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Occurrence and transport of *N*-nitrosamines in the urban water systems of the Pearl River Delta, southern China

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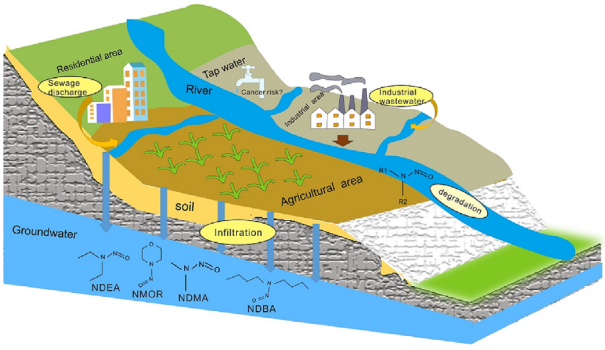
HIGHLIGHTS

- NDMA, NDEA, and NDBA were dominant in urban water systems.
- NDEA and NMOR were easily infiltrated into groundwater from river water.
- Industrial activities have a much greater impact on *N*-nitrosamine pollution in rivers.
- The cancer risk in drinking water was 1.42×10^{-4} disability-adjusted life years ppy.

GRAPHICAL ABSTRACT



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ABSTRACT

The discharge of substantial amounts of *N*-nitrosamines-contained wastewater into receiving rivers can significantly deteriorate water quality, as these carcinogenic compounds can be easily transported into groundwater and drinking water systems. This study investigated the distribution of eight species of *N*-nitrosamines in river water, groundwater, and tap water located in the center of the Pearl River Delta (PRD), China. The results showed that three major *N*-nitrosamines, including *N*-nitrosodimethylamine (NDMA), *N*-nitrosodiethylamine (NDEA), and *N*-nitrosodibutylamine (NDBA), with concentrations of up to 64 ng/L, were observed in river water, groundwater, and tap water, whereas the other compounds occurred sporadically. In river water and groundwater, high concentrations of NDMA, NDEA, *N*-nitrosomorpholine (NMOR), and NDBA were found in industrial and residential lands as compared to agricultural lands owing to the influence of various human activities. The primary sources of *N*-nitrosamines in river water were industrial and domestic wastewater, and the infiltration of river water was responsible for the high levels of *N*-nitrosamines in groundwater. Among the target *N*-nitrosamines, NDEA and NMOR with long biodegradation half-lives (>4 days) and low LogK_{ow} values (<1) displayed the highest potential for groundwater. *N*-nitrosamines in groundwater and tap water pose significant potential cancer risks to residents, especially children, and juveniles, with lifetime cancer risks of over 10^{-4}, necessitating advanced water treatments for drinking water and critical controls on primary industrial discharge in urban areas.

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1. Introduction

N-nitrosamine belongs to one class of non-halogenated disinfection byproducts of drinking water and wastewater (Bei et al., 2016a, 2016b; Charrois et al., 2007; Jurado-Sánchez et al., 2010; Schreiber and Mitch, 2006). Interest in N-nitrosamines in aquatic systems, particularly in natural water systems and wastewaters, has grown worldwide for two primary reasons. Firstly, several *N*-nitrosamines have been classified as probable human carcinogens and mutagens by EPA IRIS (2012). Moreover, *N*-nitrosamines present in aquatic environments have demonstrated acute and chronic toxic effects on organisms, as noted by Draper III and Brewer (1979) and Wagner et al. (2014). Secondly, the discharge of large amounts of wastewater or algal blooms has resulted in high concentrations of natural water *N*-nitrosamines. *N*-nitrosodimethylamine (NDMA) has received much attention because of its high concentration and frequent occurrence in water (Asami et al., 2009; Kadmi et al., 2014; Kosaka et al., 2010; Ma et al., 2012; Zhou et al., 2009a). The ubiquity of potentially toxic *N*-nitrosamines in the environment has jeopardized the safety of drinking water and the health of ecosystems, underpins the need to better understand their occurrence, source, and fate. It's worth noting that the water pollution caused by *N*-nitrosamines in China has attracted considerable attention because of the higher concentrations and detection frequencies compared with other countries such as US, Japan, or Canada, probably due to high population density and the consequent huge amount of wastewater discharge (Bei et al., 2016a, 2016b; Ikehata et al., 2018; Luo et al., 2020). The highest dietary intake of *N*-nitrosamines by Chinese residents (251 ng/d) was reported, with drinking water identified as an important contributor (Li et al., 2021). At the city level, Shanghai and Shenzhen have established the local NDMA criteria (100 ng/L) (Shanghai Water Authority, 2018; Shenzhen Water Authority, 2020). However, the drinking water criteria for *N*-nitrosamines is lacking in China at the national level. In addition, the behavior, transport, and effect of *N*-nitrosamines in the aquatic environment, including river water, groundwater, and drinking water, is still limited, particularly in highly industrialized cities.

Water systems in urban areas with high population densities and well-developed industries are susceptible to being polluted by *N*-nitrosamines (Lee and Oh, 2016; Rodgers et al., 2018). *N*-nitrosamines are hard to completely removed from water treatment systems by sorption because of their high polarity and excellent water solubility (Krauss et al., 2009). Elevated *N*-nitrosamine concentrations have been reported in urban river waters, even with high wastewater collection and treatment rates in urban areas (Schreiber and Mitch, 2006). Additionally, river water might be easily exchanged with groundwater, which leads to *N*-nitrosamine pollution in the water systems and ultimately threatens drinking water safety. Therefore, investigation of the occurrence of *N*-nitrosamines and their transport behavior from river water to groundwater and drinking water are undoubtedly helpful for controlling *N*-nitrosamine pollution.

The Pearl River Delta (PRD) has abundant surface water resources, developed industries, and intensive agricultural activities (Lu et al., 2009). Chen et al. (2019a) observed that high mass loadings of *N*-nitrosamines were discharged in the PRD owing to the increasing discharge of wastewater from various industrial and domestic activities with high *N*-nitrosamine contents. Therefore, surface rivers in the PRD have received various *N*-nitrosamines with the highest concentration of 4000 ng/L (Chen et al., 2017a, 2019a; Chen et al., 2021; Liu et al., 2016). However, the information on *N*-nitrosamine transport behavior after entering rivers is still limited. Due to the high mobility of *N*-nitrosamines and strong hydraulic interaction between surface and groundwater, these compounds are easily transported to groundwater or drinking water and finally impact human health due to their toxicity properties (Rogers et al., 2015; Wang et al., 2013). Notably, (Lin et al., 2000) reported a high incidence rate of liver cancer (7.5×10^{-5} per year) in a city of the PRD. This value was much higher than the average incidence in China (2.7×10^{-5} per year) (Chen et al., 2017b) and USA (3.3×10^{-6} to 1.25×10^{-5}) (Ryerson et al., 2016). As chronic ingestion of *N*-nitrosamines can enhance the risk for liver cancer for humans (Mitacek et al., 1999), the high occurrence of liver cancer might relate to high *N*-nitrosamines in drinking water. The exposure data of *N*-nitrosamines in various waters is important to prevent their pollution.

Potential lifetime cancer risk assessment has been widely used to provide a critical basis for controlling *N*-nitrosamine risks in water (Chen et al., 2019b; Ma et al., 2012). However, risks of different contaminants cannot be compared directly. To set a common unit for risk, disability-adjusted life years (DALYs) are recommended by the World Health Organization (WHO) to assess the health impacts of cancer risk factors (Ah and Jm, 2003). DALYs is a time-based measurement, combining the healthy life lost due to premature mortality and morbidity. Some studies have been conducted on the disease burden caused by pollutants using DALYs, such as *N*-nitrosamines and other disinfection byproducts (Chen et al., 2019b; Pan et al., 2014; Zhang et al., 2018), and arsenic (Ling and Liao, 2007), in drinking water. However, the cancer risks assessment associated with low-level *N*-nitrosamines using DALYs in the PRD is still limited although high cancer risks have been reported in this region. Therefore, the evaluation of cancer risks and DALYs due to exposure to *N*-nitrosamines in drinking water may shed light on cancer studies.

