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Water Pollution Impact Assessment of Beijing from 2011 to 2015: Implication for Degradation Reduction

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Water resource is an essential element for all lives on this planet. With the rapid growth of the economy, urban population, as well as the changes of land use, water degradation issues are becoming more severe. Beijing, as the capital and one of the megacities of China, faces the issue of water degradation. To investigate the water degradation variations of Beijing, the present study has determined the water degradation impacts of the major pollutants, regarding water eutrophication, acidification, and ecotoxicity, and used the cumulative water degradation potential (WDP) curves to effectively identify the most critical pollutants for water degradation reduction. The results show that: (1) The water eutrophication fluctuated at around 9,500 kt COD_{eq} from 2011 to 2015, and phosphorus (P) is the critical pollutant for monitoring eutrophication reduction. (2) The water ecotoxicity decreased during this period, and reduced dramatically from 2013 to 2015, with a reduction rate up to 91 %. This dramatic change is related to the reduction of coal consumption and steel production. Hg and Cd are identified as the two most critical pollutants for ecotoxicity reduction. (3) The water acidification decreased gradually from 229.71 kt SO_{2eq} to 167.51 kt SO_{2eq}, with a decrease rate of 27 %. SO_2 is the most critical pollutant for acidification reduction. In conclusion, the overall water degradation decreased during this period, by 1.5 % for water eutrophication, 27 % acidification and 90 % for ecotoxicity. Phosphorus (P), SO_2, Cr, and Hg are the most important pollutants for water degradation reduction of Beijing.

1. Introduction

Water pollution has been one of the most critical issues in the world. It affects human health as well as nature in direct and indirect ways. Pollutant emissions in drinking water source can lead to serious health problems, and irrigation with polluted water can shift the pollutants into agricultural products such as rice (Clemens et al., 2016). With the increasing serious incidents caused by water pollution, the decline in water quality, i.e. water degradation, is a growing concern for many countries (Klemeš et al., 2017). As one of the largest and fast developing countries, China, is facing serious tensions between economic development and environment remediation, especially with haze (Gao et al., 2017) and water pollution (Ding et al, 2016).
Beijing, as the capital city, exemplifies the seriousness of water pollution issues. According to the environmental quality standards for surface water (MEP, 2002), the surface water in China is divided into six categories based on water quality, from Class I (the best) to Class V or lower (the worst). More than half of the water in four out of five main river basins in Beijing are classified as Class V or lower in 2015 (BMEPB, 2015). Consequently, water pollutant management in Beijing is a major focus of the local government.
Many studies have analysed the water consumption, degradation, and footprint of Beijing. For example, Zhang et al. (2011) analysed the water footprint of Beijing using an input-output method. Qian et al. (2016) built an integral model and assessed the water shortage risk of Beijing. Zeng et al. (2013) using COD as the critical pollutant to determine the grey water footprint (Mekonnen and Hoekstra, 2010.) found that this footprint for Beijing decrease by 69 % from 1995 to 2009. Yuan et al. (2016) used statistical methods to analyse the temporal and spatial variations of water pollution of a reservoir in Beijing to identify the source of some pollutants. Yan et al. (2017) determined the water degradation footprint of Beijing from 2004 to 2013 and found that phosphorus

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(P) was the main contributor for water eutrophication and Cd was the critical pollutant for ecotoxicity. But the results were limited by recognised data availability and quality issues. Water quality degradation is an issue related not only to the environment, but very much impacting clean water availability and human health. Effective monitoring and management of pollutants are the important steps to improve quality of life and increase the availability of natural water resources. There is a need for targeted research on the identification of critical pollutants, and the development of effective communication tools to present the research results and provide practical recommendations to policy makers (Klemeš, 2012).

