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Estimation of the consumption of illicit drugs during special events in two communities in Western Kentucky, USA using sewage epidemiology

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Abstract

Sewage epidemiology is a cost-effective, comprehensive, and non-invasive technique capable of determining semi-real-time community usage of drugs utilizing the concentration of drug residues in wastewater, wastewater inflow, and the population size served by a wastewater treatment plant. In this study, semi-real-time consumption rates of ten illicit drugs were determined using sewage epidemiology during special events including Independence Day, the 2017 solar eclipse, and the first week of an academic semester in the Midwestern United States. The average per-capita consumption rate of amphetamine, methamphetamine, cocaine, and THC were significantly different between two similar-sized communities during Independence Day observation week (p <0.046) and a typical week (p <0.001). Compared to a typical day, the consumption rate of amphetamine, methamphetamine, cocaine, morphine, and methadone was significantly higher on Independence Day (p <0.021) and during solar eclipse observation (p = 0.020). The estimated percentage of the population that consumed cocaine in a community is similar to the conventionally estimated consumption of cocaine; however, the combined estimated population that consumed amphetamine and methamphetamine based on sewage epidemiology was ~2 to 4 fold higher than the conventional estimates. This study is the first to compare community use of drugs during special events in the USA using sewage epidemiology.

Graphical abstract

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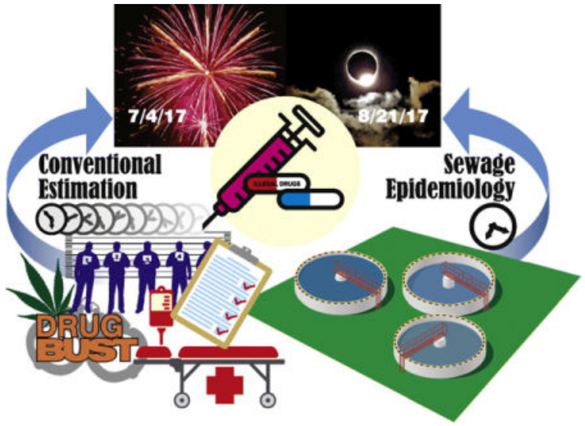

Keywords

Illicit Drugs; Wastewater; Sewage Epidemiology; Drug Consumption; Suspended Particulate Matter; Special Events

1. Introduction

Drug abuse is a global burden for public health as well as for social and economic welfare. In the USA, drug abuse has been a major public concern over a half a century, and the recent opioid epidemic has been declared as a national public health emergency (Johnson and Wagner, 2017). In 2016, approximately 7.4 million people aged ≥12 had an illicit drug use disorder (UNODC, 2017b). In that year, the total drug-related deaths increased by 11.5% to the highest level ever recorded accounting for nearly one-quarter of drug-related deaths worldwide (UNODC, 2017b). Midwestern and Southeastern United States, as transshipment and distribution hubs for drug trafficking organizations, are facing an epidemic level of diversion and abuse of drugs including cocaine, opioids, methamphetamine, marijuana, and heroin (KODCP, 2015; USDJ, 2011). The total heroin seizures in the state of Kentucky increased by 428% from 2010 to 2013 (USDEA, 2014). In addition, clandestine meth-labs and indoor/outdoor cannabis cultivation in this region have consistently posed a threat of drug abuse (KODCP, 2015; USDJ, 2011).

Conventional methods of determining the rate of drug use in a community consist of self-reported surveys, overdose/toxicological reports, and drug-related crime statistics (Asimakopoulos and Kannan, 2016; Banta-Green et al., 2009; Subedi and Kannan, 2014). Self-reported surveys suffer from high cost, time delays for the prompt need of intervention, low coverage, and biases including nonresponse bias and bias in the selection of sample populations with higher use of drugs (Keshaviah et al., 2016).

Sewage epidemiology can provide a more comprehensive, real-time, and cost-effective measure of drug abuse in a community as a complement to other conventional methods (Subedi, 2018; Subedi and Kannan, 2014). Sewage epidemiology, a rapidly expanding approach of determining community usage of drugs, utilizes the concentration of target drugs (and/or metabolites) in wastewater influent from centralized wastewater treatment plants (WWTPs), wastewater inflow, and the population size and location served by WWTPs to back-calculate the per-capita rate of drug use. The usefulness and limitations of the sewage epidemiology approaches have been reviewed in detail elsewhere (van Nuijs et al., 2011). Though many European countries including Italy, Spain, Switzerland, and the UK have successfully utilized sewage epidemiology to provide an early warning system of new drugs of abuse, identify the effectiveness of new drug treatment and prevention, and identify susceptible areas/populations for policy development (Been et al., 2015; Castiglioni et al., 2014; Gonzalez-Marino et al., 2016; McCall et al., 2016), sewage epidemiology has been underutilized in the USA (Chiaia et al., 2008; Subedi and Kannan, 2014).

