Evaluation of rural wastewater treatment processes in a county of eastern China†

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With the rapid urbanization and industrialization in China, wastewater treatment in rural areas has become an increasing national concern. The selection of appropriate treatment processes closely based on the actual local status is crucial for the prevention of water quality deterioration in rural areas of China. This study presents a full year survey on the performances of various rural wastewater treatment processes at a county level in eastern China including seven three-chamber septic tanks (ST), five micro-power biological facilities (MP), seven constructed wetlands (CW), three stabilization ponds (SP) and five centralized activated sludge treatment plants (AS). It was found that although ST could remove a notable portion of total suspended solids (TSS) and chemical oxygen demand (COD_{Cr}), it was ineffective in reducing nutrients and pathogens. Reliability and stability analyses showed that the centralized AS and decentralized CW processes outperformed the SP and MP processes. There were obvious discrepancies between the mean design concentrations, which ensure that 95% of the effluents meet the discharge standards, and the actual effluent concentrations determined for each process. The expected compliance with the tentatively adopted second-grade discharge standards (GB 18918-2002) was unsatisfactory for most of the water quality parameters examined, indicating an urgent need to design more practical discharge standards for decentralized treatment processes. Based on an overall assessment of reliability, stability and cost-effectiveness, the centralized AS was suitable for densely populated towns while the decentralized CW was suitable for sparsely populated villages.

1. Introduction

Although the economic and social developments have been impressive in the past decades, more than 90% of villages in China lack drainage channels and wastewater treatment facilities. Rural wastewaters from domestic and industrial sources

have polluted most of the surface waters and are also posing a serious threat to groundwater. According to the report *Chinese Practice and Exploration of Secure Supply Management of Rural Drinking Water*, published by the Ministry of Water Resources of China, the quality of water sources is worsening and the drinking water of more than 100 million people in the rural areas of China is more or less polluted.¹ Sufficient and effective wastewater treatment is crucial to prevent further pollution of the aquatic environment, which has emerged as an increasing public concern recently.

Decentralized treatment modes are being preferentially adopted for the areas where wastewater collection is difficult given to the dispersed layout, small scale and complicated

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Environmental impact

Sufficient and effective treatment of rural wastewater is crucial to prevent further deterioration of water quality, which has emerged as an increasing public concern in China. Although the planning and construction of wastewater treatment facilities of various types and capacities have been promoted rapidly in many developed rural regions of China in recent years, continuous routine maintenance and monitoring are usually unaffordable due to the deficiencies in local budget and trained staff. This study presents a full year survey on the performances of various rural wastewater treatment processes at a county level. The results are expected to help select the most feasible processes and guide the design of practical discharge standards for rural wastewater treatment in China and other developing countries as well.

geographic situation.² Continued efforts have been made to develop and integrate appropriate decentralized treatment processes for rural wastewater treatment including septic tank (ST), stabilization pond (SP), constructed wetland (CW) and aerobic biological treatment unit.^{3–6} In the United States decentralized systems have been responsible for treating approximately 25% of the wastewater generated and are no longer considered as a temporary solution to be replaced eventually by centralized treatment systems.⁷ In Finland, approximately one million residents and over one million vacationers are serviced with decentralized treatment processes. However, the planning and construction of rural wastewater treatment facilities have just started and are being promoted rapidly in the developed regions of China (*e.g.* the eastern region) which cover various treatment processes and treatment capacities. Because of a large uncertainty underlying the design and operation of these treatment facilities, failure risks and serious performance fluctuations are often inevitable, and thus may entail detrimental environmental impacts. Due to the deficiencies in budget and trained operators, continuous routine monitoring is usually unaffordable in most rural areas. This necessitates a comprehensive evaluation of the performances of different treatment processes to guide future policy making for rural wastewater treatment. On the other hand, at present China lacks the discharge standards for decentralized wastewater treatment facilities, thus evaluation of the actual performance of available treatment processes helps to design more applicable discharge standards.

