Dynamics of rain-induced pollutographs of solubles in sewers

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Abstract:
When looking at acute receiving water impacts due to combined sewer overflows the characteristics of the background diurnal sewage flux variation may influence the peak loads from combined sewer overflows (CSO) and wastewater treatment plant (WWTP) effluent significantly. In this paper, effects on the dynamic compounds transport in the sewer, on CSO discharge and WWTP loading are evaluated by means of hydrodynamic simulations. The simulations are based on different scenarios for diurnal dry-weather flow variations induced by different infiltration rates.

Keywords:
Compounds transport, diurnal variation, hydrodynamics, extraneous water, infiltration rate, pollution mass flux,

INTRODUCTION

Peak loads in sewer pipes caused by rain runoff may be detrimental for various compartments of the urban wastewater system. Rivers may be endangered by a release of undiluted wastewater in case of a CSO discharge. The control of a WWTP must be adjusted to the sudden hydraulic changes and the sewer system may be hydraulically overloaded as well. Peak loads are magnified by sediments erosion and for solubles by the process of wave propagation (see Krebs et al., 1999a). Huismann et al. (2000) experimentally proved a separation of a pulse induced wave and the flowing water body in a transport sewer. Transferred to the processes of a rain event, this wave develops in front of the main (diluted) water body exhibiting almost dry-weather concentrations.

In this study the impact of rain events on peak loads and discharges in a real sewer catchment was investigated. In the simulations artificial pulses are created representing the discharge into the sewer caused by rain events and surface-runoff. Impacts of the infiltration rate on pollution fluxes during rain events have not been investigated yet and were assumed negligible. So, we observed those impacts considering different diurnal variations due to an altered infiltration rate into the sewer. At last, the influence of the time of day when the rain event occurs was investigated.

CATCHMENT AND MEASUREMENTS

The investigated catchment is situated in North Rhine-Westphalia in Germany. The catchment and the conducted measurements are characterised as follows:

- No industrial waste water is discharged to the sewerage.
- Extensive data, such as number of inhabitants and catchment area, and sewer data (slope, length, dimension, and profile) were available.
- The sewers are in a bad condition and thus heavily influenced by infiltrating groundwater.

For the simulation three sub-catchments with relatively homogeneous characteristics were identified (see Figure 1).

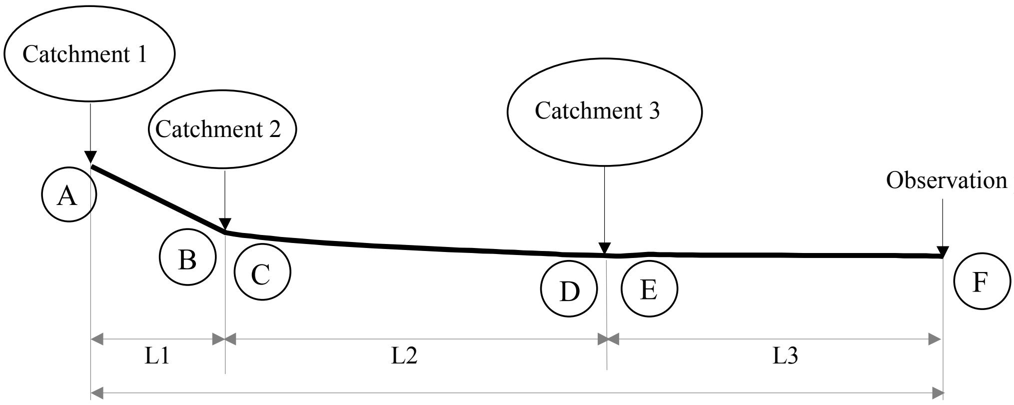

Figure 1: Schematic figure of the investigation site

The simulation distance refers to the length of the main sewer and is split into three sections according to slope and dimension (Figure 1). The sub-catchments are connected to the main sewer at the upstream manhole of each section (points A, B, and D). In Table 1 the system characteristics are summarized.

Table 1: System characteristics

		L 1	L 2	L 3
Length	m	130	510	460
Diameter	mm	600	1000	1400
Slope	-	0.016	0.003	0.003
Area	ha	16.1	11.8	25.7
Impervious area	ha	7.48	2.57	9.96

The measurement campaign was conducted over a period of 2 weeks, recording flow rate with an ultrasonic-doppler probe and COD- and TSS-concentrations with a UV-VIS spectrometer measuring light absorption spectra, which was carefully calibrated on-site. The data for this study were collected in February 2004 after a long rainy period with approximately 140 mm of rainfall.

