Research on pollution characteristics of Expressway runoff in Guizhou, China

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Abstract The author selected three expressways in Guizhou as the research objects, and the runoff pollution characteristics were researched by sampling, measuring and analyzing runoff during the rainfall. According to the research data, the primary pollution factors in expressway runoff such as SS, COD and Petroleum had greater pollution intensity; the BOD5, NH3-N, TP and Pb had medium pollution intensity, which were defined as the secondary pollution factors; the range of BOD5/COD was 0.0351~0.1025, which means a poor biodegradability for the expressway runoff. The expressway runoff showed different pollution characteristics and discharge rules, which were mainly affected by the rainfall and rainfall intensity. The first flush effect (FFE) was mainly medium and weak in the research area, and the degree of FFE was relatively weak under the light rain conditions, FFE didn’t occur in some rain events. This work is expected to pave the way for the pollution control of expressway runoff.

1. Introduction
Expressway runoff pollution refers to the situation that deposited pollutants on the expressway are leached, flushed and dissolved during the natural rainfall, and then flow with runoff into the surrounding receiving water, causing pollution to the water environment [1]. According to related research, the expressway runoff produced from a suburban expressway whose traffic volume is 30,000 vehicles a day can greatly increase the content of SS, organic compounds, heavy metals and other pollutants in the receiving water along the line and destroy the function of water environment [2]. Expressway runoff pollution, as a major source of water non-point source pollution, attracts more and more attention.

Developed countries have consecutively conducted a series of researches on expressway runoff pollution since the 1970s[3-9]. Zhao Jianqiang[10], Li He[11], Zhang Wei[12], Huang Jinliang[13], and other Chinese scholars have also conducted related researches in recent years. But because it starts late, and the measurements as well as researches on runoff pollutants mainly focus on certain areas, so related data and documents are not enough, especially for the west area like Guizhou where has no systematic experimental data and researches results. Besides, the expressway runoff pollution in various areas which is significantly affected by the location, climate, expressway conditions and other factors shows different characteristics. In view of that, the author selected three expressways in Guizhou as the research objects, and the runoff pollution characteristics were researched by sampling, measuring and analyzing runoff during the rainfall, aiming to provide related data and references to the regulation and control of expressway runoff pollution in research area.
2. Research Methods

2.1. Research sites
One set of each of three expressways- Liuzhen Expressway, Liuli u Expressway and Zhensheng Expressway which have different operation times and traffic volumes was chosen as research object. The expressway runoff sampling points were set on respective outfalls of each expressway, that is, on the bridge outlet entrances or subgrade ditches.

2.2. Sampling and measuring methods
Combining the characteristics of rainfall in Guizhou and previous studies, the experiment adopted on-the-spot sampling and measuring of expressway runoff during the rainfall. To be specific, sampling was started once the runoff induced by the rainfall forms. Sampling which lasted for an hour was taken every 10 minutes. In the process of sampling, traffic volumes and all parameters of rainfall would be recorded. Water analysis on samples would be conducted once they were collected. Pollutants to be measured according to the Technical Specifications Requirements for Monitoring of Surface Water and Waste Water were primary particular pollutants in expressway runoff, which included SS, COD, BOD5, NH3-N, TP, Petroleum, Pb, Zn, etc.

2.3. Sampling time and rainfall conditions.
Samples of rainfall in the research area were taken many times from January 2017 to June 2017, and available samples from 6 rainfalls were selected for the measuring and analyzing of expressway runoff. According to the degree of rainfall intensity, the 6 selected samples included 2 light rain, 2 medium rain and 2 heavy rain. The research was conducted on main rainfall types in the research area. The basic situations of each rainfall experiment was shown in Table 1.

| Rainfall experiment | Rainfall during sampling (mm) | Maximum rain intensity during sampling (mm.min⁻¹) | Traffic volume during sampling (vehicles.h⁻¹) |
|--------------------|-------------------------------|-----------------------------------------------|-----------------------------------------------|
| 1                  | 2.0                           | 0.0587                                        | 364                                           |
| 2                  | 2.5                           | 0.0766                                        | 241                                           |
| 3                  | 6.1                           | 0.2923                                        | 299                                           |
| 4                  | 15.4                          | 0.5418                                        | 258                                           |
| 5                  | 11.1                          | 0.4162                                        | 275                                           |
| 6                  | 5.4                           | 0.2113                                        | 256                                           |

a Section 1, Section 2, Section 3 are the expressway sections where the sampling points were located.

