Comparative analysis of the runoff peak and non-point source pollution load of the initial area and the residential community developed from the area in Wuhan

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Abstract. Urban water environment and water safety problems are growing increasingly severe along with the accelerating rate of urbanization. It is very important to study the influence of traditional development model on water quality and quantity. In this study, SWMM model was developed to simulate and analyse the peak flow and pollution load changes before and after development in Wuhan residential communities with the short duration rainfall lasting 2 hours. It was found that under the traditional development model, the impervious surface area increased greatly, the peak runoff of rainwater increased by 66%~183% compared with that before development, and the relationship between peak flow increment and rainfall before and after development can be calculated with $\Delta R=-0.023 H^2 +1.49 H +160$. The confluence speed of rainwater decreased by 6.82%~20.19%. After the development, the amount of pollutants and the initial concentration of pollutants increased significantly, and the concentration of pollutants converged faster. The maximum concentration of COD, TN and TP increased to 2.09 times, 2.19 times and 2.16 times, respectively. The annual pollution load of COD, TN and TP increased by 52.31%, 45.27% and 43.54%, respectively.

1. Introduction
The urbanization rate of China reached 59.58 percent in 2018 [1]. With the accelerating rate of urbanization, the originally infiltrated green land or farmland is replaced by “grey buildings” such as reinforced concrete. The hardened area of the city is increasing, the rainwater convergence time is greatly shortened, and the runoff and the peak flow are sharply increased. The problem of non-point source pollution becomes increasingly prominent.

Low Impact Development (LID), the concept of rainwater management, was proposed at the mid-1990s in Maryland, USA [2]. The small-scale and decentralized control measures to manage comprehensively rainwater was applied. Based on the concept of LID, the “sponge city” was proposed to make the hydrological function of the aera after development consistent with its pre-development status in China [3-4]. Although many people are aware of the traditional development model has drawbacks, few scholars quantitatively analyze the variation of runoff quality and quantity between initial area and developed aera.

In this paper, SWMM (Storm Water Management Model) model and short-duration Chicago rain type were used to simulate the runoff peak and pollution load changes before and after the traditional development in a residential community, and to investigate the impact of traditional development mode...
on runoff peak and runoff pollution. The objective of this study is to provide theoretical support for the “sponge city” designing.

2. Construction of SWMM model

2.1 Modeling of residential plot
The researched object named Pauli Lafite Community is located in Hongshan District, Wuhan City. The annual average rainfall is about 1260 mm in Wuhan, which is a subtropical monsoon humid climate. The plot covers 9.32 hectares and the surface slope is about 1%. The proportion of hardened area and green area in the developed area is 48.8 % and 51.2 %, the pre-development area is natural. In general, the grassland runoff coefficient is 0.15-0.2 [5], the runoff coefficient of the pre-development cell was taken as 0.2.

After developed, the community is divided into four different catchment areas. The rainwater is collected by four stormwater pipes, entering to the urban municipal stormwater drainage system through four discharge ports (as shown in Fig.1b). According to the community’s terrain and the runoff’s situation, the developed community is divided into 243 sub-catchments, and the stormwater pipe network is generalized to 228 nodes and 231 segments. The pre-development community is also divided to P1, P2, P3 and P4, and the catchment area of each catchment point is the same as that after developed (as shown in Fig.1a).

![Fig 1. The map of the community.](image)

2.2 Modeling of rainstorm
Because the research object is a small watershed area, the short-lived rainstorm intensity formula of Wuhan was adopted to simplify the analysis, as shown in formula (1) to formula (3). The Chicago rain-type was adopted to simulate rainfall process line. The total rainfall duration was 2 h; the water withdrawal time was 3 h; the simulated total runoff time was 5 h; and the time interval was 1 min. According to the statistical analysis of rainfall data in Wuhan, the peak position coefficient is taken as: P ≥ 10 years, r = 0.50; 5 ≤ P < 10 years, r = 0.45; P < 5 years, r = 0.40.

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

\[
q = \frac{885[1+1.58 \lg (P+0.66)]}{(t+6.37)^{0.604}} \quad (0.5a \leq P<10a) \quad (2)
\]

\[
q = \frac{577[1+0.96 \lg P]}{(t+2.26)^{0.432}} \quad (10a \leq P<50a) \quad (3)
\]

Where q represents the intensity of rainstorm, L/(s·hm²); p-the design return period, a; t- the duration of rainfall, min.

When the quantity of the runoff peak was simulated and investigated, the rainfall recurrence period were taken as P = 1, 2, 5, 10, 20 a. When the quality of the runoff was simulated and investigated, 20
rainfalls with different recurrence periods in one year were taken as shown in Table 1.

| Recurrence Period (a) | Times |
|-----------------------|-------|
| p=1a                  | 1     |
| p=0.5a                | 1     |
| p=0.33a               | 1     |
| p=0.2a                | 2     |
| p=0.1a                | 5     |
| p=0.05a               | 10    |

2.3 Basic survey of the model

The parameters in the model were inputted based on the characteristics of hydrogeology in Wuhan, recommended values in the user’s manual of SWMM and the actual situation of the community. The infiltration model adopts the Horton model; the maximum infiltration rate is 76.2 mm/h; the minimum infiltration rate is 3.81 mm/h; the corresponding attenuation coefficient is 4 h⁻¹; the permeable surface’s Manning coefficient is 0.2, the impervious surface’s Manning coefficient is 0.015; the water depth of the permeable surface is 6 mm, and the impervious surface is 2 mm; the impervious surface of the impounded water storage covers 25%; the slope is 1%; the convergence model uses a nonlinear reservoir model; the hydraulic model uses a dynamic wave model.

