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RESEARCH ARTICLE

Methamphetamine use in typical Chinese cities evaluated by wastewater-based epidemiology

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Abstract

Methamphetamine has become one of the most widely used illicit drugs in China. To understand the current situation in China, the prevalence and consumption of methamphetamine were estimated through wastewater-based epidemiology (WBE) in the present study. Methamphetamine concentrations ranged from 42.6 ng/L (Harbin) to 700 ng/L (Xi'an) in influent wastewater samples collected from 27 wastewater treatment plants (WWTPs) in 22 Chinese cities. The estimated consumption of methamphetamine was 23.0 (Dingxi) to 376 (Xi'an) mg/day/1000 inhabitants with a mean value of 157 mg/day/1000 inhabitants. The annual consumption in 2018 was estimated to be 84 tons (95% confidence interval, 44–136), which was 26% lower than that in 2014. The prevalence of methamphetamine use was 0.64% (95% confidence interval, 0.18–1.25), indicating that more than five million people used methamphetamine in 2018. Although drug abuse is common in the country, the consumption showed a different spatial pattern, with the highest values in Central China and the lowest use in Northeast China, so drug use is still considered a geographic and culture-dependent behaviour. The results indicated that WBE can not only be used to assess the trends of illicit drug use, but also to analyse the spatial differences in the whole country, which will provide complementary evidence for the prevention and control of methamphetamine use.

Keywords Methamphetamine · Prevalence · Monte Carlo · Spatial variability · Uncertainty

Highlights

Methamphetamine use in China was assessed through wastewater-based epidemiology.
The consumption of methamphetamine was estimated to be approximately 84 tons in 2018.
More than five million people in China used methamphetamine.
The consumption of methamphetamine decreased from 2014 to 2018.
A discarding event was identified in the sampling campaign.

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Introduction

Methamphetamine dependence has posed a significant threat to health care and public security in China due to its high prevalence in recent years (Guo et al. 2017; Hu et al. 2019; NNCC 2017; Sun et al. 2014). The National Drug Abuse Monitoring Annual Report in 2018 revealed that the number of the methamphetamine users has declined (NNCC 2018). The statistics from the Chinese National Narcotics Control Commission reported that approximately 1.54 million registered people had a methamphetamine dependence in China, accounting for 60% of the total number of people who use drugs (NNCC 2017). Therefore, timely assessment of methamphetamine use in the general population has become a critical issue for sufficient monitoring and control of methamphetamine dependence.

Traditional methods including questionnaire and survey research for the investigation of drug use are time-consuming and have low accuracy (Zuccato et al. 2008). Recently, wastewater-based epidemiology (WBE) has been deemed an effective and complementary approach for monitoring drug use at the national level (Bruno et al. 2018;

Kasprzyk-Hordern and Baker 2012; Lai et al. 2016). WBE relies on the detection of illicit drugs and their selected metabolites, which are excreted in raw wastewater after consumption. The obtained concentrations are used to back-calculate the consumption and prevalence of the use of the drug (Banta-Green et al. 2009; Lai et al. 2016; Zuccato et al. 2008). As is reported, WBE is superior over conventional methods for providing evidence-based and objective data in near real time for a defined population (Castiglioni et al. 2013).

Moreover, WBE has been successfully applied to estimate the consumption of methamphetamine in some Chinese cities in the previous years, and it was concluded that methamphetamine was quite popular in China with very high consumption rates compared to those of some European countries (Du et al. 2015; Khan et al. 2014; Lai et al. 2013; Li et al. 2014; Ort et al. 2014; Thomas et al. 2012; Zheng et al. 2019). Additionally, methamphetamine consumption showed upward trends in Australia (Lai et al. 2016; Tscharke et al. 2015) and some European countries based on long-term monitoring using WBE (Been et al. 2016; Mastroianni et al. 2017; Zuccato et al. 2016). Considering the increasing prevalence of methamphetamine use in China and other countries, the Chinese government implemented many measures and policies to control the abuse of methamphetamine (NNCC 2014, 2017, 2018). Subsequently, significant reduction trends from 2015 to 2018 were reported in some Chinese cities (Li et al. 2014; Wang et al. 2019). However, no updated nationwide WBE study has been conducted to test the effectiveness of drug interventions on methamphetamine control in China in the past 4 years.

Therefore, the present study aims to assess the current status of methamphetamine use in China. Wastewater samples from 27 WWTPs were collected in 2018 and 2019 in 22 major Chinese cities. The concentrations of methamphetamine in wastewater, population size, and other parameters for back-calculation were investigated and used to display the trend and prevalence of methamphetamine consumption (Pei et al. 2016). Furthermore, a probabilistic method of Monte Carlo simulation was used to assess the uncertainty and variability of the estimation results.

Materials and methods

Reagents and materials

Methamphetamine (METH), amphetamine (AMP), trifluoroacetic anhydride (TFA), and naphthalene-d_8 (NAP-d_8) were obtained from Sigma-Aldrich Inc. (Saint Louis, MO, USA). Methanol (MeOH), acetonitrile, and ethyl acetate (EAC) (HPLC ≥ 99.8%) were obtained from Kemiou Chemical Reagent Co., Ltd. (Tianjin, China). A vacuum pump manifold with 20 connections and Oasis MCX (60 mg, 3 mL) solid-phase extraction (SPE) cartridges were purchased by Waters Corporation (Waters, USA).

