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An exploration of comprehensive evaluation method of sewage treatment construction project in small and medium towns: theory and application

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ABSTRACT

Based on the investigation of Chinese sewage treatment construction projects, it is of importance to develop a comprehensive evaluation method associated with socioeconomic and environmental consideration, especially in small and medium towns. A comprehensive evaluation method was established based on analytic hierarchy process method with the quantitative or semi-quantitative evaluation indexes from field of technical benefit, economic benefit, environmental benefit, and social benefit. The weights of technical benefit, economic benefit, environmental benefit, and social benefit were 0.4597, 0.3437, 0.1272, and 0.0694, respectively. The technical and economic benefits were relatively more important. A practical sewage treatment plant in Economic Development Zone of Huangzhou, China, was put forward to test and verify this improved method. Results indicated that the pretax financial internal rate of return (FIRR) (7.43%) and after-tax FIRR (4.53%) of the plant were all greater than benchmark yield of sewage treatment industry (5% pretax and 4% after tax). The pretax payback period (P_t) was 15.34 years, while that of after-tax was 15.77 years. In addition, environmental benefit evaluation indicated that environmental cost–benefit ratio was 1.38 in the first phase and 1.67 in the second phase, which meant positive benefit for environment. Evaluation of technical benefit and social benefit also confirmed that the project meet demands of the industrial park and society. The final comprehensive benefit evaluation result was 7.0249, which indicated that the sewage treatment plant was in average level to maintain normal operation.

Keywords: Sewage treatment; Construction project; Comprehensive evaluation; Socioeconomic consideration; Small and medium towns

1. Introduction

With the rapid advancement of urbanization in China, the water pollution is an increasingly serious problem, and the contradiction between economic development and environment protection is gradually highlighted. Especially in most of small and medium towns in Chinese central cities, the water pollution phenomenon is generally common due to the shortcomings of economic stagnation, imperfect infrastructure, severe agricultural pollution, and backward environmental awareness [1]. Township sewage treatment plant is an important measure to achieve comprehensive treatment of water pollution. Under the current condition, comprehensive benefit evaluation for township sewage treatment plants can improve benefits of wastewater treatment plants, promote comprehensive utilization of resources, and provide scientific evidence for local government to promote environmental planning [2].

The research on project benefit evaluation at home and abroad has been in the process of continuous development and improvement. The evaluation methods have developed from the emphasis on economic benefits to the combination of

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economic and noneconomic benefits, such as set pair analysis method [3], fuzzy evaluation method [4], and life cycle theory [5]. The research on project evaluation has been deepened and the scope has been expanding, however, most of the innovation researches are the enrichment and improvement of the existing evaluation methods [6]. Domestic researches about benefit evaluation of sewage treatment plant mainly pays attention to the technical and economic benefits, and relatively neglected the social service property of sewage treatment plant [7]. This study aims to add environmental and quantitative analysis into the comprehensive evaluation system in addition to technology and economic benefits. Fuzzy indexes are to be evaluated by using qualitative and quantitative analyses and the macroscopic and microcosmic way to make the result has practical maneuverability and reference use. Furthermore, the established evaluation method will be applied to evaluate the comprehensive benefit of a sewage treatment plant in Economic Development Zone of Huangzhou, China.

2. Establishment of comprehensive benefit evaluation system

Comprehensive evaluation method was established with the quantitative and semi-quantitative evaluation indexes from field of technical benefit (including technical feasibility and technical economy), economic benefit (including investment estimation and financial evaluation), environmental benefit (including environmental quality, contamination, and cost), and social benefit (including coverage rate, growth rate, and development outcomes) (Table 1).

2.1. Technical benefit evaluation

According to the functional requirements, sewage treatment is divided into harmless treatment system (i.e., reach the discharge standards) and recycling treatment system (i.e., provided for special users). The former one generally sets up primary treatment and secondary treatment, while the latter one usually adds tertiary treatment or advanced treatment on the basis of the former. At present, most of township sewage treatment plants in China are designed with primary treatment and secondary treatment. Tertiary treatment is not taken into account of implementation, but its location and areas are reserved at design time. Primary treatment usually removes solid waste with physical processes, such as grill, grit chamber, and sedimentation tank. Differences among sewage treatment processes mainly embody in secondary treatment. The commonly used secondary treatment processes of sewage treatment include conventional activated sludge process, oxidation ditch process, anoxic/oxic method, and adsorption biodegradation method.