In this study, the occurrence and spatial distribution of eight *N*-nitrosamines, including target compounds listed in the US Environmental Protection Agency (EPA) method 521 (Munch and Bassett, 2004) including NDMA, *N*-nitrosomethylethylamine (NMEA), *N*-nitrosodiethylamine (NDEA), *N*-nitrosodi-*n*-propylamine (NDPA), *N*-nitrosopyrrolidine (NPYR), *N*-nitrosopiperidine (NPIP), and *N*-nitrosodibutylamine (NDBA) and another widely detected compound of *N*-nitrosomorpholine (NMOR), were studied in several river water, groundwater, and tap water samples in the PRD to, (1) evaluate factors that could contribute to their occurrence including land use types and water parameters based on significance testing and correlation analysis, (2) estimate the transports of *N*-nitrosamines among urban water systems based on correlation analysis and their physicochemical properties, (3) quantify the contributions from different sources to *N*-nitrosamines in both river water and groundwater by using *N*-nitrosamine compositions, principal component analysis (PCA), and multiple linear regression analysis (MLRA), which are useful for distinguishing various sources, and (4) calculate the cancer risks and the disease burden caused by *N*-nitrosamines in drinking water using the values of DALYs lost, which were measured in terms of years of life lost (YLLs) and years lived with disability (YLDs). Fig. 1 presents the flowchart illustrating the study structure.

2. Material and methods

2.1. Study area and water sampling

The PRD has a monsoon climate with an annual average precipitation of 1600–2000 mm. The study area is an alluvial plain located in the center of the PRD, South China, with an area of approximately 806 km^2 (Fig. 2). A total of sixteen main rivers and over 120 streams converge in this area before flowing into the South China Sea, leading to highly developed water networks of dikes and ponds that cover 70.7 % of the total area (He, 2014). The major land use types are residential, industrial, and agricultural lands (Fig. S1).

The sampling activity was conducted in November 2017. No rainfall was observed before the sampling date to the end of the sampling period to avoid the interference of dilution from rain. A total of sixteen river water samples were collected from four rivers and their tributaries (Figs. 2, S1, and Table S1). As shown in Fig. 1, river water samplings including R1, R2, and R6-R9 were in drinking water source area. The groundwater samples were pumped from the aquifer through 18 monitoring wells, two private wells, and one spring (Table S2). The groundwater depths in monitoring wells ranged from 3.63 to 1.32 m, with well depths of 25.7–45.4 m. For the tap water, a total of fifteen tap water samples were collected during the sampling procedures. Among them, five water samples were distributed from drinking water treatment plants (DWTPs) using traditional water treatment processes, i.e., coagulation/flocculation → sedimentation → sand filtration → chlorination, while others were from DWTPs using advanced

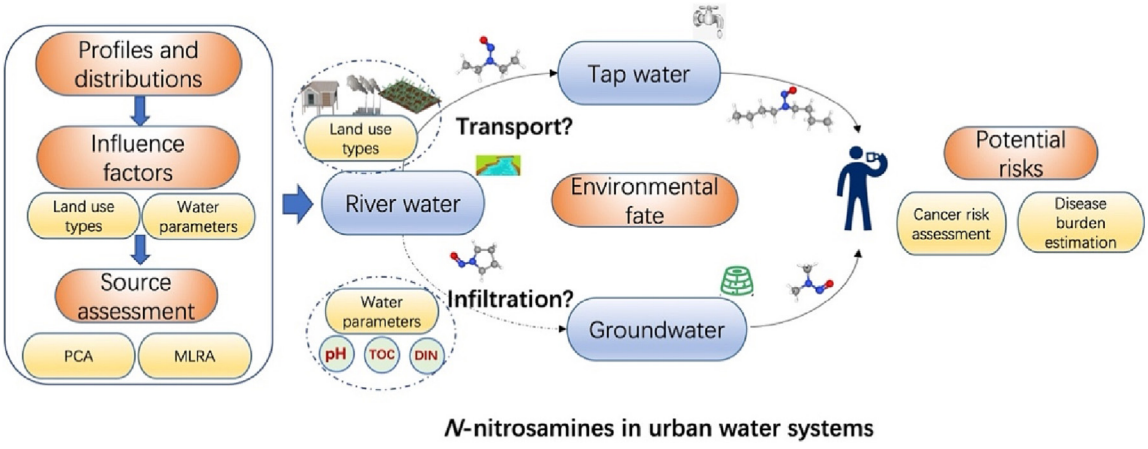

Fig. 1. The flowchart of the study structure.

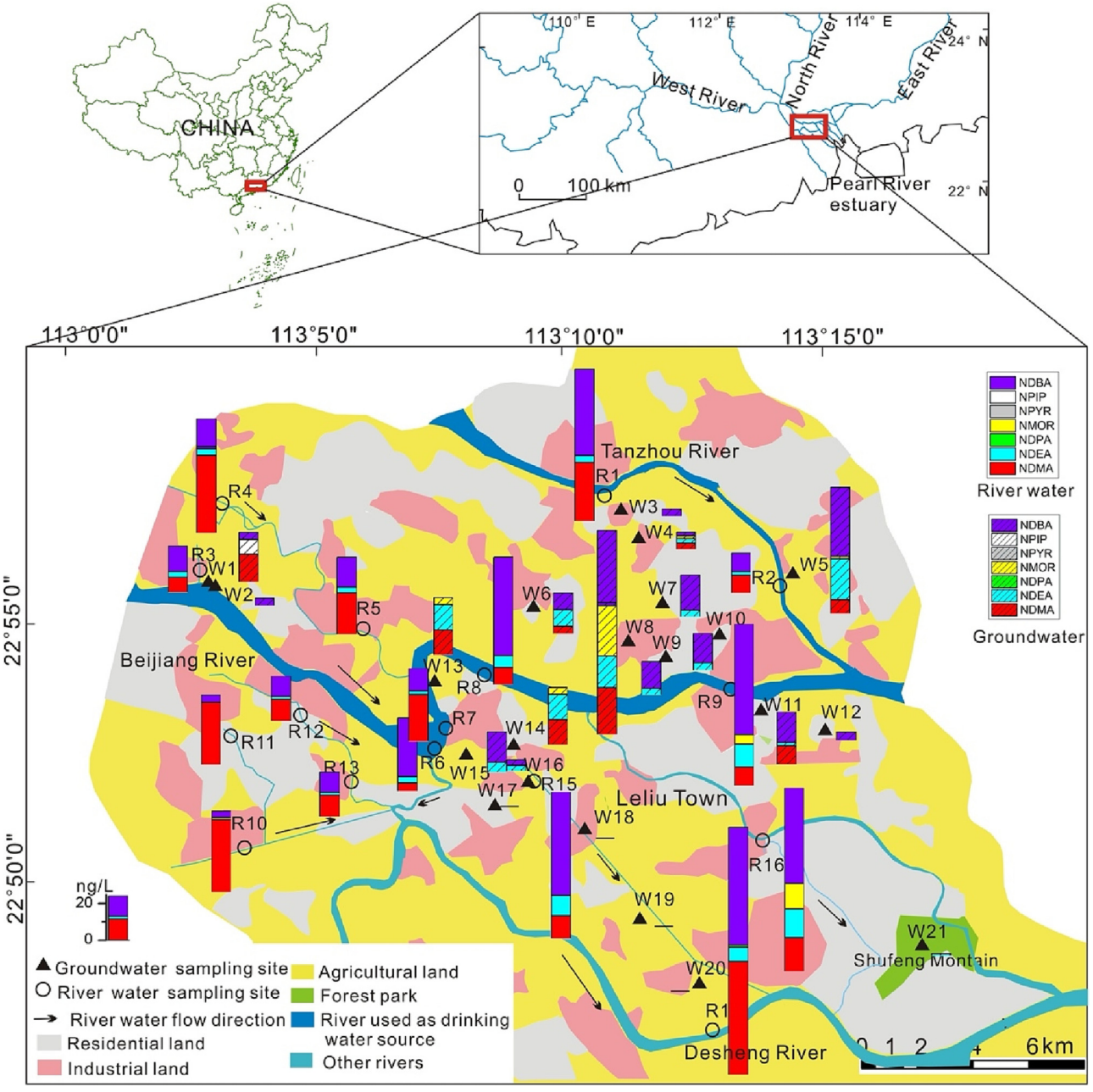

Fig. 2. Sampling locations and the spatial variations of *N*-nitrosamines in the river water and the groundwater samples from the studied area.