Wastewater sampling

The sampling campaign was conducted during 2018 and 2019 (Table 1). Wastewater samples were collected from 27 WWTPs in Beijing (BJ), Yinchuan (YC), Lanzhou (LZ), Dingxi (DX), Xi'an (XA), Changzhou (CZ), Kunming (KM), Chengdu (CD), Changdu (CAD), Chongqing (CQ), Hefei (HF), Guiyang (GY), Harbin (HRB), Huhehot (HHHT), Baoding (BD), Zhengzhou (ZZ), Xiangtan (XT), Guangzhou (GZ), Qingdao (QD), Weihai (WH), and Jinan (JN). These cities belong to seven geographic regions of China: Northeast China (HRB), North China (BJ, BD, and HHHT), Northwest China (LZ, XA, DX, and YC), Central China (ZZ and XT), East China (CZ, HF, QD, WH, and JN), Southwest China (KM, CQ, CD, CAD, and GY), and South China (GZ) (Fig. S1).

According to recent census data, the urban population of these cities ranged from 0.03 million in CAD to 3.37 million in BJ, representing 12.2% of the urban population of China. In most cities, samples were collected from only one WWTP, while in GY, XT, BD, and CQ, two or more WWTPs were selected for wastewater sample collection. The WWTPs were named QY-1 (first WWTP of Guiyang), XT-2 (second WWTP of Xiangtan), etc. A time proportional mode was applied during sampling with 60 mL collected every 30 min using an automatic sampler. After collection, the samples were immediately acidified to pH 2 using HCl, carried back to the laboratory on ice, and stored at − 20 °C until analysis. The duration of sample collection to analysis was less than 1 week.

Extraction and analysis

Each sample was analysed in duplicate. The determination of NH_4-N was performed according to the 350.1 standard methods from the United States Environmental Protection Agency using the Nessler Method (Zheng et al. 2017). The MCX SPE cartridges were conditioned with 6 mL MeOH, 4 mL water, and 4 mL acidic water (pH = 2), consecutively. Then, the wastewater was loaded on the cartridges. After drying under vacuum, the column was eluted with 4 mL MeOH and 4 mL 4% ammonia/methanol. The eluate was dried under a soft stream of nitrogen and re-dissolved using 200 μL of EAC. For derivatization, 25 μL TFA was added into the solution and incubated for 60 min at 45 °C. After the reaction, 10% $NaHCO_3$ solution was used to remove the remaining derivative reagent. The mixture was centrifuged at 2000 rad/s for 3 min. Then, 50 μL of the upper organic phase was transferred to chromatographic bottle, followed by adding an internal standard of NAP-d_8 (5 μL) before analysis, which can monitor the injection efficiency.

Table 1 Region, sampling date, city, METH and AMP concentrations, flow, population, consumption, and AMP/METH in all sampling WWTPs

