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China pollutant discharge permits as a link between total emission control and water quality: a pilot study of the pesticide industry

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ABSTRACT

The deficiency of China's current pollution discharge permit system lies in the failure to improve the water quality effectively. This paper discusses the premise that the water quality of a water environmental functional zone (WEFZ) is mostly affected by industrial pollution sources. By reviewing the related policy, we noted the link between total emission control, effluent limitations and pollutant discharge permits us to configure a practical framework for pollutant discharge permits based on water quality. China's pollutant discharge permit system provides an administrative foundation for reducing polluters' total emissions at the scale of the WEFZ, and it is best implemented through the imposition of limitations on polluters to identify the related treatment technology levels. Owing to the importance of limitations, the methodology of limitation classification and the related treatment technology classification are presented for the pesticide industry. Additionally, a comprehensive analysis of the pollutant reduction potential for the pesticide industry is conducted to determine the current level of sewage treatment. More importantly, this study offers an innovative way to investigate pollutant reduction potential and provides an example that may be useful to other key industries.

Key words: Pesticide industry, Pollutant discharge permit, Total emission control, Water quality

HIGHLIGHTS

- China's policy review of total emission control and pollutant discharge permit was discussed.
- A practice framework of pollutant discharge permit based on water quality was configured.
- The classification methodology in case of pesticide industry was present.
- Analysis of national statistical and typical case was conducted for pollutant reduction potential.
- Decision-makers can consider the reduction potential of specific polluters accordingly.

INTRODUCTION

Since the 1970s, pollution discharge permits have gradually become an important source of water pollution control in many countries around the world, and they currently represent the core system for achieving water quality goals. In the United States, for example, in the determination of the pollutant discharge limit prescribed by the permit for stationary pollution sources, it is necessary to consider the technical pollutant permit limit, so that the pollutant treatment level at this stage can meet the requirements as well as consider the pollutant permit limit based on water quality to ensure that the receiving water body can maintain its specific use. The European Union requires member states to combine natural water environment management with pollutant discharge management and stipulate the use of the best available technology and the water quality standard inversion method to verify the pollutant discharge permit limit. Thus, developed countries implement the pollution permit system to improve the quality of the water environment.

Compared with the pollutant discharge permit systems used worldwide, China has drawbacks in improving water quality. First and foremost, the current total emission amount limit based on the capacity of the water function zone is distributed and controlled by the administrative region (Hu *et al.*, 2018), while the limit for the emission amount stipulated by pollutant discharge permits is measured at the enterprise level rather than at the regional level. As a result, the limit for the total amount in a specific water function zone does not have a relationship with the stationary sources. While the limit for the emission amount in pollutant discharge permit system is only based on the pollutant emission standard or official total emission quota, there is a need for further improvement on reduction decisions in the purpose of water quality. In this respect, it would benefit from a practice framework designed for reduction and decision feedback mechanism by pollutant reduction potential investigation.

Chinese scholars have proposed some possible solution to improve water quality in a water environmental functional zone (WEFZ), such as inter-zonal tradable discharge permit system (Cao & Saburo, 2005), pollutant total amount control technique in control unit (Meng *et al.*, 2007) and allocating total emission pollutant control (Bai *et al.*, 2019). However, the related studies are mainly theoretical and lack connections with current policies, leading to implementation difficulties. Moreover, as watershed processes are very complex, making full use of current policies is critical to the success of water quality improvement practices.

The aim of this study was to configure a practical framework of pollutant discharge permits based on water quality and present a comprehensive analysis of pollutant reduction potential for the pesticide industry. First, we reviewed the link between total emission control, effluent limitations and pollutant discharge permits to seek a starting point. Second, a framework integrating emission standards and wastewater treatment technique classification was proposed for determining the total emission reduction at the WEFZ scale. Third, national statistical treatment analysis, typical case cost analysis and correlation analysis were conducted to indicate the pollutant reduction potential. To comprehensively support policy decision-making, this pilot study focused on the pesticide industry but was intended to be applicable to other key industries as well.

METHODS

Study industry

Enterprises producing chemical pesticides, biological pesticide or pesticide preparations are classified as the pesticide industry, which must follow certain technical specifications (Ministry of Ecology and Environment of the People's Republic of China (MEE) and Nanjing Institute of Environmental Science, 2017) when applying for a pollutant discharge permit. There were nearly 2,000 enterprises with pesticide production qualifications in China as of the end of 2017. Nearly 1,500 enterprises produced only pesticide preparations. A total of 1,021 pesticide enterprises had applied for pollutant discharge permits by May 2018. In addition, the pesticide industry was listed as a key industry for water pollution prevention and control (The State Council, 2015) in characteristics of large sewage production and high difficulty in wastewater treatment. Accordingly, the large number of applications and the high attention made the pesticide industry good to study.

