Prediction of organic combined sewer sediment release and transport

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ABSTRACT

Accurate predictions of sediment loads released by sewer overflow discharges are important for being able to provide protection to vulnerable receiving waters. These predictions are sensitive to the estimated sediment characteristics and on the site-conditions of in-pipe deposit formation. Their application without a detailed analysis and understanding of the “initial conditions” under which in-sewer deposits were formed normally results in very poor estimations. In this study, in-sewer sediment samples deposited during dry-periods in a combined sewer system were collected, and their properties assessed. Parameters in the sediment transport relationship first proposed by Skipworth for in-pipe deposits were estimated based on simulating the in-pipe deposit formation conditions in laboratory erosion tests. The measured parameters were then used to simulate sediment transport through a small combined sewer network for a number of rain events for which rainfall, hydraulic and water quality data were available. Results showed that the model of Skipworth can provide good predictions of the sediment loads released from such in-sewer deposits. The experimentally-derived calibration parameters used with Skipworth’s model allowed for a realistic simulation of the in-sewer sediment behaviour and so can be used to accurately estimate the sediment load released from combined sewer systems during rainfall events.

Keywords

In-sewer erosion; quality modelling; organic sediments; in-sewer sediment transport

Nomenclature

The following symbols are used in this paper:

A_s [m^2]	Sediment surface exposed to erosion	M [g s^{-1} m^{-2}], b [-]	Calibrated transport parameters
C_{SS} [g l^{-1}]	Suspended solids concentration	V_s [m^3]	Sediment volume
d [mm]	Cumulative depth of erosion	ρ_s [kg m^{-3}]	Sediment bulk density
d_e [mm]	Sediment eroded depth per time step	ρ_m [kg m^{-3}]	Sediment-water mixture density
d' [mm]	Thickness of the upper sediment layer of the deposit	τ_b [N m^{-2}]	Applied bed shear stress
d''[mm]	Thickness of the surficial layer eroded during consolidation period	τ_c [N m^{-2}]	Critical shear stress
d_{50} [mm]	Characteristic particle size	τ_{cs} [N m^{-2}]	Critical surficial shear stress
E [kg m^{-2} s^{-1}]	Erosion rate	τ_{cu} [N m^{-2}]	Critical shear stress of the underlying layer

INTRODUCTION

Existing software packages for the hydraulic modelling of sewer network systems generally show good predictive performance. However, the simulation of water quality processes in sewer system network models has been less reliable (e.g. Ashley *et al.*, 1999; Kanso *et al.*, 2005) and sewer flow water quality data are generally less available (e.g. Willems 2010).

Water quality modelling in combined sewer systems predicts sediment and pollutant loads for time varying flows. Research has shown that a significant contribution of suspended sediment originates from the release and re-suspension of sediment from in-sewer deposits during the initial period of storms (Ahyerre and Chebbo 2002; Ashley *et al.* 2004; Gromaire-Mertz *et al.* 2001; Saul and Thornton 1989; Tait *et al.* 2003a). The rapid suspension of previously deposited in-pipe sediment has been observed in releases from combined sewer overflows during intense rainfall events. This phenomenon has been termed a *first foul flush* (Gupta and Saul 1996) The *first-flush* phenomenon (Obermann *et al.* 2009) is often observed in regions with a semi-arid climate, such as in Mediterranean catchments which are characterized by dry-weather periods followed by intense storm events. The high variability of the flow regime of the rivers in these regions are also strongly dependent on the seasonal rainfall, this can result in a quite limited dilution capacity of the natural receiving waters (Prat and Munné 2000) thus, in areas of water scarcity, *first flush* can cause a very significant impact. In the Mediterranean region where the case study catchment is based, it is therefore important to achieve reliable predictions of sediment and pollutants loads that can reach the receiving waters through combined sewer overflows (CSOs) during intense rainfall events. An improved prediction of sediment loads could allow for action to better manage pollutants that are released and are known to generate high oxygen demand in receiving waters. Most sediment transport research has been focussed on sediment movement in rivers. The findings resulted in predictive relationships, empirically calibrated, and developed from observations of the movement of mainly granular sediments. The application of existing granular based fluvial transport models, such as Ackers (1984, 1991) and May (1993), modified to simulate erosion and transport of granular and organic sediments through piped sewer systems does not perform well (Ashley *et al.* 2004; McIlhatton *et al.* 2005; Schellart *et al.* 2008b; De Sutter *et al.* 2003). Considering the additional processes that can occur in sewer sediment deposits, the use of sediment transport relationships originally developed for fluvial environments and granular sediment can be reasonably questioned.

Biochemical transformation processes, interactions between particles, and microbiological activity can have a significant influence on the resistance to erosion of in-pipe deposits (Banasiak and Tait 2008; McIlhatton *et al*. 2005; Sakrabani *et al.* 2005; Seco *et al*. 2014b; Vollertsen and Hvitved-Jacobsen 2000). The available sediment transport relationships for cohesive deposits oversimplify the process occurring in sewers (Freni *et al*. 2008; Mannina *et al*. 2012; Schellart *et al.* 2010).

The deposit erosion methodology developed by Skipworth *et al*. (1999) links the sediment erosion rate to critical shear stress levels related to different layers within the sediment deposit in pipes. The methodology is derived from laboratory observations obtained from the erosion and transport of cohesive-like synthetic sediment previously deposited in a pipe and subjected to steady flow conditions.

Results obtained by Skipworth *et al.* (1999) and later verified by Rushford *et al.* (2003), confirm that their methodology improves prediction of the transport rate of cohesive sediment. The potential for improvements in the prediction of sediment erosion rates when using Skipworth's model, can only be attained if realistic values for the calibration parameters of the deposit erosion model can be obtained. In this study field data is used to test this type of deposit erosion to assess its utility for modelling sediment releases from sewer system overflows during intense rainfall events.

