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Review Article

Could wastewater analysis be a useful tool for China? — A review

Jianfa Gao[1], *Jake O'Brien*[2], *Foon Yin Lai*[2], *Alexander L.N. van Nuijs*[3], *Jun He*[1], *Jochen F. Mueller*[2], *Jingsha Xu*[1], *Phong K. Thai*[2,*]

1. *Faculty of Science and Engineering, University of Nottingham Ningbo China, Ningbo 315100, China. E-mail:* JGao_uq@yeah.net
2. *National Research Centre for Environmental Toxicology, The University of Queensland, Brisbane, QLD 4108, Australia*
3. *Toxicological Center, University of Antwerp, 2610 Antwerp, Belgium*

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ABSTRACT

Analysing wastewater samples is an innovative approach that overcomes many limitations of traditional surveys to identify and measure a range of chemicals that were consumed by or exposed to people living in a sewer catchment area. First conceptualised in 2001, much progress has been made to make wastewater analysis (WWA) a reliable and robust tool for measuring chemical consumption and/or exposure. At the moment, the most popular application of WWA, sometimes referred as sewage epidemiology, is to monitor the consumption of illicit drugs in communities around the globe, including China. The approach has been largely adopted by law enforcement agencies as a device to monitor the temporal and geographical patterns of drug consumption. In the future, the methodology can be extended to other chemicals including biomarkers of population health (*e.g.* environmental or oxidative stress biomarkers, lifestyle indicators or medications that are taken by different demographic groups) and pollutants that people are exposed to (*e.g.* polycyclic aromatic hydrocarbons, perfluorinated chemicals, and toxic pesticides). The extension of WWA to a huge range of chemicals may give rise to a field called sewage chemical-information mining (SCIM) with unexplored potentials. China has many densely populated cities with thousands of sewage treatment plants which are favourable for applying WWA/SCIM in order to help relevant authorities gather information about illicit drug consumption and population health status. However, there are some prerequisites and uncertainties of the methodology that should be addressed for SCIM to reach its full potential in China.

Contents

* *Corresponding author*. E-mail: p.thai@uq.edu.au (Phong K. Thai).

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Introduction

Wastewater analysis (WWA) or Sewage epidemiology was first proposed to estimate drug consumption by US EPA environmental scientist Daughton in 2001 (Daughton, 2001). The approach was based on the assumption that when particular drugs are consumed, the active parent compounds and its metabolites are excreted through urine and faeces into the sewer system, and thus enter the sewage treatment plants (STPs). By measuring levels of target parent compounds and/or metabolites, back-estimation of drug use in the population of a STP catchment area could be realised. Compared with conventional methods such as questionnaires and socio-epidemiological surveys including crime statistics, medical records, drug production and seizure rates, WWA has the advantage of providing objective, continuous, near real-time estimates of drug consumption in the population (van Nuijs et al., 2011a). Additionally, using WWA to estimate illicit drug consumption can overcome ethical issues associated with some other methods (Hall et al., 2012; Khan et al., 2014).

A lot of effort has been made to improve all aspects of WWA. These include sampling protocol development to get representative samples, developing robust, sensitive analytical methods and more recently normalizing chemical loads to per capita estimates that allow more accurate comparisons between different cities and even countries (Zuccato et al., 2005; Ort et al., 2010a, c; Zuccato et al., 2011; O'Brien et al., 2014). Many researchers from a wide range of fields including but not limited to analytical chemistry, environmental science, epidemiology, forensic science, sociology and statistics from all over the world have joined the 'WWA research community' to improve the innovative approach during the past years. This is evident by a series of conferences organised by the European Monitoring Centre for Drug and Drug Addiction called *Testing the Waters* starting in May 2013 in Lisbon, Portugal and the next session is planned for 2015 in Ascona, Switzerland.

This review article attempted to present a brief overview of the development of WWA to date with a focus on its successful application to estimate illicit drug consumption and the future applicability of this approach in China.

1. Current state of WWA

1.1. *Application of WWA in estimating illicit drug consumption*

The approach of WWA was applied for the first time in Italy in 2005 (Zuccato et al., 2005) and was soon applied in several other cities in Europe and the US (van Nuijs et al., 2011a). Since then WWA has been applied to monitor the use of the classical illicit drugs such as cocaine, heroin, amphetamines and cannabis (van Nuijs et al., 2011a; Thomas et al., 2012) and more recently to identify the use of new psychoactive substances (Reid et al., 2014; van Nuijs et al., 2014).

