Wastewater treatment design parameter analysis using the Nan-Men contact bed treatment facility in Northern Taiwan

Hoei-Yuan Hwang, Shu-Min Shen and Hung-Yuan Fang

ABSTRACT

Contact bed treatment is one of the methods used for constructed wetlands. Taiwan introduced contact bed treatment to treat sewage in 2004. The reference design parameters are based on data obtained from developed countries. These foreign designs ignore the unique hydrological environment and climate of Taiwan. This study tried to analyze the water quality of the contact bed treatment system and to assess the efficiency of design parameter, based on that to propose design parameters to similar facilities on Taiwan. This study shows that the out-site contact bed treatment design should be changed to increase the aeration and disinfection parameters with the DO greater than 5 mg/L, BOD_5 optimal concentration of 10–25 mg/L, COD of 32–60 mg/L, SS of 15–25 mg/L, NH_3-N concentration can be greater than 16 mg/L, hydraulic retention time of two hours, gravel size of 10–15 cm, porosity of 30–50%, with the water flow rate less than 10 cm/s and sludge accumulation of 10 to 15 days. These studies conducted long term observation in accordance with local conditions. The above data are available to provide local design parameters for future follow-up designs.

Key words | constructed wetland, contact bed treatment, hydraulic retention time (HRT), Intermittent sand filter, loading rate (LR), subsurface flow wetland

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INTRODUCTION

Constructed wetlands used for wastewater treatment began in Germany in 1952. Countries around the world subsequently began to apply this technology. The United States began to use constructed wetlands to treat domestic wastewater, fish products and phosphorus containing wastewater in 1967, 1971 and 1974. Japan set up the 1st contact bed treatment on the Tamagawa River in 1981. These systems cost less than conventional sewage treatment with flexible treatment site selection.

Contact bed treatment is one of the methods used to construct wetlands providing a fast, effective sewage treatment method. W. J. Debden, a sewage treatment engineer in London, designed a natural treatment method in the 19th century. Sewage should be allowed to flow rapidly through coarse gravel, allowing the organic matter in the wastewater to be decomposited into biofilm on the gravel (Kinnicutt 1902). This functions as a short term sewage treatment. The water purification mechanisms include precipitation, adsorption and decomposition.

Dr. Alexander Muller from Berlin, Germany (1865) constructed an intermittent sand method to treat sewage. He set a contact bed with sand particle sizes less than 0.02 m. The sewage moved intermittently through to the contact bed with a hydraulic load of 0.000047–0.0705 m/day. In 1953 K. Seidel constructed a subsurface flow wetland to treat sewage. Aquatic plants were cultivated onto sand with a particle size less than 0.06 m or small stones, so that more micro-organisms could attach to the root surface area removing organic matter that included part of the nitrogen and phosphorus. Hung (2004) built a

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contact bed treatment system in the Horikawa River with slow flow in Chiba Japan. The river water flowed directly through the system being continuously filtered by natural forces. The bed treatment area was 0.62 ha, deep of 1.60 m, with an HRT of 0.05 days, inflow of 32,852 m^3/day, hydraulic load rate of 4.0 m/day, air traffic of 34.2 m^3/min, removal rate of BOD_5 and SS of 75% and 78%. Spieles & Mitsch (2000) determined the construction costs were relatively high at about 362,000 U.S. dollars per hectare more than 7 times the cost of a surface flow wetland. However this method can accept a high sewage load and will not breed mosquitoes and odor. It is suitable for use in a smaller area with a higher treatment effect.

Taiwan introduced contact bed sewage treatment in 2004. The design parameters are base on data obtained from developed countries. Current wetland designs ignore the unique hydrological environment and climate of Taiwan. This study conducted a comprehensive assessment of the water quality treatment using the Nan-Men contact bed treatment system in Hsinchu city. Local design parameters are provided for the future design of similar facilities in Taiwan. The design information is first collated followed by analysis of pH, DO, BOD_5, COD, SS, NH_3-N and *E. coli* concentration removal rate, hydraulic retention time and response factor. These data are compared with information from developed countries. Design parameters and recommendations for improvement in Taiwan wetland design are given.

MATERIALS AND METHODS

Research steps

This study collected information including the environmental background, pollutants, water quality characteristics, and water sampling and analysis methods. A pollutant removal efficiency assessment was conducted in accordance with the analysis results. The pollutant removal impact factors, including the inflow concentration and pollutant removal rate ratio, nutrient loading rates, water quality dissolved oxygen, gravel size and porosity, biofilm and sludge exclusion are discussed and compared with similar methods used in foreign countries. Recommendations for current treatment system improvement and design parameters that are appropriate for constructing similar future facilities in Taiwan.

The Nan-Men contact bed treatment system at Hsinchu

The Nan-Men River originates in the Gau-yeng region of Hsinchu City. This river is a tributary of the Keh-Yea River, close to the Hsinchu Industrial Science Park, The Nan-Men River has a total length of 2.14 kilometres, with an average gradient of 0.021. The annual average rainfall is 1,639 mm. More rainfall fall occurs in May to August each year. The dry season is September to January of the following year. The average temperature range is between 18.9–26°C. The population is about 35,000 in the coastal area. The river flow is 7,200–14,000 CMD, with an average of 10,000 CMD. The water is contaminated due to domestic sewage and livestock wastewater discharged into the river with BOD_5 of 14–25 mg/L, COD of 20–40 mg/L, SS of 7–20 mg/L. In order to improve the river water quality, the Hsinchu City Government set up contact bed water treatment on the river to treat sewage in January 2006. The facility was completed in December 29, 2006. The total length of this system is 140 m, width of 8 m, an area of 2,400 m^2, with an elevation gradient of 1–1.2 m. The Nan-Men River water first enters the treatment facility through gravity flow. The water flows into a 3 column grid and into 3 sedimentation tanks after screening. The water then flows into 3 contact bed treatment tanks. After the water purification is completed, the water flows into the original river through 3 channels. The water flow over design directs the excess water into a direct overflow system. The design data reference is "the guidelines for river purification" from Japan as follows: (1) 3 precipitation tanks (30 m × 8 m × 1.5 m); (2) 3 contact bed treatment tanks (35 m × 8 m × 2.5 m); (3) Design flow 10,000 CMD; (4) retention time in the contact bed treatment tank of 1.5 hr; (5) flow through length the contact bed treatment tank length of 135 m; (6) gravel size of 10–15 cm; (7) porosity of 50%; (8) contact material surface area of 50 m^2/m^3; (9) effective water depth of 1.7 m; (8) gravel thickness of 1.7 m; (9) BOD_5 inflow concentration of 25 mg/L, removal rate is expected to be more than 30%; (10) SS inflow concentration of 20 mg/L, removal rate is expected to be more than 40%; (11) COD inflow concentration of 40 mg/L, removal rate is expected to be more than 40%; (12) BOD_5 coefficients $K = 0.01\,\text{day}^{-1}$; (13) sludge accumulation of 90 days; (14) sludge concentration Sc = 10%.