Contrary to conventional methods of drug use estimation, sewage epidemiology operates on a rapid timescale, such that day to day variations in drug use can be measured. Lai et al. found that the consumption of illicit drugs such as cannabis, cocaine, MDMA (3,4-methylenedioxymethamphetamine), and methamphetamine during special events such as Christmas and New Year's Eve increased in urban areas in Australia (Lai et al., 2013a). MDMA was found an order of magnitude higher in wastewater during youth music festivals in Taiwan and Australia (Jiang et al., 2015; Lai et al., 2013b). However, only one study to our knowledge reported the variability in the rate of consumption of illicit drugs during a special event in the USA – cocaine consumption was slightly elevated during the Super Bowl game weekend whereas methamphetamine consumption was decreased (Gerrity et al., 2011).

In this study, community usage of three stimulants (cocaine, amphetamine, and methamphetamine), three narcotics (heroin, morphine, and methadone), four hallucinogens [MDMA, MDEA (3,4-methylenedioxyethylamphetamine), MDA (3,4 methylenedioxyamphetamine), and THC (Δ^9-tetrahydrocannabinol)], and seven of their metabolites were determined in wastewater influent from two WWTPs in two similar-sized communities (A and B) in Western Kentucky. Residual levels of illicit drugs were utilized to determine the per-capita usage of drugs in both communities during special events including Independence Day, the 2017 solar eclipse, and the first week of an academic semester versus a typical week. Independence Day (July 4th) is one of the most celebrated national holidays in the USA; therefore, per-capita use of drugs during Independence Day was assessed in both communities. The total solar eclipse on August 21st 2017 was visible across the entire contiguous USA after ~100 years and observed by ~100,000 people in the western belt of Kentucky including the community B. In one of the communities under this study, university professionals/students constitute ~40% of the population. Population dynamics of a student-dominant community can be significantly altered during the first week of an academic semester. In addition, estimated per-capita usage of illicit drugs in this study was compared to a similar study in New York, USA as well as survey-based estimations of use of drugs reported by the United Nations Office on Drugs and Crime (UNODC) and the Substance Abuse and Mental Health Service Administration (SAMSHA). This study is the first to compare special occasion drug use using sewage epidemiology in the USA.

2. Materials and methods

2.1. Sample collection

Wastewater influent (24-h composite of aliquots of every 15 minutes using time-proportional autosampler at ~8:00 AM) samples were collected in one-liter capacity certified amber glass bottles (Fisher, Hampton, NH) from two WWTPs (designated A and B) in Western Kentucky and transported on ice to Murray State University. Samples were collected for seven consecutive days from both WWTPs on June 30th to July 6th (covering the US Independence Day celebration) and July 26th to August 1st, 2017 (a typical week). $WWTP_A$ was also sampled from August 11th to August 17th (first week of University's academic semester). $WWTP_B$ was also sampled from August 19th to August 22nd (a total solar eclipse observation day). $WWTP_A$ treats an average of 4.56 million gallons per day (MGD) of wastewater serving ~20,000 people whereas $WWTP_B$ treats an average of 6.42 MGD of wastewater serving ~25,000 people. The wastewater treated by both WWTPs constitute ~90% domestic origin. Influent samples were collected after the primary screening of large-sized debris and grit removal.

2.2. Sample preparation

One hundred milliliters of wastewater samples were centrifuged (Thermo Scientific, Waltham, MA) at 4500 rpm (1924 × g) for 5 min and vacuum-filtered through 1.0 μm glass fiber filter paper for the separation of solid particulate matters (SPM). The SPM was stored at −20°C until extraction. Filtered wastewater samples were spiked with a mixture of internal standards (50 or 150 ng each, list of standards are provided in Supporting Information, SI) and extracted using an Oasis HLB solid phase extraction (SPE) cartridge (200 mg, 6 cm^3, Waters, Milford, MA) within 12 h of sample collection. SPE cartridges were conditioned with 3 mL of methanol and 3 mL of ultrapure water, extracted wastewater samples at ~1 mL/min, and eluted with 4 mL of methanol followed by 3 mL of 5% ammonia in methanol. The combined eluate was concentrated to ~500 μL under a gentle stream of nitrogen using the Reacti-Vap™ Evaporator (Thermo Fisher Scientific, Waltham, MA). The concentrate was quantitatively transferred to an amber liquid chromatography vial, and the final volume was adjusted to 1 mL with methanol. SPM were spiked with a mixture of internal standards, vortexed with 6 mL of methanol for ~5 minutes, and ultrasonicated (Branson CPXH series) for 30 min. The supernatant liquid was collected, and the extraction was repeated with another 6 mL of methanol. Extracts were combined, concentrated to ~500 μL under a gentle stream of nitrogen, quantitatively transferred to an amber LC vail and adjusted to a final volume of 1 mL with methanol. One and a half microliters of prepared samples were injected for HPLC-MS/MS analysis.

2.3. Instrumental analysis

Target analytes were analyzed using Agilent 1290 Infinity II LC System coupled to Agilent 6460 Triple Quadrupole mass spectrometer (Santa Clara, CA). Analytes were separated using methanol and a 0.1% aqueous solution of formic acid (Table S1) through a Force Biphenyl column (100 mm × 2.1 mm × 1.8 μm) (Thermo Fisher Scientific, Waltham, MA). Identification of analytes was based on retention time (±0.05 min), quantitative and qualitative m/z ion transitions (Table S2) in positive ionization mode, and a relative abundance of qualitative to quantitative ions (±20%). Analytes were quantified based on an isotopic dilution method of quantification. The calibrations curves were prepared by plotting concentration-dependent response factor of each analyte (peak area of analyte divided by peak area of internal standard) versus the response-dependent concentration factor (concentrations of analyte divided by the concentration of internal standard). The regression coefficients (r^2) for five- to ten-point calibration standards calculated by linear regression were ≥0.99 for all analytes.

