Simulation Analysis of Annual Pollution Load of Combined Sewer Overflow in Wuhan City Based on SWMM

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Abstract. With the acceleration of urbanization, the urban water environment problem has become increasingly severe. The combined sewer overflow (CSO) pollution control has become the focus and problem which urgently needed to be solved in China’s sponge city construction and black smelly water treatment. Simulating and calculating the annual pollution load of the CSO is of great significance for the quantitative analysis of the cause of the water environment pollution. In this paper, the improved SWMM model coupled with the module for scouring the silting on the bottom of the pipes was used to simulate the combined sewer system with a drainage area of 1666ha. The results show that under the same drainage area, the larger the interception ratio is, the smaller the annual pollution load of CSO is; under the same interception ratio, the larger the drainage area is, the smaller the annual pollution load of CSO is. For the combined sewer system in Wuhan, the annual COD, TN and TP load of CSO can be calculated by three formulas: 

\[ W_{\text{COD}} = 378.58 - 33.71 \ln F \]

\[ W_{\text{TN}} = 51.032 - 5.7871 \ln F \]

\[ W_{\text{TP}} = 13.667 F - 0.404, \]

respectively when the interception ratio is equal to 1.0.

1. Introduction
With the development of economy, science and technology, China's sewage treatment technology has been continuously improved and innovated. Most of the point source pollution problems have been solved in earlier years, which leads to the increasing contribution rate of urban non-point source pollution load to water environment pollution [1]. On the basis of initial control of point source pollution, urban non-point source pollution has now become an important cause of deterioration of water quality and degradation of ecological functions [2]. In 2000, US monitoring data in polluted waters showed that 55% of pollution in coastal areas came from urban non-point source pollution [3].

In the early stage of construction in China, the direct-discharge combined sewer system was widely adopted, resulting in combined sewer overflow (CSO) pollution, which has seriously restricted the improvement of water environment quality in China for a long time and has become one of the main sources of non-point source pollution [4]. Although many cities have invested tremendous manpower and material resources to control the CSO pollution in recent years with the improvement of black smelly water and the promotion of sponge city construction [5-6], the improvement effect of urban water is still limited. Statistics in 2016 show that there are 109,000 km of combined pipelines in China,
accounting for 18.8% of the total length of drainage pipelines. It can be seen that CSO pollution is a major problem to be solved urgently in the water environment control of many cities in China, especially in some big cities. The calculation of annual pollution load of CSO is of great significance for urban water environment control.

This paper selects COD, TN and TP three pollutants as research subjects, and uses the improved SWMM generalization model to simulate and analyse the CSO annual pollution load under different drainage area and interception ratio, and to study the relationship between the annual CSO pollution load and drainage area in Wuhan. The research results can provide reference for the control of CSO pollution in Wuhan.

2. SWMM model establishment

2.1 SWMM generalization model

The study area is located in Jianghan District, Wuhan City, Hubei Province, with a total drainage area of 1666 ha. Land use is comprehensive, including residential areas, commercial pedestrian streets, hospitals, squares, parks, green spaces and so on. The average annual rainfall in Wuhan is about 1260 mm. The rainstorm mostly concentrates in summer. Wuhan has a subtropical monsoon humid climate with climatic characteristics such as abundant rainfall, cold winters and hot summers, and four distinct seasons. The study area pipe network is generalized into 607 sub-catchments, 403 pipe sections, 365 nodes and 1 outlet, as shown in Figure 1. It is assumed that nodes A1 to A5 are overflow wells, and the overflow is discharged into the Huangxiao River. The main pipe of the merged pipe network starts from the A1 node at the intersection of Erqi Road and Jiefang Avenue, passing through Development Avenue, Wenxin Road and Xingfu Street, and is collected at the end node A5 (located on the Third Ring Road) before the discharge port. The catchment area of each node is shown in Table 1.

