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Design and actual performance of constructed wetlands for river renovation in Taiwan

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ABSTRACT

This study evaluated the treatment efficiencies of constructed wetlands having design flow rates greater than 3,000 m^3/d by using Wetland Contribution Index (WCI) and Wetland Grant Index (WGI). The process of river renovation of Tamsui River Water shed in Taiwan is also studied. The results showed WCI_{Design} values ranged between 1 and 74.9 kg/10^3 m^3 with an average of 16.6 kg/10^3 m^3. WCI_{Actual} values ranged between –2.48 and 40.8 kg/10^3 m^3 with an average of 14 kg/10^3 m^3. WGI_{Design} values ranged between 2.59 and 2350 kg/10^3 m^3-million USD with an average of 265 kg/10^3 m^3-million USD. WGI_{Actual} values ranged between –17 and 1650 kg/10^3 m^3-million USD with an average of 221 kg/10^3 m^3-million USD. Larger WCI values imply that wetlands have higher pollutant removals; larger WGI values have higher benefit-construction cost ratios for pollutants. In renovation of Tamsui River, water quality has been improving by the in-situ wastewater treatment facilities. Non (slightly)-polluted length increased from 168.3 km in 2006 to 242.2 km in 2016, while severely-polluted length decreased from 27.8 km in 2006 to 9.3 km in 2016. Heavy rainfalls usually led to lower River Pollution Index (RPI) values.

Keywords: Wetland; Taiwan; River renovation; Index; Wastewater

1. Introduction

In-situ wastewater treatment facilities have been applied to river renovations for a long period of time. There were over 300 constructed wetlands in the Northern America, and over 500 in Europe [1]. Constructed wetlands used as wastewater treatment facilities to treat polluted urban rivers [2] and some index technologies have been developed to evaluate river rehabilitation [3]. In Taiwan, most pollutants in rivers are originated from urban sewage and industrial wastewater. Taiwan Environmental Protection Administration (EPA) began utilizing constructed wetlands as treatment facilities to improve water quality in rivers. Many constructed wetlands for wastewater treatment are in operation since 2002.

Wetlands were developed in German in early 1950s and applied in wastewater treatments in late 1960s in America, and the installations increased dramatically in 1970s [4]. Constructed wetlands have been used to remove contaminants, included suspended solids, organic compounds, nutrients, pathogens, metals, and emerging contaminants [5]. The bio-mechanism of wetland to remove ammonia-nitrogen is by denitrification, and the capacity of wetland to remove all nitrates in waters is strongly influenced by the loading [6]. The role of wetlands, whether natural and man-made, have been demonstrated to improve water quality of streams, rivers, and lakes, while wetlands captured sediments and nutrients from the river itself and served as a

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buffer between uplands and rivers [7]. Wetlands are viewed as important parts of natural landscapes, and their functions are not only providing a habitat, cleaning and retaining water naturally, preventing floods, but also as food sources for plants and animal species [8]. Constructed wetlands are usually classified into free water surface (FWS) [9] and subsurface flow (SSF) [10].

Generally, the water quality of southern Taiwan was worse than that of northern Taiwan, and the water quality of eastern Taiwan was better than that of western Taiwan. Before wastewater treatment plants (WWTPs) getting populated in Taiwan, the local governments applied in-situ water quality treatment facilities to control pollution in rivers.

The objectives of the study were to (i) analyze all the existing wetlands with the design flow rates greater than 3,000 m^3/d to evaluate their BOD_5 removals and the cost effectiveness, (ii) compare their original design treatment goals to their real operational performances, and (iii) investigate the improvement in water quality of Tamsui River Water shed by its wetlands and treatment facilities.

2. Methods and procedures

2.1. The constructed wetlands in taiwan

Taiwan EPA strategically promoted constructed wetland projects since 2002 before the WWTPs became populated. As of 2016, there are at least 115 of in-situ wastewater treatment facilities used for river renovation. The study analyzed these wetlands with design capacity > 3,000 m^3/d to evaluate their performance and the associated costs using Wetland Contribution Index (WCI) and Wetland Grant Index (WGI).

2.2. Characteristics of the tamsui river water shed

Fig. 1 shows the locations of water quality monitoring stations in Tamsui River watershed, which has an area of 2,726 km^2 in Taiwan. Tamsui River has a total length of 159 km and crosses through six cities/counties of northern Taiwan, including Taipei City, New Taipei City, Taoyuan City, Keelung County, Hsinchu County, and Yilan County. It has three main tributaries: Dahan River (135 km), Keelung River (96 km), and Xindian River (84 km). Tamsui River begins at the confluence of Xindian River and Dahan River at the western boundary of the Taipei City and the New Taipei City, just north of Banqiao District, and flows northward and northwestward, passing Tamsui District, and then enters the Taiwan Strait.

