First flush analysis of urban stormwater runoff from an urban catchment in Johor, Malaysia

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Abstract. An increase of pollutants that are present in the initial stage of stormwater runoff hydrograph compared to a later stage of runoff is defined as a first flush phenomenon. This study aims to investigate the occurrence of first flush from samples of urban stormwater runoff obtained from the grounds of a University in Skudai, Johor, Malaysia. In order to achieve the study's objective; field investigations, manual sampling of urban stormwater runoff, laboratory testing and data analysis were carried out and the evaluation of the first flush phenomenon was calculated using concentration-based first flush (CBFF) and mass-based first flush (MBFF. A total of 90 stormwater samples were collected from six (6) rainfall events and were tested for total suspended solids (TSS). For each rainfall event, the pollutographs and the dimensionless curves of the cumulative pollutant mass versus the cumulative discharged volume were plotted. The first flush coefficient was also determined in order to evaluate the occurrence of first flush. The results indicated that the storm events demonstrated a weak presence of first flush.

1 Introduction

Urbanization processes alter the function and structure of landscapes as it transforms pervious surfaces into impervious surfaces. It has been found that the process of urbanization has caused an increase in the discharge of pollutants to waterbodies [1][2]. Therefore it can be said that pollutant mass is intensifying due to high population and the rapid progress of urbanization. During the first flush phenomenon, pollutants that are contained in stormwater runoff during rainfall events can be a major contributor to the quality of receiving water in urban areas [3][4][5]. First flush is defined as the phenomenon where large portions of

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pollutant loads exist during the initial stage of the stormwater runoff compared than in the later stage of a rainfall event [3].

Numerous methodologies have been introduced in order to evaluate the effects of first flush. According to [6], first flush analyses are categorized into three categories, namely: mass-based first flush (MBFF), concentration-based first flush (CBFF), and empirically based first flush. For the purpose of this study, concentration-based first flush (CBFF) and the mass-based first flush (MBFF) were used to determine first flush occurrence and first flush coefficient was determined to quantify the magnitude of first flush stormwater pollutants with specific focus on Total Suspended Solids (TSS). Suspended solids were chosen as an indicator due to the reason that it is the most common pollutant found in urban stormwater runoff. In [7], suspended solids can be accepted as the substitute for other pollutants. Stormwater runoff from urban areas contain significant loads of inorganic elements, particularly heavy metals [8]. Most of the heavy metals found in urban stormwater runoff are attached to suspended solids [9]. These fine particles of sediment and the pollutants that are attached to them are measured by TSS.

2 Materials and Methods

2.1 Study Area

The stormwater runoff samples for this study were collected from the Faculty of Civil Engineering, Universiti Teknologi Malaysia, Skudai, Johor. These samples of stormwater runoff were specifically monitored and analysed in a small catchment at the M50 building on the university grounds. This part of the building was chosen due to its convenience to carry out research work based on the close distance to student residences thus enabling it to be easily and immediately accessed during peak hours.

Fig. 1 shows the location of the sampling site while Fig. 2 indicates the catchment area. In Fig. 3, the 1150 m long drain which is the catchment area used to collect the stormwater runoff is shown. The slope range is from 1.2% to 9% and the catchment drainage system separates the stormwater system from the sewerage system. Data collection was carried out for six (6) rainfall events that began from the middle of 2017 and ended at the end of 2017.

2.2 Flow measurement and stormwater sampling

Stormwater runoff samples were taken from six (6) observed rainfall events from May 2017 until December 2017. These samples were collected manually using one (1) litre polyethylene bottles and in total, 10 to 15 litres of stormwater samples were obtained during each event on both rising and falling limbs of the hydrograph. The stormwater samples were collected from the beginning to the end of each storm event. For the respective samples that were taken, the level of stormwater in the drain and sampling time were recorded at intervals of every two to four minutes depending on the storm intensity. Every bottle was labelled with the date, time and sample number.

After the sampling work had been carried out, the stormwater samples were immediately transferred to the Environmental Laboratory at Universiti Teknologi Malaysia for laboratory analysis. The laboratory analysis was carried out based on the Standard Methods for the Examination of Water and Wastewater [10] and the pollutant analysed were the Total Suspended Solids (TSS). In this study, TSS was identified as the dry-weight of particles trapped by a 0.45- m filter and it does not include the dissolved solids in stormwater. TSS was also measured by filtration, drying at 103–105°C [11].

