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A sustainability strategy of integrated highway wetlands for urban water management in China

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ABSTRACT

The rapid expansion of urban space has caused many problems all around the world. This is especially true in China, where we need to face challenges such as limited spaces, wastewater treatment, decreasing water resources, ecological preservation, and so on. In the management of urban water, an economic, environmental, and social balance needs to be. The aim of this study was to develop a freeway strategy of Integrated Constructed Wetlands to achieve this balance. This strategy combined several disciplines of civil engineering, ecology, landscape design, and agricultural irrigation, and this conceptual idea will be demonstrated through a design for Huai'an city in Jiangsu province, which sits on the East-route Water Transfer Project of China. The project consists of surface flow wetlands, ecotype corridors, retention facilities, and stabilization ponds. Importantly, it is designed beside the Ning-Lian freeway that goes around the city. The whole system could treat effluents from city and wastewater plants. In rainy seasons, it could store and treat extra sewer discharges and freeway surface runoff. During farming seasons, it could potentially treat the effluents from irrigation fields and it was also designed that the outflow of this whole system would be reused for irrigation. The environment surrounding the freeway could derive multiple benefits from the proposed strategy and could provide recreation, habitat creation, and education possibilities for the city and local community.

Keywords: Urban water management; Integrated highway wetlands; Wastewater treatment; Ecological design; Low carbon; Sustainability

1. Introduction

Populated areas ranging from small, rural communities to large, urban complexes all require adequate access to freshwater resources, but as population increases and anthropogenic influences expand, meeting freshwater demands will require a balance between wastewater disposal and water resource protection [1]. Estimates indicate that 60% of the world will reside in urban areas by 2030 [2], with the combined effect of increasing populations and greater water demand creating larger volumes of wastewater in concreted areas. According to the 2011 report from the National Bureau of Statistics of China, in 2010 there was a 13.5% population increase in city areas compared to 2005. Improving water quality in ways that are low cost and have low carbon emissions, particular in urban centers, will be critical in the sustainable future. Constructed wetlands have been used worldwide to improve water quality

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for domestic reuse, irrigation, and environmental protection [3]. However, these systems are most often designed by engineers who focus primarily on functionality of the treatment rather than landscape design, so the potential value, beautiful landscapes will be neglected. On the other hand, it is difficult to locate in cities as they occupy lot of limited spaces in cities and the land value is inefficient.

To begin with, this paper presents four key green directions for urban wastewater management in the future. These directions will be applied in conjunction to make urban wastewater management more sustainable and effective. These four directions are: (1) separated infrastructures and limited spaces utilization, (2) ecological processes, (3) a wide variety of effluent collection and reuse, (4) multifunctional systems that benefit human and ecological community. The article also describes a case study which demonstrates these functions for Huai'an city in China. This designed system is a self-sustainable system and it will provide as much recreation, habitat creation, and education as possible to the students and visitors on importance of our precious natural resource.

2. Sustainable development for future urban water management

Conventional wastewater treatment plants involve large capital investments and operating costs [4]. In addition, these traditional plants always focus on single treatment function rather than on multifunctions. This paper presents some beautiful and green ways to address urban water quality challenges.

Firstly, wastewater treatment plants in the future should provide resilience against human or natural disasters. In this paper, we proposed separated infrastructures to allow several treatments flexibility. Compared to the traditional treatments, this system is spatially adaptive and allows each treatment for a particular site or neighborhood. There are smaller pipe networks between these separated infrastructures, so they are less prone to catastrophic failure.

In China, because of large population, the spaces are very limited in urban area. It is important to consider the land use efficiency. Not to waste the land potential value is a sustainable way that the designer should insist in. The integrated constructed wetlands system discussed later is designed beside a freeway which not only used the large free lands around cities, but also beautified the landscape on the way.

Secondly, wastewater plants should depend on natural treatment processes and low-carbon systems to improve water quality. Natural treatment systems rely on vegetative and microbial metabolism with little energy consumption. It is green and low carbon, such as this proposed system. Through this whole constructed wetlands system, we could see the natural treatment processes under solar power mainly. These human-built systems that draw from nature's lessons have been shown to be efficient, attractive, and inexpensive worldwide [5].