The complexity of the process and the amount of investment are not decisive factors in identification of the overall level for the sewage treatment plant. It is significantly necessary to determine the processing technology and construction scale of the sewage treatment plant by combining the local water quality conditions and the service population. The goal is to get a more economical and reasonable construction plan to maximize the funds efficiency.

2.2. Economic benefit evaluation

Investment estimation is to collect and analyze the information about total investment and financing ways of the project based on the understanding of project attributes (construction scale, construction contents, and project duration). And financial evaluation is the method to evaluate investment feasibility of sewage treatment plant from the perspective of engineering economics. The main evaluation indexes include financial net present value (FNPV), financial internal rate of return (FIRR) and, payback period (P_t).

FNPV is as follows:

$$\mathrm{FNPV} = \sum_{t=1}^{n} (\mathrm{CI}-\mathrm{CO})(\mathrm{CI}-\mathrm{CO})_t (1+i_c)^{-t} \tag{1}$$

where n is the calculation period; CI represents cash inflow; CO represents cash outflow; $(\mathrm{CI}-\mathrm{CO})_t$ is the net cash flow in period t; and i represents benchmark yield.

FIRR is as follows:

$$\sum_{t=0}^{n} (\mathrm{CI}-\mathrm{CO})_t (1+\mathrm{FIRR})^{-t} = 0 \tag{2}$$

Table 1
Evaluation system of comprehensive benefits

Evaluation system of comprehensive benefits (M)	Technical benefit (B_1)	Technical feasibility (C_1)
		Technical economy (C_2)
	Economic benefit (B_2)	Investment estimation (C_3)
		Financial evaluation (C_4)
	Environmental benefit (B_3)	Environmental quality (C_5)
		Environmental contamination (C_6)
		Environmental cost (C_7)
	Social benefit(B_4)	Coverage rate (C_8)
		Growth rate (C_9)
		Development outcomes (C_{10})

The priority consideration of static P_t is investment recovery capacity of the project. The expression is as follows:

$$P_t = (N-1) + \text{CNCT}_t / \text{NCF}_t \quad (3)$$

The dynamic payback period takes the time value of capital into account, which can more accurately reflect the payback time.

$$P_t' = (N-1) + (\sum_{t=1}^{n} \text{NPV}_{t-1}) / \text{NPV}_t \quad (4)$$

where N is the period when cumulative FNPV is beginning to be positive; $\sum_{t=1}^{n}(\text{NPV}_{t-1})$ is the absolute value of cumulative FNPV last year; NPV_t is current net present value.

2.3. Environmental benefit evaluation

Different from economic benefits associated with clear quantitative evaluation indexes, environmental benefit is mainly based on semi-quantitative evaluation. Sewage treatment plants are public infrastructure projects, thus its environmental benefits are beyond doubt. Meanwhile, how to quantify environmental benefits in the form of currency is the development direction of environmental benefit evaluation.

2.3.1. Environmental quality

Environmental quality is a comprehensive evaluation index that people determine whether environment (water, air, noise, and smell) is suitable for living according to their own needs. In the comprehensive evaluation system of sewage treatment plant, this index can be seen from the perspective of human senses, including vision, olfaction, taste, and hearing, and feel the changes of water pollution before and after the construction of sewage treatment plant.

2.3.2. Environmental contamination

The pollutants in urban sewage are various, such as oil, urine and stools, detergents, dyes, organic and inorganic compounds, heavy metals, bacteria, viruses, and other pathogenic microorganisms [8]. Overall, the characteristics of urban sewage are as follows: containing sediment and ammonia; neutral pH; large ratio of biochemical oxygen demand (BOD_5) to chemical oxygen demand (COD); good biodegradability; and stable water quality. Combining with the development characteristics of small and medium towns, monitoring indexes of sewage treatment plant generally include pH, COD, BOD_5, suspended solids (SS), total nitrogen (TN), ammonia nitrogen (NH_4^+-N), and total phosphorus (TP).

Operation of sewage treatment plants can reduce water pollution caused by the above-mentioned pollutants. Meanwhile, reclaimed water or energy can be recycled in production processes, which is in line with the requirements of environmental protection and sustainable development in China.

