (Table 1) and have limited impact on the national drug market estimate. However, sampling outside holidays and especially events presumably underestimated the markets size, but including this requires extensive sampling to obtain representative sampling of events, which is beyond the scope of this study.

All in all, the estimated Dutch market volume and monetary value can be considered conservative because the potential biases discussed above rather underestimate than overestimate annual consumption. The results are triangulated with estimates based on different, independent information sources.

Triangulation of the Dutch market size

The Netherlands holds a tradition of monitoring drug consumption through national surveys and drug checking services for over three decades [8]. Based on prevalence figures and consumption scenarios, Baarsma *et al.* [48] estimated an annual consumption of 8750 kg street quality cocaine, 4500 kg street quality amphetamine and 8 000 000 MDMA pills. These figures are 56% (cocaine), 52% (amphetamine) and 55% (MDMA) of the estimated annual consumption volumes from wastewater in this study. The difference of less than a factor two between both independent estimates might be regarded as similar, taking all uncertainties into account. Contrastingly, estimates of Tops *et al.* [4], based on confiscated precursors of amphetamine and MDMA exceed the figures from this study by more than one order of magnitude. However, these results are based on assumptions of 20% confiscation, 20% Dutch market share and 100% production efficiency that are considered weak [49, 50]. The figures from this study can also be linked to European market estimates.

Cocaine

According to the European Drug Market report a conservative estimate of the European Union (EU) market size for cocaine in Europe is 10.5 billion euros in 2020 [27]. This study estimates the Dutch market size to be 775 million, which is 7.3% of the estimated European market. The Netherlands represent 3.4% of the EU population (January 2020, before the Brexit) and 6.0% of the gross domestic product

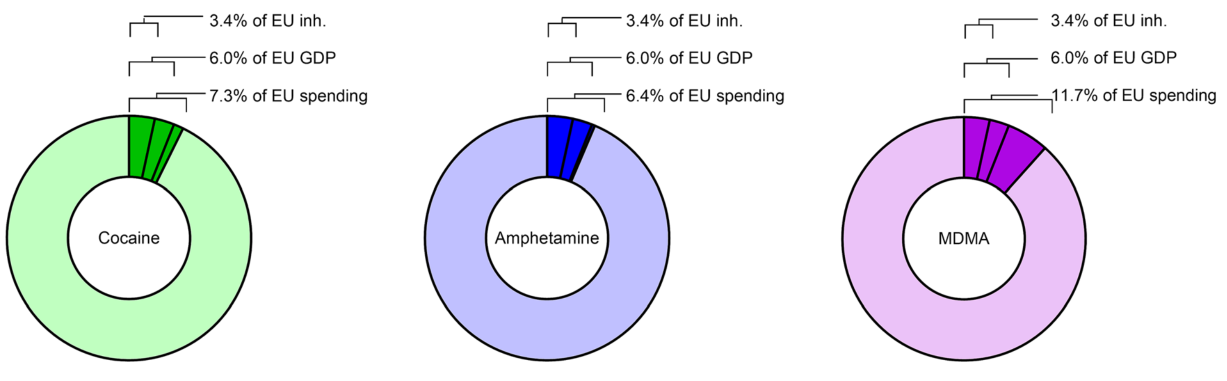

FIGURE 5 Projected Dutch contributions of each illicit drug to estimated European Union market size.

(GDP) of the EU (Figure 5). Apparently, the estimated Dutch per capita spending is more than twice the European average, but the GDP of the Netherlands is closer to the share of the EU cocaine market. This only reflects the monetary value. Considering the absolute consumed volume gives more prominent figures because the purity of cocaine in the Netherlands is on the high end of the European spectrum, and the price per gram is roughly one-third of the European average [27], which makes the volume of the Dutch per capita consumption significantly higher than the European average. This observation is in agreement with Dutch prevalence figures that are only exceeded by the United Kingdom and Spain in Europe [48] and observations of the European wide wastewater analysis on drug residues, where cocaine consumption in selected Dutch cities is structurally in the top of a wide spectrum of European cities over the past decade [51].