3. The results and discussion

3.1. The evaluation of pollution intensity
126 water samples were taken and 1008 monitoring data of pollutant concentration were acquired in the experiments. The single factor index method is used to classified evaluations on monitoring values of pollutant concentration of each pollutant and the event mean concentration (EMC) of pollutants during different rainfall events. Based on the quality function of the receiving water, the evaluation criteria are implemented referring to the Class III standard in the Surface Water Environment Quality Standard and the first discharge standard in the Integrated wastewater discharge standard. The evaluation results are shown in Table 2 and Table 3.
Table 2. Pollution intensity evaluation of runoff- Monitoring value

| Pollutant Item | SS    | COD   | BOD₅ | Petroleum | NH₃-N | TP     | Pb     | Zn     |
|----------------|-------|-------|------|-----------|-------|--------|--------|--------|
| Concentration range | 19~813 | 20~583 | 1.58~35.22 | 0.25~9.34 | 0.244~9.746 | 0.04~1.14 | 0.014~0.281 | 0.023~0.853 |
| Evaluating on the quality standard | Over-standard rate | 94.4% | 99.2% | 81.7% | 100% | 71.4% | 68.2% | 72.2% | 0 |
| Evaluating on the discharge standard | Over-standard rate maximum over-standard multiple | 26.1 | 28.2 | 7.8 | 185.8 | 8.7 | 4.7 | 4.6 | - |
| Evaluating on the discharge standard | Over-standard rate over-standard multiple | 84.1% | 69.1% | 15.3% | 25.4% | 0 | 1.6% | 0 | 0 |
| Evaluating on the discharge standard | Over-standard rate over-standard multiple | 10.6 | 4.8 | 0.8 | 0.9 | - | 0.1 | - | - |

Table 3. Pollution intensity evaluation of runoff- EMC value

| Pollutant Item | SS    | COD   | BOD₅ | Petroleum | NH₃-N | TP     | Pb     | Zn     |
|----------------|-------|-------|------|-----------|-------|--------|--------|--------|
| Concentration range | 80~512 | 69~392 | 4.43~19.42 | 0.95~6.12 | 1.041~5.496 | 0.10~0.78 | 0.027~0.170 | 0.062~0.575 |
| Evaluating on the quality standard | Over-standard rate | 100% | 100% | 100% | 100% | 66.7% | 72.2% | 0 |
| Evaluating on the discharge standard | Over-standard rate maximum over-standard multiple | 16.1 | 18.6 | 3.9 | 121.4 | 4.5 | 2.9 | 2.4 | - |
| Evaluating on the discharge standard | Over-standard rate over-standard multiple | 100% | 91.2% | 0 | 16.7% | 0 | 0 | 0 | 0 |
| Evaluating on the discharge standard | Over-standard rate over-standard multiple | 6.3 | 2.9 | - | 0.2 | - | - | - | - |

It can be seen from Table 2 and Table 3 that of all pollutants in the expressway runoff from the research area, all other factors, except for Zn, exceed discharge standards of the first discharge standard in the Integrated wastewater discharge standard or the Class III standard in the Surface Water Environment Quality Standard to different degrees. Detailed analysis are as follows:

