Clustered Constructed Wetland Systems in Metropolitan Taipei

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ABSTRACT

Since 2004, fourteen clustered constructed wetland systems have been built along the Danshui River and its tributaries. This "big-dig" project was designed to: 1) achieve water-quality standards according to the regulations of the Taipei municipal governments for connecting households to public sewage systems from clustered constructed wetland systems, 2) improve wastewater purification, and 3) use all corridor wetlands to promote sustainable development while supporting urban recreation, environmental education, and habitat restoration for biodiversity. Total construction cost was $33,706,600 ($US) for the systems. For 10 years, we studied and examined their functional capabilities associated with treating non-point source pollution. To date, monitoring water indicators, such as dissolved oxygen, biochemical oxygen demand, suspended solids, ammonia, and *Escherichia coli*, at 13 sampling sites have demonstrated that water quality in Taipei metropolitan rivers has improved. Constructed wetlands in Metropolitan Taipei thereby play a crucial role in preventing extreme deteriorations in water quality. Our work has also shown that these constructed wetlands also control the flow of rivers in drought/flood seasons and increase biodiversity in this river corridor.

BACKGROUND

The metropolitan area of Taipei (25°03'N, 121°30'E), with a population of 6.5 million people representing 28% of the total population of Taiwan (23 million), is one of the most condensed megacities in Asia (Figure 1). As a small island nation with an overall population density of 644 people/km^2, the areas of Taipei City (9,808 people/km^2) and New Taipei City (1,919 people/km^2) carry the burden of both a large population and high population density. The Danshui River, with a length of 158.7 km and a drainage basin of 2,726 km^2, is the only natural corridor remaining within this metropolitan area. Located within the Taipei basin and surrounded by mountainous areas, the Danshui River receives a relatively high loading of sand (5-14.5 g/L) mainly from natural erosion in the steep slope, and 9.28 million cubic meters per year of sediment. This produces siltation and the formation of sand bars in the river corridors during Typhoon seasons. The presence of sand bars at river's edge makes it possible to create constructed wetlands in floodplain areas. Such wetlands could help reduce sediment loads from the river. The Taipei municipal government has built a series of constructed wetlands to remediate and mitigate heavy sediment loadings that could also help address water pollution and flooding issues in the watershed, among other benefits.

Historically, the Danshui River was notorious for the odor in her waters. Prior to building constructed wetlands, dissolved oxygen (DO), biochemical oxygen demand (BOD_5), suspended solids (SS), and ammonia (NH_3-N) were detected at levels in excess of a local statutory level: DO>6.5 mg/L; BOD_5<3.0 mg/L; SS<20.0 mg/L; NH_3-N <0.50 mg/L in the water (Cheng et al. 2011). For example, the lowest recorded value for DO from data obtained from 13 monitoring stations was 2 mg/L between 2002 and 2003. The median of SS ranged from a minimum of 25 mg/L to a maximum of 125 mg/L between 2004 and 2007. Following a drought period between 2002 and 2003, a flood during 2004 containing hilly debris led to a dramatic increase in the level of SS. The ammonia (NH_3-N) level, which strongly affects the health of citizens in metropolitan areas, peaked at 5 mg/L during 2003.

The Dashui River and its tributaries meander through the most densely populated areas of the island of Taiwan. Since 2004, 14 clustered wetlands have been built to help improve water quality, reduce siltation, and provide flood control in the Danshui River (Cheng et al. 2011).

OBJECTIVES OF CONSTRUCTED WETLAND SYSTEMS

The quality of Danshui River has declined due to anthropogenic influences, such as residential wastewater, landfills, and swine wastewater. The 14 clustered constructed wetland systems (CCWS) were to develop a mechanism to deal with high sediment loads, reduce water pollution, as well as take advantage of the environmental benefits of constructed

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wetlands for municipal wastewater treatment for public health priorities. The water they receive at a point source are waters polluted with non-point source contaminants, especially runoff from agricultural fields. The objectives of these constructed wetlands are sand-loading reduction, water-quality improvement, biodiversity conservation, and environmental education.

- To reduce sand loading, siltation, and the formation of sand bars in the river corridors during typhoon seasons.
- To meet water-quality standards as Table 1 for “not (slightly) contaminated” in the entire river corridors according to the regulations of the Taipei municipal governments concerning the connection of households to public sewage systems from CCWS;
- To develop and maintain an international network of wetlands that are important for the conservation of global biological diversity, including water bird flyways and fish populations in ecological corridors as well as sustaining human life; and
- To contribute to the concept of environmental education from ecotourism and outdoor activities, increase aesthetic and “sense of place” values, and maintain or enhance other natural values of wetland ecosystem services (Lo et al. 2019).

Table 1. River water-quality standards in Danshui River.

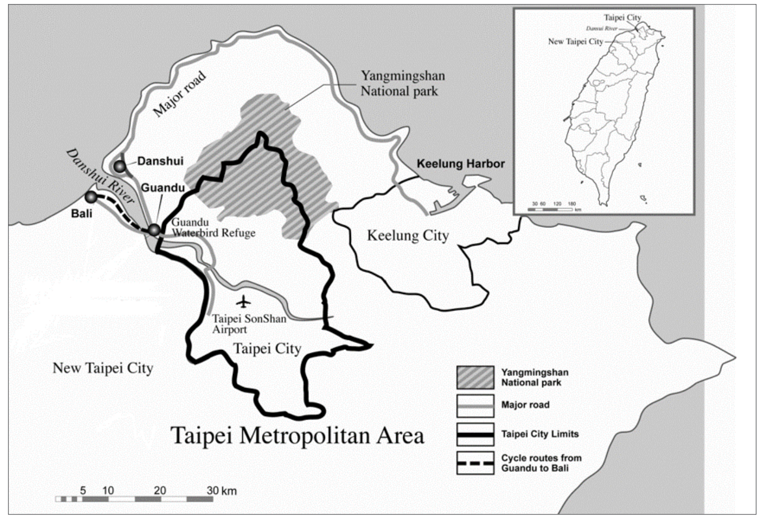
Parameters	Not (slightly) contaminated	Lightly contaminated	Moderately contaminated	Seriously contaminated
Dissolved oxygen (DO) mg/L	>6.5	4.6~6.5	2.0~4.5	2.0<
Biochemical oxygen demand (BOD) mg/L	<3.0	3.0~4.9	5.0~15.0	>15.0
Suspended solids (SS) mg/L	<20.0	20.0~49.9	50.0~100	>100
Ammonia (NH3-N) mg/L	<0.50	0.50~0.99	1.00~3.00	>3.00

Source: Taiwan Environmental Protection Agency (2008).

DESCRIPTION OF THE CONSTRUCTED WETLANDS

Following rapid industrialization, urbanization, and the expansion of the population over the last decades of the 20th century, the discharge of source pollutants into rivers in the metropolitan Taipei area has increased significantly, threatening the riverine ecosystem along Danshui River and the health of humans alike. It has become increasingly necessary to examine the role played by this drainage basin on the metropolitan area.