Methodology of pollutant reduction potential investigation

A large amount of basic data on pollutant discharge permits for the pesticide industry are available, and information on 383 pesticide enterprises was collected from the database on the pollutant discharge permit information platform (http://permit.mee.gov.cn/permitExt/) for national statistical analysis. A profile of the complex relationship between cost and pollutant reduction was derived for typical cases. Questionnaires were distributed to 100 pesticide enterprises in China, and 54 pesticide enterprises responded. After data filtering and random on-site verification, the number of valid cases was reduced to 36.

RESULTS AND DISCUSSION

Current situation of China's water environment

In 2018, MEE released an announcement on China's ecological environment, which reported the results of 1,935 monitoring sections for surface water in seven water systems throughout the country (MEE, 2018a). The ratios of monitoring sections in levels I–III, levels IV–V and inferior level V were 74.3, 18.9 and 6.9%, respectively. There were still a large number of rivers and lakes that did not meet their water quality targets that might cause water problems with respect to watersheds, agriculture, fisheries, industries and eco-development (Jia *et al.*, 2019). Sun *et al.* (2015) found that surface water with high-level pollution seemed to be diffused across the country from 2006 to 2010, which appeared in the lower reaches of the Han River, the Yangtze River, the whole reaches of the Hai River and the middle and lower reaches of the Pearl River. For a long time, one of the major strategies for water quality improvement was to set a target of 10% reduction for the total pollutant emission by the government while not considering the differences in ecosystem conditions and environmental carrying capacities across different areas and the lack of scientific guidance on how to reduce them. Accordingly, although the discharge of water pollutants has been reduced dramatically by total emission pollutant control, water pollutants sometimes still significantly exceeded the carrying capacity of water environment.

Policy review and enlightenment

In China, some of the construction systems for pollution prevention and control has foreign influences. One such system is the pollutant discharge permit system. However, enforcement seemed inadequate until 2016. The plan for implementing a pollutant emission control permit system (The State Council, 2016) first provides a basis for reforming the pollutant discharge permits, which would serve as a core system for the environmental management of stationary sources. Pollutant discharge permit management (MEE, 2016, 2018b) includes comprehensive rules for standardizing application, issuance and implementation. A list of stationary sources (MEE, 2017a) classifies dischargers by industry type. Dischargers must obey specific technical specifications to access pollutant permits. An application on the pollutant discharge permit information platform (http://permit.mee.gov.cn/permitExt/) covers aspects from the production to the discharge of water, air, noise and solid waste pollutants, as well as the monitoring and management of environmental protection. Moreover, a workable pollutant discharge permit system may be accomplished by the harmonization of the Administrative Permit Law (P.R.C.) and the provisions in individually promulgated laws on pollution prevention and control.

The total emission control policy is an effective tool that curbs environmental pollution by setting emission quotas and targets, but it is critical to clearly define the obligations and duties for pollutant control of local governments and industrial enterprises and acquire reliable and accountable pollution and emission data (Hu *et al.*, 2018). The pollutant discharge permit system is a good lever for controlling the total emissions from industrial enterprises. For instance, industrial enterprises can calculate their annual total quantity of water pollutants using the following equation or by following the official total emission quota, depending on which is stricter:

$$E = C \times \sum_{i}^{n} (S_i \times Q_i) \times 10^{-6} \qquad (1)$$

where E represents the annual total quantity of water pollutants (t/a), C is the effluent limitation (mg/L) and Q_i is the water discharge benchmark of product i. If there is no benchmark available, Q_i is the actual average water discharge of product i (m^3/t). S_i is the actual average annual production of product i (t/a) in the last 3 years when running >3 years, actual average annual production when running >1 year and <3 years, or annual capacity when running <1 year.

To improve the environmental water quality, many studies mainly focused on controlling the total pollutant emission amount related to the water carrying capacity (Meng *et al.*, 2007; Hu *et al.*, 2010; Yang *et al.*, 2015). Total emission control also led to many complexities, such as the trade-off between treatment technology optimization, waste load allocation (WLA) and system cost in the water quality management. The WLA, as an efficient, effective water pollution control management method, can restrict pollution discharges into river systems and seek to strike the balance between water basins, administrative units and dischargers (Xu *et al.*, 2017). Designs of the WLA scheme for river basins require the participation of all decision-makers, including river basin authorities, regional environmental protection agencies, and especially the numerous dischargers, which rely on environmental policy, currently valid standards and environmental management systems.