2.4 Setting of initial pollutant on the ground surface

In this case, the characteristics of runoff pollutants were evaluated by COD, TN and TP. The parameters in the pollutant accumulation model were assigned. The exponential function model was used as pollutant flushing model with flushing coefficient and flushing index. It was assumed that the amount of initial pollutants on the ground surface is linearly related to the amount of local dust pollutants. According to the monitoring results of atmospheric dustfall and the fitted results of the initial pollutants in the catchment area of the Dongtang Road in Chaohu City by Zhang Chao [6], the monitoring results of atmospheric dustfall in the main urban area of Wuhan by Liu Shenghong [7], the initial pollutants in the main urban area of Wuhan had been calculated as shown in Table 2 by Yang Fengkai [8]. According to the actual monitoring data, the background content of pollutants in rainwater in Wuhan is adopted as: COD=20mg/L, TN=1mg/L, TP=0.02mg/L.

The scour coefficient and scour index of five different physical forms of pollutants on the underlying surface had been obtained by Zhang Chao through artificial simulated rainfall test [6]. According to the calculation method of pollutant parameters proposed by Zhang Chao, The flushing parameters on the underlying surface of Pauli Lafite Community are shown in Table 3.

3. Results and discussion

There are four discharge ports P₁, P₂, P₃ and P₄ in the plot. To simplify the result, The following simulation results are only about the P₁ discharge port to simplify the analysis process.

3.1 Comparison of runoff peak before and after development

The SWMM model was used to simulate the runoff process lines under the recurrence periods of 1a, 2a, 5a, 10a, and 20a before and after development. The results were as shown in Fig. 2 and Table 4.
Fig. 2. Different recurring period flow process lines before and after development.

Table 4. Peak flow increments for different recurrence periods before and after development.

| recurrence periods | rainfall (mm) | Peak flow (L/s) before development | Peak flow (L/s) after development | increments (%) |
|--------------------|--------------|------------------------------------|-----------------------------------|----------------|
| P=1a               | 34.43        | 100                                | 283                               | 183            |
| P=2a               | 50.81        | 157                                | 436                               | 178            |
| P=5a               | 72.45        | 267                                | 671                               | 151            |
| P=10a              | 88.83        | 387                                | 799                               | 106            |
| P=20a              | 105.2        | 505                                | 837                               | 66             |

After the development, the underlying surface of the community has undergone tremendous changes, which made the convergence conditions changed, and the convergence speed of the runoff increased sharply. The larger the recurrence period of rainfall is, the longer the confluence time is. For the pre-development catchment area, the runoff will basically end the confluence in about 5h (as shown in Fig.2a), and after development, the rainfall will end the confluence within 3h (as shown in Fig.2b), the convergence time is shortened by 6.82% to 20.19%. It can be seen that traditional development has greatly shortened the convergence time of runoff.

Due to the greatly increased proportion of impervious ground after development, the peak runoff of runoff has also increased significantly. For the rainfall of P=1a, the runoff peak after the development of the community increased by 183% compared with that before the development, and the increase gradually decreased with the increase of the rainfall return period. When P=20a, the runoff peak ratio after the development also increased by 66% than before (as shown in Table 4). It can be seen that the traditional development has greatly increased the peak flow rate in each recurrence period, and the impact on the small rainstorm is more obvious. Fitting the relationship between the rainfall H of the whole field and the peak flow increment ratio \( \Delta R(\%) \) before and after development, it is found that \( \Delta R \) decreases with the increase of H, \( \Delta R=-0.023H^2+1.49H+160 \), and \( R^2 \) can reach 0.9947 (as shown in Fig.3).
It can be found from Table 4 that for the catchment area of the $P_1$ point, the runoff peak under $P=1a$ after development is greater than the runoff peak under $P=5a$ before development, and the runoff peak under $P=5a$ after development is greater than the runoff peak under $P=20a$ before development, which is one of the reasons why people have formed the illusion of "It's raining heavily now than before."

For the concealed stormwater drainage system that has been formed around the development zone, it is generally designed according to the gravity flow, and the runoff contribution is often calculated according to the undeveloped natural state of the zone. It can be found from Table 4 that for the rainstorms of different recurrence periods, the peak runoff in the catchment area during the traditional development is much larger than before the development, and the stormwater discharge in the downstream section of the drain off system is inevitably larger than the original designed the peak runoff. If the peak runoff after development is more the peak runoff designed, the flow in the stormwater drainage pipelines will become a pressurized flow, the water level in the inspection well will go up and even spill over the ground to form a flood, which is also of the reasons why people have formed the illusion of "the torrential rain is getting bigger and bigger in recent years.".