The aim of this study is to analyse the water Pollutant Emissions (PE) and their associated degradation potentials in the waste discharge water network of Beijing municipal region from 2011 to 2015. The scope of the study includes pollutants relating to water eutrophication, acidification, and ecotoxicity. To achieve the aim, pollutant data from the National Bureau of Statistics databases (NBS, 2016), which were gathered according to ISO 14046 (ISO, 2014), has been extracted. The data are analysed using a cumulative water degradation potential (WDP) Curve approach, which is developed based on the Stacked Composite Curve similar to Carbon Emissions Pinch Analysis (Tan and Foo, 2007). The degradation potential for each category is determined using relative weightings from Heijungs et al. (1992).

2. Assessment approach

This study determines the Water Degradation Potential (WDP) of the Pollutant Emissions (PE) that relate to three categories: (i) Water Eutrophication (WE), (ii) Water Acidification (WA), and (iii) Water Ecotoxicity (WT) (ISO, 2014). WDP for each pollutant in Beijing have been collated for 2011 – 2015 from the Beijing Statistical Year Books of 2011 – 2015 (BMBS, 2016) and China's National Bureau of Statistics (NBS) database (NBS, 2016). Pollutants are reported on a mass basis in kg/y. With the extracted data, this study firstly determined the WDP regarding the three categories. The WDP results are then analysed using cumulative WDP curves Stacked Composite Curve approach similar Carbon Emissions Pinch Analysis (Tan and Foo, 2007). Based on the composite curve, the critical pollutants are identified, and suggestions on water pollutant monitoring are provided.

Each pollutant for each degradation category is weighted for its relative Water Degradation Potential (WDP) impact on water quality (Heijungs et al., 1992) using Eq(1)

$$WDP_j = \sum_i \left(PE_i \cdot w_i\right) \tag{1}$$

Where PE is the pollutant emission using either a mass or volume basis, *w* is the weighting factor of the pollutant relative to its impact, subscript *i* refers to a pollutant, and the subscript *j* refers to the degradation categories of WE, WA, and WT.

Table 1: Weighting factors for determination of Water Degradation Potential (Heijungs et al., 1992)

Category	Pollutant	Unit	w_i
Water Eutrophication	N	kg COD_{eq}/kg	118.64
	P		1,281.82
	COD		1.00
Water Acidification	SO_2	kg SO_{2eq}/kg	1.00
	NO_x		0.70
Water Ecotoxicity	Cd	kg Cr_{eq}/kg	200.00
	Cr		1.00
	Pb		2.00
	Hg		500.00

Water Eutrophication (WE) refers to the eutrophication effect of water discharges. The characteristic pollutants related to this metric depend on the localised degradation pollutants, and the total nitrogen (N), total phosphorus (P) and chemical oxygen demand (COD) are identified as the characteristic pollutants for water eutrophication in Beijing (BMEPB, 2015). Heijungs et al. (1992) calculated the WDP of WE pollutants relative to phosphate, PO_4^{3-}. However, phosphate has not been measured as critical water pollutant for Beijing, and COD is considered as a more important indicator for water quality monitoring. As a result, the basis of impact weightings is changed to COD.

Water Acidification (WA) is the impact of pollutant discharge on the acidification of water bodies, and the important pollutants for this category are SO_2 and NO_x (Heijungs et al.,1992). WDP_{WA} uses SO_2 as the relative impact standard.

Water Ecotoxicity (WT) is assessed with the maximum tolerance concentration (Abourached et al., 2014), which is the highest concentration of a heavy metal in water that does not cause the death of aquatic species. The critical pollutants are Cd, Cr, Pb, and Hg (NBS, 2016). WDP_{WT} is expressed as the relative impact compared to Cr.
For this study, the water degradation impact weighting factors for each pollutant are based on the foundational study of Heijungs et al. (1992), and factors for eutrophication and ecotoxicity are converted from kg PO_4^{3-}eq and m^3 polluted water to kg COD_{eq}/kg and kg Cr_{eq}/kg. These weighting factors are presented in Table 1.