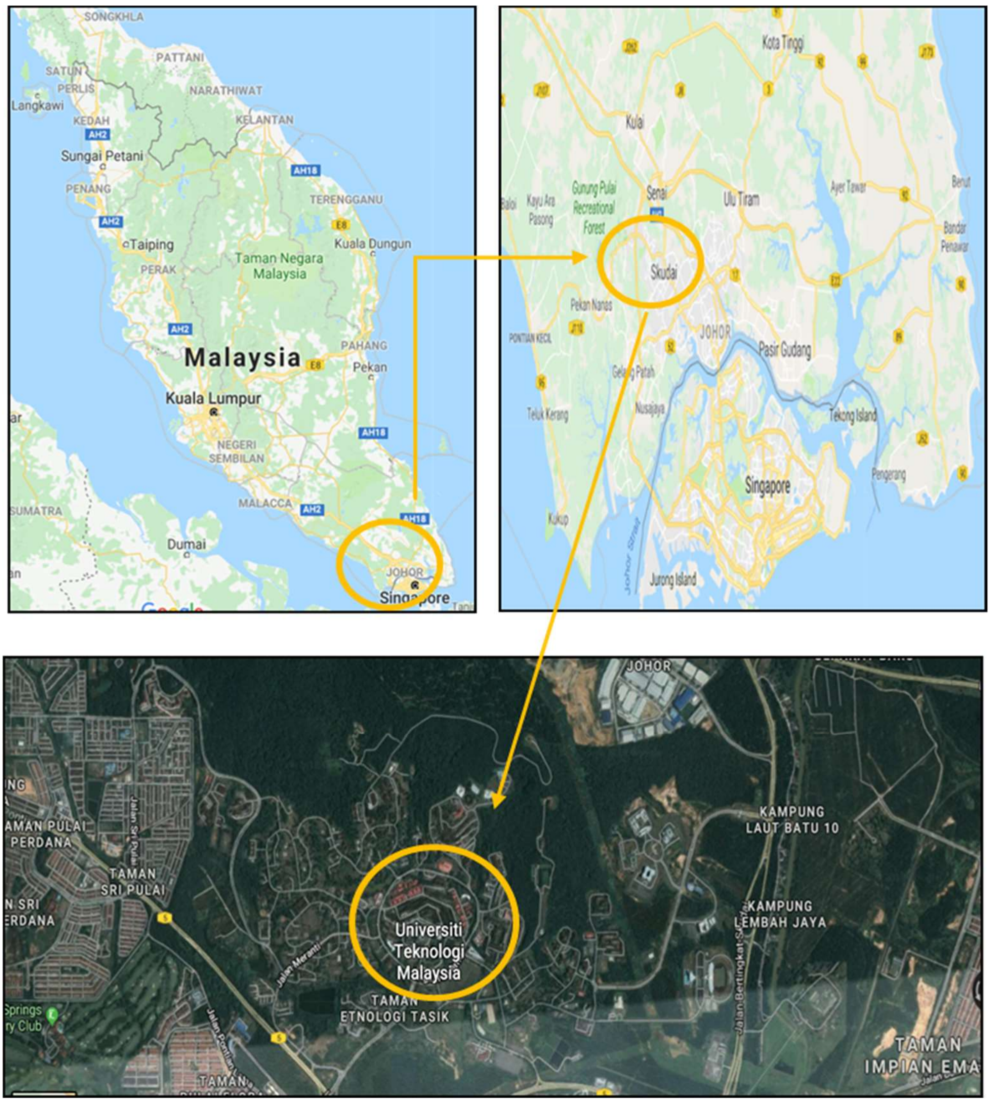

Fig. 1. Location of the sampling site.