3.2 Comparison of non-point source pollution before and after development

SWMM was used to simulate the change of COD concentration and total pollutant amount ($Q \times C$) of the drain port $P_1$ with the runoff time before and after development under the recurrence period of 0.05a, 0.1a, 0.2a, 0.33a, 0.5a, 1a. During the simulation, it was found that the changes rule of COD concentrations and their quantities were basically similar before and after development. The following is only the case of COD as an example. The results are shown in Fig. 4.

![Fig 3. Relationship between rainfall and peak flow increment ratio before and after development](image)

**Fig 3. Relationship between rainfall and peak flow increment ratio before and after development**

![Diagram of COD concentration before and after development](image)

(a) COD concentration before development  
(b) COD concentration after development
It can be found that because the runoff will wash away the pollutants accumulated on the surface, the initial runoff pollution concentration is very high, and the concentration of pollutants in the runoff continues to decrease with the runoff process progresses. The recurrence period is larger, the flushing rate on the underlying surface is faster; the pollutant concentration decreases faster as the runoff time increases. After developed, the proportion of hardened area in the plot increased greatly, and the concentration of pollutants in the early stage also increased significantly. The maximum COD concentration after development is 426.14mg/L, and the maximum COD concentration before development is 204.18mg/L. Due to the development, the maximum value of COD concentration in runoff has increased to 2.09 times. The simulation results show that TP and TN are similar to it and the maximum concentration after development increased to 2.19 times and 2.16 times respectively.

The quantity of contaminants is not only related to the concentration of contaminants at each moment, but also to the runoff process line. The amount of pollutants in the runoff before and after development increased with the recurrence period. Because the peak concentration of pollutants and the peak time of runoff are different, and their process lines are more "slim" shape after development, so there are two peaks in the process line of the amount of pollutants after development in P=1a, P=0.5a, P=0.33a, and P=0.2a. The dominant factor of the first peak was the concentration of pollutants, and the second peak was the peak runoff. There are only one peak occurs at P = 0.1a, P = 0.05a, and the dominant influencing factor is the peak runoff. Because the process line of pollutant concentration before development is relatively flat, the peak amount of pollutants is synchronized with the peak time of runoff peaks. So only one peak appears in the process line of pollutants in the runoff before development.

The comparison of the total amount of pollutants under different recurrence periods of rainfall before and after the development is shown in Fig. 5. The annual runoff pollution loads of COD, TN and TP before and after development are shown in Table 5.
the amount of TN

Fig 5. Total amount of pollutants in different return periods before and after development

The annual runoff pollution load value before and after development can be calculated by the total amount of pollutants excluded from the $P_1$ outlets dividing with the service catchment area of $P_1$ based on Table 1 and Fig.5 (Shown in Table 5).

Table 5. Comparison of annual runoff pollution load before and after development.

| pollution | annual runoff pollution load (kg/ha·a) | increments (%) |
|-----------|--------------------------------------|----------------|
| COD       | before development: 71.49             | after development: 108.89 | 52.31          |
| TN        | before development: 5.68              | after development: 8.26   | 45.27          |
| TP        | before development: 0.31              | after development: 0.45   | 43.54          |

It can be found that the total amount of pollutants in the runoff under each recurrence period after development is increased compared with that before development, and the increment increases with the decrease of the recurrence period. When $P=0.05a$, the total amount of COD, TN and TP increased maximally, which were 106.24%, 103.24% and 122.59% respectively. The annual runoff pollution load of COD, TN and TP increased by 52.31%, 45.27%, 43.54% after development. It can be found that the traditional development model has greatly increased the annual runoff pollution load, which will aggravate the water environment pollution.

At the same time of economic development, the traditional "grey building" should be changed to "green building", and the traditional "quick-row" mode should be changed to the natural-infiltration, low-impact development mode, which can reduce the peak runoff and the increment of pollution load, solve the problem of water pollution and safety, realize the concept of sponge city.

4. Conclusions
(1) After the traditional development, the area of impervious ground surface is greatly increased. For the
rainfall under 1a ≤ P ≤ 20a, the runoff peak are 66%~183% higher than that before development, which is easy to cause the water unsafe illusion of "the torrential rain is getting bigger and bigger in recent years". The increase rate decreases with the rainfall return period increases. The larger the field rainfall, the smaller the increment ratio of the runoff peak, ΔR=-0.023H²+1.49 H+160. After the development, the convergence speed of rainfall increased sharply, the convergence time was shortened by 6.82%~20.19%, and the convergence time was extended with the increase of the recurrence period.

(2) After the traditional development, the green area that can retain and absorb pollutants is greatly reduced, which results in a significant increase in the amount of pollutants and initial pollutant concentrations. The maximum concentrations of COD, TN, and TP have increased respectively to 2.09, 2.19, and 2.16 times. The total amount of pollutants in the runoff under each recurrence period has a certain increment compared with that before development, and the increment increases with the decrease of the recurrence period. The pollution load of COD, TN and TP in the annual runoff increased respectively by 52.31%, 45.27% and 43.54% after the development, which aggravates the water environmental pollution.

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