Meanwhile, in urban contexts, the existing sewerage is aging, undersized and insufficient in China, and it is still a conventional centralized sewer system. This system can relieve the combined sewer networks, and they can be used as a tertiary wastewater treatment.

Thirdly, in the face of poor water quality, quantity, and carbon emission regulations wastewater infrastructure should detain, treat, and reuse a wide variety of effluent resources. This system collects urban stormwater, irrigation water, flood, freeway runoff, and urban wastewater.

In China, the potable water resources are very limited. Today, an important direction is that wastewater treatment system should provide recycled water for local reuse. To replace and reduce potable water consumption, the recycled water is used to flush toilets [6], fight fires, clean streets, irrigation [7], and river rehabilitation [8]. By treating and reusing the wastewater from residents and surface runoff, cities can save precious freshwater resources [9].

Additionally, the proposed wastewater treatment system has a dual purpose, primarily in terms of infrastructure but also in terms of landscaping. The aim is to create a functioning system that fits in well with the surrounding environment. There are multiple potential functions, such as recreation, education, and as green spaces for the benefit of local communities. The proposed system discussed in later detail will be built beside freeways around the city. It will provide a picturesque backdrop for the drivers using the freeway and will give a good first impression of the city for visitors.

3. Case study

3.1. Background

In 2002, China launched the South-to-North Water Transfer Project in context of water shortage in the acid north [10,11]. The project consists of three south-to-north canals (i.e. East, Middle, and West), stretching more than 1,100 km across the east, middle, and west parts of China [12]. This integrated constructed wetlands system is designed for the wastewater plant of Huai'an city, which sits on the East-route Water Transfer Project of China (Fig. 1). It is more important to control the water quality along the East Water Transfer Route.

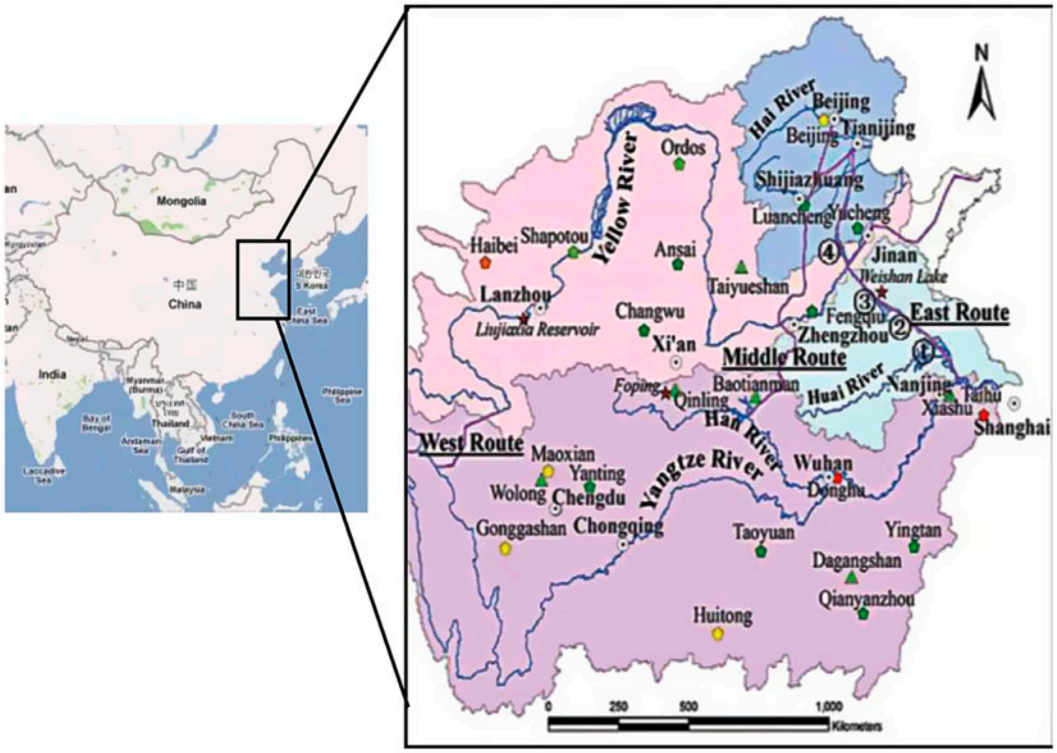

Fig. 1. East-route water transfer project of China.

