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Cost function for treating wastewater in rural regions

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ABSTRACT

The purpose of this paper was to provide an cost-effective methodology for assessing wastewater treatment technology. This methodology may be useful in the planning of treatment facilities in rural regions. The existing cost models focus mainly on municipal wastewater treatment plants, which mostly consider the influence of the capacity of plant ordinarily expressed as inhabitants or flow rate. In this paper, we propose a new model of cost function in rural regions that includes both the capacity of plant and the removal rate of pollutants. The water quality indicator chemical oxygen demand and NH_3-N are chosen to be factors for a rural wastewater treatment model. The cost model enables us to understand the influence of pollutants' removal rate and to compare various treatment technologies from an economic point of view. The statistical information comes from a sample of 221 wastewater treatment plants in rural regions located in Changshu, Jiangsu province of China adopting four treatment technologies such as membrane bioreactor technology, sequencing batch reactor, purification tank, biological filter and artificial wetland.

Keywords: Cost function; Bioreactor technology (MBR); Sequencing batch reactor (SBR); Purification tank (PT); Biological filter (BF); Artificial wetland (AW)

1. Introduction

Since China is a typical agriculturalized country, about 70% of the total population lives in rural regions. With an increasing amount of untreated domestic sewage and irrigation water drained into the rivers and lakes around the village randomly, the water environment in rural regions has deteriorated in recent years. How to improve the water environment in rural areas depends mainly on the construction of wastewater treatment plants, which needs financial support from the government. Thus, the cost of constructing wastewater treatment facilities has become a matter of great concern. When the costs of the available technologies for rural wastewater treatment are definite, we could compare them from the technological and economic points of view as well. Prediction of investment cost (IC) and operation & maintenance cost (O & MC) of wastewater treatment facilities could be influential for the economic feasibility of various levels of water pollution control programmes.

The cost models of Municipal Wastewater Treatment Plants (MWWTPs) have been studied in the literature [1–5]; however, the cost models of Decentralized Wastewater Treatment Plants (DWWTPs) have seldom appeared in recent literature because of small treatment quantity and a variety of treatment processes.

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An analysis of MWWTPs reveals that the principal determinants of treatment cost are size—expressed either by designed flow or served population size (for example, population equivalent, simplified as p.e.), water quality of sewage to be treated and required water quality of the effluent. The cost function is often expressed in the form of a linear equation or an exponential equation. The form of linear equation is expressed as follows:

$$C = a + bx \tag{1}$$

where C is the cost (RMB), x is the designed flow (m^3/d) or population equivalent (p.e.), a, b is the coefficients. The exponential form is expressed as follows:

$$C = a \cdot x^b \tag{2}$$

the variables in Eq. (2) are the same as those in Eq. (1) [6].

Since the cost function is relevant to the effluent water quality, the analysis of the cost function is determined by the wastewater treatment process, which is ordinarily divided into three groups: primary treatment, secondary treatment and tertiary treatment. Molinos-Senante et al. [3] summarized the IC and O & MC of secondary treatment including nine different technologies such as Pond System, Intermittent Sand Filter, Wetlands (CWS), Trickling Filter, Moving Bed Biofilm Reactor, Rotating Biological Contactors, Membrane Bioreactor (MBR), Extended Aeration and Sequencing Batch Reactor (SBR) expressed with both Eqs. (1) and (2). However, the main limitation is that the models obtained only provide information about the influence of the plant size. To overcome this weakness, Onkal and Demir [7] analysed the total cost of three cases including classical sewer and WWTP systems, cluster systems and package treatment system and concluded optimized strategy under different scenarios. Hernandez-Sancho et al. [6] considered that different treatment processes have different removal rates of pollutants such as Chemical Oxygen Demand (COD), nitrogen (N), phosphorus (P) and Suspended Solids (SS), which have some relationship with the cost function. He assumed the form of cost function as follows:

$$C = AV^b e^{\left(\sum_{i=1}^{n} \alpha_i x_i\right)} \tag{3}$$

where A, b, α_i are the parameters, C is the total cost per year (RMB/year), V is the volume of wastewater treated per year (m^3/year), n is the number of variables considered in the model, x_i are the different kinds of variables representative of the treatment processes such as the age of the facility and the removal rate (%) of the following contaminants: SS, COD, N, P and Biochemical Oxygen Demand (BOD).

In rural areas in China, the technology adopted to treat wastewater mainly includes MBR, SBR, Purification Tank (PT), Biological Filter (BF) and Artificial Wetland (AW), etc. The idea of this paper was to compare these technologies by modelling their treatment costs including IC and O & MC. We could gain insight into the key role of the economies of scale of these technologies, as well as understand the influence of all the factors including not only the quantity of treated wastewater but also the removal rates of pollutants among various treatment technologies from an economic point of view.

