Area Estimation and Distribution Analysis of Subsurface Flow Constructed Wetlands at Regional Scale --Take Guangzhou City for Example

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Abstract. In this paper, Area of Constructed Wetlands (CWs) required for treatment of domestic sewage generated by 13 million people was calculated in accordance with the distribution of existing population in Guangzhou City and mathematical model of CWs. By comparing this with land use data, the distribution of constructed wetlands at construction regional scale was simulated with GIS. The results show that, Guangzhou generate about 3.88 million m^3 domestic sewage per day, which shall be treated with 59.37 km^2 CWs. Assuming that a single wetland bed is 300 m^2, total 197,905 wetland beds shall be required in the city. Based on the analysis and statistics on data of second national land survey of Guangzhou City with GIS, there are enough ponds, bare lands, other grasslands and other garden plots in Guangzhou that can be used for construction of regional scale CWs, but the distribution of available lands in different regions is uneven. Constructed wetlands at regional scale are mainly distributed around Baini Channel, Tianma River, Xinjie River, Liuxi River Valley, Zengjiang River Valley and on both sides of the Pearl River through Panyu and Nansha.

1. Introduction

Constructed wetland is a sewage treatment technology developed since the 1970s [1]. Sewage treatment with CW will provide better social, economic and ecological benefits. There are more than 600 CW projects in the U.S. for municipal, industrial and agricultural wastewater treatment [2]. At least 200 CW systems are in operation in Denmark, Germany and Britain [2], more than 80 CW systems also have been put into use in New Zealand [3]. The first research on CW sewage treatment in China was carried out in 1987 by Tianjin Institute of Environment Protection, which established the first reed wetland treatment system covering an area of 6 hectares and providing a treatment capacity of 1400 m^3/d[4]. After 20 years of research and extension, Sewage treatment with constructed wetland has developed a relatively mature theory and practice system. The natural sewage treatment technology uses biological-ecological method to overcome shortcomings of chemical sewage treatment method which can cause secondary pollution. Furthermore, CWs possess advantages such as low investment cost and construction and operational cost, high economic efficiency [5-6] and good sewage treatment effect [2, 7-10]. Meanwhile, CWs consist of landscapes such as water, plants, animals, land and channel, which conform people's aesthetic requirements and form wetland landscape for the city [11-14]. Therefore, constructed wetlands can produce great ecological benefits, and this enables it to become one of the important options for domestic sewage treatment in the process of ecological city construction.

Guangzhou is an economically developed city with large population. There are about 13 million permanent residents [15] generating about 1.41 billion m^3 [16] municipal domestic sewage per year. Treatment of large amount of domestic sewage and control of canal pollution is a serious problem that the government of Guangzhou has been confronting for years [17-20]. In recent years, the government of Guangzhou has actively implemented ecological city construction, many researches on relevant policies are making effort on the construction of "Flower City, Green City and Water City"[21-23]. The functions and characteristics of CWs fit with the general goal of constructing ecological Guangzhou. Assuming that all domestic sewage of Guangzhou is treated with CWs, then many science questions at intermediate level shall come up, e.g., "how much area of wetlands shall be required in order to achieve effective treatment based on existing population and the volume of generated sewage in Guangzhou?" and "how to locate and distribute the regional scale constructed wetlands in Guangzhou?".

Most CWs scholars focused on the various pollutants in wastewater, removal of pollutants, wetland plant selection, water conditions, and related topics, while urban planners want to know whether it’s possible to put the CWs which have the effect of sewage purification and landscape characteristic into a megacity and how to do this. In this paper, by combining the existing CWs researches and GIS technology, we estimated the area of subsurface flow wetlands required for the treatment of existing sewage in Guangzhou based on practical situation, and analyzed the distribution of regional-scale constructed wetlands, so as to provide a reference for ecological infrastructure planning in the process of ecological city construction or relevant fields.