2.3.3. Environmental cost

The quantitative analysis of environmental benefit is to compute economic loss of environment. Only when the revenue of the sewage treatment plant is greater than the cost, the project is necessary to be constructed. Due to the characteristics of small scale and stable contaminations, sewage treatment plants in small and medium towns only need to make simple analysis of environmental economic benefits. Owing to uneven economic development level and sewage treatment processes among towns, the sewage treatment costs are different, so market price estimation was not applicable [9,10]. Detailed analysis method (Eqs. (5)–(7)) was suitable for the requirements. The method can subdivide income and cost to ensure the results more accurate and authentic.

$$\sum \text{Cost} = a + b + c + d + e \quad (5)$$

$$\sum \text{Revenue} = f + g \quad (6)$$

$$\sum \text{Environmental benefit} = \sum \text{Revenue} - \sum \text{Cost} \quad (7)$$

where a is equipment depreciation fee. A certain amount of funds will be withdrawn as recovery of investment at the end of each year; b is maintenance fee. It generally includes equipment maintenance costs, instrument calibration costs, equipment overhaul costs, and pipeline maintenance costs; c is wage and welfare funds. It includes wages, welfare funds, subside and management fees for workers in sewage treatment plant; d is power cost. It mainly includes electricity and transportation charges; e is cost of raw materials and auxiliary materials. It includes costs of various reagents required for wastewater treatment; f is sewage treatment fee; g is value of recycled products, such as waste oil reuse, wastewater reuse, and fuel gas recovery.

2.4. Social benefit evaluation

The social benefit of a project is generally focused on the macroscopical benefits. The social attribute of public service for the sewage treatment plant determines that it takes "satisfaction" as the core content of the social benefit evaluation. Its satisfaction is mainly reflected in three aspects: coverage rate, growth rate, and development outcomes. Coverage rate means the extent of beneficiaries or area of a sewage treatment plant (Eq. (8)). Growth rate of a public facility includes the growth rate of infrastructure (Eq. (9)) and employment (Eq. (10)).

$$\text{Coverage rate} = \frac{\text{Number of beneficiaries / benefited area}}{\text{Total number of local people / area}} \quad (8)$$

$$\text{Infrastructure growth rate} = \frac{\text{Service area in report year}}{\text{Service area in last year}} - 1 \quad (9)$$

$$\text{Employment growth rate} = \frac{\text{New employment}}{\text{total investment}} \quad (10)$$

Development outcomes is to analyze problems from the state or local government perspective: whether social needs of the project is consistent with the development of society; whether the project can directly or indirectly promote the development of local economy; whether the project is in line with local and national policies.

2.5. Comprehensive benefit evaluation

All the indicators in the comprehensive benefit evaluation system have been described in detail earlier. For indicators that could not be clearly quantified by mathematical method, were quantified by Delphi Method. Furthermore, comprehensive benefit was evaluated through analytic hierarchy process (AHP). AHP can establish the contrast matrixes by analyzing the relationship between indexes. In this study, six senior experts in the environmental protection and engineering field were invited to mark for different indexes. The weight of each index can be determined based on experts' comments. In practical application, each index will be assigned according to the real situation, and the comprehensive benefit evaluation result could be calculated based on weights and actual situation of the project (details are shown in Supplementary information).

3. Empirical analysis of a sewage treatment plant

3.1. General situation of the study area and project

A province in central China has built about 50 township sewage treatment plants by 2014. However, only 8 sewage treatment plants are under conditions of normal operation, while 30 plants run from time to time and the rest lay dormant. Half of the normally working sewage treatment plants are with the operating load rates less than 50%. The highest operating load rate of the 8 plants only reaches 75%. Designed daily capacity of these sewage treatment plants is 193 thousand tons, but the actual daily sewage treatment capacity is merely 31 thousand tons. 31 thousand tons are equivalent to the daily sewage treatment capacity of a county with 200 thousand people. It means that the actual daily sewage treatment rate of towns in this province was only 16%, and 162 thousand tons of sewage is discharged directly into rivers and lakes every day. The majority of the 50 towns have the population of more than 30 thousand. Therefore, considering the limitation of design capacity and actual collection rate, more than 200 thousand tons of sewage is directly discharged every day. The negative impact posed by water pollution in rural areas really cannot be underestimated.

The Economic Development Zone is located in Huangzhou of Hubei Province, China. It's a specialized chemical industrial park reviewed by National Development and Reform Commission, and approved by provincial government in 2006. Pharmaceutical chemical and smelting coking are the backbone industries in the industry park. The park has the total planning area of 20 km^2, which is the only industrial park passing regional environmental impact assessment in Huangzhou. In order to support the development of the industry park, Local Economic Development Zone Administrative Committee plans to set up a sewage treatment plant with designed capacity of 40,000 ton/d in the northeast of the industry park (20,000 ton/d in the first phase and 40,000 ton/d in the second phase). The first-stage project was formally completed in December 21, 2012, and run into the trial stage in August 2013.