Some researchers^{8–10} have proposed using reliability to describe the performance of a wastewater treatment process, specified as the expected percentage of time at which the effluent concentrations meet the designated discharge standards. A wastewater treatment process is considered reliable if its effluent meets the discharge standards during most of the time. On the contrary, if the standards are usually violated, the process is considered unreliable. Oliveira and von Sperling¹¹ investigated the reliability of six different wastewater treatment processes in Brazil and pointed out that few plants had a reliable performance considering the compliance with the adopted discharge standards. Oakley *et al.*¹² reported that the low reliability of onsite wastewater treatment processes with respect to nitrogen removal was due to the inherent variability of decentralized raw wastewater characteristics and the lack of appropriate operational control after comparing 20 onsite wastewater treatment facilities with 15 centralized wastewater treatment plants (WWTPs).

The stability of a wastewater treatment process is defined as a measure of the variation from the annual mean concentrations. As the influent loading, environmental conditions, and operational parameters (dissolved oxygen, sludge retention time, *etc.*) all have a direct or indirect impact on the performance of a wastewater treatment facility, Niku *et al.*¹³ proposed using descriptive statistics, *i.e.*, the mean and range concentrations *vs.* the standard deviation to determine the stability cutoff point. This cutoff point represents a standard deviation value below which the performance of a facility is considered stable. The investment of construction and the costs of operation and maintenance, which are the two most restrictive factors in rural areas, are significantly affected by the desired reliability. In combination with cost analysis, the comparison of reliability and stability among different wastewater treatment processes tends

to highlight the most feasible processes for the rural areas of China.

This study continuously monitored the effluent qualities of five types of commonly-used wastewater treatment processes in a representative developed county in eastern China over a period of one year. The effluent qualities of a primary treatment process (*i.e.*, ST) in four different seasons were analyzed. Moreover, the performances of three types of decentralized secondary treatment processes, including micro-power (MP) biological contact oxidation, CW, and SP processes and the centralized activated sludge (AS) process, were comparatively evaluated through the reliability and stability analyses. Finally, the costs of construction, operation and maintenance for different processes were assessed based on a field survey. This study is expected to help select the most feasible processes and guide the design of applicable discharge standards for rural wastewater treatment in China and other developing countries as well.

2. Methods

2.1 Characteristics of the treatment processes evaluated

This investigation was conducted over a period of 12 months between June 2010 and May 2011 at a county level in Zhejiang Province, China. Five types of representative wastewater processes were chosen including decentralized ST, MP, CW, SP processes and the centralized AS process. The decentralized CW, SP and MP processes are generally built in sparse villages which collect the effluent of onsite ST through simple channels while the centralized AS process is constructed in densely populated towns. The location of the studied area and representative photographs of the four secondary treatment processes are shown in Fig. 1 and the detailed descriptions about these treatment facilities are summarized in Table 1. The decentralized CW, SP and MP processes had a treatment capacity ranging from 200 to 1200 population equivalent (PE), while the centralized AS process had a much larger treatment capacity of 8000–60 000 PE.

2.2 Sampling and analytical methods

Because of the discontinuous nature of the decentralized wastewater influents, a composite sampling method was adopted that spread over a certain period of time to eliminate the high variation in influent load. The samples were collected three times on a sampling day (*i.e.*, in the morning, noon and evening) and then mixed together. In each month, the sampling was conducted on three separate days. Note that during the sampling campaigns, no rainfall events were recorded and the hydraulic loading rates of the treatment facilities remained nearly constant. The collected samples were preserved at 4 °C in portable ice boxes during transportation to the laboratory and were analyzed within 2 days. The analyses of BOD₅, TSS and fecal coliform (FC) were carried out following the Standard Methods for the Examination of Water and Wastewater.¹⁴ The concentrations of chemical oxygen demand (COD_{Cr}), ammonia nitrogen (NH₃-N), and total phosphorus (TP) were analyzed according to Hach methods 8000, 10031 and 8190 on a UV-Vis spectrophotometer (DR5000, Hach, Loveland, CO), respectively. There were 81 effluent samples collected monthly during 12 months, giving a total of 972 samples.