Reports of illicit drugs estimated by WWA have come from multiple countries including Australia, Belgium, Canada, Croatia, Finland, France, Italy, Ireland, The Netherlands, Sweden, the UK and the US. Estimation of illicit drug use has been performed not only in small communities such as prisons (Postigo et al., 2011), and recreational regions (Lai et al., 2012), but also in large cities like Paris and Hong Kong (Karolak et al., 2010; Lai et al., 2013). Most obtained results are in agreement with data from traditional socio-epidemiological surveys, however some underestimation and/or overestimation has been identified for some particular drug(s) (Baker et al., 2014). Thomas et al. (2012) conducted a comparison of illicit drug consumptions in 19 cities across Europe through WWA and identified distinct temporal and spatial differences in drug consumption between these cities during a single week of sampling in 2011. In 2013, Nefau et al. (2013) studied the presence of 17 illicit drugs both in influent and effluent sewage from 25 French STPs. Consumption maps were drawn for cocaine, opiates, cannabis and amphetamine-like compounds. Significant geographical differences were observed which highlighted that drug consumption within a country might not be homogeneous. Similarly, Khan et al. (2014) applied WWA to evaluate the use of 10 illicit drugs in 4 megacities in

China and found different consumption patterns between north and south China. At the same time, Li et al. (2014) also reported the use of amphetamines across a range of communities in the metropolitan area of Beijing. A summary of WWA applications for assessing illicit drug consumption worldwide is shown in Table 1.

1.2. Exploration in other areas

In addition to illicit drugs, there are some initial attempts to estimate the use of alcohol and tobacco, the two most common substances that have potential to negatively impact population health and cause several social problems such as crime and injuries. Reid et al. conducted the first study to estimate the use of alcohol in Oslo, Norway using WWA (Reid et al., 2011) where the highest consumption of the alcohol was observed during weekends. Sixty one percent of weekly alcohol consumption was reported on Friday and Saturday alone. Over the last year, two studies were carried out to estimate the total amount of tobacco use (nicotine consumption) in different communities through WWA (Castiglioni et al., 2014; Lopes et al., 2014). The findings produced by WWA were in close agreement with survey data and can differentiate the level of tobacco consumption among different populations.

In addition to monitoring common substances of abuse (illicit drugs, alcohol, and tobacco), WWA can be considered as Sewage chemical-information mining (SCIM). In a broader sense, because the interpretation of acquired information from WWA can measure a vast amount of chemicals, WWA can provide a variety of information about the population living in a particular STP catchment. It could also be used as a powerful tool to evaluate community-wide human health with isoprostanes (stress biomarkers) already proposed by Daughton as ideal candidates (Daughton, 2012b). Daughton also conceptualised an approach to estimate the real-time population size in the sewer catchment using coprostanol as a population biomarker (Daughton, 2012a) although further study should be conducted to validate the applicability of coprostanol in WWA (Chen et al., 2014).

Venkatesan and Halden (2014) have applied SCIM to forecast ecological and human health risks of manmade chemicals by analysing sewage sludge instead of wastewater for persistent organic pollutants (POPs) which are non-polar and thus less likely to be in the wastewater itself. The result revealed 70% agreement between WWA and biological specimens' analysis, and suggested that analysing sewage sludge can inform human health risk assessments by providing real-time information on toxic exposures in human populations and associated body burdens of harmful, accumulative, environmental pollutants. More outcomes could be achieved if the efforts across several disciplines including clinical chemistry, environmental chemistry, environmental science, medicine and microbiology were combined. With continuous improvement of the method, SCIM appears a feasible and effective tool to identify the connection between population

Table 1 – Research conducted around the world regarding illicit drug consumption through WWA.