Figure 2 illustrates the recorded hydrographs and pollutographs and the estimated infiltration rate. The infiltration rate was estimated by a combined analysis of time series of COD concentrations and flow rate, developed by Kracht and Gujer (2004).

A strong exponential decrease of the infiltration rate is visible, induced by the preceding rain event. The decrease of the infiltration rate causes a slight increase in the amplitude of the pollution concentration, further signifying the decrease of the infiltration rate.

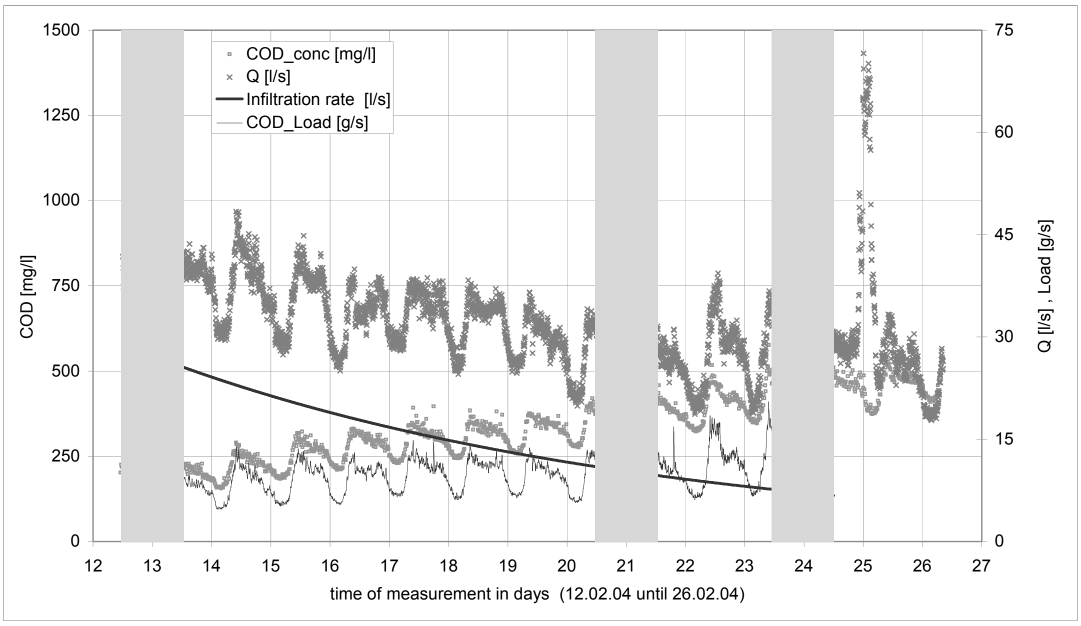

Figure 2: Recorded time series of flow and COD concentration, estimation of infiltration rate with the method of Kracht and Gujer (2004), grey-coloured days are subject of the investigation

SIMULATION APPROACH

Hydrodynamic background

Dynamic flow conditions in the sewer are modelled with the Saint Venant equations (French, 1985). The characteristic velocities $\lambda_{1,2}$ ($m \cdot s^{-1}$) are eigenvalues of the Saint Venant equations:

$$\lambda_{1,2} = \frac{Q}{A} \pm \sqrt{\frac{g \cdot A}{b}} = \bar{u} \pm c \qquad \text{Equation 1}$$

where Q = flow rate, A = flow cross section area, g = gravity acceleration, b = width of water surface, $\bar{u}$ = average flow velocity, c = wave celerity relative to the water body. The eigenvalues λ are the wave velocities relative to a fixed observer (Krebs et al., 1999a, Huismann et al., 2000). One of the solutions of Equation 1 indicates that the wave travels faster than the main water body (see also Figure 3).