Fig. 1 Location of sampling sites and photos of four secondary treatment processes evaluated.

2.3 Reliability and stability analysis methods

The reliability analysis method proposed by Niku *et al.*⁸ was adopted to evaluate the performance of different processes. The coefficient of reliability relates the values of the mean design concentrations to the discharge standards to be achieved, on a probability basis:

$$m_x = (\text{COR})X_s \quad (1)$$

where m_x is the mean effluent concentration (design or operational values) X_s is the effluent concentration as specified by the discharge standards and COR represents the coefficient of reliability.

The value of COR is calculated as follows:

$$\text{COR} = \sqrt{(\text{CV})^2 + 1} \times \exp \left\{ -Z_{1-\alpha} \sqrt{\ln[(\text{CV})^2 + 1]} \right\} \quad (2)$$

where CV is the coefficient of variation; α is the probability of failure to meet the discharge standards; and $Z_{1-\alpha}$ is the standardized normal variate (obtained from the standard normal variate tables).

Eqn (3) is used to estimate the probability of compliance with the discharge standards for a measured m_x in this study. Because of a current lack of the discharge standards for decentralized wastewater treatment facilities in China, the second-grade values

of *Discharge Standards of Pollutants for Municipal Wastewater Treatment Plants (GB 18918-2002)*, i.e., $\text{BOD}_5 = 30 \text{ mg L}^{-1}$, $\text{COD}_{\text{Cr}} = 100 \text{ mg L}^{-1}$, $\text{TSS} = 30 \text{ mg L}^{-1}$, $\text{TP} = 3 \text{ mg L}^{-1}$, $\text{NH}_3\text{-N} = 25 \text{ mg L}^{-1}$, $\text{FC} = 10^4 \text{ CFU L}^{-1}$, were tentatively adopted in this work to evaluate the probability of compliance:

$$Z_{1-\alpha} = \frac{\ln X_s - (\ln m_x - 0.5 \ln[(\text{CV})^2 + 1])}{\sqrt{\ln[(\text{CV})^2 + 1]}} \quad (3)$$

According to the modified stability analysis method proposed by Oakley *et al.*,¹² a plot of the mean and 10–90% range of effluent concentrations vs. standard deviation was used to analyze the stability of different treatment processes instead of a full range of effluent concentrations that is not as sensitive as the 10–90% range to outliers.

3. Results and discussion

3.1 Primary treatment processes

ST is widely adopted as the primary treatment process by most rural families. In the United States, the most common onsite treatment system involves a ST unit followed by dispersal to a subsurface soil infiltration unit.¹⁵ Because of its simplicity of internal structure and operation, ST is inexpensive to build and maintain. However, malfunctions of the ST systems have been often reported because of unsuitable soil and site characteristics.¹⁶ Due to incomplete digestion and removal of pollutants in ST, the soil infiltration unit plays an important polishing role to meet the discharge standards. Given the relative scarcity of house land resources in eastern China, the soil infiltration process is usually unaffordable and thus the modified three-chamber ST has been commonly constructed as the only household wastewater treatment process. The structural modification of the three-chamber ST provides quiescent and anaerobic conditions, thus facilitating the separation of sludge and grease. Consequently, the separated sludge can be removed less frequently.