Figure 1. The main Danshui River corridor associated with uplands with a peak elevation of 1,120 m (Yanmingshan National Park) in the Taipei Metropolitan Area.

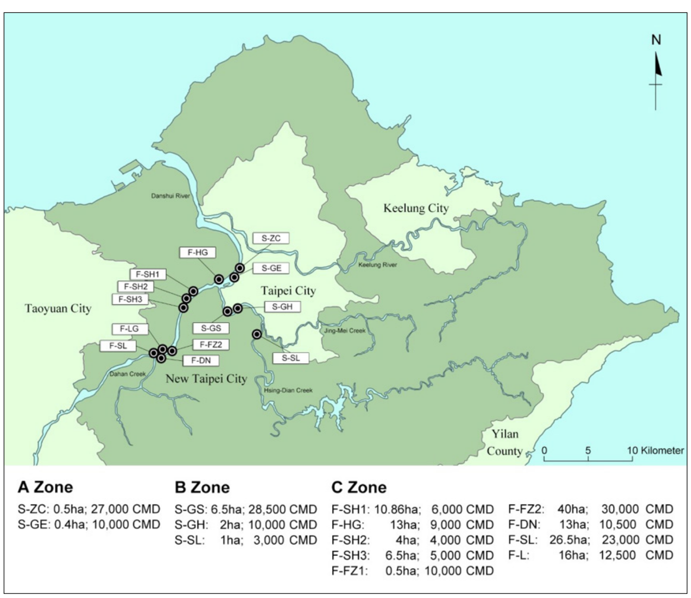


Since 2004, the Taiwan EPA has provided support to municipal governments for wetland construction. In the metropolitan area, Taipei County Hall was reconstituted as a new entity - New Taipei City - in 2010. This new entity has attempted to mitigate the effects of water pollution. A number of remediation programs were proposed including: 1) increasing the percentage of public sanitary sewage systems through takeovers and the implementation of a deep tunnel operation to collect and treat domestic wastewater in the different sub-basins of the Danshui River, 2) removing illegal sand and gravel excavations and factories from riparian zones, and 3) building wetlands within levees on riverine floodplains. The initiative was promoted by the previous Mayor Hsi-Wei Chou and the former Deputy Mayor Hong-Yuan Lee through establishing policies that supported the building of wetlands in Taipei County during 2004. (Note: Lee also became the Minister of the Interior from 2012 to 2014.)

Ninety-three constructed wetlands were built in Taiwan between 2000 and 2010. These wetlands occupy 517 ha and have a capacity of 542 megaliters/day of wastewater (Cheng et al. 2011). Between 2004 and 2010, approximately 15% of these wetlands (14 wetlands; 140.76 ha) were located in the riparian zone within the levee borders of the Danshui River and its tributaries, such as at Xindian Creek (right upstream) and Dahan Creek (left upstream) (Figure 2). The constructed wetlands, sponsored by the Taiwan Environmental Protection Administration (Taiwan EPA), use both free water surface systems (FWS) and subsurface flow systems (SFS) (Kao et al. 2001; Cheng et al. 2011). Free water surface systems (FWS) are wetland systems where the water surface is designed to be exposed to the atmosphere allowing for colonization by aquatic grasses and emergent macrophytes. Subsurface flow systems (SFS) involve directing horizontal subsurface flows through large gravel beds to filter out particles and microorganisms, and include planting of wetland vegetation in sand-filled basins. SFSs are also called gravel-contact oxidation treatment systems.

The wetlands were designed as a supplement to the existing public sewage system in this metropolitan area. They would work in combination with existing public sanitary sewage systems piped out from houses; this represented about 43% for all households in New Taipei City during 2012. The rest of household wastewaters (57%) discharged directly to the Bali sewage treatment station without treatment by these metropolitan wetlands. The wetlands were designed as a part of a water clarification plan for urban rivers to support an area without sanitary sewage systems to treat wastewaters. Since there were questions whether these wetlands (i.e., free water surface water systems) alone could effectively handle sewage treatment because of limited spaces along river sides, both the free water surface systems (FWS) and subsurface flow systems (SFS or gravel-contact treatment system) were chosen as the standard procedures of multi-functional clarification in the river systems of the metropolitan Taipei area. For the metropolitan Taipei area, discharge rates and loading rates for these constructed wetlands were obtained from historical records from 2006 to 2012. In 2006, only three wetlands were in operation treating a water volume of 21 megaliters/day, or 21,000 cubic meters per day (m^3/day) (CMD). Since 2007, 14 wetlands with a total area of 140.76 ha are now treating 188 megaliters/day, or 188,000 CMD in the metropolitan area.

Figure 2. Constructed wetlands in the metropolitan areas of Taipei. Abbreviations for A Zone: S-ZC (Subsurface flow- Zhong Cao) and S-GE (Subsurface flow- Gui Eng); B Zone: S-GS (Subsurface flow- Gang Suei), S-GH (Subsurface flow- Guang Ho), and S-SL (Subsurface flow- Siou Lang); C Zone: F-SH1 (Free water surface- Shin Hai Section 1), F-HG (Free water surface- Hua Gang), F-SH2 (Free water surface- Shin Hai Section 2), F-SH3 (Free water surface- Shin Hai Section 3), F-FZ1 (Free water surface- Fu Zhou), F-FZ2 (Free water surface- Fu Zhou Bridge), F-DN (Free water surface- Da Niao Pi), F-SL (Free water surface- Shia Lin), and F-L (Free water surface- Lo Ga Kei).



Type of System

These clustered wetlands were designed to collect all regional drainage (RD) waters including urban surface runoff, agricultural wastewater (i.e., F-LG) in the upper stream, industrial wastewater (i.e., S-GS, F-HG in Figure 2) in the middle streams, municipal wastewater (i.e., S-GS, F-HG, F-FZ2, and F-LG), and domestic wastewater (i.e., S-GS, F-HG, F-FZ2, and F-LG) in the upper & middle streams. Two types of constructed wetlands treat the water: subsurface flow (gravel-contact oxidation treatment) system and free water surface system (Kao et al. 2001; Cheng et al. 2011).

Area, Volumes, Discharge Rates, and Loadings

Between 2004 and 2010, the 14 constructed wetland areas (140.76 ha) in the Taipei metropolitan area were limited to an inflow discharge of 188 megaliters/day. Unfortunately, records of initial operation for the pollution reduction rate (PRR) in each area are lacking. Table 2 shows the characteristics of the 14 wetlands from Taipei City and New Taipei City in 2010. The removal rate of BOD_5 was 81% to 98% in the six gravel-contact oxidation treatment systems (subsurface flow systems), whereas 63% to 81% of BOD_5 was removed by the eight free water surface systems.

Design Approaches

Hydrological engineers used universally accepted equations to design the systems. The equations utilized in these approaches are shown in Table 3, while the rationale behind using each equation is provided below.