3. Beijing case study

In this study, Beijing is considered as a point source of water pollutants and the evaluation area is covering its municipal boundaries. Considering time availability and consistency, the evaluation period is from 2011 to 2015, which falls under the 12th five-year plan of Beijing. During this period, the National Bureau of Statistics (NBS) increased the database of measured water and air pollutants and improved the data consistency. The emission quantities for each pollutant and category for Beijing are presented from 2011 to 2015 in Table 2.

Table 2: The pollutant emissions (PE) of Beijing from 2011 to 2015 in waste discharge water/air

Impact Category	Indicators	Unit	2011	2012	2013	2014	2015
Eutrophication	COD	kt	193.20	186.50	178.50	168.80	161.50
(NBS, 2016)	N	kt	32.80	32.60	31.30	37.10	32.90
	P	kt	4.50	4.40	4.00	4.80	4.40
Ecotoxicity	Pb	kg	186.18	215.91	201.00	41.21	3.57
(NBS, 2016)	As	kg	28.09	21.34	15.11	8.00	11.04
	Hg	kg	1.72	0.49	0.64	0.10	0.33
	Cd	kg	12.44	17.90	17.45	0.58	0.70
	Cr	kg	508.68	460.10	438.05	266.65	93.59
Acidification	SO_2	kt	188.33	177.50	166.33	150.96	137.63
(BMBS, 2016)	NOx	kt	97.88	93.85	87.04	78.91	71.17

4. Results and discussion

The WDPs of water eutrophication, acidification and ecotoxicity for Beijing from 2011 to 2015 are shown in Figure 1. It shows that the water eutrophication fluctuated about 9,500 kt COD_{eq}, and increased slightly in the last two years. A possible reason is the increase of discharges (BMBS, 2016). Water acidification decreased in this period by a total of 27 %, reaching 167.51 kg SO_{2eq}. The water ecotoxicity of heavy metals fluctuated at around 4,500 kg Cr_{eq} during the first three years and then dropped sharply to below 520 kg Cr_{eq} in 2014 and 2015, with a reduction rate of 89 % and 91 %. The decrease of water acidification and ecotoxicity are also related to the closure of coal-based power plants and steel-making factories.

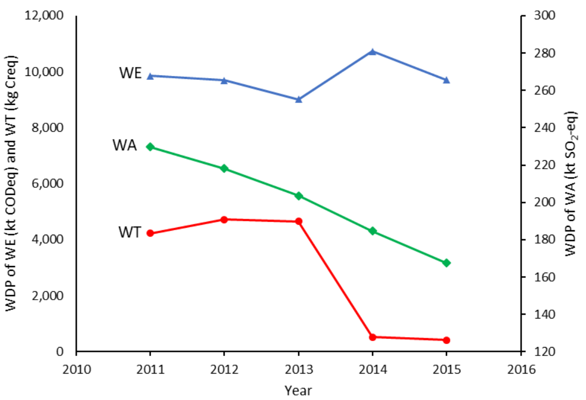

Figure 1: WDP of water eutrophication, acidification and ecotoxicity for Beijing from 2011 to 2015

To effectively present the assessment results and clearly identify the critical pollutants for water degradation reduction, the water PE and WDP impact was analysed using a cumulative WDP Curve. The slope of each segment equals to its weighting factors (ascending order), and the emission of the pollutants are also arranged in an ascending order, the curve curls upwards, as is shown in Figures 2, 3 and 4.

Figure 2 illustrates the water eutrophication pollutants compared to their relative WDP impacts. Phosphorus (P) is the smallest pollutant by mass but the most important contributor to water degradation due to eutrophication. This demonstrates that targeting reductions of phosphorus (P) should be the most effective way to reduce water eutrophication for Beijing. The COD emission decreased by 31.7 kt (16 %) compared with 2011, but only reaching about 0.3 % reduction WDP by eutrophication. While a small phosphorus (P) reduction of 0.1 kt reaches a relatively higher WDP by eutrophication reduction of 1.3 %.