3.2. Technical benefit evaluation

3.2.1. Technical feasibility analysis

According to the natures of enterprises in the industry park, the main pollution factors of wastewater were COD, BOD_5, NH_4^+-N, and petroleum. The amount of hazardous pollutants involved in sewage was small, and the complexity of sewage composition was relatively stable. The treated wastewater was discharged into the Yangtze River (Grade III standard of "Surface Water Environmental Quality Standard"), so the discharged sewage should meet class I-B criteria of "Discharge standard of pollutants for municipal wastewater treatment plant (GB 18918-2002)" [11]. In addition, inlet water should meet Grade III standard of "Integrated wastewater discharge standard (GB 8978-1996)" [12]. Quality standards of effluent water in the sewage treatment plant are shown in Table 2.

The major targets of primary treatment were solid pollutants under suspended or floating state. Primary treatment mainly adopted physical treating methods. After the treatment of grill and grit chamber, removal rate of SS was up to 70%–80%, while that of BOD_5 was only 30% [13]. Therefore, the treatment effect of BOD_5 had not reached discharge requirements, and it still needed to enter secondary treatment system. Primary treatment was important to the subsequent treatment processes. It is an indispensable pretreatment process in the wastewater treatment process, and locates at the top of the system.

Secondary treatment generally uses biological treatment as the main process, so it is also known as biological treatment. The major targets of secondary treatment were dissolved and colloidal organic contaminations (i.e., BOD_5), and soluble inorganic pollutants such as nitrogen and phosphorus. The removal rate of BOD_5 after secondary treatment was up to more than 90%. In general, BOD_5 can be reduced to 20–30 mg/L. After secondary treatment, the water quality of sewage can reach the discharge standard.

3.2.2. Technical economy analysis

Sewage treatment process should be adapted to the local conditions. The appropriate wastewater treatment technology

Table 2
Quality standards of effluent water in sewage treatment plant

Major control indexes	Pollutant concentrations of inlet water (mg/L)	Pollutant concentrations of outlet water (mg/L)	Removal rate (%)
COD	400	≤60	≥85
BOD_5	180	≤20	≥88.89
SS	200	≤20	≥90.00
TN	35	≤20	≥42.86
NH_4^+-N	25	≤8	≥68
TP	3	≤1	≥66.67

can not only reduce the cost of the project, but also ensure the quality of the effluent. In this industry park, 40% of the sewage came from domestic sewage and 60% came from industrial wastewater. Therefore, main requirement of the sewage treatment was nitrogen and phosphorous removal. Compared with conventional activated sludge process, oxidation ditch process had better feasibility. Moreover, modified oxidation ditch process had technical advantages of better treatment effects, stable effluent quality, advanced and mature technology, better flexibility and reliability (Fig. 1). In addition, the operation, management, and maintenance of modified oxidation ditch process were relatively simple, so it is particularly suitable for sewage treatment plants in small and medium towns.

3.3. Economic benefit evaluation

3.3.1. Investment estimation

According to the surveys, the gross investment of the sewage treatment plant mainly includes sewage treatment engineering, auxiliary engineering, and power supply. The estimated gross investment was 69.08 million yuan. Investment was 48.89 million yuan in first phase and 20.19 million yuan in the second phase.

Economic calculation period of the project was tentatively scheduled for 27 years, including construction period of 2 years and operation period of 25 years. In first phase of the construction, bank loans were 30 million yuan and self-collected money of development zone was 18.89 million yuan. Within 2 years of construction, bank loans in first year were 10 million yuan and 20 million yuan in second year, and lending rate was 7.83%.

3.3.2. Financial evaluation

Evaluation indexes of financial evaluation are shown in Table 3 [14].

Generally, benchmark yield in sewage treatment industry was 5% pretax and 4% after tax [15]. As shown in Table 3, FIRR of this sewage treatment plant was greater than 5% pretax and greater than 4% after tax. In addition, FNPV was greater than zero before tax and after tax, indicating that profitability of the sewage treatment plant can meet the minimum requirements of the industry. In other words, it is acceptable in terms of economic benefits. Furthermore, benchmark payback period of infrastructure industry such as sewage treatment plant was recommended as 16 years [16]. Table 3 indicated that payback period of this sewage treatment plant was less than 16 years no matter pretax or after tax. It illustrated that the project can get payback within the specified time. In summary, sewage treatment plant in the Economic Development Zone was economically feasible.