2. Methodology

In China, the cost function of WWTPs considering both the sewage flow and removal rate is usually expressed as:

$$C = a \cdot Q^b + c \cdot Q^b \cdot \eta^d \tag{4}$$

where a, b, c, d are the parameters, C is the total cost per year (RMB/year), Q is the designed flow (m^3/d) and η is the removal rate (usually means COD). Eq. (4) is derived through large quantities of industrial wastewater treatment plants in "Economic handbook of industrial wastewater and urban sewage treatment technology" (in Chinese) [8]. However, in rural regions, domestic sewage turns out to be the dominant source of wastewater. The exceeding contaminants refer to COD and ammonia nitrogen (NH_3-N), respectively. In the present design and operation of industrial wastewater treatment plants, the water quality of effluents should meet the discharge standard of Class 1 in "Discharge standard of pollutants for MWWTP" (GB18918-2002). Since there has been no discharge standard for rural areas, respectively, so far, the discharge standard for MWWTP is also applied in rural areas. In order to meet the discharge standard, sewage treatment facilities for rural regions usually take the processes of AW, SBR, MBR, BF and PT that are mentioned above. Sometimes a combined process is also adopted, for example, the process of BF + AW is widely used for wastewater treatment in rural regions. In Eq. (4), η only refers to COD. But in rural areas, both COD and NH_3-N should be considered. Thereby in this paper, we suggest the cost function as the form shown in Eq. (5) to compare with the above-mentioned treatment process.

$$C = a \cdot Q^b \cdot \left(\sum_{i=1}^{n} w_i \eta_i\right)^d \tag{5}$$

where the meaning of a, b, d, Q and C is the same as that in Eq. (4), w_i is the weights of pollutants, η_i is the removal rate of pollutants (%), n is the number of pollutants, w_i is defined as follows considering the ratio of concentration of the pollutants at inlet to that of the pollutants at outlet.

$$w_i = \frac{c_{\text{in}_i}/c_{\text{out}_i}}{\sum_{i=1}^{n} c_{\text{in}_i}/c_{\text{out}_i}} \tag{6}$$

where c_{in_i} is the concentration of the i-th pollutant at the inlet of facilities, c_{out_i} is the concentration of the i-th pollutant at the outlet of facilities. In this paper, the pollutants refer to COD and NH_3-N, respectively.

The model parameters are obtained by software SPSS.

In Eq. (5), C is the total cost including IC and O & MC. For the convenience of comparing, the Total Annualized Equivalent Costs (TAEC) should be decided by adding the annualized IC to annual O & MC for the time period which they occur as:

$$\text{TAEC} = \frac{r \cdot (1+r)^t}{(1+r)^t - 1} \cdot \text{IC} + \text{O \& MC} \tag{7}$$

where TAEC is the Total Annualized Equivalent Cost (RMB/year), IC is the Investment Cost (RMB/year), O & MC is the Operation and Maintenance Costs (RMB/year), r is the discount rate and t is the useful life of the facility (year).

3. Sample and variables

The samples used in this empirical application consist of 309 DWWTPs located in Changshu region of Jiangsu Province, China. The research scope includes the Bixi district, Southeast street, Yushan town, Meili town, Haiyu town, Guli town, Shajiabang town, Zhitang town, Dongbang town, Shanghu town and Xinzhuang town. Altogether there are 11 districts. Among the 309 DWWTPs, there are only 221 sets that are running normally. Among these 221 sets, four kinds of technologies are adopted such as MBR, SBR, BF + AW and PT. Table 1 shows the mean value of each variable and in parentheses is its standard deviation for the four technologies. The ICs are supplied by Construction Bureau in the Changshu City. The O & MCs are supplied by Suzhou Hongyu Water Treatment Engineering Limited Corporation.

Statistical information has been collected for the year 2012. The inlet water quality of all DWWTPs studied is very similar; consequently, it does not affect the result in the analysis. It has been assumed that the service life of all different facilities is 10 years and the discount rate r is assumed to be 3.5%. The TAEC of the four processes including MBR, SBR, BF + AW and PT are calculated by Eq. (7). The weights of COD and NH_3-N in Eq. (5) are calculated by normalizing the ratio of the average influent concentration to the effluent standard (60 mg/L for COD and 8 mg/L for NH_3-N). In rural regions, the weights of COD and NH_3-N are 0.36 and 0.64, respectively.

4. Results and discussion

Using the investigated data of the DWWTPs adopting the four treatment processes is shown in Table 1; the cost functions and the relevant coefficients have been determined as described in Table 2. In order to evaluate the difference between the actual and estimated costs, both have been plotted in Figs. 1–4.

