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Analysis on Water Quality Characteristics of Typical Black and Stinking River in Chengdu City by SWMM

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Abstract: In this paper, based on Storm Water Management Model (SWMM) mechanism, referring to the model parameters of domestic and foreign related research achievements, combined with field monitoring data, a non-point source pollution load calculation model is constructed, and the corresponding parameters are calibrated. The pollution load and pollution change process of chemical oxygen demand (COD_{Cr}), ammonia nitrogen (NH_3-N) and total phosphorus (TP) under different rainfall conditions were analyzed in the investigation area. The model calculated values are in good agreement with the actual measure results. Under different rainfall conditions, the maximum value of pollutants appeared in early and middle rainfall stage, while gradually decreased in latter, with the increase of rainfall, pollution of receiving water becomes greater, and the pollutant concentration shows a downward trend during rainfall process. Measured value of COD_{Cr} is higher than the simulated one, both decreased gradually with the rainfall, measured NH_3-N concentration in mid-term rainfall increased slightly due to the uninterrupted direct emission of domestic sewage in this area, measured TP concentration in early stage of rainfall declined not obvious, but with the rainfall enhancement, various phosphorus compounds by erosion gradually dissolved finally into the river, partially offset by a dilution effect, as the subsequent rainfall carried over, total phosphorus pollutants continued to decline. While as impervious surface area goes on, both runoff and total pollutants increase.

Keywords: SWMM, Black and Stinking River, Non-Point Source Pollution, Pollution Load, Rainfall Runoff

1. Background

Because of population growth and the expansion of urban land use, especially impermeable land, non-point source pollution caused by natural rainfall and artificial runoff has become an important cause of deterioration of water quality in urban rivers [1]. However, due to the lag and imperfection of drainage network construction in some areas, especially on both sides of the river, domestic sewage and industrial wastewater are directly discharged into the river, resulting in "black odor" of the river water body, accompanied by rainfall runoff, which aggravates the impact on the surrounding environment [2, 3]. On the one hand, the emergence of black and stinking river shows the imperfection of drainage network; on the other hand, runoff caused by rainfall washes surface pollutants into the river and aggravates the deterioration of water quality. The water quality of urban river network is facing a serious threat from non-point source pollution in urban areas, especially in high impermeable land areas [4-6]. There is no method to calculate the pollution load of black and stinking river which can be fully used for reference, and less research in this field in China.

The research on non-point source pollution of urban water has always been a hot topic [7, 8]. Some calculation methods of non-point source pollution can provide help for the pollution study of urban black and stinking rivers. Since the 1960s, a number of mature non-point source pollution calculation models have emerged. Among them, SWMM (Storm Water Management Model) is a tool for predicting and managing urban rainfall and water quality developed by the United States Environmental Protection Agency (USEPA) in 1971 to solve the growing urban non-point source pollution [9]. As a distributed and continuous simulation model, SWMM has been widely applied to the study of urban non-point source pollution.

A typical black and stinking river with direct sewage discharge in Chengdu city has been selected as the research object in this work. Referring to the model parameters of relevant domestic and foreign literature, combined with field monitoring data, the final calibration was carried out, and the cumulative changes of non-point source pollution load and pollution load caused by rainfall on river water body were analyzed, thus providing scientific basis and technical support for the control and prevention of non-point source pollution in urban surface rivers.

2. Summary of SWMM

The Storm Water Management Model (SWMM) of EPA (Environmental Protection Agency) in the United States is a dynamic rainfall-runoff simulation model [9]. It is mainly applied to simulate water quantity and water quality of single or long-term precipitation events in cities. The model includes rainfall module, statistical module, mapping module, joint module and execution module, which integrates functions such as data input, urban hydrology, hydraulic and water quality simulation and simulation results browsing, etc. in a certain research area [10]. By inputting rainfall data, soil characteristic conditions, land use, pollutant accumulation and rinsing parameters, the flow and pollution process lines of rainfall runoff, channel or pipeline output section can be simulated.