Amphetamine

According to European Monitoring Centre for Drugs and Drug Addiction (EMCDDA) and Europol, a conservative estimate of the EU market size for amphetamine and methamphetamine in Europe is 1.1 (0.9–1.4) billion a year [52]. According to the current study the Dutch amphetamine market is 70 million euros annually in the period of 2015 to 2022. This is 6.4% of the estimated European market (Figure 5). Similar to cocaine, Dutch per capita spending is almost twice the European average. If we take into account that the purity of amphetamine in the Netherlands is at the high end of the European spectrum and the price per gram is at the low end of the range in Europe, the Dutch per capita consumption is significantly higher than the European average. This observation is similar to cocaine and in agreement with Dutch prevalence figures that are among the highest in Europe [48] and observations of the European wide wastewater analysis on drug residues, where the amphetamine consumption in selected Dutch cities is structurally at the higher end of a wide spectrum of European cities over the past decade [51].

MDMA

According to EMCDDA and Europol a conservative estimate of the EU market size for MDMA in Europe is 0.5 billion euros [3]. The current study estimates the Dutch MDMA market at 58 million euros annually in the period of 2015 to 2022. This is 11.7% of the total European market size (Figure 5). This renders that the Dutch per capita spending is 3.4 times the European average. If we take into account that the MDMA price per pill in the Netherlands is at the low end of the European spectrum, the per capita consumption exceeds this factor. This observation is in agreement with Dutch prevalence figures that are the highest in Europe [48] and observations of the European wide wastewater analysis on drug residues. The MDMA consumption in selected Dutch cities is practically always the highest of all European cities over the past decade [51].

Future implications

Various studies have discussed that per capita drug consumption is higher in cities compared to rural areas [28–30] and correlations also have been observed for specific demographic cohorts [53, 54]. However, population-wide quantitative figures on drug consumption in relation to urbanity or other demographic indicators have hardly been studied [31, 55, 56]. Currently, international wastewater analysis research underrepresents rural areas. This study illustrates that the Dutch per capita drug consumption correlates with urbanity for cocaine and MDMA. Therefore, research on rural areas can improve market size estimates [55]. Furthermore, correlations with other demographic indicators as well as seasonal trends and event related dynamics should be studied to further refine (inter)national consumption estimates.

This proof of concept-study shows that wastewater based annual Dutch financial market size estimates are in line with national and EU market size estimates and consumption prevalence figures of the studied stimulants in Europe. The study shows the importance of reliable wastewater data as well as representative data on street price levels, purity or dose, relative contribution of routes of administration (e.g. oral, nasal, smoking, intravenous) [45] and excretion related to these administration routes, to refine consumption estimates from wastewater analysis.

We advocate to improve the analysis consumption dynamics related to seasons, holidays and events and to triangulate wastewater data with statistics on use prevalence, drug related crimes and drug-related medical incidents to understand drug use and its user. This allows public health professionals, policy makers and law enforcement to target their activities and government officials to quantitatively assess how policy measures affect consumption. In addition, scaling health statistics such as intoxications and problematic use or drug related crime figures to total consumption also enables one to evaluate and compare harm reduction measures and law enforcement activities between cities or countries. Concluding, wastewater analysis is complementary to other monitoring tools of illicit drug use and its health related and social effects.

AUTHOR CONTRIBUTIONS

Thomas L. ter Laak: Conceptualization (equal); data curation (equal); funding acquisition (equal); investigation (equal); methodology (equal); project administration (lead); supervision (lead); validation (lead); visualization (lead); writing—original draft (lead); writing—review and editing (lead). **Erik Emke:** Conceptualization (supporting); data curation (lead); investigation (supporting); methodology (supporting). **Nicole Dolot:** Investigation (supporting); methodology (supporting); software (supporting). **Emiel E. van Loon:** Data curation (equal); software (equal); validation (equal); writing—review and editing (supporting). **Margo M. E. van der Kooi:** Data curation (equal). **Arian C. van Asten:** Conceptualization (equal); supervision (supporting); writing—review and editing (supporting). **Pim de Voogt:** Conceptualization (supporting); funding acquisition (equal); methodology (equal); supervision (lead); writing—review and editing (supporting).

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DECLARATION OF INTEREST

None.

DATA AVAILABILITY STATEMENT

Data available on request due to privacy/ethical restrictions (of the municipalities for which the data were collected).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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