Optimising Wastewater Management During Wet Weather Using an Integrated Model

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ABSTRACT
In this article, the overall impact on the receiving waters of different emptying scenarios for combined sewer retention tanks (RT) was evaluated. To this end, a modelling study was conducted with an integrated sewer-treatment plant model. This model was inspired by a real case study, for which extensive measurement campaigns were conducted over the last 5 years. The modelled system consisted of three combined sewer catchments, each equipped with a RT. The modelled wastewater treatment plant (WWTP) consisted of a grit chamber and primary settling tank, the latter with possibility of chemical enhancement by alum addition. All unit process models described the dynamics of the suspended solids concentration using an approach based on particle settling velocity distributions. Nine wet weather scenarios were simulated by varying the RTs emptying procedure and the alum addition strategy. The results showed a significant reduction in mass of suspended solids discharged into the receiving water, unfortunately at the expense of an increase in RT emptying times that were deemed acceptable though. Alum dosing allowed improving of primary treatment efficiency, leading not only to a further decrease in suspended solids discharge, but also permitting more water to be sent to the biofilter-based secondary stage of the WWTP.

KEYWORDS
CEPT, integrated urban wastewater model, real-time control, wet weather management

INTRODUCTION
Combined sewers overflows (CSOs) are a major cause of receiving water quality degradation. To reduce their occurrence, construction of combined sewer retention tanks (RTs) can be used to store storm water which exceeds the sewer network capacity. These infrastructures are quite expensive though and they are rarely managed to their full potential. Indeed, RT emptying is usually controlled by water quantity-based rules: as a precaution, rules are set so the storage capacity is recovered as soon as possible to face an eventual subsequent rain event. RTs are thus emptied by applying a maximum flow to the WWTP. However, when no rain is forecast, a more gradual emptying could be considered to reduce the wet weather impact on the WWTP and, hence, also on the receiving water quality.

This study aims to show the interest of setting the flow during RT emptying considering the weather forecast. The interactions between the sewer system and the wastewater treatment plant (WWTP) can be relatively complex. An integrated model can thus assist the real-time management of an urban wastewater collection and treatment system. This paper focuses on the impact of emptying strategies of retention tank (RT) on the overall system performance.

Context

The case study describes a virtual catchment inspired by Québec City's infrastructures (Québec, Canada). In the late 90s, the city decided to equip its collection system with twelve RTs for a total storage volume of more than 100,000 m³. These RTs were successfully incorporated into the sewer network management system which is equipped with a real-time control (RTC) system to protect the receiving water by reducing CSOs (Fradet *et al.*, 2011). Previously, about fifty CSOs were observed per summer season (from May 15th to September 15th). Since the RT became operational, the number of CSOs was found to almost comply with the regulations. This significant reduction of CSOs in itself is a great achievement.

However, in view of efficiently protecting the environment, not only the number of CSOs is important; the total loads of pollutants discharged should also be considered. This paper suggests estimating the pollutant load by means of an integrated model. The proposed integrated model can predict water quality in terms of total suspended solids (TSS) both in the combined sewers and the WWTP. Further reduction of CSO impacts on the receiving water is evaluated by optimising the management of the emptying of the RTs.

MODELS DESCRIPTION

Integrated model

The integrated model was developed using the modelling and simulation platform WEST® (mikebydhi.com). It includes three catchment areas, each of them equipped with an offline RT. These three catchments are connected to a main interceptor leading to a WWTP. The plant is modelled by a grit chamber, a primary clarifier and three bypasses (Figure 1). The secondary treatment step, using biofiltration, is not modelled at this stage of the study. In each unit process, sedimentation is modelled using a particles settling velocity distribution (PSVD) approach with five particle classes. The integrated model has been calibrated so that the simulated results in terms of TSS concentration and PSVD fit with experimental results collected on the field (Bachis *et al.*, 2014; Maruéjouls *et al.*, 2013b).

Catchment and combined sewers

The catchment model was inspired by a section of Québec City's sewer network (Saint-Sacrement) for which Maruéjouls *et al.* (2013a) conducted a detailed experimental study of the sewer characteristics. The two other catchments of the model are just duplicates of the Saint-Sacrement catchment. Each catchment area is equipped with a RT which describes settling and resuspension of pollutants (Maruéjouls *et al.*, 2012). The 3 km long combined sewer is modelled by a series of ten linear reservoirs, calibrated using the Kalinin-Milujkov method (Solvi, 2006). No pollutant transformations were considered in the sewer system.