Evaluating on the quality standards, the over-standard proportion of monitoring values of SS and COD ranges from 94.4% to 100%, and 100% for EMC values; Evaluating on the discharge standards, the over-standard proportion ranges are 69.1%~99.2% and 91.2%~100%; Evaluating on the quality standards, the maximum over-standard multiples of monitoring values of Petroleum and EMC values can reach 185.8 and 121.4 respectively. The above three pollutants are primary pollution factors with greater pollution intensity in expressway runoff, which may exert great impact on the receiving water. As for BOD₅, NH₃-N, TP and Pb, though most monitoring values and all EMC values meet the discharge standards, but they generally exceed the quality standards. The ranges of over-standard multiples of monitoring values and EMC values are 4.6~8.7 and 2.4~4.5 respectively, which may have a certain impact on the receiving water, which are labeled as medium pollution intensity, thus they are defined as secondary pollution factors. All values of Zn can reach the quality standards, thus having a minor effect on the receiving water.

Thus, in the control of pollution, priority should be given to the removal of primary particular pollutants, like SS, COD, and Petroleum, and the disposal of BOD₅, NH₃-N, TP, Pb as well as other pollutants should be considered at the same time.

3.2. The analysis of biodegradability

BOD₅/COD is used to assess the biodegradability of expressway runoff. When BOD₅/COD > 0.3, the sewage is considered to be biodegradable, and biological methods are feasible; when BOD₅/COD < 0.3, it is considered that the sewage has a poor biodegradability and biological methods are not
feasible. It can be seen from the statistics that in the research area, the BOD5/COD in expressway runoff ranges from 0.0351 to 0.1025, with an average of 0.0642. So, we can conclude that it has a poor biodegradability, and biological methods are not advisable.

3.3. The analysis of pollution characteristic in different rainfall conditions

Selecting three rainfalls which represent light rain, medium rain and heavy rain respectively to analyze the change of pollutant concentration under different rainfall conditions and rainfall intensities. Details are shown from Figure 1 to Figure 3.

--- Fitting curve: the fitting curve fits the correlation between pollutant concentration and rainfall duration

Figure 1. Change characteristics of pollutants concentrations with rainfall duration (rainfall) in the second rainfall (2.5mm)

Figure 2. Change characteristics of pollutants concentrations with rainfall duration (rainfall) in the third rainfall (6.1mm)
Figure 3. Change characteristics of pollutants concentrations with rainfall duration (rainfall) in the fourth rainfall (15.4mm)

The results show that:

1) The change of pollutant concentration in the expressway runoff at different rainfall events has good exponential function correlation with the change of rainfall duration. The goodness of fit can reach from 0.7003 to 0.9565. In the same rainfall event, the pollutant concentrations of SS, COD, BOD5, Petroleum, NH3-N, TP, Pb and Zn change subtly with different rate, but the tendencies are quite similar.

2) In the same rainfall event, rainfall and rainfall duration have negative correlation with the pollutant concentration, which means as rainfall continues, the more rainfall it has, the lower pollutant concentration it is. This phenomenon is caused by the fact that with no other discharge in a rainfall, the pollutants on the expressway are leached, flushed and dissolved gradually. Once the pollutants are released, the pollutant concentration drops off.