Within the Tamsui River watershed, the contributions to the total sewage productions are: Keelung River (33.5%), Dahan River (25%), Xindian River (20%), Tamsui River (17%) and Jingmei River (4.5%). The contributions to the total sewage discharged to the Tamsui River watershed are: Dahan River (31%), Xindian River (24.5%), Keelung River (22%), Tamsui River (17%) and Jingmei River (5.5%). The sources of the sewages are domestic sewage (85.5%), industrial wastewater (10.2%), and swine wastewater (4.3%). (Data are from the open database of Taiwan EPA)

2.3. River pollution index

Taiwan EPA uses River Pollution Index (RPI), an integrated indicator, to assess river quality. The index values are calculated using the concentrations of four parameters, and they are dissolved oxygen (DO), biochemical oxygen demand (BOD_5), suspended solids (SS) and ammonia-nitrogen (NH_3-N). The ranges of the parameter values, the designations of pollution levels, and the RPI values are shown in Table 1.

For examples, hypothesize a river with water quality as follows: DO = 3 mg/L, BOD_5 = 2.2 mg/L, SS = 13.6 mg/L, and NH_3-N = 1.54 mg/L. As shown in Table 1, their point scores are 6 points, 1 point, 1 point, and 6 points, respectively. The average of total point scores is 3.5 (S = total points 14 / water quality items 4), so the RPI value corresponding to 3.1 ≤ S ≤ 6.0 is moderately-polluted level.

Fig. 1. Locations of water quality monitor stations in the Tamsui River watershed.

2.4. Wetland contribution index and wetland grant index

When a constructed wetland was set up, an index, called Wetland Contribution Index (WCI), was used to reflect its treatment efficiency (BOD_5 removals). The definition of WCI could be classified as design WCI and actual WCI, shown in Eq. (1) and Eq. (2), respectively.

$$\mathrm{WCI}_{\mathrm{Design}}\left(\frac{\mathrm{kg}}{10^3\mathrm{m}^3}\right)=\frac{Design\,Pollutant\,movals\left(\frac{kg}{d}\right)}{Design\,Flow\,Rate\left(\frac{10^3\mathrm{m}^3}{d}\right)} \quad (1)$$

where WCI_{Design} = the design BOD_5 removal per unit of design flow rate. Large values of WCI_{Design} indicate that the wetlands have more contributions in reducing organic pollutant loadings to the rivers.

$$WCI_{Actual}\left(\frac{kg}{10^3m^3}\right)=\frac{Actual\,BOD_5\,removals\left(\frac{kg}{d}\right)}{Actual\,Operation\,Flow\,Rate\left(\frac{10^3m^3}{d}\right)} \quad (2)$$

where WCI_{Actual} = the actual BOD_5 removal per unit of operation flow rate. A WCI_{Actual} close to that of WCI_{Design}, indicates that the wetland performs closer to the design.

To assess the cost benefits of a purposed use of a wetland for management decision, an index called, Wetland Grant Index (WGI), is applied. The cost only includes the capital cost, not the operation and maintenance cost. WGI are also classified as design WGI and actual WGI, shown in Eq. (3) and Eq. (4), respectively.

$$WCI_{Design}\left(kg/10^3m^3-million\,of\,USD\right)=\frac{WCI_{Design}\left(\frac{kg}{10^3m^3}\right)}{Budgetary\,Capital\,\mathrm{Cos}\,ts\left(million\,of\,USD\right)} \quad (3)$$

where WGI_{Design} = WCI_{Design} per million USD. A large WGI_{Design} value indicates a better removal efficient per unit budgetary capital cost.

$$WCI_{Actual}\left(kg/10^3m^3-million\,of\,USD\right)=\frac{WCI_{Actual}\left(\frac{kg}{10^3m^3}\right)}{Funded\,Capital\,\mathrm{Cos}\,ts\left(million\,of\,USD\right)} \quad (4)$$

where WGI_{Actual} = WCI_{Actual} per unit funded capital cost. A WGI_{Actual} value close to that of WGI_{Design}, indicates the actual benefit-capital cost ratio of wetland is closer to the design value.

3. Results and discussion

3.1. Evaluation of the in-situ wastewater treatment facilities

Table 2 tabulates the site area, water regime, design BOD removal rate, design flow rate, budgetary capital cost, as well as the calculated design WCI and WGI values of the constructed wetlands evaluated.

As shown in Table 2, most WCI_{Design} values ranged from the range of 1–74.9 kg/10^3 m^3. Larger WCI_{Design} values imply that these wetlands could provide better pollutant removals. In an urban area, a wetland not only provides bio-treatment for river renovation, but also creates a nice area for recreation uses and for the ecosystem. There are flood-control, water-purification, cultural heritage, as well as scenic creation wetlands [11]. In practice, the success of an in-situ wastewater treatment facility relies heavily on its location; however, choosing a proper location is not easy. The site selection criteria includes land site, agency agreement, proposed use of the wetland, amount of sewage to be treated, target renovation of river, and more.