![Figure 1. SWMM generalized model of Huangxiao River rainwater pipe network.](image)

| Node number | Catchment area (ha) |
|-------------|---------------------|
| A1          | 156                 |
| A2          | 324                 |
| A3          | 413                 |
| A4          | 947                 |
| A5          | 1666                |

In SWMM model, there are rainwater module for rainwater quality and quantity simulation and sewage module for urban sewage quality and water quantity simulation. In order to reflect the scouring situation of bottom sediment in rainy days, Zhang embedded the bottom sediment scouring the silting module in the commonly used SWMM and constructed an improved SWMM to improve the simulation accuracy [7].
2.2 Model parameters of rainwater module

The attribute parameters of the area, length, diameter and slope of the sub-catchment in the study area are integrated by MapInfo software and the data of the study area pipeline network. Horton model is used for infiltration calculation. The maximum infiltration rate is 76.2 mm/h, the minimum infiltration rate is 3.0 mm/h, and the corresponding attenuation coefficient is 4 h\(^{-1}\). Manning coefficients of pipeline, impervious surface and pervious surface are 0.013, 0.011 and 0.15, respectively. The confluence model is a non-linear reservoir model, and the hydraulic model is a dynamic wave model.

In this simulation, three types of pollutants, COD, TN and TP were set up. In order to explore the scouring characteristics of pollutants in rainfall, the parameters of pollutant accumulation model, initial surface pollutant values, were assigned. Assuming that the initial surface pollutant amount is linearly correlated with the local dust pollutant amount, based on Zhang’s monitoring results of atmospheric dust in Chaohu City and the calibration results of the initial surface pollutant amount parameters in the catchment area of Dongtang Road in Chaohu City [7], the initial surface pollutant amount in the main urban area of Wuhan City can be calculated by comparing the monitoring results of Liu on the atmospheric dust in the main urban area of Wuhan City as shown in Table 2 [8].

| Location | Atmospheric dust [mg/(m\(^2\)·d)] | Initial surface pollutants (kg/ha) | | |
|---|---|---|---|---|
| Chaohu | COD 111.56 | TN 24.17 | TP 0.46 | COD 5.81 | TN 0.848 | TP 0.033 |
| Wuhan | COD 123.74 | TN 15.68 | TP 0.46 | COD 6.44 | TN 0.55 | TP 0.033 |

In the SWMM pollutant accumulation model, the exponential function model is used in the pollutant scouring module. The input parameters are scouring coefficient and scouring index. The pollutant scouring equation is as follows:

\[ W_1 = B_1 C_1 q C_2 \]  

Where \( W_1 \) is the scouring rate of pollutants on underlying surface per unit area [kg/m\(^2\)·min]. \( B_1 \) is the initial surface contamination [kg/m\(^2\)]. \( C_1 \) is the scouring coefficient of surface pollutants [mm\(^{-1}\)]. \( C_2 \) is the scouring index of surface pollutants. \( Q \) is the average rainfall intensity [mm/min].

Zhang obtains the scour coefficients and scour indices of five kinds of underlying surfaces by artificial simulated rainfall test, and puts forward a method to calculate comprehensive scour parameters according to the proportion of different surface coverage in catchment area. The results show that the scour parameters obtained by this method have high accuracy in simulating the water quality of rainwater outflow from Dongtang Rainwater Pipeline Network in Chaohu City on rainy days. Referring to Zhang Chao's method of determining scouring parameters [7], according to the surface coverage of the catchment area of Huangxiao River drainage network, the comprehensive scouring parameters of the area can be obtained as shown in Table 3.

| Pollutant | Scouring coefficient \( C_1 \) (mm\(^{-1}\)) | Scouring index \( C_2 \) |
|---|---|---|
| COD | 0.49 | 1.0 |
| TN | 0.51 | 1.0 |
| TP | 0.47 | 1.0 |

2.3 Model parameters of the module for scouring the silting at the bottom of combined sewers

In order to make the improved SWMM be able to simulate the situation of combined sewage system in an all-round way, it is necessary to consider the effect of silting at the bottom of the combined sewage pipeline on the quality of the combined sewage in sunny days and scouring in rainy days. The bottom sediment scouring module is coupled into SWMM model to realize one-dimensional hydraulic and water quality simulation in pipeline and two-dimensional hydraulic simulation of surface overflow.
The principle of the pipeline scouring and silting formula is the same formula type as that of the surface pollutant scouring model of runoff, as shown in equation (2).

\[ W = B_2 C_3 Q C_4 \]  \hspace{1cm} (2)

Where \( W \) is the scouring amount of sludge pollutants in pipeline \([\text{kg/m}^3 \cdot \text{s}]\). \( B_2 \) is the initial contaminant content of sludge in pipeline \([\text{kg/m}^3]\). \( C_3 \) is the scouring coefficient of bottom sediment \([\text{m}^{-3}]\). \( C_4 \) is the scouring index of bottom sediment. \( Q \) is the quantity of flow in pipeline \([\text{m}^3/\text{s}]\).