Targeted drugs	Country	Sampling time	Number of STPs (population size served by each STP, in 1000 people)	Reference
Cannabis, cocaine, heroin, METH	Italy	2005–2009	2 (100; 1250)	Zuccato et al. (2011)
Codeine, morphine, norcodeine, normorphine	Ireland	2006	5 (40; 48; 65; 80; 1700)	Bones et al. (2007)
AMP, heroin, cocaine, MDMA, METH, MTD	Belgium	2009	1 (1000)	van Nuijs et al. (2011b)
AMP, BEZ, cocaine, MDMA, METH	Canada	2009	3 (75; 500; 1600)	Metcalfe et al. (2010)
AMP, cocaine, heroin, cannabis, MDMA	Croatia	2009	1 (650)	Terzic et al. (2010)
Cocaine, METH	Norway	2009	1 (500)	Reid et al. (2011)
AMP, BEZ, cocaine, codeine, EDDP, EME, MDA, MDEA, METH, morphine, MTD, THC, THC-COOH	Australia	2009	3 (1.1–2.4; 120; 350)	Lai et al. (2012)
AMP, BEZ, buprenorphine, cocaine, MDMA	France	2009	2 (100; 3670)	Karolak et al. (2010)
AMP, METH, MDA, MDMA	United Kingdom	2010	7 (10; 11; 15; 190;190; 240; 244)	Kasprzyk-Hordern and Baker (2012)
BEZ, caffeine, cocaine, METH	United States	2010	1 (54)	Brewer et al. (2012)
AMP, cocaine, MDMA, METH	Finland	2012	(58; 60; 80; 100; 147; 150; 200; 275; 310; 800)	Kankaanpää et al.(2014)
AMP, BEZ, cocaine, MDMA, METH, ketamine, norketamine	Hong Kong	2011	1 (3500)	Lai et al. (2013)
AMP, BEZ, cocaine, EDDP, EME, MDPV, 6-monoacetylmorphine, MDMA, METH, mephedrone, MTD, THC-COOH, ketamine, norketamine	China	2012	9 (1520; 2420; 100; 130;1500; 2260; 1500; 2000; 200)	Khan et al. (2014)
AMP, METH	China	2013	13 (345,2; 152,0; 333,8; 285; 685; 180; 257; 519; 571; 186; 456; 87; 60;)	Li et al. (2014)

AMP: Amphetamine, BEZ: Benzoylecgonine, EDDP: 2-thylidene-1,5-dimethyl-3,3-diphenylpyrrolidine, EME: Ecogonine Methyl ester, MDA: 3,4-methylenedioxyamphetamine, MDEA: 3,4-methylenedioxymethamphetamine, MDMA: Methylenedioxymethamphetamine, MDPV: Methylenedioxypyrovalerone, METH: Methamphetamine, MTD: Methadone, THC: Δ9-tetrahydrocannabinol, THC-COOH: 11-nor-9-carboxy-Δ9-tetrahydrocannabinol.

health and chemical consumption and/or exposure and thus enabling better protection of the population from such hazards.

1.3. Current research to improve the methodology

Current research mostly focuses on evaluating and minimizing uncertainties of the whole WWA procedure such as collecting representative sewage samples, simplifying sample pre-treatment, selecting suitable biomarkers in terms of sensitivity and stability, optimizing instrumental analysis, and refining the back calculation of results. Castiglioni et al. integrally addressed uncertainties associated with all the steps necessary to estimate community drug consumption through WWA (Castiglioni et al., 2013). Using data gathered from 12 laboratories, the uncertainties can range from 5%–10% for sampling to 1%–34% for replicated chemical analysis and 26% for back-calculation of cocaine use. But the highest uncertainty comes from the estimation of population size, which varied from 7% to 55%. Based on this study, the authors also suggested a best practice protocol to minimize the overall uncertainties of the entire procedure (Castiglioni et al., 2013).

Several studies have attempted to address individual issues facing WWA. For instance, Martínez Bueno et al. developed a solvent-free method for simultaneous identification and quantification of 22 illicit drugs by liquid chromatography coupled to tandem mass spectrometry (LC–MS/MS), which is deemed to be a good technique for WWA due to its simplicity, cost-effectiveness and lower environmental footprint (Martínez Bueno et al., 2011). Meanwhile, Baker and Kasprzyk–Hordern evaluated the commonly used methodologies for sample collection, storage and preparation for SCIM with solid-phase extraction (SPE) and LC–MS/MS analysis (Baker and Kasprzyk-Hordern, 2011). They concluded that from the perspective of stability, composite samples are unsuitable with regard to certain compounds like heroin and 6-acetylmorphine; these two drugs reported a decrease in stability of 66% and 26% respectively after 12 hr in raw sewage at 2°C. Baker and Kasprzy-Hordern also emphasised that more rigorous reporting of method validation data is needed as underreported parameters might have major impacts on the overall performance.