In the beginning of planning stage, a wetland project could only use the WCI plan to predict its contributions to the river renovations. The WCI design chosen depends greatly on the location and the design capacity of sewage interception. As over-estimated urban sewage, it would lead to over-design safety factors for wetland's design capacity. If the actual sewage or wastewater flow is lower, the actual operation flow rate of the treatment facility would be less than the original design flow rate. The actual water quality to the wetland also needs to be estimated. In this study, the average value of WCI_{Design} was 16.6 kg/10^3 m^3 as shown in Table 2.

For the budgetary cost, the local government needs to have a good understanding on the pollutant removals and the associated benefits before committing to a project. WGI is the index to tell whether the capital cost is proportional to the wetland's treatment efficiency. Table 2 shows that the WGI_{Design} values ranged between 2.59 and 2350 kg/10^3 m^3-million USD with an average of 265 kg/10^3 m^3-million USD. A large WGI_{Design} value implies a better treatment performance.

As shown in Table 3, the WCI_{Actual} value ranged between –2.48 and 40.8 kg/10^3 m^3 with an average of 14 kg/10^3 m^3. A negative WCI_{Actual} value means that the BOD_5 of the wetland's effluent was higher than that of its influent. The

Table 1
The definition of River Pollution Index

Water quality /Item	Non(slightly)-polluted	Lightly-polluted	Moderately-polluted	Severely-polluted
DO (mg/L)	DO ≧ 6.5	6.5 > DO ≧ 4.6	4.5 ≧ DO ≧ 2.0	DO < 2.0
BOD5 (mg/L)	BOD5 ≦ 3.0	3.0 < BOD5 ≦ 4.9	5.0 ≦ BOD5 ≦ 15.0	BOD5 > 5.0
SS (mg/L)	SS ≦ 20.0	20.0 < SS ≦ 49.9	50.0 ≦ SS ≦ 100	SS > 100
NH_3-N (mg/L)	NH_3-N ≦ 0.50	0.50 <NH_3-N ≦ 0.99	1.00 ≦ NH_3-N ≦ 3.00	NH_3-N > 3.00
Point Scores	1	3	6	10
RPI value	S ≦ 2.0	2.0 < S ≦ 3.0	3.1 ≦ S ≦ 6.0	S > 6.0

Table 2
The design parameters of in-situ wastewater treatment facilities

County	Wastewater Treatment Facility Project	Site Area (ha)	Water Regime (ha)	Design BOD Removals (kg/d)	Design Flow Rate ($10^3m^3/d$)	Design WCI ($kg/10^3m^3$)	Budgetary Capital Costs (million USD)	Design WGI ($kg/10^3m^3$-million USD)
Taipei City	Gandu Nature Pack Wastewater Treatment Facility	6.40	—	24.00	3.00	8.00E+00	0.021	3.81E+02
	Cheng-Mei Wastewater Treatment Facility	0.70	—	55.00	9.00	6.11E+00	0.257	2.38E+01
New Taipei City	Dahan River-Xinhai Bridge Wetland (I) (FWS)	8.00	6.00	34.00	6.00	5.67E+00	0.043	1.31E+02
	Dahan River-Fuzhou Wetland (FWS)	13.00	8.50	264.00	11.00	2.40E+01	0.094	2.55E+02
	Dahan River-Xinhai Bridge Wetland (II) (FWS)	5.00	3.41	106.00	4.00	2.65E+01	0.060	4.41E+02
	Dahan River-Lujiaoxi Wetland	16.00	—	898.60	12.00	7.49E+01	0.148	5.07E+02
Taoyuan City	Nankan River-Nankanxi Bridge Wetland (FWS & SSF)	2.00	0.32	20.00	13.50	1.48E+00	0.028	5.23E+01
Hsinchu County	Touqianxi Wetland (I & II) (FWS & SSF)	34.00	4.50	280.80	12.00	2.34E+01	0.086	2.71E+02
	Touqianxi Wetland (III & VI) (FWS & SSF)	13.00	3.66	124.50	15.50	8.03E+00	0.173	4.66E+01
	Fengshanxi Mayuan Wetland	47.00	2.50	25.00	5.00	5.00E+00	0.062	8.12E+01
Taichung City	Dalixi Dali Bridge Wetland (FWS)	2.16	0.10	144.50	3.90	3.71E+01	0.016	2.35E+03
Chiayi City	Niuchouxi Wastewater Treatment Facility	0.04	—	170.00	19.00	8.95E+00	0.057	1.58E+02
Tainan City	Huweiliao Wastewater Treatment Facility	1.10	—	100.00	10.00	1.00E+01	0.167	5.98E+01
	Erren River & San-Yei River Wastewater Treatment Facility	0.80	—	60.00	33.00	1.82E+00	0.103	1.77E+01
Kaohsiung City	Fengshan River-Zhongzheng Park & Paijung Park wetland	1.50	—	5.00	5.00	1.00E+00	0.385	2.59E+00
Pingtung County	Wuluo River Wetland (I)	2.00	9.00	2750.00	50.00	5.50E+01	0.073	7.50E+02
	Wuluo River Wetland (II) (FWS)	18.00	3.00	750.00	50.00	1.50E+01	0.150	1.00E+02
	Old Railroad Bridge Wetland	9.00	—	84.00	4.00	2.10E+01	0.073	2.86E+02
Hualien County	Meilun River-Chiali NO.2 Bridge & Jiaxin Village Treatment Facility	2.60	0.65	27.00	9.00	3.00E+00	0.030	1.00E+02
	Meilun River-Wangshou Wetland	4.08	0.41	39.00	4.00	9.75E+00	0.074	1.32E+02
	Yushuitsun Wetland	4.95	1.69	60.00	6.00	1.00E+01	0.151	6.60E+01
	Jian River Wetland (I)	1.81	1.75	92.30	3.15	2.93E+01	0.143	2.05E+02
	Jian River Wetland (II)	3.90	1.83	50.00	3.85	1.30E+01	0.145	8.93E+01
Taitung County	Beinan River-Guanshan Township Wetland (II) (FWS)	6.40	2.50	55.00	5.00	1.10E+01	0.147	7.46E+01
	Luye Township Wetland	4.95	2.40	26.01	5.00	5.20E+00	0.146	3.55E+01