3) Besides, the discharge rules of expressway runoff in different periods of rainfall varies from that of expressway runoff in different rainfall events. ①It can be seen from the fitted curve and regression equation of the change of pollutant concentration at different periods of rainfall that as rainfall continues, the change rate of pollutant concentration becomes lower, that is, the change rate of pollutant concentration at the beginning of the rainfall is the fastest, then it declines as rainfall continues, and reaches the lowest at the end of sampling. The main cause is that pollutants have accumulated a lot at the beginning of the rainfall. Once it rains, those pollutants get leached and released. In the late rainfall, the pollutants are cleared enough and the leaching function gets less. So, the release of pollutants lowers down, leading to the decline of change rate of pollutant concentration. ②The descending rates of pollutant concentration in the rainfall are the fourth rainfall (15.4mm) > the third rainfall (6.1mm) > the second rainfall (2.5mm). It shows that during the sampling, the larger the rainfall is, the faster the descending rate of pollutant concentration is which means there is a positive correlation between them. There are two reasons for that. For one thing, the volume of runoff on the expressway increases along with the increase of rainfall in the process of sampling, producing more significant dilution effect on pollutants. For another, as rainfall and rainfall intensity increases, the flush energy on the expressway grows stronger, fastening the release of pollutants on the expressway. Besides, the pollutant concentration of expressway runoff at different period of different rainfall events shows different change characteristics. The pollutant concentration of the second rainfall (2.5mm) and the third rainfall (6.1mm) increase first and then decrease, but the former changes greatly. The fourth rainfall (15.4mm) has been declining. This occurs because the first two rainfall
have less precipitation at the beginning, but as rainfall and rainfall intensity increase, some particulate pollutants which have large particle size and pollutants deposited in the lower layer on the expressway would enter the runoff, so the pollutants will be released and expand temporarily; when the flushing water of rainfall and energy accumulate to a certain extent, the load of pollutants that enter the runoff after being flushed and dissolved would reach a maximum value, and then decreases gradually. The above process leads to the increase first and then decrease of the pollutant concentration during the rainfall. If rainfall during the sampling continues longer and the rainfall intensity gets bigger, the transient expansion originally will last shorter and the fluctuation will be the smaller at last. In particular, the fourth rainfall has a large rainfall and high rainfall intensity at the beginning (nearly close to the intensity value of the heavy rain). Its flushing water of rainfall and energy basically exceed the energy needed to release the pollutants, so the pollutant concentration keeps decreasing after the runoff taking shape.

3.4. The first flush effect (FFE)

In this research, the $M(V)$ curve was drawn based on the correlation between the cumulative runoff volumes during the rainfall and the cumulative discharge of pollutants with runoff, which is proposed by Bertrand $^{[14]}$, and the data was fitted in this paper, from which the index is used to judge the degree of initial flush so as to research the FFE of expressway runoff. That is, $M(V)$ curve is drawn to fit the power exponent $a$ in the formula of $Y = X^a$ to represent flush coefficient. Different values represent different degrees of flushing at the initial stage of rainfall. The specific judgment relationship is shown in Table 4.

| $a$ value | The degree of the FFE |
|-----------|-----------------------|
| $0 < a < 0.185$ | Strong FFE |
| $0.185 < a < 0.862$ | Medium FFE |
| $0.862 < a < 1$ | Weak FFE |
| $1 < a < \infty$ | Non-FFE |

According to the $M(V)$ curve, flush coefficients of pollutants in each rainfall event are fitted as shown in Table 5.