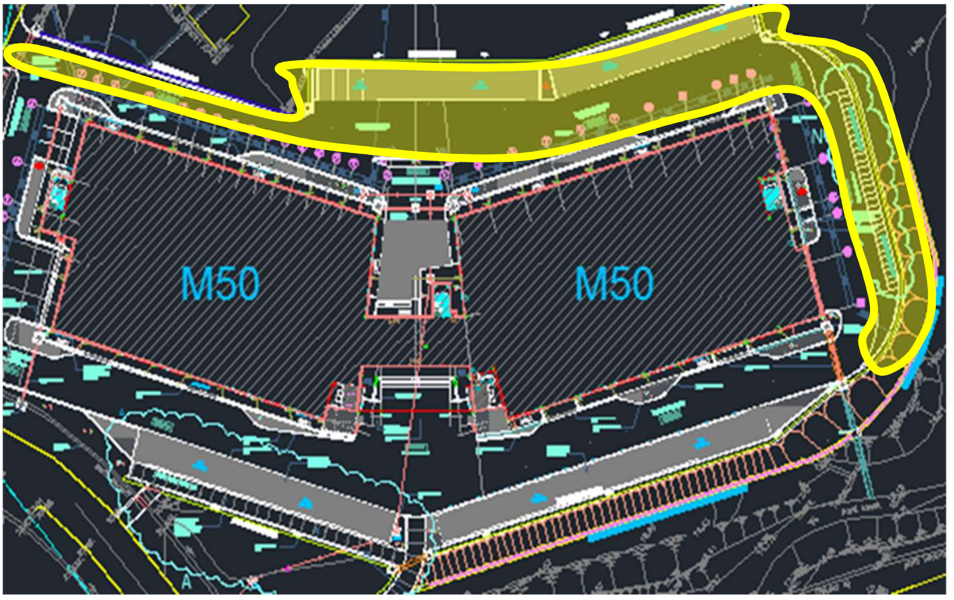

Fig. 2. Catchment area.

Fig. 3. Catchment area (1150 m long drain around car park behind the M50 building).

2.3 Rainfall Measurement

A tipping bucket rain gauge (ISCO) with volume resolution 0.01 inch/tip rainfall was used continuously to measure rainfall intensity. For recording and analysis purposes the unit was then converted to mm/hr. The rain gauge was set up on a levelled platform on a roof at the M50 building to ensure sufficient exposure and minimize any obstructions. Fig. 4 demonstrates the measurement of runoff velocity.

Fig. 4. Measurement of runoff velocity.

3 Results and discussion

3.1 Characteristics of Rainfall Events

Table 1 presents the summary of rainfall characteristics such as rainfall duration, total rainfall depth, rainfall intensity and antecedent dry period (ADP). Six (6) rainfall events were captured in this study. The event with the shortest duration of 39 minutes was Event 3 whereas the longest duration of 164 minutes was recorded for Event 6. It can be observed that the antecedent dry period range from 13.5 hours to 94 hours, while the total rainfall depths range between 8.16 mm and 59.76 mm. Event 3 has been found to have the highest intensity which is at 21.05 mm/hr.

Table 1. Characteristics of rainfall events.

Event	Date	Rainfall Characteristic			
		Duration (min)	Total Rainfall Depth (mm)	Rainfall Intensity (mm/hr)	ADP (hr)
1	14 May 2017	60	8.16	8.16	94
2	22 May 2017	56	12.96	13.89	13.5
3	24 May 2017	39	13.68	21.05	48.37
4	8 Aug 2017	84	11.76	14.58	48
5	9 Nov 2017	92	59.76	12.73	24
6	12 Dec 2017	164	34.8	2.71	24

3.2 Hydrograph, hyetograph and pollutograph

A total of six (6) storm events were monitored from May 2017 till December 2017. Fig. 5 to Fig. 10 illustrate the hydrograph, hyetograph and pollutograph of TSS for Event 1 to Event 6. From these graphs it can be observed that the rainfall depths range between 0.254mm and 16mm for all the rainfall events. According to the data, Event 1, 3, 4, 5 and 6 experienced higher rainfall depths at the beginning of the respective rainfall events while Event 2 had a higher rainfall depth in the middle of the storm.

From the pollutographs, it is observed that Events 1, 2, 3 and 5 illustrate a similar pollutograph pattern; where a higher concentration of TSS was observed at the initial part of the Event and eventually the TSS concentration started to decrease until the event ended. This finding suggests that the pollutants that build up during dry days were washed away with the rainfall at the initial stage of the runoff event. The decreased concentration of pollutants at a later stage of the runoff event might also be due to higher rainfall depth with lower amount of pollutants. Based on the category of concentration-based first flush (CBFF), this suggests that there is an occurrence of first flush phenomenon [5].