Table 3
The efficiency of in-situ wastewater treatment facilities

County	Wastewater Treatment Facility Project	Design BOD Removals (kg/d)	Design Flow Rate (10^3m^3/d)	Actual BOD Removals (kg/d)	Actual Operation Flow Rate (10^3m^3/d)	Actual WCI (kg/10^3m^3)	Funded Costs (million USD)	Actual WGI (kg/10^3m^3-million USD
Taipei City	Gandu Nature Pack Wastewater Treatment Facility	24.00	3.00	3.76	2.00	1.88E+00	0.016	1.21E+02
	Cheng-Mei Wastewater Treatment Facility	55.00	9.00	46.60	3.34	1.39E+01	0.257	5.42E+01
New Taipei City	Dahan River-Xinhai Bridge Wetland (I) (FWS)	34.00	6.00	132.80	4.50	2.95E+01	0.043	6.81E+02
	Dahan River-Fuzhou Wetland (FWS)	264.00	11.00	139.00	7.02	1.98E+01	0.090	2.21E+02
	Dahan River-Xinhai Bridge Wetland (II) (FWS)	106.00	4.00	70.50	3.00	2.35E+01	0.069	3.41E+02
	Dahan River-Lujiaoxi Wetland	898.60	12.00	276.50	7.20	3.84E+01	0.174	2.21E+02
Taoyuan City	Nankan River-Nankanxi Bridge Wetland (FWS & SSF)	20.00	13.50	11.37	10.77	1.06E+00	0.023	4.53E+01
Hsinchu County	Touqianxi Wetland (I & II) (FWS & SSF)	280.80	12.00	3.64	9.10	4.00E-01	0.083	4.83E+00
	Touqianxi Wetland (III & VI) (FWS & SSF)	124.50	15.50	3.15	6.22	5.06E-01	0.193	2.63E+00
	Fengshanxi Mayuan Wetland	25.00	5.00	13.36	3.51	3.80E+00	0.062	6.18E+01
Taichung City	Dalixi Dali Bridge Wetland (FWS)	144.50	3.90	136.70	5.25	2.61E+01	0.016	1.65E+03
Chiayi City	Niuchouxi Wastewater Treatment Facility	170.00	19.00	300.00	19.00	1.58E+01	0.057	2.79E+02
Tainan City	Huweiliao Wastewater Treatment Facility	100.00	10.00	440.00	10.77	4.08E+01	0.197	2.08E+02
	Erren River & San-Yei River Wastewater Treatment Facility	60.00	33.00	88.50	17.84	4.96E+00	0.099	5.04E+01
Kaohsiung City	Fengshan River-Zhongzheng Park & Paijung Park wetland	5.00	5.00	_	_	_	0.335	_
Pingtung County	Wuluo River Wetland (I)	2750.00	50.00	760.00	33.33	2.28E+01	0.073	3.11E+02
	Wuluo River Wetland (II) (FWS)	750.00	50.00				0.150	1.52E+02
	Old Railroad Bridge Wetland	84.00	4.00	_	_	_	0.073	_
Hualien County	Meilun River-Chiali NO.2 Bridge & Jiaxin Village Treatment Facility	27.00	9.00	17.20	9.56	1.80E+00	0.029	6.25E+01
	Meilun River-Wangshou Wetland	39.00	4.00	2.85	4.76	5.98E-01	0.071	8.45E+00
	Yushuitsun Wetland	60.00	6.00	-14.85	6.00	-2.48E+00	0.145	-1.70E+01
	Jian River Wetland (I)	92.30	3.15	229.82	7.18	3.20E+01	0.131	2.45E+02
	Jian River Wetland (II)	50.00	3.85				0.134	2.39E+02
Taitung County	Beinan River-Guanshan Township Wetland (II) (FWS)	55.00	5.00	50.00	3.86	1.30E+01	0.141	9.22E+01
	Luye Township Wetland	26.01	5.00	24.00	4.10	5.85E+00	0.140	4.18E+01

wetlands of negative WCI_{Actual} values usually situated in the eastern Taiwan where river typically had good water quality before treatment. The particulate organic matters were the main source leading to the increase in BOD_5 concentrations. The WGI_{Actual} values ranged between –17 and 1650 kg/10^3 m^3-million USD with an average of 221 kg/10^3 m^3-million USD. A negative WGI_{Actual} value has the similar meaning to a negative WCI_{Actual} value. These wetlands with slightly negative WGI and WCI values still provided other benefits, such as a nice area for recreation and for the ecosystem.