treatment procedures (i.e., pre-oxidation → coagulation/flocculation → sedimentation → sand filtration → ozone oxidation → carbon adsorption → chlorination) as the use of pre-oxidation, ozone oxidation, and the depth adsorption processes.

At each site, 1 L of water was collected in an amber glass bottle and added 100 mg of sodium thiosulfate immediately for dechlorination. The samples were then transported to the lab on the same sampling day, stored in the dark at 4 °C, and analyzed within seven days. The water parameters were monitored on-site using a portable YSI-Pro 2030 (YSI Incorporated, OH, US).

2.2. Sample pretreatment and analysis

The liquid sample was added with 2 g of $NaHCO_3$ (pH = ~8) and 25 ng of NDMA-d_6 (recovery surrogate) after filtration and subsequently extracted through a coconut charcoal cartridge, which had been preconditioned with dichloromethane, methanol, and ultrapure water, at flow rates of <20 mL/min (Chen et al., 2017a, 2017b). Afterward, the analytes were eluted from the SPE bed with dichloromethane (12 mL) and then concentrated under a stream of ultrahigh-purity nitrogen (99.99 %) to a final volume of 500 μL. Before the instrument analysis, the internal standard NDPA-d_{14} (25 ng) was added to the cell bottle. The extracts were either analyzed immediately or stored at −20 °C until analysis using an Agilent 7890B gas chromatograph (GC) coupled with a 7000C triple quadrupole mass spectrometer (MS/MS) with tandem capillary columns of DB-35 MS and HP-5 MS (Chen et al., 2017a, 2017b). Ultrahigh-purity helium (99.99 %) was used as the carrier gas at a constant flow rate of 2.0 mL/min in the columns.

Ammonium (NH_3-N) was measured according to Nessler's reagent spectrophotometry method from the National Standard of the People's Republic of China (HJ536-2009). Total organic carbon (TOC) was analyzed by a TOC analyzer (TOCV, Shimadzu). The concentrations of nitrate and nitrite were evaluated using ion chromatography (761 Compact IC, Metrohm).

2.3. Quality assurance and quality control

N-nitrosamine concentrations were quantified by the internal standard isotope dilution method using the mean relative response factors determined from the standard calibration runs. The absolute recoveries of NDMA-d_6 ranged from 50 to 70 % (avg. ± standard deviation: 63 ± 5 %). A laboratory blank was incorporated into the analytical procedures in every batch of 10 samples. No target compounds were detected in the blank samples. The method detection limits (MDLs) were calculated by multiplying the standard deviation of seven replicates by the Student's *T* value of 3.14 (one-sided *T* distribution for six degrees of freedom at the 99 % confidence level) (McDonald et al., 2012). The MDLs of the *N*-nitrosamines were 0.50 (NDMA), 0.60 (NMEA), 0.85 (NDEA), 0.90 (NDPA), 0.70 (NMOR), 1.10 (NPYR), 0.85 (NPIP), and 1.60 ng/L (NDBA).

2.4. Cancer risk assessment

Direct oral ingestion and dermal contact are primary exposure pathways for *N*-nitrosamines in water (Chen et al., 2019b; Ma et al., 2012). The lifetime average daily doses (LADD, (mg/kg)/day) of individual *N*-nitrosamines were calculated using the following equations (Chen et al., 2019b; Wang et al., 2007):

$$\mathrm{LADD_{oral}} = \frac{\mathrm{C_w} \times \mathrm{IR} \times \mathrm{EF} \times \mathrm{ED} \times \mathrm{CF_{oral}}}{\mathrm{BW} \times \mathrm{AT}} \quad (1)$$

$$\mathrm{LADD_{dermal}} = \frac{\mathrm{C_w} \times \mathrm{SA} \times \mathrm{F} \times K_p \times \mathrm{ET} \times \mathrm{EF} \times \mathrm{ED} \times \mathrm{CF_{dermal}}}{\mathrm{BW} \times \mathrm{AT}} \quad (2)$$

where $\mathrm{LADD_{oral}}$ and $\mathrm{LADD_{dermal}}$ are the LADD values via drinking water and dermal contact, C_w is the measured concentration of *N*-nitrosamines in water (ng/L), *IR* is the ingestion rate (L/day), *EF* is exposure frequency (days/yr.), *ED* is the exposure duration (yr.), CF is the conversion factor, *BW* is the average body weight (kg), *AT* is the averaging time (lifetime in years), *SA* is the skin area (cm^2), *F* is the fraction of surface skin that absorbed water (0.9, unitless) (Williams et al., 2002), K_p is the permeability constant (cm/h), and *ET* is the exposure time (h/d).

The lifetime cancer risk of each *N*-nitrosamine through the two exposure routes was evaluated using the following equations (EPA, 1997):

$$\mathrm{CR_{oral}} = \mathrm{LADD_{oral}} \times \mathrm{SF_{oral}} \times \mathrm{ADAF} \quad (3)$$

$$\mathrm{CR_{dermal}} = \mathrm{LADD_{dermal}} \times \frac{\mathrm{SF_{oral}}}{\mathrm{GAF}} \times \mathrm{ADAF} \quad (4)$$

$$\mathrm{CR}_T = \mathrm{CR_{oral}} + \mathrm{CR_{dermal}} \quad (5)$$

where CR_T, CR_{oral} and CR_{dermal} are the total cancer risk and cancer risks through oral ingestion and dermal absorption, respectively; SF_{oral} is the chemical slope factor through oral ingestion [/(mg/kg/day)], *ADAF* is the age-dependent adjustment factor, *GAF* is the gastrointestinal absorption factor (1) (US EPA, 1989). These assessment parameters are provided in Tables S3–S4.

2.5. Disability-adjusted life year (DALY) estimation

The disease endpoint of *N*-nitrosamines is considered to be liver cancer (IRIS, 2010). To assess the disease burden caused by *N*-nitrosamines in drinking water, the values of DALYs lost were measured in terms of years of life lost (YLLs) and years lived with disability (YLDs), respectively. DALYs are a combination of YLLs and YLDs. The calculations are given in Eqs. (6)–(8) (Soerjomataram et al., 2012):

$$\mathrm{DALYs} = \mathrm{YLLs} + \mathrm{YLDs} \quad (6)$$

$$\mathrm{YLLs} = \sum_x n_x P_x (1 - S_x)\left(e_x^* - T_D\right) \quad (7)$$

$$\mathrm{YLDs} = \sum_x n_x P_x DW_y L_y \quad (8)$$

where *x* is the age that is stratified into 6 groups: 0–1, 1–6, 6–18, 18–60, and >60, *n* is the number of population (Bureau of Statistics of Foshan City, China, 2022). S*x* is the mortality rate (0.87) (Chen et al., 2017b), e^*_x is the standard life expectancy (77.9 years) (National Bureau of Statistics of China, 2022), and T_D is time to death. Due to limited data, the median values of T_D for liver cancers (1 yr) were used (Kocarnik et al., 2022). *y* is the disease phase, *DW* is disability weight, and *L* is the duration. P_x is the liver cancer incidence rate induced by *N*-nitrosamines, which can be converted into the annual value and calculated as:

$$P_x = CR_x \times \frac{RS_x}{Sp_x} \quad (9)$$

where RS_x is the age-specific relative sensitivity, which means the ratio of the age-specific incidence rates of liver cancer to the total incidence rates. These values were computed based on the corresponding data reported in the nearby city of Guangzhou, China (Li et al., 2016). Sp_x is the age span for each age group (1, 5, 12, 42, and 15 for 0–1, 1–6, 6–18, 18–60, and >60, respectively). All assessment parameters with specific values are provided in Tables S4 and S5.