Table 2 shows the characteristics of the effluents from seven three-chamber STs investigated. It was found that the mean concentrations of BOD_5 , COD_{Cr} , FC, TP, TSS and $\text{NH}_3\text{-N}$ all exceeded the second-grade discharge standards (*GB 18918-2002*). The environment within the ST was reported as ineffective in

Table 1 Information about rural wastewater treatment processes evaluated

Treatment processes	Process description	Number	PE ^a served (inhabitants)	Construction and engineering commissioning
Septic tank (ST)	Three chambers	7	3–8	2005–2008
Micro-power (MP)	Biological contact oxidation	5	200–900	2007–2009
Constructed wetland (CW)	Subsurface flow	7	350–1000	2007–2009
Stabilization pond (SP)	Facultative pond	3	500–1200	2001–2008
Activated sludge (AS)	Anoxic/oxic	5	8000–60 000	2005–2009

^a PE: population equivalent.

Table 2 Characteristics of the effluents from seven three-chamber septic tanks in four sampling seasons

Parameters (mg L ⁻¹)	Summer			Autumn			Winter			Spring			Second-grade discharge standards ^b
	Min	Max	Mean ± SD ^a	Min	Max	Mean ± SD	Min	Max	Mean ± SD	Min	Max	Mean ± SD	
BOD ₅	40	510	130 ± 89	105	500	305 ± 97	210	980	530 ± 181	80	420	233 ± 88	30
COD _{Cr}	70	660	207 ± 118	150	710	445 ± 117	350	1340	732 ± 214	145	675	354 ± 120	100
FC ^c	2	38	17 ± 9	10	312	36 ± 42	10	202	52 ± 43	5	72	19 ± 12	1
TP	2.4	15.3	6.8 ± 3.4	4.2	19.1	10.2 ± 3.5	5.3	22.1	12.0 ± 3.8	3.6	13.2	7.3 ± 2.2	3
TSS	48	394	174 ± 86	26	486	298 ± 90	210	776	398 ± 128	86	412	210 ± 64	30
NH ₃ -N	5.2	52.3	20.3 ± 10.7	11.9	48	29.2 ± 9.3	12.2	82	38.1 ± 15.8	6.9	47.2	19.8 ± 8.9	25
TN	9	62	30 ± 13	21	62	41 ± 10	21	114	50 ± 19	13	58	29 ± 10	N/A ^d

^a SD = Standard deviation ($n = 252$). ^b From the *Discharge Standards of Pollutants for Municipal Wastewater Treatment Plants (GB 18918-2002)*. ^c FC unit: 10⁴ CFU L⁻¹. ^d N/A: Not applicable.

reducing the nutrients and pathogens.¹⁷ The ST merely converted the influent organic-N to ammonium and most of the influent phosphorus (P), in forms of organic and condensed phosphate (polyphosphate), to soluble ortho-P,¹⁸ thus leading to a low removal of total nitrogen (TN) and total phosphorus (TP). The effluent qualities in spring and summer were generally superior to those in autumn and winter. Apart from the variations of influent concentrations induced by local meteorological conditions and human living habits, the activity of anaerobic microorganisms in ST mainly accounted for the effluent deterioration in cold seasons. The anaerobic ST acted as the only treatment process for household wastewater in more than 70% of villages in the surveyed area. The effluents were commonly discharged into nearby surface waters and thus polluted the receiving water

bodies, which implies the necessity for secondary treatment of the effluents from STs.

3.2 Reliability analysis

Fig. 2 presents the CVs and CORs of six water quality parameters (*i.e.*, BOD₅, COD_{Cr}, FC, TP, TSS and NH₃-N) of four secondary treatment processes evaluated (*i.e.*, MP, AS, CW and SP). The CV of each water quality parameter was calculated from the corresponding standard deviation and mean concentration. Consistent with the observations of Oliveira and von Sperling,¹¹ most of the CVs were lower than 1.0 except FC whose values were obviously higher than those of other quality parameters. The high CV of FC meant a vast variation in effluent

Fig. 2 Coefficients of variance (CV) and coefficients of reliability (COR) for the treatment processes evaluated.