The calculation process of SWMM includes: subbasin generalization, surface runoff generation calculation, surface confluence calculation and pipeline network confluence subsystem budget. The surface confluence calculation is to transform the surface runoff process of each subbasin into a drainage process and simulate each catchment area as a non-linear reservoir, that is, simulate each catchment area as a non-linear reservoir, that is, to solve Manning equation (1) and continuous equation jointly (2).

$$Q=W\frac{1.49}{n}(d-d_p)^{5/3}\cdot S^{1/2} \tag{1}$$

$$\frac{dv}{dt}=A\frac{dd}{dt}=A\cdot i^*-Q \tag{2}$$

In upper formulas, v is total water volume of sub-catchment area, m^3; d is water depth, m; t is time, s; A is surface area of sub-catchment area, m^2; i^* is rainfall intensity, i.e. rainfall intensity minus evaporation and infiltration, mm/s; Q is outflow rate, m^3/s; W is sub-catchment area width, m; n is Manning coefficient; d_p is stagnation depth, m; S is slope of sub-catchment area, m/m. For the river or pipeline system, the convergence of network is calculated by the transport module or the extended transport module in the model, and solved by Saint-Venant system of equations.

3. Model Establishment

3.1. Generalization of Study Area

A typical built-up area in Chengdu city including black and stinking river was selected as the study area for simulation analysis, with a total area of 4.45 km^2. This area mainly includes residential housing, green belt, logistics park and so on. The construction of pipeline network in this area is lagging behind, and there exists the situation that the production and domestic sewage is directly discharged into the river. If natural rainfall or manual washing (such as road sprinkling, car washing and other activities) occurs, most of the surface runoff will directly enter the river through rainwater pipelines or overflow, resulting in a change of artificial drainage channel in this area into a smelly ditch.

According to the characteristics of topography and pipeline network layout in the study zone, it is divided into 17 sub-catchment areas by using GIS software, each catchment area corresponds to a node. The river receiving sewage is divided into 18 sections, and the cross-section of river bed is assigned according to the measured value, as shown in Figure 1. The generalization map is shown in Figure 2.