- Aquatic vegetation was employed to increase the pollutant removal ratio from waterbodies (equation 1).
- The use of both a free water surface system and a gravel-contact oxidation treatment system (subsurface flow system) would increase the mixing, diffusion, and retention time and therefore, increase the effective volume of the wetlands (equations 2-5).
- The creation of a number of wetlands-in-series would improve hydraulic efficiency using the concept of clustered constructed wetlands and their functions (equation 6).
- The creation of ecological habitats would benefit wetland wildlife in order to increase species biodiversity (no referenced equation).

Table 2: Information for the constructed wetlands along the riparian zones of the Danshui River 2010.

Location of river reach	Name	Area (ha)	Design treatment types	Design treatment flows (m^3/day)(CMD)	Main type of the water sources[1]	Initial operation records (pollution reduction rate, PRR)	Construction cost (US Dollars)[3]
A zone	S-ZC	0.5	G	27,000	RD[2]	No record	7,153,000
A zone	S-GE	0.4	G	10,000	RD	No record	3,481,000
B zone	S-GS	6.5	G	28,500	MDW & IW	98% BOD_5 94% SS 94% NH3-N	4,025,000
B zone	S-GH	2	G	10,000	RD	No record	2,779,900
B zone	S-SL	1	G	3,000	RD	81.7% BOD_5 93.1% SS 91.2% NH3-N	2,084,000
C zone	F-SH1	10.86	F	6,000	RD	81% BOD_5 6.97% SS 96.4% NH3-N	960,000
C zone	F-HG	13	F	9,000	MDW & IW	74% BOD_5 74% SS 67% NH3-N	1,343,000
C zone	F-SH2	4	F	4,000	RD	71% BOD_5 71% SS 65% NH3-N	689,000
C zone	F-SH3	6.5	F	5,000	RD	71% BOD_5 71% SS 65% NH3-N	732,000
C zone	F-FZ1	0.5	G	10,000	RD	No record	2,246,000
C zone	F-FZ2	40	F	30,000	MDW	73% BOD_5 72% SS 67% NH3-N	3,318,000
C zone	F-DN	13	F	10,500	RD	63.2% BOD_5 58.3% SS 74.4% NH3-N	900,000
C zone	F-SL	26.5	F	23,000	RD	No record	2,084,000
C zone	F-LG	16	F	12,000	AW & MDW	74% BOD_5 76% SS 73% NH3-N	1,911,700
Totals		140.76		188,000			33,706,600

[1]*G: Gravel-contact oxidation treatment method (subsurface flow); F: Free water surface; RD: Regional drainage2; USR: Urban surface runoff, AW: Agricultural wastewater; IW: Industrial wastewater; MDW: Municipal wastewater and domestic wastewater.*

[2]*Regional drainage (RD) includes: urban surface runoff, agricultural wastewater, industrial wastewater, municipal wastewater, and domestic wastewater.*

[3]*Construction cost was $33,706,600 in US Dollars (USD) (based on the January 2010 exchange rate from New Taiwan Dollars - NTD).*

Limitations and Constraints of the CCWSs in Metropolitan Taipei

The constructed wetlands, with a central government sponsored budget of USD $33,706,600 from the Taiwan EPA, were designed using free water surface systems (FWS) and subsurface flow systems (SFS). Since the central government sponsored the total construction cost, the main limitations and constraints for the operation of CCWS in Metropolitan Taipei are a lack of public awareness and citizen participation in the wetland planning and design phrase and funding from local agencies to maintain the systems.

Public Awareness. In metropolitan areas in Taiwan, constructed wetlands are commonly located beyond city limits and are historically separated from urban populations by concrete levees constructed to reduce the risk from flooding. Consequently, citizens living in metropolitan areas have lost the visual connectivity with the rivers. Experiences of outdoor activities and wetland cultural

Table 3. The following equations were used in the design of clustered constructed wetlands (CCWs) derived from their hydrologic functions calculated by hydrological engineers in Taiwan.

(1) Pollutant removal ratio

$$R = 1 - \frac{C_e}{C_i} = 1 - e^{-K_v t} \quad (1)$$

where,

C_e	Effluent concentration, mg/L;
C_i	Influent concentration, mg/L;
K_v	First-order decay rate constant, 1/day; the recommended K_v for estimating BOD removal is between 0.2 and 0.45 /day (Shih et al. 2013).
t	Retention time, day; the recommended retention time for treating BOD and NH_3-N are 5-6 days and 5-10 days, respectively, under the situation of air temperature of 25-30℃ (Shih et al. 2013).

(2) Hydraulic Retention Time (HRT) approach

The most direct way to estimate the retention time (or residence time) is through the HRT approach. The HRT retention time is calculated from the volume of water divided by the daily discharge.

$$t_{\mathrm{HRT}} = \frac{V}{\mathrm{Q}} \quad (2)$$

where,

t_{HRT}	Retention time calculated by the HRT approach
V	wetland volume, m^3
Q	wetland flow discharge, m^3/sec

(3) Residence Time Distribution (RTD) approach

The RTD approach considers the mixing, diffusion, and retention time distribution of a fluid in a reactor vessel and models the flow conditions of fluids in a reactor more effectively (Levenspiel 1999; Shih et al. 2017; Su et al. 2009). Levenspiel (1999) suggested that the wetland should be treated as a large reactor, and conducted a pulse experiment at the inlet by adding a tracer such as rhodamine, bromide, or chloride of a given concentration within a short time. Based on the tracer concentration measurement at the outlet of the wetland, the retention time distribution (RTD) curve was derived. The flow condition inside a wetland can be revealed by the position and distribution of a RTD curve. The position of the RTD curve can be represented as the mean retention time (t_{RTD}). As a numerical model was used, the t_{RTD} can be evaluated by the entire RTD curve by applying following equation (Kadlec 1994; Su et al. 2009),

$$t_{RTD} = \frac{\int_0^\infty tC\,dt}{\int_0^\infty C\,dt} \quad (3)$$

where,

t_{RTD}	Retention time calculated by the RTD approach, day
C	Tracer concentration distribution, mg/,
t	time, day

(4) Effective volume

Thackston et al. (1987) defined the ratio of t_{RTD} to t_{HRT} as the effective volume ratio, which ranges from 0 to 1.

$$e_v = \frac{t_{RTD}}{t_{HRT}} \quad (4)$$

where,

e_v	Effective volume
t_{RTD}	Retention time calculated by the RTD approach,
t_{HRT}	Retention time calculated by the HRT approach

(5) Hydraulic efficiency

Persson et al. (1999) proposed the hydraulic efficiency index（λ）to identify the RTD curve position and distribution. The λ calculated from the RTD curve can provide an indication of the uniformity of fluid flow inside a wetland.

$$\lambda = e_v \times \left(1 - \frac{1}{N}\right) \quad (5)$$

where,

λ	Hydraulic efficiency
e_v	Effective volume
N	Number of tank-in-series

experiences were beyond the regular lives of urban residents. In this case, strategies for raising the awareness and perceptions of citizens to link to one of the objectives as "sense of place" have been discussed and organized by the former Deputy Mayor Hong-Yuan Lee. Being a Professor in the Department of Civil Engineering at National Taiwan University (with a Ph.D. in hydrological engineering from the University of Iowa, USA), he was happy to engage in a constructive dialogue in the public forum when he served as the Deputy Mayor from 2005 to 2009.