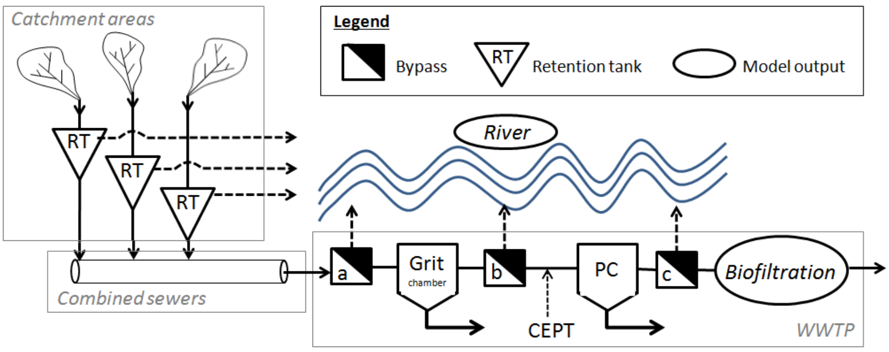

Figure 1. Configuration of the integrated system including three catchment areas with their retention tank (RT), a wastewater treatment plant (WWTP – grit chamber, primary clarifier (PC), biofiltration and three possible bypasses named a, b and c) and the receiving water. CEPT stands for Chemically Enhanced Primary Treatment.

Wastewater treatment plant

The WWTP model consists of a grit chamber, a primary clarifier with possibility of chemical enhancement by alum addition and a secondary treatment by biofiltration (not modelled at this stage). All modelled processes are described using the PSVD approach. The integrated modelled presented in this paper is adapted from Maruéjouls *et al.* (2013b). Five particles classes enabled to adequately predict the TSS fluxes throughout the system.

Grit chamber and primary clarifier. Both separation processes are modelled by discretizing the water column in ten homogeneous layers. The process units were re-scaled to take into account the reduced size of the sewer network compared to the real scale system that was studied extensively (Tik *et al.*, 2013).

Chemically enhanced primary treatment (CEPT). To model the CEPT process, the PSVD at the inlet of the primary clarifier is modified whenever alum is added. Indeed, experimental data show that the PSVD is generally lower, meaning a bigger mass fraction for the particles classes with high settling velocity, when chemicals are added (Bachis *et al.*, 2014). For this study a constant dosage of chemicals during the whole simulated period is considered.

Biofiltration. Québec City's WWTP performs secondary treatment by biofiltration. It should be noted that a major difficulty of biofilters management is the occurrence of clogging due to increased incoming TSS loads. The biofiltration process and its clogging rate is not modelled at this stage of the study, but since TSS loads at the outlet of the primary clarifier can be simulated realistically using the previously described models, the probability of clogging and the necessity of discharging untreated water before the biofiltration can be estimated.

INPUTS

Data used for the model input files were collected by sampling at the Saint-Sacrement RT during the summer of 2009. The model input was constructed by pulling together a series of typical dry weather days on top of which a rain event is supplemented. To ensure data consistency, the TSS concentrations during the diluted phase of the rain event were adjusted to make sure that the dry weather influent load is respected.

Dry weather data

In dry weather conditions, flow rates and pollutant concentrations in the sewer mainly follow diurnal dynamics. Punctual samplings were carried out at different time of the day and night and different day of the week. These data were pulled together to create a typical dry weather day data in terms of flow rate and TSS concentration (cf. Figure 4, second day reproduced).

Wet weather data

To characterise the rain events, automatic samplers associated with flow measurements were installed at the inlet and outlet of the RT. The selected rain event, typical for Québec's climate, was short (about 1h) and intense, producing a noticeable first flush. It was nicely captured by the RT (Figure 2). The RT was filled at about half its capacity and the emptying was started shortly after the rain stopped. During emptying, a typical "U" form is observed for the evolution of the effluent TSS concentration (Maruéjouls *et al.*, 2013a). Comparison between measured (dot) and simulated (solid line) TSS concentration on the right of Figure 2 indicates that the underlying resuspension phenomena are well represented by the model (Maruéjouls *et al.*, 2013b). A characteristic increase in flow rate can be noticed at the end of emptying (Figure 2); it is designed to wash off the remaining particles in the RT.