With reference to Fig. 7, it can be seen that Event 3 has the highest rainfall intensity and highest concentration of pollutants at the beginning of the event (between 8.30am and 8.38am). However, an increase of rainfall intensity will ultimately lead to the decrease of first flush magnitude during a rainfall event [12].

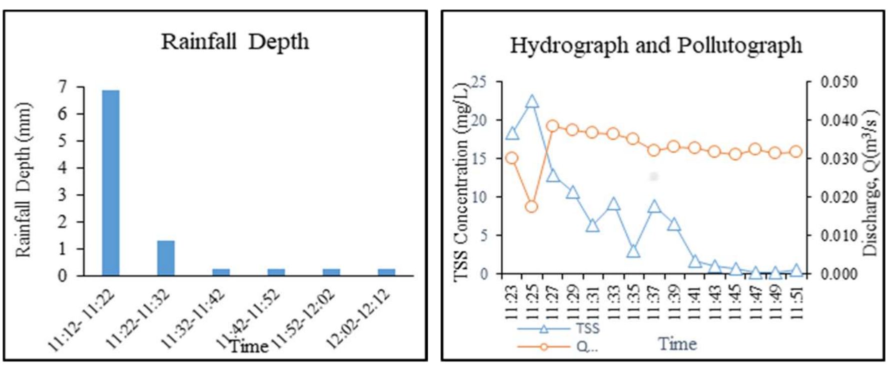

Fig. 5. Hydrograph, Hyetograph and Pollutograph of Event 1.

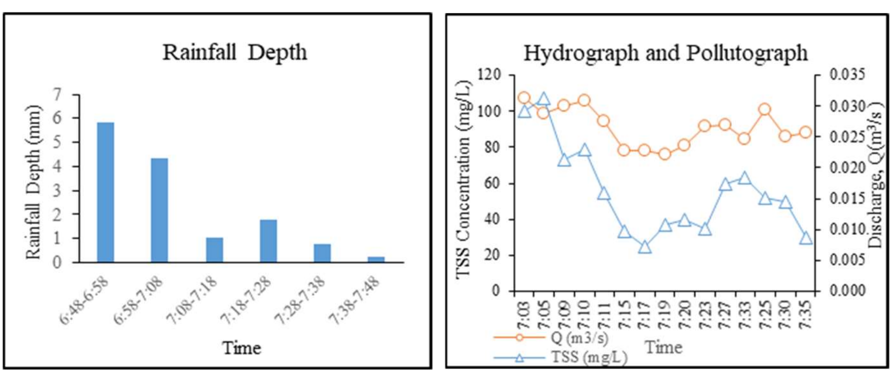

Fig. 6. Hydrograph, Hyetograph and Pollutograph of Event 2.

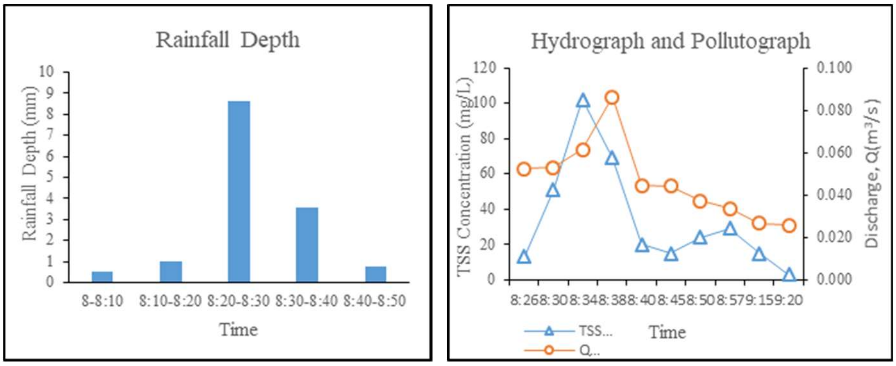

Fig. 7. Hydrograph, Hyetograph and Pollutograph of Event 3.

