

Raising discharge standards leads to environmental problem shifting in China

Lingyun Zhu, Beibei Liu, Feng Wang and Jun Bi

ABSTRACT

The discharge standards for wastewater treatment plants (WWTPs) in China are trending towards increasingly stringent nutrient removal requirements over recent decades. However, the current paradigm for WWTPs has a singular focus on effluent quality, seldom considering the broader environmental consequences of the treatment required to meet these more stringent limits. In this article, the operating data of 17 WWTPs with three different discharge standards were collected. Using an inventory-type approach, greenhouse gas (GHG) emissions and eutrophication potential (EP) of each plant were calculated. Results show diminishing marginal returns in terms of pollution reduction as the level of treatment increases, taking environmental influences into consideration. Therefore, the strictest standards are not the most cost-effective ones in current China. Rather than focusing strictly on point source dischargers and requiring advanced treatments, regulatory agencies should reconsider their water quality protection strategies.

Key words | discharge standards, eutrophication, greenhouse gas, life-cycle inventory

Lingyun Zhu

Beibei Liu

Feng Wang

Jun Bi (corresponding author)

State Key Laboratory of Pollution Control &

Resource Reuse,

School of the Environment,

Nanjing University,

Nanjing 210046,

China

E-mail: jbi@nju.edu.cn

INTRODUCTION

Over recent decades, the discharge standards for wastewater treatment plants (WWTPs) in China have trended towards increasingly stringent nutrient removal requirements to cope with the cumulatively serious water pollution. For example, Circular No. 110, issued by State Environmental Protection Administration (SEPA) in 2005, requires that all plants that discharge into important river basins and enclosed water bodies shall be required to meet Class 1A standards (this standard requires expensive tertiary treatment for the reduction of two nutrients, nitrogen and phosphorus. The standard also mandates extremely low levels for biological oxygen demand and suspended solids (10 mg/l)) (Browder *et al.* 2008).

Considering the highly degraded water bodies in China, strict discharge standards could improve water quality and benefit the water sustainability. However, raising the discharge standards may have to compromise with the consequences such as resources consumption (e.g. energy, chemicals, and infrastructure), other environmental burdens, as well as the economic performance of WWTP. Given the long-term needs for ecological sustainability, the goals for wastewater treatment systems need to move beyond the protection of human health and surface waters

to also minimizing the loss of resources, reducing the use of energy and water, reducing waste generation, and enabling the recycling of nutrients (Lundin *et al.* 1999). Hence, there is a need for a detailed life cycle assessment (LCA) of a range of wastewater treatment options, which also includes the broader environmental consequences and impacts of their construction and operation.

LCA has been widely applied to evaluate the environmental performance of WWTPs (IPCC 1997; Beavis & Lundie 2003; Dixon *et al.* 2003; Lassaux *et al.* 2006; Ortiz *et al.* 2007; Wenzel *et al.* 2008; Lim & Park 2009). Some of these have examined competing technology configuration, and consistently identified the strong influence of energy consumption on the overall environment impact (Emmerson *et al.* 1995; Gallego *et al.* 2008). Other studies have focused more upon small and decentralized wastewater systems (Nogueira *et al.* 2007) and the toxicity-related impacts, caused by the heavy metals as well as the pharmaceutical and personal care products, both in water (Larsen *et al.* 2010) and in the sludge (Hospido *et al.* 2005; Hospido *et al.* 2010).

However up till now, only a few studies have examined the environmental impacts associated with different nitrogen

and phosphorus removal standards (Oleszkiewicz & Barnard 2006) and found contradictory results. While WWTPs with advanced treatments, which are utilized to meet high water quality standards, seem to have significant impact on global warming (Beavis & Lundie 2003), some studies found that increased levels of nutrient removal are generally considered highly beneficial (Gaterell *et al.* 2005, Lassaux *et al.* 2006), while Foley *et al.* (2010) found that primary treatment caused large CH₄ emissions in the receiving environment, and nitrogen removal leads to increased risk of N₂O emissions, especially when the discharge standard of total nitrogen is less than 5 mg N L⁻¹. Rodriguez-Garcia *et al.* (2011) have used a streamlined LCA with eutrophication potential (EP), greenhouse gas (GHG) and operational costs to evaluate the performance of 24 WWTPs; the results show that organic matter removal plants were found to be less costly both in environmental and economic terms; more demanding typologies such as reuse plants showed a trade-off between lower EP and higher cost and GHG.