From Table 2, we can see that the values of the relevant coefficients R are all greater than 0.5, which means the results are in the acceptable scope. As we all know, as far as relevant coefficient R is concerned, the closer it is to 1.0, the better the fitting result is.

4.1. Case 1. MBR

Recently, more attention has been paid to the MBR technology for decentralized wastewater treatment because of its higher efficiency in pollutant removal, excellent effluent quality, low/zero sludge production, compact size and lower energy consumption. Previous researches on MBR have shown that MBR is extremely efficient in the removal of bacteria and viruses [9]. In addition, with the help of a membrane filter, some suspended substances and big molecule matter can be eliminated, so the turbidity of the effluent is reduced to below 0.2 NTU. In the past, membranes have been considered unsuitable for wastewater treatment due to high operating costs caused by low resilience of the then available membranes, which were generally unreliable and had only a short operation period between cleaning cycles. However, increasing stringent standards and decreasing costs are making the

Table 1
Description of the sample (mean pollutant removal rate in % and standard deviation in parentheses)

Technology	Total sets	Operation sets	IC (10^4 RMB/year)	O & MC (10^4 RMB/year)	Total cost (10^4 RMB/year)	Total volume (m^3/year)	Removal rate of COD (%)	Removal rate of NH_3-N (%)
MBR	8	7	45.8	3.55	49.35	158,775	0.73 (0.0365)	0.65 (0.058)
SBR	263	180	109.44	7.47	116.91	346,750	0.58 (0.156)	0.62 (0.149)
BF + AW	6	5	14.32	0.73	15.05	69,350	0.56 (0.17)	0.55 (0.17)
PT	32	29	45.30	5.49	50.79	133,955	0.70 (0.118)	0.55 (0.161)
Total	309	221	214.86	17.24	232.1	708,830		

Table 2
Cost functions and relevant coefficient for four wastewater treatment technologies

Technology	Cost function	R^2
MBR	$\text{TAEC} = 0.203\ Q^{0.962}\ (0.36\ \eta_1 + 0.64\ \eta_2)^{1.069}$	0.767
SBR	$\text{TAEC} = 0.293\ Q^{0.74}\ (0.36\ \eta_1 + 0.64\ \eta_2)^{0.306}$	0.906
BF + AW	$\text{TAEC} = 0.125\ Q^{0.92}\ (0.36\ \eta_1 + 0.64\ \eta_2)^{0.23}$	0.999
PT	$\text{TAEC} = 0.468\ Q^{0.552}\ (0.36\ \eta_1 + 0.64\ \eta_2)^{0.1}$	0.807

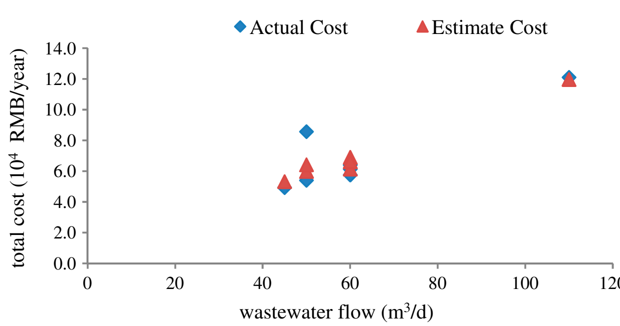

Fig. 1. Actual and estimated costs for MBR.

use of MBR systems for decentralized wastewater treatment more economically available. Fig. 1 shows the actual and estimated costs of DWWTPs with MBR technology.

4.2. Case 2. SBR

Traditional SBR has features such as simple process flow, stable efficiency, small floor area, stronger ability for resisting shock load, convenient operation and low cost. The main equipment is only SBR without secondary sedimentation tank and sludge return system. It can operate flexibly according to the quality and quantity with good nitrogen and phosphorus removal efficiencies. Using the SBR method for rural sewage treatment, the removal rates of pollutants such as COD, BOD, SS, TN and NH_3-N are high, and the effluent quality can reach "Integrated wastewater discharge standard" (GB8978–1996) level 1 Emission standard. Fig. 2 shows the actual and estimated costs of DWWTPs with SBR technology.