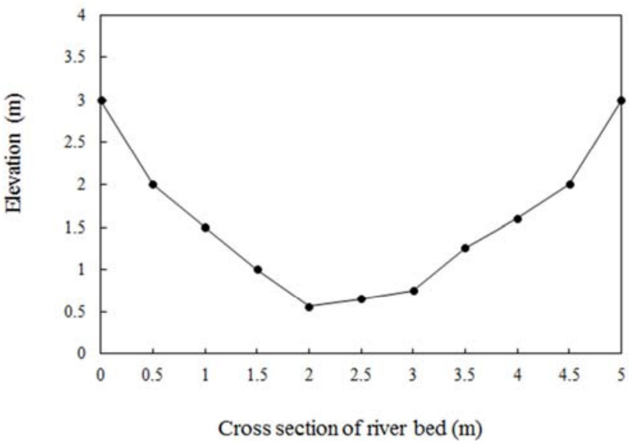

Figure 1. *Cross section sketch of a certain river course.*

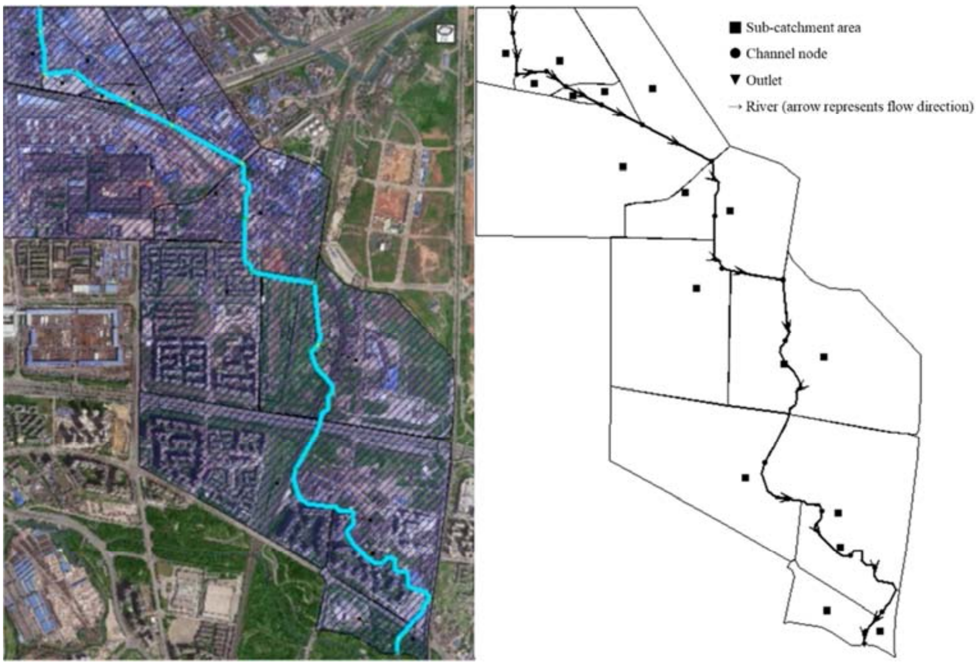

Figure 2. *Generalization map of sub-catchment areas in the study zone.*

3.2. Model Parameter Calibration

Surface runoff includes pervious surface runoff, impervious surface runoff with storage capacity and impervious surface runoff without storage capacity. Green-Ampt infiltration model was used to simulate rainfall infiltration process. Referring to SWMM model manual, initial soil moisture deficit value and soil hydraulic conductivity were set at 0.38 mm/mm and 2.2 mm/h respectively. Storage capacity of pervious and impervious surface were 5mm and 1.5mm respectively. As drainage channels in the region are all artificially hardened, Manning coefficients of pervious surface, impervious surface and drainage channel were set to 0.23, 0.015 and 0.015 respectively according to the features.

Through on-site investigation, land use types in catchment areas were divided into six types: roof, grassland, asphalt, cement, brick land and bare soil. Selecting COD_{cr}, NH_3-N and TP as pollution factors, the exponential function cumulative model was used to simulate. According to the SWMM model application manual and some related research achievements [9-15], calibrated parameters are shown in Table 1.

Table 1. *Different types of land use simulation parameters.*

Land type	Parameter name	COD_{Cr}	NH_3-N	TP
Roof	Maximum cumulative volume (kg/hm^2)	40	4	0.4
	Cumulative constant	0.5	0.2	0.2
	Scour coefficient	30	8	5
	Scour index	1.7	1.9	1.7
Grassland	Maximum cumulative volume (kg/hm^2)	15	2	0.3
	Cumulative constant	0.4	0.1	0.2
	Scour coefficient	15	5	5
	Scour index	1.7	1.8	1.6
Asphalt	Maximum cumulative volume (kg/hm^2)	80	5	0.5
	Cumulative constant	0.5	0.5	0.2
	Scour coefficient	40	10	8
	Scour index	2.2	2.0	1.7
Cement	Maximum cumulative volume (kg/hm^2)	60	5	0.4
	Cumulative constant	0.6	0.5	0.2
	Scour coefficient	50	30	10
	Scour index	1.7	1.7	1.7
Brick land	Maximum cumulative volume (kg/hm^2)	70	5	0.5
	Cumulative constant	0.8	0.6	0.2
	Scour coefficient	30	10	5
	Scour index	2.0	1.7	1.8
Bare soil	Maximum cumulative volume (kg/hm^2)	150	10	0.8
	Cumulative constant	0.6	0.3	0.3
	Scour coefficient	40	20	10
	Scour index	1.8	1.7	1.7

3.3. Rainfall Intensity Design

According to the research results of Zhu Gang et al. [16], the revised formula of rainfall intensity in Chengdu was adopted in this study, as in.

$$i=\frac{202.434(1+0.339\lg P)}{(t+43.155P^{0.051})^{1.124}} \quad (3)$$

i is rainfall intensity (mm/h); t is rainfall duration (min); P is recurrence year.

The formula (3) meets the requirement of accuracy and the recurrence period is within the range of 1~30 years. Chicago method was used to plot rainfall curve. The relative position of the rain peak is r=0.4, and the rainfall process lasts for 120 minutes, as shown in Figure 3.