City	WWTP	Sampling date	METH (ng/L)	AMP (ng/L)	NH_4-N (mg/L)	Wastewater flow (10,000 m^3)	Population (10,000)	METH consumption (mg/d/1000inh)	AMP/METH (%)
Chongqing	CQ-1	Oct 23rd, 2018	410 ± 44	22.5 ± 2.1	27.0 ± 0.6	1.7	7.64	328 ± 36	5
	CQ-2	Oct 24th, 2018	225 ± 3	28.0 ± 5.7	33.3 ± 1.0	1.2	6.66	146 ± 2	12
Chengdu	CD	Sep 30th, 2018	168 ± 1	15.9 ± 4.6	21.2 ± 0.2	5	17.8	170 ± 1	9
Guiyang	GY-1	Oct 11th, 2018	102 ± 8	16.0 ± 4.2	8.88 ± 0.01	6.1	9.03	249 ± 19	16
	GY-2	Oct 11th, 2018	115 ± 31	15.8 ± 6.2	12.3 ± 0.2	8	16.4	201 ± 54	14
Changdu	CAD	Nov 20th, 2018	154 ± 25	43.9 ± 17.6	33.4 ± 0.3	0.9	5.02	99.7 ± 15.8	29
Kunming	KM	Nov 30th, 2018	94.1 ± 12.1	42.8 ± 6.0	15.3 ± 0.02	30.5	77.8	133 ± 17	45
Dalian	DL	Feb 11th, 2018	102 ± 9	65.4 ± 10.0	25.5 ± 0.03	10	42.5	55.7 ± 4.8	64
Harbin	HRB	Oct 11th, 2018	42.6 ± 0.5	18.4 ± 4.6	9.54 ± 0.17	3	4.77	96.5 ± 1.1	43
Changzhou	CZ	Oct 13th, 2018	100 ± 35	16.1 ± 3.0	29.9 ± 0.8	16.1	80.3	72.3 ± 25.2	16
Hefei	HF	Sep 27th, 2018	144 ± 4	17.4 ± 3.7	26.1 ± 0.6	30	130	119 ± 3.5	12
Qingdao	QD	Sep 30th, 2018	163 ± 3	31.5 ± 26.1	21.7 ± 0.3	14	50.6	162 ± 3	19
Jinan	JN	Sep 28th, 2018	163 ± 5	23.7 ± 0.7	51.2 ± 1.0	2.5	21.3	68.6 ± 2.1	15
Weihai	WH	Oct 19th, 2018	467 ± 30	48.4 ± 2.1	63.7 ± 1.1	4	42.4	159 ± 10	10
Beijing	BJ	Nov 20th, 2018	208 ± 8	22.5 ± 10.5	50.6 ± 0.3	40	337	88.6 ± 3.4	11
Huhehot	HHHT	Oct 18th, 2018	103 ± 1	20.3 ± 15.1	22.3 ± 0.2	4	14.8	99.5 ± 0.7	20
Baoding	BD-1	Oct 24th, 2018	3315 ± 302	46.4 ± 4.22	11.55 ± 0.18	5	9.6	6402 ± 589	1.4
	BD-1	Jan 11th, 2019	69.8 ± 10.7	19.0 ± 0.4	8.26 ± 0.02	5	6.9	122 ± 18.7	27
	BD-2	Jan 11th, 2019	290 ± 56	30.8 ± 2.4	23.0 ± 0.9	3	11.5	139 ± 27.1	11
	BD-3	Jan 11th, 2019	123 ± 6	30.2 ± 12.8	6.73 ± 0.05	3	3.37	262 ± 12	25
Zhengzhou	ZZ	Oct 18th, 2018	454 ± 13	27.1 ± 10.2	26.7 ± 0.1	20	88.9	368 ± 11	6
Xiangtan	XT-1	Oct 25th, 2018	118 ± 6	48.6 ± 3.1	15.8 ± 0.4	14.1	37.1	162 ± 8	41
	XT-2	Oct 25th, 2018	156 ± 21	17.9 ± 1.6	11.6 ± 0.2	7.5	14.4	292 ± 38	11
Guangzhou	GZ	Oct 31st, 2018	103 ± 12	29.2 ± 24.0	26.1 ± 0.6	50	217	85.2 ± 9.8	28
Xi'an	XA	Sep 28th, 2018	700 ± 8	48.9 ± 1.1	40.2 ± 1.3	20	133	376 ± 5	7
Lanzhou	LZ	Sep 29th, 2018	589 ± 71	173 ± 58.5	55.5 ± 1.7	26	240	229 ± 28	29
Dingxi	DX	Nov 10th, 2018	114 ± 13	26.7 ± 15.5	107 ± 0.5	0.8	14.3	23.0 ± 2.6	23
Yinchuan	YC	Oct 24th, 2018	137 ± 19	14.2 ± 3.6	23.9 ± 0.1	10	39.9	124 ± 13	10

The samples were analysed by an Agilent 7890B gas chromatograph connected to an Agilent 5977 A mass spectrometer (GC–MS) equipped with an HP-1 column (0.25 mm i.d., 0.25 μm film thickness, J&W Scientific). One microlitre of sample was injected and the injector temperature was set to 230 °C. The initial oven temperature was 90 °C, and the temperature was then increased to 180 °C at a rate of 10 °C/min. The mass spectrometry was operated in electron impact ionization mode at 230 °C and 70 eV. Quadrupole was maintained at 150 °C. The quantification and qualitative ions of methamphetamine and amphetamine are listed in Table S1.

The recoveries of methamphetamine and amphetamine investigated using 50 mL spiked water (50 ng/mL) were 109 ± 23% and 76 ± 32% ($n = 7$), respectively. The blank method was run for every six samples to monitor the contamination levels. The linearity was evaluated by the calibration curves obtained by the analysis of seven standard solutions at the following concentrations for METH-TFA and AMP-TFA: 0, 10, 20, 50, 100, 200, and 500 ng/L. Linearity produced by the squared correlations coefficient (r^2) was 0.998 for methamphetamine and 0.997 for amphetamine. The limits of quantification (LOQs) of methamphetamine and amphetamine calculated as 10 times the signal-to-noise ratio were 2.86 and 3.36 ng/L, respectively.

Estimation of consumption and prevalence

The per inhabitant daily consumption of methamphetamine (m_{METH}) (mg/day/1000 inhabitants) based on specific WWTPs was estimated using the following equation:

$$m_{\mathrm{METH},i} = \frac{C_{\mathrm{METH},i} \times F_i \times f}{P_i} \quad (1)$$

where $C_{\mathrm{METH},i}$ (ng/L) is the concentration of methamphetamine in a sample from a WWTP i, F_i is the flow rate of raw wastewater in a WWTP i, and P_i is the population served by a WWTP i. The correction factor for METH, and the value of f used in this study was estimated to be 3.7 based on the excretion rate 27% of smoking (Khan et al. 2014). NH_4-N is used as an indirect marker of the population. The population was estimated by NH_4-N as follows:

$$P_i = \frac{C_{\mathrm{NH4-N},i} \times F_i}{m_{\mathrm{NH_4}-N}} \tag{2}$$

where $C_{\mathrm{NH4\text{-}N},i}$ (mg/L) is the concentration of NH_4-N measured in wastewater from WWTP i and $m_{\mathrm{NH4\text{-}N}}$ is the average amount of daily NH_4-N produced by each person. The value of $m_{\mathrm{NH4\text{-}N}}$ was determined to be 6 g/day/person in China (Zheng et al. 2017). Therefore, Eq. (1), used to calculate the consumption of methamphetamine at specific WWTPs, can be simplified as follows:

$$m_{\mathrm{METH},i} = \frac{C_{\mathrm{METH},i} \times m_{\mathrm{NH_4-N}} \times f}{C_{\mathrm{NH_4-N}}} \tag{3}$$