Management Regime. The Taiwan EPA provided the entire construction budget for 93 constructed wetlands in Taiwan, including the fourteen in Metropolitan Taipei. Due to a budget reduction in 2010, the Taiwan EPA requested that the local government support the maintenance of their wetlands under a policy of financial self-sufficiency. Since then local government is responsible for managing these wetlands, yet they have insufficient funds for proper maintenance. The annual maintenance cost for a few of the wetlands has been recorded: F-FZ2: USD $53,083, F-SL: USD $42,274, F-HG: USD $38,412, and F-SH3: USD $37,087.

SCHEME APPRAISAL

This section describes the major strengths and weaknesses of the design and implementation of the CCWSs in Metropolitan Taipei including consideration of their design, construction, management, costs, and ecosystem service values.

Water Quantity

The CCWSs in Metropolitan Taipei have been considered a successful design case to control the flow of rivers in drought/flood seasons. During floods, floodgates were adjusted to control water flow in flood barrier and levee systems (Cheng et al. 2011). Constructed wetlands serve as natural sponges in regional drainage. During flood seasons, they trap and slowly release surface water to maintain hydrological balance in the baseflow. Constructed wetlands improve water quantity in dry seasons to a greater degree than during flood seasons. Low river flow might lead to short-term deficits in river discharge, providing insufficient baseflow to meet the needs of a healthy ecosystem. Therefore, baseflow from the system during drought conditions could provide sufficient flow to support ecosystem service for fish spawning in Tahan Creek.

Water Quality

The CCWS in Metropolitan Taipei is considered a successful design case, for they consistently produce an outflow high in DO and low in BOD_5, SS, NH3-N, and *E. coli* (Cheng et al. 2011). Water quality of the output from all 14 wetlands has much improved since the series of wetlands was constructed in 2004 (Figure 3) but are still below local targets. An upward trend in DO was observed in 84.6 % of the sampling stations, while the trend in nine sampling stations was statistically significant ($p < 0.05$). Dahan Creek, Xindian Creek, and Danshui River downstream showed an upward trend in DO, indicating an increase in oxygen, beneficial to fish and other aquatic life. In BOD_5, 84.6 % of the stations detected a downward trend and this trend was statistically significant ($p < 0.05$) for 10 monitoring stations. However, an upward trend of SS was detected in 53.8 % of the monitoring stations, with the trend in 10 stations being statistically significant ($p <0.05$). A downward trend in NH_3-N was detected in 53.8 % of the monitoring stations; statistically significant for seven stations ($p < 0.05$).

During 2002-2003, the Central Weather Bureau reported that these two years had “less rain” in North Taiwan, with an average annual rainfall of 1,839 millimeters (mm) in 2002 compared to a long-term average annual rainfall of 2,918 mm from 1949 to 2001. So “less rain” (about 37% less rainfall) created weather-related poor water qualities during 2002-2003. Between 1993 and 2010, the lowest levels of DO (2 mg/L) were recorded during 2002–2003 whereas the highest levels of DO (6 mg/L) were recorded during 2008. The lowest level of BOD_5 was detected in 2008. We, therefore, attributed this low level of BOD_5 in 2008 and decrease in ammonia due to very high annual rainfall of 3,252 millimeters (mm) recorded by Central Weather Bureau in 2008. Ammonia (NH_3-N), which strongly affects the health of citizens in metropolitan areas, peaked at 5 mg/L during 2003, but also showed a decrease in concentration during 2008. The levels of *E. coli* detected in samples ranged between 0 and $2x10^6$ CFU/100 mL in the period between 1997 to 2003, and this level has declined to be between 0 and $0.5x10^6$ CFU/100 mL since 2004 (Cheng et al. 2011).