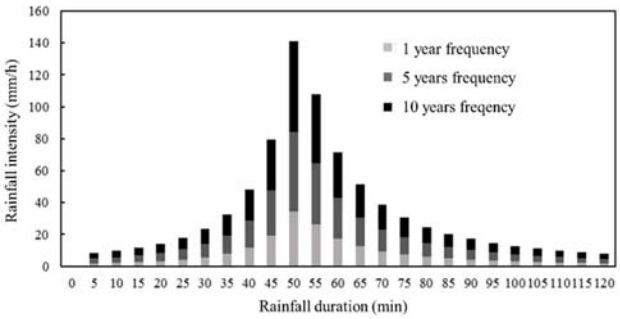

Figure 3. *Rainfall distribution at different recurrence periods.*

4. Results and Discussion

4.1. Runoff Simulation

The runoff of different recurrence periods and permeable areas were simulated and calculated to understand the situation of waterlogging in the region.

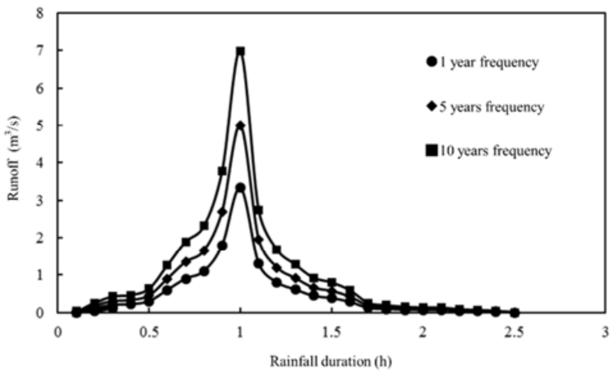

Figure 4. *Simulated runoff of different rainfall recurrence periods (constant impervious area).*

The impervious area was set at a fixed value of 65%. The end runoff of the river was simulated under different recurrence periods rainfall conditions. The results are shown in Figure 4. According to results, the peak values of rainfall in one year, five years and ten years frequency are 3.31 m^3/s, 4.99 m^3/s and 6.98 m^3/s respectively. The peak value increases with the extension of rainfall recurrence period, rainfall intensity and total rainfall also increase gradually. In addition, because of the increase of artificial ground, the permeability of the area decreases, resulting in the increase of surface runoff and peak flood.

When rainfall occurs once a year in the given zone and impervious area is different, the calculation results of the corresponding terminal flow from catchment area are shown in Figure 5. When the impervious area is 30%, 60% and 90%, the total flow is $5.68\times10^3 m^3$, $7.43\times10^3 m^3$ and $1.04\times10^4 m^3$, while the peak discharge of the river flow is 2.23 m^3/s, 3.43 m^3/s and 4.87 m^3/s respectively. The increasing proportion of impervious surface results in the decrease of surface permeability, the increase of runoff and the rise of its peak value in the process of rainfall. A large amount of rainwater washing ground not only brings pollutants into the receiving water body, but also wastes water resources caused by the direct discharge of rainwater runoff, which increases the difficulty of urban flood control and drainage.

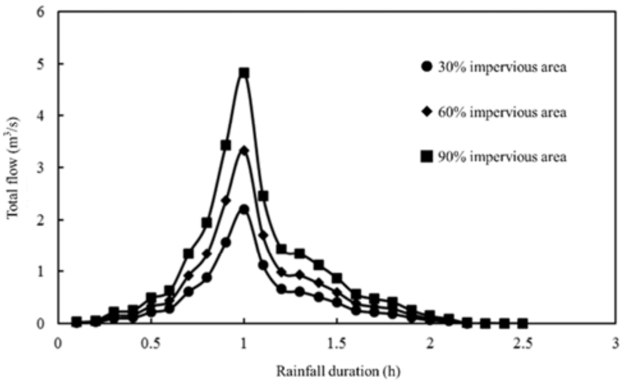

Figure 5. *Flow in catchment area with different proportion of impervious surface.*

4.2. Pollutant Simulation

COD_{Cr}, NH_3-N and TP were selected as the characteristic pollutants in the study zone. The variation characteristics of runoff pollutants were analyzed by simulating different rainfall intensities and different permeable areas.