3.4. Environmental benefit evaluation

3.4.1. Environmental quality analysis

The sewage treatment plant is located in suburbs of Huangzhou with a large population in the surrounding countryside. A large number of colorful and toxic industrial wastewater produced by the chemical industry park, which polluted rivers, gave off an irritating smell, and threatened the health of local residents. After the sewage treatment plant was built and put into operation, the amount of industrial wastewater was greatly reduced, and the air quality in the surrounding villages basically recovered.

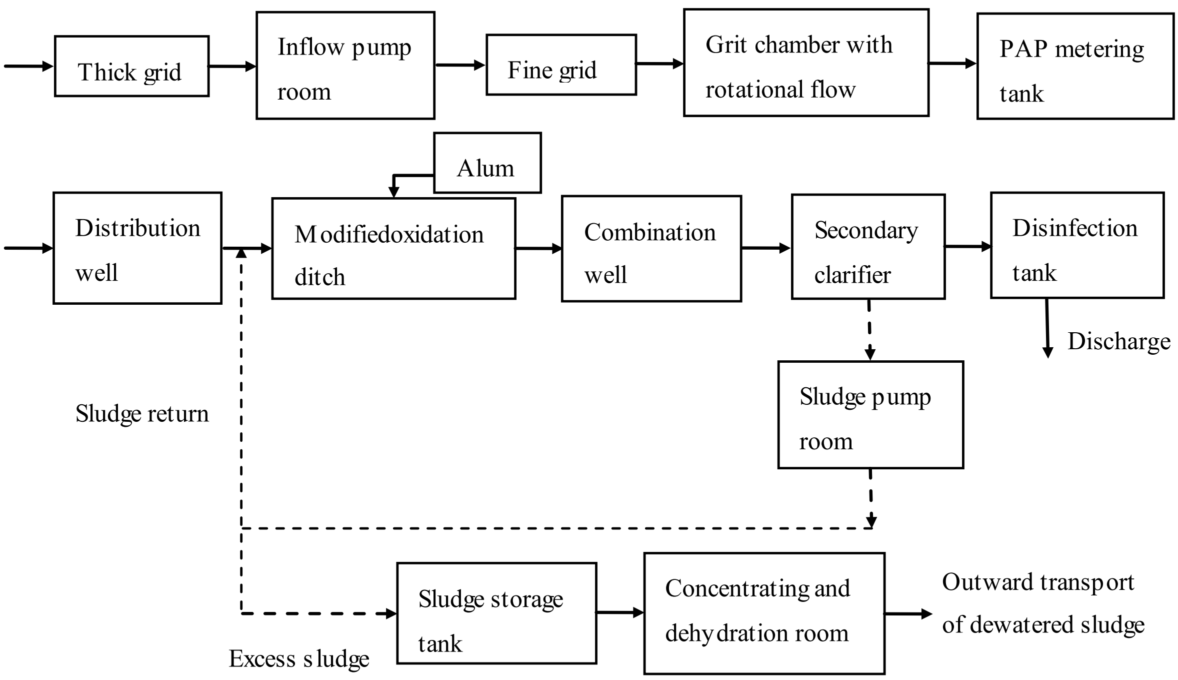

Fig. 1. Modified oxidation ditch process.

Table 3
Primary economic evaluation indexes and values

Numbers	Financial evaluation		Value
1	FNPV (million yuan)	Before income tax	25.28
		After income tax	4.36
2	P_t (years)	Before income tax	15.34
		After income tax	15.77
3	FIRR (%)	Before income tax	7.43
		After income tax	4.53

3.4.2. Environmental contaminations analysis

Since the trial run in August 2013, reduction of regional main water pollution indicators is shown as Table 4.

As shown in Table 4, it indicated that reduction of major pollutants in this sewage treatment plant was obvious. Removal rates of all pollution indicators exceeded 80%, with the descending order of SS > BOD_5 > COD > TP > NH_4^+-N. Removal rate of SS was the highest, up to 95%. Removal rate of BOD_5 was slightly lower than that of SS, which was 93.3%.

3.4.3. Environmental cost analysis

As mentioned, designed treating capacities of the sewage treatment plant in the first phase and second phase were 20,000 and 40,000 ton/d, respectively. Main calculation parameters included equipment depreciation fee, maintenance fee (1% of the fixed assets), wage and welfare funds, power cost, cost of raw materials and auxiliary materials, and sewage treatment fee. Environmental costs were calculated as in Table 5.