4.3. Case 3. Biological filter + artificial wetland (BF + AW)

By BF technology, wastewater is sprayed onto a filter full of packings, which makes wastewater flow through the filler continuously so as to decomposite organic matter by the biomembrane growing on the filler. The BF ensures sufficient oxygen supply through natural ventilation, meanwhile the collection device is set at the bottom of the filter to collect the treated wastewater to flow into constructed AW. The AW may remove insoluble organic matter in wastewater through the process of sedimentation and filtration of the wetland and decomposition by microorganisms,

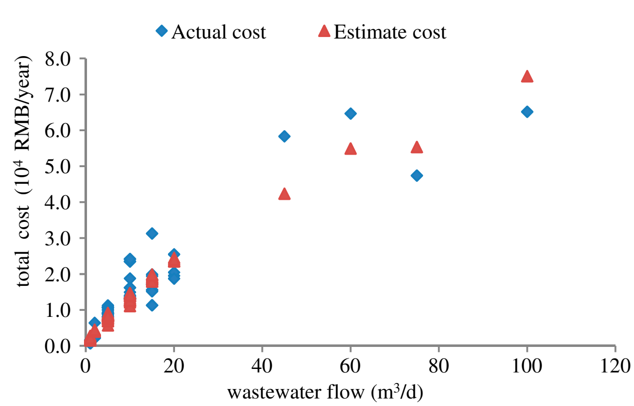

Fig. 2. Actual and estimated costs for SBR.

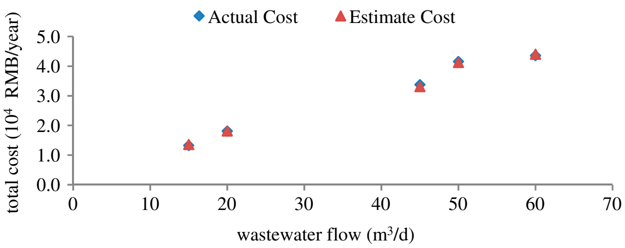

Fig. 3. Actual and estimated costs for BF + AW.

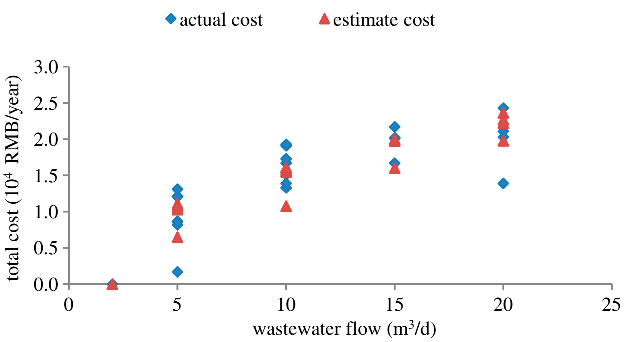

Fig. 4. Actual and estimated costs for PT.

also it may remove soluble organic matter by the process of adsorption by plants in the wetland. So the AW is often used as a supplement to wastewater treatment process to achieve a qualified wastewater treatment quality. Fig. 3 shows the actual and estimated costs of DWWTPs with BF + AW technology.

4.4. Case 4. Purification tank (PT)

PT is a glass steel tank gathered with the effect of anaerobic, aerobic, precipitation and other functions. PT has the advantages of small occupation, convenient operation and management so that it is an effective means of decentralized sewage treatment, which has a wide range of applications in decentralized sewage treatment of rural areas. Fig. 4 shows the actual and estimated costs of DWWTPs with PT technology.

5. Conclusions

From the results in Table 2, the effect of treated volume in MBR is much bigger than in PT and SBR, and it is almost as much as that in BF + AW. In the process of MBR, the effect of the treated volume is almost the same as the effect of the removal rate. However, in the other three processes (SBR, BF + AW, PT), the effect of the treated volume is greater than the effect of the removal rate. And the constant coefficient in PT is bigger than the other three treatment processes. We can also conclude from Table 2 that the most cost-effective technology is SBR for the constant coefficient is much less than the other three technologies and the exponential coefficient of the removal rate is almost the smallest among the technologies except that of the PT technology. At the same time, the MBR technology is the most expensive technology because the exponential coefficient of treatment flow and the removal rate are all much bigger than the other three technologies. Therefore, when only concerning the cost of building rural sewage treatment facilities, SBR technology should be considered first of all and MBR technology should be considered in the end.

Using a cost modelling methodology with statistical information from a sample of 221 decentralized plants located in Changshu, various cost functions have been developed that will enable us to predict DWWTP costs. Cost models provide a quantitized and scientifically rigorous approach in the planning of new treatment plants in the rural regions. Moreover, the calculations of these functions provide valuable information in a simple way and help to optimize the management of wastewater treatment systems in rural regions. This methodology is also useful for comparing different treatment technologies from an economic point of view.

In the light of the results obtained in this work and as a final conclusion, we highlight that when authorities are faced with the problem of constructing new DWWTPs in rural regions, the criteria for selecting the most appropriate technology should include not only technical practicability and effluent quality requirements but also DWWTP costs which are very important factors for assessing economic feasibility.

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