The first flush effect of different urban underlying surfaces through artificial simulated rainfall

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Abstract. Three kinds of underlying surfaces: asphalt road, impervious tiles and grassland at Chang'an University in south second ring road of Xi'an were chosen as testing sites. Self-made device was used to moderate rainfall with different raining conditions: uniform rainfall intensity of 0.3mm/min, 0.5mm/min, 1.0mm/min; front peak type rainfall and back peak type rainfall. The pollutants in the runoff were measured, that included TN, TP, NO₃⁻-N, NO₂⁻-N, NH₄⁺-N, PO₄³⁻-P and PN M(V) curves and MFF₃₀ values were analysed to drew these conclusions: under uniform rainfall intensity of 0.3mm/min, 0.5mm/min, 1.0mm/min, the mean values of MFF₃₀ from asphalt road runoff were 0.47, 0.42, 0.41, the mean values of MFF₃₀ from watertight tile runoff were 0.40, 0.39, 0.38, the mean values of MFF₃₀ from grassland runoff were 0.33, 0.34, 0.32. The first flush magnitude decreased with the increasing of rainfall intensity on asphalt road and watertight tile. The mean values of MFF₃₀ from the front peak type rainfall were larger than that from the back peak type rainfall on both asphalt road and watertight tile. Grassland should be built around asphalt road and watertight tiles to attenuate first flush effect.

1. Introduction
Rainfall runoff through the leaching, erosion, coffin to carry pollutants and it means the main driving force of various pollutants entering the water on the surface sink surface [1]. With the continuous development of urbanization, impervious area of impervious surface gradually increased, making the urban runoff pollution more serious and increasing the city surrounding rivers and lakes sewage discharge pressures [2]. Therefore, the urban surface runoff pollution has become the main form of urban non-point source pollution, and it is the second largest urban water pollution besides domestic...
sewage and industrial wastewater and gradually deteriorating urban water environmental quality [3-5]. It is found that the concentration of pollutants in the early stage of rainfall runoff is significantly higher than the later stage, and a large amount of pollutants are discharged into the receiving water in a short period of time, causing serious damage to the water environment. This is the FFE (first flush effect), that is, the initial runoff is disproportionately carrying the most of the pollutants in whole runoff [6-9]. It has important economic significance and environmental significance for the management and governance of urban storm runoff [10]. Many domestic and foreign researchers have studied the FFE from various aspects. And the results show that the main factors are rainfall characteristics (rainfall, rainfall duration, maximum rainfall intensity), number of dry days, the type of land use, etc. [11-16]. At present, the research of the FFE is based on natural rainfall, and the monitoring of the FFE under natural rainfall is complex, random and extensive. It has high monitoring time, long cycle and large consumption of human and material resources. So the data obtained is less effective, and the results are also similarities and differences [17]. Such as Li Chunli found that the number of dry days and the degree of FFE has a positive correlation [15], but J.H. Lee found that there is no correlation between the two [18].

The study used self-made artificial rainfall devices to overcome the unfavorable factors of natural rainfall, and to discuss the different types of rainfall on the FFE of common urban surfaces. So as to provide the basis for the evaluation and command of urban rainfall runoff pollution.

2. Materials and Methods

2.1. Study Sites

The study area is Chang’an University campus, which is located in south second ring road of Xi’an. The proportion of land use types in Chang’an University campus is Construction land (66.2%), road (19.9%), Greenland (11.7%), and Watertight tiles (2.2%). Three kinds of typical underlying surfaces, asphalt road, grassland and watertight tiles were selected for artificial rainfall study.

2.2. Research Methods

2.2.1. Experimental device. We used the self-made experimental device to study runoff pollution, and the device consists of simulated rainfall and runoff collection. Simulated rainfall device consists of water pump, motor, flow meter, pressure gauge (0-0.6MPa), detachable bracket (3m high, 2m wide), and control box. Nozzle has a large (aperture 4mm), medium (aperture 2.5mm), small (diameter 2mm), and each nozzle is controlled by a separate solenoid valve. The device has a high similarity to natural rainfall in terms of rainfall characteristics. Before the rain, the runoff collection device is placed on the appropriate surface and sealed between the baffle and the underlying surface. So that all the runoff within the baffle from the collection port. The complete set of experimental device diagram shown in Figure 1.
2.2.2. Water samples collection and testing. The sampling time is collected at 0 min, 2 min, 5 min, 10 min, 15 min, 20 min, 30 min, 40 min, 50 min, 60 min after runoff, and which collect until runoff ends. Sampling requires recording the volume of water sample and sampling time to calculate the available runoff. Concentrations of TN, TP, NO$_3^-$ N, NO$_2^-$ N, PN, NH$_4^+$ -N, PO$_4^{3-}$ P of water samples were tested when the water samples are collected and immediately sent to the laboratory. The above indicators are measured with reference to national standards [19].