2.4. Quality assurance and quality controls

A wastewater sample was extracted (as described above), spiked with analytes at 10 ppb level, analyzed, and calculated the minimum concentration of analytes that corresponding to the signal to noise ratio ≥10 (limits of quantitation: LOQs) and ≥3 (limits of detection: LODs). LODs for analytes ranged from 0.01 (EDDP) to 6.16 ng/mL (±)-11-hydroxy-Δ^9-tetrahydrocannabinol (THCOH) whereas LOQs ranged from 0.04 (EDDP) to 20.5 ng/mL (THCOH) (Table S3). The continuing calibration verification (the fifth calibration level) standard injected after every ten wastewater samples showed recoveries at 100 ± 26%. The continuing calibration verification (the fifth calibration level) standard injected after every ten SPM samples showed recoveries at 100 ± 30%. A method blank was analyzed at the beginning and the end of every batch of samples. All the analytical data presented herein are blank-corrected.

One sample was selected randomly for matrix spike and matrix spike duplicate analysis in each batch of sample analysis, spiked with analytes and their corresponding internal standards (50 or 150 ng), and passed through the entire analytical procedure. The average relative recoveries of analytes in wastewater ranged from 70 ± 0.5% (HER) to 126 ± 1.3% (6-acetyl morphine). The average relative recoveries of analytes in SPM ranged from 79 ± 15.2% (EDDP) to 132 ± 6.0% (MDMA). A triplicate spiking and recovery experiment as a validation of a developed analytical method for wastewater and SPM is described in SI (Table S3).

2.5. Calculation of mass loading and community usage of drugs

Mass load of drug residues and the community usage of drugs were determined using equation 1 as reported elsewhere (Subedi and Kannan, 2014).

$$\text{Mass load} = \text{C} \times \text{F} \times \left(\frac{100}{100 \times \text{Stability}}\right) \times \frac{1}{1.0 \times 10^6} \quad (1)$$

where mass load is the amount of individual illicit drugs introduced into WWTP (mg/d), C is the total nanograms of analytes in 1 L of wastewater influent and SPM combined (ng/L), F is the daily flow rate of wastewater influent (L/d) over a 24 h period, and stability is a measure of stability change (%) of analyte in wastewater up to 12 h (Baker and Kasprzyk-Hordern, 2011a). It is also important to note that the stability of illicit drugs and their metabolites can vary with the composition of collected wastewater samples, which depends on the sources of wastewater and the sampling days (Baker and Kasprzyk-Hordern, 2011a).

Similarly, community consumption of drug was calculated using the following eq 2 as reported elsewhere (Subedi and Kannan, 2014).

$$\text{Consumption}/1000\ \text{people} = \text{Mass Load} \times \left(\frac{1000}{\text{Excretion}}\right) \times \left(\frac{MW_{par}}{MW_{met}}\right) \times \left(\frac{1000}{\text{Population}}\right) \quad (2)$$

where consumption is mg/d/1000 people, mass load is mg/d as derived from eq 1, excretion is the excretion rate (%) of parent drug or metabolite excreted from the human body after administration (Postigo et al., 2008). MW_{Par} is the molecular weight of the parent compound, MW_{Met} is the molecular weight of the metabolite, and the population is the number of people served by the WWTP.

The human excretion rate of benzoylecgonine (45%, urinary biomarker of cocaine), amphetamine (30%, unchanged amphetamine), methamphetamine (43%, unchanged amphetamine), 6-acetylmorphine (1.3%, urinary biomarker of heroin), morphine (4.2%, urinary biomarker of heroin, therapeutic morphine, and other drugs), MDMA (26%, unchanged MDMA), and MDEA (19% unchanged MDEA) were used (Gracia-Lor et al., 2016; Postigo et al., 2008). Norcocaine and cocaethylene are not typically used to determine the consumption rate of cocaine as their human excretion rates are extremely lower (≤0.7%) than benzoylecgonine. (±)-11-nor-9-carboxy-Δ^9-tetrahydrocannabinol (THCA) served as a urinary biomarker of (−)-Δ^9-tetrahydrocannabinol (THC) since THC excreted as THCA (0.5%, non-active metabolite) and THC-OH (2%, an active metabolite that further degrades into THCA). Methadone excretes as unchanged compound (27.5%) and as the 2-ethylidene-1, 5-dimethyl-3,3-diphenylpyrrolidine (EDDP) metabolite (14%). Despite being measured at a higher concentration than methadone, EDDP preferentially adsorbs onto the SPM. In this study, drug residues in SPM were also determined and incorporated in the estimation of drug usage; therefore, the consumption rate of methadone was estimated based on the mass load of unchanged methadone and compared with that based on the mass load of EDDP. 3,4 methylenedioxyamphetamine (MDA) in wastewater can be an unchanged MDA, a metabolite of MDMA, and an active metabolite of MDEA (~28% excretion rate); therefore, it was not estimated. Uncertainties associated with sewage epidemiology approach of estimation of community consumption of illicit drugs are provided elsewhere (Castiglioni et al., 2013; Thomas et al., 2017). Statistical tests (Student's *t*-test or paired *t*-test) were performed using SigmaPlot (Version 12, Systat Software, Inc., San Jose, CA, USA).