The main objective of this paper is to environmentally assess the operation of 17 WWTPs in China, which are divided into three typologies by final discharge standards in China, and to testify whether a shift towards upgraded wastewater treatment is justified on the basis of whole-of-plant life cycle consideration.

METHODOLOGY

LCA is a well-established procedure quantifying inputs and outputs as well as the potential impacts associated with a product throughout its whole life cycle; in order to environmentally assess the operation of surveyed WWTPs, a streamlined methodology based on environmental indicators is presented. Firstly, WWTPs were classified into three typologies according to their final discharge standard; secondly, the most appropriate function unit, which assures that the conclusions derived from the analysis are consistent was selected; thirdly, the system boundary was clarified due to the fact that a different system boundary will inevitably affect results; fourthly, inventory data were collected and calculations carried out to indicate the environmental load of the WWTPs.

Case description

Circular No. 110, issued by SEPA in 2005, provides guidance on the application scopes of each Discharge Standard of Pollutants for Municipal WWTP (see Table 1).

Table 1 | Highest discharge concentration of water pollutants from WWTPs (daily average)

Basic parameter (mg/L)		Class IA	Class IB	Class II
Chemical oxygen demand (COD)		50	60	100
Biochemical oxygen demand (BOD ₅)		10	20	30
Suspended solids (SS)		10	20	30
Total nitrogen (TN)		5	20	–
Total phosphorus (TP)	Built before 2005/12/31	1	1.5	3
	Built after 2006/01/01	0.5	1	3

It stipulated that: (1) those who discharge into key river basins and enclosed water bodies should meet Class 1A standards. Key river basins include, the Hai, Huai, Huang, and Liao basins; (2) those who discharge into water bodies with the water quality of Class II and Class III should meet Class 1B standards; (3) others should meet Class II standards, and gradually increase control requirements based on local conditions.

Moreover, according to the 12th Five Years Plan of WWTP, the WWTP's construction should be centered on medium and small-size plants. In our study, a representative sample of 17 medium and small-sized plants with capacities of less than 50,000 m³/day, with different nutrient removal efficiency were selected nationwide.

Functional unit

Potential functional units could be (1) the volume (m³) of treated water for a certain period of time (Hospido *et al.* 2004), (2) the treatment of the wastewater generated from one person equivalent (pe) (Tillman *et al.* 1998), and (3) the removal of pollutants from the wastewater when the treated effluent is discharged to natural watercourses, according to the main purpose of WWTPs (Rodriguez-Garcia *et al.* 2011). According to Rodriguez-Garcia *et al.* (2011), the removal of both nutrients and organic matter (expressed in terms of kg PO₄³⁻ eq. removed (according to the CML environmental impact assessment method, all substances that could potentially cause eutrophication are related to the reference or equivalence substance (PO₄³⁻ eq) in order to establish the potential impact of a product/process referred to this impact category.) proved to better reflect the function of a WWTP when focus is on EP and is considered a more useful FU for comparative studies. Hence this FU is selected in our study, for it highlights the differences between the environmental and economic

performance of reducing the potential EP associated with the effluent for all the WWTPs.

System boundary

The operation of the facility is considered far more relevant in WWTP environmental analysis (Lundie *et al.* 2004; Lassaux *et al.* 2006), and ‘although environmental burdens from investing in the system are in no way negligible in comparison with those of their operation, they vary far less between alternatives from operation’ (Tillman *et al.* 1998). Therefore, the analysis was only limited to the operation stage of the WWTPs and no consideration was given to the infrastructure or dismantling of buildings or equipment, and the water distribution system.

The system includes the operation of primary and secondary treatments; final discharge of the treated effluent; the sludge treatment and its final disposal; as well as the logistics involved in the whole system. Due to the lack of data, we assumed that effluent is disposed to an environmentally sensitive estuarine environment, and sludge is mechanically dewatered, with the biosolids being transported for further disposal or reuse at a fixed distance (20 km) from the plant. All stages include the consumption of energy and materials, their production and transportation upstream, as well as the transport and treatment downstream of the sludge and other waste generated in the WWTPs.