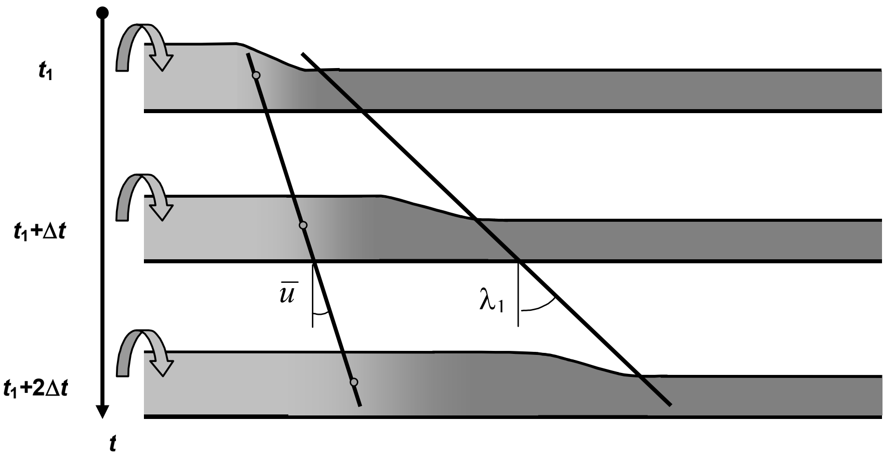

Figure 3: Wave propagation with velocity λ_1 is faster than flow velocity $\bar{u}$

The computations were carried out with the software AQUASIM (Reichert, 1994), using the diffusive-wave approximation, which allows simulating backwater effects and offers a relatively stable solution procedure. The recorded time series were used to calibrate the hydrodynamic model. With the simulations we focused on the wave propagation and its effects on pollution load and discharge caused by a rain event, where the introduced input pulse, infiltration rate, and time of day the pulses enter the system were varied to investigate the sensitivity of peak loads. The investigation is focused on dissolved compounds in the sewer, in particular COD. The rain pulses are assumed not to contribute any compounds. As the investigated sewers were free of sediments a remobilisation of sediments by an increase of the flow is not considered.

Definition of input pulses

Three input-pulses are defined to cover characteristic rain event durations relative to the travel time in the sewer:

- Pulse 1: 15 min (shorter than the mean travel time at dry weather conditions)
- Pulse 2: 30 min (as long as the mean travel time at dry weather conditions)
- Pulse 3: 60 min (longer than the mean travel time at dry weather conditions)

The pulses have a trapezoidal shape and represent the resulting surface-runoff caused by a rain event from the respective impervious area. The pulses were chosen such that the flow rate at the end of the catchment was 10 times higher compared to the dry weather flow. The duration of the flow increase from dry-weather to the maximum flow rate was set to 10 min for all pulses. The input of each sub-catchment is proportional to the respective impervious area. A homogeneous distribution over the catchment and a simultaneous discharge into the sewerage is supposed.

Infiltration rate

From the recorded time series 3 days with a high, medium, and low infiltration rate were selected (grey-coloured in Figure 2). The flow measurements were used to calibrate the hydrodynamic model. In Table 2 the selected days are characterised by mean values.

Table 2: Characterisation of diurnal sewage flow for the investigated days

Hydrograph		12./13.02.04	20./21.02.04	23./24.02.04
Mean COD conc.	mg/l	184	361	436
Mean flow rate *Q*	l/s	38	27	26
Relative infiltration rate Q_{inf}/Q_{sewage}	%	72	38	27.6
Characteristics	-	High infiltration rate	Medium infiltration rate	Low infiltration rate
	-	Day after a storm event	Fading out interflow	Dry weather day

Time of day of the rain event

To explore the influence of the time of day the rain event takes place the pulses are inserted under the conditions of the day maximum and the night minimum of flow and COD load. In the results discussion the wave propagation phenomenon is examined by looking at the sequence of peak load and peak flow, the development of the COD load over time and the produced peak loads are analysed.

DISCUSSION

Wave propagation

The wave propagation induced by a 15 min pulse added at the day maximum on a day with medium infiltration rate is illustrated in Figure 4. The illustrated curves are COD concentration, COD load and flow rate. All values are normalised with the dry-weather values at the respective points just before the events start.