Design parameter theory

The mechanism used to remove pollutants include physics, chemistry and micro-organisms reaction in the subsurface flow system, underground gravel movement is the scope of Darcy's Law, the most important pollutant decomposition conditions are the reaction rate and retention time (Environmental Protection Administration 2000). The design parameter theory is as follows:

1. Hydraulic retention time (HRT): Affected with saturated hydraulic conductivity coefficient, porosity, flow et, saturated hydraulic conductivity coefficient and porosity can be selected in the construction. The flow and water depth are determined by the wetland operating parameters.

$$\mathrm{HRT} = \frac{\phi K_s l^2 Z_0^3}{3Q^2}\left[1 - \left(1 - \frac{2Qx}{K_s l^2 Z_0^2}\right)^{3/2}\right] \qquad (1)$$

ψ is the wetland porosity, K_s is the saturated hydraulic conductivity coefficient of the gravel, l is the width of the wetland, Z_0 is the wetland water depth, Q is the flow.

2. The first order reaction rate (K_v): The reaction rate constant for a chemical substances to decompose in the wetlands.

$$\frac{C_0}{C_i} = \exp^{-K_v \mathrm{HRT}} \qquad (2)$$

C_i is concentration of the chemical substances in the wastewater inflowing into the wetland, C_0 is the concentration of the chemical substances in the wastewater out flowing from the wetland.

3. Loading rate (LR): The weight of BOD, TN, NH_4, and TP entering into the wetlands.

$$\mathrm{LR} = C_i \cdot \frac{Q}{A} = C_i \cdot \mathrm{HLR} \qquad (3)$$

LR is the weight of the nutrients entering into the wetlands per day (g/m^2 Day).

4. Removal rate (R): The changes in nutrient concentration in the inflow and outflow to the wetlands.

$$R = \frac{(C_i - C_0)}{C_i} \times 100\% \qquad (4)$$

Or change in mass.

$$R = \frac{(C_i Q_i - C_0 Q_0)}{C_i Q_i} \times 100\% \qquad (5)$$

Q_0 is the wastewater outflow from the wetland; Q_i is the wastewater flow into the wetland.

5. Removal rate per day (R_d)

$$R_d = \frac{R}{\mathrm{HRT}} \qquad (6)$$

Experimental methods

This system was completed at the end of 2006. The sampling conditions are running under normal weather conditions with no expected rainy. The sampling points include the inlet department, outlet department of 3 sedimentation tanks, outlet department of 3 contact bed treatment tanks with 7 sampling point. The sampling frequency was once every two weeks from November 2008 to May 2009. The sampling containers were five PVC 1,000 mL plastic bottles. Before sampling, the containers are first cleaned with alcohol then rinsed with deionized water and dried. The onsite test items are pH, DO, BOD_5, COD, SS, NH_3-N and *E. coli*. Samples were fixed onsite and than brought back to laboratory for analysis. The water quality sampling and analysis method were conducted in accordance with Taiwan water quality testing standard procedures. The quality control testing included a blank sample test, sample check and duplicate sample analysis.

RESULTS AND DISCUSSION

Effectiveness of water treatment

The water treatment results for November 2008 are collated in Tables 1 to 7 below. The water treatment efficiency is illustrated as following:

Table 1 | The pH trends of Hsinchu Nan-Men contact bed treatment

Sampling time	Inflow	Sedimentation tank	Outflow 1st tank	2nd tank	3rd tank
2008/11/30	7.8	7.7	7.6	7.6	7.5
2008/12/14	7.7	7.5	7.4	7.5	7.3
2008/12/28	7.4	7.3	7.1	7.0	7.2
2009/1/11	7.2	7.2	7.0	7.0	6.9
2009/1/25	7.0	6.9	6.8	6.7	6.8
2009/2/8	6.9	6.7	6.6	6.8	6.7
2009/2/22	7.6	7.6	7.5	7.3	7.4
2009/3/8	7.5	7.3	7.2	7.1	7.0
2009/3/22	8.0	7.8	7.5	7.4	7.6
2009/4/5	7.9	7.8	7.6	7.7	7.5
2009/4/19	8.2	7.9	7.7	7.6	7.8
2009/5/3	7.3	7.1	6.9	6.8	6.6
Average	7.5	7.4	7.2	7.2	7.2

The pH trends are shown in Table 1. From the table, the inflow was 6.9–8.2, with an average of 7.5 ± 0.4. The outflow from 3 contact treatment beds was 1st tank at 6.6–7.7, average of 7.2 ± 0.4; 2nd tank at 6.7–7.7, average of 7.2 ± 0.4; 3rd tank at 6.6–7.8, average of 7.2 ± 0.4. From the above data, the inlet and outlet pH was maintained at neutral, with no big change.