CML 2 baseline 2000 developed by Leiden University was used to assess the environmental impact of the system (Guinee 2002), and as environmental impacts, EP and GHG were considered. The EP has been considered the most relevant impact category in the majority of published LCAs on WWTPs (Roeleveld *et al.* 1997; Hospido *et al.* 2004). GHG emission is not among the most relevant impact categories for WWTPs (Larsen *et al.* 2007). However, it is significant from a political and social point of view, and it can also be indicative of other energy dependent impacts such as acidification (Rodriguez-Garcia *et al.* 2011). As a consequence, it was chosen as an environmental indicator and quantified in accordance with the IPCC guidelines. Using the ‘mid-point’ assessment methodologies, potential life cycle impacts are quantified, in terms of a reference compound (kg CO₂-eq and per kg PO₄³⁻).

Life cycle inventory

The data sources used to perform a life cycle inventory includes: (a) site specific operating data for year 2007 collected from a survey conducted by the Ministry of

Construction and provided by the local authority in charge of regional wastewater treatment in China (see Table 2); and (b) data from the literature and databases.

1. Electricity. The process selected includes electricity production and distributed to users. The primary fossil energy consumption and GHG emissions for the 2007 Chinese electricity mix are 3.247 MJ/MJ and 297.688 gCO₂-e/MJ, respectively, which is based on the compositions of fuel sources for Chinese electricity generation in 2007 (Ou *et al.*).
2. Chemicals. Polyelectrolyte for sludge conditioning, hypochlorite for cleaning purposes, and Iron III for P removal, the main chemicals used during wastewater treatment, were referenced to acrylonitrile (IDEMAT 2001), sodium hypochlorite 15%, Iron III 40% (Ecoinvent 1996), respectively.
3. Logistics of solid wastes, chemicals and sludge: trucks (1,836 kJ/t*km) were selected as standard transport for chemicals, waste and sludge (Owen 1989).
4. Fertilizer avoided. The application of sludge to soil as fertilizer reduces the need for the use of synthetic fertilizers containing nitrogen and phosphorus, which results in an environmental benefit if the content of heavy metals content in the sludge is kept within admissible values. The substitutability was assumed to be 70% for phosphorus and 50% for nitrogen (Bengtsson & Molander 1997). Production of these fertilizers should be included within the system boundaries and the associated data are obtained from Murray *et al.* (2008).
5. GHG emissions. CO₂ emissions from the biogas combustion from the anaerobic digestion of sludge were not taken into account since it is considered to be biogenic because it belongs to the short CO₂ cycle and doesn't contribute to the climate change according to IPCC guidelines (Rodriguez-Garcia *et al.* 2011). Methane emissions (if conditions for anaerobic degradation take place) and N₂O emissions derived from the application of sludge on agricultural land are estimated by means of emission factors from the literature (Lundin *et al.* 1999).

RESULTS

Eutrophication potential

The EP has been considered the most relevant impact category in the majority of published LCAs on WWTPs (Roeleveld *et al.* 1997; Hospido *et al.* 2004). For this

Table 2 | Life cycle inventory of 17 WWTPs classified into three typologies (m³)