2.2.3. FFE analysis method. At present, there are more analysis methods for the FFE of urban rainfall runoff [20], and the most commonly used is the cumulative pollutant-runoff curve [21, 22], that is according the ratio of cumulative runoff to total runoff (cumulative runoff ratio), the ratio of cumulative pollution load to total rainfall load (cumulative pollution load ratio) and create a dimensionless curve - M(V) curve. According to the curve deviation degree of diagonal above to determine the strength of the FFE. The more the curve deviates from the diagonal, the stronger the FFE.

FFE analysis of M(V) curve is more intuitive, but the lack of quantitative expression, which is not conducive to the application of non-point source pollution assessment and control. Saget conducted a quantitative analysis of the FFE [23], which using a power function to fit the pollutant M(V) curve: $F(X) = X^b$. $X$ is the ratio of the cumulative runoff to the total runoff, $F(X)$ is the ratio of the cumulative pollution load to the total rainfall load, $b$ is the FFE coefficient. The $b$ value can be determined by software. When $X$ is 30%, the corresponding pollutant accumulation is called $MFF_{30}$, and the calculated is:

$$MFF_{30} = 0.3^b$$  \hspace{1cm} (1)

If $MFF_{30} > 30\%$, showing the FFE occurred, and the larger the value that the FFE is more intense. The FFE can be divided into two categories, if 30% <$MFF_{30}$ <60%, showing the FFE is weak; and $MFF_{30}$ > 60%, showing the FFE is strong.

3. Results and discussion

3.1. Analysis of M(V) curve under uniform rainfall
Fig.2 shows the M (V) curves of the pollutants in the runoff of the asphalt road, the watertight tiles and
Greenland underlying surfaces, which under three uniform rain intensity, such as 0.3mm/min, 0.5mm/min, 1.0mm/min.

3.1.1. Asphalt road FFE. It can be seen from Figure 2 that NH$_4^+$-N, NO$_3^-$-N and PO$_4^{3-}$-P in the asphalt road occurred in the FFE when rainfall is 0.3mm/min, in which the M(V) curve of NH$_4^+$-N deviates from the diagonal, and the remaining pollutants has not obvious flush effect. When the rainfall intensity increased to 0.5mm/min, the M(V) curve of NH$_4^+$-N and NO$_3^-$-N is more obvious deviates from the diagonal, and the M(V) curve of PN is significantly increased in the later stage of rainfall, indicating that the flushing has occurred in the later stage. In addition, PO$_4^{3-}$-P flush effect was significantly reduced, the remaining pollutants without significant flush amplitude changes. When the rainfall intensity increased to 1.0mm/min, the flush effect of NH$_4^+$-N decreased, and TP appears more obvious flush effect.

In summary, NH$_4^+$-N and NO$_3^-$-N on asphalt road are more prone to FFE, and PN is less prone to FFE in the small rainfall intensity. When the rainfall intensity increases, the FFE gradually appears in the late rain, and when the rain continues to increase, the FFE has weakened. Rainfall has washed, leaching, dilution and other multiple effects for pollutants on the underlying surfaces. The stronger the rain, the greater the erosion effect, so it can carry more pollutants, which may be the cause of the PN FFE increased with rain increased. At the same time, when the rainfall intensity increases, the runoff on the pollutant dilution effect also will be strengthened and the pollutant concentration decreases, it will weaken the pollutant flush effect [24]. In addition, PN has two clear flush in the rain which the M(V) curve appears more substantial rise in the late-rain. Asphalt road pavement has strong adhesion to particulate contaminants because of the certain sticky, and particles are not easy to run with the flow of flush. Since then, the soaking and flush by the early runoff, the particulate gradually released in the late rain, which it may be caused by the above reasons.

