Definition of realistic disturbances as a crucial step during the assessment of resilience of natural wastewater treatment systems

A. Cuppens, I. Smets and G. Wyseure

ABSTRACT

Natural wastewater treatment systems (WWTSs) for urban areas in developing countries are subjected to large fluctuations in their inflow. This situation can result in a decreased treatment performance. The main aims of this paper are to introduce resilience as a performance indicator for natural WWTSs and to propose a methodology for the identification and generation of realistic disturbances of WWTSs. Firstly, a definition of resilience is formulated for natural WWTSs together with a short discussion of its most relevant properties. An important aspect during the evaluation process of resilience is the selection of appropriate disturbances. Disturbances of the WWTS are caused by fluctuations in water quantity and quality characteristics of the inflow. An approach to defining appropriate disturbances is presented by means of water quantity and quality data collected for the urban wastewater system of Coronel Oviedo (Paraguay). The main problem under consideration is the potential negative impact of stormwater inflow and infiltration in the sanitary sewer system on the treatment performance of anaerobic waste stabilisation ponds.

Key words | anaerobic wastewater treatment, disturbances, resilience, sanitary sewer system, stormwater inflow and infiltration

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INTRODUCTION

Now that reuse-oriented sanitation has widely been accepted as the key to sustainable wastewater management (Guest *et al.* 2009), the necessity of maintaining satisfactory treatment performance under operational conditions cannot be highlighted enough. The failure of the natural wastewater treatment system (WWTS) to deliver a hygienically safe effluent has direct negative consequences for the reuse practice. For instance, fish can only be farmed in maturation ponds if the prior treatment has sufficiently reduced the pathogen and organic load to prevent diseases and maintain oxygen levels, and similarly, biogas is only produced at a reliable rate if the anaerobic WWTS functions properly (Murray & Ray 2010). Hence, a major objective for sustainable WWTSs in practice should be to develop and design natural WWTSs that are able to cope with large fluctuations in the influent in terms of quantity and quality. The fluctuations which actually cause a decrease of treatment performance are named *disturbances* in further discussion. In order to develop and design natural WWTSs that meet this objective, an appropriate framework for performance evaluation is required.

The most common approach for evaluating the performance of natural WWTSs is to use the mean efficiency and the related variance. The overall mean, however, provides too little information about the dynamic behaviour of the natural WWTS (Loucks *et al.* 2005). Oliveira & Von Sperling (2008) recently introduced reliability as a performance indicator for the natural WWTS. They defined reliability as being the percentage of time for which the expected effluent concentrations comply with the specified discharge standards or the treatment targets. The determination of the corresponding coefficient of reliability is based on the analysis of the available monitoring data for the WWTS effluent. For existing WWTSs the frequency interval of the available monitoring data is generally quite low (e.g., weekly or monthly). Hence, the reliability focuses more on the long term behaviour of the natural WWTS, while our interest lies in the short term influences of disturbances on the treatment performance.

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To overcome this limitation, the concept of resilience of natural WWTSs is introduced in this paper together with the definitions for the measures *robustness* and *rapidity*. The research presented here however, is not aimed at quantifying the resilience of natural WWTSs. The objective is the development of a methodology to identify and generate the necessary disturbances, being the first crucial step towards the quantification of resilience of WWTSs. A five-step methodology for the identification and generation of *realistic* disturbances of WWTSs is proposed. The methodology will be applied to the urban wastewater system of Coronel Oviedo (Paraguay), an appropriate study area for identifying disturbances because large fluctuations in water quantity and quality are present at the outlet of the sanitary sewer system.

RESILIENCE AS PERFORMANCE INDICATOR

According to Bruneau *et al.* (2003) a resilient system can be identified as a system that contains the following three characteristics: reduced failure probabilities, reduced consequences from failures and reduced time to recover after disturbance. These aspects are covered by four main properties of resilience, i.e., *robustness*, *rapidity*, *redundancy* and *resourcefulness*.

The properties *redundancy* and *resourcefulness* are not considered relevant for the analysis of resilience of natural WWTSs. For most natural WWTSs – once constructed – no means are present that allow the substitution of failing components (redundancy). In addition, the natural WWTS is not able to identify and to mobilise resources when conditions exist that threaten to disrupt some elements (resourcefulness). The interpretation of the two remaining relevant measures for natural WWTSs goes as follows.