Level		Influent			Effluent			Electricity KWh	Chemical			Sludge		
Discharge standard		COD (g)	TN (g)	TP (g)	COD (g)	TN (g)	TP (g)		Polyelectrolyte (g)	Hypochlorite (g)	FeCl ₃ (g)	DS (g)	N (g)	P ₂ O ₅ (g)
Class II	WWTP1	358	25.4	3.27	39	21.1	0.875	0.19	5.04	2.71	14.37	530.35	16.33	7.74
	WWTP2	498.1	55.4	5.1	41.3	26.4	0.62	0.49	4.87	3.57	–	135.57	4.04	1.97
	WWTP3	438	38.2	5	46.8	25.3	2.2	0.32	5.14	2.24	4.2	171.43	5.11	2.49
	WWTP4	349.1	48.1	4.6	36.7	37.9	3	0.25	4.86	3.29	2.4	140.02	4.13	2.03
	WWTP5	559	22.4	5	35.9	10.7	2	0.282	5.61	2.93	9	145.35	4.48	2.12
Class 1B	WWTP1	240	26	4	52	8	1.4	0.253	5.03	3.61	11.7	493.15	14.01	6.36
	WWTP2	186.5	44.9	3.3	25.6	17	1.34	0.435	4.64	1.34	8.82	217.81	6.82	2.88
	WWTP5	600	35	10	80	15	3	0.3	5.03	1.58	10.5	136.99	4.08	1.99
	WWTP4	236	21.96	2.57	50	11.69	0.61	0.2	4.88	2.70	–	72.1	2.15	1.05
Class 1A	WWTP1	307	38	4.4	22	7.2	0.2	0.36	4.86	3.65	9.6	80.93	2.49	1.18
	WWTP2	400	80	2	30	15	0.5	0.36	4.94	4.39	31.5	236.86	7.06	3.43
	WWTP3	389.4	31.2	4.3	40.2	13.7	0.25	0.41	5.1	3.03	30.375	787.5	23.47	11.42
	WWTP4	320	30	5	48	8	0.6	0.48	5.19	3.84	26.4	118.36	3.36	1.53
	WWTP5	850	35	12	85	13	1	1.2	4.85	5.39	66	193.74	57.73	28.09
	WWTP6	311.33	36.88	3.48	41.17	14.63	0.81	0.2	4.9	2.88	16.02	125.86	3.75	1.82
	WWTP7	400	40	3	100	15	1	0.4	5.24	3.39	12	383.56	11.43	5.56
	WWTP8	500	2	0.54	120	1.6	0.4	0.35	5.02	5.39	1.05	625	19.56	8.25

All data presented are daily averages.

reason, EP indicators was selected as the main environmental sustainability indicators and quantified by means of the CML method, which converts all eutrophying substances to phosphate equivalent.

In this category, the main impact was attributed to the discharge of the treated effluent. As can be seen in Figure 1, the discharge of TN and TP and, and to a lower extent, COD in the treated water were the most relevant factors contributing to eutrophication, which is consistent with the results of Roeleveld *et al.* (1997) and Hospido *et al.* (2004). Regardless of the technology considered, treatment percentages for COD were greater than 75% in all WWTPs and often exceeded 85%. Therefore, the improvement actions proposed can be fixed on considering nitrogen and/or phosphate removal in the design and operation of WWTPs.

Overall, it was evident that from an EP perspective, Class 1A appeared to be the most favorable option. However, the EP show a relatively larger decrease (0.25) when moving from Class II to Class IB than from Class IB to Class IA (a decrease of 0.15). In other words, the credit of EP effect from discharge standard improvement is more obvious from Class II to Class IB than from Class IB to Class IA.

Results also show that for WWTPs with high influent load and low nutrient removal, the EU tend to be higher such as in the WWTP II-4, which presents a noticeably high impact which is not only due to its low nutrient removal efficiency (21% of TP and 35% of TN), but also because of its higher influent loads (48.1 g/m³ of TP and 4.6 g/m³ of TN). Moreover, it is also necessary to indicate that the treatment of low load water (WWTP 1A-8)(2 g/m³

of TN and 0.54 g/m³ of TP) has particular difficulties in nutrient removal and hence relatively high EP effect, although its influent nutrient load is rather low.

A noticeable variation was observed between WWTP II-2,5 and WWTP II-1,3,4, even though they are all required to accomplish Class II standard, which could be explained by adoption of more efficient nutrient-removal technology in WWTP II-2,5, such as A₂O etc.

WWTPs required to accomplish Class IA also show large variation between Class IA-2,3,4,5 and other WWTPs. Although WWTP Class 1A-2 and 1A-5 present high influent load, their relatively high removal yields give them lower EP impact (TP 81%/ TN 78% for WWTP 1A-2 and TP 63%/ TN 92% for WWTP 1A-5).