To obtain a general view of consumption on national scale in China, 27 WWTPs were selected in this study, and the average of the amount of methamphetamine consumed ($m_{\mathrm{METH\_Mean}}$) was calculated based on each consumption value ($m_{\mathrm{METH},i}$) multiplied by their weight (W_i) (Eq. 4).

$$m_{\mathrm{METH\_Mean}} = \sum_{i=1}^{n} m_{\mathrm{METH},i} W_i \tag{4}$$

Each WWTP accounts for a different weight in the average consumption due to the difference in population served by the WWTPs. Equation 4 normalizes the weight of each WWTP based on the mean consumption and the weight for each WWTP can be calculated based on the population served and the total population served by all WWTPs (Eq. 5). n is the number of WWTPs from 1 to 27.

$$W_i = \frac{P_i}{\sum_{i=1}^{n} P_i} \tag{5}$$

The prevalence of methamphetamine use can be calculated using the average consumption, the typical dose and frequency based on the following equation,

$$P(\%) = \frac{m_{\mathrm{METH,Mean}}}{R_{15-64} \times D \times n_{\mathrm{D}}} \times 100 \tag{6}$$

where $R_{15–64}$ is the proportion of the adult population aged 15–64 years old among the general population, which was estimated as 76.9%; D is the size of the typical dose, which was estimated at 135 ± 80 mg in China; and n_{D} is the average frequency of use per day and obtained through a traditional epidemiological questionnaire. Bao et al. (2013) reported that the prevalence of methamphetamine use among 1085 participants of less than 4 times/month was 59.24%, of 4–19 times/month was 26.78%, and of over 20 times/month was 13.98%. Based on the frequency of drug use, it was assumed as log-normal distribution with an average 0.31 times/day and a standard error of 0.31 times/day (Bao et al. 2013).

Statistical analysis

Methamphetamine consumption, prevalence of use, and annual consumption between 2014 and 2018 were analysed to compare the differences. We used the independent samples t test for multiple comparisons. Moreover, the correlation analysis test was used to analyse the correlation between methamphetamine and amphetamine. All calculations and statistical tests were performed using SPSS and Origin 8.0 software, and a p value of < 0.05 was regarded as statistically significant.

The Monte Carlo simulation (Oracle Crystal Ball software, Version 7.3.1) was used to evaluate the uncertainties of methamphetamine consumption, prevalence of use, and annual consumption. The Monte Carlo simulation defines the probability distribution of each parameter. To analysed the results of the estimated distribution, the mode, mean, and median values as point estimates, as well as the 2.5th and 97.5th percentiles, i.e., the 95% confidence interval (CI), were extracted and are presented. A detailed description of the parameters for the Monte Carlo estimation is shown in Table S2.

Results and discussion

Source of methamphetamine and amphetamine in wastewater

Methamphetamine and its metabolite amphetamine were detected in all the samples with concentrations of 42.6 (HRB) to 700 (XA) ng/L (mean, 208 ± 17 ng/L) for methamphetamine and 14.2 (YC) to 173 (LZ) ng/L (mean, 34.4 ± 12 ng/L) for amphetamine (Table 1). The legal source of methamphetamine in wastewater may be from the use of selegiline. Khan et al. (2014) reported that 0.2 mg of selegiline HCl was taken daily for every 1000 Chinese residents. It can be estimated that the legal contribution of methamphetamine in wastewater from selegiline is approximately 0.03 mg/1000 inhabitants. Due to the high prevalence of methamphetamine use in China, the contribution resulting from the metabolism of selegiline can be ignored (Khan and Nicell 2012; Khan et al. 2014). Based on our results, there was a significant correlation ($p < 0.05$) between the concentrations of methamphetamine and amphetamine, indicating that they both came from the same maternal compound. The mean concentration ratio between amphetamine and methamphetamine (AMP/

METH) was 20% (5–64%) in these WWTPs. Methamphetamine is partially metabolized into amphetamine (2.6–9.5%) and methamphetamine (27–54%) through different routes of use, and the corresponding AMP/METH ratios ranged from 5 to 24% (Khan and Nicell 2012). Therefore, it is considered that amphetamine in influent arises from methamphetamine metabolism instead of amphetamine use itself. Thus, amphetamine in sewage of the overwhelming majority of cities in China comes from methamphetamine use, indicating that amphetamine use in China is negligible overall. This idea is consistent with the fact that methamphetamine is the major illicit drug used in China.