- Robustness: ability of the natural WWTS to withstand a given disturbance without entering into a state of unsatisfactory performance.
- Rapidity: ability of the natural WWTS to regain satisfactory performance once failure has taken place due to exposure to a given disturbance. Rapidity involves the time necessary to regain satisfactory performance as well as the severity of the unsatisfactory performance.

The resilience of a natural WWTS is defined as the ability of the WWTS to maintain satisfactory performance when being exposed to disturbances representative for the considered wastewater system and to regain satisfactory performance in the event that a failure has taken place. The performance of the WWTS is defined as the extent to which the WWTS is able to comply with pre-established treatment objectives which were defined in accordance with the overall objective of the integrated wastewater system. A schematic representation of the WWTS in the context of the integrated wastewater system is provided in Figure 1(a). In Figure 1(b) the system performance being affected by a disturbance is given for the case where satisfactory performance of the WWTS means obtaining an effluent with pollutant concentration C_{WWTS} lower than a selected maximum concentration C_{target}.

DEFINING DISTURBANCES: URBAN WASTEWATER SYSTEM CORONEL OVIEDO

Coronel Oviedo is a small city in Paraguay located 130 km east of the capital Asuncion. At the outlet of the sanitary sewer system a pumping station is present to transport the wastewater towards the waste stabilisation pond (WSP) at a distance of 5.3 km. The flow at the outlet of the sanitary sewer system has been measured continuously during the period 23 February 2009 to 22 February 2011 based on the monitoring of the on/off switching of the different pumps. The pump monitoring data allowed calculation of the hourly-averaged flow to the WWTS for the measurement period. A continuous measurement of the rainfall intensity was performed by a tipping bucket rain gauge for the period 26 February 2009 to 22 February 2011. Water quality data (COD, TSS, DO, pH and T) were collected during three

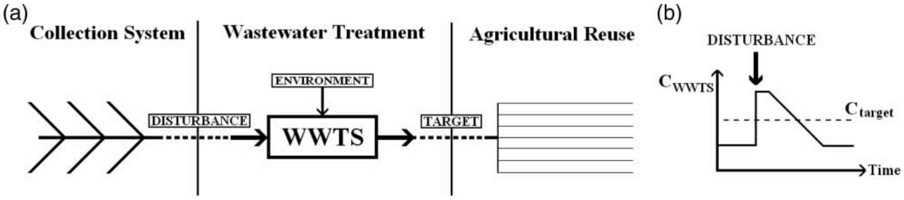

Figure 1 | Schematic representation of (a) the WWTS in the context of the integrated wastewater system and (b) the effect of a disturbance on WWTS performance in the framework of resilience.

periods (according to the Standard Methods): one during dry weather (22 February 2010) and two during rainy weather (Rain-event 1: 21–23 April 2010 with 107 mm; Rain-event 2: 13–15 March 2010 with 54 mm). Samples were taken manually as no automatic sampling equipment was available. The main question for local wastewater managers is whether an anaerobic pond should be considered for future WSP design or rehabilitation in Paraguay. Stormwater inflow and infiltration (I/I), which is a commonly observed phenomenon in Paraguay and surrounding countries, may negatively affect the treatment performance of the anaerobic pond. The identification and generation of realistic disturbances involves several steps.

Step 1: Identify the causes that are directly responsible for a decrease of performance of the anaerobic pond and motivate according to given literature

Changing organic/hydraulic loading

Strong fluctuations in organic and hydraulic loading generally will have a negative impact on the performance of the anaerobic treatment processes (van Lier *et al.* 2001) due to the slow rate of growth of the methane producing bacteria (McCarty 1964). Increased hydraulic inflow results in a smaller retention time for the anaerobic pond than initially foreseen during design. Hence, there is less time for treatment to take place. In addition, the settling process of suspended solids can be affected by the velocity of the inflowing water during heavy rain events as was observed during anaerobic pond research in Alsamra, Jordan. The high jet velocity of the incoming wastewater can create turbulent conditions not favourable for the settling process and can also agitate the accumulated sludge and cause scouring (Saqqar & Pescod 1995).