The determination of shear stress at the threshold of motion (τ_c) exerted on the sediment bed surface is crucial in the evaluation of the release of sediments from layered deposits, however, this threshold is difficult to determine in-situ. Mclhatton *et al.* (2005) and Oms *et al.* (2008) reported observed values of τ_c in the range between 0.15 and 0.85 N/m^2 for in-sewer sediment deposits in combined sewer systems in Dundee (Scotland) and in Paris (France) respectively.

Highly-organic sediment deposits can be observed in combined sewer systems serving highly urbanized areas found in the Mediterranean region where high levels of catchment imperviousness are common. Additionally, large fluctuations in combined sewer flows are associated with semiarid climates and this pattern of variation can have an effect on the sediment accumulation-flushing cycles found in sewer networks. The main aim of this paper was to examine the suspended sediment load evolution that can be discharged into natural watercourses from CSOs activated during intense rain events. The accurate estimation of the sediment discharge pattern will help in quantifying the impact of CSOs on receiving waters. With this aim, the study had the following objectives: to evaluate the process of mobilization from in-sewer sediment deposits, and to validate Skipworth's deposit relationship in a particular catchment under realistic rainfall conditions.

To achieve these objectives the empirical deposit and transport parameters were estimated based on laboratory observations. The performed tests allowed the analysis of the erosion behaviour of highly-organic sediment sampled from a real sewer network. Previous investigations on the erodibility of highly organic sediment (Seco *et al.* 2014a) provided key knowledge on the properties of sediment recovered from the same combined sewer system. The experimental and analytical procedures were modified based on the results obtained in the earlier study. Controlled environmental temperature conditions were now established. An intermediate Dry-Weather Period (DWP) between the formerly established 16 and 64 hours was also implemented to obtain a deeper comprehension on the process that influence erosion rate evolution. The results obtained from the laboratory experiments reported in this work allow for the assessment of the calibration parameters involved in the deposit-erosion model proposed by Skipworth *et al*. (1999).The use of real sewer sediments for the determination of the transport parameters allowed for the verification of the application of the Skipworth in-pipe deposit model at a network scale.

METHODS

Study site location and description

The field study site is situated in the south-east of Spain, in the city of Granollers (35 km north of Barcelona, Spain). The local rainfall pattern is irregularly distributed throughout the year and characterised by dry-weather periods often longer than a week followed by single storm events. A small urban catchment in Granollers was selected for the study, covering an area of approximately 10 hectares (Fig. 1). The land use is mainly residential and commercial, with a high population density of 150 inh/ha. The area has a significant presence of commercial food activity. The catchment surface displays a high degree of imperviousness that reaches almost 100% in some zones, with an average imperviousness of 84% over the whole catchment. Given the highly impervious conditions of the catchment, and the limited existence of soil areas, inorganic sediments are a minor contribution during storm runoff (Gómez-Valentín *et al*. 2015).

The urban area has a gravity driven combined sewer system composed of circular concrete pipes with diameters ranging from 300 to 1000 mm. General characteristics of the catchment and the combined sewer network are given in Table 1.

Hydrological, hydraulic and water quality monitoring

Flow rates, water quality data and rainfall data were collected during storm events. The purpose of the monitoring programme was to obtain field data to validate the reported modelling work. The layout and the operation of the case study sewer network is similar to that of many other combined systems throughout Europe and the eastern coast of the USA. The results of the study are therefore expected to be widely applicable. The monitoring programme was carried out over an 18-month period. The events of interest were selected based on two threshold conditions: a rainfall depth which will produce enough runoff to increase water depths and velocities in the sewer network and also have sufficient flow to produce a measurable resuspension of sediments previously deposited inside the network, and an antecedent DWP sufficient to produce enough sediment accumulation for the detection of increasing pollutant loads at the outlet of the analysed catchment. Precipitation depth of 5mm and antecedent DWP of the order of several days were established as thresholds. Events that experienced major disruptions during flow recording or water quality sampling were discarded. After pre-processing, four rainfall events satisfying these conditions remained; see events 1 to 4 in Table 2. For these events, physical samples for water quality analysis were collected at the outlet of the catchment simultaneously with rainfall data and flow data. Two additional events where no satisfactory water quality data were recorded (events 5 and 6 in Table 2) were used to calibrate the network hydrodynamic model.

Flow was continuously monitored using an automatic portable flowmeter (HACH-Lange, Sigma 950 model). The instrument was provided with a bubbler water level sensor and a doppler velocity sensor, and the flowrate was then calculated. The water samples were collected during rainfall with an automatic sampler (HACH-Lange Sigma SD900 model). The sampler was equipped with a peristaltic high speed pump taking in 1000 ml in 2 minutes through a tube with a strainer at the end, followed by a cleaning cycle that takes another 2 minutes. An increase in flowrate compared to the dry weather flow pattern triggered the collection of water quality samples. Due to the high imperviousness of the catchment, it was expected that the runoff rapidly releases and washes off sediments from the surface and erodes them from inside the network. The highest sampling frequency was therefore set at 5 minutes for the first 15 minutes of a rainfall event and then less frequently for a total of 2 hours. Following the trigger at t=0, samples were taken at: 0, 5, 10, 15, 30, 45, 60, 90, 120 minutes. The established sampling frequency was intended to focus on the beginning of a storm event in order to analyse the occurrence of a first flush pollutant phenomenon.