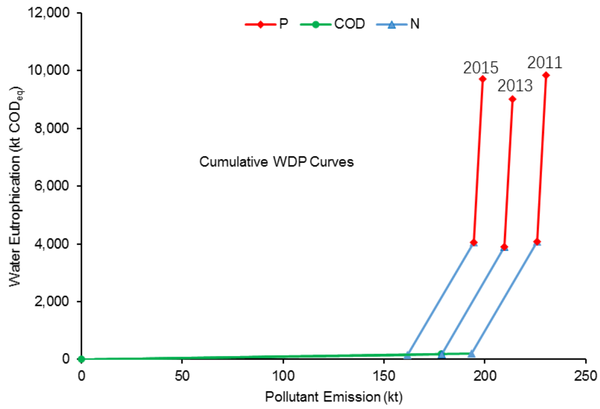

Figure 2: Cumulative WDP of different pollutants with water eutrophication in Beijing for 2011, 2013, and 2015

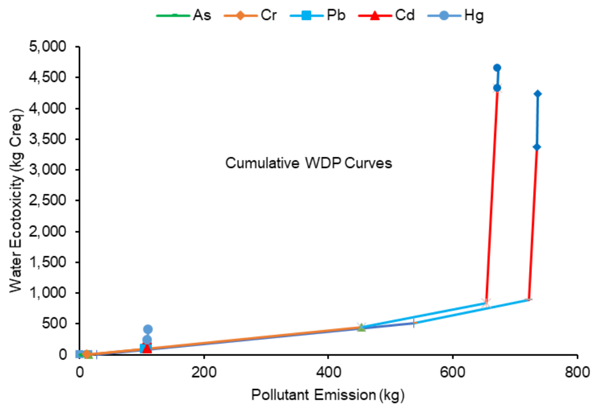

Figure 3: Cumulative WDP of heavy metals with water ecotoxicity in Beijing for 2011, 2013 and 2015

Figure 3 shows the water ecotoxicity pollutant emissions compared to their relative WDP impacts. Hg has the highest potential (slope) to water ecotoxicity, and its contribution is lower. While Cd has the second largest potential, and is the main contributor to ecotoxicity with smaller emissions. The contribution of As is the smallest and indiscernible, accounting for less than 1.0 % from 2011 to 2015. The reduction of Hg and Cd is the most effective way for ecotoxicity reduction. Comparing with 2011, the water ecotoxicity increased about 10 %, even though the emissions of Pb and Cd reduced 8 % and 40 %. It can be noticed that the water ecotoxicity from 2013 to 2014 showed a dramatic reduction due to significant drops in the emission of heavy metals Cd, Hg, and Pb. He et al. (2013) attributed the heavy metal emissions to the coal-based power plant, steel production, and mining industries. In 2013, Beijing started a coal consumption reduction and cleaner production project (Beijing Government, 2013), which resulted in the closure of 3 out of 4 coal-based power plants. As a result, coal consumption in 2014 and 2015 reduced by 14 % and 42 % compared to coal consumption in 2013. Pan (2016) analysed the air pollution using $PM_{2.5}$ in the winters of 2012 - 2013 and 2015 - 2016 in Beijing, and concluded that the heavy metal contamination was reduced to 86 %, Cd 41 % and Pb 49 %. Air pollution can be transferred into water bodies by precipitation and this result can also help explain the drop in heavy metal emissions and ecotoxicity after 2013. A third reason is that the steel production from 2011 to 2015 decreased with an annual rate of 10 % (NBS, 2016), which also demonstrated the sharp reduction of ecotoxicity from 2013 to 2015. Although the water ecotoxicity dropped significantly in 2015, Hg and Cd remained as the most critical pollutants. The water acidification pollutants compared to their relative WDP impacts is shown in Figure 4. NO_x is the major contributor to water acidification. While SO_2 has the larger potential for acidification with smaller emission but higher effect, which means a smaller reduction of SO_2 can reach to a higher degradation reduction. The acidification reduction of 2013 to 2015 is higher than 2011 to 2013, which can also be explained by the closure of coal-based power plant and steel production. Considering from pollutant sources, the contribution of industrial sources decreased from 2011 to 2015, while the contribution of domestic emission increased to 76 %, which indicates that household and transportation emission should be a target for acidification reduction.