2. Experimental Section

Sewage treatment system by utilizing subsurface flow constructed wetlands is widely applied for sewage treatment [24]. Comparing to free water surface system, subsurface flow system has advantages such as lower land area required for the treatment of equal volume of sewage, simpler operation and maintenance[25], higher nitrogen removal efficiency[26-29] and better removal effect for pollution indexes such as Total Phosphorus, Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand, Suspended solid and heavy metals[30-32]. Subsurface flow CWs mainly consist of three parts: substrate, plants and water distribution system [32]. Plants and microorganism play an important role in sewage purification of constructed wetlands, while temperature is an important key factor that influences the growth of wetland biology [33-35]. Under the premises above, this research proposes the subsurface flow wetland model as follows: domestic sewage first led to the grid pool for enhanced filtration and then led to the subsurface flow constructed wetland model with single wetland bed area $\leqq 300m^2$, length-width ratio<2 and bottom slope<1% for treatment[36]. Without regard to other influencing factors, the area of constructed wetlands required for the treatment of existing volume of the sewage in Guangzhou is calculated.

2.1. Method

2.1.1. Calculation formula for constructed wetland area. The research shows that, the surface area of subsurface flow constructed wetland can be calculated through BOD_5 [36-37], i.e., reducing BOD_5 value through constructed wetlands to allow BOD_5 to meet the effluent requirement of a certain region. It is deduced based on first-order biochemical reaction kinetics [38]. This paper utilizes the first-order biochemical reaction kinetics to deduce the surface area of subsurface flow constructed wetland with the formula below.

$$S = \frac{Q(lnC_0 - lnC_e)}{K_T H \alpha} \times 2 \quad (1)$$

In the formula, Q is sewage flow (m^3/d); C_0 is influent BOD concentration (mg/L); C_e is effluent BOD concentration (mg/L); H is aquifer depth (m), α is porosity of constructed wetland bed substrate, K_T is biochemical reaction rate constant of wetlands at temperature T, "2" is safety factor.

2.1.2. Calculation formula for domestic sewage flow. Domestic sewage flow in residential area is calculated [39] as follows:

$$Q = \frac{q \cdot N \cdot K_z}{1000} \quad (2)$$

In the formula, Q is sewage flow (m^3/d), q is average sewage volume per person per day [L/(person•d)], N is the population of a certain region, Kz is peaking variation factor.

2.1.3. Calculation formula for biochemical reaction rate constant of wetlands. Influence of temperature on reaction rate constant is calculated as follows [25]

$$K_T = K_{20} \times 1.01^{T-20} \quad (3)$$

In the formula, K_{20} is optimum biochemical reaction rate constant (d-1) at 20°C; T is the temperature of domestic sewage.

2.1.4. Regional scale constructed wetland distribution analysis. The location and distribution of constructed wetlands must be determined according to natural environment conditions such as geology, landform, hydrology and sewage outlet municipal planning, etc. [40] the terrain in Guangzhou is higher in northeast and lower in southwest. Types of landform include middle and lower mountains, hills, tablelands and plains. Lithology and structure have a great influence on the landform [41]. Located at the top of Pearl River Delta, Guangzhou is endowed with a developed water system. There are north main stream of Dongjiang, the front, back and west channel of Pearl River, and Humen, Jiaomen and Hongqimen (three passages to sea) around the city, and there are Liuxi River, Zengjiang and Pearl River Delta network channel and mountain stream through the city. There are 231 river branches with a total length of 913 km [42] in the area. This shows that the natural environment conditions in Guangzhou City are fairly ideal for the construction of constructed wetlands. However, Guangzhou as a megalopolis, its cities, designated towns and villages occupy most areas of the main districts. Intensive urban construction restricts the location of constructed wetlands.

This paper proposes to analyze the distribution of constructed wetlands in Guangzhou City at regional scale with GIS Software. Ponds, bare lands, grasslands and other garden plots are considered as available lands for wetland construction based on present situation of land use mainly. Distribution pattern is discussed through the comparative analysis of map spot dimension of available land and regional scale constructed wetland needs. Based on constructed wetland needs of various regions, available lands that have an area greater than 0.01 km^2 are screened with GIS, then distribution simulation is conducted on the condition that the available land for construction of constructed wetlands are 1 km to the nearest river system and soil sediment is non-sandy .