Global warming potential

At present, most of the sludge generated from medium- and small-sized WWTPs has been directed to landfill in China; only a small portion has been reused in agriculture. Therefore, the landfill scenario of biosolids end-use is conducted in our study; a rough calculation of the use of sludge in agricultural reuse which avoided GHG emissions was also conducted. The approximate margin for predicted GHG emissions due to avoided fertilizer use was -6-13% of the total emissions (or about 0.03 tonnes CO₂-e/ML treated).

Moreover, for heavy metals, which are a key factor determining the final destination of biosolids, the quantity of heavy metals in biosolids was fixed by the quantity of heavy metals in the influent raw wastewater. Due to the dearth of data

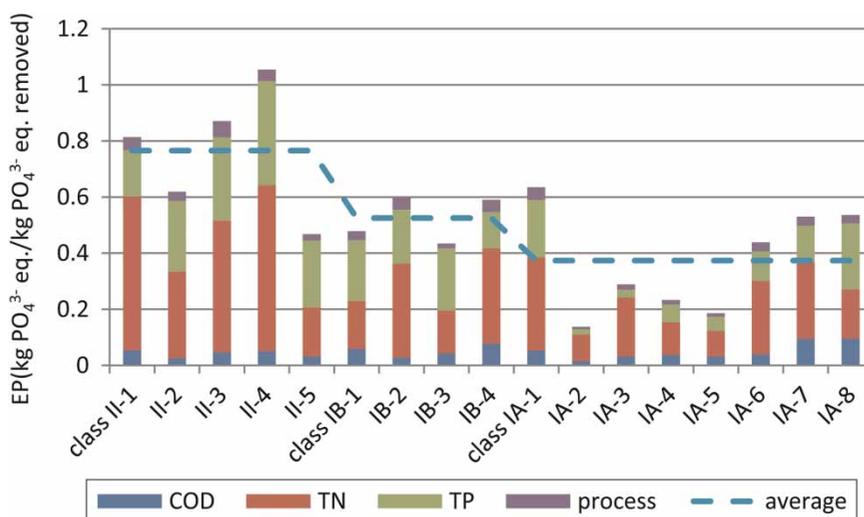


Figure 1 | Eutrophication potential of the WWTPs (the full colour version of this figure is available in the online version of this paper, at <http://www.iwaponline.com/wst/toc.htm>).

related to heavy metals, we presume that they are far below the demanding values of the legislation proposed.

GHG emissions of the 17 WWTPs are presented in Figure 2. The legend 'chemical' means GHG contributed by chemical production and transportation to WWTP; 'bio-solid' is representative of GHG originating from transport biosolid off site and landfill disposal. Direct greenhouse gas emissions were directly from the process units of the treatment plants, the effluent receiving environment and the biosolids receiving environment.

In total, GHG emissions ranged from 8.1 to 21.9 kg CO₂eq. per kg PO₄³⁻eq. removed. From a direct GHG emissions perspective, Class 1B appeared to be the most favorable option. The GHG is slightly decreased from Class II to IB and increased greatly by going from Class IB to Class IA, which is in consist with the study conducted by Foley *et al.* (2010) and could be explained by the fact that Class II might cause larger CH₄ emissions in the receiving environment whilst Class IA and higher nitrogen removal leads to the risk of increased N₂O emissions.

The results also suggest that GHG emissions are dominated by imported power followed by treatment process emission. The proportion of total GHG emissions from power varied from WWTP IA-8 of 35% to WWTP II-5 of 59%, in this sense, measures attaining remarkable savings in electrical consumption, such as online control of the aeration systems, should be practiced as an effective way to improve the overall environmental performance of a WWTP.

Not surprisingly, WWTPs accomplishing Class IA present higher impacts in GHG, which could be explained by

the increasing complexity of technology applied, and accordingly larger consumptions of electricity and chemicals. The energy consuming equipment, especially the aerobic reactor, accounts for the majority of the electricity consumed.

The higher impact of the WWTP 1A-8 can be attributed to its low influent load (WWTP 1A-8)(2 g/m³ of TN and 0.54 g/m³ of TP), which has particular difficulties in nutrient removal and hence relatively high EP effect, although its influent load is rather low. WWTP 1A-1 shows high impact which could partially be attributed to its higher average nutrient concentration in the influent, which requires larger aeration periods. Another factor would be its relatively small size (6,000 m³/day), since small plants might be more power-consuming, on a relative basis, due to economies of scale.