3.1.2. Watertight tiles FFE. It can be seen from Figure 2 that NO$_2^-$-N, NH$_4^+$-N and NO$_3^-$-N in the watertight tiles have a certain degree of flush effect when rainfall is 0.3mm/min, and the remaining pollutants has not obvious flush effect. When the rainfall intensity increased to 0.5mm/min, the flush degree of NO$_2^-$-N also increased, but flush effect of NH$_4^+$-N and NO$_3^-$-N were weakened. When the rainfall intensity is 1.0mm/min, all of the pollutants showed a weak flush effect. In the study area, the pollution source mainly comes from the sedimentation of pollutants in the atmosphere and the diffusion and transfer of pollutants on the road. Compared with the road, the accumulation of contaminants on the watertight tiles is less, and the dilution effect of the runoff on the pollutants is more obvious. So the bigger the rain is, the harder it is to observe the FFE. In addition, asphalt road water permeability is stronger, which compared with watertight tile. Therefore, it may be the one of the reasons why the FFE of the watertight tiles is weaker than the asphalt road.

3.1.3. Greenland FFE. It can be seen from Figure 2 that NH$_4^+$-N and NO$_3^-$-N in the grassland have a certain degree of flush effect when rainfall is 0.3mm/min. When the rainfall intensity increased to 0.5mm/min, the flush degree of NH$_4^+$-N and NO$_3^-$-N also increased slightly, and PN showing late flush effect that the M(V) curve increased at the later stage. When the rainfall intensity is 1.0mm/min, the M(V) curves of the pollutants are close to the diagonal, indicating that no significant flush effect.

Grassland is one of the few in the city and occupies a certain percentage of the underlying surface, so we understand that the FFE on grasslands is important for estimating and controlling urban runoff pollution. Grassland permeability is extremely strong and particle retention is very effective, which is different from poor permeability surface of asphalt road and watertight tiles. The results show that the concentration of runoff pollutants in grassland is always lower than other cities underlying surface, and the flush effect of grassland runoff is small, which has a certain interception effect on pollutants in runoff [25]. Compared with the other two underlying surfaces, the flush degree of the grassland is low, which is the same as the above research results.
Therefore, it can be judged that the rain intensity distribution, esp. pollutants was similar to the runoff rate. In general, front peak rainfall is more likely to cause FFE. However, the FFE of the front peak type rainfall on watertight tile and the output of TP fluctuates obviously in the back peak rainfall. TP on grassland in front type rains that the contaminants of two peak type rainfall have occurred in varying degrees of FFE besides NO$_3^-$-N did not occur FFE. While in the back peak rainfall, only the FFE occurred in TP, and TN and NH$_4^+$-N did not occur FFE, and the output rate of the remaining pollutants was similar to the runoff rate. In general, front peak rainfall is more likely to cause FFE. Therefore, it can be judged that the rain intensity distribution, especially the maximum rain intensity, is the main factor affecting the FFE.

3.2. $M(V)$ Curve of in unimodal rainfall

In order to be closer to the actual rainfall intensity, we use the Chicago rain-type to set the front and back peaks of two single peak rainfall situation. The Chicago rain-type was a kind of uneven design rain that based on intensity-duration-frequency relationship in 1957. After a lot of simulation and comparison, most domestic and foreign scholars believe that the effect is better and easier to determine the rainfall intensity process, and it is widely used in many research fields at home and abroad [26]. In this study, the uniform rainfall intensity changes every 5mins, and the specific changes is shown in Table 1 and 2.

The artificial rainfall is carried out on each of the underlying surfaces which according to two types in the table, and the resulting of pollutant M(V) curve is shown in Figure 3. Intuitive analysis shows that the contaminants of two peak-type rainfall have occurred in varying degrees of FFE besides NO$_3^-$-N in the asphalt road, and the FFE of the front peak type rainfall is significantly higher back peak type rainfall. The FFE of the front type rainfall on watertight tiles is higher than the back peak type, and the output of TP fluctuates obviously in the back peak rainfall. TP on grassland in front type rains showed significant FFE, and TN and NO$_3^-$-N did not occur FFE. While in the back peak rainfall, only the FFE occurred in TP, and TN and NH$_4^+$-N did not occur FFE, and the output rate of the remaining pollutants was similar to the runoff rate. In general, front peak rainfall is more likely to cause FFE. Therefore, it can be judged that the rain intensity distribution, especially the maximum rain intensity, is the main factor affecting the FFE.