3. Results and discussion

3.1. Occurrence of illicit drugs in wastewater

Cocaine, benzoylecgonine (a metabolite of cocaine), methamphetamine, amphetamine, methadone, EDDP (a metabolite of methadone), morphine, and THCA (a metabolite of THC) were detected in all wastewater influent samples from both WWTPs (Table 1). The mean concentration of drug residues ranged from 6.67 ng/L (MDA) to 1620 ng/L (THCOH) in $WWTP_A$ and 0.49 ng/L (MDMA) to 1560 ng/L (methamphetamine) in $WWTP_B$. In SPM, methamphetamine (2.33 to 25.6 ng/L), norcocaine (3.10 to 7.37 ng/L), and EDDP (18.3-62.1 ng/L) residues were consistently detected (Table S4).

3.2. Mass load of illicit drugs into the WWTP

In both WWTPs, mass loading of metabolite(s) of THC, methamphetamine, and a metabolite of cocaine were consistently higher than other illicit drugs (Table 2). The weekly average mass load of methamphetamine (33,200 mg/d) and benzoylecgonine (21,100 mg/d) in $WWTP_B$ in the typical week were 3.1 and 5.7 times higher than in $WWTP_A$, respectively (Table 2). Communities A and B are two similar sized communities (20,000 vs. 25,000 people) and are located approximately 50 miles apart. There is a relatively higher per-capita income in community B, more dynamic population (as interstate highway routes via the city and a regional airport) compared to the community A (predominantly represents a university students' population), and situated along the state-borderline can have contributed a higher mass load of illicit drugs in $WWTP_B$ than in $WWTP_A$. Similarly, during the July 4^{th} observation week, the weeklong average mass loadings of benzoylecgonine, methamphetamine, amphetamine, and THCA in community B were 1.8 to 4.8 fold higher than in community A. These results are consistent with previous findings of increased average mass loading rates of benzoylecgonine and methamphetamine during Super Bowl weekend, which was higher than on a typical weekend in the USA (Gerrity et al., 2011).

Mass load of cocaine, benzoylecgonine, amphetamine, methamphetamine, morphine, methadone, EDDP, and THCA on July 4^{th} was significantly higher ($p < 0.023$) than on July 3^{rd} and July 5^{th} in both communities (Table S5). Similarly, a mass load of benzoylecgonine, amphetamine, morphine, methadone, EDDP, and THCA on the solar eclipse observation day (Monday) in community B was significantly higher ($p = 0.031$) than on typical Monday (Table S5). However, a mass load of drugs in community A was not significantly different during the first week of fall academic semester than in a typical week.

The ratio of mass loading of parent drug and their metabolites can provide information whether drug residues in wastewater resulted from drug consumption or the direct disposal of unused drugs (Bijlsma et al., 2012). The ratio of residual levels of cocaine and benzoylecgonine in this study ranged from 0.09 to 0.65 in both communities, which suggested that cocaine and benzoylecgonine measured in wastewater influent is primarily from human consumption of cocaine rather than direct disposal. Bijlsma et al. (2012) reported the ratio of cocaine and benzoylecgonine levels upto 2.20 in wastewater influent from Schiphol Airport, Netherlands suggesting the disposal of unused cocaine in sewer network. The average ratio of mass load of cocaine to norcocaine in $WWTP_B$ (~27) was three fold higher than in $WWTP_A$. The variable ratio of cocaine to norcocaine might have resulted from a different extent of enhanced deconjugation of excreted glucuronides in two potentially different wastewater compositions from two communities (Subedi and Kannan, 2014). The mass load of cocaethylene, a metabolite of cocaine prouced after the co-consumption of cocaine and ethanol, in community A was only 1.2 fold higher than in community B during a typical week, but was 3.1 fold higher in community A during the July 4^{th} week.

3.3. Estimation of the community usage of illicit drugs

Per-capita consumption of cocaine, methadone, and THC were determined based on their most stable metabolites in wastewater, namely: benzoylecgonine, EDDP, and THCA, respectively. Per-capita consumption of illicit drugs during the typical week in community B was found highest for THC (81500 mg/d/1000 people) followed by methamphetamine (3090 mg/d/1000 people), morphine (2610 mg/d/1000 people), and cocaine (1970 mg/d/1000 people) whereas per-capita consumption of illicit drugs in community A was found highest for THC (62400 mg/d/1000 people) followed by morphine (2380 mg/d/1000 people), methamphetamine (1240 mg/d/1000 people), and methadone (1100 mg/d/1000 people) (Table 3). Different profiles of drug consumption as well as per-capita consumption rates in two similar-size communities may be attributed to their locations, demographics, and inhabitant's overall socio-economic status.