As shown in Tables 2 and 3, most of the budgetary capital costs are larger than the funded capital costs. It should be noted that data on phosphate and ammonia nitrogen are not available in the Taiwan EPA's database. Wetlands of Taipei City, New Taipei City and Hsinchu County only operated at 50% to 65% of their design flow rates, respectively. The actual BOD_5 removals of most wetlands did not meet their design values. For the cases of Chiayi City and Tainan City, their actual operational flow rates were close to or slightly larger than their corresponding design flow rates, but their actual BOD_5 removals were larger than the design values due to under-estimating influent water quality. For the case of Hualien County, most actual operation flow rates were similar to their design values; the actual BOD_5 removals were less than the design values due to over-estimating river water qualities. The BOD_5 removals of Yushuitsun wetland had negative values, implying that the river had good river quality and the influent to the wetlands typically had an average BOD_5 concentration of less than 10 mg/L. For the cases of Tainan City and Pingtung County, some wetlands'

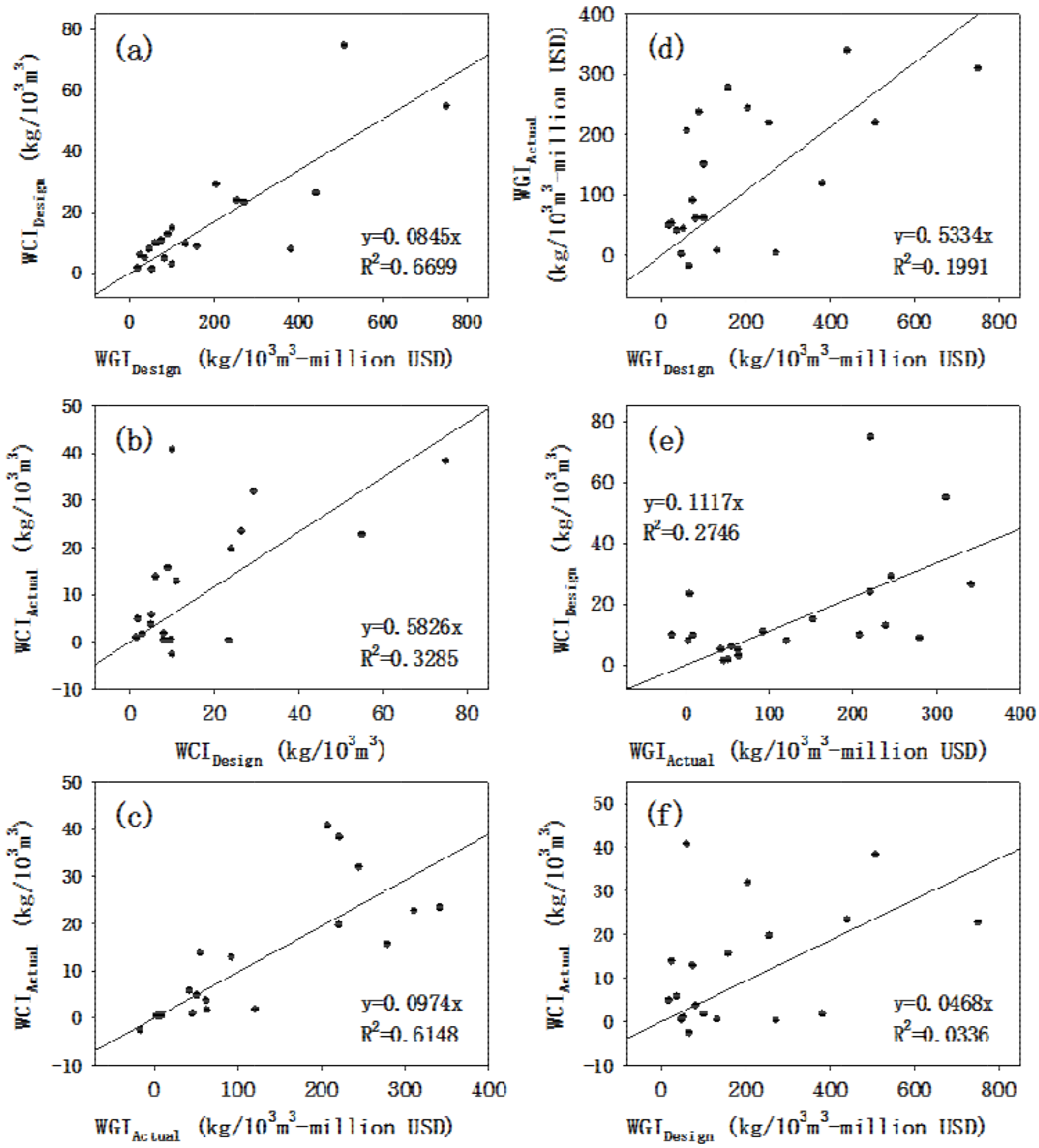

Fig. 2. The regression analysis of (a) WCI_{Design} versus WGI_{Design}; (b) WCI_{Actual} versus WCI_{Design}; (c) WCI_{Actual} versus WGI_{Rea}l; (d) WGI_{Actual} versus WGI_{Design}; (e) WCI_{Design} versus WGI_{Actual}; (f) WCI_{Actual} versus WGI_{Design}.

actual BOD_5 removals were large than the design values, whereas their operational flow rates did not reach the design flow rates. It could be attributed to the fact that the designer under-estimated the water quality, because the influent BOD_5 concentrations were higher than expected. For the case of Taichung city, Dalixi Dali Bridge wetland's actual operational flow rate was far larger than its design value. This reason was owing to river's actual BOD_5 removals were close to the design removals, and it also indicated that the designer over-estimated the water quality and under-estimated the river flow rate in the planning stage.

Fig. 2 illustrates the results of regression analysis among wetlands' WCI_{Design}, WCI_{Actual}, WGI_{Design} and WGI_{Actual}. It should be noted that the data of Dalixi Dali Bridge Wetland and Dahan River-Xinhai Bridge Wetland (I) were not included because their WCI and WGI values were considers as outliers. Fengshan River-Zhongzheng Park & Paijung Park wetland and Old Railroad Bridge Wetland were also not included because some data were not available for calculations of their WCI_{Actual} and WGI_{Actual} values.

The regression analysis on WCI_{Design} versus WGI_{Design} shows a linear relationship with an R^2 of 0.6699 (Fig. 2a). WCI_{Design} (response variable) had a weak correlation with WGI_{Design} (observed variable).