**Figure 2.** M(V) curves from uniform rainfall.

| Rainfall Intensity | Asphalt Road | Watertight Tiles | Grassland |
|-------------------|--------------|------------------|-----------|
| 0.5 mm/min        |              |                  |           |
| 0.3 mm/min        |              |                  |           |
| 1.0 mm/min        |              |                  |           |

Table 1. Cumulative Pollution Load Ratio

| Type     | Pollution Load Ratio |
|----------|----------------------|
| TN       | 0.0                  |
| NO$_3^-$-N | 0.2                  |
| NO$_2^-$-N | 0.4                  |
| PO        | 0.6                  |
| TP        | 0.8                  |
| PN        | 1.0                  |

Table 2. Cumulative Runoff Ratio

| Type     | Runoff Ratio |
|----------|--------------|
| TN       | 0.0          |
| NO$_3^-$-N | 0.2          |
| NO$_2^-$-N | 0.4          |
| PO        | 0.6          |
| TP        | 0.8          |
| PN        | 1.0          |

Table 3. Cumulative Pollution Load Ratio

| Type     | Pollution Load Ratio |
|----------|----------------------|
| TN       | 0.0                  |
| NO$_3^-$-N | 0.2                  |
| NO$_2^-$-N | 0.4                  |
| PO        | 0.6                  |
| TP        | 0.8                  |
| PN        | 1.0                  |

Table 4. Cumulative Runoff Ratio

| Type     | Runoff Ratio |
|----------|--------------|
| TN       | 0.0          |
| NO$_3^-$-N | 0.2          |
| NO$_2^-$-N | 0.4          |
| PO        | 0.6          |
| TP        | 0.8          |
| PN        | 1.0          |

Table 5. Cumulative Pollution Load Ratio

| Type     | Pollution Load Ratio |
|----------|----------------------|
| TN       | 0.0                  |
| NO$_3^-$-N | 0.2                  |
| NO$_2^-$-N | 0.4                  |
| PO        | 0.6                  |
| TP        | 0.8                  |
| PN        | 1.0                  |

Table 6. Cumulative Runoff Ratio

| Type     | Runoff Ratio |
|----------|--------------|
| TN       | 0.0          |
| NO$_3^-$-N | 0.2          |
| NO$_2^-$-N | 0.4          |
| PO        | 0.6          |
| TP        | 0.8          |
| PN        | 1.0          |
Table 1. The intensity change process of front peak type rainfall.

| t(min) | 0-5 | 5-10 | 10-15 | 15-20 | 20-25 | 25-30 |
|--------|-----|------|-------|-------|-------|-------|
| rainfall intensity (mm/min) | 0.20 | 0.30 | 0.50  | 0.65  | 0.85  | 0.75  |

| t(min) | 30-35 | 35-40 | 40-45 | 45-50 | 50-55 | 55-60 |
|--------|-------|-------|-------|-------|-------|-------|
| rainfall intensity (mm/min) | 0.30  | 0.25  | 0.20  | 0.15  | 0.10  | 0.05  |

Table 2. The intensity change process of back peak type rainfall.

| t(min) | 0-5 | 5-10 | 10-15 | 15-20 | 20-25 | 25-30 |
|--------|-----|------|-------|-------|-------|-------|
| rainfall intensity (mm/min) | 0.10 | 0.15 | 0.20  | 0.25  | 0.30  | 0.75  |

| t(min) | 30-35 | 35-40 | 40-45 | 45-50 | 50-55 | 55-60 |
|--------|-------|-------|-------|-------|-------|-------|
| rainfall intensity (mm/min) | 0.85  | 0.65  | 0.50  | 0.30  | 0.20  | 0.15  |
3.3. Quantitative analysis of FFE

3.3.1. Analysis of uniform rainfall flush effect. After FFE curve fitting by power function, the b value of FFE of different underlying surfaces pollutants in different rainfall events is determined. Then, the $M_{FF_{30}}$ values is shown in Figure 4, which are obtained by the formula $M_{FF_{30}} = 0.3^b$