concentration that could cover 2–3 orders of magnitude. The CVs of almost all the quality parameters of the centralized AS were lower than those of the three decentralized processes. This is reasonable because the AS had regular operation and maintenance as well as a large buffering space (e.g., wastewater collection system, adjusting tank) to diminish the influent variation. In contrast, for the decentralized systems, their small buffering space, lack of trained staff, different designs, and irregular operation and maintenance could all aggravate the variability of treatment performance.^{9,19}

The COR of each water quality parameter was calculated from the corresponding CV according to eqn (2) at a reliability level of 95%. In general, at the same level of reliability, a higher CV leads to a lower COR. A low COR implies the need for a low design effluent concentration according to eqn (1). As expected, the centralized AS showed higher CORs than the three decentralized processes (see Fig. 2). In terms of FC and $\text{NH}_3\text{-N}$, the CW had the lowest CORs among the four evaluated processes. It should be pointed out that as the effluent concentration was not taken into consideration, a high COR does not necessarily indicate a highly reliable performance. In fact, a stable but high effluent concentration can also lead to a high COR.¹¹ To further illustrate the difference in reliability among the four secondary

treatment processes, the mean design concentration and the expected compliance with the discharge standards were analyzed.

Fig. 3 compares the mean design concentrations, which ensure that 95% of the effluents meet the second-grade discharge standards (tentatively designated), with the actual effluent concentrations of six water quality parameters for each process. Box-whisker plots were adopted to show the maximum, median, minimum, 25%, 75% and mean concentrations. In general, being consistent with the CORs, the design concentrations of CW and AS were somewhat higher than those of MP and SP. However, the actual effluent concentrations of each process showed a great fluctuation and the gaps between the design concentrations and the actual effluent concentrations were obvious. The CW and AS processes had a relatively less variable performance than the MP and SP processes, as indicated by the 25–75% range of effluent concentration (*i.e.*, the box height). In addition, their mean effluent concentrations were also closer to the design values than those of MP and SP.

According to eqn (3), the value of $Z_{1-\alpha}$ was calculated from CV, m_x and X_s , so the expected probability of compliance with the discharge standards could be readily obtained from the standard normal variate tables. Fig. 4 compares the expected

Fig. 3 Comparison between the design concentrations (to achieve 95% compliance with the designated discharge standards) and the observed actual effluent concentrations for four secondary treatment processes evaluated.

Fig. 4 Expected probabilities of compliance with the designated discharge standards for four secondary treatment processes evaluated (reliability level = 95%).

compliance probabilities of the four treatment processes studied. The results clearly indicate that the compliance probabilities of most water quality parameters were unsatisfactory except $\text{NH}_3\text{-N}$ and COD_{Cr} . With respect to the four processes studied, the CW and AS exhibited higher compliance probabilities than the MP and SP for almost all the quality parameters. Weirich *et al.*²⁰ reported that for facilities smaller than $40\,000\text{ m}^3\text{ day}^{-1}$, the actual effluent concentrations of BOD_5 , TSS and $\text{NH}_3\text{-N}$ tended to decrease with an increasing facility size. The decentralized systems, commonly characterized by a small size, have a higher possibility of permit violation than the centralized systems. Particular caution should be given to FC because its expected compliance probabilities were all below 30% for the four treatment processes. Pathogens released from rural wastewater treatment facilities to surrounding surface and groundwaters can pose a serious threat to local residents since rural communities generally lack sanitation facilities. Accordingly, post-treatment of the effluents (*e.g.*, chlorine disinfection) would be necessary to effectively inactivate the pathogens. Note that the second-grade discharge standards of GB 18918-2002, which were tentatively adopted to evaluate the performances of various rural wastewater treatment processes in this study, were actually designed for centralized treatment systems. The poor suitability of the second-grade discharge standards implies that more practicable discharge standards need to be designed for the decentralized rural wastewater treatment systems closely based on the actual local situations.