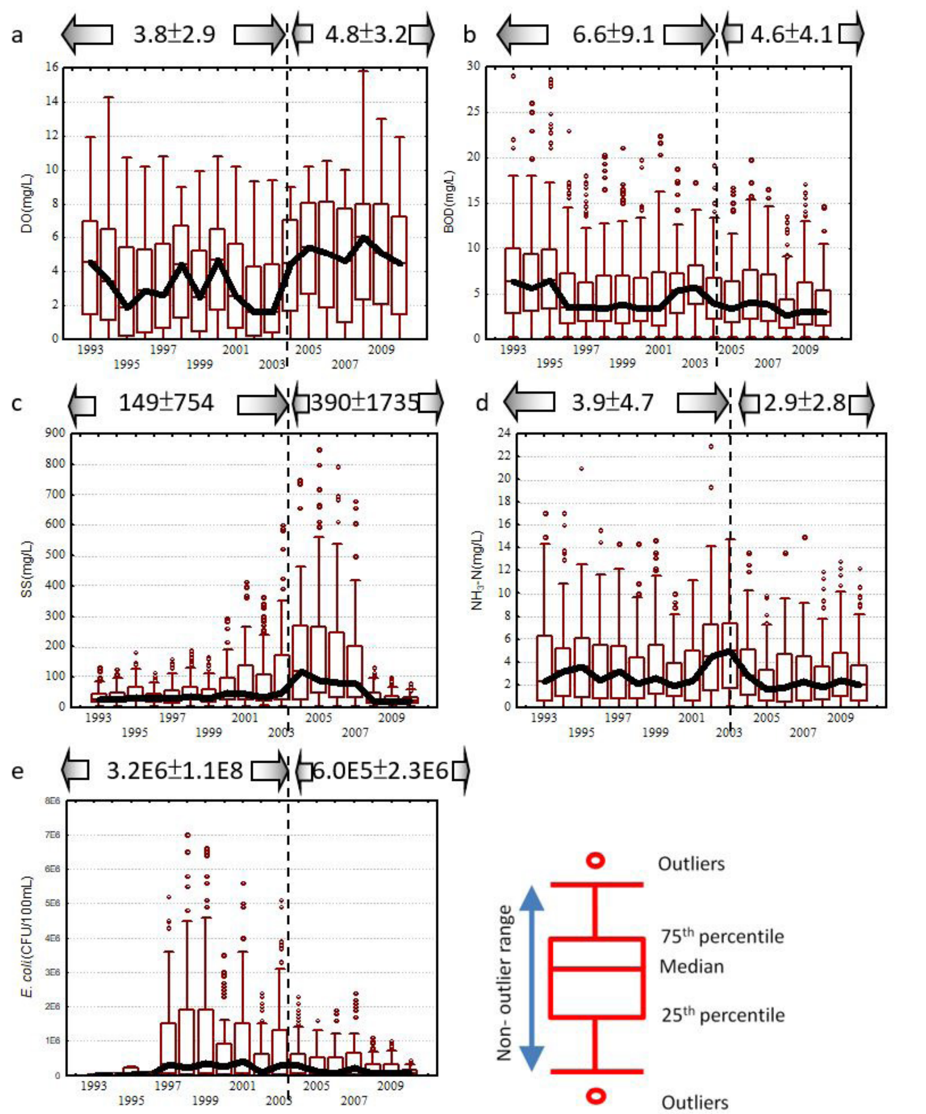


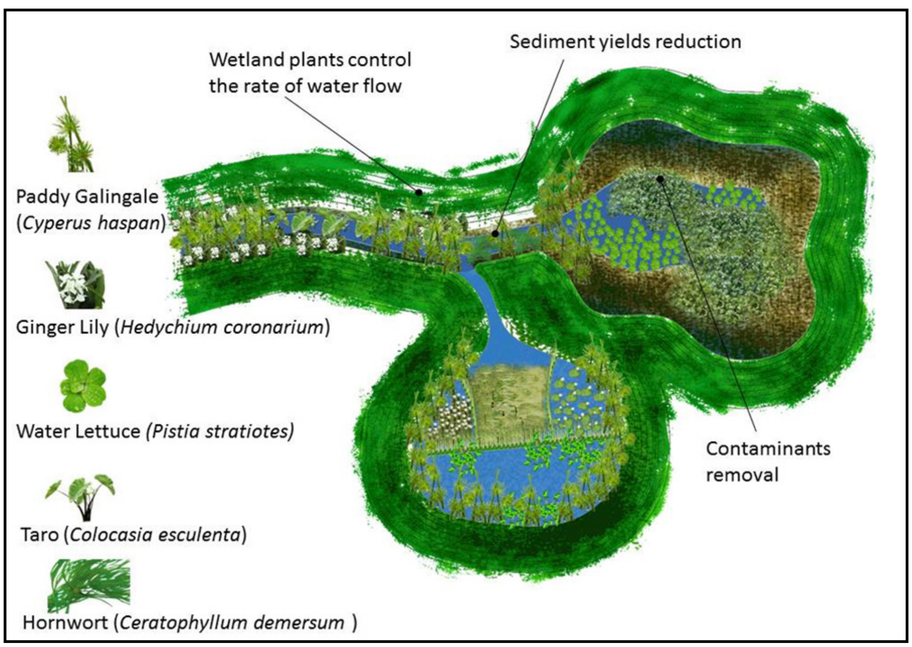
Figure 3. Variations in water quality (a: DO; b: BOD5; c: SS; d: NH3-N; e: E. coli) in the metropolitan Taipei basin of the output from all 14 wetlands surveyed in Danshui River between 1993 and 2010. (Source: Cheng et al. 2011). According to each figure, for example, please see the top left corner of a. DO. The first number of top left corner (3.8) represents an average (a mean) between 1993 and 2009, and the second number (2.9) represents a standard deviation (SD). Two periods could be compared, such as you can compare the number (3.8±2.9) for the first period before wetland construction between 1993 and 2003, and the following number (4.8±3.2) for the second period after wetland construction between 2004 and 2010. Local targets for water quality are: DO > 6.5 mg/L; BOD5 < 3.0 mg/L; SS < 20.0 mg/L; NH3-N < 0.50 mg/L in the water (Cheng et al. 2011)

The mainstream of Danshui River and its tributary Dahan Creek both indicated an upward trend in SS. Sediment loading in both Danshui River and Dahan Creek was extremely high during wet periods. Following an increase in sediment loading in Dahan Creek, the downstream segment of the main river (Danshui River) carried more SS as detected at the confluence of the rivers. The dynamics involved in SS loading at the confluence of the tributaries influences

Table 4. The species populations present before and after wetland construction in the Shin Hai Wetland (in the F-SH1, F-SH2, & F-SH3) and the Fu Zhou Bridge Wetland (F-FZ2), see Figure 4.

Species	Venues	Before wetland constructed as a riparian areas in 2003	Examples of species recorded after wetland constructed in 2013	
Birds	Shin Hai	23	83	Black-winged Stilt (*Himantopus himantopus*) and Painted Snipe (*Rostratula benghalensis*).
	Fu Zhou	20	22	Black-winged Stilt (*Himantopus himantopus*) and Painted Snipe (*Rostratula benghalensis*).
Amphibians and reptiles	Shin Hai	1	19	Gunther's Frog (*Rana guentheri*).
	Fu Zhou	2	15	Gunther's Frog (*Rana guentheri*), Brown Tree Frog (*Buergeria robusta*), and Asian Yellow Pond Turtle (*Mauremys mutica*).
Aquatic insects	Shin Hai	none	32	Water mantis (*Ranatra chinensis*), etc.
	Fu Zhou	none	12	Water Mantis (*Ranatra chinensis*) and Back-striped Firefly (*Luciola substriata*).
Aquatic plants	Shin Hai	16	65	Yellow Water Lily (*Nuphar shimadai*) and Da-Ann Hygrophila (*Hygrophila pogonocalyx*).
	Fu Zhou	16	70	Yellow Water Lily (*Nuphar shimadai*) and Da-Ann Hygrophila (*Hygrophila pogonocalyx*).

Figure 4. The recommendation for Paddy Galingale (*Cyperus haspan*), Ginger Lily (*Hedychium coronarium*), Taro (*Colocasia esculenta*), and Hornwort (*Ceratophyllum demersum*) to support diverse insect, fish, and amphibian populations. In this figure, Water Lettuce (*Pistia stratiotes*) should be controlled for its competitive nature. (Designed by Wei-Ta Fang, all rights reserved.)



the hydrological links between the slower movement of sand and clogged sedimentation. It should be noted that the meandering upstream section of Dahan Creek may have contributed sediment to the river following the extreme rainfall events during 2005. In addition, debris flows increased after 1999 due to soil erosions from unstable hilly highlands in Taipei areas associated with collateral damage due to anthropogenic influences (i.e., houses, tea plantations, and recreation uses) since the September 21, 1999 earthquake (7.6-7.7 Mw) occurred.