2.6. Statistical analysis

The concentrations below the MDLs were designated as 1/2 MDL values for the statistical analysis using IBM SPSS 19.0 software. Spearman's correlation was used to measure the relationship between variables as the data deviated from a normal distribution. The *p*-value used to indicate statistical significance with the one-way ANOVA test was 0.05.

3. Results and discussion

3.1. N-nitrosamine profiles and distributions in water

The *N*-nitrosamine concentrations in different water compartments are summarized in Table S6 and Fig. 2. The detection frequencies (DFs) and concentrations relative to the maximum contaminant level (MCL) for risk of 10^{-5} are shown in Fig. S2 and a comparison of *N*-nitrosamine concentrations with other areas is presented in Table S7.

3.1.1. River water

The total concentrations of the eight *N*-nitrosamines (ΣNAs) in river water ranged from 22 to 136 ng/L (avg. 58 ± 32 ng/L). Of the eight targeted *N*-nitrosamines, NDMA (22 ± 16 ng/L), NDEA (5.0 ± 4.6 ng/L), and NDBA (29 ± 23 ng/L) were the dominant compounds, as their relative contributions were above 85 % in all river water samples with DFs of over 88 % (Table S6 and Fig. S2a). This finding is consistent with a previous study reporting high concentrations and contributions of NDMA, NDEA, and NDBA in the Pearl River, China (Chen et al., 2019a). However, NDMA, NDEA, and NDBA in this study displayed concentrations four to five times higher than those in the previous study because of the heavy pollution of *N*-nitrosamines in tributaries that are used as drainage systems for treated and untreated wastewater in the study area. NMOR, NDPA, and NPYR were only detected in one or two of the sixteen river water samples, with average concentrations of <2 ng/L. Their sporadic detection in wastewater and river water has also been previously reported (Kadmi et al., 2017; Ma et al., 2012).

Spatially, the ΣNAs downstream of the Beijiang River (69–88 ng/L) were two to four times higher than those midstream (12–40 ng/L), as shown in Fig. 2. These results further confirm the continuous input of *N*-nitrosamines from tributaries along the Beijiang River. The highest ΣNAs concentration (136 ng/L) was observed at Site R14. This site is in an electroplating industrial park, only 5 m downstream of an industrial discharge pipe. This concentration was much lower than that reported previously in the Pearl River impacted by various industrial wastewaters (ca. 1100 ng/L) (Chen et al., 2019a) and might have been due to the low amount of effluent discharged from the industrial pipelines and the regular canal dredging activities in the river in this study.

As shown in Table S7, the NDMA concentrations in the river water (avg. 22 ng/L) were similar to those reported from tributaries of the Yangtze and Huai Rivers in China, while they were four to ten times higher than those observed in the Pearl River of China and rivers in Japan, Spain, Korea, and Canada. The average concentration of NDBA in river water is comparable to that in the Nakdong River, South Korea, but approximately four to six times higher than that in rivers in China and France (Chen et al., 2019b; Chen et al., 2021; Kadmi et al., 2017; Lee and Oh, 2016; Sanchís et al., 2021). High concentrations of NDMA and NDBA were expected in the PRD area with advanced industries and dense populations.

3.1.2. Groundwater

Six compounds were detected in the groundwater samples, with ΣNAs concentrations ranging from not detected (ND) to 112 ng/L (avg. 21 ± 26 ng/L). Similar dominant *N*-nitrosamine species (NDMA, NDEA, and NDBA with concentrations of 4.3 ± 6.7, 4.4 ± 6.2, and 10 ± 12 ng/L, respectively) were observed in groundwater, indicating the close hydraulic connection of *N*-nitrosamines between river water and groundwater (Wang and Jiao, 2012). The similar *N*-nitrosamine profiles between river water and groundwater might be attributed to the high leaching potential of *N*-nitrosamines in groundwater systems owing to their high water solubility (>1270 mg/L) (Ma et al., 2012). In this study, the concentrations of NDMA, NDEA, and NDBA accounted for >80 % of the ΣNAs in ten of the twenty-one groundwater samples. The concentrations of NDEA were approximately one to seven times higher than MCL at a risk of 10^{-5}, indicating that NDEA might pose higher human health risks than other *N*-nitrosamines (Fig. S2b). NMOR was detected in four samples with an average concentration of 1.9 ± 5.9 ng/L, while NPYR (1.8 ng/L) and NPIP (8.1 ng/L) were only detected in one sample. The concentrations of NDMA and NDBA in groundwater were significantly lower than those in river water (ANOVA, $p < 0.05$, Fig. 3), whereas the difference for NDEA was not significant ($p > 0.05$). This implies that the groundwater was

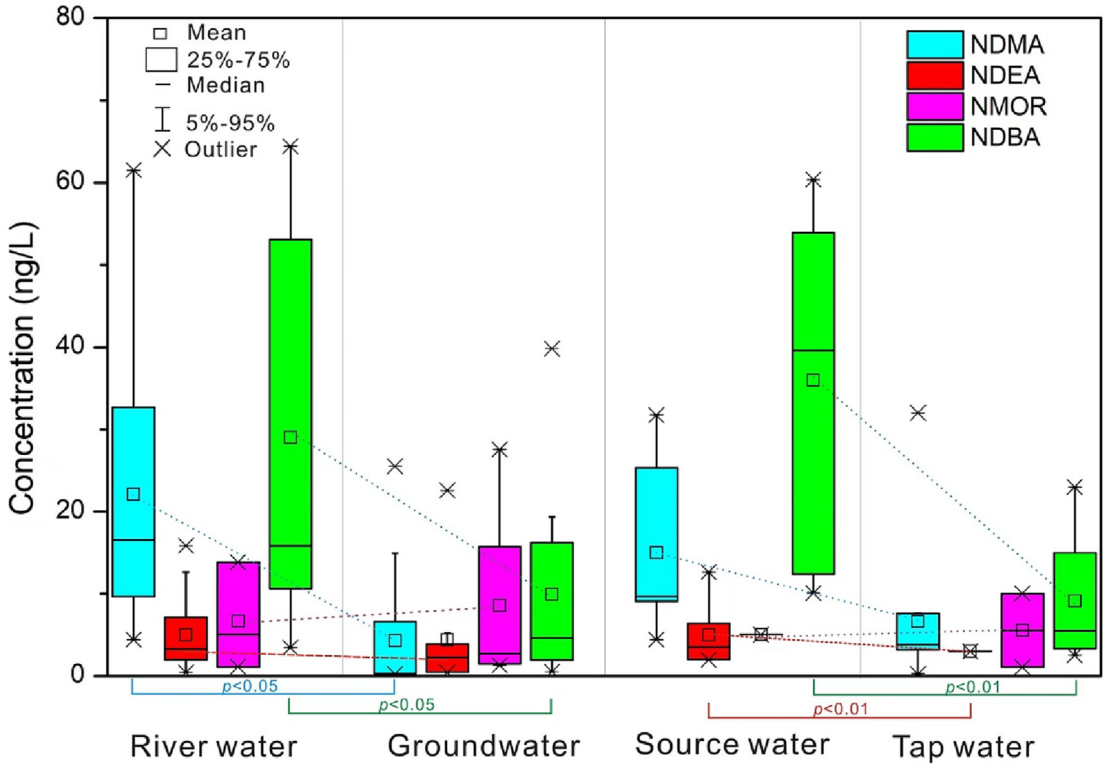

Fig. 3. Comparison of *N*-nitrosamines in the urban water systems.

more vulnerable to NDEA contamination than NDMA and NDBA. In groundwater, bio-degradation was the primary attenuation pathway for *N*-nitrosamines (Patterson et al., 2012, 2011; Plumlee and Reinhard, 2007; Szecsody et al., 2014, 2008). The anoxic biodegradation half-life for NDEA was 4.9 days, which was approximately three times lower than those for NDMA (1.42 days) and NDBA (1.26 days) (Drewes et al., 2006). Therefore, after entering the groundwater, NDEA was more likely to accumulate than NDMA and NDBA owing to its lower biodegradation rate.