2.2. Parameters settings and data

2.2.1. CW area calculation formula parameters setting. BOD_5 concentration in domestic sewage of Guangzhou is 30-200mg/L [43]. According to relevant standard of Ministry of Environmental Protection of the People's Republic of China, influent quality shall not exceed 80 mg/L [44]. In this paper, only wetlands under highest sewage concentration (i.e., 200mg/L) condition are considered to conduct theoretical discussion. The effluent quality shall be that the content of BOD_5 in water after treatment is lower than 20mg/L[45]. Yu-Lan Peng and Jin-Yong Zhang studied the influence of water depth on plants and got the idea that optimum water depth for wetland bed is 0.5m [46-47], so the optimum water depth of 0.5m is selected as the water depth (H) applied in this paper. U.S.

Environmental Protection Agency suggests that, dense vegetation area of wetlands take porosity of 0.65-0.75 while wetlands with open water take porosity of 1.06[48]. Since urban wetland is characterized by relatively low water area, average vegetation biomass and relatively dense vegetation, the value of porosity α is 0.75.

2.2.2. Domestic sewage flow calculation formula parameters setting. Domestic sewage quota of residents shall be determined according to the water quota adopted at the place in question. Other things considered include the level of water supply and drainage facilities, in addition to the universal degree of drainage system inside the building, which is usually around 80%-90% of relevant water quota at the place in question. Guangzhou is a megalopolis. Guangdong Nom of Water Use (DB44/T1461- 2014) [49] states that the mean domestic sewage quota of residents in megalopolis is 200 L/d/person. The Guangzhou Economic and Social Development Statistics Bulletin 2014 indicate that, permanent residents at the end of the year are 13.08 million [15]. Value of peaking variation factor [50] of domestic sewage volume is shown in the table 1 below:

Table 1. Value of Peaking Variation Factor Kz of Domestic Sewage Volume. The mean domestic sewage quota of residents in Guangzhou is 200 L/d/person, the *Kz* is 1.5.

Average daily flow (L/s)	5	15	40	70	100	200	500	⩾1000
Kz	2.3	2.0	1.8	1.7	1.6	1.5	1.4	1.3

2.2.3. Biochemical reaction rate constant of wetlands calculation formula parameters setting. Research of Yu-Bo Cui et al. shows that, the biochemical reaction rate is constant at 20°C K_{20}=0.86d^{-1} [25]. Nan-Qi Ren et al. believes that optimum temperature for microbial growth is 25°C [33]. Annual mean temperature in Guangzhou in 2014wasabout 22.2°C. In the year, there are six months with a temperature higher than 25oC, the lowest temperature is 13.2°C and the highest temperature is 29.5°C [16]. This research assumes the lowest temperature as 13°C and the highest temperature as 30°C. The value of K_T at multiple temperatures is calculated.

2.2.4. Distribution simulation data. The simulation is mainly based on the land use data of Guangzhou which is obtained from the Second National Land Survey, and the soil type data which is from the Guangdong Digital Soil V2.0 operated by Guangdong Institute of Eco-environmental and Soil Sciences (GIESS).

3. Result

3.1. Area of constructed wetlands

3.1.1. Total area of constructed wetlands in the city. Formula (2) shows that, domestic sewage volume in Guangzhou City is 3.88 million m^3/d. Area of constructed wetlands required for treatment of domestic sewage generated by existing population is calculated by Formula (1) as shown in Table 2.

Table 2. Area of Constructed Wetlands Required for Treatment of Sewage Generated by Existing Population in Guangzhou

Water depth (m)	Porosity	C_0 (mg/L)	C_e (mg/L)	Temperature (°C)	Area (Km^2)
0.5	0.75	200	20	13	59.37
0.5	0.75	200	20	20	55.38
0.5	0.75	200	20	25	52.69
0.5	0.75	200	20	30	50.13

As seen in Table 2, when water depth is 0.50m, porosity is 0.75, influent BOD_5 is 200 mg/L, effluent BOD_5 is 20mg/L, temperature is 13°C, the area of subsurface flow CWs required for the treatment of sewage generated by existing population in Guangzhou is 59.37 km^2; when temperature reaches 25^{o}C, the area of required CWs reduces to 52.69km^2; although when treatment temperature reaches 30^{o}C, only 50.13km^2 CWs shall be required, but few months have a mean temperature higher than 30^{o}C, so the value is just for reference. Calculated based on maximum treatment area, the population equivalent of CWs for sewage treatment in Guangzhou is about 4.59 m^2/person.

