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Impacts of sanitation improvement on reduction of nitrogen discharges entering the environment from human excreta in China

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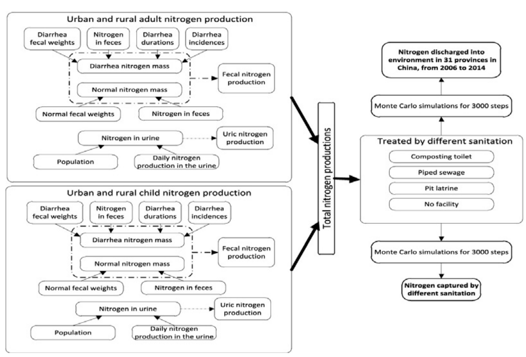
HIGHLIGHTS

- Nitrogen discharges entering environment from human excreta are determined by local population and sanitation conditions.
- The total nitrogen concentration in China's lakes might be potentially affected by local nitrogen inputs from human excreta.
- For further nitrogen control, the sanitation improvement in less-developed regions should be considered a priority.

GRAPHICAL ABSTRACT



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ABSTRACT

Identifying the sanitation efficacy in reducing contaminations entering the environment is an important step for water pollution controls and developing management strategies to further improve sanitation conditions. With continuous efforts in sanitation improvement during the past decade, reductions in discharges of aquatic nutrients are expected in China. In this study, we estimated the aquatic nitrogen discharges from human excreta in 31 provinces in China during 2006–2014. The results indicated that the nitrogen discharges entering the environment from human excreta are largely determined by both local population and sanitation conditions. In 2014, the nitrogen discharges from human excreta in the rural areas (2118(1219–3140) Gg per year) (median and 95% confidence interval) are higher than those in the urban areas (1485(626–2495) Gg per year). The significant relationship ($R^2 = 0.38$, $n = 29$) between the total nitrogen concentrations in lakes and corresponding local nitrogen discharges indicated that, the lakes might be potentially affected by the contaminant inputs from human excreta. The further calculations under two policy scenarios showed that through sanitation improvement, further reduction of nitrogen discharges from human excreta in the developed regions might be limited. The sanitation improvement in the less-developed regions, such as Tibet, Qinghai, and Ningxia, should be considered a priority due to the larger reduction potentials.

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1. Introduction

Nitrogen (N) is one of the most important chemical elements for organisms in the world (Vitousek and Howarth, 1991; Cui et al., 2013). In recent decades, the N cycling in the terrestrial systems has been markedly intensified due to the greater intensity of anthropogenic activities (Galloway et al., 2003; Galloway et al., 2008). N utilized by the human activities is mainly fixed from the atmosphere through the Haber-Bosch process (Vojvodic et al., 2014). However, not all the fixed N is used efficiently. Large quantities of excess N have been discharged into the aquatic environment in the form of NO_3-N and NH_4-N, and this process breaks the nutrient balance in the aquatic systems (Ryther and Dunstan, 1971; Smith et al., 1999; Anderson et al., 2002). Worldwide, human-induced N (and phosphorus (P)) influx into the aquatic ecosystems has caused severe environmental problems (Conley et al., 2009), leading to the degradation of freshwater quality and loss of aquatic biodiversity (Smith et al., 1999; Conley et al., 2009). Some researchers believe that P is the key factor in controlling lake eutrophication and occurrences of harmful algal blooms (HABs) (Correll, 1998; Schindler et al., 2016). However, the majority of researchers believe that the P-only paradigm is overgeneralized. The whole-lake experiments have proved that HABs are more stimulated by the combined P and N enrichment rather than by P alone (James et al., 1994; Chen et al., 2013; Cotner, 2016; Paerl et al., 2016). In China, the low N (and P) usage efficiency has resulted in continuous nutrient accumulations in freshwaters for decades (Jiang and Yuan, 2015; Liu et al., 2016a), and lake eutrophication has become the priority for water pollution controls (Ministry of Environmental Protection, China, 2000–2014). In Taihu Lake, the most damaging and extensive outbreak of HABs occurred in 2007, which severely affected the water supplies in Wuxi (a shore city near Taihu Lake), leaving over two million people without drinking waters for several weeks (Stone, 2011). Other freshwater lakes of China are also experiencing similar stories (Le et al., 2010).