Deposited sediment characteristics and behaviour

Sediment deposit sampling and analysis

A batch of 3 kg of in-sewer sediment was manually collected, directly from the invert of a 600 mm pipe with 0.002 m/m slope upstream of a diameter reduction (from 600m to 400 mm). According to the local operators, sediments deposit formations were typically observed in this section after prolonged dry-periods. The collection was conducted during dry-weather flows when the water depth was less than 5 cm. The deposited sediments were collected manually, immediately refrigerated at 4 ºC and then transported within 48 hours to Sheffield in UK, where the analysis and erosion tests were performed. Upon arrival in Sheffield the sediment temperature was found to be 4.7 ºC, after which the sediments were immediately stored in a refrigerator at 4 ºC. Despite the destruction in the layer structure of the deposit during collection, no alterations were believed to have taken place in the physical characteristics of the sediments, while biological activity and microbiological decomposition of the sediment samples were inhibited by the low temperatures during the storage and transport procedures. Thus, for physical characterization the collected sediment were considered representative of the deposit formed in the invert of the original sewer pipe during dry-weather periods.

Analysis and sediment preservation follows the *Standard Methods for the Examination of Water and Wastewater* (APHA *et al*. 2005). A summary of the sediment characteristics is shown in Table 3.

The sediments were characterized for organic content, which is defined as the proportion between the volatile solids (*VS*) and the total dry mass of sediments (*TS*) (section 2540E, *Standard Method*). An average of 95 % ±2 of *VS/TS* rate was obtained. The density of the deposit was assessed using the displacement principle method. The presence of fat, oil and greases was established through visual observation of the sediment. The characteristic particle diameter d_{50} was obtained following the British Standards (BS 1796-1:1989.Test sieving) for the gross part (>1 mm), while the fine part (< 1 mm) was performed by laser diffraction method (ISO 13320:2009 Particle size analysis. Laser diffraction methods) using a Mastersizer 2000, Malvern instrument Ltd. Figure 2 shows the particle size distribution curve of the collected sediment samples.

Laboratory erosion test procedure

The laboratory tests were carried out with a sample of sewer sediment deposit, placed in a device called an erosionmeter (developed by Liem *et al.* 1997). The erosionmeter consists of a vertical perspex tube provided with a centrally located propeller, and vertical vanes to reduce lateral circulation, and a container for the sediment deposit. By applying an angular velocity to the water column a reasonably uniform shear stress is exerted over the sediment surface. Six vertically spaced outlets are used to sample the sediment eroded from the bed that remained suspended in the water column. The samples were analysed later for *TSS* following the *Standard Methods for the Examination of Water and Wastewater* (2005). A detailed description of the equipment and calibration process is given in Seco *et al.* (2014a).

The preparation of the samples follows a defined procedure with the intention of establishing repeatable conditions and to simulate the dry weather flow conditions found in the case study sewer. The whole batch of collected disturbed sediment deposit was thoroughly mixed and separated into individual samples. The container with the individual sediment sample was then carefully filled with water and left for 72 hours at 4 ºC, in a phase of quiescent physical consolidation where the biological reactions were retarded by the low temperature. After the pre-consolidation phase the sample was placed in the bottom of the erosionmeter and allowed to assimilate to 20°C. Aerobic conditions were set by supplying air to the supernatant water. An oxygenated environment in a gravity sewer network is likely to be produced under conditions of varying flows (Hvitved-Jacobsen *et al.* 2013). A low bed shear stress (0.15 N/m^2), similar to that found during dry weather flows in the system, was applied over the bed by slowly rotating the propeller. By applying a low bed shear stress it was intended to simulate the dynamic consolidation conditions at which sediment deposits were subjected in sewers during periods of sediment deposition between rain events (DWP). Additionally, the low velocity of the propeller ensures a continuous mixing and creates a uniform environment regarding water temperature and dissolved oxygen (DO) levels. The results from this study focus therefore on the erosion and transport of sediments subjected to aerobic conditions at 20°C during the depositional DWP prior to a storm, and the tests were carried out in a temperature controlled room. Four different

DWP durations between 16 and 64 hours were considered to simulate the consolidation process thought to be present in the actual sewer system. The DWP durations were in the order of magnitude of several days for two reasons: firstly, although there are longer DWPs in the catchment, the average DWP throughout the 18 month field monitoring period was 3 days, secondly, as described in Seco *et al.* (2014b), the sediments were quite biologically active and it was assumed that during DWP the upper sediment layers are continuously being biodegraded as well as replenished with fresh sediments originating from the dry weather flow. The critical threshold of motion at the solid-fluid interface of the resulting deposit was then assessed by step-wise increase of the propeller speed. The erosion phase of the tests was then performed by increasing the applied shear stress in a stepwise fashion. Samples were collected from the water column at steady erosion state conditions (Parchure and Mehta 1985) at each step of applied bed shear stress, which lasts 45 minutes (Schellart *et al*. 2005; Tait *et al*. 2003b). The eroded material and resultant erosion rate was calculated from the measured suspended sediment (SS) concentration of the collected samples. These data are reported below and were used in the calibration of the erosion model described below.

Modelling sediment transport in a field study catchment

Hydrodynamic modelling

The *SWMM5* (Storm Water Management Model) software package was selected for the rainfall-runoff and hydrodynamic modelling through the combined sewer system in the study case. The hydrological model (Fig. 1) is defined based on a sub-catchment delineation established from topographic data of the catchment drainage areas and of the combined sewer network complemented by in-situ observations to complete information about impervious-pervious surfaces and their drainage characteristics. The hydrodynamic network model is directly related to the sewer network system information provided by the local sewerage company; it comprises 57 pipes and manholes, and 42 sub-catchments in a 10 hectare area. Flow measurements were performed at the outlet of the studied catchment, using the equipment and procedures described above.

A calibration and validation process of the hydrodynamic model was performed by comparing simulated with measured flow rates during several rainfall events. Model calibration was carried out using rainfall events 5 and 6 (Table 2). Subsequently, the model was validated by applying independent data sets corresponding to events 2 and 3. The relative errors of total runoff volume range from 1 % to 10 % for the analysed events, which are indicated in Table 4. The relative error of peak flow is between 2 % and 10 % and the difference in the elapsed time to reach the peak flow range from 2 to 8 minutes. The goodness of fit obtained can be observed in Fig. 3 and Table 4.