Table 6 shows the cost of every 1 yuan can get profits of 1.38 and 1.67 yuan in the first and second phase, respectively. Since the project belongs to public welfare facilities, it may enjoy government financial subsidies, tax exemption, and other preferential policies, so the environmental benefits will be more substantial. It was obvious that environmental benefits of the project are presentable.

3.5. Social benefit evaluation

The service area of the sewage treatment plant is 15.57 km^2, with the service coverage rate of 4.41%. The survey results indicated that the number increased fixed staff of the sewage treatment plant is 30 in addition to a large number of construction workers needed in the construction process. The growth rate of employment is 0.004 people/million yuan. From the perspective of social development, sewage treatment projects are public utilities which can protect environment and benefit future generations. Reduction and harmless treatment of wastewater can greatly improve the quality of living environment and is in line with the needs of local residents. Meanwhile, the construction of sewage treatment plants follows concepts of circular economy and sustainable development. Moreover, sewage treatment construction project is conducive to attract investment and promote employment.

Table 4
Reduction of regional water pollution indicators after implementation of the project

Pollutant	COD	BOD_5	SS	NH_4^+-N	TP
Emission before the project (ton/year)	3,650	2,190	2,920	328.5	58.40
Emission after the project (ton/year)	438	146	146	58.4	7.30
Pollutant reduction (ton/year)	3,212	2,044	2,774	270.1	51.1
Removal rate (%)	88	93.3	95	82.22	87.5

Table 5
Main parameters and values of environmental cost

Parameters	Values (million yuan)	
	First phase	Second phase
Equipment depreciation fee	1.84	2.85
Maintenance fee	0.49	0.69
Wage and welfare funds		0.61 million/year
Power cost	1.47	2.94
Cost of raw materials and auxiliary materials	0.38	0.76
Sewage treatment fee		0.9 yuan/ton

Table 6
Calculation results of environmental benefit

Parameters	First phase	Second phase
Total revenue (million)	6.57	13.14
Total cost (million)	4.77	7.85
Environmental benefit (million)	1.80	5.29
Revenue/cost	1.38	1.67

3.6. Comprehensive benefit evaluation results

According to AHP and Delphi method [17], the weights of secondary indexes are shown in Table 7. The weight of social benefit (B_4 = 0.0694) and environmental benefit (B_3 = 0.1272) were relatively lower than economic benefit (B_2 = 0.3437) and technical benefit (B_1 = 0.4597). It illustrated that technical and economic benefits were more important indicators

Table 7
Weights of secondary indexes in comprehensive benefit evaluation system

Index	Weight
B_1	0.4597
B_2	0.3437
B_3	0.1272
B_4	0.0694

Table 8
The weights and scores of third-level indexes in comprehensive benefit evaluation system

Index	Weight	Score[a]
C_1	0.3065	7
C_2	0.1522	8
C_3	0.0573	8
C_4	0.2864	6
C_5	0.0119	7
C_6	0.0797	8
C_7	0.0356	8
C_8	0.0065	6
C_9	0.0194	7
C_{10}	0.0435	7

[a]The full score was 10, and the passing score was 6.

in the comprehensive benefits evaluation system. Therefore, the sewage treatment construction projects in Huangzhou should give priority to the technical and economic benefits in the case of limited funds.

The weights of third-level indexes and actual scores of each index are shown in Table 8. And the evaluation result of comprehensive benefit was 7.0249, which indicated that the overall benefit of the sewage treatment plant was in average level to maintain normal operation.

4. Conclusions

A comprehensive evaluation method considering technical benefit, economic benefit, environmental benefit, and social benefit was established to evaluate sewage treatment construction project in small and medium towns. Results indicated that modified oxidation ditch process in sewage treatment plant was technically suitable for wastewater from the Economic Development Zone. Economically, the pretax and after-tax FIRR of the sewage treatment plant were 7.43% and 4.53%, respectively. They exceeded benchmark yield in sewage treatment industry, which predicated a pretty good return. Furthermore, payback period (P_t) of this sewage treatment plant was less than 16 years no matter pretax or after tax, which means the project can get payback within the specified time. From environmental standpoint, the project can substantially reduce regional water pollutants. SS, BOD_5, COD, TP, and NH_4^+-N can be reduced by 95%, 93.3%, 88%, 87.5%, and 82.22%, respectively. Environmental cost–benefit ratio was 1.38 in the first phase and 1.67 in the second phase. Cost–benefit ratio was greater than 1, indicating the positive environmental benefits. Social benefit evaluation also indicated that the project was consistent with local resident needs, demands of local economic development, and national policies. The comprehensive benefit of the sewage treatment plant was 7.0249, which was at a middle level. Sewage treatment construction project in small and medium towns will be an important direction to improve environment quality, control pollution, improve living quality of residents, and promote sustainable economic development.