Huai'an is a developing city with population increasing and industry prospering. The wastewater volume has exceeded the capacity of old treatment plans. On the other hand, the city operates an old combined sewer system. During heavy rain, large volumes of stormwater exceed treatment plant capacity. These large discharges of untreated and poorly treated wastewater will be received by the White Horse Lake which has been eutrophicated during these years. The yearly mean phosphorus concentration of this lake water is 0.12–0.3 mg/L. According to the district government's layout, the White Horse Lake was selected as the standby freshwater source in 2009. Therefore, it is urgent and vital to clean and protect the White Horse Lake.

Moreover, Hongze district in Huai'an city is a farming land which needs more water to irrigate. This is the opportune to explore this designed system with solar powered, multifunctional wastewater treatment for water irrigation reuse.

3.2. Materials and methods

According to the directions above, this system is located beside the Ning-Lian freeway around Huai'an city (Fig. 2). The system building zone is about 200 m wide and 7,000 m long. It consists of retention facilities, ecotype corridors, free water system wetlands, and stabilization ponds. It is designed to treat amount of 90,000 m^3 wastewater per day. There are two wastewater treatment plants (1#, 2#) we should consider. Therefore, the whole system contains almost two sets of infrastructures to purify the wastewater separately except the last stabilization pond (Fig. 3). Some schemes were adjusted to local conditions. We altered the old local fish ponds and farming areas to build water retention ponds and free water system wetlands.

In the water retention pond, we added solar powered aeration machines to help increase the oxygen level of the wastewater. In the retention pond, we planted reeds (*Phragmites australis*) and water bamboo (*Zizania latifolia*) around it to absorb nitrogen and phosphorous from the wastewater. To protect the banks from erosion, we selected vetiver grass which has a deep thick root system [13]. The retention pond 1# is about 104,000 m^2, and pond 2# is about 120,000 m^2. The hydraulic retention time (HRT) is about nine days. The total storage capacity in two ponds is 900,000 m^3. We also considered some contingencies in case of event such as regional waterlogging or a sudden failure of wastewater plants, in which a large volume of overflow could be discharged into the water retention pond directly. During these overflow events, the HRT will be

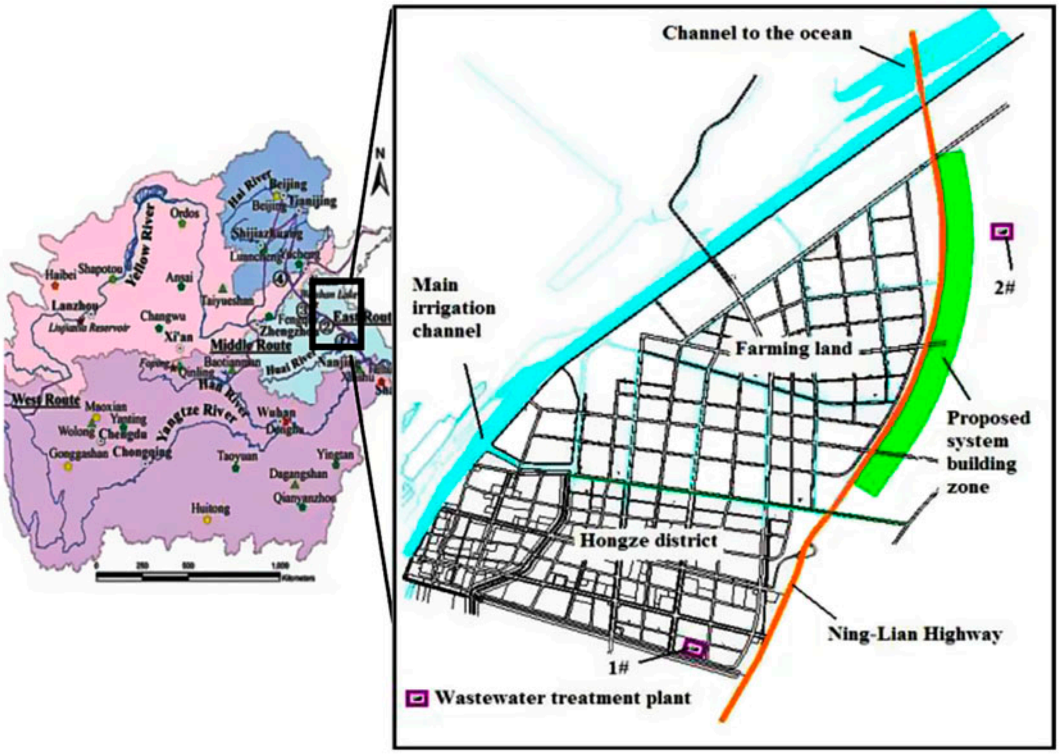

Fig. 2. Study area and location of the proposed ecosystem.