Table 2 | The DO trends of Hsinchu Nan-Men contact bed treatment

Sampling time	Inflow (mg/L)	Sedimentation tank (mg/L)	Outflow (mg/L) 1st tank	2nd tank	3rd tank
2008/11/30	3.8	3.8	3.7	3.6	3.4
2008/12/14	3.7	3.7	3.4	3.5	3.3
2008/12/28	3.4	3.4	3.1	3.2	3.2
2009/1/11	4.2	4.2	4.0	3.8	3.9
2009/1/25	4.5	4.5	4.2	4.3	4.0
2009/2/8	3.9	3.9	3.6	3.5	3.7
2009/2/22	3.6	3.6	3.4	3.3	3.2
2009/3/8	3.5	3.5	3.2	3.3	3.0
2009/3/22	4.8	4.8	4.0	4.2	4.1
2009/4/5	4.0	4.0	3.8	3.5	3.7
2009/4/19	4.2	4.2	3.9	3.7	3.6
2009/5/3	4.3	4.3	4.1	4.0	3.9
Average	4.0	4.0	3.7	3.7	3.6

The DO trends are shown in Table 2. From the table, the inflow was 3.4–4.8 mg/L, with an average of 4.0 ± 0.4 mg/L. The outflow from 3 contact treatment beds was 1st tank at 3.1–4.2 mg/L, average of 3.7 ± 0.4 mg/L; 2nd tank at 3.2–4.3 mg/L, average of 3.7 ± 0.4 mg/L; 3rd tank at 3.0–4.1 mg/L, average of 3.6 ± 0.4 mg/L. From the above data, the inflow was slightly higher than the outflow. Part of the DO was used by micro-organisms in the contact bed treatment tank.

The BOD_5 trends are shown in Table 3. From the table the inflow is 10.60–25.20 mg/L, with an average of 15.34 ± 4.82 mg/L. The outflow from 3 contact treatment beds was 1st tank at 5.80–15.00 mg/L, average of 8.88 ± 3.24 mg/L and average removal rate of 42.11 ± 8.20%; 2nd tank at 5.20–13.20 mg/L, average of 8.66 ± 3.28 mg/L and average removal rate of 43.55 ± 10.11%; 3rd tank at 5.30–13.90 mg/L, average of 8.55 ± 2.80 mg/L and average removal rate of 44.26 ± 10.26%. The total removal rate is 42.11–44.26%.

The COD trends are shown in Table 4. From the table the inflow is 31.60–76.20 mg/L, with an average of 45.38 ± 13.63 mg/L. The outflow from 3 contact treatment beds was 1st tank at 16.00–40.30 mg/L, average of 22.58 ± 8.46 mg/L and average removal rate of 50.46 ± 10.16%; 2nd tank at 15.20–40.50 mg/L, average of 24.92 ± 8.35 mg/L and average removal rate of 45.32 ± 10.67%; 3rd tank at 15.60–40.70 mg/L, average of 26.63 ± 8.53 mg/L and average removal rate of 43.77 ± 9.62%. The total removal rate is 43.77–50.46%.

The SS trends are shown in Table 5. From the table the inflow is 15.20–25.30 mg/L, with an average of 20.82 ± 3.71 mg/L. The outflow from 3 contact treatment beds was 1st tank at 7.00–16.10 mg/L, average of 11.37 ± 2.41 mg/L and average removal rate of 45.39 ± 9.50%; 2nd tank at 8.10–15.30 mg/L, average of 11.80 ± 2.09 mg/L and average removal rate of 43.32 ± 9.11%; 3rd tank at 7.90–14.00 mg/L, average of 11.12 ± 1.67 mg/L and average removal rate of 46.59 ± 7.94%. The total removal rate is 43.32–46.59%.

The NH_3-N trends are shown in Table 6. From the table the inflow is 9.20–16.40 mg/L, with an average of 13.21 ± 2.37 mg/L. The outflow from 3 contact treatment beds was 1st tank at 4.70–10.00 mg/L, average of 8.39 ± 1.51 mg/L and average removal rate of

Table 3 | The BOD_5 water quality analysis of Hsinchu Nan-Men contact bed treatment

		Outflow concentration (mg/L)			Removal rate (%)			Remove (g/m^2 day)			
Sampling time	Inflow concentration (mg/L)	1st tank	2nd tank	3rd tank	1st tank	2nd tank	3rd tank	1st tank	2nd tank	3rd tank	Inflow loading rate (g/m^2 day)
2008/11/30	25.20	15.00	13.20	11.00	40.37	47.62	56.35	2.14	2.52	2.98	5.29
2008/12/14	23.60	11.60	12.88	12.20	50.84	45.42	48.30	2.52	2.25	2.38	4.96
2008/12/28	17.30	13.20	13.50	13.90	23.70	21.97	19.66	0.86	0.80	0.71	3.63
2009/1/11	18.20	12.20	11.60	11.10	32.97	36.26	39.01	1.26	1.39	1.49	3.82
2009/1/25	14.80	8.50	7.40	8.00	42.57	50.00	45.95	1.32	1.55	1.43	3.11
2009/2/8	12.80	5.80	5.20	5.60	54.68	59.38	56.25	1.47	1.60	1.51	2.69
2009/2/22	12.20	6.10	5.40	6.20	50.00	55.74	49.18	1.28	1.43	1.26	2.56
2009/3/8	10.90	5.90	5.50	5.30	45.87	49.54	51.38	1.05	1.13	1.18	2.29
2009/3/22	13.40	7.50	7.10	7.90	44.02	47.01	41.04	1.24	1.32	1.16	2.81
2009/4/5	12.60	7.50	7.90	7.40	40.47	37.30	41.27	1.07	0.99	1.09	2.65
2009/4/19	12.50	7.20	7.80	7.50	42.40	37.60	40.00	1.11	0.99	1.05	2.63
2009/5/3	10.60	6.10	6.50	6.60	42.45	38.68	37.74	0.94	0.86	0.84	2.27
Average	15.34	8.88	8.66	8.55	42.11	43.55	44.26	1.36	1.40	1.43	3.22

Table 4 | The COD water quality analysis of Hsinchu Nan-Men contact bed treatment