Moreover, as mentioned above, electricity consumption is a key element in the overall environmental performance of a WWTP. A relationship between energy use and the CF of each WWTP is assumed; this is likely in a country such as China which is heavily reliant on fossil energy.

The proportion of total GHG emissions from power varied from 35 to 59%, whilst previous studies have reported lower GHG productions compared to the values obtained in the present study. For instance, according to Gallego *et al.* (2008), if we were to ignore the emissions associated with the processes that are required to produce the electricity we consume, we would then be ignoring around 30% of CO₂ emissions and the associated global warming impact. This could be explained by the fact that the electricity production in China is dominated by the use of fossil fuels.

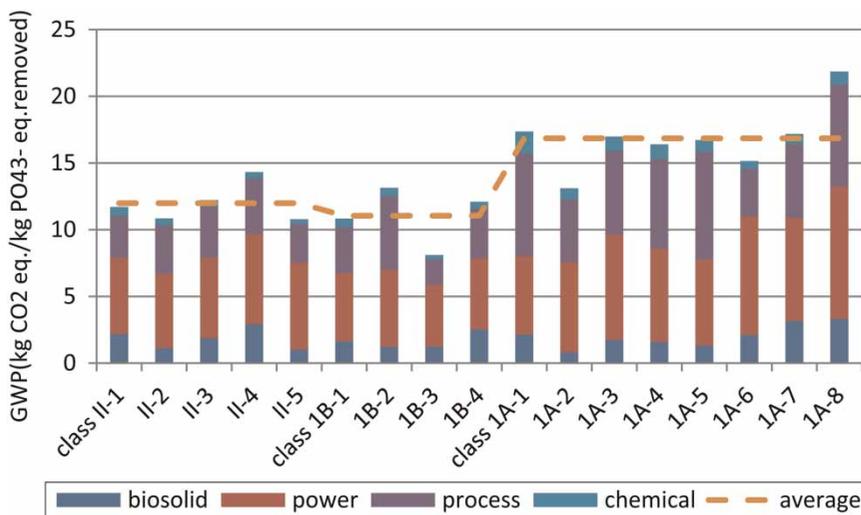


Figure 2 | Global warming potential of the WWTPs in the landfill scenario (the full colour version of this figure is available in the online version of this paper, at <http://www.iwaponline.com/wst/toc.htm>).

On the other hand, according to Wang (2004), energy consumption contributes about 30–40% of the operational costs of WWTPs in China. Therefore, its reduction is not only an environmental challenge but also an economic challenge.

Concerning the fact that sewage sludge management is a growing challenge for mechanical wastewater treatment facilities around the world, the best available technology (BAT) economically achievable as concerns energy consumption and biogas and residues' best utilisation in present China is also a prominent issue. Further analysis required more detailed data information and is expected to be studied in the subsequent study, but some existing study might give us some meaningful consideration now. For instance, Murray *et al.* (2008) conducted a detailed study to determine the optimal sludge handling options for the city of Chengdu in China. A variety of ways for utilizing the resources embodied in sludge during both the treatment and end-use phases of sludge handling were presented; according to their results, anaerobic digestion followed by land application takes advantage of both the embodied energy, to make electricity, and nutrients, to enhance agriculture.

CONCLUSIONS

Standards are a key tool in converting policy goals into action. Every society aspires to have a perfect environment with high public health standards and unpolluted water resources.

Increasingly stringent nutrient removal requirements and consequently higher resource consumption and elevated environmental emissions have raised the question of how policy directives and environmental regulations from government can best serve the complex (and potentially competing aims) of minimizing local environmental impacts, whilst also improving sustainability on the widest possible front. Based on operating data collected from 17 WWTPs in China, the aim of this paper is to assess whether the general increase in consumption of non-renewable resources and environmentally-relevant emissions caused by higher wastewater discharge standard is justified. Our results have shown diminishing marginal returns in terms of pollution reduction as the level of treatment increases; it is obvious that moving from Class IB to Class IA requires much more cost than that for moving from Class II to Class IB, whilst environmental performance increases less than expected (EP shows a relatively more huge decrease when

moving from Class II to Class IB than from Class IB to Class IA and GHG even slightly decreased from Class II to IB and increased greatly by going from Class IB to Class IA).