Presence of DO

One of the (obvious) environmental requirements for anaerobic treatment is that anaerobic conditions are maintained. Small quantities of oxygen can be quite detrimental to the methane-formers and other anaerobic organisms involved (McCarty 1964). In experimental research on the upstream anaerobic sludge blanket reactor (UASB) for municipal wastewater treatment the inhibition of methanogens due to oxygen was considered as a possible cause for decreased performance (Leitão 2004; Benetti & Peláez 2007).

Sudden changes in temperature

High temperatures are required for optimum operation of anaerobic WWTSs (McCarty 1964). The optimum temperature range for the development of methanogenic bacteria is reported to be between 35 and 40 °C (Manariotis *et al.* 2010). Temperature has a profound effect on the bacterial growth rate and the efficiency of the conversion processes (Manariotis *et al.* 2010).

Step 2: Judge the relevancy of the causes for the wastewater system under consideration and motivate according to available monitoring data

Changing organic/hydraulic loading

Although the sanitary sewer system of Coronel Oviedo was designed to only transport raw wastewater, the monitoring data revealed that large contributions of extraneous water enter the system. Figure 2 presents the hourly flow and rain during the period 13 May 2009 to 4 June 2009.

During days without influence of rain a large, constant base flow was present due to groundwater infiltration. During and directly after rain events an increased flow was observed at the outlet of the sanitary sewer system. At the start of the rain event the flow increased rapidly (<1 h) to a three-four-fold of the flow during dry weather. This high flow was maintained during several hours after the end of the rain event. For larger storm events (i.e., 24 May 2009 with 205 mm) this high flow lasted for several days. According to current design rules (Peña & Mara 2004), an anaerobic pond with a retention time of one day is sufficient for Coronel Oviedo. This would mean that in the case of a severe rain event such as the one that occurred on 24 May 2009 the retention time would significantly reduce during an extended period of time due to the long lasting period of increased inflow.

In Figure 3 hourly flow and rain are presented together with the organic loading (kg COD/h) for Rain-event 1. The dotted line represents the hourly organic loading during dry weather. The variation in organic loading during dry weather was calculated by multiplication of the hourly flow and the hourly COD concentration measured during a 24 h dry weather period (i.e., 22 February 2010). The average value of the COD concentration during the latter dry weather monitoring period was 230 mg/L while the maximum value was 360 mg/L. Notice that the wastewater is already quite diluted during dry weather due to excessive groundwater infiltration.

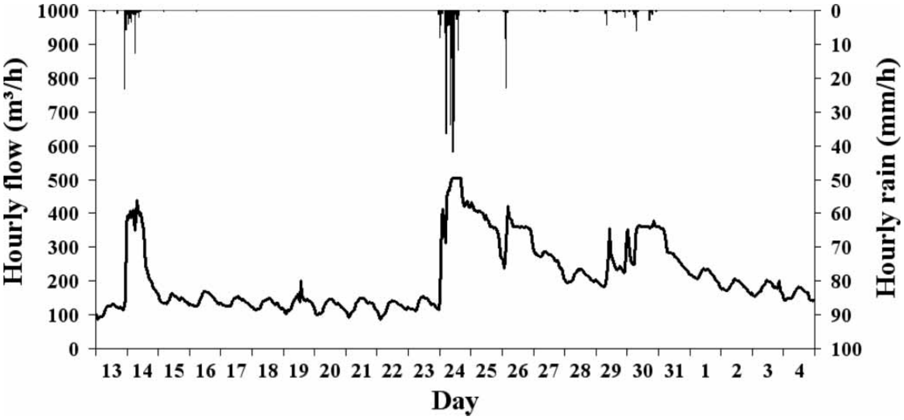

Figure 2 | Hourly flow and rain at the outlet of the sanitary sewer system of Coronel Oviedo for the period 13 May 2009 until 4 June 2009.