WBE can monitor not only drug use but also illegal incidents such as drug production or trafficking. It should be noted that a high level of methamphetamine was identified in BD-1 with a concentration of 3315 ± 302 ng/L in October 2018, which is much higher than the normal values (Been et al. 2016; Lai et al. 2016; Mastroianni et al. 2017; Ort et al. 2014; Tscharke et al. 2015; Zuccato et al. 2016). In addition, the concentration of amphetamine in wastewater was very low in BD-1, and the AMP/METH ratio was 1.4%, which was lower than the range of 5–24% (Khan and Nicell 2012). It was indicated that the wastewater contains a large amount of the parent compound of methamphetamine that is not metabolized by the human body. Thus, a discarding event was suspected. To confirm the result, a second sampling was conducted at BD-1 and two other WWTPs (BD-2 and BD-3) in January 2019. The methamphetamine concentration was 69.8 ± 10.7, 290 ± 56, and 123 ± 6 ng/L for BD-1, BD-2, and BD-3, respectively. These values were much lower than those obtained from the first sampling. Additionally, the corresponding ratios of amphetamine to methamphetamine were 27, 11, and 25%, respectively. Therefore, the above results indicated that the detected high level of methamphetamine in BD-1 in October 2018 was from discarding rather than abusing. In addition, the first sampling value (3315 ng/L) was not used to estimate the national consumption in this study.

Spatial distribution of methamphetamine concentration and consumption

The methamphetamine concentrations in the two WWTPs (XA and LZ) in Northwest China were generally higher than those in other cities (Table 1). In Central China, the mean methamphetamine concentration in ZZ (454 ± 13 ng/L) was approximately 4 times higher than those in XT-1 (118 ± 6 ng/L) and XT-2 (156 ± 21 ng/L). In Southwest China, the mean methamphetamine concentration in CQ-2 (225 ± 3 ng/L) was half of that in CQ-1 (410 ± 44 ng/L). The concentration in GY-1 (102 ± 8 ng/L) was similar to that in GY-2 (115 ± 31 ng/L). In East China, the concentration of methamphetamine in WH was the highest, with a value of 467 ± 30 ng/L.

In 2014, Du et al. (2015) reported methamphetamine concentration in 36 WWTPs from 25 cities (Du et al. 2015) (Table S3). A slight reduction in methamphetamine concentrations appeared in China compared with the values from 2014 (Fig. 1). The mean concentration of methamphetamine (208 ng/L) in 2018 decreased slowly compared with that in 2014 (229 ng/L) ($p > 0.05$, t test). Compared with the data from 8 of the same sampling cities in 2014, significant decreases were shown in four cities (HRB, YC, GY, and KM) with a range of 12–91% (Table S4).

The consumption of methamphetamine ranged from 23.0 ± 2.6 mg/day/1000 inhabitants (DX) to 376 ± 5 mg/day/1000 inhabitants (XA) (Table 1). The highest consumption was found in XA, followed by ZZ (368 ± 10 mg/day/1000 inhabitants) and CQ-1 (328 ± 36 mg/day/1000 inhabitants). The lowest consumption was observed in DX (23.0 ± 2.6 mg/day/1000 inhabitants). These results indicated that methamphetamine was widely used across the country and it appeared that the use was lower in Northeast China relative to other regions.

The average methamphetamine consumption was 164 ± 13 mg/day/1000 inhabitants in 2018, whereas in 2014 it was 226 mg/day/1000 inhabitants. Significant decreases were observed in five WWTPs, namely, HRB, YC, BJ, JN, and KM with a 48–85% decrease compared with the values in 2014 (Table S4). The reason why slight reduction in methamphetamine consumption is either that different cities were selected in two studies or the result of a series of anti-drug measures taken by the Chinese government since 2015.

Although drug use is popular in the country, it is still considered to be a geographic and culture-dependent behaviour. The consumption of methamphetamine in Central China was considered to be the highest, with an average of 274 ± 19 mg/day/1000 inhabitants, followed by the Southwest China, in which the average consumption was 189 ± 21 mg/day/1000 inhabitants. The average consumption in South and Northwest China was similar, with values of 116 ± 9 and 125 ± 12 mg/day/1000 inhabitants, respectively (Fig. 2).

A reduction in methamphetamine consumption occurred in China (Fig. 1). The average consumption of methamphetamine decreased slowly from 255 mg/day/1000 inhabitants in 2014 to 164 mg/day/1000 inhabitants in 2018 ($p < 0.05$, t test). The newly released National Drug Abuse Monitoring Annual Report in 2018 revealed that the number of people with a dependence on methamphetamine declined from 1.54 million in 2017 to 1.35 million in 2018 in China (NNCC 2017; NNCC 2018). The increasing crackdown on methamphetamine use has led to higher retail prices (from 200 RMB in 2014 to 1000 RMB in 2018, based on data provided by the police), which reduced the consumption of methamphetamine (Wang et al. 2019).