		Outflow concentration (mg/L)			Removal rate (%)			Remove (g/m^2 day)			
Sampling time	Inflow concentration (mg/L)	1st tank	2nd tank	3rd tank	1st tank	2nd tank	3rd tank	1st tank	2nd tank	3rd tank	Inflow loading rate (g/m^2 day)
2008/11/30	76.20	36.20	35.10	37.40	52.48	53.93	50.91	8.40	8.63	8.15	16.00
2008/12/14	63.50	29.30	30.20	33.20	53.85	52.44	47.71	7.18	6.99	6.36	13.33
2008/12/28	52.20	40.30	40.50	40.70	22.79	22.41	22.03	2.49	2.46	2.42	10.96
2009/1/11	55.30	36.60	34.80	33.30	33.82	37.07	39.78	3.93	4.31	4.62	11.61
2009/1/25	43.60	20.50	19.20	22.55	52.98	55.96	48.38	4.85	5.12	4.42	9.16
2009/2/8	37.90	17.40	16.60	17.60	54.09	56.20	53.56	4.31	4.47	4.26	7.96
2009/2/22	36.60	16.00	15.20	15.80	56.28	58.47	56.83	4.33	4.49	4.37	7.69
2009/3/8	31.70	16.70	17.10	15.60	47.31	46.06	50.78	3.15	3.07	3.38	6.66
2009/3/22	40.90	22.50	25.10	23.90	44.99	38.63	41.56	3.86	3.32	3.57	8.59
2009/4/5	38.90	23.50	22.90	25.40	39.59	41.13	34.70	3.23	3.36	2.84	8.17
2009/4/19	38.50	21.20	22.80	22.50	44.94	40.78	41.56	3.63	3.30	3.36	8.09
2009/5/3	31.60	20.10	19.50	19.60	36.39	38.29	37.97	2.42	2.54	2.52	6.64
Average	45.58	22.58	24.92	25.63	50.46	45.32	43.77	4.83	4.34	4.19	9.57

36.48 ± 13.41%; 2nd tank at 5.10–9.80 mg/L, average of 8.50 ± 1.40 mg/L and average removal rate of 35.65 ± 13.37%; 3rd tank at 4.90–9.80 mg/L, average of 8.43 ± 1.46 mg/L and average removal rate of 36.18 ± 12.07%. The total removal rate is 35.65–36.48%.

The *E. coli* trends are shown in Table 7. From the table the inflow is 8.85×10^5–1.45×10^6 CFU/100 mL, with an average of $1.45 \times 10^6 \pm 1.66 \times 10^6$ CFU/100 mL. The outflow from 3 contact treatment beds was 1st tank at 4.89×10^5–7.86×10^5 CFU/100 mL, average of $7.06 \times 10^6 \pm 9.40 \times 10^4$ CFU/100 mL and average removal rate of 37.08 ± 9.57%; 2nd tank at 4.95×10^5–8.05×10^5 CFU/100 mL, average of $7.00 \times 10^6 \pm 9.20 \times 10^4$ CFU/100 mL and average removal rate of 37.25 ± 9.85%;

Table 5 | The SS water quality analysis of Hsinchu Nan-Men contact bed treatment

		Outflow concentration (mg/L)			Removal rate (%)			Remove (g/m² day)			
Sampling time	Inflow concentration (mg/L)	1st tank	2nd tank	3rd tank	1st tank	2nd tank	3rd tank	1st tank	2nd tank	3rd tank	Inflow loading rate (g/m² day)
2008/11/30	25.30	11.20	13.10	12.40	55.73	48.22	50.99	2.96	2.56	2.71	5.31
2008/12/14	24.50	11.30	12.20	11.20	57.14	50.20	54.29	2.77	2.58	2.79	5.15
2008/12/28	19.30	12.50	11.80	12.20	35.23	38.86	36.79	1.43	1.58	1.49	4.05
2009/1/11	24.30	16.10	15.30	14.00	33.74	37.03	42.38	1.72	1.89	2.16	5.10
2009/1/25	17.20	9.20	10.00	10.20	46.51	41.86	40.69	1.68	1.51	1.47	3.61
2009/2/8	25.20	13.60	12.60	11.60	46.03	50.00	53.97	2.44	2.65	2.86	5.29
2009/2/22	24.40	12.80	13.20	11.80	47.93	45.90	51.64	2.44	2.35	2.65	5.12
2009/3/8	20.80	9.80	10.20	9.60	52.88	50.96	53.84	2.31	2.23	2.35	4.37
2009/3/22	15.20	7.00	8.10	7.90	53.95	46.71	48.02	1.72	1.49	1.53	3.19
2009/4/5	17.30	9.50	9.90	9.40	45.09	42.77	45.66	1.64	1.55	1.66	3.63
2009/4/19	18.70	10.40	10.80	10.50	44.38	44.39	43.85	1.74	1.66	1.72	3.93
2009/5/3	17.60	13.00	14.50	12.60	26.14	17.61	28.41	1.39	1.28	1.05	3.70
Average	20.82	11.37	11.80	11.12	45.39	43.32	46.59	1.98	1.89	2.03	4.37

Table 6 | The NH_3-N water quality analysis of Hsinchu Nan-Men contact bed treatment