With total pollution control and emission reduction tasks assigned to the different subareas, WLA plans help identify the necessary reduction goals and the numerous participating dischargers. The important role of a pollutant discharge permit system is to make these dischargers act as liability subjects such as the pollutant discharge permit provides an administrative foundation.

According to the total emission control in the pollutant discharge permit system, the assigned total emission of one specific discharger can be divided into two controllable parts: discharge and effluent concentrations (referring to Equation (1)). Generally, the discharge is closely related to cleaner production. The effluent concentration is related to the characteristics and treatment level of wastewater, which must adhere to the effluent limitation and is an important management element in the pollutant discharge permit system. When dischargers meet the more stringent total emission requirement, the more stringent effluent limitation is an indirect and effective solution. Notably, the direct demand of a stringent effluent limitation is illegal, but provincial environmental protection authorities can set higher requirements to meet the target for environmental quality improvement, which is a basic principle of the pollutant discharge permit system.

In a word, the pollutant discharge permit provides an administrative foundation to make total emission control working on dischargers, and dischargers could reduce total emission by effluent limitation. Pollutant reduction potential investigation based on effluent limitation forms a feedback loop to make an executive decision. The internal relationship of policy can be seen in Figure 1.

Pollutant discharge permits based on water quality – the design of the practice framework

The practical framework of the pollutant discharge permit based on water quality could be applied to a WEFZ with a large proportion of industrial pollution sources (Figure 2). While the pollutant discharge permit in

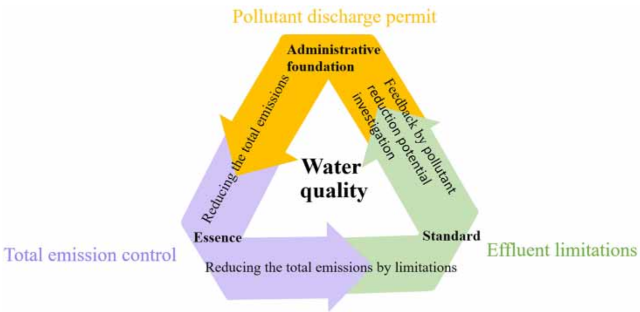

Fig. 1. | Internal relationship diagram of policy.

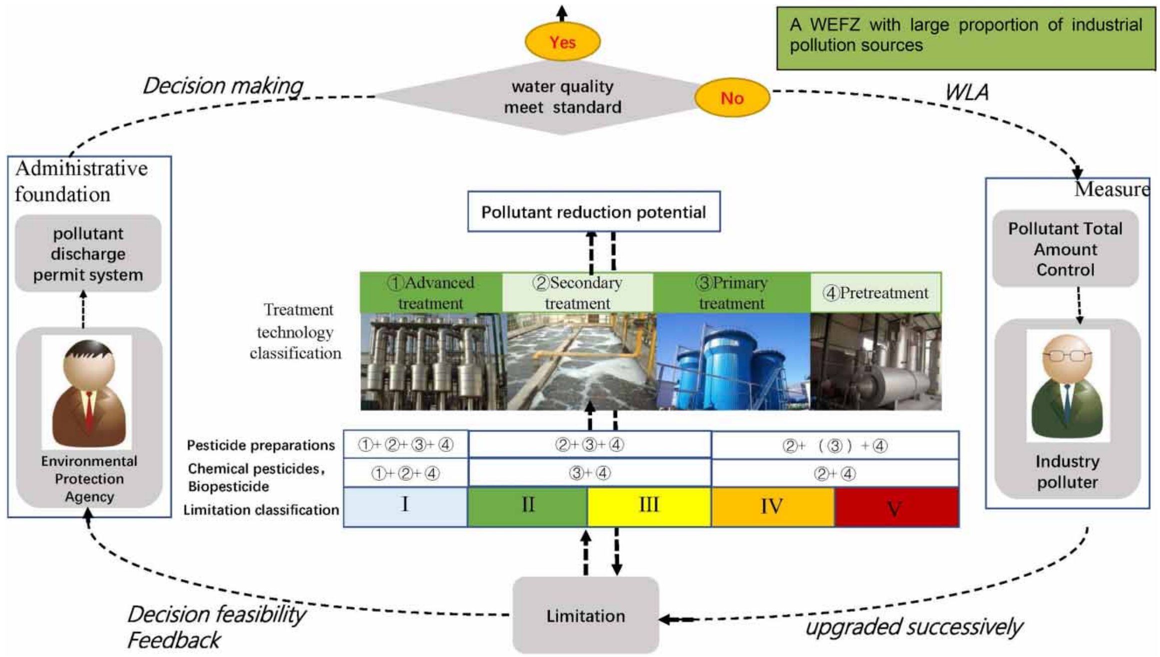

Fig. 2. | Practice framework of pollutant discharge permit based on water quality.