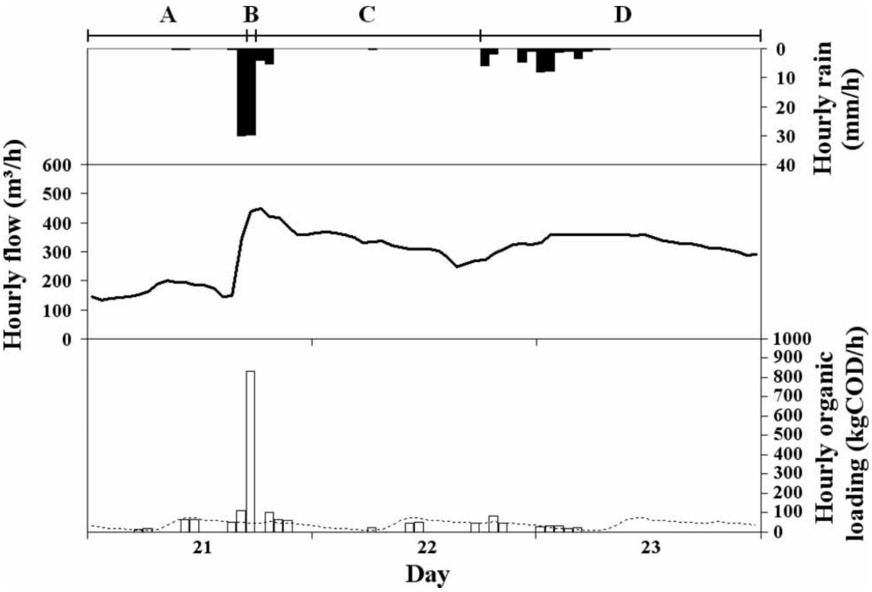

Figure 3 | Hourly flow, rain and organic loading at the outlet of the sanitary sewer system of Coronel Oviedo for Rain-event 1 (the dotted line represents the dry weather organic loading).

Before the start of the rain [Period A] the observed hourly organic loading coincides well with corresponding dry weather values with a mean absolute deviation of 23%. Approximately 1 h after the start of the rain event, a first-flush was observed with duration of approximately 1 h [Period B] and a COD concentration reaching up to 1,900 mg/L. This resulted in a high organic loading (i.e., 830 kg COD/h) during the second hour of the storm event which reached up to 17-fold of the dry weather value (i.e., 47 kg COD/h). This large first-flush event was a result of the long preceding dry weather period (1 month). Following the first rain event [Period C] a severe dilution of the wastewater was observed with the hourly COD concentration being lower than the dry weather value. The hourly organic loading remained, however, similar to the reference value with mean absolute deviation of 50%. Also during the second, low intensity rain event [Period D] dilution of the wastewater occurred but again the hourly organic loading remained similar to the dry weather value with mean absolute deviation of 31%. The monitoring data indicate that throughout a rain event the COD concentration and flow do change considerably as compared with dry weather. The organic loading, however, remains similar unless during a possible first-flush.

Presence of DO

During dry weather the DO concentration was very low and below detectable measurement levels. Sometimes during the morning hours (4–6 h) DO concentrations around 4 mg/L could be encountered. During and after rain, however, significant concentrations of DO were measured. Measurements of DO during Rain-event 1 are presented in Figure 4(a). No DO was present during the first hours of the rain, although the inflow of extraneous water was then highest. The hypothesis raised is that during the first-flush the content of organic matter is so high that DO is directly consumed by the (still) available aerobic bacteria. After the first-flush the DO started to increase then probably reached its peak (6.5 mg/L) a couple of hours later followed by a steady decline until the additional rainfall resulted in a quick increase of DO concentration with a peak of 7.3 mg/L.

The DO concentrations measured during Rain-event 2 are given in Figure 4(b) to demonstrate that the decline in DO concentration occurs gradually. Finally, measurements of DO concentration were also taken during the extreme event on 24 May 2009 (results not shown here). DO concentrations around 7 mg/L were maintained throughout the entire rain event (>10 h).

Sudden changes in temperature

The maximum change in wastewater temperature occurred during Rain-event 1 when a drop of 4 °C was observed. The temperature in the anaerobic pond itself is, however, not expected to be affected significantly.

Step 3: Identify the processes in the wastewater system that are the origin of the causes

The main phenomenon responsible for the large fluctuations in water quantity and quality at the inlet of the WWTS is I/I in the sanitary sewer system. I/I is directly responsible for: (i) variations in hydraulic/organic loading; and (ii) the entrance of oxygen rich water. Often a pure sanitary sewer system is designed and implemented but in practice stormwater and infiltration water also enter the sanitary sewer system.

