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Techno-economic analysis of municipal wastewater land treatment systems in China

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Abstract — This paper analyses the capital costs, power consumption and operation costs of municipal wastewater land treatment systems, including rapid infiltration, slow-rate infiltration, overflow and constructed wetland, by means of series engineering design. The results show that land treatment can save 50–70% of capital costs, 80–90% of power and 75–85% of operation costs when compared with secondary treatment.

Keywords: land treatment system; techno-economy; series design; cost model.

INTRODUCTION

Water shortage and pollution are worldwide problems. Municipal wastewater is a considerable water resource. At present in China, the amount of municipal wastewater is approximately equal to that of municipal water shortage on a national basis. Reasonable exploitation of municipal wastewater is of important social, environmental and economic significance in relaxing the tension of municipal water shortage and in development of production and environmental construction of urban and rural areas.

Modern science and technology has provided a variety of highly effective treatment processes of wastewater with different properties. Now in China, however, including Beijing City, the treatment capacity of municipal wastewater is very low. The reason is mainly because of lack of funds, energy and technological facilities. It is quite difficult for us to reach the goal of secondary treatment of all municipal wastewater in a period of considerable length in future. Even developed countries, such as the United States, Japan, have been unable to reach this goal. Hence, wastewater land treatment with less capital cost and power consumption and easier operation has been studied throughout the world. Land treatment systems (LTS) were initially used as one kind of third treatment and gradually tested to substitute secondary treatment. Practice has showed that LTS is not only one kind of wastewater treatment process but an effective way of wastewater utilization in agriculture and forestry as water resources. At present in China, there are several small and pilot scale experimental LTS in operation in Beijing, Tianjin, Shenyang, Kunming and Xinjiang areas and so on. As full scale LTS with treatment flow of 28000 m^3/d has been built in Xinjiang Autonomous Region. A 50000 m^3/d LTS is being planted in Jilin Province.

Land treatment is a process that purifies wastewater through physical, chemical and biological processes within soil, including filtration, adsorption and metabolism by soil microorganism. It can utilized the water and nutrients in wastewater for plant production and improve soil granular structure. According to soil permeability (k), LTS can be classified as rapid infiltration (RI) ($k \geqslant 5.0$ cm/h), slow rate infiltration (SR) ($k \geqslant 0.15$ cm/h), overflow (OF) ($k \leqslant 0.5$ cm/h) and constructed wetland (WL) ($k \leqslant 0.5$ cm/h). They have different hydraulic loading rate generally within 0.6 – 120 m/a, which are all less than those of secondary treatment. Hence, the availability of big areas is a controlling factor for LTS.

This paper analyses the techno-economic efficiency of LTS by means of series engineering design on the base of experimental results obtained from RI, SR, OF and WL LTS in Beijing, Tianjin and Shenyang and so on.

TECHNO-ECONOMIC INDEXES OF LTS

The basic method of cost analysis is establishment of cost functions or regression equations by means of mathematical statistics on the basis of huge raw data. It is also necessary for the establishment of LTS cost function to have certain amount of

Table 1 Technological indexes of LTS in series design

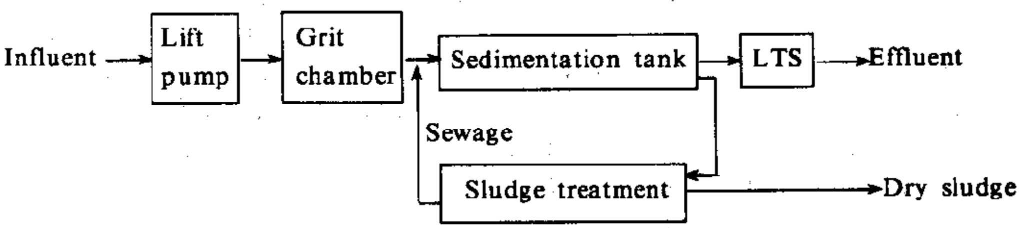
LTS	Hydraulic loading, m/a	BOD_5, mg/L		COD, mg/L		Number and size of treatment basin
		Influent	Effluent	Influent	Effluent	
RI	40	150	5	300	30	W/L = 0.33 – 0.67, 3n, square: a ≤ 200
SR_1	3.0	150	2	300	20	W/L = 0.42 – 0.75, rectangle: a = 200 b = 50
SR_2	6.5	150	2	300	20	W/L = 0.40 – 0.80, rectangle: a ≤ 200 b ≤ 50
OF	15 – 18	150	2	300	20	W/L = 0.50 – 0.83, rectangle: a ≤ 200 b ≤ 38
WL	15	150	7	300	45	W/L = 0.60 – 0.83, rectangle: a ≤ 200 b ≤ 25

W/L = The ratio of width over length of site; RI = The rapid infiltration LTS;
SR = The slow rate infiltration LTS; OF = The overflow LTS; WL = The wetland LTS

representative cost points. Since land treatment in China is still in experimental stage and lack of operation data and full scale engineering examples, series design of seven different engineering scale of all fine LTS is made to analyze their techno-economic indexes, power consumption and benefit. The technological indexes in Table 1 are used in series design according to characteristic of municipal wastewater and experimental results of LTS in China.