China provides the administrative foundation for reducing the total emissions from polluters, limitations act as a ‘gripper’ and therefore limitation classification is a feasible and efficient way. The limitations classified according to different industries to meet the water quality targets were developed to enable the identification of the related treatment technology level and emission reduction potential. The corresponding treatment technology level is described as treatment technology classification that will contribute to quickly figuring out the degree of difficulty of wastewater treatment. Pollutant reduction potential investigation will be provided to the environmental protection agency for decision-making.

Limitation classification

A point source may be subject to more stringent effluent limitations, known as ‘water quality-based effluent limitations (WQBELs)’, to ensure the attainment of state water quality standards in the United States (Jeffrey, 2007). Similar to the function of WQBELs in the United States, the water quality target limitations for industry in China are based on technology-based limitations and water quality standards. Water quality target limitations are classified into levels I–V, according to pollutant concentration, from low to high. The classification is first based on the current effective emission standards, which have sufficient executive motivation. Second, the concentration level can distinguish the corresponding treatment technology level to assess feasibility and costs. Generally, the limitation of the corresponding pollutant should be upgraded for the purpose of total emission control.

The classification of water quality target limitations for the pesticide industry includes the effluent limitations stipulated in national or industrial standards (Table 1). The most stringent is level I, referring to the level V limitations in the environmental quality standards for surface water (MEE, 2002). Levels II and III refer to limitations for discharging directly into the water environment according to industrial standards (MEE, 2017b) and national standards (MEE, 1996), respectively. Levels IV and V refer to limitations for discharging into industrial sewage

Table 1. | Limitations classification in the target of water quality.

Classification	COD	BOD	Ammonia nitrogen	Total nitrogen	Total phosphorus	TSS
I	40	10	2	2	0.4	–
II	100[a] (80[b])	20	15	20	4[c] (1[a])	50
III	150	30	25	–	–	150
IV	400[a] (200[b])	–	30	40	10[c] (2[a])	150
V	500	300	–	–	–	400

[a]Other pollutant discharge units.
[b]Production of biological pesticides.
[c]Production of organophosphorus pesticides.

treatment plants according to industrial standards (MEE, 2017b) and national standards (MEE, 1996), respectively. Pesticide enterprises must meet at least the technology-based limitations, which are usually level V for indirect emissions when the water quality in their WEFZ meets the standards. If the water quality deteriorates, the limitation regarding the corresponding pollutant is successively upgraded.

Treatment technology classification

The techniques for treating industrial process wastewater are numerous and include the source segregation and pretreatment of concentrated wastewater streams. Typical wastewater treatments are classified into pretreatment, level I treatment, level II treatment and advanced treatment, roughly according to the treatment steps (Table 2). The level of treatment steps a pesticide enterprise should take to reach the limitations of a given water quality target classification is summarized in Table 3.

Investigation of pollutant reduction potential

National statistical analysis of treatment technology

Under severe circumstances (MEE, 2015), an increasing number of pesticide enterprises chose to establish chemical industrial parks. Pesticide enterprises accounted for 67% of the wastewater discharged into industrial sewage treatment plants. Only 8.6% of pesticide enterprises discharged wastewater directly into the water environment, and 3.7% did not discharge any wastewater. The remainder of the pesticide enterprises presented a mix of direct emissions, indirect emissions and no emissions. Therefore, most pesticide enterprises in China were limited to the level V water quality target classification.

Among the wastewater treatment techniques, the highest application frequencies were oxidation (64.7%) with chemical methods, followed by precipitation with physical methods (61.8%) and anoxic–aerobic (A/O) biological methods (50.5%). Precipitation was the dominant pretreatment technology, while oxidation represented the main level I treatment technology and A/O represented the main level II treatment technology. Additionally, 39.2% of pesticide enterprises engaged in both level I and level II treatments, and 41% of pesticide enterprises chose an advanced treatment for better pollutant removal efficiency. According to treatment technology classification (Table 3), pesticide enterprises engaged in both level I and level II treatments have a large potential for reaching the level II or level III of water quality target classification, and pesticide enterprises engaged in advanced treatment even have a chance to reach the level I of water quality target classification. It can be inferred that quite a few pesticide enterprises are capable of upgrading their limitation level, instead of only limiting to the level V of water quality target classification.

Table 2. | Main technologies of pesticide wastewater treatment at each level.