| Rainfall experiment | Experimental section | SS | COD | BODs | The flush coefficient | Petroleum | NH3-N | TP | Pb | Zn |
|---------------------|----------------------|----|-----|------|-----------------------|-----------|-------|----|----|----|
| 1                   | Section 1             | 0.8632 | 0.9920 | 0.867 | 0.8615 | 0.8772 | 0.9957 | 0.9187 | 0.8971 |
|                     | Section 2             | 1.0497 | 0.9346 | 0.8531 | 0.9492 | 0.9119 | 1.0149 | 0.9426 | 1.0428 |
|                     | Section 3             | 1.0607 | 0.9066 | 0.8710 | 0.9213 | 0.9344 | 1.0377 | 0.9377 | 1.0011 |
| 2                   | Section 1             | 0.8219 | 0.9268 | 0.8770 | 0.8791 | 0.8555 | 0.8701 | 0.9092 | 0.8864 |
|                     | Section 2             | 0.9156 | 1.0216 | 0.8644 | 0.9688 | 0.8665 | 0.9758 | 0.9294 | 1.0137 |
|                     | Section 3             | 1.0710 | 0.8980 | 0.9162 | 0.9184 | 1.0524 | 0.9217 | 0.9828 | 0.8612 |
| 3                   | Section 1             | 0.8064 | 0.9338 | 0.8012 | 0.7998 | 0.6034 | 0.7527 | 0.8053 | 0.9078 |
|                     | Section 2             | 0.7464 | 0.7156 | 0.7043 | 0.7188 | 0.7634 | 0.8241 | 0.8229 | 0.6754 |
|                     | Section 3             | 0.8959 | 0.8455 | 0.8651 | 0.6745 | 0.8091 | 0.6417 | 0.8372 | 0.8932 |
| 4                   | Section 1             | 0.5069 | 0.5139 | 0.5069 | 0.4191 | 0.4813 | 0.4540 | 0.4552 | 0.4429 |
|                     | Section 2             | 0.4418 | 0.4874 | 0.5179 | 0.4049 | 0.4393 | 0.5403 | 0.4165 | 0.3987 |
|                     | Section 3             | 0.5782 | 0.6125 | 0.5949 | 0.5359 | 0.5617 | 0.5531 | 0.6454 | 0.6518 |
| 5                   | Section 1             | 0.5437 | 0.6068 | 0.5977 | 0.4987 | 0.5503 | 0.5489 | 0.6895 | 0.5072 |
|                     | Section 2             | 0.5629 | 0.6158 | 0.5986 | 0.4673 | 0.4981 | 0.5090 | 0.6172 | 0.4905 |
|                     | Section 3             | 0.5079 | 0.5222 | 0.5327 | 0.4399 | 0.5191 | 0.4468 | 0.5423 | 0.5801 |
| 6                   | Section 1             | 0.9236 | 0.9356 | 0.8813 | 0.7106 | 0.8887 | 0.9183 | 0.9100 | 0.9103 |
|                     | Section 2             | 0.9179 | 0.9527 | 0.9062 | 0.8882 | 0.8528 | 0.9214 | 0.8485 | 0.9093 |
|                     | Section 3             | 0.8038 | 0.8163 | 0.8401 | 0.8289 | 0.6914 | 0.7274 | 0.8261 | 0.9025 |
The results show that:
1) On all the pollutants found in every researched rainfall events, statistical data of 144 $FFE$ studies are collected, among which are 80 events of medium $FFE$ and 54 events of weak $FFE$, also there are 10 events with non-$FFE$. Respectively, these data account for 55.6%, 37.5%, and 6.9%. No strong $FFE$ has been found in these rainfall events.

2) Pollutants show different flushing patterns in different rainfall conditions. In this research, two events of light rain, medium rain and heavy rain are in measurement. For data in details, among measured light rainfalls, 3 are found with medium $FFE$, 35 with weak $FFE$, and 10 even non-$FFE$, accounting for 6.26%, 72.9% and 20.8% respectively, and the mean value of $a$, the flushing coefficient, is 0.9082; among medium rainfalls, 19 are found with medium $FFE$, and 29 with weak $FFE$, accounting for 39.6% and 60.4% respectively, and the mean value of $a$, the flushing coefficient, is 0.8241; medium $FFE$ is detected in every heavy rainfall events in measurement, the mean value of $a$, the flushing coefficient, being 0.5240. It can be concluded that the $FFE$ of expressway runoff in the research area is obviously affected by the rainfall intensity. The greater the rainfall intensity, the more obvious the $FFE$ is. The reasons are mainly that regional rainy climate and highway cleaning exert influences, and that, if the cumulative load of the pavement before rainfall is not much different, the greater the rainfall intensity is, the greater the flushing energy is, and the pollutants are washed and released at a faster speed, which leads to more pronounced $FFE$.

3) The above analysis shows that the $FFE$ of expressway runoff in the research area is mainly medium and weak, and strong $FFE$ hardly appears. Especially with light rainfalls, the $FFE$ tends to be weak, and even in some cases of light rainfall, there is non-$FFE$. The expressway runoff pollution in the research area cannot be effectively controlled by merely processing the initial runoff.

4. Conclusion
1) The intensity of SS, COD and Petroleum in the expressway runoff of the research area is generally high, the three, thus, being the primary pollution factors; while BOD$_5$, NH$_3$-N, TP and Pb are in medium intensity, defining as the secondary pollution factors. Pollution control should give priority to the removal of primary characteristic pollution factors, while considering the treatment of secondary pollution factors. BOD$_5$/COD detected in intensity in the surface runoff ranges from 0.0351 to 0.1025. It should not be treated by biological methods due to its poor biodegradability.