Spatially, the highest ΣNAs concentration (112 ng/L) in the groundwater was found at Site W8, which was located near an urban canal (3 m) receiving untreated industrial wastewater. Its concentration was comparable to that in the corresponding river water (Fig. 2). The high concentration of NMOR at this site (28 ng/L) suggests a possible high NMOR content in industrial wastewater. W5 displayed the second highest concentration of ΣNAs (69 ng/L), dominated by NDEA (23 ng/L) and NDBA (38 ng/L). *N*-nitrosamines were rarely detected at Sites W18–21, which were >5 km from the industrial area. It is interesting to observe distinctly different levels and profiles of *N*-nitrosamines, even between sample sites located close to each other. These results showed the high variability of *N*-nitrosamines in groundwater, and the biodegradation process could be expected to be a core reason.

All *N*-nitrosamines in the groundwater in this study showed significantly higher concentrations than those reported in Japan, Saudi Arabia, and Italy, as *N*-nitrosamines are rarely observed in these countries (Table S7) (Amayreh, 2019; Liu et al., 2016; Van Huy et al., 2011). Compared to other places in China, the concentrations of NDMA, NDEA, and NDBA were similar (Chen et al., 2017a; Ma et al., 2012). These results suggest that *N*-nitrosamines in groundwater may cause more serious environmental problems in China than in other countries.

Source and tap waters. In source water, the concentrations of ΣNAs ranged from 22 to 88 ng/L (avg. 57 ± 27 ng/L). NDMA, NDEA, and NDBA were detected in all samples with average concentrations of 15 ± 9.9, 5.0 ± 3.7, and 36 ± 20 ng/L, respectively. NMOR was detected in only one sample at a concentration of 5.1 ng/L. The lower number of *N*-nitrosamine species detected in the source water than in the river water (seven species detected) could be attributed to the source water protection by the local government (People's Government of Guangdong Province, 2018).

In tap water, the concentrations of ΣNAs ranged from 1.6 to 58 ng/L (avg. 11 ± 14 ng/L), which is comparable to that in other areas in China (Table S7). NDMA, NMOR, and NDBA concentrations in tap water went down to 6.6 ± 7.9, 1.1 ± 2.6, and 1.4 ± 1.9 ng/L, respectively compared with source water (Fig. 3 and Table S6). NDEA was detected in only one sample, with a concentration of 3.0 ng/L. These concentrations in the tap water samples were two to twenty times lower than those in the source water (ANOVA, $p < 0.01$), suggesting high *N*-nitrosamine removal efficiencies in the drinking water treatment processes. A previous study also reported lower NDMA concentrations in tap water (ND to 13.3 ng/L) than in source water (0.8 to 21.6 ng/L) in China (Luo et al., 2012). NDMA was the most frequently detected (93 %). In comparison, NMOR and NDBA were detected less frequently, with DFs of 14 % and 21 %, respectively. In tap water, NDMA dominated the composition (67 %), followed by NDBA (17 %), which varied from that in source water (Fig. S2a). The concentrations of NDMA and NDEA were approximately six times higher than the MCL at a risk of 10^{-5}, manifesting that these compounds should be given more attention in tap water owing to their adverse health effects (Fig. S3). The highest concentration of ΣNAs (58 ng/L) was found in SD05 among the tap water samples (Fig. S3). This level was much higher than that of other tap water samples, which could be due to the old equipment or inefficient water treatment process because tap water is typically produced by the local drinking water treatment plant.

3.2. Fate of N-nitrosamines in urban water systems

N-nitrosamines are easily released and transported from surface waters to groundwater because of their high mobility (Ma et al., 2012; Zhou et al., 2009a). In this section, the transport of *N*-nitrosamines from the surface water to groundwater was examined using paired samples (paired river water and groundwater samples with distances <100 m) based on the Spearman correlation analysis. However, no significant correlations in *N*-nitrosamine concentrations and compositions between river water and groundwater were found (Spearman correlation analysis, $R^2 < 0.1$, $p > 0.05$) because of the relatively low DFs of *N*-nitrosamines in groundwater. These results might be attributed to the different adsorption and biodegradation behaviors of different *N*-nitrosamine compounds. The transport potential of *N*-nitrosamines to the groundwater system was subsequently evaluated according to biodegradation half-lives and the octanol-water partitioning constant ($LogK_{ow}$) (Drewes et al., 2006). As shown in Fig. 4, *N*-nitrosamines were divided into five groups: (I) NDMA, (II) NMOR, (III) NPYR and NMEA, (IV) NPIP and NDEA, and (V) NDPA and NDBA. Compounds in Groups II–IV, including NMOR, NPYR, NMEA, NPIP, and NDEA, had higher values of biodegradation half-lives and lower $LogK_{ow}$ values, indicating their high transport potential to groundwater. These results explain the high proportions of NMOR and NDEA in the groundwater in this study. Similarly, the lower proportions of NDMA in groundwater than in river water could be attributed to its lower biodegradation half-life.

River water is an important raw source of drinking water. As shown in Fig. 3, the concentrations of NDEA and NDBA in tap water (ND and 1.4 ng/L, respectively) were significantly lower than those in source water (5.0 and 36 ng/L, respectively), stipulating that the NDEA and NDBA could be effectively removed by drinking water treatments. However, the concentrations of NDMA and NMOR in tap water were slightly lower or comparable to those in source water, which could be because of their higher formation potentials during water disinfection. This result also indicates that NDMA and NMOR were inefficiently removed by the present treatments (Maqbool et al., 2020; Zhou et al., 2009b). Therefore, the penetration of *N*-nitrosamines through drinking water treatment systems should be considered, especially in areas with high NDMA and NMOR concentrations in the source water.

3.3. Roles of land use types and water parameters

3.3.1. Land use types

The concentrations and compositions of *N*-nitrosamines in residential, industrial, and agricultural lands are shown in Fig. 5. The NDMA concentrations in the river water were ranked as follows: residential land (25 ng/L) ≈ industrial land (24 ng/L) > agricultural land (6.9 ng/L). Higher proportions of NDMA were observed in residential and industrial

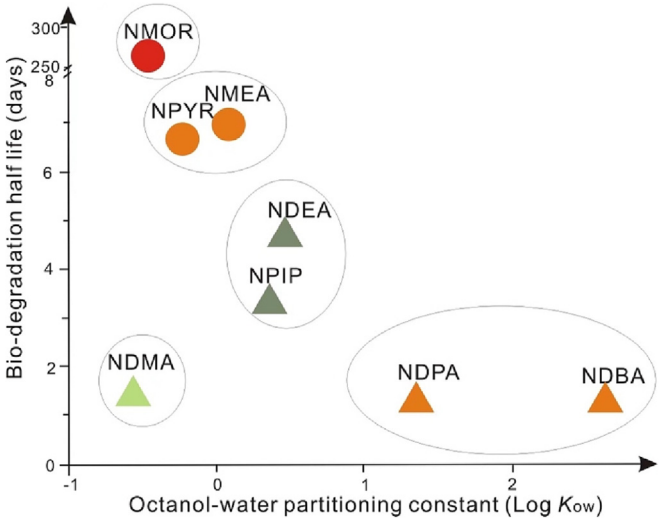

Fig. 4. A plot of the octanol-water partitioning constant ($LogK_{ow}$) versus biodegradation half-life (days) for each compound.