		Outflow concentration (mg/L)			Removal rate (%)			Remove (g/m² day)			
Sampling time	Inflow concentration (mg/L)	1st tank	2nd tank	3rd tank	1st tank	2nd tank	3rd tank	1st tank	2nd tank	3rd tank	Inflow loading rate (g/m² day)
2008/11/30	15.30	9.20	9.10	9.40	39.87	40.52	38.56	1.28	1.30	1.24	3.21
2008/12/14	15.70	9.30	9.20	9.00	40.76	41.40	42.68	1.34	1.37	1.41	3.29
2008/12/28	10.80	9.50	9.80	9.20	12.03	9.26	14.81	0.27	0.21	0.34	2.27
2009/1/11	10.30	9.10	9.30	9.00	11.65	9.70	12.62	0.25	0.21	0.27	2.16
2009/1/25	13.20	7.80	7.60	8.00	40.90	42.42	39.39	1.13	1.18	1.09	2.77
2009/2/8	15.20	8.30	8.60	8.20	45.39	43.42	46.05	1.45	1.39	1.47	3.19
2009/2/22	16.40	9.10	9.20	9.80	44.51	43.90	40.24	1.53	1.51	1.39	3.44
2009/3/8	14.80	7.80	7.90	8.10	47.29	46.62	45.27	1.47	1.45	1.41	3.11
2009/3/22	9.20	4.70	5.10	4.90	48.91	44.56	46.74	0.95	0.86	0.90	1.93
2009/4/5	11.30	6.50	6.90	6.40	42.47	38.93	43.36	1.01	0.92	1.03	2.37
2009/4/19	13.70	9.40	9.80	9.50	31.39	28.46	30.66	0.90	0.82	0.88	2.88
2009/5/3	12.60	10.00	9.50	9.60	20.63	24.60	23.80	0.55	0.65	0.63	2.65
Average	13.21	8.39	8.50	8.43	36.48	35.65	36.18	1.01	0.99	1.00	2.77

3rd tank of 4.82×10^5–8.15×10^5 CFU/100 mL, average of $7.00 \times 10^6 \pm 9.90 \times 10^4$ CFU/100 mL and average removal rate of 37.00 ± 10.37%. The total removal rate is 37.00–37.25%.

Based on the above water quality analysis, the treatment effectiveness for some pollutants such as BOD_5, COD and SS compared with the original design value. The BOD_5 inflow concentration and removal rate are similar. The COD inflow concentration is slightly high, but the removal rate is similar. The SS inflow concentration is close to the original design, but the part sampling time is slightly high and the removal rate is similar.

Table 7 | The *E. Coli* water quality analysis of Hsinchu Nan-Men contact bed treatment

		Outflow concentration (CFU/100 mL × 10^3)			Removal rate (%)		
Sampling time	Inflow concentration (CFU/100 mL × 10^3)	1st tank	2nd tank	3rd tank	1st tank	2nd tank	3rd tank
2008/11/30	1,255	735	712	748	41.43	43.27	40.39
2008/12/14	1,300	786	754	768	39.54	42.00	40.92
2008/12/28	960	780	793	805	18.75	17.40	16.15
2009/1/11	935	725	746	752	22.46	20.21	19.68
2009/1/25	1,150	640	660	620	44.34	42.61	46.09
2009/2/8	1,200	660	650	620	45.00	45.83	48.33
2009/2/22	1,450	790	800	815	45.52	44.83	43.79
2009/3/8	1,160	718	725	740	38.10	37.50	36.21
2009/3/22	885	489	495	482	44.75	44.07	45.54
2009/4/5	995	591	586	623	40.60	41.11	37.39
2009/4/19	1,120	780	805	765	30.36	28.13	32.58
2009/5/3	1,050	783	725	755	25.42	30.95	28.09
Average	1,122	706	704	707	37.08	37.25	37.00

The relationship of concentration and removal rate

A logistical regression analysis was performed using the pollutant inflow concentration and removal rate. The BOD_5 inflow concentration is between 10.60–25.20 mg/L, with the average removal rate maintained at 40%. But greater than 25 mg/L, the removal efficiency is decreased as shown in Figure 1(a) and Table 3. The COD inflow concentration is between 31.60–76.20 mg/L, with the average removal rate maintained at 45%. But greater than 80 mg/L, the removal efficiency showed a non-significant increase as shown in Figure 1(b) and Table 4. The SS inflow concentration is between 15.20–25.30 mg/L, with the average removal rate is up from 35% to 50%. But greater than 25 mg/L, the removal efficiency is slowing down as shown in Figure 1(c) and Table 5. The NH_3-N inflow concentration is between 9.20–16.40 mg/L, with the average removal rate increased from 20% to 40%. But greater than 16 mg/L, the removal efficiency is slowing down as shown in Figure 1(d) and Table 6.

A logistical regression analysis was performed using the inflow pollution loading and remove rates. When the BOD_5 inflow loading rate is between 2.00–4.00 g/m^2 day, the pollutant removal is the best of 4.00–5.29 g/m^2 day. Removal slowed but maintained greater than 6.00 g/m^2 day as shown in Figure 2(a) and Table 3. The COD inflow loading rate is between 6.60–13.00 g/m^2 day. The pollutant removal is the best of 13.00–16.00 g/m^2 day. Removal slowed but maintained greater than 16.00 g/m^2 day with no significant change as shown in Figure 2(b) and Table 4. The SS inflow loading rate is between 3.19–5.31 g/m^2 day. The pollutant removal is the best as shown in Figure 2(c) and Table 5. The NH_3-N inflow loading rate is between 1.93–3.44 g/m^2 day with the pollutant removal is good as shown in Figure 2(d) and Table 6.

Calculating the logistical regression analysis using 1.5 hr HRT with the pollutant removal rate, the known the BOD_5 removal rate is 42.11–44.26%; the COD is 43.77–50.46%; the SS is 43.32–46.59%; the NH_3-N is 35.65–36.48%. The removal rate can not be increased with the retention time left unchanged. These results show the relationship with the original design conditions (Figure 3).