Treatment steps	Pretreatment	Level I treatment	Level II treatment	Advanced treatment
Main wastewater treatment technologies	Multi-effect evaporation, oxidation, extraction, distillation, adsorption, stripping, etc.	Regulating, neutralization, hydrolysis, stripping, coagulation, precipitation, flotation, demulsification, oil–water separation (oil separation, flotation), etc.	Upflow anaerobic sludge bed (UASB), anaerobic granular sludge expanded bed (EGSB), anaerobic fluidized bed (AFB), composite anaerobic sludge bed (UBF), anaerobic internal circulation reactor (IC), hydrolytic acidification, activated sludge process, sequencing batch activated sludge process (SBR), oxidation ditch, A/O process, membrane biological process (MBR), biological aerated filter (BAF), biological contact oxidation, traditional nitrification and denitrification (AO), short cut nitrification and denitrification, simultaneous nitrification and denitrification, etc.	Evaporation crystallization, sand filtration, ozone oxidation, fenton oxidation, ultrafiltration (UF), reverse osmosis (RO), incineration, etc.

Table 3. | Summary of treatment technologies corresponding to different emission limit levels.

Limitation classification	I	II	III	IV	V
Chemical pesticides, biopesticide	Pretreatment + Level I treatment + Level II treatment + Advanced treatment	Pretreatment + Level I treatment + Level II treatment		Pretreatment + (Level I treatment) + Level II treatment	
Pesticide preparations	Pretreatment + Level II treatment + Advanced treatment	Pretreatment + Level II treatment		Pretreatment + Level I treatment	

Cost analysis of typical cases

Wastewater treatment costs were maintained within a relatively stable range for each of the techniques (Table 4), despite the variety of scales, process combinations, characteristics of wastewater, etc. In general, techniques with energy consumption had a relatively high treatment cost, followed by techniques with reagent use.

The construction cost of wastewater treatment is variable under the influence of many factors, such as scale, region and process combination, and is hard to determine. The analysis of the 36 typical cases provided a glimpse of the general situation of the pesticide industry's wastewater treatment facilities in China. The pesticide

Table 4. | Processing costs of main treatment.

Treatment	Processing costs ($/ton)
Flotation	0.077–0.770
UF	0.155–0.309
RO	0.618–0.927
Coagulation	0.155–1.55
Ozonation	0.309–1.55
Demulsification	0.309–3.09
Hydrolysis	1.55–3.09
Blow off	3.09–6.18
Fenton oxidation	0.464–4.64
Adsorbent	0.773–7.73
Extraction	1.55–7.73
Stripping	4.64–9.27
Oxidation	0.773–30.9
Multi-effect evaporation	9.27–15.5
Distillation	3.09–30.9
Evaporation crystallization	3.09–30.9
Coagulation	30.9–154.5

enterprises investigated were located in 13 provinces throughout the country. Four of the enterprises discharged wastewater directly into the environment, and the rest discharged into industrial wastewater treatment plants. Wastewater treatment facilities were first established within the last 15 years. All the enterprises surveyed had built pretreatment facilities, with the benefit of reducing the discharge load of effluent into wastewater treatment stations. The cost of investment in pretreatment facilities ranged from 92.7 thousand to 8.19 million US dollars, and the median value was 1.24 million US dollars. The cost of investment in a wastewater treatment station ranged from 139.1 thousand to 32.5 million US dollars, and the median value was 3.09 million US dollars. The total cost of investment in wastewater treatment facilities ranged from 139.1 thousand to 34.9 million US dollars, and the median value was 4.02 million US dollars. Jiangsu is a large pesticide manufacturing province, and the average sales of the pesticide enterprises in the province in 2018 amounted to approximately 61.8 million US dollars (data statistics from the China Pesticide Industry Association). Consequently, the investment cost of wastewater treatment facilities could constitute a considerable proportion of annual sales for a pesticide enterprise.

Usually, the investment intensity reflected the difficulty degree of wastewater treatment. For pesticide enterprises investigated, the cost of investment per 10,000 m^3 influent ranged from 53.4 thousand to 1,853.3 thousand US dollars, and the median value was 222.4 thousand US dollars.

Comprehensive analysis between cost and pollutant reduction

We took the main pollutants (chemical oxygen demand (COD), ammonia nitrogen and total phosphorus) as examples. In total, 32 valid samples of 36 typical cases were obtained to examine the COD reduction potential (Figure 3(a)). When COD concentrations were $<$1,500 mg/L before treatment, the COD emission concentration reached a level II limitation (a water quality target classification). Approximately 28.1% of cases faced COD concentrations as high as 10,000 mg/L before treatment, and the high COD concentration before treatment often predicted the high investment intensity.