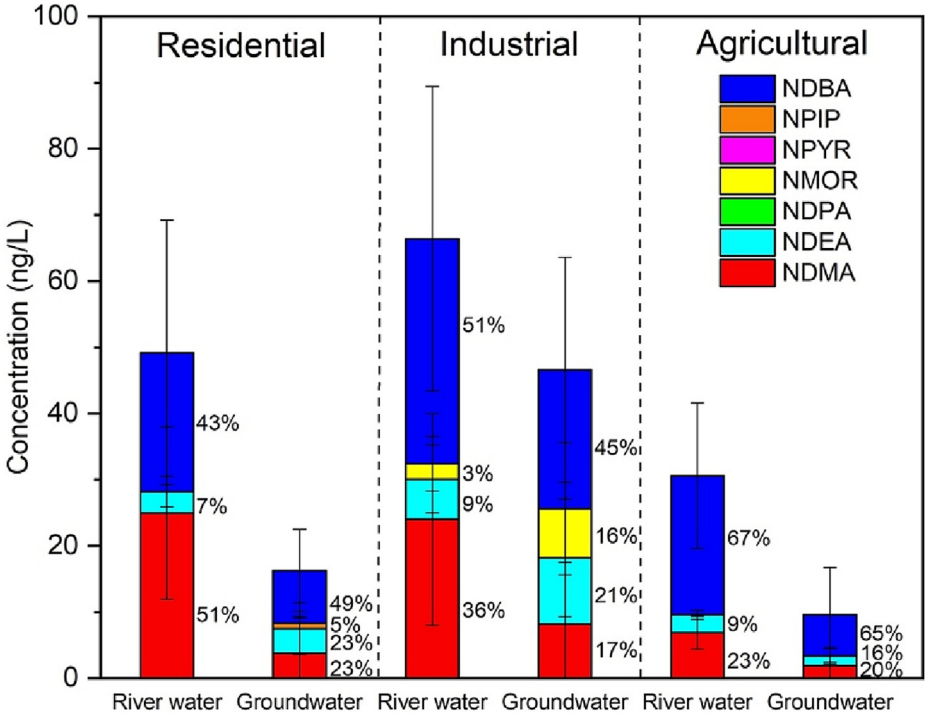

Fig. 5. *N*-nitrosamine concentrations in the river water and the groundwater samples in the residential, industrial, and agricultural lands.

lands than in agricultural lands (Fig. 5). These results deduced the high emission of NDMA from domestic and industrial activities compared to that from agricultural activities. The concentrations of NDEA, NMOR, and NDBA in the industrial land were all significantly higher than those in other lands (ANOVA test, $p < 0.05$), whereas NMOR was only observed in the industrial land. These results indicate that these compounds originate mainly from industrial effluents. Our previous study showed very low concentrations of NDMA and NDEA (<3.5 ng/L) were observed in paddy field runoff, while aquaculture pond water contained compounds including NDMA (43 ng/L), NDEA (14 ng/L), and NDBA (71 ng/L) (Chen et al., 2019a). As shown in Fig. 5, NDBA was dominant in agricultural land water, consistent with the finding in aquaculture pond wastewater from our previous study. This result indicates that the intensive aquaculture activities in this area could also contribute *N*-nitrosamines at a relatively low proportion.

Meanwhile, in groundwater, the occurrence of *N*-nitrosamines varied significantly across land-use categories (Fig. 5). The concentrations of NDMA, NDEA, NMOR, and NDBA were ranked as follows: industrial land > residential area > agricultural land, as shown in Fig. 5. Similarly, NMOR has only been observed in industrial areas because of industrial wastewater discharge. The high concentrations of *N*-nitrosamines in groundwater collected from industrial land were due to the substantial contribution of industrial activities.

3.3.2. Water parameters

In river water, the correlations among all *N*-nitrosamines and the water parameters, including NH_3-N, nitrate + nitrite, TOC, salinity, and electrical conductivity (Eh), were not significant ($p > 0.05$), as shown in Fig. 6, indicating that these parameters had less effect on the concentrations of *N*-nitrosamines. These outcomes also highlight the importance of primary emission sources for *N*-nitrosamines in river water, as all detected compounds have relatively high emission loads in this region (Chen et al., 2019a).

The pH values of groundwater ranged from 6.7 to 9.9. The concentrations of NDMA, NDBA, and NDEA were significantly correlated with the water pH (Spearman correlation analysis, $p < 0.05$). These results reflect the effect of an alkaline environment on the accumulation of *N*-nitrosamines in groundwater. Increasing the pH is known to facilitate the reaction kinetics and achieve high precursor deactivation (Lee and von Gunten, 2010). Therefore, *N*-nitrosamine enrichment was probably due to lower biodegradation rates in alkaline groundwater.

3.4. Source assessment

To identify the sources of *N*-nitrosamines, principal component analysis (PCA), and multiple linear regression analysis (MLRA) were used to identify the contribution of potential sources in the river water and groundwater. As NMEA, NPIP, NPYR, and NDPA were rarely detected (detection rates <20 %), only NDMA, NDEA, NMOR, and NDBA were introduced into the PCA analysis. In river water, two PCs, accounting for 84 % of the total variance, were extracted. Accounting for 58 % of the variance, PC1 had a high positive loading on NDEA, NMOR, and NDBA. As they are the dominant compounds in river water due to industrial activities, PC1 might reflect industrial sources. A high load of NDMA was observed in PC2, accounting for 26 % of the total variance. High concentrations of NDMA were observed in river water in both residential and industrial areas, as illustrated in Section 3.3. An earlier report also observed large NDMA loadings in domestic and industrial wastewater (Chen et al., 2019a). Hence, PC2 represents the sewage source, which includes both domestic and specific industrial wastewater. MLRA was subsequently performed using the factor scores of two PCs as independent variables and the standardized concentrations of ΣNAs as the dependent variable (Huang et al., 2020; Larsen et al., 2009). The results are shown in Fig. 7. A high consistency was observed between the modeled concentrations of ΣNAs and the measured water ΣNAs ($R^2 = 0.98$). The average contribution of industrial source-containing *N*-nitrosamines into the river was 83 %, while that of the sewage source was 16 % (Fig. 7).