The impervious ratio of all catchment areas was set at 65%, and the concentration varieties of pollutants under different rainfall conditions were calculated. Figure 6 to 8 describes the variation of COD_{Cr}, NH_3-N and TP concentration with the time course of rainfall, showing a trend of first increasing and then decreasing with the rainfall, the specific values are shown in Table 2. With the prolongation of rainfall recurrence period, the concentration of pollutants decreases, and the increase of rainfall leads to the raise of runoff and water volume in river, which has obvious dilution effect on pollutants. At the same time, the scouring pollutants are mainly concentrated in the first 30 minutes of the rainfall process. It can be seen that controlling the growth of pollutants in the initial stage of rainfall and reducing the scouring rate of pollutants are important measures to depress non-point source pollution.

Table 2. *Variation of maximum concentration of pollutants with rainfall intensity.*

Rainfall recurrence period	**COD_{Cr} (mg/L)**	**NH_3-N (mg/L)**	**TP (mg/L)**
1 year frequency	141.3	5.62	3.26
5 years frequency	84.7	3.58	2.02
10 years frequency	76.2	2.74	1.71

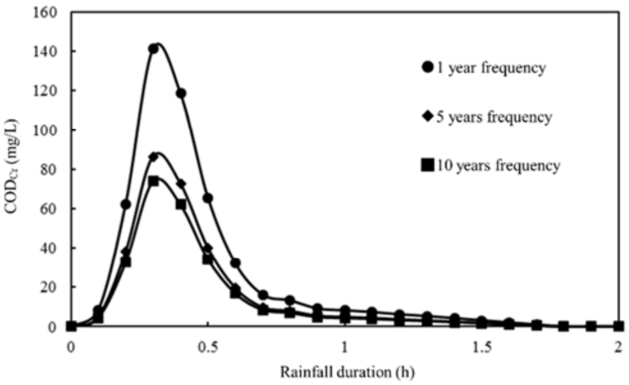

Figure 6. *Variation of COD_{Cr} concentration with rainfall in catchment area.*

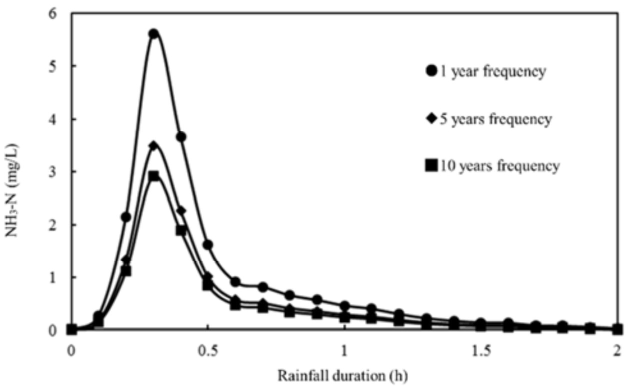

Figure 7. *Variation of NH_3-N concentration with rainfall in catchment area.*

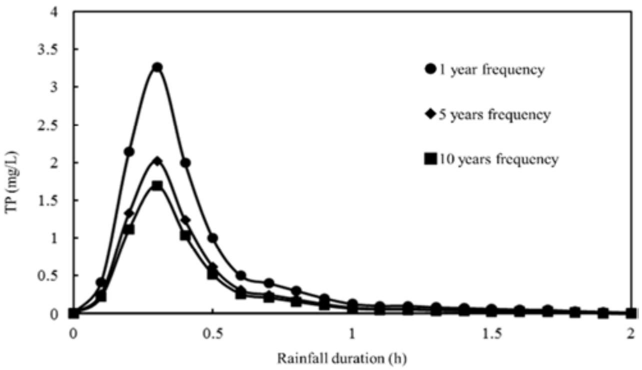

Figure 8. *Variation of TP concentration with rainfall in catchment area.*

Similarly, assuming that rainfall occurs once a year, the influence of different pervious areas on pollutant concentration can be analyzed by model calculation. The impervious areas are 30%, 60% and 90% respectively, the concentration of COD_{Cr}, NH_3-N and TP varies with rainfall duration as shown in Figure 9 to 11. With the increase of impervious area, the greater the runoff formed on the surface, the more obvious the scouring effect of pollutants, which leads to increase of pollutants concentration in receiving water. The peak concentration value of each pollutant varies with the