In total, 29 valid samples of 36 typical cases were obtained to examine the ammonia nitrogen reduction potential (Figure 3(b)). The emission concentration seemed irrelevant to the concentration before treatment and the investment intensity, because some enterprises with low costs or difficult sewage processing could still achieve effective ammonia nitrogen treatment. However, the high ammonia nitrogen concentration before treatment can also predict the high investment intensity like COD.

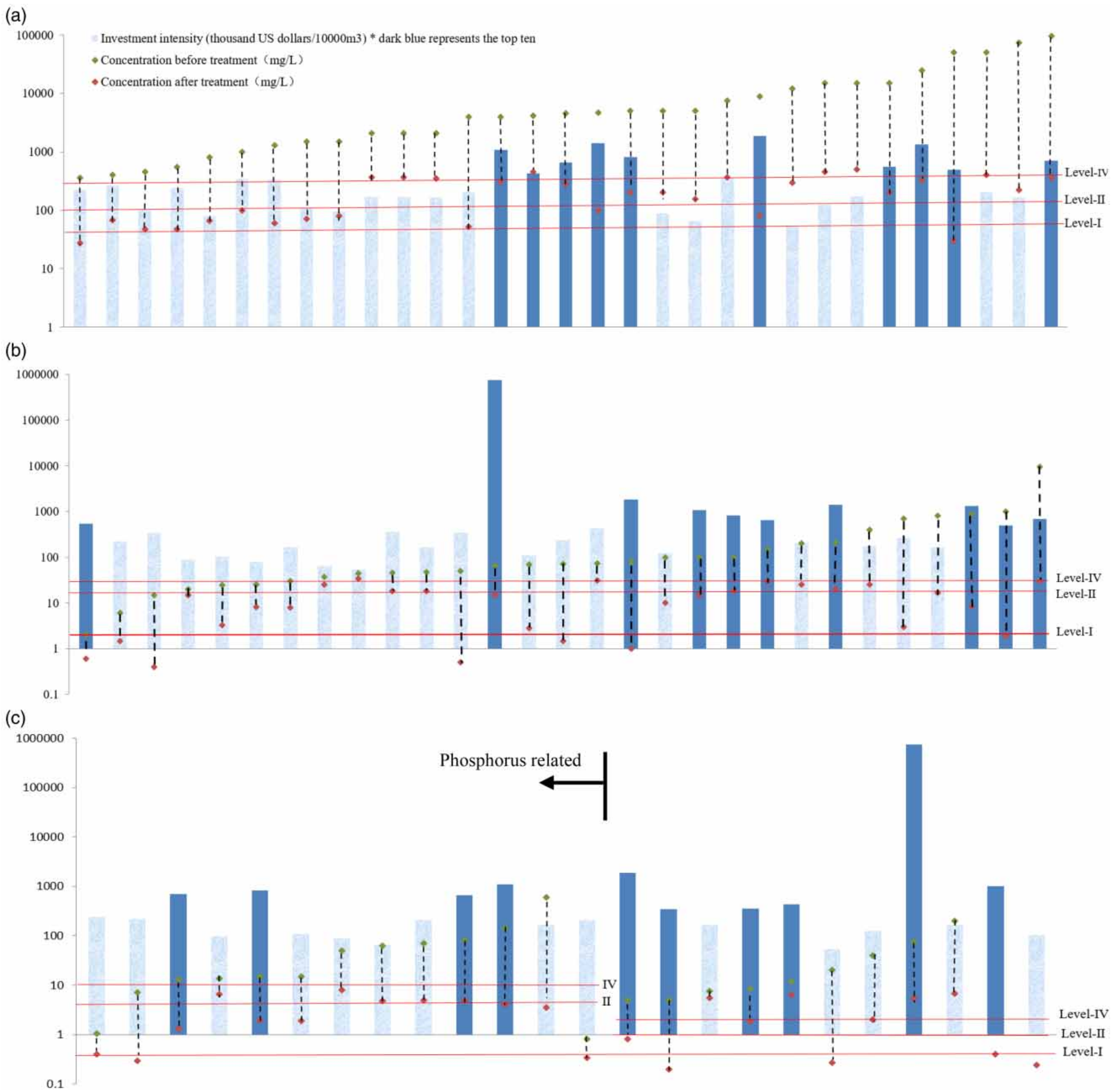

Fig. 3. | Profile of main pollutants' reduction potential: (a) COD; (b) ammonia nitrogen; (c) total phosphorus.