For the estimation of consumed drug masses in the catchment using the optimum sampling method as outlined by Ort et al. (2010b) and common chemical analysis, Lai et al. calculated the overall uncertainty to be in the range of 20%–30% (relative standard deviation, RSD) (Lai et al., 2011). Lai et al. also suggested using chemicals of relatively high use in the population as a basis to estimate the population size. To further address this issue, O'Brien et al. (2014) have screened wastewater samples and found 14 chemicals which could be used as real-time population markers. They then developed a model to estimate the population contributing to the sewage influents based on the load of those chemicals. Through calibrating their model with mass loads of 14 chemicals with accurate population counts (the samples were taken on Census day), they found that relatively accurate population sizes can be estimated for catchment >100,000 people (O'Brien et al., 2014).

2. General procedure of WWA

WWA is generally carried out using the procedure shown below (Fig. 1). Simplification and standardization of the method as well as improvement of the accuracy and reliability of the final estimates are crucial in promoting WWA for routine monitoring.

2.1. Pre-investigation

A systematic and comprehensive pre-investigation about the catchment area and STP under investigation is critical for reliable and accurate WWA estimates. Socio-economic conditions of the study area, contemporary and historical environmental monitoring data, population size and mobility in and out of the STP catchment area, and crime statistics should all be put into consideration to achieve reliable results. The investigation could be carried out through multiple approaches such as literature reviews, visiting and surveying STPs, discussions with local authorities such as law enforcement officers, relevant medical staff as well as environmental officers, and local and national councillors. The pre-investigation may strengthen the results' reliability of WWA studies particularly where drug consumption estimates are the goal. The use of alternate methods for assessing community drug consumption are not limited to the pre-investigation stage but may also be relevant to reconsider during or even post the sampling period. Examples of this include combining drug seizure data with loads in the wastewater and assessing the scale of the market based on the mass load of drugs removed.

2.2. Sampling

Samples are taken from the inlets of STPs since the influent can be regarded as a pooled urine sample (although diluted and contaminated) from a large population before it is altered by different treatment processes in the STPs. However, in addition to sewage influent, activated sludge from the aerobic or anaerobic tanks has also been used as samples for WWA (Venkatesan and Halden, 2014).

For sample volume, 1 L is the most common. However, sample volumes from 0.05 to 10 L have been reported. A variety of sampling methods have also been studied. Continuous flow, volume and time proportional sampling with commercialized auto-samplers have all been used in different studies. Grab samples have also been used in several studies (Hummel et al., 2006). Ort et al. (2010b) found continuous flow proportional samples collected over a 24 hour period as the optimum sampling method as these are more representative of a whole day and are better at capturing events. Samples from weekdays, weekends and public holidays across the whole year have all been investigated to reveal temporal patterns of drug consumption. While it is possible for each research group to establish a continuous flow proportional sampling system, there is a need for the development of a commercial auto-sampler that uses this optimal sampling method. This would allow for a standardised sampling approach for WWA while sampling at the different STPs (Ort et al., 2010b).

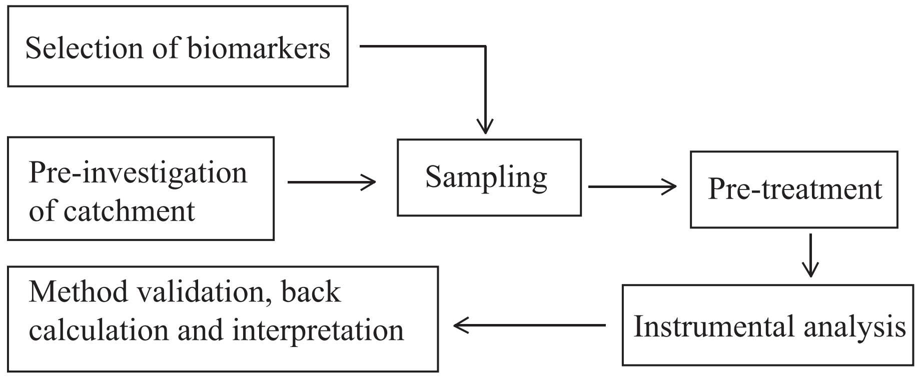

Fig. 1 – General procedure for WWA.

Detailed discussion about sampling practices for wastewater has been conducted and a comprehensive sampling guide with the aim of reducing uncertainties has been proposed (Ort et al., 2010c). Evaluation of flow measurement, choice of sampling mode, determination of frequency and location have all been discussed in the abovementioned paper. For long-term routine monitoring, on-line auto-samplers are essential for representative sampling with reliability, efficiency and from economic aspects. More research should be conducted to evaluate uncertainties brought by different sampling parameters in the future.