3.3 Stability analysis

A wastewater treatment process is regarded as stable if its effluent quality is not notably impacted by the variation in influent loadings and environmental or operational conditions. Fig. 5 shows the mean and 10–90% range of effluent concentrations *vs.* standard deviation for each water quality parameter of the four treatment processes. Through overall evaluating the distribution patterns of the standard deviations and effluent concentrations of six water quality parameters, it was found that the stabilities of the four treatment processes generally followed a decreasing order of $\text{AS} > \text{CW} > \text{SP} > \text{MP}$. In combination with the above results of the reliability analysis, the AS and CW outperformed the SP and MP for rural wastewater treatment.

3.4 Cost-effectiveness analysis

As the charging system for wastewater discharge has not yet been established in rural areas of China, the costs of construction, operation and maintenance mainly rely on the investment of local governments. As a result, the cost-effectiveness analysis of different wastewater treatment processes is crucial considering the limited budget of local governments in rural areas. According to the cost estimation approaches developed by the USEPA,⁷ decentralized systems are usually more cost-effective for rural wastewater treatment than conventional centralized

Fig. 5 Stability analysis for four secondary treatment processes evaluated.

systems, especially in sparsely populated areas. However, due to a large variation in population density, land price, human living habits, and economic development level, the total costs for a wastewater treatment facility may vary greatly in different rural areas.²¹

The construction, operation and maintenance costs of the four secondary treatment processes studied are summarized in Table 3. The SP generally used ponds naturally existing and required little management, thus both its construction cost and its operation and maintenance cost were the lowest among the four processes. However, due to its large demand on land and odor emission problem, SP is seldom adopted in eastern China for rural wastewater treatment. The unit construction cost of AS (per ton) was lower than that of MP taking into consideration their different scales. Although MP occupied less land than CW and SP, a certain large scale was required to make it function well and be economically feasible. However, as described above, the MP was the least stable among the four processes due to its small scale designed. The centralized AS showed a more stable and effective performance, but required a remarkably higher

operation and maintenance cost than the other three decentralized treatment systems. Apart from the costs, the AS also required complex equipment, operational expertise and extensive energy to keep running, which restricted its application in rural areas. The AS process is more suitable for large towns that are densely populated and economically developed.

Without power input requirement, the CW had moderate construction, operation and maintenance costs. Due to its good cost-effectiveness among the three decentralized systems, this process has been commonly adopted in developed rural regions for wastewater treatment from single houses to small communities.^{22,23} With a designed organic loading in the range of 5–20 gBOD₅ m⁻² day⁻¹, the inner volume of CW could supply a large buffering space to alleviate the influent fluctuation. Moreover, the multiple purifying mechanisms such as substrate adsorption, microbial degradation, and plant absorption all contributed to a stable and reliable removal of pollutants. It also had a low requirement for regular operation and maintenance. Therefore, the CW is more suitable for sparsely populated villages with adequate land.

Table 3 Construction, operation and maintenance costs of four secondary treatment processes evaluated

Treatment processes	Construction capital cost (RMB m ⁻³)	Operation and maintenance cost (RMB m ⁻³)
Micro-power (MP)	1800–2200	0.20–0.40
Constructed wetland (CW)	800–1200	0.05–0.20
Stabilization pond (SP)	300–500	0.05–0.10
Activated sludge (AS)	1200–1500	0.80–1.30

4. Conclusions

Although ST could remove a notable portion of TSS and organic matter, its ineffectiveness in reducing the nutrients and pathogens made a secondary treatment necessary to prevent water quality deterioration in rural areas.

There were obvious discrepancies between the mean design concentrations and the actual effluent concentrations for the four secondary treatment processes evaluated (*i.e.*, MP, AS, CW and SP). The expected probabilities of compliance with the second-grade discharge standards of GB 18918-2002, which were tentatively adopted as the evaluation basis in this work, were unsatisfactory for most of the water quality parameters examined. Thus, more practicable discharge standards need to be designed for decentralized rural wastewater treatment systems closely based on the actual local situations.