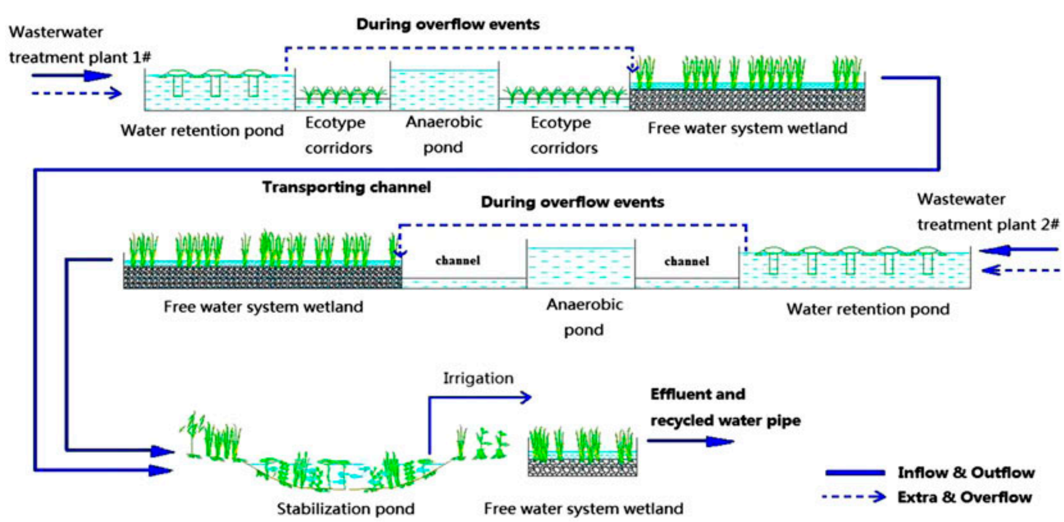

Fig. 3. Flowchart and hydraulic of the proposed complex constructed wetland system.

shortened and the extra mixed wastewater will be pumped directly to the constructed wetland downstream (Fig. 3).

The ecotype corridor is designed and built based on the old irrigation channel in order to connect retention pond, anaerobic pond, and free water system wetlands. Its total length is about 1,100 m with the average slope of 1%. The 0.6 m deep substrate consists of a mixture of gravel and crushed rock, which has a high binding capacity for phosphorus [14]. On the both sides of the corridor, we plant several kinds of flowers like *Calamus*, *Thalia dealbata*, and *orris* to beautify the environment.

The anaerobic pond is designed as a part of water retention facilities. Its main purpose is to make up an anoxic/oxic (A/O) system with retention ponds and corridors. As we know, this system can remove carbon and nitrogen simultaneously. At the same time, we planted some algae in the pond and *Typha* on the surrounding surface near the bank. In this way, we could find the symbiosis between bacteria and algae which could help to treat the wastewater efficiently. The anaerobic pond's area in all is about 175,000 m^2, and its storage capacity for water is about 788,000 m^3. The HRT is about eight days.

The free water system wetland is constructed on original agricultural lands. With dikes surrounding wetlands, we also planted reeds, *cannas, orris*, and *Typha latifolia* in it to make it as a decorative element in the whole landscape. Meanwhile, in order to increase the HRT, we dug many curving ditches in wetlands. The total free water system wetland has an area of 796,000 m^2 with an average slope of 1.5%. Its hydraulic loading rate is about 0.14 m/d and the free water depth in it should be controlled at no more than 0.4 m.