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Supplementary information

1. Analytic hierarchy process

AHP is an evaluation model which is suitable for subjective factors to play an important role. AHP is a good method to determine the weight of indexes.

- Establishment of hierarchical structure

The classification and stratification of the studied problems is the basis of AHP. Each hierarchy is made up of several elements, and element in the same hierarchy is independent of each other (Fig. S1).

- Establishment of judgment matrix

Elements were marked from 1 to 9 based on the important degree of one element to another in a same hierarchy. The corresponding judgment matrix can be obtained according to the result of the scoring results. Target M has n element, $M = \{b_1, b_2, \ldots, b_n\}$. The importance of element b_1 to M was determined through being given score by experts, and calculated the weight of b_1 to M. By analogy, finally all the elements are sorted and compared.

Generally, the structure of judgment matrix $M = (b_{ij})n \times n$ is shown as follows:

$$M = \begin{Bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ b_{n1} & b_{n2} & \cdots & b_{nn} \end{Bmatrix} \tag{S1}$$

The judgment matrix M has four characteristics:

- The matrix is a positive reciprocal matrix.
- All the elements in the matrix are positive numbers, $b_{ij} > 0$.
- $b_{ij} = 1/b_{ji}$ $(i \neq j)$
- $b_{ii} = 1$ or $b_{ij} = 1$ $(i = j)$

Scale method proposed by Saaty was applied to quantify the importance of different elements in the matrix, which determined the weight of each element through comparison between two elements. The meanings of scores 1–9 are shown in Table S1.

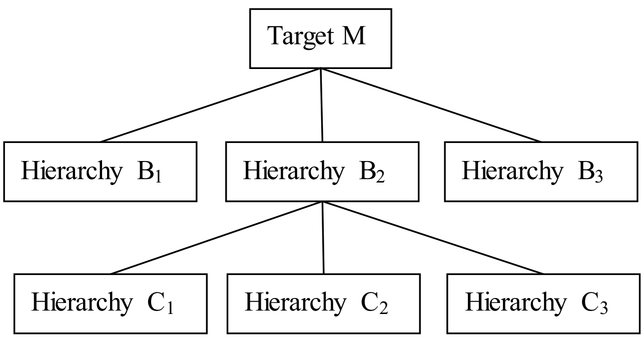

Fig. S1. Hierarchical structure diagram.

Table S1
1–9 scale method and the meanings of different score

Score	Meaning
1	*i* is as important as *j*.
3	*i* is a little more important than *j*.
5	*i* is obviously more important than *j*.
7	*i* is significantly more important than *j*.
9	*i* is totally more important than *j*.
2, 4, 6, 8	The comparison result is between the above judgments.

b_{ij} represents the importance of element i to j.

- Hierarchical single ordering

The weights of two elements (indexes) or multiple elements (indexes) to the final target were determined based on the maximum characteristic root and the corresponding eigenvector of the judgment matrix. The process of calculating the weight vector is called hierarchical single ordering, which is shown as Eq. (S2).

$$W_i = \frac{1}{n}\sum_{j=1}^{n}\frac{a_{ij}}{\sum_{k=1}^{n} a_{k1}} \tag{S2}$$

If $b_{ij} \times b_{jk} = b_{ik}$, then the matrix is called consistent matrix. Consistency index, random consistency index, and consistency ratio were used to carry out the consistency test of the results. If the test is qualified, the normalization results of elements in each column are the corresponding weights, and on the contrary, the judgment matrix should be restructured.

- Hierarchical overall ordering

Hierarchical overall ordering is to calculate the weight vector of the lowest index layer for the highest target layer, and to determine the importance of each element to the final

Table S2
Hierarchical overall ordering of layer *C*

Hierarchy *B* / Hierarchy *C*	B_1	B_2	……	B_m	Total sequencing of hierarchy *C*
	b_1	b_2	……	b_m	
C_1	c_1^1	c_1^2	……	c_1^m	$\sum_{j=1}^{m} b_j c_1^j$
C_2	c_2^1	c_2^2	……	c_2^m	$\sum_{j=1}^{m} b_j c_2^j$
……	……	……	……	……	……
C_n	c_n^1	c_n^2	……	c_n^m	$\sum_{j=1}^{m} b_j c_n^j$

target. The calculation method is generally from top to bottom and progressively layer by layer, and the results can be obtained based on the weights of hierarchical single ordering. For instance, if the overall ordering of the previous layer B has been completed, and the weights of B_1, B_2, …… B_m are b_1, b_2, …, b_m. Then the underlying elements and ordering results of C_1, C_2, …… C_m corresponding to B_j are $[c_{1j}, c_{2j}, …, c_{nj}]^T$ (if C_i is not associated with B_j, $c_{ij} = 0$), and the ordering results of layer C are shown in Table S2.