Biodiversity

All the wetlands were designed to improve both water quality and wildlife habitat. The wetlands are dominated by three species: reed (*Phragmites australis),* Oriental cattail (or narrowleaf cat-tail) (*Typha angustifolia*), and water lettuce (*Pistia stratiotes*). All of which have benefitted from the high nutrient-loading conditions. The planting of wetland aquatic vegetation was designed to control the flow rate through the wetland, to reduce the sediment yields from upland sand loadings, and to remove waterborne pollutants. While these three species can facilitate the control of flow rates, contaminant removal, and sediment reduction in some cases, they become the dominant species due to their competitive and aggressive nature. Therefore, it is recommended that the constructed wetlands be planted with endemic species or functional species for structurally diversity reasons, such as paddy galingale (*Cyperus haspan*), ginger lily (*Hedychium coronarium*), taro (*Colocasia esculenta*), and hornwort (*Ceratophyllum demersum*). Such a plant community would support diverse insect, fish, and amphibian populations (Figure 4). Table 4 shows the number of species present before wetland construction compared with those after wetland construction for the Shin Hai Wetland and the Fu Zhou Bridge Wetland. The baseline year for this comparison 2003 for the pre-construction and 2013 for post-construction. Before 2003, Shin Hai Wetland and the Fu Zhou Wetland were represented by reed-dominant riparian zones and upland areas. The post-construction survey was done in 2013. The populations present in the Shin Hai Wetland (in the F-SH1, F-SH2, & F-SH3) have increased by 60 species of birds, 18 species of amphibians and reptiles, 32 species of aquatic insects, and 49 species of aquatic plants. For the Fu Zhou Bridge Wetland (F-FZ2), populations have increased by two species of birds, 13 species of amphibians and reptiles, 12 species of aquatic insects, and 54 species of aquatic plants. Both cases used a planting scheme aimed to restore endangered species, including yellow water lily (*Nuphar shimadai*) and Da-Ann hygrophila (*Hygrophila pogonocalyx*).

Figure 5. Stable terraces and relatively gentle slope gradients of less than 30 degrees utilized to mitigate the impacts of typhoons on aquatic plants. (Designed by Wei-Ta Fang, all rights reserved.)

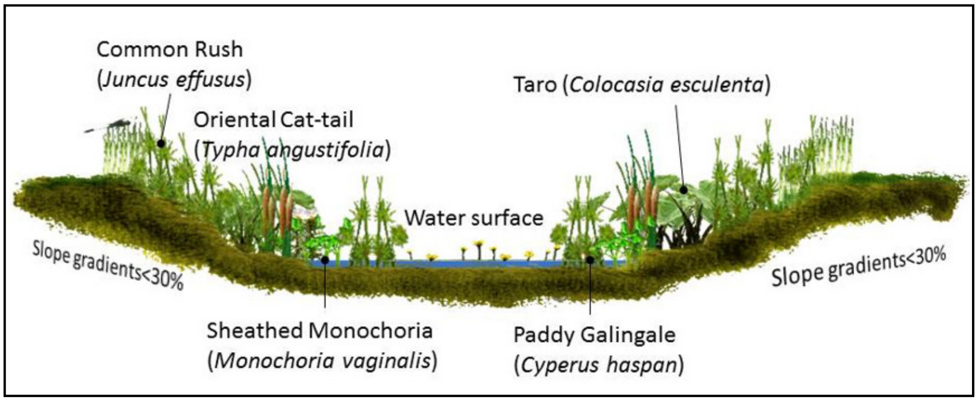
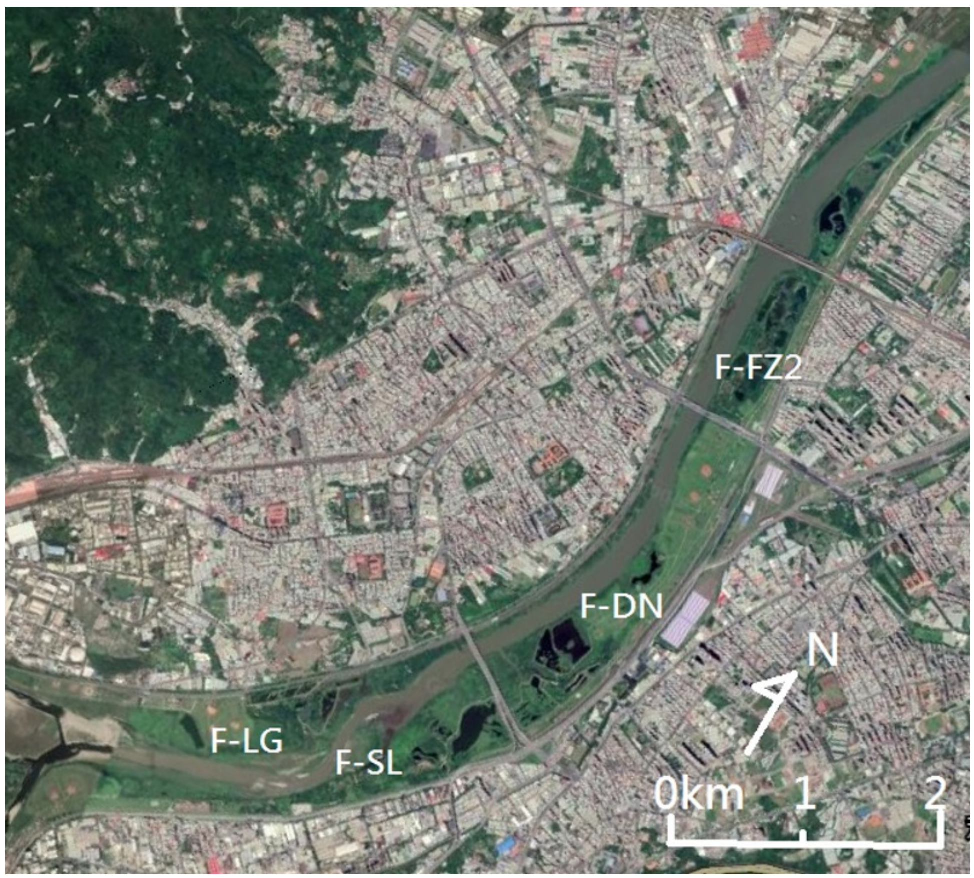


Figure 6. View of constructed riparian wetlands to support urbanized municipal wastewater treatment.



Construction and Management

Since Taiwan is subject to typhoons, understanding the risk to the constructed wetlands (built in the riparian zones within the levee borders of the Danshui River) from flooding is vitally important. During 2007, Typhoon Aere destroyed the Shin Hai Section 1 Wetland (F-SH1 site). This site has since been reconstructed and remodeled utilizing vegetation planting on relatively gentle slopes with gradients of less than 30 degrees and using stable terraces to help restore the common rush (*Juncus effusus*), Oriental cat-tail, taro, sheathed monochoria (*Monochoria vaginalis*), and paddy galingale (Figure 5). While typhoons may produce short-term impacts on water quality due to high rainfall and associated energy, no long-term abnormal malfunction of an individual wetland has been detected. Consequently these systems appear functionally resilience as aided through replanting, vegetation retreatment, and natural dispersal from natural disturbance.

Costs and Benefits

Construction costs of the CCWSs were relatively low when compared to other water treatment systems (Table 5). Both types of constructed wetland systems (gravel-contact oxidation treatment system and free water surface system) have helped improve urban water quality. Other systems that achieve the same level of water-quality improvement from domestic sewage water piped out from households are much more expensive than the CCWS alternatives. The difference in costs between the two types of constructed wetlands are that a free water surface system is cheaper than that of a gravel-contact oxidation treatment system, but the former system requires more open space.