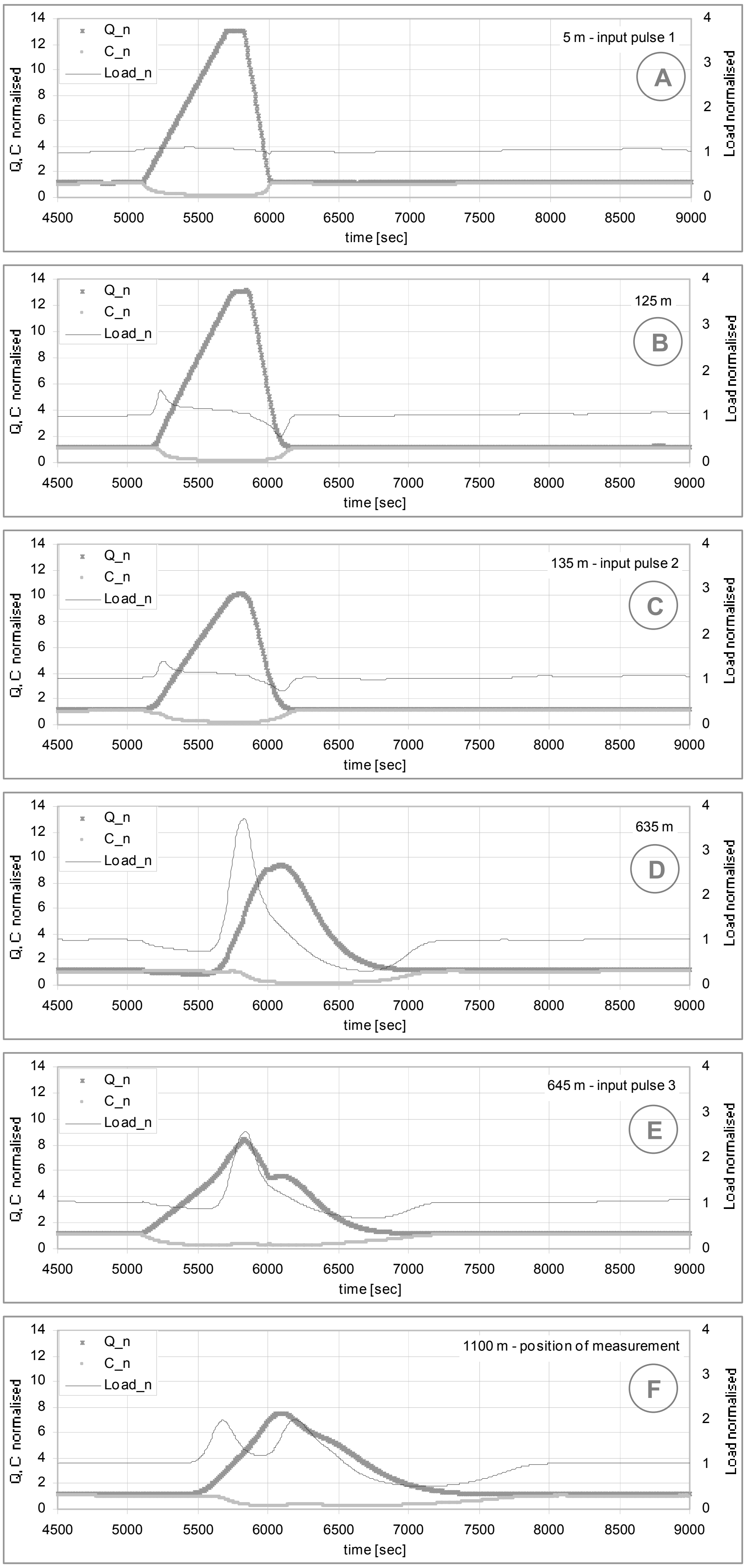

Figure 4: Wave propagation, 15 min pulse, day maximum, medium infiltration

At the input of the simulation distance (Figure 4.A) the first pulse with 36 % of the total pulse volume is discharged into the sewer. Consequently, the flow rate increases sharply and the pollution concentration decreases. After 125 m (Figure 4.B) the wave front that consists of dry-weather wastewater is slightly ahead of the dilution and thus a small load increase is developed at 5230 s. The input of the second pulse (Figure 4.C) with 11 % of the total pulse volume causes a further increase of the flow rate, while also the pollution load rises due to the input of sewage at point C. The considerable higher volume of pulse 1 and the short travel time between A and C lead to a superposition of pulse 1 and 2. The wave front with the dry-weather concentration of the preceding period is accelerated by the higher flow depth of the superposed pulses 1 and 2 (Figure 4.D) and therefore the peak load induced by the evoking wave is further increased up to the 3.6 fold of the dry-weather load.