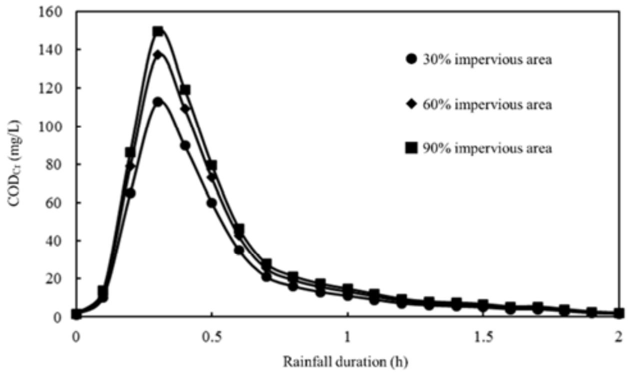

Figure 9. *Variation of COD_{Cr} concentration with impermeable area.*

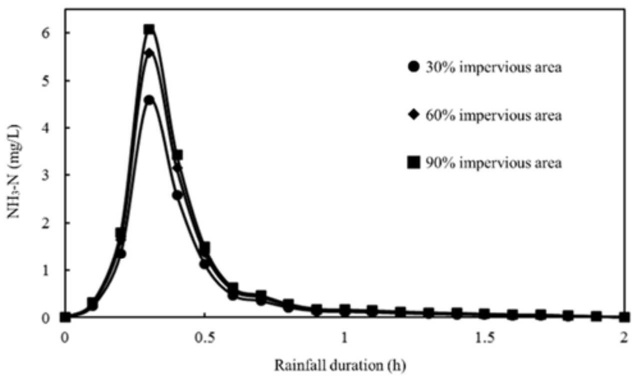

Figure 10. *Variation of NH_3-N concentration with impermeable area.*

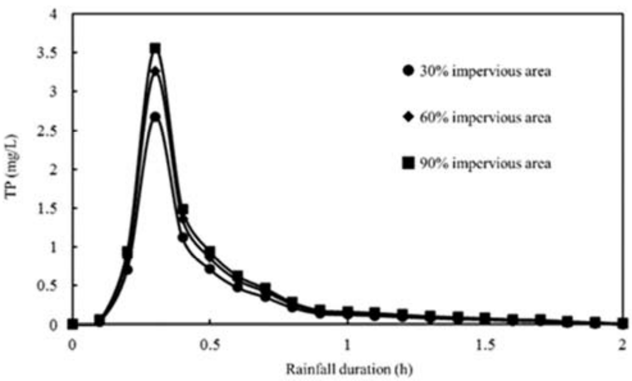

Figure 11. *Variation of TP concentration with impermeable area.*

Table 3. *Variation of maximum concentration of pollutants with proportion of impervious area.*

Impervious area ratio	COD_{Cr} (mg/L)	NH_3-N (mg/L)	TP (mg/L)
30%	112.8	4.63	2.67
60%	137.2	5.57	3.23
90%	149.6	7.33	3.56

4.3. Measurement and Simulation

Rainfall monitoring data in the study area on July 18, 2017 were selected as the basis, which are shown in Table 4. During the rainfall period, water samples were collected at the end of the river (outlet) according to a certain time series.

Table 4. *Rainfall intensity data.*

Rainfall duration(min)	5	10	15	20	25	30	35
Rainfall intensity(mm/h)	1.2	2.2	2.6	15.1	27.8	20.1	18.6
Rainfall duration(min)	40	45	50	55	60	65	70
Rainfall intensity(mm/h)	9.6	12.5	5.8	9.6	1.5	2.6	0.4

Comparing measured results with simulated results of the model, it is found that the measured value of COD_{Cr} concentration is higher than the simulated one, however, the variation of the both values is consistent. The concentration decreases gradually with rainfall, as shown in Figure 12. The higher measured value may be due to the obvious cumulative effect of surface pollutants, the large amount of pollutants and the stronger scouring effect of runoff, resulting in higher COD_{Cr} concentration in the river. Figure 13 shows the concentration curve of NH_3-N. The measured and simulated values also both decrease with rainfall process. A slight increase in the mid-term measured values may be related to human activities in the region. Domestic sewage discharge still leads to no decreasing trend in river inflow, which cannot be considered in the model. The variation of TP concentration is shown in Figure 14. The decrease of measured TP concentration in the early and middle stages of rainfall is not obvious compared with the simulated values, which may be related to the amount of phosphorus contaminants on the land surface. With the enhancement of rainfall scouring, various phosphorus compounds gradually dissolved in water after being scoured, eventually entered the river and counteracted some dilution. With continuous rainfall process, total phosphorus pollutants continued to decline.