Step 4: Characterise the dynamic behaviour of the processes

The main driving force for I/I in sanitary sewer systems is rainfall. The traditional methodologies for modelling I/I can be divided in two groups. Firstly, there are the classical hydrological methodologies like unit hydrographs and rainfall/flow regression (Vallabhaneni *et al.* 2007) which model the rainfall-runoff process in stormwater drainage systems. However, such methods do not take into account: (i) the severe backwater effects and surcharge present in the sewer system; and (ii) the overall conveyance capacity already being exceeded for smaller rain events. Both arise from the fact that the sanitary sewer system of Coronel Oviedo has been designed for conveyance of wastewater only. Therefore, the assumptions made by classical hydrological methods are not valid. One could try to overcome that with more physically-based methodologies. These methods require a large amount of detailed data and an accurate description of the entire sanitary sewer system (Lockie &

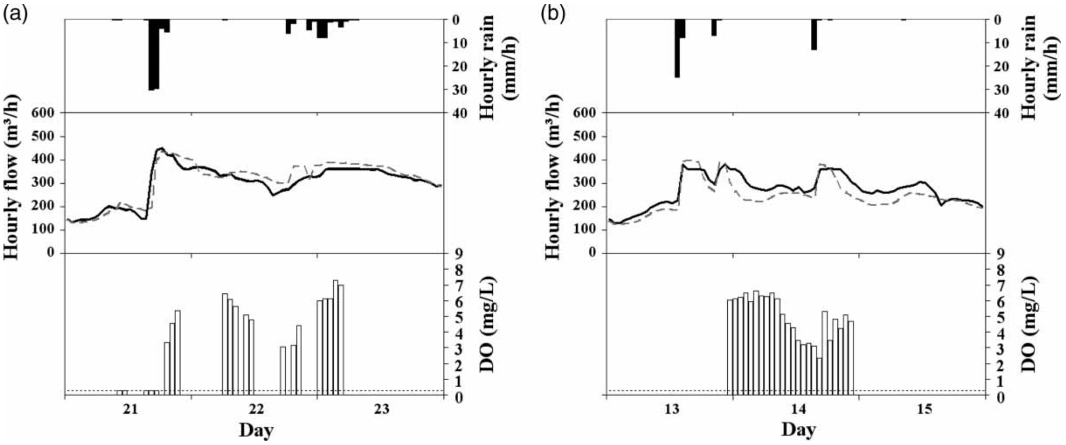

Figure 4 | Hourly flow, rain and DO concentration at the outlet of the sanitary sewer system of Coronel Oviedo during (a) Rain-event 1 and (b) Rain-event 2 (the dashed line represents the modelled flow; the dotted line represents the dry weather DO concentration).

Joseph 2008). For Coronel Oviedo this information is neither available, nor practical to collect without a high degree of uncertainty. One important reason is that the inflows of stormwater and infiltration water have not been planned and, therefore, are to a large extent illegal and not documented.

Alternative approaches are phenomenological models, which can be used for generating influent time series in case of limited or no monitoring data (Langergraber *et al.* 2008; Gernaey *et al.* 2011), and adaptive grey-box models (Carstensen *et al.* 1998). For the sanitary sewer system of Coronel Oviedo, however, a stepwise and diagnostic approach to model development was used in order to take into account the complex reality of excessive I/I. A conceptual sewer model was obtained that can simulate the outflow of the sanitary sewer system of Coronel Oviedo. The modelled flow during Rain-event 1 and Rain-event 2 is given as an example in Figure 4. The model performance was assessed by calculation of the Nash-Sutcliffe Efficiency (NSE) for both the calibration (7 months) and validation (12 months) periods, yielding values of respectively 0.89 and 0.74.

Step 5: Translate the available data into representative disturbances of the WWTS

For research purposes the approach is to perform long term simulations with an integrated model that consists of three model components: the sanitary sewer system (see Step 4), the WWTS and the reuse practice (irrigation). For practical applications, e.g., experimental evaluation of robustness/ rapidity of natural WWTSs, an option is to design realistic disturbances of the WWTS from simulation results of the sewer model for representative rain events.