2) The research shows a good exponential function correlation between the pollutants concentration in the runoff of each rainfall event and the rainfall duration. As the rainfall progresses, the concentration of each pollutant goes downward. However, the characteristics of expressway runoff pollution and the discharge rules vary under different rainfall conditions, and they change mainly under the influence of rainfall and rainfall intensity. The rainfall EMC is negatively correlated with rainfall intensity. The increase of runoff caused by the increase of rainfall intensity has a greater effect on the dissolution and dilution of pollutants than the increase of pollutants carried by runoff, and it plays a dominating role in the change of pollutant concentration.

3) The first flush effect of surface runoff in the researched area is primarily medium and weak. With light rainfalls, the $FFE$ tends to be weak, and even in some cases of light rainfall, there is non-$FFE$. The expressway runoff pollution cannot be effectively controlled by merely processing the initial runoff.

References
[1] Zhang Yu-fen. Traffic Environment Engineering [M]. Beijing: China communication press, 2001.
[2] Sriyaraj K, Shutes R B. An assessment of the impact of motorway runoff on a pond, wetland and stream [J]. Environment International, 2001, 26(5-6): 433~439.
[3] Pollutant loading and impacts from stormwater runoff, Vol.III. Analytical Investigation and Research Report [R]. Washington D C: Federal Highway Administration, 1990.
[4] Stotz G. Investigations of the properties of the surface water runoff from federal highways in the FRG [J]. The Science of the Total Environment, 1987(59): 329-337.
[5] Desta M B, Bruen M, Higgins N, Johnston P. Highway runoff quality in Ireland [J]. Journal of Environmental Monitoring, 2007, 9(4): 366-371.

[6] Li M H, Barrett M E, Rammohan P, Olivera F, Landphair H C. Documenting stormwater quality on Texas highways Adjacent vegetated roadsides [J]. Journal of Environmental Engineering, 2008, 134(1): 48-59.

[7] Drapper D, Tomlinson R, Williams P. Pollutant concentrations in road runoff: Southeast Queensland case study [J]. Journal of Environmental Engineering, 2000, 126(4): 313-320.

[8] Ellis J B, Revitt D M. The contribution of highway surfaces to urban stormwater sediments and metal loadings [J]. The Science of Total Environment, 1987(59): 339-349.

[9] Barrett M E, Irish L B, Malina J F, Charbeneau R J. Characterization of highway runoff in Austin, Texas, area [J]. Journal of Environmental Engineering, 1998, 124(2): 131-137.

[10] Zhao Jian-qiang, Qiu Yan-hua. Discussion on road runoff pollution and control techniques [J]. Journal of Chang’an University (Arch. & Envir. Science Edition), 2004, 21(3): 50-53.

[11] Li He, Zhang Xue, Gao Hai-ying, Fu Da-fang. Characterization of contaminated runoff on free way surface [J]. China Environmental Science, 2008, 28(11): 1037-1041.

[12] Zhang Wei, Zhang Shu-cai, Yue Da-pan, Wan Chao, Ye You-bin, Hu Jun-dong, Wang Kai-yan, Gao Yan, Wang Xue-jun. Study on PAHs concentrations in urban road runoff in Beijing [J]. Acta Scientiae Circumstantiae, 2008, 28(1): 160-167.

[13] Huang Jin-liang, Du Peng-fei, Ao Chi-tan, Lei Mui-heong, Zhao Dong-quan, Ho Man-him, Wang Zhi-shi. Characterization of urban roadway runoff in Macau [J]. China Environmental Science, 2006, 26(4): 469-473.

[14] Bertrand K J, Chebbo G, Saget A. Distribution of pollutant mass vs volume in stormwater discharges and the first flush phenomenon [J]. Water Research, 1998, 32(8): 2341-2356.