2. Results and discussion

The hierarchical structure of comprehensive benefit evaluation system is shown as Table 1 . The judgment matrixes of indexes in comprehensive benefit evaluation system were obtained based on Delphi Method. Six senior experts in the environmental protection and engineering field were invited to mark for different indexes, and the results were as follows:

$$M = \begin{bmatrix} 1 & 2 & 4 & 4 \\ 1/2 & 1 & 4 & 5 \\ 1/4 & 1/4 & 1 & 3 \\ 1/4 & 1/5 & 1/3 & 1 \end{bmatrix} \quad B_1 = \begin{bmatrix} 1 & 2 \\ 1/2 & 1 \end{bmatrix} \quad B_2 = \begin{bmatrix} 1 & 1/5 \\ 5 & 1 \end{bmatrix}$$

$$B_3 = \begin{bmatrix} 1 & 1/5 & 1/4 \\ 5 & 1 & 3 \\ 4 & 1/3 & 1 \end{bmatrix} \quad C_3 = \begin{bmatrix} 1 & 1/4 & 1/5 \\ 4 & 1 & 1/3 \\ 5 & 3 & 1 \end{bmatrix} \quad C_1 = \begin{bmatrix} 1 & 1/3 & 1/5 \\ 3 & 1 & 1/3 \\ 5 & 3 & 1 \end{bmatrix}$$

$$C_2 = \begin{bmatrix} 1 & 1/3 & 5 \\ 3 & 1 & 6 \\ 1/5 & 1/6 & 1 \end{bmatrix} \quad C_3 = \begin{bmatrix} 1 & 1/4 & 1/3 \\ 4 & 1 & 3 \\ 3 & 1/3 & 1 \end{bmatrix} \quad C_4 = \begin{bmatrix} 1 & 1/5 & 1/3 \\ 5 & 1 & 4 \\ 3 & 1/4 & 1 \end{bmatrix}$$

$$C_5 = \begin{bmatrix} 1 & 1/5 & 1/3 \\ 5 & 1 & 4 \\ 3 & 1/4 & 1 \end{bmatrix} \quad C_6 = \begin{bmatrix} 1 & 1/2 & 1/3 \\ 2 & 1 & 1/2 \\ 3 & 2 & 1 \end{bmatrix} \quad C_7 = \begin{bmatrix} 1 & 1/2 & 5 \\ 2 & 1 & 6 \\ 1/5 & 1/6 & 1 \end{bmatrix}$$

$$C_8 = \begin{bmatrix} 1 & 2 & 1/5 \\ 1/2 & 1 & 1/5 \\ 5 & 5 & 1 \end{bmatrix} \quad C_9 = \begin{bmatrix} 1 & 1/3 & 4 \\ 3 & 1 & 7 \\ 1/4 & 1/7 & 1 \end{bmatrix} \quad C_{10} = \begin{bmatrix} 1 & 1/3 & 1/5 \\ 3 & 1 & 1/3 \\ 5 & 3 & 1 \end{bmatrix} \tag{S3}$$

Weights of indexes were calculated based on matrix and YAAHP software. The results are shown as Table S3.

The hierarchical overall ordering is shown in Table S4.

Table S3
The weights of hierarchical indexes in comprehensive benefit evaluation system

M	Weight	B_1	Weight	B_2	Weight	B_3	Weight	B_4	Weight
B_1	0.4597	C_1	0.6667	C_3	0.1667	C_5	0.0936	C_8	0.0936
B_2	0.3437	C_2	0.3333	C_4	0.8333	C_6	0.6267	C_9	0.2797
B_3	0.1272					C_7	0.2797	C_{10}	0.6267
B_4	0.0694								

Table S4
The weights of overall indexes in comprehensive benefit evaluation system

C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
0.3065	0.1522	0.0573	0.2864	0.0119	0.0797	0.0356	0.0065	0.0194	0.0435