Based on the above analysis, the pollutant inflow concentration is within a certain range, the removal rate is up to the original target, but over a certain range, the efficiency may be reduced or slowed down. The reasons are as follows:

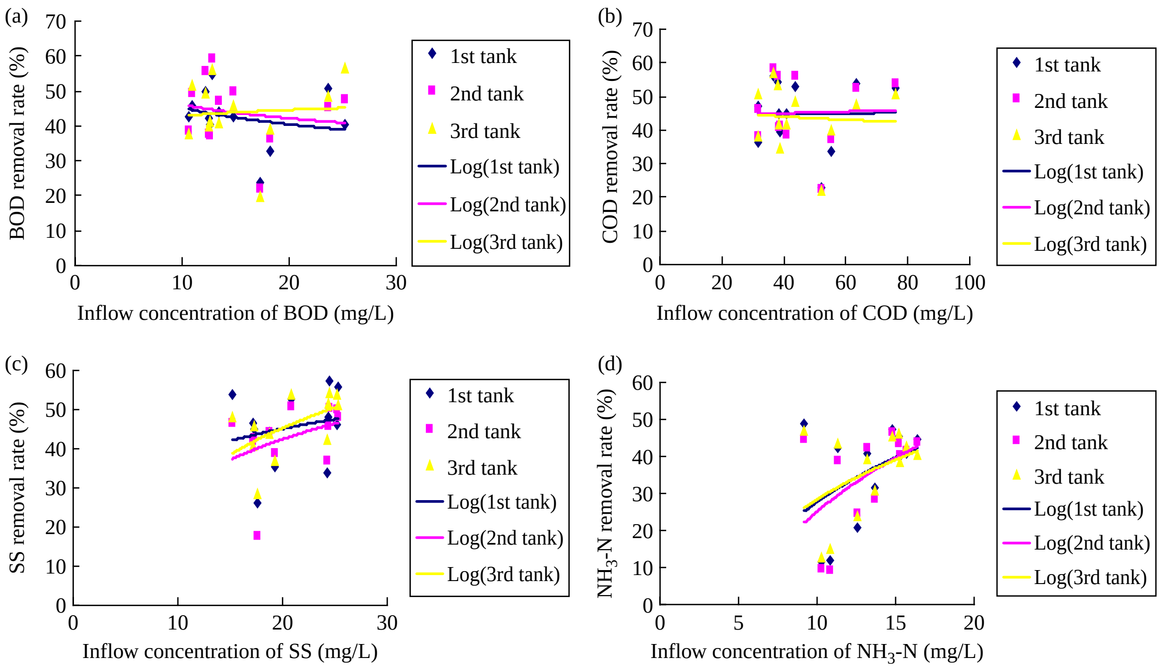

Figure 1 | The relationship of inflow concentration of pollutant and removal rate.

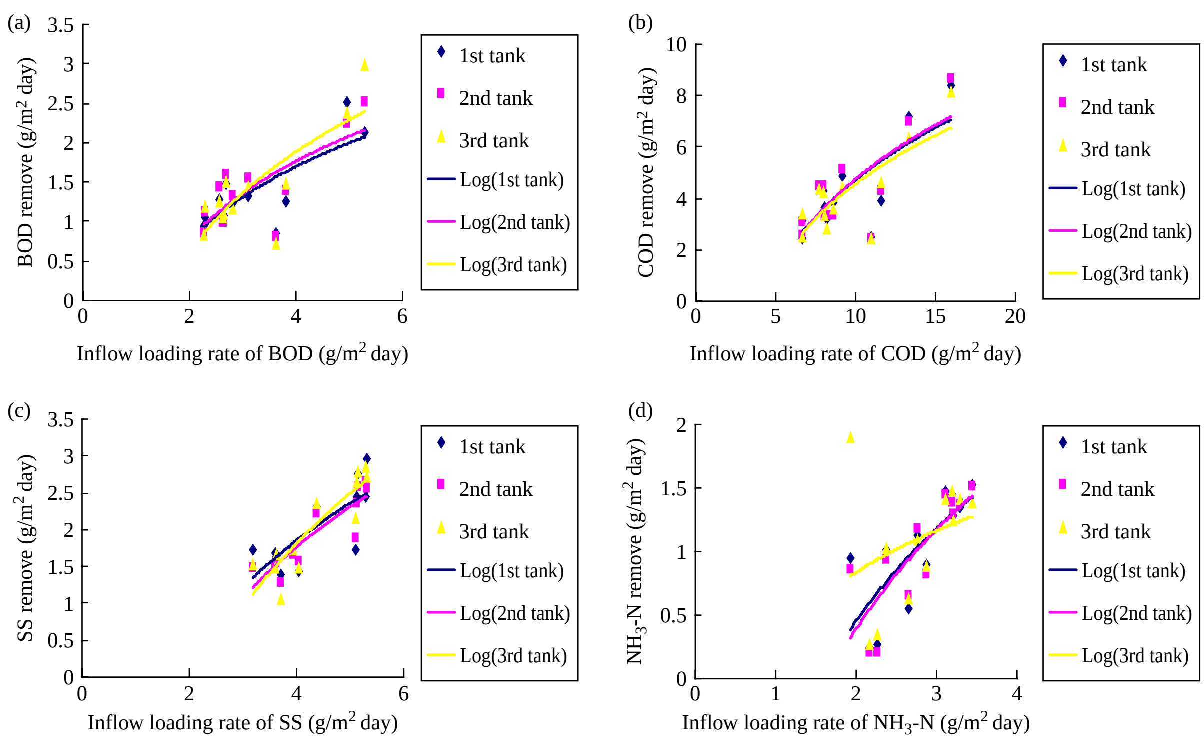

Figure 2 | The relationship of inflow loading rate of pollutant and remove.