According to our findings, the main factors that determine the environmental performance of the WWTPs includes: discharge of COD, TP and TN, especially TP and TN; electricity use and discharge of sludge. As to eutrophication potential, the improvement actions proposed can be fixed on considering nitrogen and/or phosphate removal in the design and operation of WWTPs. Regarding global warming potential, special attention should be paid to electrical consumption; measures to attain remarkable savings in the electrical consumption should be promoted.

The current study expands the literature on WWTP performance by investigating environmental performance of WWTPs associated with increasing discharge standards; however, further work is needed.

Firstly, due to lack of detailed information concerning residues characteristics, we have only made a superficial discussion of BAT as concerns energy consumption and biogas and residues' best utilisation, further work is expected to be studied in subsequent study.

Secondly, all operational data were collected from small scale plants under 50,000 ton/d. Considering the plant scale, maintenance level and stability of operation, etc., data from large scale plants should be collected in the next phase of study for further analysis.

This study helps inform water authorities and regulatory agencies for future policy and funding strategies. A shift towards upgraded wastewater treatment should be justified on the basis of whole-of-plant life cycle consideration, and using a LCA perspective may significantly change the results of WWTP performance comparison.

ACKNOWLEDGEMENTS

This work has been partially financed by the National Science Foundation of Jiangsu Province. We acknowledge the program (Reference-BK20130572) for its financial support.

REFERENCES

- Beavis, P. C. & Lundie, S. 2003 Integrated environmental assessment of tertiary and residual treatment-lca in the wastewater industry. *Water Science and Technology* **47** (7–8), 109–116.