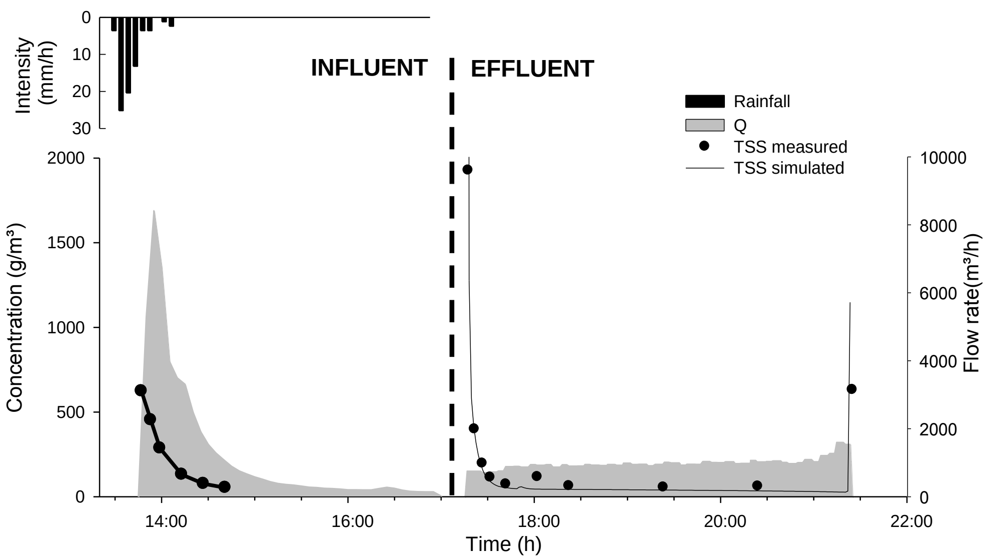

Figure 2. Flow and TSS concentration dynamics at the Saint-Sacrement catchment for the July 27th 2009 rain event. Left: rainfall intensity (on top) and RT influent characteristics (filling phase). Right: RT effluent characteristics (emptying phase). The solid line during the emptying phase represents the model simulation.

Particles settling velocity distribution (PSVD)

The PSVDs, determined by using the ViCAs protocol (Chebbo and Gromaire, 2009), were measured at different locations in the system. Based on a large number of experiments, a region of PSVDs typical for each location in the system could be determined. The zone itself reflects the time-variation of PSVD. Figure 3 represents the typical PSVD zone observed in the sewer (in grey). It was found that a linear relation exists between the TSS concentration of a sample and the position of its PSVD in the zone (Bachis *et al.*, [in preparation]). Indeed, the higher the TSS concentration, the lower its associated PSVD will be in the zone (i.e. a larger fraction of particles has a high settling velocity). With this TSS-based relation the influent PSVD-based TSS fractionation in five particles classes changes with time, depending on the actual TSS concentration. An example of the fractionation is shown in Figure 3.