In E, after the input of pulse 3 with 53 % of the total pulse volume all flows are superposed. The peak load of the 2.6 fold at the dry-weather load caused by the superposed pulses 1 and 2 incidentally passes point E at the same time as the flow rate maximum induced by the input of pulse 3, while the small load wave induced by pulse 3 is not yet visible in E. In F (system outlet) the wave has been smoothened due to dispersion, decreasing from 8.5 in E to 7.5 times the dry-weather flow in F. The first load peak arriving at 5700 s in F originates from pulse 3. The load of the superposed pulses 1 and 2 at 6200 s has already been diluted by pulse 3. The fact that the peak load induced by pulse 3 is smaller than that induced by pulses 1 and 2 at point E is attributed to the short travel distance between E and F. Therefore, the volume of dry-weather wastewater in the sewer line between E and F, which is "waved" by pulse 3 is smaller than the volume of dry-weather wastewater, which is accelerated by the superposed pulses 1 and 2 upstream of E. Overall, this analysis shows that the relative peak load resulting from the wave effect is reduced due to the presence of several inputs into the main sewer.

Analysis of pollution load development

In Figure 5, the pollution mass fluxes from the beginning of the rain input pulses are illustrated for the three pulse durations. The load induced by the wave effect on top of the dry-weather load is shown cumulative and normalised with the total additional load. The same was done with the flow rate on the horizontal axes.

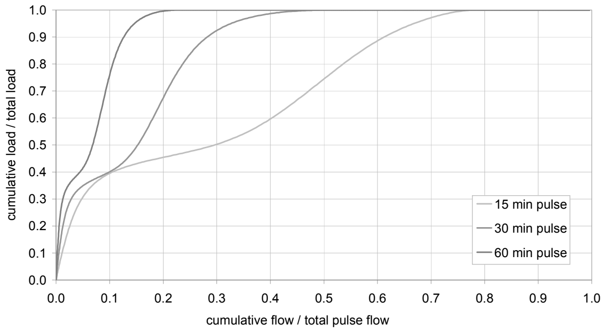

Figure 5: Accumulation of mass fluxes and flow rates

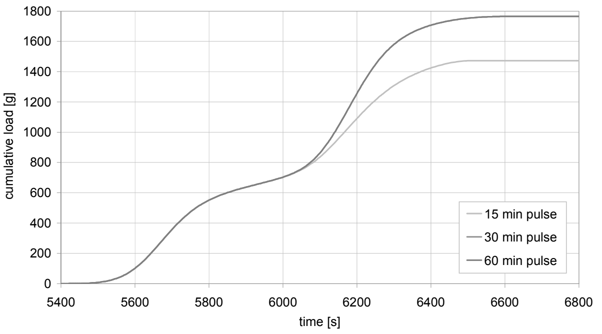

Figure 6: Accumulation of absolute mass fluxes

The first waves result from pulse 3, the second waves from the superposed pulses 1 and 2. The longer the pulse the more distinct is the inclination to the load maximum in Figure 5. The major load occurs at the beginning of the event with the passage of the waves. For a 60 min pulse almost 100% of the additional load have left the system after only 20 % of the additional flow volume have done so, as the following major additional water volume is of low concentration and does not contribute to additional load. For the effects in WWTPs and the receiving water after CSO discharges the cumulative curves shown in Figure 5 are not relevant, it is the absolute extent of the loads that counts. In Figure 6 the cumulative development of the three scenarios loads are shown in absolute terms. It turns out that the loads developments induced by all three pulses are initially identical. In the second phase the 15 min pulse that is shorter than the travel time causes less excessive load than the two other scenarios of a pulse duration equal or longer than the travel time in the system. Therefore, with regard to shock loads, the initial phase of the hydrograph is decisive rather than the events duration.

Analysis of peak loads

The absolute values of flow rate and loads over the events duration shown in Figure 7 show the impact of the infiltration rate on the pollution load.