Human excreta are an important contaminant source for aquatic environment due to the high nutrient contents, high production rates and inadequate disposal (Ronteltap et al., 2009; Fuhrmeister et al., 2015; Zhang et al., 2015c; Tong et al., 2016). The safe disposal of human excreta is of paramount importance for prevention of pollutants from entering the freshwaters (WHO, 2006; Fuhrmeister et al., 2015). Reduction of aquatic N discharges mainly relied on decreasing N concentrations released into the environment, capturing waste streams and treating waste streams (Fuhrmeister et al., 2015). The importance of sanitation improvement on the control of nutrient discharges and spread of diseases has been recognized by the international community when the coverage targets in the low-income countries were set in Millennium Development Goals (MDGs) of the United Nations (WHO, 2006; Prüss-Üstün et al., 2008; WHO, 2014). MDGs have set the target to reduce, by half, the proportion of the population without access to improved sanitation from 51% in 2010 to 25% by 2015 (WHO, 2006). In the Sustainable Development Goals (SDGs) in 2015, the United Nations set another target that, by 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations (UNDP, 2015). This improved sanitation is defined as the access to facilities that hygienically separate the faeces from human contacts, including flush or pour flush to a piped sewer system, septic tank or pit latrine, ventilated improved pit latrines, pit latrines with a slab and composting toilets (Cairncross et al., 2010; Fuhrmeister et al., 2015). However, due to the large variations in the economic levels, huge disparities in sanitation development still exist among countries (Prüss-Üstün et al., 2008; Fuhrmeister et al., 2015), and between the developed and less-developed regions within a country (Graham and Polizzotto, 2013).

Currently, the major control strategies for the water pollutions in China are the national wastewater discharge standards (Standing Committee of the National People's Congress, China, 2008) and pollutant cap-control targets, set by the central government every five years (Ministry of Environmental Protection, China, 2012). The existing policies largely prioritized the point-source control measures, such as the improved sanitation facilities in both urban and rural regions (Ministry of Environmental Protection, China, 2000–2014). In 2014, the daily treatment capacity for sewages in the urban areas had reached ~110 million m^3 per day, with a treatment ratio >90% of all the industrial and domestic sewages (Ministry of Environmental Protection, China, 2006–2015). In the rural regions, the sanitation improvement was mainly achieved by a sanitation project, known as the Toilet Revolution (Ministry of Environmental Protection, China, 2015). Before 2005, the majority of the sanitation types in the rural areas were bucket or pit latrines. The practice of open defecation was also very common. Pit or bucket latrines generally lacked the physical barriers between the stored excreta and freshwater, and they are not effective in the removal of aquatic contaminants (Nelson and Murray, 2008). Through the “Toilet Revolution”, the access rates to toilets in the rural regions increased sharply to ~76% in 2014 (National Bureau of Statistics, China, 2006–2014).

During the past decade, continuous efforts have been devoted to improve the sanitation in both urban and rural China. However, the effects on reduction of N discharges from human excreta to the aquatic systems have not been addressed by any previous studies yet. In this study, we have taken N, a key nutrient element responsible for the water eutrophication, as an example, and developed a mechanistic-stochastic model to estimate the N discharges from human excreta and its removal efficiencies in the urban and rural regions of 31 provinces from 2006 to 2014. Based on the total nitrogen (TN) monitoring data collected from over 800 freshwater lakes of China in 2014, we tried to explore the statistical correlations between the local N discharges and corresponding TN concentrations in the freshwater lakes. We also estimated the N discharges from human excreta entering the aquatic environment under two future policy scenarios. This work aims to bridge a knowledge gap between the information needed for the further policy-making and the lack of experimental human-waste data and statistical information in China.

2. Methods and materials

2.1. Conceptual framework

We used a mechanistic-stochastic model (shown in Fig. 1) to estimate the N discharges from human excreta (including faeces and urine from both children and adults) in the rural and urban regions of 31 provinces from 2006 to 2014 in China. This applied model basically follows the modelling efforts by Fuhrmeister et al. (2015) and Tong et al. (2016). In Fuhrmester's study, the researchers focused on the efficiency of sanitation technologies by modelling nutrient and microbial pollutions entering the environment from human waste due to inadequate sanitation in the less-developed countries (Fuhrmeister et al., 2015). In our previous study, we have also used similar mechanistic-stochastic model to identify the impacts of sanitation upgrading to the reductions of faecal coliforms discharges from human waste in the urban and rural of China (Tong et al., 2016).

To be consistent with the existing statistical divisions, our calculation applied the province-level data, divided into the urban and rural regions in each province, on types of different sanitation technologies (i.e., piped sewer connected with sewage treatment, composting toilets, pit latrines, etc.) to estimate the N discharges. The N discharge in each province was calculated according to Eqs. (1)–(6). The reduction potentials of future improvements in sanitation to N discharges were discussed under two policy scenarios (details in Section 2.3). The N removal efficiency by sanitation was calculated using Eq. (7). During these calculations, stochasticity was introduced via a Monte Carlo simulation constructed by the Crystal Ball (Oracle, USA), using the