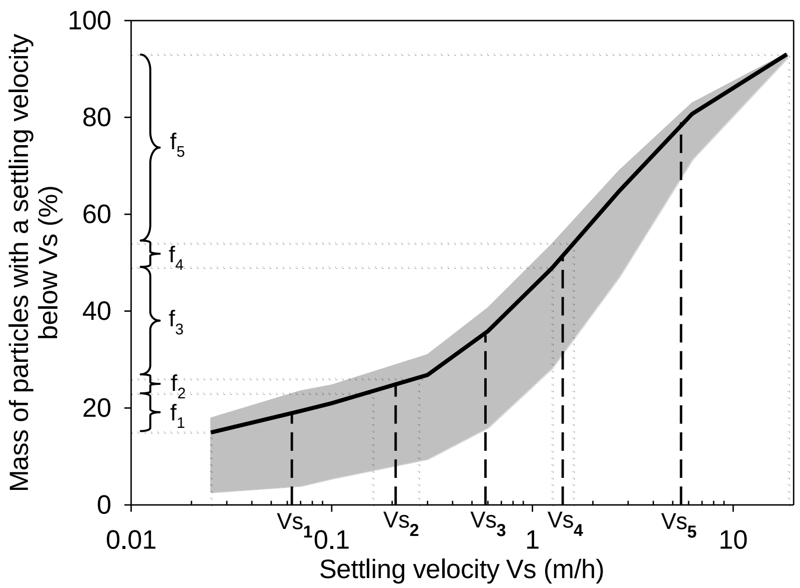

Figure 3. Typical PSVD zone (grey) observed in the sewer. An example of TSS fractionation in five particle classes is presented. Each particle class, characterized by a mean settling velocity (Vs_1 to Vs_5) is associated with its TSS mass fraction (f_1 to f_5) given by the curly brackets.

SCENARIOS SELECTION

To optimize the system's management rules, different scenarios, inspired by the case study, were tested. For each scenario, a sequence of dry, wet and dry weather day was simulated and its performance evaluated for a 24h-period, including the effect of the rain event (Figure 4).

Baseline scenario

For the baseline scenario, the three RT are simultaneously emptied according the flow rate data collected at Saint-Sacrement for the actual event (scenario 0, 1 and 2 in Table 2). This corresponds to the quickest recovery of the RT's storage capacity. This flow rate generates CSOs upstream of the WWTP, hence representing the worst case scenario. Given Québec City's specific situation, this is an acceptable scenario. Indeed, CSOs impact the Saint-Charles River, a relatively small and sensitive urban river, whereas the discharges of untreated water at the level of the WWTP overflow directly to the Saint-Lawrence River, with a huge dilution capacity. Thus, when the weather forecast is uncertain, RT emptying is performed as quickly as possible to avoid potential CSOs that may be very harmful to the Saint-Charles River, even if this means that untreated water will be discharged into the Saint-Lawrence River.

Alternative scenarios for retention tanks emptying

Under the hypothesis that no other rain event is forecast over a sufficiently long horizon, the emptying rate of the RT is reduced to avoid bypassing untreated water upstream of:

(1) the **grit chamber** (scenario 3, 4 and 5 in Table 1)
(2) the **primary clarifier** (scenarios 6, 7 and 9 in Table 1)

Furthermore, the other previously explained emptying characteristics, especially the flow peak observed at the end of the emptying process (cf. Figure 2, on the right) are maintained. In order to spread their effect on the WWTP over time the emptying of the three RTs is initiated at different times, with a delay between them. Figure 5 shows the flow and TSS concentrations at the inlet of the WWTP for the three tested emptying strategies.