- Bengtsson, M. & Molander, S. (eds) 1997 *Life Cycle Assessment of Wastewater Systems: Case Studies of Conventional Treatment, Urine Sorting and Liquid Composting in Three Swedish Municipalities*. Chalmers University of Technology.
- Browder, S. X., Yoonhee, K., Lixin, G., Mingyun, F. & Ehrhardt, D. 2008 Improving the performance of China's urban water utilities.
- Dixon, A., Simon, M. & Burkitt, T. 2003 Assessing the environmental impact of two options for small-scale wastewater treatment: comparing a reedbed and an aerated biological filter using a life cycle approach. *Ecological Engineering* **20** (4), 297–308.
- Ecoinvent 1996 Database. Switzerland: Swiss Federal Environmental Protection Agency.
- Emmerson, R. H. C., Morse, G. K., Lester, J. N. & Edge, D. R. 1995 The life-cycle analysis of small-scale sewage-treatment processes. *Water and Environment Journal* **9** (3), 317–325.
- Foley, J., De Haas, D., Hartley, K. & Lant, P. 2010 Comprehensive life cycle inventories of alternative wastewater treatment systems. *Water Research* **44** (5), 1654–1666.
- Gallego, A., Hospido, A., Moreira, M. T. & Feijoo, G. 2008 Environmental performance of wastewater treatment plants for small populations. *Resources, Conservation and Recycling* **52** (6), 931–940.
- Gaterell, M. R., Griffin, P. & Lester, J. N. 2005 Evaluation of environmental burdens associated with sewage treatment processes using life cycle assessment techniques. *Environmental Technology* **26** (3), 231–250.
- Guinee, J. 2002 Handbook on life cycle assessment operational guide to the iso standards. *International Journal of Life Cycle Assessment* **7** (5), 311–313.
- Hospido, A., Carballa, M., Moreira, M., Omil, F., Lema, J. M. & Feijoo, G. 2010 Environmental assessment of anaerobically digested sludge reuse in agriculture: Potential impacts of emerging micropollutants. *Water Research* **44** (10), 3225–3233.
- Hospido, A., Moreira, M., Fernández-Couto, M. & Feijoo, G. 2004 Environmental performance of a municipal wastewater treatment plant. *International Journal of Life Cycle Assessment* **9** (4), 261–271.
- Hospido, A., Moreira, T., Martín, M., Rigola, M. & Feijoo, G. 2005 Environmental evaluation of different treatment processes for sludge from urban wastewater treatments: Anaerobic digestion versus thermal processes (10 pp). *The International Journal of Life Cycle Assessment* **10** (5), 336–345.
- IDEMAT 2001 Inventory data of materials. Faculty of Design, Engineering and Production, Delft University of Technology, Delft, The Netherlands.
- IPCC 1997 Module 4-agriculture.
- Larsen, H. F., Hansen, P. A. & Boyer-Souchet, F. 2010 Decision support guideline based on ICA and cost/efficiency assessment. Technical University of Denmark, Lyngby.
- Larsen, H. F., Hauschild, M. Z., Wenzel, H. & Almemark, M. 2007 Homogeneous ICA methodology agreed by Neptune and Innowatch. Technical University of Denmark, Lyngby.
- Lassaux, S., Renzoni, R. & Germain, A. 2006 Life cycle assessment of water: from the pumping station to the wastewater treatment plant. *International Journal of Life Cycle Assessment* **12** (2), 118–126.
- Lim, S.-R. & Park, J. M. 2009 Environmental impact minimization of a total wastewater treatment network system from a life cycle perspective. *Journal of Environmental Management* **90** (3), 1454–1462.
- Lundie, S., Peters, G. M. & Beavis, P. C. 2004 Life cycle assessment for sustainable metropolitan water systems planning. *Environmental Science and Technology* **38** (13), 3465–3473.
- Lundin, M., Bengtsson, M. & Molander, S. 1999 Life cycle assessment of wastewater systems: Influence of system boundaries and scale on calculated environmental loads. *Environmental Science and Technology* **34** (1), 180–186.
- Murray, A., Horvath, A. & Nelson, K. L. 2008 Hybrid life-cycle environmental and cost inventory of sewage sludge treatment and end-use scenarios: A case study from china. *Environmental Science and Technology* **42** (9), 3163–3169.
- Nogueira, R. B., Machado, A., Salas, J., Martel, G. & Vera, L. 2007 Economic and environmental assessment of small and decentralized wastewater treatment systems.
- Oleszkiewicz, J. A. & Barnard, J. L. 2006 Nutrient removal technology in North America and the European Union: a review. *Water Quality Research Journal of Canada* **41** (4), 449–462.
- Ortiz, M., Raluy, R. G. & Serra, L. 2007 Life cycle assessment of water treatment technologies: wastewater and water-reuse in a small town. *Desalination* **204** (1–3), 121–131.
- Ou, X., Xiaoyu, Y. & Zhang, X. Life-cycle energy consumption and greenhouse gas emissions for electricity generation and supply in china. *Applied Energy* **88** (1), 289–297.
- Owen, K. ed. 1989 *Wastewater Treatment Energy Consumption and Energy Efficiency (in Chinese)*. Beijing Energy Publisher of Energy Research Institute, NDRC.
- Rodriguez-Garcia, G., Molinos-Senante, M., Hospido, A., Hernandez-Sancho, F., Moreira, M. T. & Feijoo, G. 2011 Environmental and economic profile of six typologies of wastewater treatment plants. *Water Research* **45** (18), 5997–6010.
- Roeleveld, P. J., Klapwijk, A., Eggels, P. G., Rulkens, W. H. & Van Starckenburg, W. 1997 Sustainability of municipal waste water treatment. *Water Science and Technology* **35** (10), 221–228.
- Tillman, A.-M., Svingby, M. & Lundstrom, H. 1998 Life cycle assessment of municipal waste water systems. *The International Journal of Life Cycle Assessment* **3** (3), 145–157.
- Wang, X. 2004 The study on the development and benchmarking of wastewater treatment industry in china. Graduate thesis. Tsinghua University.
- Wenzel, H., Larsen, H. F., Clauson-Kaas, J., Hibye, L. & Jacobsen, B. N. 2008 Weighing environmental advantages and disadvantages of advanced wastewater treatment of micro-pollutants using environmental life cycle assessment. *Water Science and Technology* **57** (1), 27.