2.3. Biomarker selection

Selection of suitable biomarkers is an important factor for WWA. There are several criteria for appropriate WWA biomarkers as suggested by Daughton (Daughton, 2012b) including: produced exclusively by humans (*i.e.*, not introduced by unrelated, exogenous mechanisms, *e.g.* illicit drug discharge), excreted in sufficient quantities (to allow detection in sewage), sufficiently stable in the sewer pipeline, amenable to cost-effective, reproducible analysis, and for several health status biomarkers they should be excreted at elevated levels under "stressed condition" significantly different to the baseline range of the chemicals excreted under "normal condition".

While biomarkers have been one of the most popular research topics in clinical science in the past decades, there were limited studies on biomarkers that can be used in WWA. As suggested by Daughton, one should start at the list of common clinical biomarkers and test them against the appropriate criteria (Daughton, 2012b). One of the criteria that has been tested in several studies is the stability of the biomarkers in the wastewater matrix and under sewer conditions. Until recently, most parent compounds and metabolites were used as biomarkers in WWA for monitoring of illicit drug consumption with the assumption that they were stable in the sewer system. But some of these biomarkers (such as cocaine or 6 acetyl morphine) are quite unstable (Thai et al., 2014; van Nuijs et al., 2012) which means that previous studies may have underestimated the amount of drugs consumed in certain catchments. To address this, excretion profiles of biomarkers including parent to metabolite ratio should be further investigated by pharmacologists, biochemists and sewer engineers to get a better grasp of consumed load *versus* measured load within wastewater.

For WWA to reach its full potential, more biomarkers should be identified and tested against all of Daughton's proposed criteria to expand the WWA application to evaluate other markers of population health, real-time population size estimation, and pollutant exposure, and promote WWA as a routine monitoring approach in STPs.

2.4. Pre-treatment

Filtration or centrifugation of the collected sample is essential to remove solids in the sample. However, this step may cause loss of certain analytes due to substantial affinity for particulate for some chemicals (Baker and Kasprzyk-Hordern, 2011; Plósz et al., 2013). Adding isotope labelled internal standards before filtration or centrifugation is an effective approach to evaluate and minimize these uncertainties. Full and accurate understanding about biomarker absorption kinetics is also useful to minimize the uncertainties associated with correction factors for the back calculation process.

The observed concentrations of target compounds and their metabolites in raw sewage are often at the level of ng/L or even lower and thus pre-concentration is required. In most cases solid-phase extraction (SPE) is conducted prior to LC–MS/MS analysis in order to concentrate and remove matrix interferences from the samples.

Baker and Kasprzyk-Hordern have critically evaluated the whole sample preparation process from sample collection to storage and preparation for analysis. This was conducted for both pharmaceuticals and illicit drugs in surface water and wastewater using SPE–LC–MS/MS techniques (Baker and Kasprzyk-Hordern, 2011). The study showed that uncertainties associated with biomarker degradation can be minimized if proper pre-treatment is applied. The current optimal method is to collect samples in a refrigerated (4°C) container, subsample them, acidify with hydrochloric acid and then either refrigerate at 4°C in the dark or freeze if the samples are to be analysed at a later date to minimize biotransformation/degradation of the biomarkers. Degradation of illicit drugs and metabolites in wastewater has been evaluated by van Nuijs et al (2012). They concluded that most parent compounds and metabolites of illicit drugs such as amphetamine, methamphetamine, ecstasy and EDDP are considerably stable for 12 hr or longer, however some drugs such as cocaine and ecgonine methylester showed a clear decrease in concentration over this period.

Since the SPE process is costly, time consuming and requires larger sample volumes, simpler procedures are starting to be developed. Berset et al. developed a large volume direct injection method for the simultaneous analysis of licit and illicit drugs in surface water and waste water (Berset et al., 2010). It should be noted that analytical instruments are becoming more sensitive and when combined with the development of optimized methods, it seems plausible that reliable methods for analysing illicit drugs in wastewater with acceptable limits of detection (LOD) without the need for SPE are possible. This would then enhance the argument for routine WWA monitoring as a tool for measuring drug consumption. The improved sensitivity of some instruments (*i.e.* LC–MS/MS) is already adequate for determination of numerous chemicals in wastewater using simple pre-treatment technique such as acidifying and filtering only (*e.g.* the pharmaceuticals in O'Brien et al., 2014).