Based on the latest census data on population in China and the per capita methamphetamine consumption (159 mg/day/

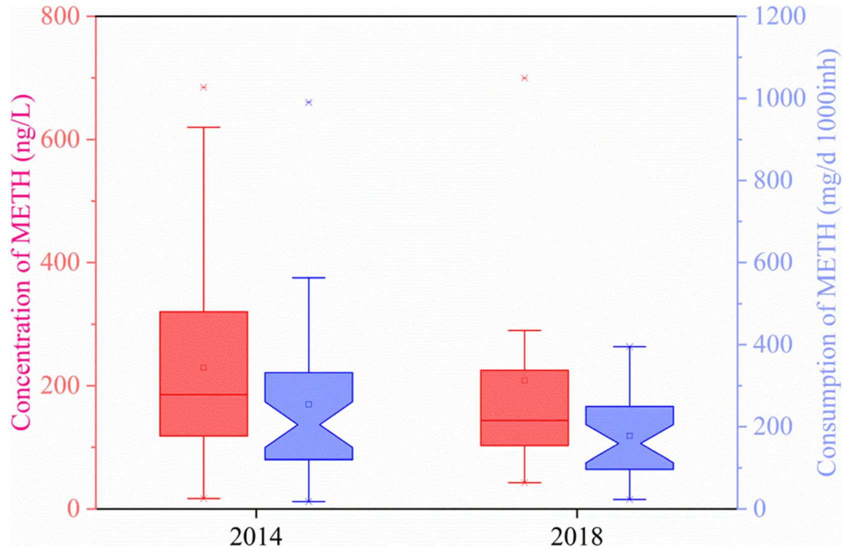

Fig. 1 Methamphetamine concentrations and consumptions in 2014 and 2018 (the present study). The concentration data in 2014 from 36 WWTPs from 27 Chinese cities (Du et al. 2015) and the consumption was calculated using the same factor in present study

1000 inhabitants) predicted by Eq. (4), the spatial pattern of methamphetamine consumption at the province and city levels was obtained (Fig. 3) (census data comes from http://www.stats.gov.cn/.) The consumption of methamphetamine in most provinces ranged from 100 to 500 g/day. The lowest and highest methamphetamine consumption were found in Hainan Province (13.5 g/day) and Xinjiang Uygur Autonomous Region (889 g/day), respectively. Low consumption of methamphetamine was also observed in Tibet (20.3 g/day), Shaanxi (47.9 g/day), Qinghai (58.5 g/day), and Hubei (80.1 g/day) provinces.

The consumption of methamphetamine in most cities ranged from 20 to 100 g/day. More than 20 cities had very low consumption in a range of 1–2 g/day. As four major cities in China, Shanghai, Beijing, Chongqing, and Tianjin showed high consumption, with values of 359, 307, 294, and 208 g/day, respectively. The consumption of illicit drugs in different regions or cities can be affected by many factors, such as population, price, income, availability, and culture. However, no significant relationship was shown between these factors and consumption. Our analysis showed that methamphetamine was widely used across the country and that consumption showed no clear geographical trend in China. This result could indicate that the consumption of methamphetamine was not restricted to a particular area but was present in all cities throughout China.

Prevalence of methamphetamine use in China

The prevalence of methamphetamine ranged from 0.08% (DX) to 1.25% (XA) (mean, 0.55%) in 22 cities among the adult population aged 15–64 years. This result agreed well with the value (0.58%, 95% CI 0.08–3.16) in Beijing (Pei et al. 2016) and with the prevalence (0.57%, range of 0.22–1.29) of the use of amphetamine-type stimulants in East and Southeast Asia (UNODC 2016; UNODC 2016). The high

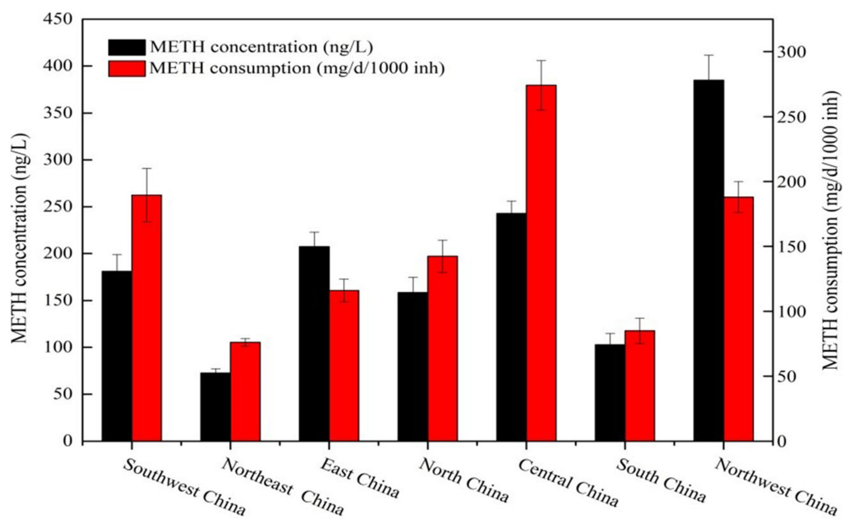

Fig. 2 Methamphetamine concentration and consumption of seven geographic regions of China in 2018