COST FUNCTIONS OF LTS

The following technological process is used in the series design:



When a site is laid out in series design, it is assumed that the gradient of conveyance channel agree with the natural slope of the site, costs for levelling the site are considered for all kinds of LTS but RI, costs for construction of overflow slope is also included in OF design, and ponds with storage volume of wastewater for 8–16 hours is taken into account in SR design.

The costs of LTS include three parts: (1) cost of purchasing land, (2) capital costs and (3) yearly operation costs. Cost of purchasing land is dependant on the size of LTS and land price. Although LTS cover larger areas than activated sludge treatment process, all kinds of LTS, except RI, have profits. For instance, trees and agricultural crops can be grown in SR, forage grasses in OF and reeds in WL. For this, the area covered by a LTS is related to agricultural and forestry production. Capital costs include expenses of main and auxiliary engineering structures, of management of unit in charge of construction, of test, design and reconnaissance, of necessary complementary engineering such as residence of staff and workers and their family members, and unexpectable expenses. Results of series design are illustrated in Table 2 to Table 5. They show that as the treatment flow increasing, capital costs do not increase proportionally and linearly and the increment become less and less. The unit capital costs decrease as the treatment flow increases and the unit power consumption and operation costs also have the same relationship with treatment flow that hold about the form of power function as listed in Table 6. So the costs of a LTS should be a variable that changes according to treatment flow. The Q's indexes (a) of capital costs function are within the range of 0 to 1 ($0< a< 1$), which means that the increment of capital costs decrease as the increasing of treatment flow. While the unit capital costs, power consumption and operation costs with indexes (a) greater than -1 and less than 0 ($-1< a< 0$) reduce as the treatment flow increasing. This kind of relationship is referred to size-economic benefit of wastewater treatment plant.

Table 2 Capital cost indexes in series design ($\times 10^4$ RMB Yuan)

Flow, m^3/d	500	1000	5000	10000	20000	50000	100000
RI	59.50	78.68	140.21	219.36	324.68	547.98	874.76
SR_1	67.18	86.86	196.82	310.49	566.19	1089.18	1971.94
SR_2	60.66	78.96	145.89	236.38	404.59	708.25	1232.10
OF	50.79	65.77	113.64	188.98	284.24	379.95	633.46
WL	59.54	79.70	136.44	209.40	341.35	614.39	931.08

Table 3 Unit capital cost indexes in series design, RMB Yuan/($m^3 \cdot d$)

Flow, m^3/d	500	1000	5000	10000	20000	50000	100000
RI	1190.00	768.86	280.42	219.36	162.34	109.60	87.48
SR_1	1343.60	868.60	393.64	310.49	283.10	217.84	197.19
SR_2	1213.20	789.62	291.79	236.38	202.30	141.65	123.22
OF	1015.80	657.70	227.28	188.98	140.12	75.99	63.35
WL	1190.88	767.06	272.88	209.40	170.68	122.88	93.11

Table 4 Power consumption indexes in series design

Flow, m^3/d		500	1000	5000	10000	20000	50000	100000
Electricity consumption, $\times 10^4$ kWh/a	RI, SR & WL	4.54	7.00	31.55	63.09	84.09	173.45	231.27
	OF	5.18	7.64	32.18	64.36	86.73	180.18	248.81
Power kWh/($m^3 \cdot d$)	RI, SR & WL	0.25	0.19	0.172	0.173	0.115	0.095	0.063
	OF	0.28	0.21	0.176	0.176	0.118	0.099	0.068

Table 5 Operation costs in series design, RMB Yuan/($m^3 \cdot d$)

Flow, m^3/d	500	1000	5000	10000	20000	50000	100000
RI	0.184	0.123	0.047	0.038	0.025	0.017	0.011
SR_1	0.199	0.124	0.052	0.042	0.029	0.020	0.014
SR_2	0.170	0.109	0.045	0.036	0.025	0.017	0.012
OF	0.157	0.102	0.039	0.034	0.023	0.016	0.011
WL	0.183	0.129	0.050	0.039	0.026	0.017	0.012