Table 5. Cost and benefit analysis from capital, design and maintenance between different systems.

Types	Domestic sewage water piped out from households to a centralized treatment plant	Urban sewage waters collected from upstream, middle stream, and downstream to several small treatment plants and finally piped out to a centralized treatment plant	CWs (Gravel -contact oxidation treatment system)	CWs (Free water surface system)
Construction cost (unit: US Dollars/ m^3/day)	600~830	10~33	141~695	85~172
Maintenance cost (unit: US Dollars/ m^3/day)	0.15~0.3	0.15~0.3	0.02~0.04	0.02
Water quality for Biochemical oxygen demand after treatment (BOD_5)(unit: mg/L)	180	180	80	80
Water volume	River base flow is reduced.	River base flow is reduced.	River base flow is maintained.	River base flow is maintained.
Construction period	2 years and more	1 year	8 months to 1 year	8 months to 1 year
Space requirement	Requested to build wastewater treatment plants	Requested to build wastewater treatment plants, and water simply sprayed on a large piece of land	Requested to build gravel aeration systems	Requested to build free water surface systems
Evaluation	High cost; Large spaces	Few cost; Large spaces	Medium cost; Small spaces	Medium cost; Large spaces

Water quality was tested for BOD_5 and levels were found to be relatively low when compared to that from urban sewage systems post-treatment. Dr. Chia-Ji Teng, the former Commissioner (2006 to 2012) of Environmental Protection Department in New Taipei City, analyzed economic benefits to apply constructed riparian wetlands to support urbanized municipal wastewater treatment. (Note: Teng also became the Deputy Mayor for Taipei City from 2014 to 2019.) Teng et al. (2012) reported that the total costs to remove BOD_5 from the CWs were between 0.425 USD and 3.621 USD per kg. The highest cost was attributed to the construction cost of subsurface systems on a large piece of land for pretreatment of wastewaters prior to reaching Fu-Zhou (F-FZ2) wetland (Figure 6). By comparison, the costs to remove BOD_5 from the centralized wastewater treatment plant was approximately 1.186 USD per kg.

Maintenance costs for CWs are relatively low, ranging from 0.02 to 0.04 US Dollars/m^3/day for maintaining biodiversity. This work involves mowing, and removal of terrestrial and aquatic dominant grasses and other aquatic plants. Maintenance of the centralized wastewater treatment plant which received only domestic wastewater was much higher, approximately from 0.15 to 0.3 US Dollars/m^3/day (Table 5).

Description of Planned and Other Ecosystem Services (ES)

The clustered constructed wetland systems in Metropolitan Taipei are unique. All wetlands produce "value creation" (Mazzucato 2018) - providing public goods and services in the real nature economy. Mazzucato, an economist, created a new framework that presented a clear definition and approach to assess "value creation" regarding public interest in "managerism". The latter term implies that management can optimize the impact decisions to create value by expanding benefits from ecosystem services. It is possible to generate one set of scores for all 14 wetlands to evaluate both planned and actual ecosystem services in a rationale regional system. The following table derived from the Millennium Ecosystem Assessment (MEA; Millennium Ecosystem Assessment 2005; De Groot et al. 2006; Ghermandi et al. 2010; Ramsar Convention on Wetlands 2018) was used to evaluate ecosystem services for the CCWS in Metropolitan Taipei (Table 6). The means of scores in two columns are represented from the interval between 0 and 3, such as: 0 = ES not relevant; 1 = ES of low importance/significance; 2 = ES medium importance/significance, 3 = ES of high importance/significance. Scores were assigned by ten experts that analyzed by calibration from our team. This process consists of wetland system that were designed and construction by engineers and scored by wetland scientists/experts in the evaluation of all wetland ecosystem service (ES). We specified the criteria used to evaluate the planned phase (i.e., wetland technical proposals) versus the actual phase (i.e., wetland technical reports) and the points given to each. As one can see, there were more ES benefits than originally planned because some were not initially considered. The criteria proposed by the MEA include: 1) adequacy of the planned phase in responding to the MEA, 2) actual wetland qualifications, and 3) stakeholder competence (i.e., key professional staff, local school kids, visitors, and community citizens) for the MEA evaluated in New Taipei City.

Table 6. Study case to be detected by the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment [MEA] 2005; De Groot et al. 2006; Ramsar Convention on Wetlands 2018).

			Planned	Actual
Provisioning Services	Food for humans	Sustenance for humans (e.g. fish, mollusks)	0	0
	Fresh water	Drinking water for humans and/or livestock	0	0
		Water for irrigated agriculture	0	0
		Water for industry	0	0
		Water for energy production (hydro-electricity)	0	0
	Wetland products non-food products	Timber	0	0
		Fuel wood	0	0
		Peat	0	0
		Livestock fodder	0	0
		Reeds and fiber	0	2
		Other	0	0
	Biochemical products	Extraction of material from biota	0	0
	Genetic materials	Medicinal products	0	0
		Genes for tolerance to certain conditions (e.g. salinity)	0	0
		Genes for resistance to plant pathogens	0	0
		Ornamental species (live and dead)	0	3
Regulating Services	Maintenance of hydrological regimes	Groundwater recharge and discharge	0	1
		Storage and delivery of water for agriculture and industry	0	0
	Erosion protection	Soil, sediment and nutrient retention	3	2
	Pollution control and detoxification	Water purification/waste treatment or dilution	3	3
	Climate regulation	Local climate regulation/ buffering of change	0	0
		Regulation of climactic processes	0	0
	Biological control of pests and disease	Support of predators of agricultural pests	0	0
	Hazard reduction	Flood control, flood storage	3	3
		Coastal shoreline/river bank stabilization and storm protection	3	3
	Pollination	Acts as a source for pollination of other areas	0	0
Cultural Services	Recreation and tourism*	Recreational hunting and fishing	0	0
		Water sports and activities	3	3
		Picnics, outings, touring	3	3
		Nature observation and nature-based tourism	3	3
	Spiritual and inspirational	Inspiration	0	1
		Cultural heritage	0	0
		Contemporary cultural significance	0	0
		Spiritual and religious values	0	0
		Aesthetic and "sense of place" values	3	3
	Scientific and educational*	Educational activities and opportunities	3	3
		Important knowledge systems, and importance for research	3	3
		Long-term monitoring site	0	3
		Major scientific study site	0	3
		'Type location' for a taxon	0	2
Supporting Services	Biodiversity	Supports a variety of all life forms	2	2
	Soil formation	Sediment retention	3	1
		Accumulation of organic matter	3	3
	Nutrient cycling	Storage, recycling, processing and acquisition of nutrients	3	3
		Carbon storage/ sequestration	0	1

RECOMMENDATIONS

The key lesson learned from this case study is that well-designed constructed wetlands (CWs) can satisfy the requirements of wastewater purification and provide habitat for native flora and fauna and thereby support species diversity. These wetland systems can also act as aesthetic leisure spots - attractive destinations for tourists and urban residents alike. Results from this study indicate that levels of water quality indicators, such as DO, BOD_5, SS, NH3-N, and *E. coli*, have gradually improved during recent years. Furthermore, constructed wetlands control the flow of rivers in drought/flood seasons, and play a crucial role in preventing extreme deteriorations in water quality. Therefore, our final recommendations are based on application of the Millennium Ecosystem Assessment.