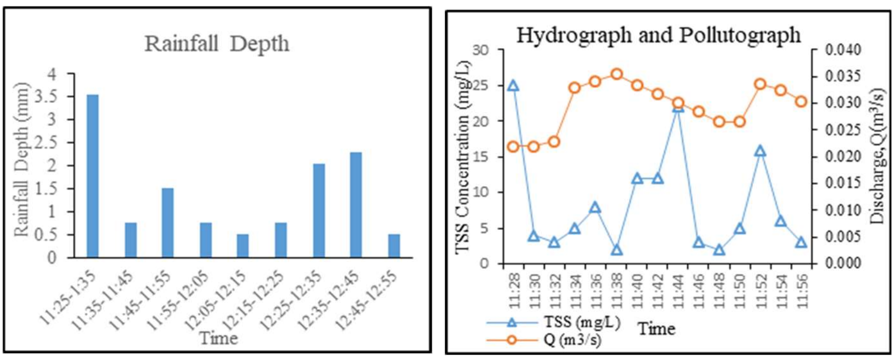

Fig. 8. Hydrograph, Hyetograph and Pollutograph of Event 4.

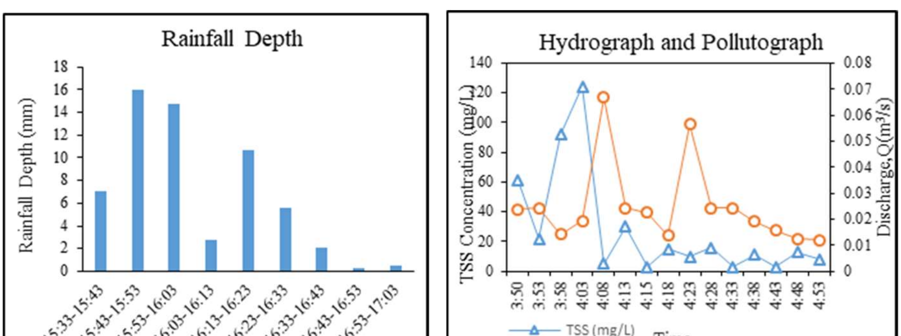

Fig. 9. Hydrograph, Hyetograph and Pollutograph of Event 5.

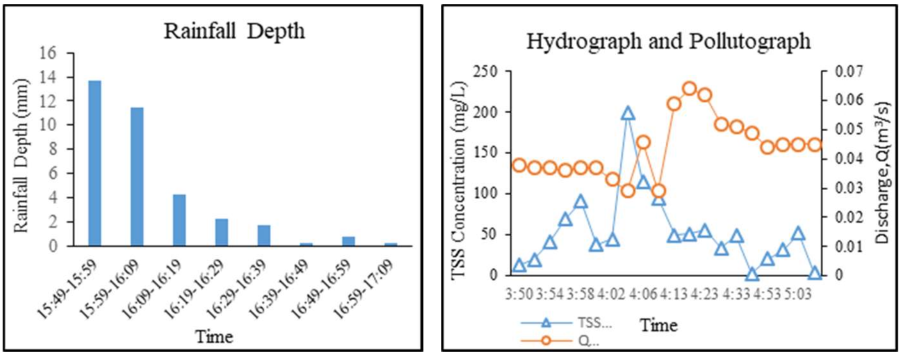

Fig. 10. Hydrograph, Hyetograph and Pollutograph of Event 6.

3.3 Mass Based First Flush Analysis

The distribution of pollutant mass versus volume in stormwater discharges using dimensionless M(V) curves was also considered in order to investigate the existence of first flush phenomenon [13].

$$M(t) = V(t)^a \tag{1}$$

In Equation 1, *a* is known as the first flush coefficient which indicates the difference between the bisector line and M-V curve as shown in Fig. 11. The symbol V(t) represents the ratio of the total runoff at the time (t) to that of the total volume runoff of the event. Symbol M(t) is the ratio of the total pollutant mass at the time (t) to that of the total pollutant mass of the rainfall event [14].

According to [15], the data that lies above the bisector (45° diagonal line) displays a higher loading during storms which suggest the occurrence of first flush phenomenon [15]. Subsequently, the 45° diagonal line suggests that the pollutants load that is removed from the catchment is directly proportional to the discharge volume leaving the catchment. However, when the M(V) curves fall below the bisector line, this represents a condition where dilution has occurred or most of the pollutants are delivered at the late stages of the rainfall event [16].