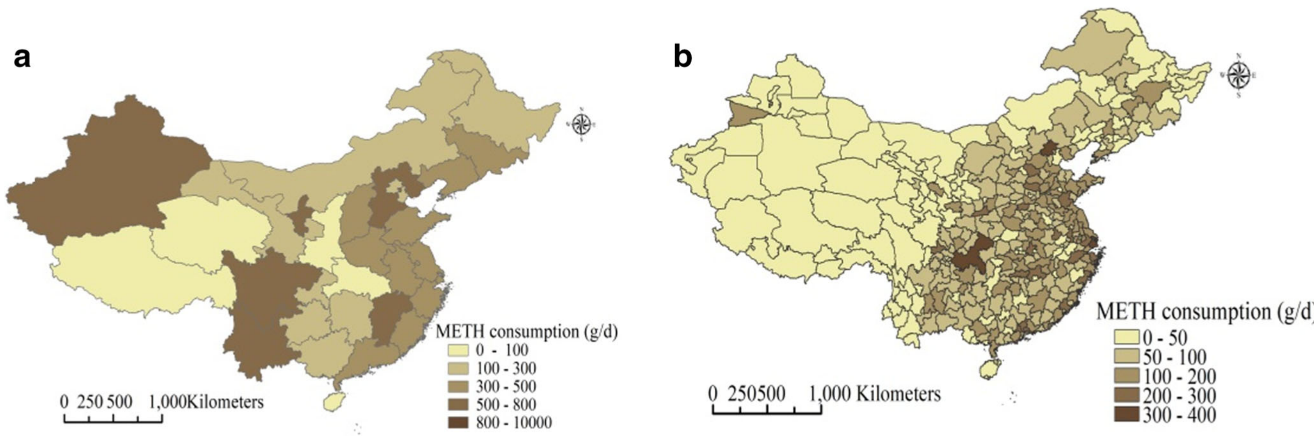

Fig. 3 Special pattern of methamphetamine consumption in all provinces (**a**) and cities (**b**) in China, 2018

prevalence of methamphetamine use was attributed to methamphetamine remaining more readily available in China. Unlike opium production, there is little restriction on the geographic location of synthetic drug manufacturing. The police seizures showed that crystalline methamphetamine domestic production and methamphetamine table trafficking from the Golden Triangle increased with increasing methamphetamine use. Therefore, the government has strengthened the regulation of methamphetamine precursor availability to reduce methamphetamine production (NNCC 2017).

The population aged 15–64 years accounts for 74.6% of the total population in China (1.37 billion). The prevalence of methamphetamine use in adults (15–64 years) was 0.57%. Therefore, it is estimated that a total of 5.8 million people in China used methamphetamine in 2018. In recent years, adults in rural areas have gradually migrated to urban cities for work. Most people who stay in rural areas are children under 15 years old and elderly people over 65 years old. Although we predicted the number of drug users in urban cities, this value can represent the number of drug users across the country, including in rural areas.

In China, new methamphetamine users accounted for a high proportion among all users. The number of methamphetamine users has increased markably during the past decade, and 1.35 million people who had been arrested by the police in 2018 (NNCC 2018) Therefore, the estimated number of methamphetamine users in China is approximately 4.3 times the number of registered methamphetamine users. The invisible use of methamphetamine is still serious, and increased surveillance is needed to effectively control illicit drug use.

Uncertainty analysis

To reduce the uncertainty of these estimations, a Monte Carlo simulation was conducted, and the probability distribution density of the methamphetamine consumption and prevalence are shown in Fig. 4. The average consumption of methamphetamine was estimated to be 169 mg/day/1000 capita (95% CI, 87–272) in 2018. Since the estimation was calculated as the product of several probability distributions, the consumption distribution showed an approximate beta distribution. With the average consumption per capita and total population of 1.37 billion, we calculated the total consumption of methamphetamine as 84 tons per year in 2018 (95% CI, 44–136). According to the National Drug Abuse Monitoring Annual Report in 2017, 17.4 tons of white crystal (mean 73% purity) and 11.6 tons of tablet forms (Ma Old, mean 10% purity) were seized by the police. This result suggested that only approximately 16% of smuggled methamphetamine was seized in China.

According to the report of methamphetamine use in 2014 (Du et al. 2015), the average consumption of methamphetamine was estimated to be 226 mg/day/1000 inhabitants (95% CI, 127–345). It can be concluded that the total consumption was 114 tons per year (95% CI, 63–173) in 2014. Hence, the total consumption in 2018 was estimated to be 84 tons in the whole country, with a 26% decreased from 2014, which was reflected by the fact that registered people with a dependence on drugs in China showed a 19% decrease from 2.94 million in 2014 to 2.40 million in 2018 (NNCC 2014, 2018). The prevalence of methamphetamine use among the adult (15–64 years) population also decreased from 1.09% (95% CI, 0.19–2.42) in 2014 to 0.64% (95% CI, 0.18–1.25) in 2018. The reduction could be attributed to a series of anti-drug measures taken by the Chinese government since 2015. Preventive education and publicity were implemented to encourage students in school not to use drugs. Additionally, some community-based rehabilitation and treatment projects for people who use drugs were implemented to offer support for overcoming dependence. New regulations on the dynamic control of people who use drugs have resulted in the online control and dynamic tracking of people dependent on drugs through the national network information database. As a result, the number of drug users under 35 years old decreased by 19% from 2016 to 2017. Moreover, the government have started to combat the source and circulation of drugs, and