The centralized AS and decentralized CW exhibited a higher reliability and stability than the decentralized SP and MP. In combination with the cost-effectiveness analysis results, the AS is preferred for large towns that are densely populated and economically developed, while the CW is preferred for sparsely populated villages with adequate land.

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References

- 1 W. J. Ni and W. C. Ma, *Chinese Practice and Exploration of Secure Supply Management of Rural Drinking Water*, China Water Power Press, Beijing, 2010 (in Chinese).
- 2 T. Ichinari, A. Ohtsubo, T. Ozawa, K. Hasegawa, K. Teduka, T. Oguchi and Y. Kiso, *Process Biochem.*, 2008, **43**, 722–728.
- 3 J. García, R. Muijerio, J. M. Obis and J. Bou, *Water Policy*, 2001, **3**, 341–350.
- 4 S. Carroll, A. Goonetilleke, E. Thomas, M. Hargreaves, R. Frost and L. Dawes, *Environ. Manage.*, 2006, **38**, 286–303.
- 5 M. Tsalkatidou, M. Gratziou and N. Kotsovinos, *Desalination*, 2009, **248**, 988–997.
- 6 S. B. Wu, D. Austin, L. Liu and R. J. Dong, *Ecol. Eng.*, 2011, **37**, 948–954.
- 7 USEPA, *Response to Congress on Use of Onsite and Decentralized Wastewater Treatment Systems*, EPA 832-R-97e001b, Washington, DC, 1997.
- 8 S. Niku, E. D. Schroeder and F. J. Samaniego, *J. Water Pollut. Control Assoc.*, 1979, **51**, 2841–2857.
- 9 G. Tchobanoglous, F. L. Burton, H. D. Stensel, *Wastewater Engineering: Treatment, Disposal, and Reuse*, 4th edition, McGraw-Hill, New York, 2003.
- 10 S. M. A. C. Oliveira and M. von Sperling, *Water Sci. Technol.*, 2007, **55**, 127–134.
- 11 S. C. Oliveira and M. von Sperling, *Water Res.*, 2008, **42**, 1182–1194.
- 12 S. M. Oakley, A. J. Gold and A. J. Oczkowski, *Ecol. Eng.*, 2010, **36**, 1520–1531.
- 13 S. Niku, E. D. Schroeder and R. S. Haugh, *J. Water Pollut. Control Assoc.*, 1982, **54**, 129–134.
- 14 APHA, *Standard Methods for the Examination of Waste and Wastewater*, 19th edition. Am. Public Health Assoc., Washington, DC, 1999.
- 15 K. S. Lowe and R. L. Siegrist, *J. Environ. Eng.*, 2008, **134**, 93–101.
- 16 D. Les and G. Ashantha, *Environ. Geol.*, 2003, **44**, 467–477.
- 17 C. D. Beal, E. A. Gardner and N. W. Menzies, *Aust. J. Soil Res.*, 2005, **43**, 781–802.
- 18 J. E. McCray, S. L. Kirkland, R. L. Siegrist and G. D. Thyne, *Ground Water*, 2005, **43**, 628–639.
- 19 N. Srinivasan, R. W. Weaver, B. J. Lesikar and R. A. Persyn, *Bioresour. Technol.*, 2000, **75**, 19–25.
- 20 S. R. Weirich, J. Silverstein and B. Rajagopalan, *Water Res.*, 2011, **45**, 4279–4286.
- 21 J. Parkinson and K. Tayler, *Environ. Urban.*, 2003, **15**, 75–90.
- 22 D. Konnerup, T. Koottatep and H. Brix, *Ecol. Eng.*, 2009, **35**, 248–257.
- 23 G. D. Gikas and V. A. Tsihrantzis, *Water Sci. Technol.*, 2010, **62**, 603–614.