2.5. Instrumental analysis

Liquid chromatography coupled with tandem mass spectrometry (LC–MS/MS) is used in almost all WWA studies due to its high sensitivity, versatility and selectivity. A variety of mass spectrometers have been used in different WWA studies (Castiglioni et al., 2011). These include triple quadrupole mass spectrometer (QqQ), Orbitrap, and quadrupole time-of-flight mass spectrometers (QTOF). Most applications use QqQ since it provides better selectivity and thus can achieve low detection limits. For some compounds the use of QqQ may eliminate the need for sample extraction and clean-up by using direct-injection technique (Trenholm and Snyder, 2011). Since QTOF and linear ion trap fourier transform (LIT-FT) have higher mass resolution and mass accuracy than QqQ, they can be better choices for drug identification and new synthetic drug screening in samples with complex matrix (de Voogt et al., 2011; Hernández et al., 2011).

Multiple reaction monitoring (MRM) mode is used for both qualification and quantification. Several studies grouped illicit drugs according to their physicochemical properties and different analytical parameters (such as chromatography and ionization mode) in order to achieve optimum separation and the highest MS resolution. As newer, more sensitive LC–MS/MS, QTOF and Orbitrap instruments are developed, it is expected that these will have a significant role in WWA applications for their incomparable advantages in rapid wide-scope screening and providing accurate mass data of both parent molecules and daughter ions for identification in complex matrices. Some of these instruments such as QTOF and Orbitrap have the ability to acquire both qualitative and quantitative information from samples in one injection and thus chemicals of interest can be retrospectively identify in these samples. Once the spectra are obtained, there is no need for reanalysing the sample. This is particularly useful for emerging drugs or pollutants where the analytical chemists usually have to catch-up to those producing the chemicals. In the future, standardised configurations could be implemented for routine illicit drug consumption monitoring while customised configuration will play an important role in the expanding WWA applications.

2.6. Back estimation of consumption/exposure data

The estimation of illicit drug consumption (IDC, mg/per person/per day) in the population is carried out by using the equation below (Zuccato et al., 2008):

$$\mathrm{IDC} = \frac{C_i \times F \times R_i/E_i}{P}$$

where, C_i is the concentration of a given drug residue *i* (parent drug or metabolite) measured in raw sewage samples (mg/L), *F* is the total flow (L) during the sampling period (usually 24 hr), *P* is the number of people in the catchment, R_i is the ratio of molar mass of parent drug to its metabolite measured in the wastewater sample and E_i is the average excretion rate of a drug residue *i* ($0<Ei<1$).

While C_i, *F* and R_i can be measured readily in the laboratory or at the STP, estimating the values of P and Ei is more challenging. *Ei* can be estimated through meta-analysis of clinical data (Khan and Nicell, 2011). Meanwhile, estimation of population size could be performed by using resources like census data, STP design capacity, or using wastewater parameters such as BOD, COD, total phosphorus, and total nitrogen (van Nuijs et al., 2011b). O'Brien et al. used a combination of 14 chemical markers of population size (most of them pharmaceuticals) to estimate the population size using a Bayesian inference model (O'Brien et al., 2014). Chen et al. evaluated seven potential population biomarkers and found that 5-hydroxyindoleacetic acid and cotinine could potentially be used as biomarkers for population estimation (Chen et al., 2014). There are also attempts to evaluate real-time population size by analysing mobile phone signals in the catchment area which could also be applied for population estimation (Ran et al., 2013).

It should be noted that there may be some licit sources of biomarkers used to estimate illicit drugs (*e.g.* morphine can be generated from the consumption of both heroin and licit codeine) and hence estimates of illicit drug consumption can be affected by this phenomenon. In such cases, cautious interpretation should be taken. The typical way to solve this issue is to subtract the average amount of legal medication/pharmaceutics that are used in the studied population from the total chemical load measured in wastewater samples. The input load coming from licit source could be better evaluated by analysing prescription data and wastewater from the hospitals in the studied catchment. If the input from licit source is significant (*e.g.* morphine input from the use of codeine compared to morphine input from heroin), the lack of accurate data on licit input could render the WWA estimate less valid and thus WWA should not be used in such case.

For other chemicals, the process of back estimation is similar as long as the necessary parameters are available (especially *Ei* and *P*). Some chemicals may also come from other sources such as dumping parent compounds into the sewer which should be taken into account when interpreting the estimated values.