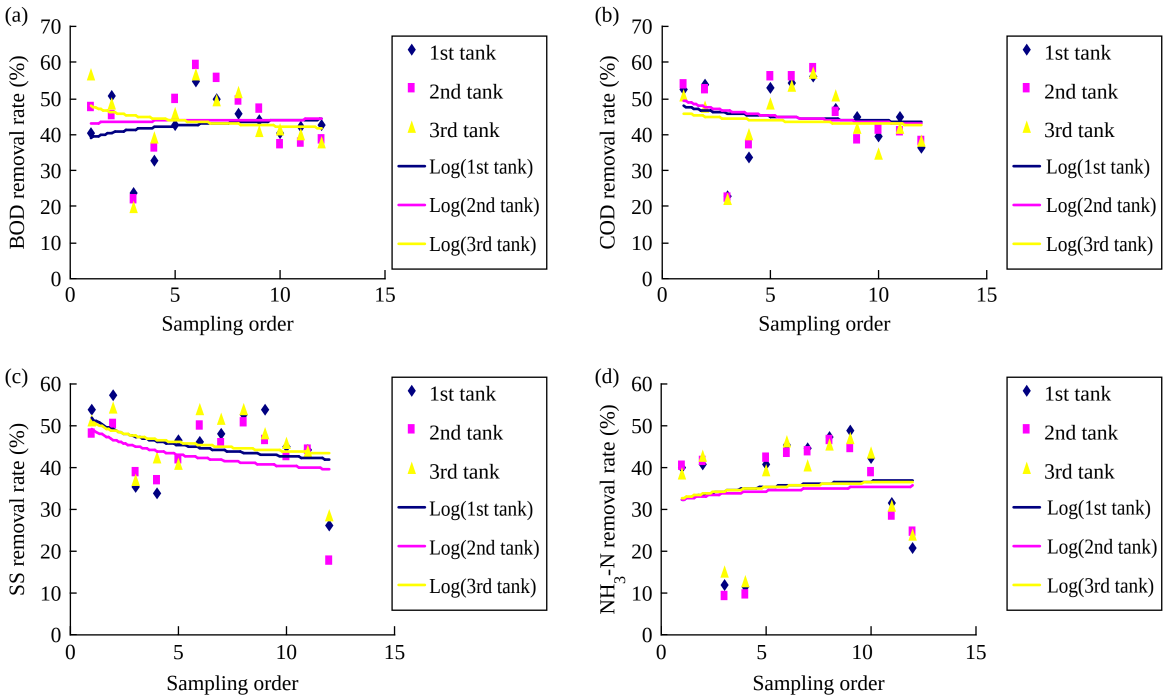

Figure 3 | The relationship of 1.5 hr retention time with pollutant removal rate.

1. No aeration facilities impact the treatment effectiveness. According to the Japanese literature, the BOD_5 removal rate was 70% of the HRT at 1 hour. The BOD_5 removal rate was 75% of the HRT at 1.2 hours. The BOD_5 removal rate was 80% of the HRT at 2 hours. When the HRT of this system was 1.5 hours, the BOD_5 removal rate was only 42.11–44.26%. One of the reasons is the DO was insufficient because this system is a closed body with anaerobic patterns. The biofilm is attached to the gravel and needs oxygen. The treatment effectiveness is affected if there is a shortage of DO. This system did not have aeration facilities producing a lower the BOD_5 removal rate.
2. Insufficient HRT impacts the treatment results. Based on the literature, the COD removal rate will be reduced if the HRT is extended. When the COD removal rate partial sampling time is lower, biofilm is still left in the tank bottom along with other deposits that the system has failed to clean. These deposits continue to decompose releasing carbon compounds, thereby affecting the COD removal rate.
3. Onsite treatment system impacts the treatment effectiveness. According to the Japanese research literature for contact bed water treatment efficiency showed that the SS inflow concentration is limited to 30 mg/L below non-aeration contact bed treatment systems. The highest SS concentration from this system is 25.30 mg/L and does not exceed the above limits. However this system an onsite method that the directly excavated under the river. The top of the slot is the bottom of the river bed. The river sediments may then be raised impacting the removal rate. In addition, the biofilm thickness on the gravel surface can increase with time impacting the SS removal rate.
4. The limit area impacts the treatment effectiveness. According to the literature, high temperature can increase the first-order BOD_5 and NH_3-N decomposition coefficient and simplify BOD_5 decomposition and denitrification. The average temperature of this system is 18.9–26°C, higher than that Europe or the United States. However the removal rate is better when the NH_3-N inflow concentration is 9.20–16.40 mg/L. The remaining concentrations are not impacted significantly. The reasons could be the limited area affected HRT, providing inadequate response time when the inflow concentration is increased, affecting the treatment effectiveness.

Table 8 | The comparison of Hsinchu Nan-Men with foreign contact bed treatment

	BOD_5			SS			NH_3-N		
Item	**Nan-men**	**Japan**	**Europe**	**Nan-men**	**Japan**	**Europe**	**Nan-men**	**Japan**	**Europe**
Inflow concentration (mg/L)	10.60–25.20	3.60–26.50	12.00–27.00	15.20–25.30	1.40–43.30	20.00–61.00	10.30–16.40	–	1.40–8.30
Ave. inflow concentration (mg/L)	15.34	12.20	15.34	20.82	8.60	32.57	13.21	–	4.78
Outflow concentration (mg/L)	5.20–15.00	1.00–16.80	2.00–4.00	7.00–16.10	0.60–13.00	4.00–8.00	4.70–10.00	–	0.50–0.70
Ave. outflow concentration (mg/L)	8.69	4.80	2.84	11.43	2.90	5.18	8.44	–	3.04
Removal rate of concentration (%)	19.66–59.38	28.80–90.20	72.70–88.90	17.61–57.14	39.00–98.90	76.70–87.60	9.26–48.91	–	−28.1–90.2
Ave. removal rate of concentration (%)	43.30	71.80	81.0	45.10	79.80	83.1	36.10	–	35.6
Inflow loading rate (g/m^2day)	2.27–5.29	–	0.21–0.46	3.19–5.31	–	0.46–1.22	1.93–3.44	–	0.02–0.17
Ave. inflow loading rate (g/m^2day)	3.22	–	0.27	4.37	–	0.65	2.77	–	0.10
Remove (g/m^2 day)	0.71–2.98	–	0.16–0.39	1.05–2.96	–	0.36–1.06	0.21–1.53	–	−0.02–0.10
Ave. remove (g/m^2 day)	1.39	–	0.25	1.96	–	0.54	1.00	–	0.04
K_v (1/day)	0.01	–	0.28–0.46	–	–	–	–	–	−0.01–0.46
Ave. K_v (1/day)	0.01	–	0.30	–	–	–	–	–	0.14
Area (ha)	0.24	3.00	0.05–0.09	0.24	3.00	0.05–0.09	0.24	3.00	0.05–0.09
Death (m)	1.7	0.69	–	1.7	0.69	–	1.7	0.69	–
Ave. porosity (%)	50	50	–	50	50	–	50	50	–
Ave. inflow (m^3/day)	10,000	86,400	148	10,000	86,400	148	10,000	86,400	148
retention time (day)	0.06	0.05	4.47	0.06	0.05	4.47	0.06	0.05	4.47

Remark: Japan information come form Nogawa facilities.