Sediment erosion model of Skipworth et al. (1999)

The methodology proposed by Skipworth et al. (1999) is based on the concept of a bed structure with different layers, in which each layer displays a different resistance to erosion.

The simulation method proposed by Skipworth *et al.* (1999) is based on an excess shear stress relationship to predict the sediment erosion rate for estuarine deposits so-called Ariathurai-Partheniades equation (1) (Ariathurai 1974, as referenced by McAnally and Mehta 2000)

$$E = M \cdot \left(\frac{\tau_b - \tau_c}{\tau_c}\right) \quad (1)$$

where E is the erosion rate in kg/m^2/s for the applied bed shear stress τ_b [N/m^2] and τ_c [N/m^2] is the critical shear stress, M is a transport parameter used as a calibration factor that has the same units as E and is equal to the erosion rate when $\tau_b = 2.\tau_c$.

By examining the erosion rate over time, Skipworth concluded that in-pipe deposits showed a weaker upper layer transitioning to a stronger underlying layer. It was later observed, also verified by Schellart *et al*. (2005) and Seco *et al*. (2014a), that the organic content, oxygen availability and length of the consolidation period have an influence on the subsequent erosion resistance of the deposited layers. The sketch in Fig. 4 shows the variation of the erosional resistance with depth for cohesive-like sediment deposits. At the upper layer, the erosional strength increases in depth from a surface erosional strength (τ_{cs}) until a value of deposit strength (τ_{cu}). Once the thickness of the upper layer (d') is exceeded and the lower layer is reached, the deposit has an almost uniform resistance to erosion.

Skipworth *et al.* (1999) proposed a power law shown in equation (2), that represents the depth variation of the shear stress necessary to erode the upper weak layer.

$$\tau_c = \left[\left(\frac{d}{d'} \right)^{1/b} . (\tau_{cu} - \tau_{cs}) \right] + \tau_{cs} \qquad \text{for} \quad 0 \leq d \leq d' \qquad (2)$$
$$\tau_c = \tau_{cu} \qquad \text{for} \quad d > d'$$

Where d is the cumulative depth of erosion, d' represents the thickness of the upper layer (Fig. 4), b is a calibration parameter which describes the rate of change in bed strength with depth. The factor M is also a model calibration parameter. Due to the high dependency on the sediment bed properties, the values of M, b, d', τ_{cs} and τ_{cu} must be empirically determined to obtain a realistic prediction of sediment erosion and transport.

Coupling of a sediment transport model and SWMM5

In order to analyse the performance of this model for predicting sediment release in a combined sewer network under time-varying hydraulic conditions, the erosion relationship of Skipworth was coded using MATLAB and then coupled with a sediment transport network model also coded in MATLAB. This code was based on the concept of a model previously used by Schellart *et al*. (2008a), which simulates the transport of sediment eroded from in-pipe deposits, based on hydraulic parameters simulated by an uncoupled hydrodynamic sewer network model, and assuming conservation of sediment mass between sediment advection, released sediment and the sediment stored in the in-pipe deposits. Predictions from the calibrated SWMM5 hydraulic model were used as inputs for the sediment erosion and transport model coded in MATLAB. The linked modelling structure is shown in Fig. 5.

Performance evaluation criteria

The goodness of fit between observed and simulated suspended sediment (SS) concentration values was evaluated by using the following criteria: the sum of squared errors *SSE* (Eq. (3)); the percent peak error *PE* (Eq. (4)); and the Nash-Sutcliffe efficiency (NSE) (Eq. 5) where $C_{SS,m,i}$, $C_{SS,s,i}$ are the SS concentration measure and simulated at time i respectively, and $C_{SS,peak}$ is the concentration peak, defined as the maximum SS concentration value of the event.

NSE values range between 1 for a perfect fit and -∞.

$$SSE = \sum_{i=1}^{n} \left(C_{SS,m,i} - C_{SS,s,i}\right)^2 \tag{3}$$

$$PE = \frac{\left(C_{SS,m,\mathrm{peak}} - C_{SS,s,peak}\right)}{C_{SS,m,peak}} . 100 \tag{4}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n} \left(C_{ss,m,i} - C_{ss,s,i}\right)^2}{\sum_{i=1}^{n} \left(C_{ss,m,i} - \overline{C_{ss,m,i}}\right)^2} = 1 - \frac{SSE}{\sum_{i=1}^{n} \left(C_{ss,m,i} - \overline{C_{ss,m,i}}\right)^2} \tag{5}$$

RESULTS AND DISCUSSION

Assessment and optimization of transport parameters based on laboratory results

The values of the calibration parameters of the equation proposed by Skipworth (Eq. 1 and 2) can be derived from analysis of the data obtained from laboratory erosion tests.

The determination of the erosional strength with depth is derived from each time step application of increased shear stress linked with the stable SS concentration measured ($C_{SS,m}$) at the end of each time step. The relationship between applied shear stress and erosion rate is shown in Fig. 6, for tests carried out under aerobic conditions and for different durations of antecedent dry-weather period. The errors in the determination of the applied shear stress (± 0.07 N/m^2) derived from the erosionmeter calibration process were also represented (refer to Seco *et al*. (2014a) for more detail). Through a regression analysis a series of best fit trend functions were obtained (Fig. 6).

Assessment of parameters τ_{cs} ,τ_{cu}, d'' and d'

At the end of each time step during the erosion test, the mass of sediment obtained from the SS sample concentration can be translated to a sediment erosion depth (d_e), and so it is possible to link the deposit properties to the applied shear stress (τ_b). The bulk density of the bed formed by collected sewer organic-cohesive sediment is of 1310 kg/m^3 (± 146 kg/m^3). Sediment bed density was assumed to remain constant during the test since the duration of the erosion test is relatively short compared to any consolidation processes that can produce significant changes in density of the deposit structure due to excess pore water effects.