As shown in Fig. 2b, WCI_{Actual} and WCI_{Design} had a linear regression with an R^2 of 0.3285. The low R^2 value implies that these two variables are independent or having a very weak correlation. The results indicate that the operational conditions are not close to the design conditions (WCI_{Design}).

As shown in Fig. 2c, WCI_{Actual} and WGI_{Actual} had a linear regression with an R^2 of 0.6148, implying that pollutant removals and cost-benefit are poorly correlated.

As shown in Fig. 2d, WGI_{Actual} and WGI_{Design} had a linear regression with an R^2 of 0.1991, implying that the correlations among pollutant removals, budgetary costs, and funded costs were extremely poor.

As shown in Fig. 2e, WCI_{Design} and WGI_{Actual} had a linear regression with an R^2 of 0.2746, implying that the correlations among the design pollutant removals, actual pollutant removals, and funded costs were extremely poor.

As shown in Fig. 2f, WCI_{Actual} and WGI_{Design} had a linear regression with an R^2 of 0.0336, implying that actual pollutant removals, design pollutant removals, and budgetary capital costs had barely any correlation.

3.2. Constructed wetlands and wastewater treatment facilities applied in Tamsui River watershed

Tamsui River watershed has been renovated for more than years. Table 4 shows the lengths having non (or slightly)-polluted or severely-polluted levels in the Tamsui River watershed. The results indicate that water quality of Tamsui River watershed has been improving. Non (slightly)-polluted length increased from 168.3 km in 2006 to 242.2 km in 2016, while severely-polluted length decreased from 27.8 km in 2006 to 9.3 km in 2016. The non (slightly)-polluted percentage of the total length increased from 52.0% in 2006 to 74.9% in 2016, and severely-polluted percentage of the total length decreased from 8.6% in 2006 to 2.9% in 2016.

In this study, PRI index was used to assess the level of river pollution. Fig. 3 plots four water quality data of Tamsui River watershed from 2014/7 to 2016/7. The ammonia-nitrogen average concentrations of Keelung River, Xindian River, Jingmei River and Tamsui River were 2.40 (moderately-polluted), 2.28 (moderately-polluted), 1.00 (moderately-polluted), and 3.96 mg/L (severely-polluted), respectively. (Fig. 3a)

The suspended solid average concentrations of Keelung River, Xindian River, Jingmei River and Tamsui River were 20.0 (non (slightly)-polluted), 39.3 (lightly-polluted), 12.3 (non (slightly)-polluted), and 26.4 mg/L (lightly-polluted), respectively. (Fig. 3b)

The BOD_5 average concentrations of Keelung River, Xindian River, Jingmei River and Tamsui River were 3.7 (lightly-polluted), 3.9 (lightly-polluted), 3.1 (lightly-polluted), and 3.6 mg/L (lightly-polluted), respectively. (Fig. 3c)