For groundwater, only one PC was extracted, accounting for 72 % of the total variance. High loadings of all *N*-nitrosamines were observed. This result could be attributed to the fact that these compounds were easily transported into groundwater through surface water because of their high water solubility (>1000 mg/L) (*University of Hertfordshire*, 2017) as well as the intimate hydraulic connection between river water and groundwater

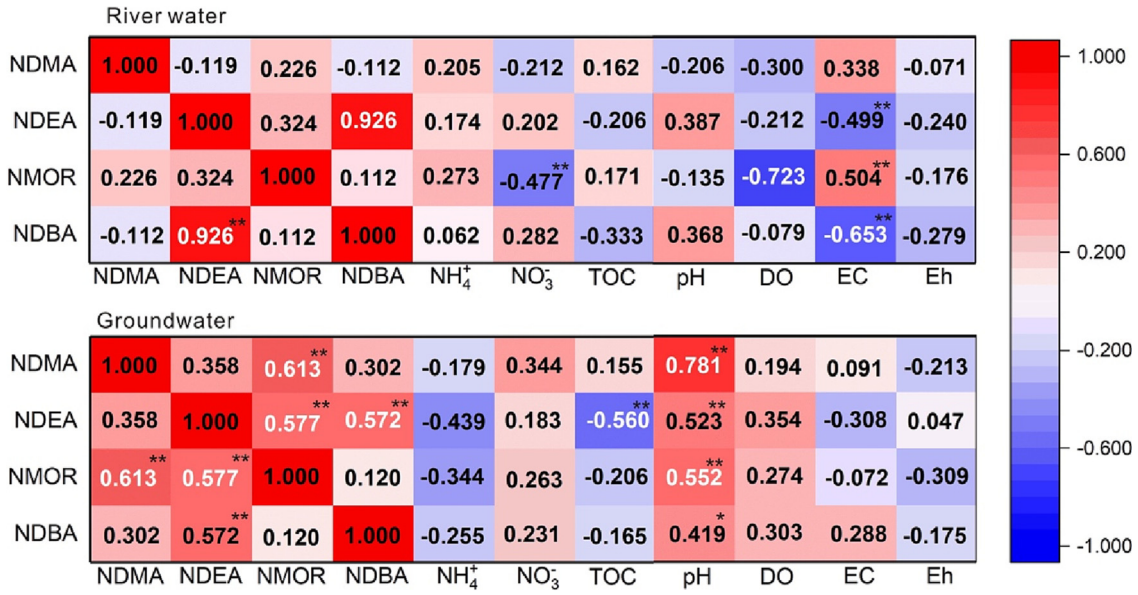

Fig. 6. The correlation map of *N*-nitrosamines and water parameters in river water and groundwater.

in the PRD (Jiao et al., 2010). Thus, PC in the groundwater represents the river water infiltration source of *N*-nitrosamines.

3.5. Potential risks induced by N-nitrosamines

3.5.1. Potential lifetime cancer risks

Tap water produced from local drinking water treatment plants has been extensively consumed by residents of the PRD over the years. However, shallow groundwater is also an important source of drinking water for people living in the countryside. As shown in Fig. 8 and Table S8, the average lifetime cancer risks for 0–1, 1–6, 6–18, and >18 groups were 2.51×10^{-4}–9.54×10^{-4}, 1.34×10^{-4}–5.10×10^{-4}, 3.36×10^{-5}–1.27×10^{-4}, 1.36×10^{-5}–5.16×10^{-5}, respectively. The lifetime cancer risks for the 0–1, 1–6, and 6–18-year-old groups exposed to *N*-nitrosamines in water were significantly higher than those for adults (ANOVA, $p < 0.05$) (Fig. 8). Comparisons between different water compartments revealed that the cancer risks for groundwater consumers were significantly higher than those for tap water consumers ($p < 0.05$) (Fig. 8A and C). Drinking treated tap water rather than groundwater can reduce the associated risks to residents, highlighting the importance of drinking water treatment. The cancer risks caused by *N*-nitrosamines in groundwater and tap water in adults were at an average of 2.85×10^{-5} and 1.36×10^{-5}, respectively, which were slightly lower than the hepatocellular carcinoma disease (HCC) (7.5×10^{-5} person per year) in this area (Ling et al., 2017). These are reasonable, as other factors, such as hepatitis B virus infection, smoking, drinking, and exposure to *N*-nitrosamines by the consumption of tobacco products (22,000 ng/d) and food (1900 ng/d) (Gushgari and Halden, 2018) could also contribute to the occurrence of HCC.

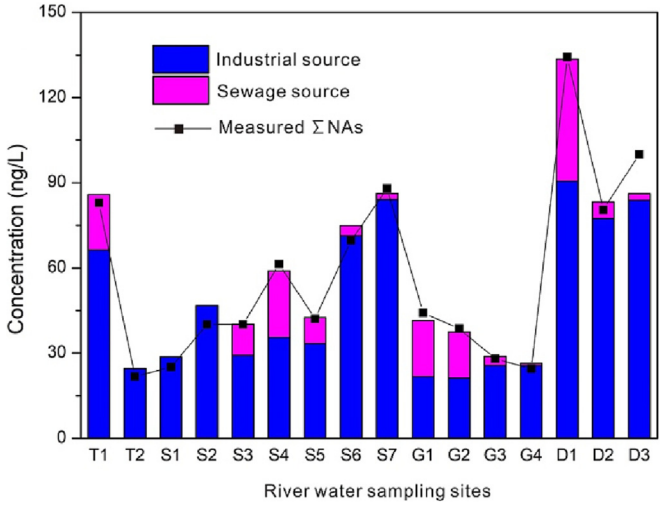

Fig. 7. Contributions of different sources on ΣNAs in river water by PCA and MLRA.

As shown in Fig. 8, compared with dermal contact, oral ingestion was the most prominent exposure pathway, causing >99.9 % of cancer risks. A comparison between different *N*-nitrosamine compounds showed that NDMA and NDEA posed the most significant cancer risks to residents through groundwater, source water, and tap water. Hence, control of NDMA and NDEA should be prioritized to reduce cancer risks from groundwater and tap water.

Generally, after the treatment of drinking water, the carcinogenic risks could be reduced significantly, as indicated by the significantly lower cancer risk values in tap water than in groundwater and source water (AVONA, $p < 0.05$). Furthermore, the carcinogenic risks in tap water treated by advanced treatment processes were lower than those in tap water treated by traditional treatment procedures. For example, the carcinogenic risks in tap water treated by traditional procedures for the 1–6-year-old group (1.94×10^{-4}) were eighteen times higher than those treated by advanced treatment processes (1.05×10^{-5}). The results of this study demonstrate that advanced treatment processes, including ozone oxidation and carbon adsorption in the study area, could effectively reduce the cancer risks caused by *N*-nitrosamines. Previous studies have also suggested that ozone peroxidation reduces *N*-nitrosamine formation more efficiently than peroxidation with sodium hypochlorite (Chen et al., 2019b).

3.5.2. DALYs estimation for exposure to low-level N-nitrosamines

The loss of DALYs, YLLs, and YLDs was calculated based on the cancer risk values, and the results are shown in Table 1. The DALYs caused by *N*-nitrosamines in groundwater and tap water were 113.78 and 54.78 person per year, respectively. The higher DALYs lost values caused by *N*-nitrosamines in groundwater were due to the higher cancer risks caused by groundwater. The DALYs lost for the 18–60-year-old group were the highest (173.44 and 82.59 for groundwater and tap water, respectively), followed by the >60-year-old group (121.60 and 57.90 for groundwater and tap water, respectively). This is likely to be attributed to the higher population numbers for the age group of 18–60 than the others. The DALYs lost in the age groups of 0–1, 1–6, and 6–18 were lower than one person per year due to the lower age-specific incidence rates of liver cancer.