Table 6 Models of costs and power consumption of LTS

LTS	Capital costs, $\times 10^4$ RMB Yuan	Unit capital cost, RMB Yuan/($m^3 \cdot d$)	Power consumption, kW/m^3	Operation costs, RMB Yuan/($m^3 \cdot d$)
RI	$C_C=38.0+0.3401Q^{0.6780}$	$C'-560+70533Q^{-0.6648}$	$E_0=0.0453Q^{-0.2283}$	$C=4.334Q^{-0.5150}$
SR_1	$C_C=46.0+0.1140Q^{0.8453}$	$C'=171+88657Q^{-0.6968}$	$E_0=0.0453Q^{-0.2283}$	$C=3.662Q^{-0.4859}$
SR_2	$C_C=44.0+0.1302Q^{0.7915}$	$C'=100+93643Q^{-0.7130}$	$E_0=0.0453Q^{-0.2283}$	$C=3.300Q^{-0.4887}$
OF	$C_C=25.0+0.6648Q^{0.5903}$	$C'=31+55259Q^{-0.6422}$	$E_0=0.0554Q^{-0.2427}$	$C=3.260Q^{-0.4964}$
WL	$C_C=38.0+0.2787Q^{0.7017}$	$C'=69+82377Q^{-0.6913}$	$E_0=0.0453Q^{-0.2283}$	$C=4.609Q^{-0.5200}$

COMPARISON BETWEEN LTS AND ACTIVATED SLUDGE PROCESS

Area index of a LTS is higher than corresponding secondary treatment plant, which limits the application of LTS to certain degree. But since capital, operation and management costs of secondary treatment processes are higher than LTS, LTS are still economical in certain range of land price and site size in point of total costs.

$$\text{Total costs: } C=C_C+P_0\times C_G+A\times P_r \quad .$$

where, C is total costs. $\times 10^4$ RMB Yuan; C_C is Capital costs, $\times 10^4$ RMB Yuan; P_0 is year for calculation of operation costs, 5 years are used here for calculation; C_G is yearly operation costs, $\times 10^4$ RMB Yuan; A is site area, ha; P_r is land price, $\times 10^4$ RMB Yuan/h.

Table 7 shows the critical land price of LTS which have the same total costs as secondary treatment process. Critical land price decreases as the treatment flow increasing. It has a decreasing order of RI > OF > WL > SR_2 > SR_1 . According to the present land price in China, LTS are suitable to wastewater treatment with flow of $\leqslant 50000 m^3/d$ for medium and small cities and not suitable to higher flow and higher land price.

Taking the RI as example, comprehensive comparison of techno-economic indexes between LTS and secondary treatment is illustrated in Table 8. LTS can save 50－75% of capital costs, 80－90% of power and 75－85% of operation costs over secondary treatment process.

Table 7 Critical prices of LTS

Flow, m^3/d	5000	10000	15000	20000	30000	40000	50000	75000	100000	200000
RI	<120	≤120	<105	<105	≤105	<90	<90	<90	≤90	≤75
SR_1	≤9.0	<7.5	≤7.5	<6.0	<6.0	≤6.0	<4.5	<4.5	<4.5	≤4.5
SR_2	<18	<18	≤18	<15	<15	≤15	<12	<12	≤12	≤7.5
OF	<53	<53	≤53	<48	≤48	<45	<45	≤45	≤42	≤38
WL	<45	≤45	<38	<38	≤38	<35	≤35	<30	≤30	≤27

Table 8 Comparison between RI- LTS and activated sludge process

Flow,	Capital costs, RMB Yuan/(m^3· d)			Power consumption, kWh/(m^3· d)			Operation costs, RMB Yuan/(m^3· d)		
m^3/d	RI	ASP	RI/ASP, %	RI	ASP	RI/ASP, %	RI	ASP	RI/ASP, %
≤100000	80－100	600－700	13－14	0.048－0.072	0.43－0.53	11－14	0.012－0.017	0.13－0.15	9－12
≤50000	100－120	700－800	14－15	0.072－0.096	0.48－0.72	15－13	0.017－0.024	0.15－0.16	12－15
≤20000	120－180	800－900	15－20	0.096－0.120	0.60－0.96	16－13	0.024－0.037	0.16－0.18	15－21
≤10000	180－300	900－1200	20－25	0.120－0.200	0.67－1.44	18－14	0.037－0.068	0.18－0.21	21－33
≤5000	300－800	1200－1900	25－42	0.200－0.240	1.15－1.44	17－16	0.068－0.170	0.21－0.26	33－63
≤1000	800－1200	1900－2200	42－55	0.240－0.290	1.20－1.68	20－17	0.170－0.230	0.26－0.28	63－83

ASP＝Activated sludge process.

From what mentioned above, LTS have advantages over secondary treatment not only in treatment effects but also in capital costs, power consumption and operation and management in certain range of site size and land price. When agricultural profits taken into account, LTS are much more advantageous than secondary treatment. Consequently, we hope that land treatment can be widely accepted and applied to a degree of actual engineering scale in the future.

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