The dissolved oxygen average concentrations of Keelung River, Xindian River, Jingmei River and Tamsui

Table 4
The renovation of Tamsui River watershed from 2006 to 2016

Year	Total length (km)	Non (slightly) - polluted (km)	Severely-polluted (km)	Non (slightly) - polluted percentage of the total length (%)	Severely-polluted percentage of the total length (%)
2006	323.4	168.3	27.8	52.0	8.6
2007	323.4	192.7	32.4	59.6	10.0
2008	323.4	216.2	16.2	66.9	5.0
2009	323.4	217.0	22.0	67.1	6.8
2010	323.4	221.2	24.4	68.4	7.5
2011	323.4	187.9	20.3	58.1	6.3
2012	323.4	226.7	6.4	70.1	2.0
2013	323.4	241.9	16.8	74.8	5.2
2014	323.4	239.1	17.6	73.9	5.4
2015	323.4	226.2	22.0	69.9	6.8
2016	323.4	242.2	9.3	74.9	2.9

Note: Data sourced from the open data of EPA; Total length of Tamsui River watershed is 323.4 km.

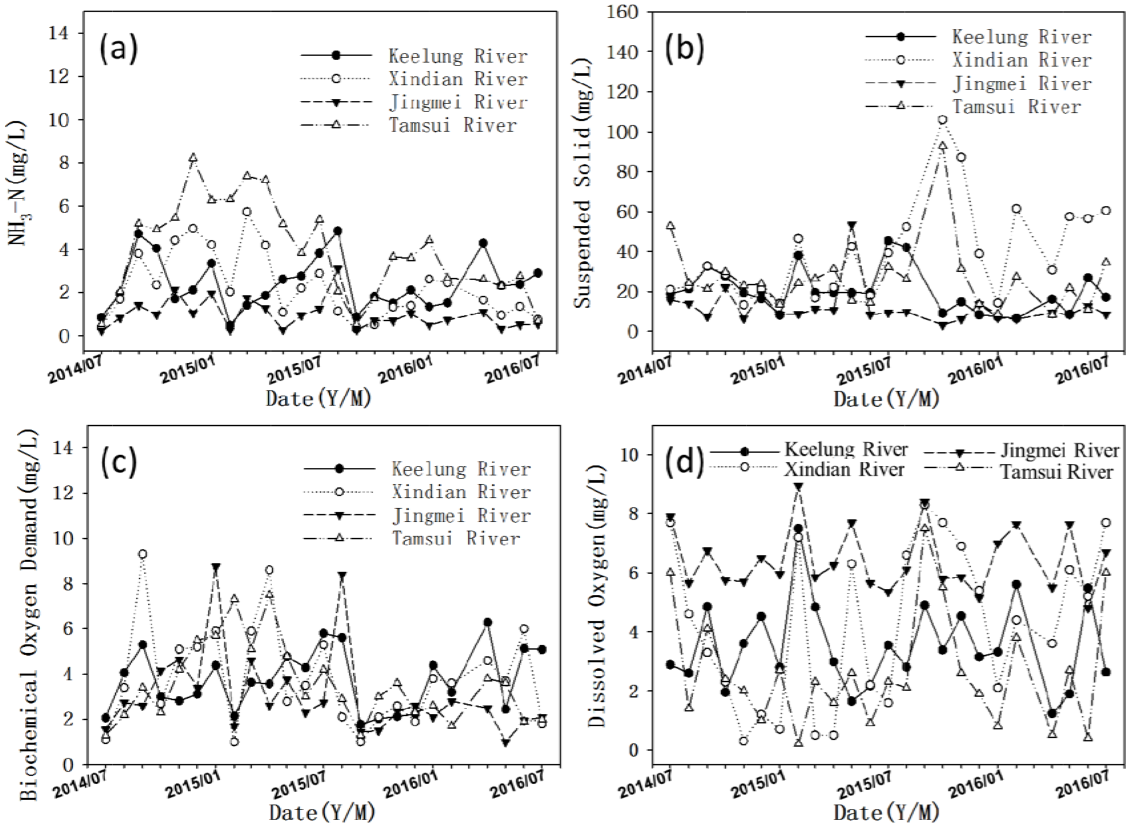

Fig. 3. Four water quality data :(a) ammonia-nitrogen; (b) suspended solid; (c) biochemical oxygen demand; (d) dissolved oxygen in the Tamsui River watershed from 2014/7 to 2016/7.