The average per-capita consumption rate of amphetamine, methamphetamine, cocaine, and THC in community B was significantly higher ($p < 0.046$) on the July 4th observation week as well as in the typical week ($p < 0.001$) compared to community A (Table S6). Lai et al. reported higher use of cocaine in urban areas than in semi-rural area in Queensland, Australia (Lai et al., 2013a). Special occasion-associated drug use has also been reported, as residual levels of cocaine, its metabolite, and MDMA were found significantly higher in wastewater during music festival in Spain (Bijlsma et al., 2014) and wastewater-impacted surface water after Christmas Day and New Year's Eve in Spain (Huerta-Fontela et al., 2008). However, the consistent consumption rate of morphine (~2500 mg/d/1000 people), and methadone (~1300 mg/d/1000 people) throughout this study period in both communities suggests a potential uniform consumption of morphine and methadone containing prescribed formulations.

In both communities, weekly average consumption rates of drugs were not significantly different; however, day-to-day fluctuations in the per-capita consumption of some drugs on special occasions were significantly different. Van Nuijs et al. (2011) also reported significant higher consumption of cocaine, amphetamine, and MDMA during weekends in Brussels, Belgium (van Nuijs et al., 2011). Consumption of amphetamine, methamphetamine, cocaine, morphine, and methadone on July 4th were significantly higher ($p < 0.021$) than in July 3rd and 5th in both communities (Table S7). Similarly, the per-capita consumption of amphetamine, methamphetamine, cocaine, morphine, methadone, and THC on the 2017 solar eclipse observation day was significantly higher ($p = 0.020$) than a normal Monday in community B (Table S7).

For an illicit drug, such as cocaine and methadone, where the residual level of the metabolite was significantly higher than the parent drug, per-capita consumption rates were determined using both the parent illicit drug and metabolite separately (Fig. 1). It was found that the per-capita consumption of cocaine utilizing a residual level of parent cocaine was higher than using its metabolite benzoylecgonine. Metabolics-based metabolite analysis suggested that cocaine undergoes phase I reactions such as hydrolysis (and forms benzoylecgonine) as well as phase II reactions such as glucuronidation and glucosidation (Yao et al., 2013). Potential transformation of glucuronide forms of cocaine to the parent cocaine in sewer networks may have contributed to a higher level of cocaine in wastewater than an expected 5% unchanged cocaine in human urine (Postigo et al., 2008). Unlike cocaine, the estimation of per-capita consumption of methadone utilizing parent methadone is significantly lower than using residual level of its metabolite EDDP. Wastewater was found to have significant induction potential of drug metabolizing cytochrome P450 (CYP) genes (Guruge et al., 2015). Methadone can have potentially transformed into EDDP in wastewater in presence of P450. It is important to note that most of the studies reported the per-capita consumption rate of cocaine and methadone based on the residual levels of their metabolites benzoylecgonine and EDDP, respectively (Baker et al., 2014; Baker and Kasprzyk-Hordern, 2011b; Banta-Green et al., 2009; Metcalfe et al., 2010; Zuccato et al., 2008). However, our results suggest a careful consideration is required regarding the analyte (i.e. whether the target drug or its metabolite) used while comparing consumption rates of drug use.

3.4. Per-capita consumption compared to conventional estimations

The UNODC estimates the consumption rate of drugs conventionally (based on drug seizures statistics, surveys, etc.) in global communities while the SAMSHA estimates the consumption rate of drugs based on a national surveys of all 50 states and the District of Columbia in the USA (NSDUH, 2016; UNODC, 2017a). The estimated percentage of the population that consumed cocaine in community B in the present study (Table 3) is similar to UNODC's estimation (2.3% in 2015) (UNODC, 2017a) and the National Survey on Drug Use and Health (1.74% population of ≥12 years in Kentucky in 2015/16) (NSDUH, 2017a). However, the combined estimated population that consumed amphetamine and/or methamphetamine is approximately two fold higher in community A and four times higher in community B than the UNODC's estimation (2.9%). Consumption of ecstasy-related compounds was found significantly lower in these communities using sewage epidemiology than the UNODC's estimation (1.2%). Chiaia et al. (2008) also reported that the estimated consumption rate of ecstasy-related compounds utilizing sewage epidemiology in the Southern and Midwestern USA (7-17 mg/d/1000 people) was significantly lower than two communities in Northeastern USA (Subedi and Kannan, 2014) and other European studies (van Nuijs et al., 2011; Bijlsma et al., 2014). Morphine may have resulted from several other prescribed drugs including codeine, ethylmorphine, pholcodine, and nicomorphine. Morphine is the most commonly used analgesic in hospital, and Kentucky was one of the eight most opioid prescribing States (>107 prescriptions per 100 people in 2014) in the USA (CDC, 2015). Similarly, methadone is used to treat opiate addiction in approximately 98% of opioid treatment facilities in the USA (NSDUH, 2017b). Therefore, multiple sources of morphine and opioid treatment facilities in communities may have contributed to the higher estimation of morphine and methadone consumption than the UNODC's estimation for prescription opioids (5.5% in 2015), NSDUH's estimation (4.78% population of ≥12 years in Kentucky in 2015/16), and SAMSHA's estimation (4.4% in 2016) (SAMSHA, 2017). The estimated percentage population that consumed drugs in this study did not account for the potential overdoses and multiple consumptions of drugs. It is also important to note that the percentage population that consumed drugs was estimated based on the weeklong average levels of residues in wastewater and compared with the conventional annual estimation of drug consumption in communities. The percentage of the population which consumed amphetamine and methamphetamine in this study is up to two orders of magnitude higher than SAMSHA's estimations.