The applied shear stress against the depth of erosion is shown in Fig. 7.

During the antecedent DWP simulated in the tests, the erosion meter was set to exert τ_{DW}=0.15 N/m^2 on the sediment bed. This τ_{DW} value was estimated by examination of the bed shear stress value at the outlet pipe predicted during DWF in the case study network.

It was noticed that during all DWP tested, a near constant and thin surficial layer was eroded at the end of the consolidation period. The depth of this eroded layer can be assessed from the sample of the sediment concentration at the end of DWP (Eq. (6)), which allows establishment of the value of a parameter *d''* as the observed value 1.25 mm (standard deviation SD = 0.13 mm). There were no significant changes observed in the depth of the eroded layer with different DWP durations. Hence, it is assumed that the value of the critical shear stress at the surface layer τ_{cs} can be considered equal to the applied shear stress during the antecedent DWP (0.15 N/m^2). This means that the τ_{cs} and *d''* can be considered independent of the length of the DWP when consolidation of the sediment deposit takes place.

$$d_e = \left(C_{SS}.\frac{V_s}{A_s}\right).\frac{1}{\rho_s} \qquad (6)$$

Following the profile of sediment resistance against erosion shown in Fig. 4, the value of τ_{cu} would be obtained when the resistance strength becomes uniform with depth. The experimental tests, however, did not achieve a completely uniform resistance against erosion. Therefore, the thickness of the upper layer of sediments (*d'*) is estimated by assuming that a gradient of 0.03 ($\Delta\tau_b/\Delta d$) practically marks the transition between the upper layer (*d'*) and the lower more uniform layer. Fig. 8 (a) shows the values of *d'* and τ_{cu} estimated from the erosion tests performed after different consolidation periods, a dot marks the estimated transition point below which the τ_{cu} is assumed to be sensibly constant. In Fig. 8a, the errors in the assessment of the sediment depth of erosion (± 6 mm) and the accuracy of the applied shear stress (± 0.07 N/m^2 after, Seco *et al.* 2014a) are indicated by shaded error bands. From this plot it can be observed that after 24 hours of consolidation, the increase in the resistance against erosion of the sediment bed is not significant.

Determination of the values adopted by the model parameters b and M

In order to apply Eq. 1 and Eq. 2, the values of the parameters *M* and *b* need to be determined. An optimization for calibration parameters *b* and *M* is therefore performed by comparing the calculated erosion rate E_c against measured erosion rate E_m, given the applied shear stress τ_b. This optimization was carried out by varying both parameters at the same time, in order to obtain a minimum value for the root mean square error *RMSE* (Eq. (7)).

$$RMSE = \sqrt{(E_c - E_m)^2} \quad (7)$$

The ranges in which the values of the parameters *b* and *M* were varied during the optimization were initially assumed to be those determined by Skipworth and Rushforth and presented in Table 5. However, this did not lead to a minimum, hence the range of variation for the *b*-parameter was increased to 0.025 and 1 (with increments of 0.025), and for the *M*-parameter varying from 0.05 and 2 (with increments of 0.05).

The optimization results produced a narrow range of values for *b* (Fig. 9 a) where the mean value obtained is b = 0.125 (SD = 0.071). Regarding the value of the parameter *M*, the variation is wider (Fig. 9 b). However, a relationship between the value adopted by the *M*-parameter and the applied shear stress for each test could be observed, and this trend changes with the length of the DWP analysed. Thus, it can be suggested that a weak relation exists between the duration of the consolidation period and the parameter *M* (coefficient of proportionality between 0.51 and 0.74). The optimised values for *b* and new ranges found for *M* and the other parameters involved in the calculation or erosion rate are included in Table 5.

Fig. 8 indicates that after 24 hours of consolidation the resistance against erosion throughout the depth of the deposit stabilized. Based on that finding, the values of the sediment transport parameters *b* and *M* that were used for the network sediment transport model were those average values obtained in the tests with DWP longer than 24 hours. A linear relationship (Eq. (8)) was implemented for the evaluation of the *M*-parameter for each applied shear stress (τ_b) during the simulations, valid for values of τ_b higher than 0.40 N/m^2. For lower values of τ_b the value of *M* was constant and equal to 0.05.

$$M = 0.725.\tau_b - 0.0487 \quad ; \tau_b > 0.40\ N/m^2 \tag{8}$$

Modelling Sediment Transport in the Case Study Catchment

Hydrodynamic predictions were obtained from the calibrated SWMM5 model for the four rainfall events 1 to 4 from Table 2. These predictions were input into the sediment transport model using Skipworth's erosion relationship calibrated with the case study sediment. Initial conditions for the available in-pipe sediment deposits were set to a 5 cm deep sediment deposit, as this allowed for analysis of sediment transport not to be limited by the availability of sediment in the simulations (i.e. after all the simulations there was still sediment left in each pipe). This ensured that the initial model boundary conditions did not impact on the model predictions. A selection of computation time-steps were examined and were seen to influence the simulated erosion rate. A time step higher than 1 minute started to reduce the peak values of sediment concentration; hence a time-step of 20 seconds was used.

In this study, based on previous research (Ahyerre and Chebbo 2002; Gromaire-Mertz *et al*. 2001; Tait *et al*. 2003a) it was hypothesised that the sediment transport inside pipes due to incoming rainfall runoff does not include significant sediment wash-off from catchment surfaces, and that the main source of suspended sediment is re-erosion of previously deposited in-pipe sediments.