A total of 24 valid samples for the 36 typical cases were obtained to examine the total phosphorus reduction potential (Figure 3(c)). The difficulty of total phosphorus treatment mainly depends on whether the manufacturer is phosphorus-related, but a phosphorus-related manufacturer could generally reach level II due to the high attention. It was noteworthy that a few phosphorus-free manufacturers failed to reach the level IV limitation.

The Spearman correlation between the investment cost and parameters of sewage treatment (the emission concentration, annual output of sewage, concentration before treatment, etc.) was analyzed. The investment cost was observed as strong positive correlations (Spearman $r = 0.633$, $p < 0.01$) with an annual output of sewage, as described in Table 5, which also became the remarkable linear relations by the linearity regression analysis ($y = 9.437x + 295.953$, $R^2 = 0.7633$), setting the investment cost as y and an annual output of sewage as x. There were also some strong negative correlations (Spearman $r = -0.524$ to -0.347, $p < 0.01$ or <0.05) between the investment cost and the emission concentration (Table 5). However, the relation between the investment cost and the emission concentration was complex and seemed hard to accurately fit a conventional linear regression mode. That conforms with the situation where the emission concentration is also affected by many other factors, for example, properties of wastewater, selection of treatment process and regional differences, but the investment cost is still a practical and quantifiable indication to the possibility of pollutant reduction.

CONCLUSION AND RECOMMENDATIONS

Some thoughts about water quality improvement were evolved from the policy review. In essence, China's pollutant discharge permit system provides the administrative foundation for the total emission reduction of polluters when the water quality deteriorates. Nevertheless, it is best implemented for polluters through the imposition of limitations to identify the related treatment technology level. It also helps decision-makers consider the reduction potential of specific polluters.

Accordingly, a practical framework of the pollutant discharge permit based on water quality was proposed for determining the total emission reduction at the WEFZ scale. The limitation classification was the core of framework design, which was developed to enable the identification of the related treatment technology level and emission reduction potential. The corresponding treatment technology level was described as treatment technology classification that would contribute to figuring out the difficulty degree of wastewater treatment quickly. In this study, the limitation classification and related treatment technique classification were provided in the example of the pesticide industry.

Pollutant reduction potential investigation based on the effluent limitation forms a feedback loop to make executive decisions. By national statistical analysis of the treatment technology, it could be inferred that quite a few pesticide enterprises are capable of upgrading their limitation level, instead of only limiting to the level V water quality target classification. Costs analysis described general status of investment cost for wastewater treatment facilities. As for comprehensive analysis between cost and pollutant reduction, the high COD or ammonia nitrogen concentration before treatment often predicted the high investment intensity. The investment cost was observed as strong positive correlations (Spearman $r = 0.633$, $p < 0.01$) with an annual output of sewage,

Table 5. | Correlation between investment cost and parameters of sewage treatment.

		Emission concentration			
	Annual output of sewage	**COD**	**Ammonia nitrogen**	**Total phosphorus**	**TSS**
Investment cost	0.633*	−0.524*	−0.364**	−0.347**	−0.282

*Correlation is significant at the 0.01 level (two-tailed).
**Correlation is significant at the 0.05 level (two-tailed).

which also became the remarkable linear relations by the linearity regression analysis. There were some strong negative correlations (Spearman $r = -0.524$ to -0.347, $p < 0.01$ or <0.05) between the investment cost and the emission concentration as well, which made the investment cost a practical and quantifiable indication to the possibility of pollutant reduction.

There are many industrial enterprises located in a certain WEFZ, and water quality target classification, treatment technology classification and pollutant reduction potential vary across dischargers. In the case of the pesticide industry, this paper provides a classification methodology, as well as a creative way to investigate pollutant reduction potential. We recommend that a similar study covers all the key industries to comprehensively evaluate the feasibility of reducing emission discharges.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Bai, H., Gao, W., Wang, D., Chen, Y., Zhang, H. Z., Zhao, Y. X., Zhao, K. P., Sun, Y. H. & Sun, Z. H. (2019). Allocating total emission pollutant control based on water environmental carrying capacity: model establishment and case study. *Water Policy 21*(6), 1–18.

Cao, H. B. & Saburo, I. (2005). Inter-zonal tradable discharge permit system to control water pollution in Tianjin, China. *Environ. Sci. Technol. 39*, 4692–4699.

Hu, F. P., Hou, J., Luo, J. W. & Hu, W. R. (2010). Analysis of pollution loading and water environmental capacity of Gan River in Nanchang. *Environ. Sci. Technol. 7*, 213–234.

Hu, Q., Li, X. L., Lin, A. J., Qi, W. K., Li, X. J. & Yang, X. J. (2018). Total emission control policy in China. *Environ. Dev. 25*, 126–129.