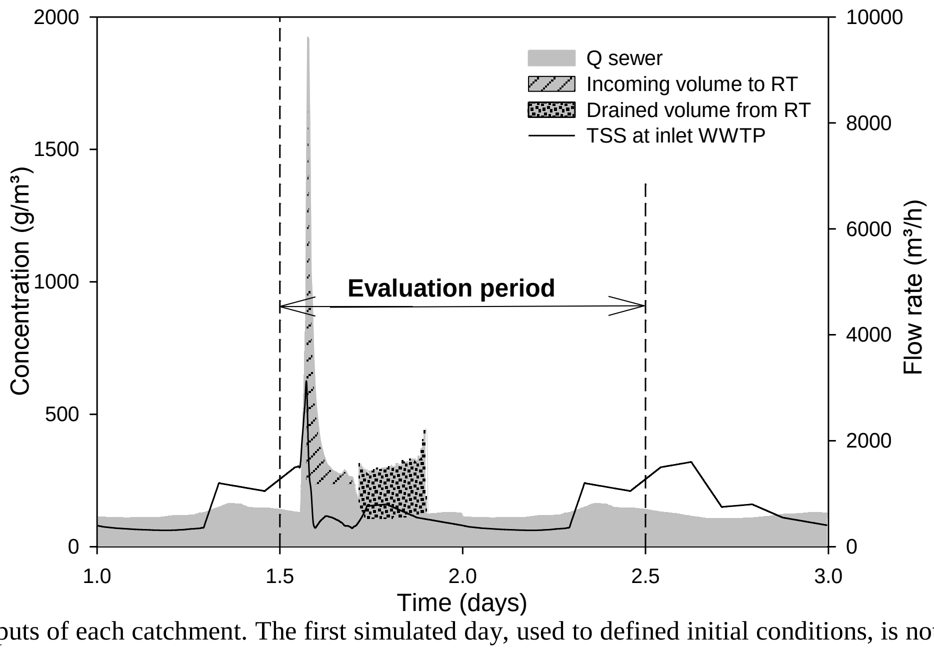

Figure 4. Inputs of each catchment. The first simulated day, used to defined initial conditions, is not reproduced here. The grey area represents the flow (Q) generated by the catchment, the hatched zone indicates the volume of water stored in the RT and the spotted zone represents the volume emptied from the RT. The evolution of the TSS concentration from the catchment is given by the solid line.

Table 1. Description of the scenarios evaluated by simulation.

Scenario number	*CEPT*	*Maximum flow to biofiltration*	*RT emptying characteristics*
0	no	60 000 m³/d	The three retention tanks are simultaneously emptied at a flow rate given by the flow rates measured during the actual event.
1	yes	60 000 m³/d	
2	yes	70 000 m³/d	
3	no	60 000 m³/d	Emptying flow rates are limited and delayed one from another so that no overflow occurs at the inlet of the **grit chambers**.
4	yes	60 000 m³/d	
5	yes	70 000 m³/d	
6	no	60 000 m³/d	Emptying flow rates are limited and delayed one from another so that no overflow occurs at the inlet of the **primary clarifiers**.
7	yes	60 000 m³/d	
8	yes	70 000 m³/d	

Chemical enhancement of primary clarification

In this study, the simple case of a constant alum addition is considered (scenario 1, 2, 4, 5, 7 and 8 in Table 1). The effect of CEPT is modelled using an adapted PSVD presenting a higher fraction of particles with high settling velocity in case of alum addition, reproducing an increase in removal performance of the primary clarifier (Tik and Vanrolleghem, 2012).

Secondary treatment capacity

During wet weather conditions, higher TSS concentrations are observed at the outlet of the primary clarifier due to the higher hydraulic loading. This increased TSS loading is a major concern for biofilter clogging. A higher frequency of biofilter backwashing is then needed, reducing the biofiltration process hydraulic capacity. With CEPT, the primary clarifier effluent TSS load is reduced, allowing an increase in the allowed flow on the biofilters. Based on experimental observations of biofilter clogging, the maximum flow rate to biofiltration is set to 60,000 m³/d, increased to 70,000 m³/d for scenarios 2, 5 and 8 (Table 1).

RESULTS AND DISCUSSION

Overall impact on the receiving water

Table 2 summarizes the impact of each scenario on the receiving water: the volume and TSS load discharged to the receiving water at the three bypasses a, b and c (Figure 1), calculated for a 24h-period that includes the impact of the rain event on the WWTP (Figure 4).

The successive reductions in RT emptying flow rates in order not to discharge upstream of the grit chamber (scenario 3 in Table 2) and upstream of the primary clarifier (scenario 6 in Table 2) results in a reduction of, respectively, 26% and 43% of the TSS load discharged to the receiving waters compared to the baseline scenario, named 0 in Table 2.

Table 2. Volumes of water and flux of TSS discharged to the receiving waters at bypasses a, b and c (cf. Figure 1) for each of the 9 scenarios.

	Bypass	*Scenario number*								
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Discharged water volume (m³)	a	2430	2430	2430	0	0	0	0	0	0
	b	2039	2039	2039	1943	1943	1943	0	0	0
	c	8040	8040	4393	8997	8997	4777	9690	9690	5187
	Total	12509	12509	8862	10940	10940	6720	9690	9690	5187
TSS load discharged (kg)	a	267	267	267	0	0	0	0	0	0
	b	223	223	223	195	195	195	0	0	0
	c	514	166	84	551	176	87	572	182	92
	Total	1004	656	574	746	371	282	572	182	92