DISCUSSION

To define realistic disturbances of a WWTS it is important to realise that disturbances are highly dynamic and, in addition, interdependent. During experimental studies to assess the impact of disturbances on WWTS performance the dynamic behaviour of the disturbances is often not taken into account. As for disturbances of anaerobic WWTSs Leitão (2004) and Benetti & Peláez (2007) both consider a pulse with constant intensity (e.g., three times the dry weather flow). Our monitoring data, however, clearly reveal that the intensity will vary throughout the event. In addition, the most critical situation – when several rain events follow each other in a short time – is not considered properly. In both studies the maximum duration of a disturbance is 6 h which can be considered relatively short in comparison with the observation data collected for this case-study.

With the exception of the occurrence of the first-flush, the total organic load remained relatively constant throughout the rain event. This is logical because the total amount of wastewater produced by an urban area is not expected to change drastically within terms of days or months. During rainy weather the flow and COD concentration will vary significantly but the total organic load will not change (except during a first-flush). This was taken into account during experimental research on anaerobic WWTSs (UASB) by Benetti & Peláez (2007) but not by Leitão (2004). In the latter research disturbances were always seen as organic shock-loads, obtained by imposing an increased hydraulic loading with the same COD concentration or the same hydraulic loading with higher COD concentration. Our monitoring data revealed that only during a possible first-flush will a significant increase in organic loading take place. The duration of the increased organic loading is, however, relatively short in comparison with the subsequent period of dilution (otherwise it would not be called first-flush!). In addition, a first-flush is not present for all sanitary sewer systems and is only expected to be significant after an extended dry weather period.

When defining disturbances of anaerobic WWTSs Leitão (2004) did not explicitly take the entrance of DO into account. This was motivated in an earlier stage by referring to the work of Kato *et al.* (1997) who during experimental research observed that methanogens demonstrated a high tolerance to DO. The hypothesis formulated by the authors was that facultative bacteria rapidly consume DO creating anaerobic micro-environments inside the granules where the methanogens are well protected against oxygen. To explain a decreased performance observed during experimental research on the UASB Leitão (2004), however, formulates the hypothesis that due to hydraulic shock-loads the amount of oxygen introduced to the system may have exceeded the capacity of the facultative bacteria. This finding is supported by Benetti & Peláez (2007). In addition, Kato *et al.* (1997) concluded that the temporary DO concentration of 3.8 mg/L has no detrimental effect on the anaerobic WWTS for low strength wastewater (Leitão 2004). However, during the rain events monitored in our study-area DO concentrations of 6–7 mg/L were measured. Toprak (1999) also measured high DO concentrations, i.e., up to 7.2 mg/L, at the outlet of a sanitary sewer system in Portugal. Hence, the value of 3.8 mg/L considered by Kato *et al*. (1997) during research on the impact of oxygen on anaerobic treatment processes is low in comparison with the high values of DO concentration occurring in our system.

CONCLUSION

The design and operation of natural WWTSs is normally based on the assumption of operation as steady-state systems. Based on experimental measurements we demonstrated that in practice a WWTS is a very dynamic system that is susceptible to a variety of disturbances. This statement is supported by earlier work of Beck (1996) on transient events in water resources systems. We, therefore, propose to introduce resilience as a performance indicator. At the design stage one must attempt to foresee the different types of unavoidable disturbances that may, during the lifecycle of a WWTS result in a decrease in treatment performance. An important step during the evaluation process of resilience is the correct definition of disturbances of the WWTS. By means of water quantity and quality data collected for an urban wastewater system the dynamic behaviour of disturbances of WWTSs was discussed. For an anaerobic WWTS at the outlet of the sanitary sewer system of Coronel Oviedo the most critical disturbances are the long lasting increased hydraulic loading, the massive entrance of DO and the short organic overloading during the first-flush if one should occur. These disturbances are a direct consequence of the process of I/I taking place in the sanitary sewer system during and after rain events. Researchers involved in wastewater treatment technologies neglect or simplify too much the processes in the sewer system. The dynamic nature of the disturbances and the consequences for disturbance definition are often not taken into account when evaluating the performance of WWTSs for municipal wastewater. For anaerobic WWTSs the focus is often set on organic overloading (Leitão 2004) which is, however, less relevant for municipal wastewater (though relevant for industrial wastewater). Instead, the priority should be on understanding the impact of the increased inflow of diluted wastewater with significant DO concentration on the performance of anaerobic WWTSs.

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