3.1.2. Area of constructed wetlands in each district. As seen in Table 3, the area of CWs required for the treatment of sewage generated by entire population in Guangzhou is 59.37 km^2, which is equivalent to the total area of Liwan (close to the size of Florida Everglades Nutrient Removal project), but only accounts for 0.80% of the total area of the administrative districts (including Zengcheng and Conghua) in Guangzhou. Area of CWs required in Yuexiu accounts for 15.50% of the area of the administrative district, and this proportion is the highest among all districts. Area of CWs required in Haizhu, Tianhe and Liwan respectively accounts for 8.04%, 7.08% and 6.91% of the area of respect administrative districts, which are also very high. Area of constructed wetlands required in Conghua accounts for only 0.14% of the area of the administrative district; these numbers is the lowest. Considering that area of single wetland bed doesn't exceed 300m^2, total 197,905 wetland beds shall be required in the city, and each wetland bed can be used for the treatment of the domestic sewage generated by 66 persons.

Table 3. Area of Constructed Wetlands Required For Treatment of Sewage Generated by the Population in Each District of Guangzhou City

District	Population (unit:10,000 persons)	Sewage flow （10,000m^3/d）	Area of required constructed wetlands （km^2）	Area of the administrative district （km^2）	Proportion in the administrative district	Constructed wetland bed (unit: piece)
Baiyun	226.57	67.97	10.41	795.79	1.31%	34687
Conghua	61.02	18.31	2.80	1974.50	0.14%	9342
Panyu	144.86	43.46	6.65	529.94	1.26%	22178
Haizhu	158.34	47.50	7.27	90.40	8.04%	24241
Huadu	96.48	28.94	4.43	970.04	0.46%	14771
Huangpu	46.67	14.00	2.14	90.95	2.36%	7145
Liwan	88.92	26.68	4.08	59.10	6.91%	13613
Luogang	39.61	11.88	1.82	393.22	0.46%	6064
Nansha	62.51	18.75	2.87	783.86	0.37%	9570
Tianhe	148.43	44.53	6.82	96.33	7.08%	22724
Yuexiu	114.09	34.23	5.24	33.80	15.50%	17467
Zengcheng	105.18	31.55	4.83	1616.47	0.30%	16103
Total	1292.68	387.80	59.37	7434.40	0.80%	197905

3.2. Regional scale constructed wetland distribution simulation

3.2.1. Conditions of lands for constructed wetlands in each district. Table 4 is obtained from analysis and statistics on data of second national land survey of Guangzhou with GIS. Part or whole of the ponds, bare lands, other grasslands and other garden plots can be used for the construction of CWs. By comparing the table with Table 3, we can see that there are enough lands in all districts for the construction of CWs except for Haizhu, Liwan, Tianhe and Yuexiu. A total of 7.27 km^2 CWs are required in Haizhu. At present, 8.69 hectares wetland parks have been constructed in the district. Construction needs can be met if part of the wetland parks is transferred to sewage treatment purpose and meanwhile Haizhu Lake and other land resources are utilized. Since the four types of lands above reach an area of 208 km^2 in Panyu and Nansha, domestic sewage generated by Liwan, Tianhe and Yuexiu can be transported and treated in these two districts, thus 16.14 km^2 CWs must be further constructed in Panyu and Nansha. Therefore, in view of the available land, there are sufficient conditions in Guangzhou City for the construction of enough CWs for domestic sewage treatment.

Table 4. Area and Proportion of Ponds, Bare Lands, Other Grasslands and Other Garden Plots and in Each District of Guangzhou City