3.5. Comparison with a similar study in Albany, New York

Per-capita consumption rate of illicit drugs was found in the order of morphine > cocaine > methadone > amphetamine > MDA in a smaller community (~15,000 inhabitants) compared to an order of cocaine > morphine > MDA > amphetamine > methadone in a relatively larger community (~100,000 inhabitants) in Albany, NY (Subedi and Kannan, 2014). In the present study, the per-capita consumption rate of illicit drugs was found in the order of methamphetamine > morphine > cocaine > methadone > amphetamine. Overall, the cocaine consumption rate was over an order of magnitude higher than amphetamine/methamphetamine in Albany, NY whereas methamphetamine consumption rate was found 2 to 3 fold higher than cocaine in the present study. The Midwestern USA has been considered for the clandestine production of methamphetamine as well as a transshipment and/or distribution hub for Mexican drug trafficking organizations (USDJ, 2011). Relatively higher production and use volume of methamphetamine in the Midwestern region compared with several other parts of the country may have resulted in a higher consumption rate of methamphetamine. Although similar consumption rates of morphine were found in both studies, the consumption rate of methadone in this study was 3 to 5 fold higher than in Albany, NY. Moreover, the consumption rate of amphetamine was 25 to 40 fold higher than methamphetamine in Albany, NY while the consumption rate of methamphetamine was found 2 to 3 fold higher than amphetamine in this study.

4. Conclusions

The semi-real-time consumption rates of ten illicit drugs were determined using sewage epidemiology in Western Kentucky during special events including Independence Day, the 2017 solar eclipse, and the first week of an academic semester. The average per-capita consumption rate of amphetamine, methamphetamine, cocaine, and THC were significantly different between two similar-sized communities during Independence Day observation week ($p < 0.046$) and a typical week ($p < 0.001$). Compared to a typical day, the consumption rate of amphetamine, methamphetamine, cocaine, morphine, and methadone was significantly higher on Independence Day ($p < 0.021$) and during solar eclipse observation ($p = 0.020$). The estimated percentage of the population that consumed cocaine in a community is similar to the conventionally estimated consumption of cocaine; however, the combined estimated population that consumed amphetamine and methamphetamine based on sewage epidemiology was ~2 to 4 fold higher than the conventional estimates. Overall, these findings suggest sewage epidemiology is an effective tool to determine trends in community drug use during special occasions. This information can be an invaluable resource for authorities to map hot spots of drug use, assess trends over time/seasons, prompt intervention, identify new drugs of use in the community, and correlate the abuse activities with social and demographic characteristics. Moreover, an increased mass loading of drugs during special events (as demonstrated in this study) may warrant design or operational considerations for wastewater treatment plants.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Appendix A: Supplementary data

Supplementary data to this article can be found online at

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Highlights

1. Consumption rates of illicit drugs during special events were determined using sewage epidemiology

2. Per-capita consumptions of illicit drugs were significantly different between two similar-sized communities

3. Consumption rates of illicit drugs were significantly higher on special events including Independence Day and/or the solar eclipse observation day

4. Percentage population that consumed cocaine was similar to the conventional estimate

5. Percentage population that consumed amphetamine and methamphetamine was >2 fold higher than the conventional estimate

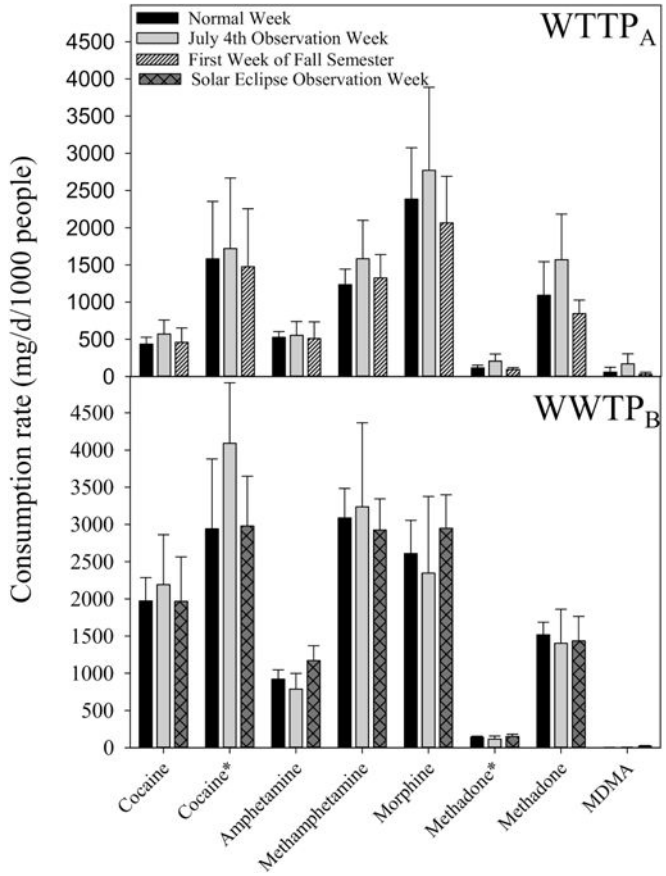

Fig. 1.