Sensitivity analysis

A sensitivity analysis of some parameters of the erosion model was carried out by applying controlled variations of their values in a valid rage. In particular, the effect and influence of the bed porosity and the bulk density were estimated. Porosity and bulk density were both included in the model in order to calculate the volume of eroded sediments, which enables an update of the remaining sediment deposit depth available for erosion. Porosity of the sediments was initially assumed as 0.20 based on initial measurements (p = 0.215 ± 0.05 performed by desiccation of fresh samples at 105ºC during 24 hours). During the sensitivity analysis, the porosity values were changed over the range 0.10 to 0.30, as sewer deposits with fats and greases have been observed to have porosity ranging from 0.10 to 0.24 (Keener et al. 2008). No significant influence on the eroded sediment depth evolution was observed under porosity variation. Results obtained by using the event ID 2 are shown as an example in Fig. 10 (a).

Less than 8 % of variation in sediment concentration peak and around 10 % in sediment mass mobilized was simulated, compared to simulation results obtained with $p = 0.20$.

The effects of changes in the sediment bulk density in the assessed range of variation for the local sediments (1066 – 1458 kg/m^3; average 1310 kg/m^3) were also verified (Fig. 10 (b)). For event ID 2 shown as an example, variation from values calculated with the average sediment bulk density were found between 1.5 to 6.4% regarding maximum sediment concentration, and between 9.4 and 16% regarding total mass of sediment mobilized.

The greatest influence on the sediment transport loads is exerted by the hydraulic conditions. The remobilization of sediments is directly related to the hydraulics that determined the boundary shear stress values.

Model results and performance

The performance of the coupled SWMM5 and the calibrated Skipworth model (Fig. 5) was tested by comparing measured versus modelled sediment peak concentrations and calculating NSE (Eq. 5). Performance of the sediment transport model was analysed in the periods for which SS concentration was measured and the obtained values are shown in Table 6.

Unfortunately, the total mass of sediment could not be considered for testing model performance because of the adopted sampling strategy, addressed mainly to collect the first flush by including a sampling collection for a total of 120 minutes which in most cases covered the first part of the rainfall event duration.

Fig. 11 shows the sediment transport loads evolution assessed by the proposed model which is based on the relationship of Skipworth with calibrated parameters. The SS concentration values obtained were represented as an average value over the pumping interval (pumping-cleaning cycle in sample collection).

During the rain event 1 (Fig. 11 a), the first phase of runoff arriving to the outlet of the catchment generates an increase in water depth that was lower than the threshold water depth established for the start of the operation of the automatic sampling collection. Thus, the first SS peak that can be observed in the modelling results (Fig. 11a) were not covered by the measured SS data. Collected SS concentration data corresponds instead with a second simulated peak when greater flow rates triggered the collection of samples. It can be observed that there is a slight delay (6 minutes) between the sediment concentration peak time measured and simulated during the event. It can be hypothesised that this could be due to the 4 minutes delay between observed and measured peak flow. The 4 minutes delay observed at Fig. 11 (b) between simulated and measured C_{SS} for the event 2 might also be linked with delays in the hydrodynamic results (8 minutes delay between observed and measured peak flow from Table 4).

Both the NSE values and visual analysis of the pollutographs (Fig. 10) indicated a good fit between simulated and observed data for events 1 and 2, a reasonable fit for event 3 and a poor fit for event 4. Lower total precipitation and lower rainfall intensity for the event 4 might influence the predicted results since the lower shear stresses generated in the SWMM model are very close to the anticipated surface threshold shear stress of the water sediment interface.

Fig. 12 shows that for the events 1 and 2 the applied bed shear stress (τ_b) observed at the outlet of the analysed sewer system reaches values higher than the critical value of the deeper layer (τ_{cu}). Meanwhile much lower values of applied shear stress are observed for the events 3 and 4. In these events the shear stress does not even reach the level at which the superficial layer (d') is fully eroded. This indicated that for rainfall events in which the shear stress is low and for thin surface layers in which the shear stress threshold changes quickly, such calibrated models struggle to accurately simulate erosion rates.

CONCLUSIONS

Transport parameters assessment

Based on the laboratory findings for the highly organic sewer sediments collected in this study, it can be confirmed that the critical shear stress values can be linked to the sediment bed depth, and hence the values of the parameters *d'*, τ_{cs}, τ_{cu}, *b* and *M*, depend on the characteristics of the sediment and on the structure of the in-pipe deposit.

From the analysis of the results obtained regarding the performance of the parameters it can be suggested that the variation of the parameter *M* might be dependent on other sediment characteristics, such as the median particle size (d_{50}) of the eroded sediments. The range of values adopted by *b* and *M* might be also dependent on the density of the sediment eroded.

The sediment erosion and transport model performed well for three out of four rainfall events for which flow and suspended sediment data were collected in the case study catchment. It predicted the peak SS concentrations in these events with a Nash-Sutcliffe efficiency ranging from 0.73 to 0.85. However, it needs to be stressed that the collection of the sewer sediment samples for the laboratory analysis is practically difficult and assumptions had to be made in the design of the consolidation periods to simulate deposition conditions in the sewer environment in the laboratory. The design of the laboratory consolidation conditions may have an influence on the estimation of the values of the calibration parameters used in the sediment erosion and transport model. Furthermore, temporal and spatial variability of the sediment characteristic in the system might introduce a level of uncertainty that was not examined, as the laboratory tests were all completed using samples collected at a single location on a single day.

Because of site-specific sewer sediment characteristics, the parameters involved in the sediment erosion model must be determined using local sediments. Performing erosion tests in the laboratory gives the possibility of assessing the necessary parameters to deliver a more reliable prediction of in-sewer transport and erosion.

Results from the assessment of the critical shear stress through the erosion tests confirmed the structure of the sediment deposit model proposed by Skipworth regarding the existence of a weak upper layer and increasing resistant erosional strength with depth through the bed. A power law trend was found to describe the variation of the erosional resistance against the depth of the deposit. Furthermore, the values obtained in the present work for the critical shear stress τ_c, varying from 0.15 up to 1.4 N/m^2 (depending on the consolidation period for a deposit of 30mm depth), are in the range found from previous in-situ and laboratory work with real sewer sediments carried out by Mclhatton *et al.* (2005) and Oms *et al.* (2008) who reported values in the range between 0.15 and 0.85 N/m^2.