2.4 Water quantity and quality parameters of urban sewage

The specific discharge of sunny sewage is obtained from the design data of drainage pipe network in Huangxiao River District of Wuhan provided by Wuhan Planning Institute. The water quality parameters of sunny sewage are taken from the annual average of the influent quality of a sewage plant in Wuhan. The water quality and quantity parameters of sunny sewage are taken as shown in Table 4.

| Specific discharge (ha·L/s) | COD concentration (mg/L) | TN concentration (mg/L) | TP concentration (mg/L) |
|----------------------------|--------------------------|--------------------------|-------------------------|
| 1.44                       | 181.4                    | 23.95                    | 2.34                    |

Referring to the monitoring results of sediment characteristics and pollutant indicators of combined sewage pipelines in Chaohu City by Zhang [7], the average ratio of sediment thickness at the bottom of the pipeline to the effective section height is about 20%. The sediment content of the pipeline in the scouring silting module of the coupled model can be calculated as shown in Table 5.

| COD (kg/m³) | TN (kg/m³) | TP (kg/m³) |
|-------------|------------|------------|
| 0.362       | 0.012      | 0.0032     |

Zhang [7] have calibrated the scouring parameters of the bottom pollutants in the improved SWMM according to the monitoring results of the outflow water quality of the combined sewerage system around the city of Chaohu in rainy days. The results are shown in Table 6.

| Pollutant | Scouring coefficient \( C_3 \)(m\(^3\)) | Scouring index \( C_4 \) |
|-----------|------------------------------------------|------------------------|
| COD       | 0.013                                    | 1.0                    |
| TN        | 0.012                                    | 1.0                    |
| TP        | 0.012                                    | 1.0                    |

2.5 Rain pattern

In this study, the formula of short-duration rainstorm intensity in Wuhan is used, as shown in equation (3) and equation (4). The Chicago rainfall pattern was used to simulate the rainfall process. The total rainfall duration was 2 hours, and the retreat time was 3 hours, the simulated total runoff time was 5 hours and the time interval was 1 minute. According to the statistical analysis of rainfall data in Wuhan, the peak coefficient \( r \) of rainfall pattern is 0.40 for the rainfall with a recurrence period of less than 5 years.

\[ q = \frac{983[1+0.65 \lg (P+0.66)]}{(t+4)^{0.56}} \quad (P<0.5a) \]  \hspace{1cm} (3)

\[ q = \frac{885[1+1.58 \lg (P+0.66)]}{(t+6.37)^{0.604}} \quad (0.5a \leq P < 10a) \]  \hspace{1cm} (4)
Where \( q \) is the rainstorm intensity \([L/(s\cdot hm^2)]\). \( P \) is the design recurrence period \([a]\). \( t \) is the rainfall time \([\text{min}]\).

When studying the pollution load of the combined system, 20 rainfall events with different recurrence periods in a year are assumed according to the probability theory. The recurrence periods, occurrences and rainfall amounts are shown in Table 7.

| Recurrence period | \( P=1a \) | \( P=0.5a \) | \( P=0.33a \) | \( P=0.2a \) | \( P=0.1a \) | \( P=0.05a \) |
|-------------------|----------|----------|----------|----------|----------|----------|
| Times             | 1        | 1        | 1        | 2        | 5        | 10       |
| Rainfall(mm)      | 46.41    | 37.94    | 32.93    | 26.16    | 16.77    | 7.39     |