1. Provision of advanced operation and maintenance budgets. In order to successfully maintain this artificial ecosystem, the municipalities should focus on supporting the budgetary requirements necessary to aid the sustainability for wetland ecosystems.

2. Soil, sediment, and nutrient retention. Since typhoons are stochastic and occasional events, design modelling suggests that to mitigate debris flows and vegetation damage an eco-engineering approach coupled with replanting of vegetation covers is necessary.

3. Native, ornamental, and educational plant species restoration (Figure 7). An endangered species list is suggested to encourage schemes that focus on restoring these species, such as Taoyuan' marsh weed (*Limnophila taoyuanensis*), Lungtan floatingheart (*Nymphoides lungtanensis*), sheathed monochoria, and paddy galingale around the Tahan Creek basins in the Taoyuan Tableland of the northern regions of Taiwan. Yellow water lily is another species used in the design (Figure 8).

Figure 7. Native, ornamental, and educational plant species restoration design. (Designed by Wei-Ta Fang, all rights reserved.)

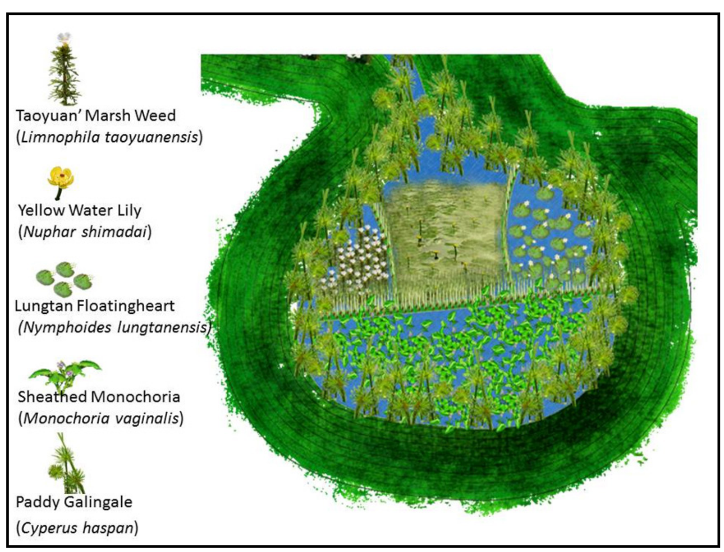
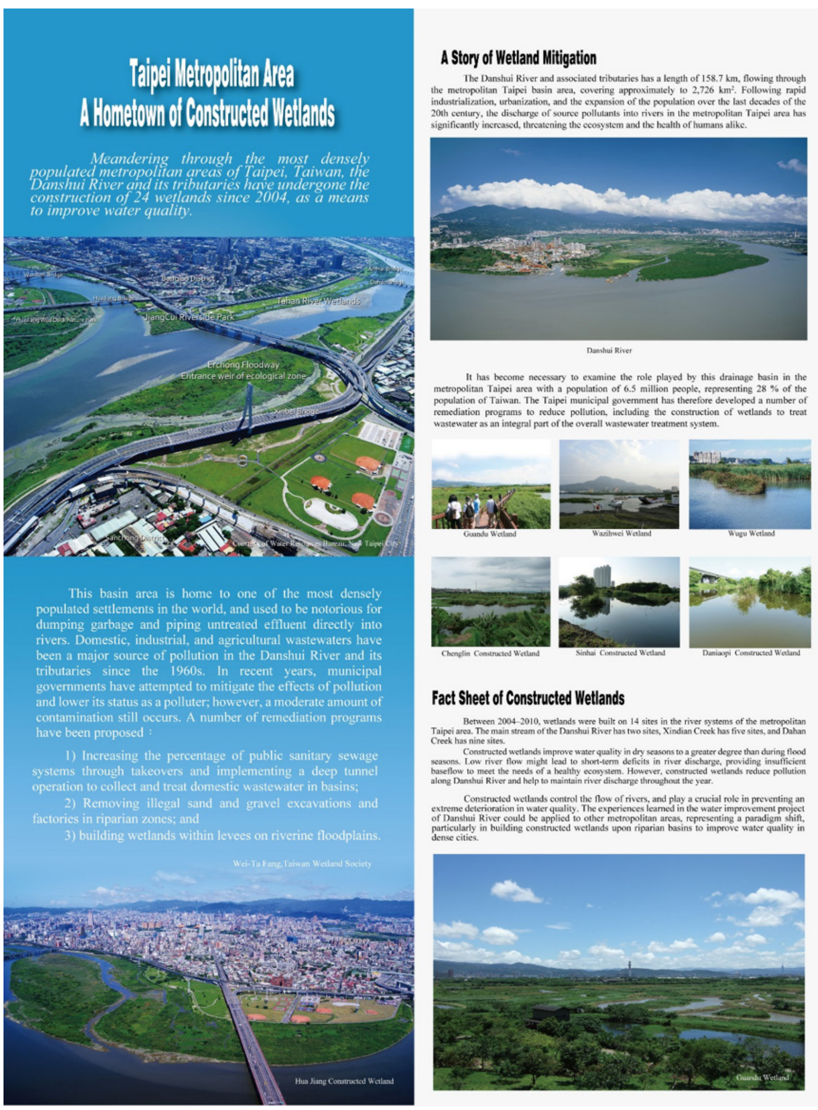


Figure 8. Yellow water lily (*Nuphar shimadai*), a Taiwanese endemic species, typically grows in a number of limited ponds in Longtan, Taoyuan, northern region of Taiwan. (Photo courtesy of Te-Hong Chen)

Figure 9. Poster highlighting Constructed Wetland Systems in Metropolitan Taipei. Designed by Wei-Ta Fang, all rights reserved.



4. Scientific and educational opportunities to create the wildness for bird watching. Constructed Wetland Systems in Metropolitan Taipei were also built to increase contemporary cultural significance for bird watching, flood control, and natural preservation (Figures 9 and 10).

5. Creating opportunities for additional constructed wetlands. Constructed wetlands in Metropolitan Taipei play a crucial role in preventing extreme deteriorations in water quality as well as water quantity. We therefore recommend that local governments consider building more constructed wetlands to improve water quality. These constructed wetlands, a simulated wild land, will also provide various opportunities of biophilic participation by metropolitan citizens. ■

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Figure 10. Wildlife found in Taipei wetlands:

a. Eurasian green-winged teal (*Anas crecca*; wintering male).

b. Common snipe (*Gallinago gallinago*).

c. Common moorhen (*Gallinula chloropus*).

d. Little egret (*Egretta garzetta*). (All photos by Wei-Ta Fang.)

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