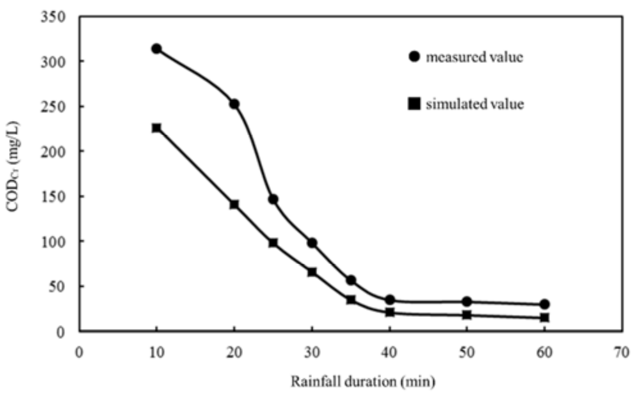

Figure 12. *Comparison of measured and simulated concentration for COD_{Cr}.*

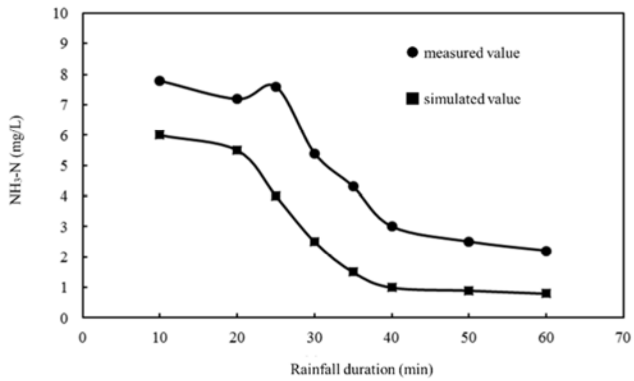

Figure 13. *Comparison of measured and simulated concentration for NH_3-N.*

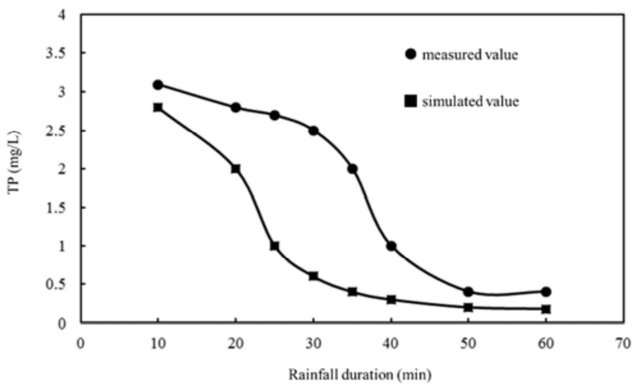

Figure 14. *Comparison of measured and simulated concentration for TP.*

5. Conclusion

Using SWMM can calculate the pollution of the black and stinking River with direct sewage discharge under the influence of rainfall runoff. The region selected in this work is urban residential living area with imperfect pipeline network, through which domestic sewage enters river directly. The simulation study can reflect the runoff yield, confluence and variation of pollutant concentration with rainfall in a certain region, which can provide support and help for flood control, drainage, surface water environmental protection in the process of urban construction.

The simulated results are consistent with the measured ones. When land use type and impervious rate are fixed, the total runoff and peak runoff increase with the rainfall recurrence; when rainfall intensity remains unchanged, runoff and total pollutants both raise with the increase of impervious surface area.

The concentration of pollutants decreased gradually in rainfall course. Because of different physical and chemical properties, the rate of concentration decline will be different under the action of runoff scouring, which can better reflect the characteristics of water quality change.

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