Per-capita consumption rate (mg/d/1000 people) of illicit drugs in two communities in Western Kentucky, USA. *represents the estimation based on the residual levels of their parent drugs in wastewater influent. Error bars indicate standard deviation, n=3.

Table 1

Concentration of illicit drugs and their select metabolites (ng/L) in wastewater influent from two centralized wastewater treatment plants in Western Kentucky, USA. The number after forward slash "/" represents the detection frequency.

Analytes	Mean Concentration ± SD at $WWTP_A$			Mean Concentration ± SD at $WWTP_B$			
	Independence Day Observation Week	Typical Week	First Week of Semester	Independence Day Observation Week	Typical Week	Solar Eclipse Observation Week (n=4)	Other US studies
Stimulants							
Cocaine (CCN)	88.8 ± 58.4/100	105 ± 40.1/100	79.6 ± 43.2/100	197 ± 65.7/100	160 ± 56.9/100	201 ± 65.6/100	43.2-1110[a,b,d]
Benzoylecgonine (BEG)	254 ± 91.9/100	276 ± 56.2/100	228 ± 99.0/100	959 ± 319/100	987 ± 204/100	1200 ± 390/100	157-3020 [a,b,d]
Norcocaine (NCCN)	48.9 ± 48.0/100	25.7 ± 23.5/100	9.22 ± 5.72/100	4.93 ± 2.01/57	9.73 ± 1.93/100	6.54 ± 3.04/100	2.92-36[a,b,d]
Cocaethylene (CCE)	43.4 ± 38.6/100	20.0 ± 16.7/100	8.57 ± 7.25/100	14.5 ± 7.84/71	9.39 ± 4.14/86	6.87 ± 3.12/100	2.71-7.18[d]
Amphetamine (APT)	184 ± 83.5/100	243 ± 13.5/100	182 ± 72.0/100	248 ± 51.7/100	333 ± 40.8/100	517 ± 55.1/100	15.8-362[a,b,d]
Methamphetamine (MAPT)	603 ± 152/100	690 ± 91.9/100	577 ± 96.9/100	1200 ± 238/100	1350 ± 107/100	1560 ± 128/100	3.82-2750[a,b,c,d]
Opioids/Narcotics							
Heroin (HER)	859 ± 248/86	226 ± 76.8/100	ND	385 ± 258/43	ND	ND	
6-acetyl morphine (AMPH)	554 ± 572/86	224 ± 279/100	11.2 ± 11.7/100	63.6 ± 47.3/57	5.42 ± 3.00/43	2.06 ± 1.45/100	
Morphine (MPH)	138 ± 72.7/100	161 ± 28.6/100	110 ± 25.0/100	107 ± 27.5/100	141 ± 30.7/100	193 ± 14.5/100	62.4-1540[b,d]
Methadone (MTD)	55.9 ± 27.8/100	43.4 ± 8.46/100	27.9 ± 5.92/100	28.9 ± 4.82/100	42.0 ± 3.74/100	55.4 ± 8.81/100	5.41-33.7[a,d]
EDDP	166 ± 77.0/100	158 ± 47.4/100	97.9 ± 14.2/100	137 ± 23.1/100	177 ± 25.1/100	204 ± 45.0/100	11.8-70.2[d]
Hallucinogens							
MDMA	47.9 ± 42.4/86	19.7 ± 19.6/100	8.36 ± 7.30/100	<LOQ	<LOQ	6.53 ± 2.88/100	1.09-2083[a,b,d]
MDEA	42.4 ± 39.9/86	19.2 ± 18.8/100	6.85 ± 6.89/100	ND	ND	ND	2.33-10.6[d]
MDA	56.2 ± 42.6/100	26.8 ± 24.4/100	6.67 ± 5.14/100	4.96 ± 4.43/86	<LOQ	ND	5.0-3010[a,b,d]
THC	21.7 ± 24.2/71	22.1 ± 8.31/100	ND	8.33 ± 9.35/57	38.1 ± 63.7/86	65.2 ± 75.7/50	NA
THCA	275 ± 181/100	499 ± 143/100	435 ± 211/100	562 ± 146/100	505 ± 79.0/100	767± 353/100	NA
THC-OH	1620 ± 3270/100	1130 ± 390/100	622 ± 433/100	98.0 ± 64.2/100	176 ± 71.0/100	263 ± 106/100	NA

[a] in seven WWTP across the USA (Chiaia et al., 2008);

[b] in a WWTP in the USA (Gerrity et al., 2011);

[c] in a WWTP from KY, USA (Loganathan et al., 2009);

[d] in two WWTPs from Albany, NY (Subedi and Kannan, 2014).

Table 2

Mass loading of illicit drugs and their metabolites (mg/d) into two wastewater treatment plants in Western Kentucky, USA.