The variation of the cumulative pollutant mass curve from the diagonal line was used to measure the strength of the first flush phenomenon. Fig. 11 represents the cumulative mass curves for all the six (6) events. It was found that only the cumulative mass curve of Event 2 lies above the bisector and this proves that a high percentage of mass has been delivered at the initial part of the rainfall event. Conversely, other events lie below the bisector line and this demonstrates that a low percentage of mass has been delivered at the initial part of the rainfall event.

The magnitude of first flush for different rainfall events can be evaluated based on the first flush coefficient (a-coefficient) value. First flush coefficient (a-coefficient) defines the first flush strength as the dependent variable, while the rainfall characteristics are the independent variables. The numerical fitting between M(V) and F(X) is usually acceptable when the correlation coefficient $r^2 > 0.95$ [4].

Generally, the first flush phenomenon is assumed to have occurred when a-coefficient is >1 [15]. Based on the findings in Table 2, the results confirm that first flush existed during Event 2 and was absent for the other five (5) events. Table 2 shows that the values of a-coefficient vary between 0.44 and 1.37 for TSS. The ranking order of the first flush coefficient for all five (5) events is as follows: Event 2 > Event 1 > Event 4 > Event 5 > Event 6 > Event 3.

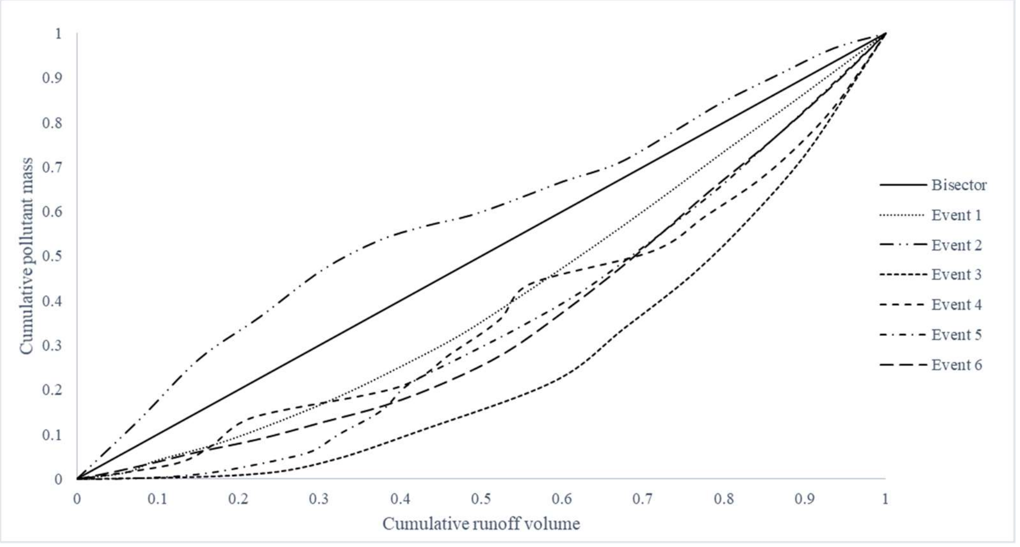

Fig. 11. M(V) curve for TSS.

Table 2. Range of the first flush coefficient a.

Event	a-Coeff	FF	r^2
1	0.6853	No	0.9972
2	1.3707	Yes	0.986
3	0.3531	No	0.9968
4	0.6639	No	0.9698
5	0.6599	No	0.9884
6	0.4387	No	0.9878

4 Conclusions

Information from six (6) rainfall events were recorded, monitored and analysed over the duration of eight (8) months. From the observation that has been made it was found that only one event (Event 2) had demonstrated the occurrence of first flush phenomenon. For the rest of the events that were examined, first flush was non-existent. The occurrence of first flush was investigated using concentration-based first flush (CBFF) and mass-based first flush (MBFF) whereas the strength of the first flush was determined using first flush coefficient. The relative strength of the first flush was ranked as Event 2 >Event 1 > Event 4 > Event 5 > Event 6 > Event 3. The knowledge obtained from this study is expected to contribute to a better understanding of the first flush phenomenon that ultimately affects the water quality in urban areas. Thus, these findings can be used to enhance the design of stormwater treatment systems. The authors recommend that further research is essential to fully develop this analysis.

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