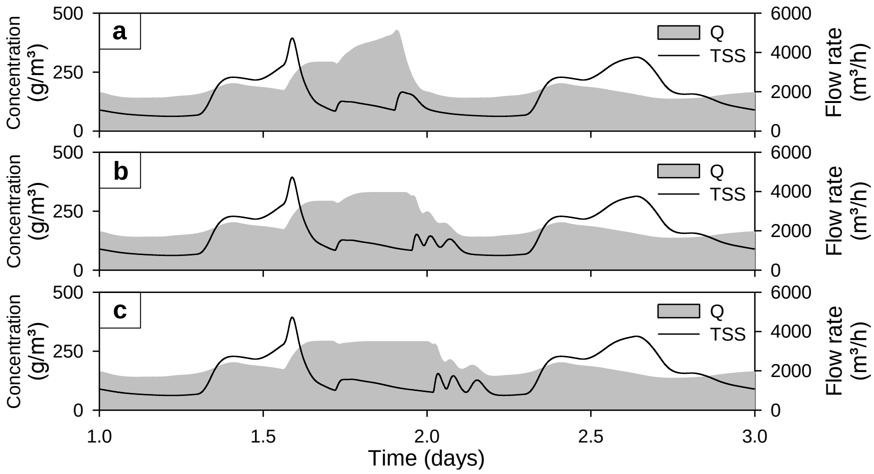

Figure 5. Flow rate and TSS concentration at the inlet of the WWTP : (a) for scenarios 0, 1 and 2; (b) for scenarios 3, 4 and 5; (c) for scenarios 6, 7 and 8.

Emptying time

When applying the RT emptying flow rate measured during the sampling campaign, i.e. the baseline scenario, the emptying time is 4h20 (scenarios 0, 1 and 2 in Table 2). In order not to discharge upstream of the grit chamber and the primary clarifier, respectively, the emptying time had to be increased by 65% in the former case (scenarios 3, 4 and 5), representing 7h10 and by 110% for the latter case (scenarios 6, 7 and 8), representing a 9h10 emptying before all three RTs have recovered their storage capacity. The increased RT unavailability is acceptable for this case study, considering the reliability of weather forecasts with a 12-24h horizon. Figure 5 shows the extended impact of the RT emptying on the WWTP due to increased emptying time (b and c), compared to baseline scenario (a).

Chemical enhancement of primary clarification

When the weather forecast prohibits an extended emptying period, CEPT can be considered to increase the volume of water to be treated. Scenario comparison (0 with 1, 3 with 4 and 6 with 7) shows a reduction of the TSS discharge at location c, even though the discharged volume remains the same. This reveals the increased primary clarification process efficiency. Furthermore, the larger TSS load reduction is mainly apparent for the particle classes with the higher settling velocity that can basically be associated to 'bigger' particles, which tend to cause biofilter clogging. Since these particles are more efficiently removed with CEPT, the biofiltration process can be expected to become more efficient. This hypothesis is translated into the increased maximum allowable flow rate to the biofilters (scenarios 2, 5 and 8 in Table 2). An environmental benefit is produced, i.e. a reduction from 11% to 51% of the TSS load discharged to the receiving water compared to baseline scenario.

Outlook

Scenarios including controlled RT emptying allow reducing the total discharge to the receiving water. However, the uncertainty on weather forecasts needs to be taken into account while implementing such RT emptying strategies. Further work will consist in simulating not one event, but a series of rain events. This will allow comparing the impact of CSOs at the retention tanks due to a lack of sufficient storage capacity (caused by a too slow emptying of the RT), with the impact of discharges at the inlet of the WWTP when quickly recovering RT storage capacity.

CEPT, which already shows its potential at constant dosage, could be integrated into the overall management rules. The use of a controller can also optimise the process in terms of benefit/cost of alum addition (Tik *et al.*, 2013).

CONCLUSIONS

This modelling study was performed on a virtual, though realistic, case study. It shows the interest of taking into account weather forecasts for the simultaneous optimization of the RT emptying rate and the maximization of wastewater volumes receiving full treatment. For the selected case study, the results show an acceptable increase of the unavailability of full RT storage capacity, while the environmental benefit is substantial, i.e. a considerable reduction of pollutant loads discharged to the receiving water.

At the WWTP, the availability of CEPT adds flexibility to the management of the system. The possibility of increasing the flow rate to be accepted by the primary clarifiers, while maintaining acceptable performance, may be considered.

Finally, this paper has presented an integrated sewer-WWTP model, able to predict water quality, that allows:

- evaluating the overall impact of the wastewater system on the receiving water.
- testing control scenarios that take into account the interactions between the sewers and the WWTP, in the goal to develop better management practices.

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