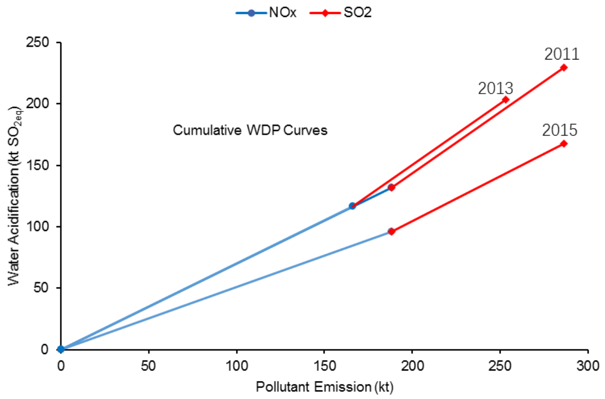

Figure 4: Cumulative WDP of different pollutants with water acidification in Beijing for 2011, 2013, and 2015

The application of this approach in regional water pollutant emission analysis still has two significant limitations. Firstly, the regional water degradation assessment highly depends on data availability and quality. Long-term regional data of pollutant emission is difficult to obtain because many of the important pollutants were not measured before 2011. Even since 2011, it is possible that the assessment based on the data released by the National Statistical Bureau can only reveal part of the problem because some emissions sources are difficult to be measured. For example, tourists and people living around the rivers may emit pollutants, including heavy metals from electronic waste, directly into rivers and waterways that are not captured as part of discharge water (He et al., 2017). Secondly, the water degradation potentials are calculated separately with different impact categories, e.g. acidification, eutrophication, and ecotoxicity. However, these pollutants are often mixed in the same water bodies. The existence of one pollutant can affect the performance of another pollutant. It is difficult to consider the cumulative effect of all pollutants in the degradation evaluation. In future studies of city-level water degradation assessment, the determining area can be divided into smaller grids (or municipal districts) to ensure higher data availability and quality, which can help with city pollutant monitoring. Pollutant weighting factors should be also updated with more accuracy, and consider the synergistic effect of different pollutants (Klemeš, 2015). More specific data can lead to a more reliable assessment, and facilitate the determination of overall water degradation potentials and reduction.

5. Conclusions

This study investigated the water degradation of Beijing from 2011 to 2015, regarding water eutrophication, acidification, and eco-toxicity. In conclusion, during the studying period, the water eutrophication remained at around about 9,500 kt COD_{eq}. The water ecotoxicity decreased from 4,234.66 kt Cr_{eq} in 2011 to 407.94 kt Cr_{eq} in 2015, with a reduction rate of 90 %. The dramatic reduction is mainly because of the sharp reduction of coal consumption and steel production. Water acidification decreased gradually from 229.71 kt SO_{2eq} to 167.51 kt SO_{2eq}, with a reduction rate of 27 %. The cumulative WDP Curves clearly showed that Phosphorus (P) is the largest contributor and the most significant pollutant for eutrophication reduction. Cd is the main contributor for ecotoxicity, and Hg is the most important pollutant for water ecotoxicity reduction. For water acidification, NO_x is the larger contributor and SO_2 is the most major monitoring pollutant. The suggestions for city water quality management is that monitoring and reduction of phosphorus (P), SO_2, Cr, and Hg, which is the most effective approach for water degradation reduction.

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