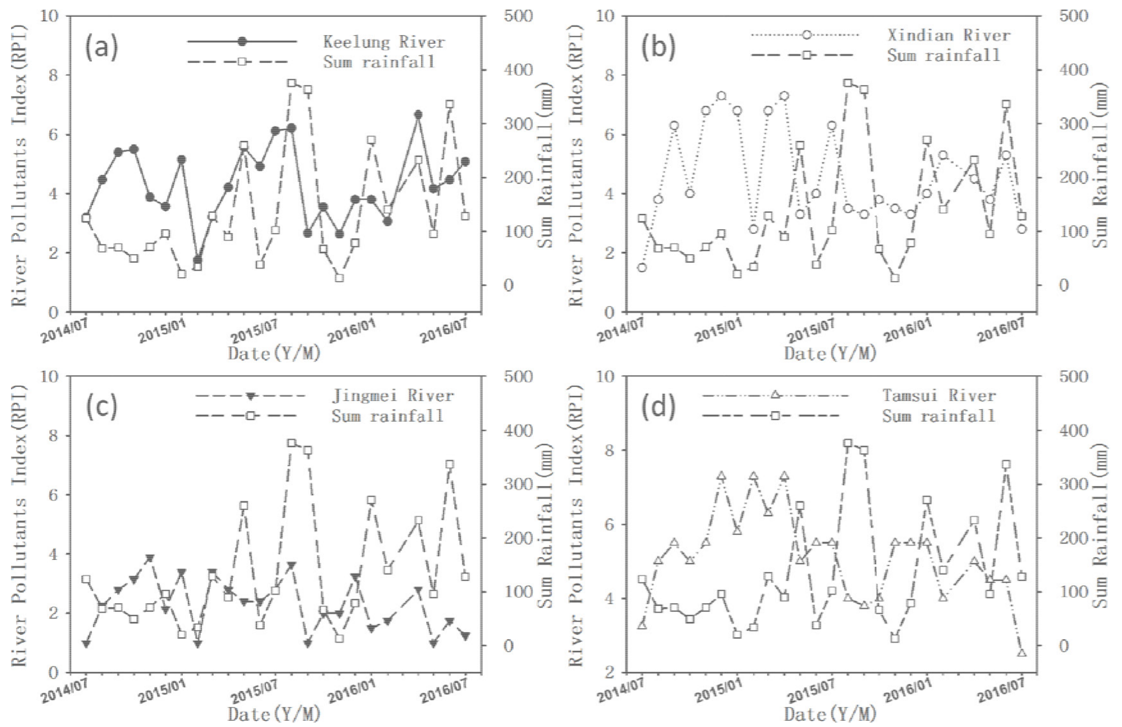

Fig. 4. Variations of RPI index and sum rainfall versus time: (a) Keelung River, (b) Xindian River, (c) Jingmei River, and (d) Tamsui River.

River were 3.5 (moderately-polluted), 4.3 (moderately-polluted), 6.4 (lightly-polluted), and 2.6 mg/L (moderately-polluted), respectively (Fig. 3d).

Fig. 4 shows variations of RPI index and sum rainfall versus time in the Tamsui River watershed. As for the case of Keelung River (Fig. 4a), the values of maximum, minimum, and average RPI were 6.8, 1.8, and 4.3 (moderately-polluted), respectively. For the case of Xindian River (Fig. 4b), the values of maximum, minimum, and average RPI were 7.3, 1.5, and 4.6 (moderately-polluted), respectively. For the case of Jingmei River (Fig. 4c), the values of maximum, minimum, and average RPI were 3.9, 1.0, and 2.3 (lightly-polluted), respectively. For the case of Tamsui River (Fig. 4d), the values of maximum, minimum, and average RPI were 7.3, 2.5, and 5.1 (moderately-polluted), respectively. The results from all these cases show there was an inverse correlation between rainfall and RPI, implying that heavy rainfalls corresponded to low RPI values, whereas light rainfalls corresponded to high RPI values.

4. Conclusions

Constructed wetlands have been applied to treat urban sewage for several years. This study evaluated WCI and WGI values of constructed wetlands with design flow rates of greater than 3,000 m^3/d. The results show that WCI_{Design} ranged between 1 and 74.9 kg/$10^3 m^3$ with an average of 16.6 kg/10^3 m^3. WCI_{Actual} values ranged between –2.48 and 40.8 kg/10^3 m^3 with an average of 14 kg/10^3 m^3. WGI_{Design} values ranged between 2.59 and 2350 kg/10^3 m^3-million USD with an average of 265 kg/10^3 m^3-million USD. WGI_{Actual} values ranged between –17 and 1650 kg/10^3 m^3-million USD with an average of 221 kg/10^3 m^3-million USD. Although some wetlands' actual operational flow rates were close to or slightly larger than their design corresponding values, but their actual BOD_5 removals were larger than design values due to under-estimating water quality. On the other hand, some wetlands' actual operational flow rates were subject to their design values, but actual BOD_5 removals were usually less than design removals due to over-estimating river water quality. In addition, a special case showed that actual operational flow rate was far larger than the design value owing to the designer over-estimated the water quality and under-estimated the river flow in the planning stage.

In the case of Tamsui River renovation, the water quality had been improving from 2006 to 2016. Besides, RPI values are highly correlated with rainfalls, which shows heavy rainfalls corresponded to low RPI values. The roles of wetlands not only provide sewage treatments, but also provide nice areas for recreation and for the ecosystem in urban areas.

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Thank government providing these wetlands open data for free in the web site (https://opendata.epa.gov.tw/Data/Details/WAT00528).

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