### 3. Results and discussion

#### 3.1 Relationship between annual pollution load of CSO, catchment area and interception ratio

For the five overflow wells A1 to A5, the interception ratio was assumed to be 0 to 5, and the combined drainage network with catchment area of 1666 ha was taken as the research object under different rainfall intensities. The improved SWMM was used to simulate the process of overflow quantity \( Q \) and overflow pollutant concentration \( C \) in five overflow wells with the recurrence periods of 0.05a, 0.1a, 0.2a, 0.33a, 0.5a and 1a and the interception ratio of 0, 1, 2, 3, 4 and 5, respectively. The variation process lines of COD, TN, TP pollutant amount \((Q \cdot C)\) with runoff time at each overflow outlet under specific \( P \) and \( n_0 \) conditions were calculated. Based on this, the total amount of overflow pollutants can be calculated for each overflow well with specific \( P \) and \( n_0 \) conditions. For each overflow outlet under certain \( n_0 \) conditions, the total amount of overflow pollutants caused by 20 rainfall events can be calculated. For the overflow well \( A_j \), the service area of its drainage system is \( F_j \). The total amount of overflow pollutants in the overflow well is \( W_j \), and there are \( j \) overflow wells in the combined drainage system with service area of \( F_j \). The total amount of overflow pollutants in the combined drainage system is \( \sum W_j \). The annual overflow pollution load of the system is \( \sum W_j/F_j \). The annual pollution load of CSO with different drainage area under different interception ratio is shown in Figure 2.

![Figure 2. The annual CSO pollution load of COD, TN and TP.](image)
It can be showed from Figure 2 that along with the increase of interception ratio, the pollution load of overflow decreases with the same service area of the combined drainage system. At the same interception ratio, the pollution load decreases with the increase of drainage area. On the one hand, in the combined drainage network with larger drainage area, the overflow volume is less. On the other hand, the concentration of pollutants in mixed sewage is diluted due to the time difference between upstream and downstream inlets in the runoff process, so the annual CSO pollution load is lower with larger service area.

3.2 The relationship between annual pollution load of CSO and catchment area in Wuhan

For the existing combined drainage system in Wuhan, the interception ratio \( n_0 \) is generally 1.0. Therefore, the annual pollution load of CSO with different drainage area in Wuhan is shown in Table 8.

| Drainage area (ha) | COD [kg/(ha·a)] | TN [kg/(ha·a)] | TP [kg/(ha·a)] |
|-------------------|-----------------|---------------|---------------|
| 156               | 207.83          | 23.87         | 1.99          |
| 324               | 187.35          | 15.74         | 1.22          |
| 413               | 170.75          | 14.63         | 1.08          |
| 947               | 151.10          | 11.84         | 0.85          |
| 1666              | 126.69          | 8.94          | 0.73          |
| average           | 168.7           | 15.00         | 1.17          |

From Table 8, it can be found that the annual CSO pollution loads of COD, TN and TP are 126.69 kg/(ha.a), 8.94 kg/(ha.a) and 0.73 kg/(ha.a) respectively for the combined sewer system of Huangxiao River in Wuhan with 1666 ha drainage area.

The total pollution load of CSO is \( W \). According to table 8, the empirical formulas of COD, TN and TP load \( W \) varying with drainage area \( F \) at \( n_0=1.0 \) can be obtained with fitting as shown in equation (5), equation (6) and equation (7).

\[
W_{COD} = 378.58 - 33.71 \ln F, \quad R^2 = 0.9868 \quad (5)
\]

Where the \( W_{COD} \) is annual COD load of CSO with drainage area of \( F \) [kg/(ha.a)]. \( F \) is the drainage area of combined sewer system [ha].

\[
W_{TN} = 51.032 - 5.7871 \ln F, \quad R^2 = 0.9133 \quad (6)
\]

Where the \( W_{TN} \) is annual TN load of CSO with drainage area of \( F \) [kg/(ha.a)].

\[
W_{TP} = 13.667F - 0.404, \quad R^2 = 0.9416 \quad (7)
\]

Where the \( W_{TP} \) is annual TP load of CSO with drainage area of \( F \) [kg/(ha.a)].

4. Conclusion

Under the same drainage area, the larger interception ratio is, the smaller the annual pollution load of CSO is; under the same interception ratio, the larger drainage area is, the smaller the annual pollution load of CSO is.

For the combined sewerage system in Wuhan, the interception ratio is generally 1.0, and the annual pollution load of COD, TN and TP can be calculated and determined by \( W_{COD} = 378.58 - 33.71 \ln F, \) \( W_{TN} = 51.032 - 5.7871 \ln F \) and \( W_{TP} = 13.667F - 0.404 \), respectively.
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