	Mean Mass Loading ± SD at $WWTP_A$			Mean Mass Loading ± SD at $WWTP_B$		
Analytes	**Independence Day Observation Week**	**Typical Week**	**First Week of Semester**	**Independence Day Observation Week**	**Typical Week**	**Solar Eclipse Observation Week (n=4)**
Stimulants						
Cocaine (CCN)	1720 ± 948	1580 ± 772	1480 ± 779	5120 ± 1020	3680 ± 117	3730 ± 836
Benzoylecgonine (BEG)	4880 ± 1620	3720 ± 791	3930 ± 1660	23500 ± 7210	21100 ± 3340	21000 ± 6390
Norcocaine (NCCN)	1000 ± 894	448 ± 462	192 ± 129	94.9 ± 101	255 ± 60.7	142 ± 72.1
Cocaethylene (CCE)	797 ± 646	308 ± 301	159 ± 145	258 ± 218	209 ± 92.6	128 ± 52.6
Amphetamine (APT)	3320 ± 1130	3160 ± 462	3060 ± 1350	5920 ± 1570	6900 ± 949	8780 ± 1510
Methamphetamine (MAPT)	13600 ± 5550	10600 ± 1800	11400 ± 2700	34800 ± 12100	33200 ± 4250	31500 ± 4480
Opioids/Narcotics						
Heroin (HER)	41200 ± 22700	8990 ± 255	N/A	10300 ± 6160	N/A	N/A
6-acetyl morphine (AMPH)	11100 ± 12200	4640 ± 6350	268 ± 298	1120 ± 1300	78.2 ± 121	47.4 ± 32.2
Morphine (MPH)	1800 ± 727	1550 ± 452	1340 ± 409	1910 ± 840	2120 ± 364	2400 ± 367
Methadone (MTD)	1150 ± 537	647 ± 197	527 ± 146	809 ± 284	987 ± 94.3	1070 ± 203
EDDP	3790 ± 1480	2640 ± 1090	2040 ± 440	4230 ± 1380	4580 ± 506	4330 ± 996
Hallucinogens						
MDMA	874 ± 413	306 ± 343	154 ± 145	N/A	N/A	126 ± 61.3
MDEA	706 ± 39.9	274 ± 304	117 ± 125	N/A	N/A	N/A
MDA	1020 ± 673	379 ± 413	119 ± 97.8	126 ± 104	N/A	N/A
THC	379 ± 410	312 ± 139	N/A	190 ± 223	799 ± 1270	1330 ± 1590
THCA	2540 ± 2820	6860 ± 1881	7675 ± 3880	14700 ± 5400	11200 ± 1860	14500 ± 8150
THC-OH	27600 ± 56000	16000 ± 7090	11000 ± 7980	2500 ± 1540	3860 ± 1450	4980 ± 2810

Table 3

Estimated per-capita consumption of drugs (mg/d/1000 people) during special events in two communities in Western Kentucky. Values in parentheses represent the % of the population consumed illicit drugs based on a typical dose of drugs reported elsewhere* (Postigo et al., 2008).

Community A					
Drugs	**Typical Week Avg.**	**July 3rd**	**July 4th**	**July 5th**	**First Week of Semester Avg.**
Amphetamine	526 (1.1%)	368 (0.74%)	706 (1.4%)	350 (0.70%)	510 (0.10%)
Methamphetamine	1240 (4.1%)	1060 (3.5%)	2500 (8.3%)	1190 (4.0%)	1330 (4.4%)
Cocaine	434 (0.43%)	337 (0.34%)	773 (0.77%)	287 (0.29%)	458 (0.46%)
MDMA	59 (0.04%)	83.4 (0.06%)	43.9 (0.03%)	na	29.7 (0.02%)
MDEA	72 (0.06%)	94.5 (0.08%)	36.3 (0.03%)	na	30.7 (0.02%)
Morphine	2380 (32%)	1650 (22%)	3340 (45%)	1310 (18%)	2060 (28%)
Methadone	1100 (13%)	906 (11%)	1720 (20%)	793 (9.3%)	844 (9.9%)
THC*	62400	35200	51900	36400	69800
Community B					
Drugs	Typical Week Avg.	July 3rd	July 4th	July 5th	Solar Eclipse Day
Amphetamine	919 (1.8%)	792 (1.6%)	1200 (2.4%)	592 (1.2%)	1450 (2.9%)
Methamphetamine	3090 (10%)	3270 (11%)	5600 (19%)	2420 (8.1%)	3400 (11%)
Cocaine	1970 (2.0%)	2030 (2.0%)	3240 (3.2%)	1290 (1.3%)	2280 (2.3%)
MDMA	1.72 (0.001%)	na	na	na	27.6 (0.02%)
MDEA	na	na	na	na	0.42 (0.0003%)
Morphine	2610 (35%)	2000 (27%)	4610 (62%)	1630 (22%)	3470 (46%)
Methadone	1520 (18%)	1260 (15%)	2200 (26%)	1780 (21%)	1750 (21%)
THC**	81500	134000	129000	172000	169000

* typical dose of drugs were amphetamine: 50 mg, methamphetamine: 30 mg, cocaine: 100 mg, MDMA: 140 mg, MDEA: 125 mg, morphine: 7.5 mg, and methadone: 8.5 mg.

** number of doses of THC were not calculated due to the inconsistently reported dose of THC.