The results from erosion tests also suggested that the behaviour of newly-deposited surficial sediments subject to dynamic consolidation for up to around 24 hours show an increasing resistance against erosion, and when the period of consolidation exceeds the 24 hours; any further increase in resistance becomes insignificant (Fig. 8).

Further research is needed to identify a more direct relationship between the parameter *b* and *M* with the sediment characteristics.

Sediment transport modelling application

For the case study described in this paper it was verified that the initial conditions regarding sediment deposit properties and hydraulic parameters are indeed relevant in the prediction of SS loads released and mobilized from in-sewer pipes during rainfall events. The large variation in the nature and behaviour of the deposited sediments, the highly variable hydraulic conditions, and the complexities of the processes occurring in-sewer makes a calibration process and validation against locally measured data essential.

The predictive capacity of the sediment transport model proposed by Skipworth *et al*. (1999) was verified with NSE between 0.85 and 0.73 for three out of four events. The indicated performance on the results is directly related to an adequate assessment of the values of the transport parameters considering the local sediment characteristics, and to an adequate calibration of the hydraulic model using locally measured rainfall and flow data.

Following the analysis of the simulation results it can be observed that the rapid change in SS concentrations is due to the quick response of the system influenced by a high level of imperviousness in the catchment as well as the pattern of rainfall. It was concluded that reducing the sampling frequency at the beginning of the event is desirable so as to be able to capture with more detail the highly variable start of the pollutograph. Sampling interval adjustments will depend on the catchment characteristics and concentration time on the case study. As an alternative, the on-line probes that can make indirect measurements of the SS concentration could be used to obtain data with a higher temporal resolution. The locally calibrated data can then be directly compared with the temporal pattern of the SS concentration prediction.

Improved *first flush* prediction is required to better manage the pollution events on receiving natural watercourse pollution through CSOs. The sediment modelling provided a better fit for the three largest rainfall events, indicating that more research may be needed in defining how exactly the weak layer at the very top of the in-sewer deposits erodes.

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REFERENCES

Ackers, P. (1984). “Sediment transport in sewers and the design implication.” *lntern. Conf. on Planning, Construction, Maintenance and Operation of Sewerage Systems, BHRAMR*, England, Septemb, 215–230.

Ackers, P. (1991). “Sediment aspects of drainage and outfall design.” *Proceedings of the International Conference on Environmental Hydraulics*, Hong Kong, 215–230.

Ahyerre, M., and Chebbo, G. (2002). “Identification of In-Sewer Sources of Organic Solids Contributing to Combined Sewer Overflows.” *Environmental Technology*, 23(9), 1063–1073.

APHA, AWWA, and WEF. (2005). *Standard Methods for the Examination of Water and Wastewater*. (A. W. W. Association, W. E. Federation, and A. P. H. Association, eds.), American Public Health Association/American Water Works Association/Water Environment Federation, Washington DC.

Ariathurai, R. (1974). “A finite element model for sediment transport in estuaries.” University of California, Davis, CA.

Ashley, R. M., Bertrand-Krajewski, J.-L., Hvitved-Jacobsen, T., and Verbanck, M. A. (2004). *Solids in Sewers. Characteristics, effects and control of sewer solids and associated pollutants. Scientific and Technical Report No.14*. (R. M. Ashley, J.-L. Bertrand-Krajewski, T. Hvitved-Jacobsen, and M. a. Verbanck, eds.), IWA (International Water Association) Publishing. Joint Commitee on Urban Drainage, London.

Ashley, R. M., Hvitved-Jacobsen, T., and Bertr. (1999). "Quo vadis sewer process modelling?" *Water Science and Technology*, 39(9), 9–22.

Banasiak, R., and Tait, S. J. (2008). "The reliability of sediment transport predictions in sewers: influence of hydraulic and morphological uncertainties." *Water Science & Technology*, IWA Publishing, 57(9), 1317–1327.

Freni, G., Mannina, G., and Viviani, G. (2008). "Uncertainty assessment of sewer sediment erosion modelling." *Urban Water Journal*, Taylor & Francis, 5(1), 21–31.

Gómez-Valentín, M., Pouget, L., Cabello, A., Sunyer, D., and Russo, B. (2015). "Estudio de la erosión de un sedimento orgánico en la red de alcantarillado [Study of the erosion on organic sediment in the sewerage network]." *V Jornadas de Ingenieria del agua. La precipitación y los procesos erosivos*, Córdoba, Spain, 897–906.

Gromaire-Mertz, M. C., Garnaud, S., Saad, M., and Chebbo, G. (2001). "Contribution of different sources to the pollution of wet weather flows in combined sewers." *Water Research*, 35(2), 521–33.

Gupta, K., and Saul, A. J. (1996). "Specific relationships for the first flush load in combined sewer flows." *Water Research*, 30(5), 1244–1252.

Hvitved-Jacobsen, T., Vollertsen, J., and Haaning Nielsen, A. (2013). *Sewer Processes - CRC Press Book*. (C. Press, ed.), Taylor and Francis Group.

Institut Cartogràfic i Geològic de Catalunya. (2017). "Geodesy, cartography and spatial data infrastructure of Catalonia. Vissir. Institut Cartogràfic i Geològic de Catalunya (ICGC)." <http://www.icgc.cat/en/> (Jul. 10, 2017).

Kanso, A., Chebbo, G., and Tassin, B. (2005). "Stormwater quality modelling in combined sewers: calibration and uncertainty analysis." *Water Science & Technology*, IWA Publishing, 52(3), 63–71.