It can be seen from Figure 4 that most of the rainfall pollutants $M_{FF_{30}}$ are between 0.3 and 0.6. Compared with the underlying surfaces, the FFE of the grassland was weak, and some scenes of rain pollutants $M_{FF_{30}}$ value was less than 0.3. The relation between the strength of FFE on different underlying surfaces is asphalt road > watertight tiles > grassland. However, for NO$_2$-N, the $M_{FF_{30}}$ value on the watertight tiles is significantly larger than the $M_{FF_{30}}$ value on the asphalt road. It can be seen that we should give priority to controlling NO$_2$-N pollution of the watertight tiles. It is found that the $M_{FF_{30}}$ values of NH$_4^+$-N and TP are the highest in each pollutant, indicating that the two pollutants are prone to FFE. In addition, although TP and PO$_4^{3-}$-P similar in origin, but the latter FFE to be significantly weaker than TP. The $M_{FF_{30}}$ value of TN and NO$_3$-N on the asphalt road increased slightly with the increase of rainfall intensity, indicating that the greater the rainfall intensity, the more obvious the flush effect of the two pollutants. And the $M_{FF_{30}}$ of NH$_4^+$-N, TP and PO$_4^{3-}$-P decreases with the increase of rainfall intensity, which indicates that these pollutants are not easily washed by runoff, and the runoff dilution effect is stronger. The $M_{FF_{30}}$ of NO$_2$-N and TP decreases with the increase of rainfall intensity, but PN increases slightly, and the variation of other pollutants is not obvious. Finally, there was no significant change in the remaining pollutants except that the $M_{FF_{30}}$ of the grassland increased with the increase of the rainfall intensity.

Figure 3. M(V) curves from unimodal rainfall.

Figure 4. $M_{FF_{30}}$ values from uniform rainfall.
Table 3 shows the MFF\textsubscript{30} average values of contaminants for different rainfall intensity on each underlying surface. In the table, the FFE of asphalt road and watertight tiles decreases with the increase of rainfall intensity, indicating that the dilution of pollutants on the two underlying surfaces is more pronounced. While the FFE of the grassland increased first and then decreased with the increase of rain intensity, which indicated that the grassland was less prone to dilution.

| underlying surfaces | 0.3mm/min | 0.5mm/min | 1.0mm/min |
|---------------------|------------|------------|------------|
| asphalt road        | 0.47       | 0.42       | 0.41       |
| watertight tiles    | 0.40       | 0.39       | 0.38       |
| grassland           | 0.33       | 0.34       | 0.32       |

3.3.2. Analysis of single-peak rainfall flush effect. The pollutants MFF\textsubscript{30} values of single-peak rainfall on the underlying surface are shown in Figure 5, and the average values of the pollutants MFF\textsubscript{30} is shown in Table 4. In conjunction with Figure and Table, it can be concluded that the top 30% of the runoff in the pre-peak rainfall is significantly higher than back-type rainfall that on the surface of the asphalt road. Similarly, in addition to NO\textsubscript{2}-N, the contaminants MMF\textsubscript{30} values of pre-peak rainfall were higher than those the post-peak in the watertight tiles. The reason is that the runoff is often formed at the beginning in the impervious surface, and can carry a large number of pollutants. The results showed that the post-peak rainfall MMF\textsubscript{30} value of TN, NO\textsubscript{3}-N and TP was higher than the former peak on the grassland, indicating that the FFE of the post-peak rainfall on the grassland was stronger. Because the permeability of the grassland is strong, and the higher descent rate of early rainfall is difficult to form a large number of runoff, and the flush of the pollutants is also less. Therefore, for the impervious surface, we should pay attention to controlling the early pollutants when the pre-peak rainfall. While for the permeable surface, we should focus on pollutant control that late post-peak rainfall.

![Figure 5](image)

Figure 5. MFF\textsubscript{30} values from unimodal rainfall.

Table 4. The mean values of MFF\textsubscript{30} from unimodal rainfall.

| underlying surfaces | MFF\textsubscript{30} |
|---------------------|----------------------|
|                     | front peak | back peak |
| asphalt road        | 0.40    | 0.30       |
| watertight tiles    | 0.38    | 0.33       |
| grassland           | 0.32    | 0.35       |

4. Conclusion

4.1 Under the condition of uniform rainfall, the results of the MFF\textsubscript{30} are similar to those of the M(V) curve. Most of the rainfall pollutants occurred weak FFE, and the relationship between FFE of the different underlying surface is asphalt road> watertight tiles> grassland.
4.2 Intuitive analysis of M(V) curve, all the underlying surface of the FFE is more obvious, when the rainfall is maintained at 0.5mm/min. With the MFF\textsubscript{30} value analysis, the asphalt road and watertight tiles, all show the rain increased and the FFE intensity decreased.

4.3 In the unimodal rainfall, the MFF\textsubscript{30} value of each pollutant is generally lower than the MFF\textsubscript{30} value of uniform rainfall. The FFE of back peak type rainfall of asphalt road and watertight tiles is weaker than that of the former peak type rainfall, and the results on the grassland are the opposite. Asphalt roads and watertight tiles on MFF\textsubscript{30} of the pollutants is generally higher than the grassland. So grassland should be built around asphalt road and watertight tiles to attenuate FFE.

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