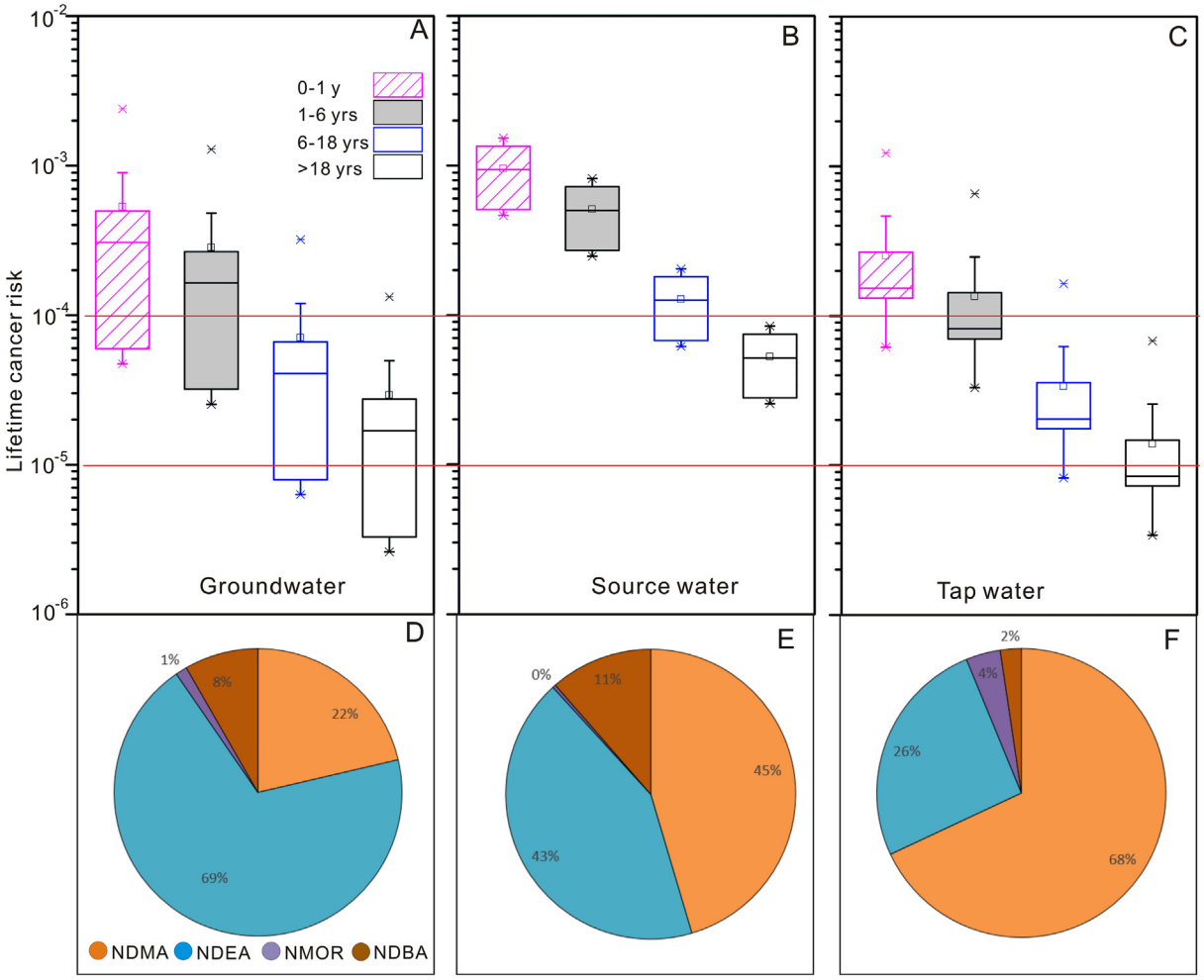

Fig. 8. Lifetime cancer risks associated with exposure to *N*-nitrosamines in the groundwater (A), source water (B), and tap water (C), and cancer risks caused by different *N*-nitrosamines in the groundwater (D), source water (E), and tap water (F).

To eliminate the influence of population size, the DALYs lost per person due to *N*-nitrosamines were also calculated and are summarized in Table 1. In groundwater and tap water, the total individual DALYs lost were 2.93×10^{-4} and 1.40×10^{-4} per person-year (ppy), respectively, which were about 300 and 150 times higher than the reference risk level defined by the WHO (1.00×10^{-6} ppy) (WHO, 2011). The DALYs per person in tap water in the study area were comparable to the loss caused by *N*-nitrosamines in Shanghai, China (1.08×10^{-4} ppy) (Chen et al., 2019b), but were higher than the loss caused by arsenic (3.40×10^{-6} ppy) and trihalomethanes ($<8.04 \times 10^{-7}$ ppy) in the drinking water of Xi'an City, China (Zhang et al., 2018), indicating that the *N*-nitrosamines in drinking water in this area are hazardous, and further measures to ensure drinking water safety are urgently needed.

Table 1
Disability-adjusted life years (DALYs) for different age groups (person-year) and DALYs per person in each group (per person-year) exposed to *N*-nitrosamines in groundwater and tap water.

Age group	Groundwater (person-year)			Tap water (person-year)		
	YLLs	YLDs	DALYs	YLLs	YLDs	DALYs
0–1	0.03	0.01	0.04	0.01	0.00	0.01
1–6	0.21	0.03	0.24	0.10	0.01	0.11
6–18	0.26	0.02	0.28	0.13	0.01	0.14
18–60	171.29	2.15	173.44	81.56	1.03	82.59
>60	116.34	5.26	121.60	55.40	2.50	57.90
Total	288.13	7.47	295.60	137.20	3.56	140.76
Age group	Groundwater (per person-year)			Tap water (per person-year)		
	YLLs	YLDs	DALYs	YLLs	YLDs	DALYs
0–1	4.09E-07	1.50E-07	5.59E-07	1.94E-07	7.12E-08	2.65E-07
1–6	1.09E-06	1.44E-07	1.23E-06	5.20E-07	6.85E-08	5.89E-07
6–18	6.27E-07	3.82E-08	6.53E-07	2.99E-07	1.82E-08	3.17E-07
18–60	8.46E-05	1.07E-06	8.57E-05	4.03E-05	5.08E-07	4.08E-05
>60	2.06E-04	9.33E-06	2.15E-04	9.83E-05	4.44E-06	1.03E-04
Total	2.93E-04	1.07E-05	3.04E-04	1.40E-04	5.11E-06	1.45E-04

4. Conclusion

To investigate the influence of *N*-nitrosamines-contained wastewater on water quality in urban areas, this study measured eight *N*-nitrosamines in urban water systems in the PRD of China. The results showed the prevalence of NDMA, NDEA, and NDBA in river water, groundwater, and tap water, with concentrations of up to 63 ng/L. NDPA, NPYR, and NPIP sporadically occurred at concentrations lower than 8.1 ng/L. Primary industrial discharge significantly increased the *N*-nitrosamine concentrations in river water and groundwater and showed greater influence compared with agricultural and residential activities. The infiltration of *N*-nitrosamines was observed from the surface to the groundwater system. *N*-nitrosamines in groundwater, source water, and tap water pose significant potential cancer risks to residents, especially children and juveniles. With the lower lifetime cancer risks of using tap water compared with those of using raw source water and groundwater, the importance of water treatment was emphasized for risk control. In addition, local governments should resort to controlling industrial discharges or conduct

advanced treatment of industrial wastewaters to ensure the safety of urban drinking water. While this study has improved our understanding of the transport behavior of these compounds, our investigation only provided a brief overview of the transport pathway. Once these compounds enter the groundwater, there remain limited insights into the biodegradation rates and mechanisms of various *N*-nitrosamines. Additionally, our analysis only covered eight *N*-nitrosamine species, leaving out numerous others since there are over 300 *N*-nitrosamines. To mitigate contamination levels, future research on the biodegradation or formation mechanisms of *N*-nitrosamines in the aquatic environment is essential. Moreover, as our investigation only offered a recapitulative description of the transport path, it will be crucial to predict the detailed transport and transformation of N-nitrosamines in groundwater using innovative and robust techniques, such as compound-specific stable isotope tracing and molecular biological methods.

CRediT authorship contribution statement

In this work, all authors listed in the manuscript have made substantial contributions. Their detailed contributions are listed below.

Wenwen Chen: work design, data analysis, writing, and editing.

Shengyang Li: data analysis;

Huanfang Huang: project administration, data analysis, writing, review, and editing;

Yingjie Chen: sampling investigation and instrumental analysis;

Wei Chen: writing, review, and editing;

Yanpeng Liang: resources;

Yang Ding: review and editing;

Kuang Cen: resources;

Shihua Qi: supervision, writing, review, and editing.

Huanfang Huang on behalf of the co-authors.

Data availability

Data will be made available on request.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.164251.

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