2.7. Uncertainties and limitations

Uncertainties may occur in every step from sampling to back-calculation in WWA studies. Evaluations about uncertainties related to the whole procedure and also individual aspects have been performed in previous studies. Castiglioni et al. (2013) evaluated uncertainties associated with all the steps commonly used in WWA with optimized experimental parameters for each step defined. Plósz et al. (2013) investigated the biotransformation kinetics and sorption of cocaine and its metabolites. Factors influencing the estimation of cocaine in sewage with WWA have been evaluated. Results show that omitting in-pipe bio-transformation affects the accuracy of back-calculated cocaine use estimates. In addition, *ex-vivo* biotransformation of target compounds should be considered during back calculation (Plósz et al., 2013). van Nuijs et al. evaluated the stability of nine illicit drugs and metabolites in samples collected from wastewater influent. The results suggest that it is quite important to take the compound stability into account when dealing with drugs that show significant biotransformation in sewage (van Nuijs et al., 2012).

3. Applicability in China

3.1. Research related to wastewater in China

China has the largest population (1.4 billion) in the world. The total sewage created across the country is estimated as high as 280 billion litres per day (calculation based on 200 L per capita per day), and most of the populated areas are sewered and connected to STPs. WWA could thus be used in the evaluation of illicit drug consumption as well as alcohol, tobacco (Reid et al., 2011) and other chemicals which are closely related to public health and social sustainability.

Recently a small number of WWA studies were conducted in China for estimating illicit drug consumption. Lai et al. utilised WWA in Hong Kong in 2011 to evaluate daily and diurnal patterns of illicit drug consumption in the megacity (Lai et al., 2013). Khan et al. applied WWA in mainland China for the first time to monitor the consumption of 14 illicit drugs in 4 megacities with samples from 9 STPs covering approximately 11.4 million inhabitants. The results demonstrate that China has different drug consumption patterns to European countries. Even within China, the difference in drug use between the north and south could be observed (Khan et al., 2014). It is proposed that licit manufacture of drugs is more stringent and thus distinguishing licit from illicit sources of drugs may be possible by further research on isomer production ratios of the parent compounds and conducting chiral analysis of wastewater samples. This could potentially lead to monitoring drug manufacture, formulation, distribution and consumption (Daughton, 2011).

Several review articles (Xie et al., 2004; Liu, 2005; Zhou et al., 2007; Liu et al., 2009; Nie et al., 2011) have presented a range of research on persistent organic pollutants (POPs) and emerging pollutants such as pharmaceuticals and personal care products (PPCPs) in the aquatic environment, particularly in regard to wastewater and how to better manage these chemicals. The articles cover studies on the occurrence of POPs and PPCPs in STPs (Fan et al., 2011; Zhao et al., 2011), pollutant removal mechanism in STPs (Jiao et al., 2012), fate and degradation of certain group of POPs or PPCPs particularly in regard to river water (Liu, 2011; Lian and Liu, 2013; Zhang, 2013), development and optimization of analytical method to qualitatively and quantitatively determine pollutants in various matrices (Chen et al., 2011; Yuan et al., 2013). However, most studies work 'downstream' focusing on environmental outcomes rather than 'upstream' which could provide the ability to evaluate human exposure and the associated health risks.

3.2. Drug consumption and control in China

Illicit drug abuse in China can be traced back to the 1760s during the Qing dynasty. The number of drug users in China increased dramatically after the Opium War. Issue of drug abuse re-emerged in the last two decades which is mainly attributed to global drug trafficking activities during the implementation of governmental reform and the open-door policies of the late 1980s (Qian et al., 2006; Lu et al., 2008). Evidence has shown that over the past decade cocaine and other illicit drug abuse has increased in East and Southeast Asia. The Ministry of Public Security in China estimates that there are currently more than two million illicit drug users in China (XinhuaNews, 2013). Also, e.g. cocaine seizures in Hong Kong increased from approximately 600 kg in 2010 to 800 kg in 2011 (UNODC, 2013).

Illicit drug consumption has caused significant consequences for human health and social stability. In response the Chinese government monitors illicit drug prevalence and control. However, during the past decade the number of people abusing drugs has increased significantly and younger generations have become victims of drug addiction. Synthetic psychotropic drugs (like methamphetamine) prevail among drug consumers. This situation requires the authorities to design effective policies to control drug abuse as well as monitoring the effectiveness of these policies.

The ability of WWA to measure near real-time consumption of drugs can assist authorities in assessing the impact of the strategies they've adopted and thus better manage the situation. In order to develop and implement effective anti-drug strategies, authorities need information about temporal and geographical patterns of illicit drug consumption. Wastewater analysis could provide continuous and objective illicit drug consumption information to the relevant authorities.