The final part is the stabilization pond which is used to collect clean water from the wetlands, and we designed as a beautiful lake for the community. It has an area of 138,000 m^2 and a depth of 1.6 m (HRT = 2.5 days). In the pond, we planted a few of floating aquatic plants like water lily, spatterdock, and water chestnut to add some colors in the sceneries. On the other hand, this pond is also an irrigation pond from which the water will be pumped into farming lands.

Furthermore, the monitoring on-line system was built to take wastewater samples from every infrastructure effluent. It is important to monitor the removal rate effectiveness and to adjust the flow rate of the system if necessary.

4. Discussion

A bird's eye view of this integrated freeway wetlands system has been shown in Fig. 4. This proposed system has just been completed when this paper is written. Based on the existing wastewater treatment plant, after a period of experimental operation (the system inflow is 24,000 m^3 per day), we got the removal rates of COD_{cr}, TN, NH_3-N, and TP which have been listed in Table 1 through different facilities. The results seem to be acceptable. But the system cannot be fully in operation now, and we still should adjust the flow rate, HRT, and the initial discharge of the wastewater into the system.

In rainy seasons, the system could store and treat extra urban sewer discharges and freeway surface runoff via the pipe connected to the sewer network, and deposited into the retention pond directly. During farming season, it is also designed that the outflow of the system would be reused for irrigation. Based on a

Fig. 4. The bird's eye view of this whole system. (1) Stabilization pond; (2) free water system wetland; (3) ecotype corridor; (4) retention facility.

Table 1
The removal rates of four main indexes through different facilities

Removal rates	COD_{cr} (%)	TN (%)	NH_3-N (%)	TP (%)
Retention pond	40	36	41	20
Ecotype corridor	22	12	16	25
Anaerobic pond	13	8	6	10
Free water system wetland	20	24	26	33
Stabilization pond	2	6	9	8
Overall	97	86	98	96

simple first-order plug flow volumetric loading model: $C(\text{out})/C(\text{in}) = e(-k \times t)$, $\text{HRT} = V/Q$ [15], we could moderate the HRT and the inflow volume to the wetland. So, the main nutrients' concentration of outflow will be controlled to suit for the state standard of irrigation through the real-time monitors. During overflow events, the extra mixed wastewater will be pumped directly to the surface flow wetlands as mentioned. And they will not stay in the anaerobic pond. Of course, the nutrients will also be treated in the other facilities. Because in these situations, the nutrient concentration will always be much lower than usual, so the outflow concentration could achieve the design standard. Especially, if not, we should retreat these volume of wastewater via pipes to the first facility and store them partly in the pipes and ponds.

In the design, we utilized gravity mostly as the whole system's momentum, including some pump stations and siphons. Whether in the ponds or in the wetlands, we must make sure that plants do not cover the entire pond. That situation will destroy the ecosystem around and reduce the effectiveness of this whole system. We placed a rhombus barrier made of PVC piping to solve this problem. To demonstrate the theory of sustainable design and educate the visitors, a sprinkler system has been built which pumps the water from stabilization pond to clean the garden and water the plants in all seasons. Several educational signs were placed everywhere to introduce the plants and explain how the system operates.

According to the former experiences, we estimate the whole system will reach its full operating capacity after 12 to 18 months. But in the next five months, many flowers will be blooming and we will have a beautiful garden beside the Ning-Lian freeway.

5. Conclusions

This paper introduced several directions to wastewater reuse and management, using a strategy of integrated freeway wetlands system for a combined sewer network and an aging, undersized wastewater treatment plant. This proposal provides as much education, recreation, and habitat creation as possible to local community.

Although this system has so many benefits such as water reuse, low carbon, less cost, and landscapes for the community, it is important to know that in urban or other industrial countries, these natural treatment systems cannot fully replace the conventional wastewater treatment plant. But in rural areas, compared to the traditional wastewater plants, this system could collect more nonpoint sources more easily. So, more researches should be done between city and country water circle.

The lifetime of the whole system is a significant problem. Successful applications of this proposed system need to rely on ecological materials. More efforts should be made to decipher the plant treatment mechanisms and moderate the related parameters, so as to provide more effective approaches for the natural wastewater treatment systems.

In China, even all around the world, we human face the shortage of freshwater resources and the deterioration of the ecological environment. Sustainable methods are fast becoming a global trend, especially in field of water management. We hope this initial ecosystem may provide more experiences to the water purification in the future.

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