Jeffrey, M. G. (2007). *Generally Illegal: NPDES General Permits Under the Clean Water Act. The Harvard Environmental Law Review*. Available at: https://www.researchgate.net/publication/228203759.

Jia, Y. L., Cora, S., Aliaksandra, S., Monika, H. W., Anne, G., Tim, A. B. B., Yin, D. Q., Qin, B. Q., Zou, H., Elke, D. & Henner, H. (2019). Toxicological and ecotoxicological evaluation of the water quality in a large and eutrophic freshwater lake of China. *Sci. Total Environ. 667*, 809–820.

Meng, W., Zhang, N., Zhang, Y. & Zheng, B. H. (2007). The study on technique of basin water quality target management I: pollutant total amount control technique in control unit. *Res. Environ. Sci 20*, 1–8.

Ministry of Ecology and Environment of the People's Republic of China (1996). *Integrated Wastewater Discharge Standards (GB8978-1996)*. Available at: http://www.mee.gov.cn/home/ztbd/rdzl/yjcz/bzgf/201106/t20110601_211492.shtml (in Chinese).

Ministry of Ecology and Environment of the People's Republic of China (2002). *Environment Quality Standards for Surface Water (GB3838-2002)*. Available at: http://www.mee.gov.cn/home/ztbd/rdzl/yjsp/fgbz/201110/t20111013_218260.shtml (in Chinese).

Ministry of Ecology and Environment of the People's Republic of China (2015). *Pesticide Industry Policy*. Available at: http://zfs.mee.gov.cn/hjjj/gjfbdjjzcx/hbzhmljyy/201506/t20150611_303375.shtml.

Ministry of Ecology and Environment of the People's Republic of China (2016). *Provisional Regulation on the Administration of Pollutant Discharge Permits*. Available at: http://www.mee.gov.cn/gkml/hbb/bwj/201701/t20170105_394012.htm (in Chinese).

Ministry of Ecology and Environment of the People's Republic of China (2017a). *Stationary Sources List for Pollutant Discharge Permits Management*. Available at: http://www.mee.gov.cn/gkml/hbb/bl/201708/t20170803_419132.htm (in Chinese).
Ministry of Ecology and Environment of the People's Republic of China (2017b). *Effluent Standards of Pollutants for Pesticides Industry (Unpublished)*. Available at: http://www.mee.gov.cn/gkml/hbb/bgth/201702/t20170228_397911.htm (in Chinese).
Ministry of Ecology and Environment of the People's Republic of China (2018a). *Announcement on China's Ecological Environment*. Available at: http://www.mee.gov.cn/home/jrtt_1/201905/t20190529_704841.shtml (in Chinese).
Ministry of Ecology and Environment of the People's Republic of China (2018b). *Measures for the Administration of Pollutant Discharge Permits (Trial Implementation)*. Available at: http://www.mee.gov.cn/gkml/hbb/bl/201801/t20180117_429828.htm (in Chinese).
Ministry of Ecology and Environment of the People's Republic of China and Nanjing Institute of Environmental Science (2017). *Technical Specification for Application and Issuance of Pollutant Permit Pesticide Industry HJ862-2017*. Available at: http://kjs.mee.gov.cn/hjbhbz/bzwb/other/hjbhgc/201710/t20171009_423144.shtml (in Chinese).
Sun, J., Chen, Y., Zhang, Z., Wang, P., Song, X., Wei, X. & Feng, B. (2015). The spatio-temporal variations of surface water quality in China during the 'Eleventh Five-Year Plan'. *Environ. Monit. Assess*. *187*, 1–12.
The State Council (2015). *Action Plan on Water Pollution Prevention*. Available at: http://www.gov.cn/xinwen/2015-04/16/content_2847709.htm (in Chinese).
The State Council (2016). *The Implementation Plan of Pollutant Emission Control Permit System*. Available at: http://www.gov.cn/xinwen/2016-11/21/content_5135579.htm (in Chinese).
Xu, J. P., Hou, S. H., Yao, L. M. & Li, C. Z. (2017). Integrated waste load allocation for river water pollution control under uncertainty: a case study of Tuojiang River, China. *Environ. Sci. Pollut. Res*. doi:10.1007/s11356-017-9275-z.
Yang, J. F., Lei, K., Khu, S., Meng, W. & Qiao, F. (2015). Assessment of water environmental carrying capacity for sustainable development using a coupled system dynamics approach applied to the Tieling of the Liao River Basin, China. *Environ. Earth Sci*. *73*, 1–11.

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