3.3. Overview of sewage treatment plants and analytical laboratory capabilities in China

There are more than 3000 domestic STPs in China covering most densely populated areas. The number of STPs is still rapidly increasing with substantial investment from the Chinese government to reduce environmental impacts. The capacity of these plants ranges from less than 10 ML/day to more than 1000 ML/day. Population size served differs from a few thousand to hundreds of thousands. Most STPs have online monitoring of flow, pH, COD and ammonia using auto-samplers and nearly all of these plants take regular samples for compliance purposes which may make it easier to get samples for WWA applications. Therefore, WWA could potentially capture chemical consumption and/or exposure for a variety of population sizes with considerably small effort and cost compared with traditional surveys.

China has strong analytical chemistry capabilities with hundreds of research centres and laboratories located across the country equipped with state of the art analytical instruments. There are more than 200 laboratories equipped with LC–MS/MS instruments in various configurations and thus have sufficient analytical abilities to apply WWA at the national level. Chen et al. (2011) developed a paper strip extraction ultra-performance liquid chromatography tandem mass spectrometry (PSE-UPLC–MS/MS) method to determine 9 PPCPs in sewage sludge. With further optimization, this method could be suitable for WWA applications for drug consumption estimation as well as for the measurement of other chemical biomarkers of consumption and exposure. More recently Yuan et al. (2013) developed and applied an automated solid phase extraction-high performance liquid chromatography coupled with electrospray ionization tandem mass spectrometry (ASPE-HPLC–ESI–MS/MS) method for the quantification of 13 antipsychotics. Eleven of the thirteen pharmaceuticals were detected in all 35 samples from one STP. Further studies on wastewater treatment processes, human health biomarkers and risk assessment could all benefit through promoting WWA as a feasible and powerful tool for forensic science, environmental science and epidemiology.

3.4. Potential issues with applying WWA/SCIM in China

There is no doubt that WWA can provide indicative information for the assessment of illicit drug consumption. By sampling a variety of STPs and collaboration with the many advanced research facilities across China, WWA/SCIM could produce valuable information on current community health status, which could help define key areas of concern for both community health and maintaining social justice. However, investigation and assessment about the study area and objectives should be carried out before conducting WWA to maximise results. Most STPs constructed before the 1990s receive influent that is a mixture of domestic sewage, industrial wastewater and stormwater. This may make it more challenging to apply WWA in these areas as the chemicals in the industrial sewage could interact with the chemicals in domestic sewage and during rainfall events chemicals of interest may become too diluted to analyse feasibly.

By comparing concentrations of target chemicals in ambient environmental monitoring with the results of available biomonitoring studies and WWA data, chemical consumption/exposure models could be developed for pollutants chemicals, biomarkers of human health, per capita environmental impact and others. One should also consider that there are huge population relocations during certain national holidays such as Chinese spring festival. Therefore real-time population estimates of the studied catchment area is essential to reduce under/overestimation of the per capita consumption and/or exposure of chemicals. These markers would also require some form of calibration for the studied catchment such as collecting samples during a census period.

As most of the STPs in a given city belong to a drainage group governed by the water resource bureau or the environmental protection agency in the municipal government, there might be concerns regarding ethical issues related to WWA studies. However, it was suggested that WWA doesn't raise major ethical concerns when used for public health purposes to monitor illicit drug use in large populations (Hall et al., 2012) although ethical issues may arise from concerns about possible indirect harm from using WWA in small areas such as prisons or entertainment venues. More effort is required from the research community, industry and government departments to promote WWA as an additional tool for illicit drug consumption monitoring.

4. Conclusions

Wastewater analysis is a promising approach to estimate illicit drug consumption and consumption/exposure of other chemicals of concern at the population level. Our review suggests that WWA could be a very useful tool in China. It could provide a relatively easy approach for China to monitor drug consumption and potentially drug trafficking and manufacturing. Early adoption of WWA/SCIM and archiving samples would allow China to both make assessments using the current knowledge, as well as create a sample bank that archives and allows reassessment of samples once analytical methods are developed or new chemicals of interest are identified. Combined with traditional survey methods, WWA could be a powerful tool to optimize illicit drug consumption estimates and provide near real-time and objective data for the development of strategies concerning drugs of abuse. With progress in research on other WWA biomarkers, the approach will provide useful epidemiological data for health status including levels of certain diseases in different communities and might lead to the establishment of new monitoring approaches for population health.

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