5. Biofilm membrane and hydraulic situation impact the treatment effectiveness. Biofilm membranes have different activities and growth situations under different hydraulic circumstances. According to Lau (1990, 1995) and Lau & Liu (1993) the high biofilm membrane accumulates at a lower speed. Yuhei *et al.* (1990) found that the speed is more than 10 cm/s. The biofilm membrane can be easily stripped. Lu (2006) found that the nitrification rate has a positive relationship when the speed is below 1.0 cm/s. If the speed is too great, the biofilm membrane at the bottom is easy to wash and rise, making the treatment effectiveness no good. The speed of this system is 0.5 m/s. A speed faster than this would affect the removal rate.

The relationship between inflow water quality and DO

Based on Japan International Construction Technology Development-river water quality report, the BOD_5 water quality in the 20–30 mg/L range and DO greater than 5 mg/L are better produced by contact bed treatment. If the contact bed treatment is aerated BOD_5 in the 50–80 mg/L range is appropriate. This system is non-aeration contact bed treatment with the actual BOD_5 inflow concentration in the10.60–25.20 mg/L range, with an average of 15.34 ± 4.82 mg/L; the actual DO is 3.4–4.8 mg/L, with an average of 4.0 ± 0.4 mg/L. This is still in line with the conditions described in the literature.

The gravel-filled and porosity

The gravel materials are generally natural river gravel and its effective surface area are important factors for biological attachment. The gravel size used in Japan is 2–15 cm with a porosity 30–40%. The inter-gravel water volume will also affect the porosity and the gravel arrangement. This system used mixed gravel 10–15 cm diameter, arranged irregularly with 50% porosity. The design is still in line with the literature.

The sludge excluded

The SS was purified by the contact bed treatment. The sludge accumulated in the sedimentation tank and the contact bed treatment tank, so that the sludge exclusion process must be considered. The common the sludge exclusion method is aeration and backwashing. This system has a sludge sedimentation tank. The backwashing frequency and sludge pumping operation are once per 10–15 days. The sludge exclusion operation is once per a month.

Water treatment comparison of Nan-Men and foreign contact bed treatment

We choose water quality of BOD_5, SS and NH_3-N, to compare the effectiveness of contact bed water treatment for Nan-Men, Europe and Japan. The results are collated in Table 8. The average inflow concentration, the BOD_5 is similar; SS larger than Japan, but less than the Europe; NH_3-N is also greater than in Europe. The outflow average concentration BOD_5, SS and NH_3-N are more than in Japan and Europe. The pollutant removal rate, the NH_3-N is similar with the Europe; BOD_5 and SS are less than in Japan and Europe. The average loading rates were more than in Japan and Europe. The wastewater treatment areas are smaller than in Japan, but higher than in Europe. The depth is greater than in Japan. The hydraulic retention time is similar to that in Japan, but lower than in Europe. Based on the above analysis, some features such as narrow land area, short river length, rapid flow, high inflow pollutant concentration, and high annual average temperature in Taiwan, are difference from Japan or Europe. Therefore local conditions must be considered when using contact bed treatment.

CONCLUSION

After the Nan-Men River was treated using contact bed water treatment, the pH of the effluents averaged 7.2 ± 0.4; DO of 3.6 ± 0.4 mg/L; BOD_5 of 8.55 ± 2.80 mg/L; COD of 25.63 ± 8.53 mg/L; SS of 11.21 ± 1.67 mg/L; NH_3-N of 8.34 ± 1.46 mg/L; *E. coli* of $7.0 \times 10^5 \pm 9.9 \times 10^4$ CFU/100 mL. It was found that most of the effluent quality was below the effluent standards for Taiwan except *E. coli* higher than standard and in line with the original design. The results also confirmed that river pollution can be prevented using constructed wetlands with sewage flowing directly into rivers in areas where a sanitary sewer system is not universal.

Analyzing the relationship between the inflow concentration with removal rate and inflow loading rate with removal rate, it was found that the efficient treatment can achieve the original objectives when the inflow concentration is within a certain range. However if the inflow concentration is over a certain range, the efficiency may be reduced or slowed. The impact factors include non-aeration, rapid flow, raised river sediment, the biological film on the gravel surface worn off. The above situation will affect the treatment effectiveness. In the future, the above impact factors must be taken into account when designing contact bed water treatment.

The contact bed treatment system is constructed directly at the river. It must take into account the natural river conditions in Taiwan. Natural features such as narrow land area, short river length, rapid flow, high pollutant inflow concentration lack of sewage pre-treatment facilities and high annual average temperature. These factors were disadvantages in operating on-site contact bed treatment. To improve the above adverse factors, it is suggested that out-site contract bed treatment methods be adopted to control the inflow speed, set up aeration facilities to increase the BOD_5 and COD decomposition, disinfection facilities to reduce *E. coli* emissions, and increasing the hydraulic retention time.

The design parameters of this system were drawn using "The river purification guidelines of Japan". However these design parameters are not in line with the natural situation in Taiwan. To fit the local conditions, it is suggested that design parameters include that DO is greater than 5 mg/L, BOD_5 optimal concentration of 10–25 mg/L, COD optimal concentration of 32–60 mg/L, SS optimal concentration of 15–25 mg/L, NH_3-N concentration can be greater than 9–16 mg/L, hydraulic retention time of two hours, the gravel size of 10–15 cm, porosity of 30–50%, and water flow rate should be less than 10 cm/s for a sludge accumulation of 10–15 days.

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