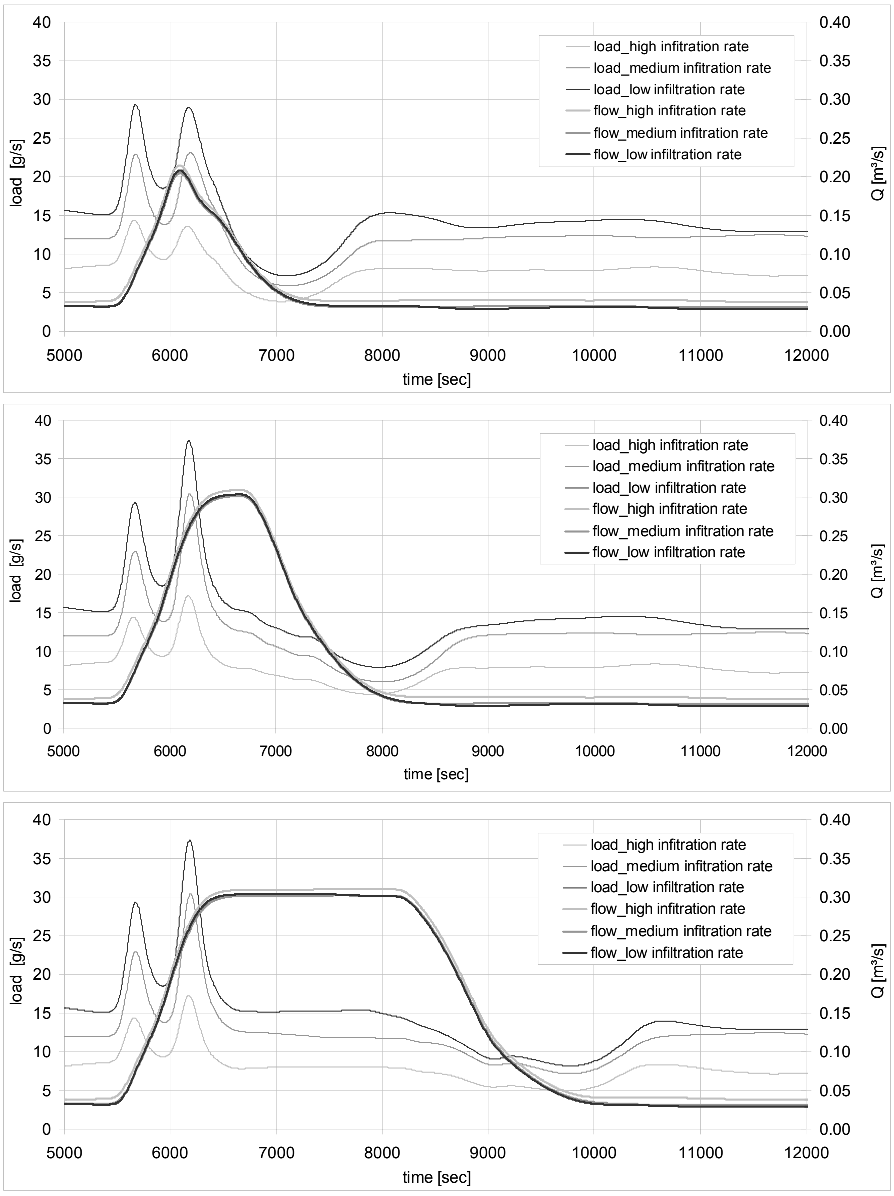

Figure 7: Loads induced by 15 min, 30 min, and 60 min pulses comparing the effect of different infiltration rates

According to the wave propagation theory the peak loads of solubles increase with increasing additional flow rate and concentration of the dry-weather wastewater. Consequently, the peak loads at low infiltration rates are higher. In our case study the low-infiltration case (see Table 2) exhibits peak loads up to 50% higher than those at high infiltration rates. The peak load caused by pulses longer than the travel time in the system is higher than that caused by a short pulse (see also Figure 6), since the push-out effect is stopped before the entire pollutograph has passed the system outlet.

CONCLUSION

In this paper the importance of wave transport phenomena for load development was demonstrated. At the beginning of a storm event the load of solubles originating from the sewage rises with flow rate increase, and decreases after dilution takes place. Both the WWTP performance and acute effects in receiving waters caused by CSO discharge during and after wet-weather conditions are influenced by these transport phenomena (Krebs et al., 1999b). The resulting peak load depends on whether the duration of stormwater input into the system is shorter or longer than the travel time within the system. The pollutographs of excessive solubles load are identical if rain water input duration equals or exceeds travel time within the system. This does not apply for particulates: here, transport dynamics correspond directly to the flow rate, i.e. pollutographs are similar to hydrographs if sufficient sewer sediments are present (Krebs et al., 1999b, Ashley et al., 2002).

The major excessive load occurs throughout the first phase of the event. Thus, the acute pollution impact on the receiving water, caused by CSO discharge during moderate intensity rain events can be reduced by first-flush tanks (see also Holzer and Krebs, 1998). Decentralised retention and stormwater infiltration in the catchment is also effective in reducing the wave effect since a decrease of the input pulse reduces the resulting peak load almost proportionally. An analysis of the peak loads reveals that low infiltration rates cause significantly higher peak loads since the initial solubles concentration is higher. This would be an argument among many pros and cons on the benefits and drawbacks of omitting extraneous water in the sewer system. However, an integrated approach evaluating positive and negative effects of extraneous water in the sewage system under both wet- and dry-weather conditions is necessary.

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