Districts	Ponds （km^2）	Bare lands （km^2）	Other grasslands （km^2）	Other garden plots （km^2）	Total （km^2）	Area proportion of required wetlands
Baiyun	54.18	8.83	7.76	1.54	72.31	14.39%
Conghua	23.43	0.92	2.50	0.61	27.47	10.20%
Panyu	106.40	1.62	10.50	2.88	121.40	5.48%
Haizhu	0.54	0.06	0.39	0.00	0.99	737.56%
Huadu	106.91	11.71	9.00	21.66	149.27	2.97%
Huangpu	1.60	0.04	0.49	0.01	2.15	99.67%
Liwan	0.18	0.38	0.95	1.27	2.78	146.90%
Luogang	15.08	4.13	1.64	0.95	21.81	8.34%
Nansha	82.39	1.27	2.97	0.30	86.93	3.30%
Tianhe	1.87	0.89	1.00	0.12	3.87	175.95%
Yuexiu	0.02	0.00	0.00	0.00	0.02	30181.10%
Zengcheng	78.37	0.44	8.92	0.05	87.78	5.50%
Total	470.96	30.29	46.12	29.41	576.77	10.29%

[a] Data source: the second national land survey.

3.2.2. Distribution pattern of constructed wetland construction. According to 3.1.2, certain districts require very large area of constructed wetlands for treatment of their sewage. Total 10.41 km^2 CWs are required to be constructed in Baiyun District which has the largest population. Although this only accounts for 1.31% of the total area of the district, it is extremely difficult to implement planning for such a large area of wetlands. Analysis and statistics on more than 40,000 map spots of ponds, bare lands, other grasslands and other garden plots with GIS show that, there are few available lands with an area greater than 1 km^2(Figure 1). The area of most available lands is less than 0.1 km^2, therefore, regional scale CWs can't be constructed intensively but distributed dispersedly in the city.

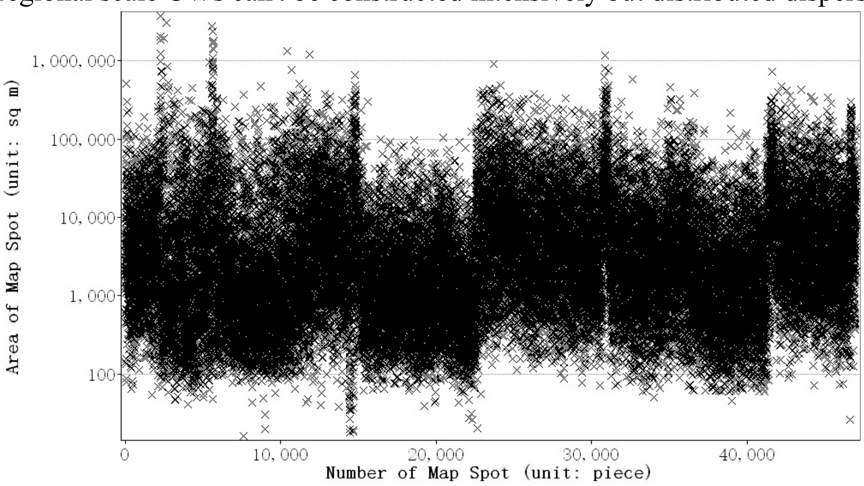

Figure 1. Scatter Diagram of Area of Available Lands. (Statistics on more than 40,000 map spots of ponds, bare lands, other grasslands and other garden, there are few available lands with an area greater than 1000000 m^2)

3.2.3. Regional scale constructed wetland distribution simulation. The results of simulation show that, main soil types in Guangzhou City include Ma Red Soil, Fluvial Alluvium Soil, Hydromorphic Paddy Soil, Ma Latosolic Red Soil etc. and Minor Sandy Soil. Most of the available lands are suitable for construction of CWs. CWs at regional scale are mainly distributed around Baini Channel, Tianma River, Xinjie River, Liuxi River Valley, Zengjiang River Valley and on both sides of rivers near Panyu and Nansha (Figure 2). There are enough lands in all districts except the five main districts - Haizhu, Huangpu, Liwan, Tianhe and Yuexiu for the construction of CWs. The total available lands in Huangpu are just enough for the construction of CWs, but insufficiency appears after inapplicable lands are excluded through analysis with GIS. Table 4 and Figure 2 show that there aren't enough CWs that can be constructed in the five main districts for the treatment of domestic sewage generated by their dense population. A few regional scale CWs can be distributed in the five main districts. Available lands in Panyu and Nansha shall be utilized to meet the most sewage treatment needs of the five main districts.