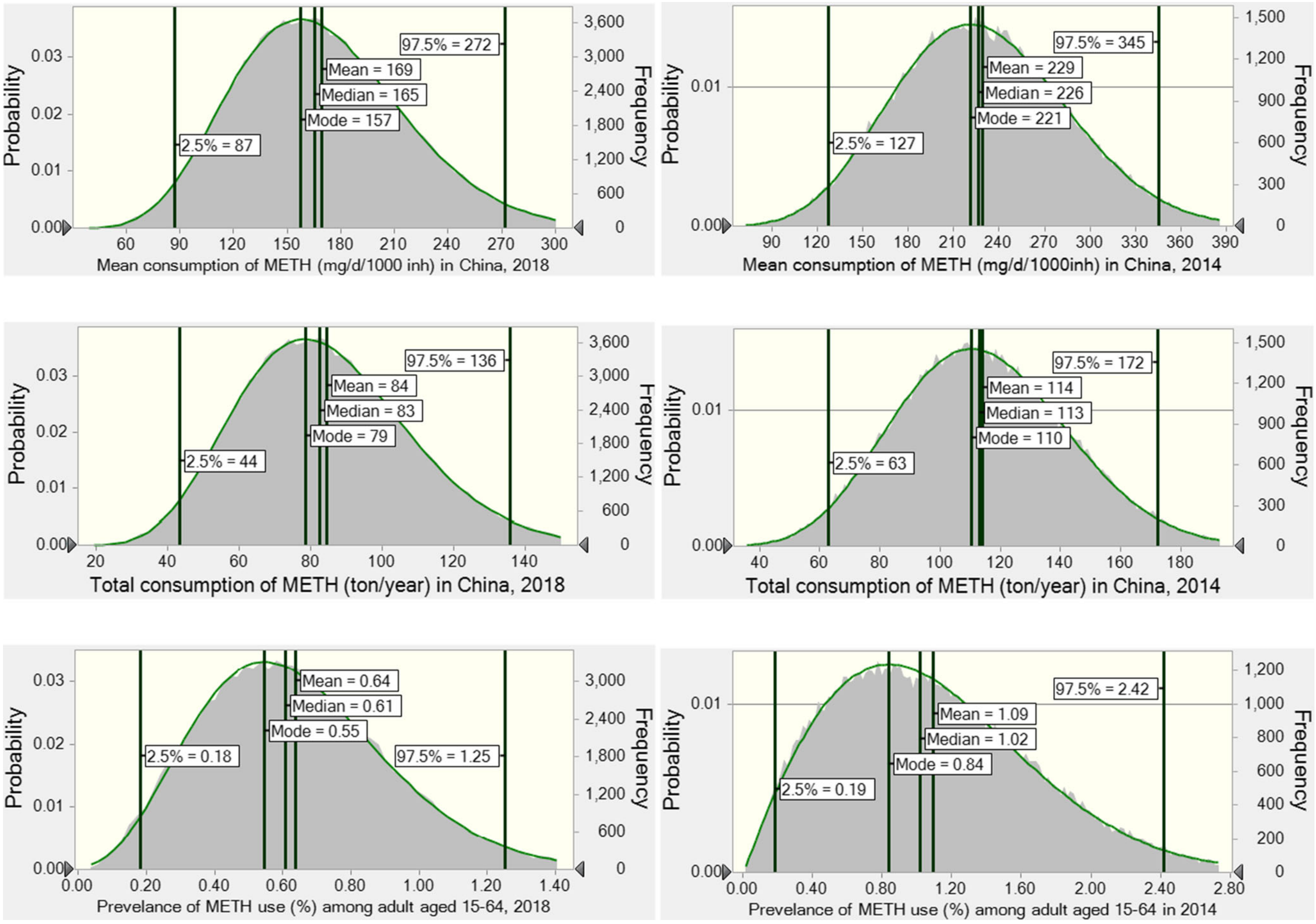

Fig. 4 Comparison of probability distribution of estimated the mean (mg/day/1000 inh), total consumption (ton/year), and prevalence of methamphetamine (%) in 2014 and 2018: mode, median, mean, 2.5th and 97.5th percentiles

amount of the seized drugs and precursor chemicals increased by 19 and 51%, respectively, from 2016 to 2017 (NNCC 2016; NNCC 2017).

Conclusion

This study applied WBE to assess the current status of methamphetamine use in China. The prevalence of methamphetamine use was estimated to be 0.55% among the general population in 22 major Chinese cities. A total of 5.8 million people were estimated to use methamphetamine in China and the total consumption was 84 tons in 2018. It is worth noting that a discarding event was found in one WWTP, indicating the possibility of investigating the origin of methamphetamine in wastewater through the WBE method. Thus, the present study could provide complementary evidence and suggestions for related authorities for the prevention and reduction of drug production and consumption. To better understand the association of methamphetamine use with socio-economic status in China, more specific regional monitoring and long-term investigation of methamphetamine use should be conducted in further work.

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