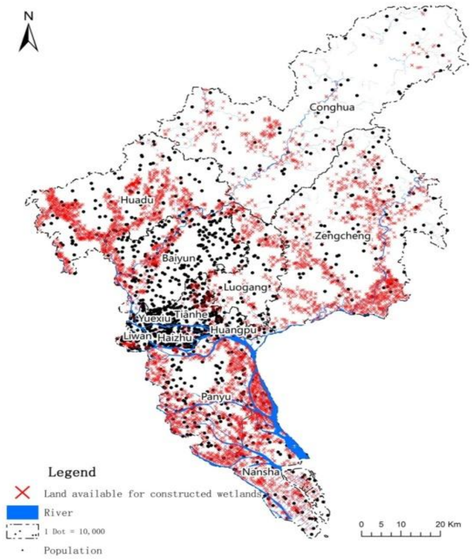

Figure 2. Distribution Simulation of Constructed Wetlands in Guangzhou at Regional scale (Land available for constructed wetlands: Including ponds, bare lands, other grasslands and other garden plots; Population: Population of Each District of Guangzhou City in 2014; 1Dot=10,000 Persons; "×" This mark only shows the location of the available land)

4. Discussion

Compared to traditional sewage treatment plant, CWs possess advantages such as low investment and operational costs, high economic efficiency and good sewage treatment effect. Furthermore, CWs can serve as city wetland landscapes, increase ecological environment benefit [2, 5, 14] and play an important role in the improvement of water environmental quality of the city. On the basis of artificial lake, total 2.07 km^2 and 1.5 km^2 lake wetlands are newly constructed in Baiyun and Haizhu of Guangzhou respectively in recent years. Though construction of CWs is different from lake excavation, project quantities and engineering measures indicate that the construction of constructed wetlands is feasible to some extent.

The results show that population equivalent of CWs for sewage treatment in Guangzhou is about 4.59 m^2/person, which is close to the population equivalent 5 m^2/person specified in the "rule of thumb" for design of CWs [36, 51], this maybe shows that the calculated value of this article is close to the actual value. Upper limit of total area of CWs is not set in the Technical Specification of Constructed Wetlands for Wastewater Treatment Engineering [44], and the daily sewage treatment capacity of large-scale constructed wetland sewage treatment project is$\geqslant$10,000m^3/d, as the sewage volume generated in the districts of Guangzhou has gone far beyond this value. Large area of available lands shall be selected for wetland construction.

In this paper, area of subsurface flow CWs required for the treatment of domestic sewage generated by existing population of Guangzhou was calculated .The distribution of CWs for regional scale sewage treatment in Guangzhou is also briefly analysed with GIS under few limiting factors. However, since concentration of organic matters in sewage keeps changing [43], calculations conducted in this paper are based on single observed value as one cannot cover all possible situations. Many procedures such as pre-treatment, post-treatment, sludge treatment, odor gas treatment, auxiliary engineering facilities and supporting facilities [44] have to be considered in the practical construction of constructed wetlands. Therefore, the results of measurement and calculations made in this paper shall be provided just as a reference for ecological infrastructure planning in the process of ecological city construction or relevant fields.

5. Conclusions

Area of constructed wetlands required for the treatment of domestic sewage generated by existing population was calculated in accordance with domestic sewage flow in Guangzhou and mathematical model of existing CWs. The results show that, 13 million people generate about 3.878 million m3 domestic sewage per day, which shall be treated with 59.3715 km2 CWs. Assuming that a single wetland bed is 300 m2, total 197,905 wetland beds shall be required in the city. Analysis and statistics on data of second national land survey of Guangzhou with GIS show that, there are enough ponds, bare lands, grasslands and garden plots in Guangzhou that can be used for the construction of regional scale constructed wetlands, but the distribution of available lands in different regions is uneven. Most of the available lands are suitable for construction of CWs. Constructed wetlands at regional scale are mainly distributed around Baini Channel, Tianma River, Xinjie River, Liuxi River Valley, Zengjiang River Valley and on both sides of rivers near Panyu and Nansha. A few regional scale constructed wetlands are distributed in the five main districts. The insufficiency part can be distributed and constructed in Panyu and Nansha. Wetlands construction can be implemented in other districts selectively according to actual need of sewage treatment.

Acknowledgments

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