Keener, K. M., Ducoste, J. J., and Holt, L. M. (2008). "Properties Influencing Fat, Oil, and Grease Deposit Formation." *Water Environment Research*, 80(12), 2241–2246.

Liem, R., Spork, V., and Koengeter, J. (1997). "Investigations on erosional precess of cohesive sediment using an in-situ measuring device." *International Journal of Sediment Research*, 12(3), 139–147.

Mannina, G., Schellart, A. N. A., Tait, S. J., and Viviani, G. (2012). "Uncertainty in sewer sediment deposit modelling: Detailed vs simplified modelling approaches." *Physics and Chemistry of the Earth, Parts A/B/C*, 42–44(1), 11–20.

May, R. W. P. (1993). *Sediment transport in pipes and sewers with deposited beds. Report SR 320. HR Wallingford*.

McAnally, W. H., and Mehta, A. J. (2000). *Coastal and Estuarine Fine Sediment Processes, Volume 3*. Elsevier

Science.

McIlhatton, T. D., Ashley, R. M., and Tait, S. J. (2005). “Improved formulations for rapid erosion of diverse solids in combined sewers.” *Water Science & Technology*, 52(5), 143–150.

Obermann, M., Rosenwinkel, K.-H., and Tournoud, M.-G. (2009). “Investigation of first flushes in a medium-sized mediterranean catchment.” *Journal of Hydrology*, 373(3–4), 405–415.

Oms, C., Gromaire-Mertz, M. C., Saad, M., Milisic, V., and Chebbo, G. (2008). “Bed shear stress evaluation in combined sewers.” *Urban Water Journal*, 5(3), 219–229.

Parchure, T. M., and Mehta, A. J. (1985). “Erosion of soft cohesive sediment deposit.” *Journal of Hydraulic Engineering*, 111(10), 1308–1326.

Prat, N., and Munné, A. (2000). “Water use and quality and stream flow in a Mediterranean stream.” *Water Research*, 34(15), 3876–3881.

Rushforth, P. J. (2001). “The erosion and transport of sewer sediment mixtures.” University of Sheffield.

Rushforth, P. J., Tait, S. J., and Saul, A. J. (2003). “Modeling the Erosion of Mixtures of Organic and Granular In-Sewer Sediments.” *Journal of Hydraulic Engineering*, American Society of Civil Engineers, 129(4), 308–315.

Sakrabani, R., Ashley, R. M., and Vollertsen, J. (2005). “The influence of biodegradability of sewer solids for the management of CSOs.” *Water Science & Technology*, IWA Publishing, 51(2), 89–97.

Saul, A. J., and Thornton, R. C. (1989). “Hydraulic performance and control of pollutants discharged from a combined sewer storage overflow.” *Water Science & Technology*, 21(8–9), 747–756.

Schellart, A. N. A., Buijs, F. A., Tait, S. J., and Ashley, R. M. (2008a). “Estimation of uncertainty in long term combined sewer sediment behaviour predictions, a UK case study.” *Water science and technology*, IWA Publishing, 57(9), 1405–11.

Schellart, A. N. A., Tait, S. J., and Ashley, R. M. (2010). “Estimation of Uncertainty in Long-Term Sewer Sediment Predictions Using a Response Database.” *Journal of Hydraulic Engineering*, 136(7), 403–411.

Schellart, A. N. A., Tait, S. J., Ashley, R. M., Farrar, D., and Hanson, D. (2008b). “Uncertainty in deterministic predictions of flow quality modelling and receiving water impact.” *11th International Conference on Urban Drainageth International Conference on Urban Drainage*, Edingurgh, 1–10.

Schellart, A. N. A., Veldkamp, R. G., Klootwijk, M., Clemens, F., Tait, S. J., Ashley, R. M., and Howes, C. (2005). “Detailed observation and measurement of sewer sediment erosion under aerobic and anaerobic conditions.” *Water Science & Technology*, 52(3), 137–46.

Seco, I., Gómez-Valentín, M., Schellart, A. N. A., and Tait, S. J. (2014a). “Erosion resistance and behaviour of highly organic in-sewer sediment.” *Water Science & Technology*, IWA Publishing, 69(3), 672–679.

Seco, I., Schellart, A. N. A., Jensen, H. S., Gómez-Valentín, M., and Tait, S. J. (2014b). “Effect of the biodegradability on erosion of highly organic sewer sediment.” *13th International Conference on Urban Drainage*, Sarawak, Malaysia. September 2014.

Skipworth, P. J., Tait, S. J., and Saul, A. J. (1999). “Erosion of Sediment Beds in Sewers: Model Development.” *Journal of Environmental Engineering*, American Society of Civil Engineers, 125(6), 566–573.

De Sutter, R., Rushforth, P. J., Tait, S. J., Huygens, M., Verhoeven, R., and Saul, A. J. (2003). “Validation of Existing Bed Load Transport Formulas Using In-Sewer Sediment.” *Journal of Hydraulic Engineering*, 129(4), 325–333.

Tait, S. J., Chebbo, G., Skipworth, P. J., Ahyerre, M., and Saul, A. J. (2003a). “Modelling in-Sewer Deposit Erosion to Predict Sewer Flow Quality.” *Journal of Hydraulic Engineering*, 129(4), 316–324.

Tait, S. J., Marion, A., and Camuffo, G. (2003b). “Effect of environmental conditions on the erosional resistance of cohesive sediment deposits in sewer.” *Water Science & Technology*, 47(4), 27–34.

Vollertsen, J., and Hvitved-Jacobsen, T. (2000). “Resuspension and oxygen uptake of sediments in combined sewers.” *Urban Water*, 2(1), 21–27.

Willems, P. (2010). “Parsimonious Model for Combined Sewer Overflow Pollution.” *Journal of Environmental Engineering*, American Society of Civil Engineers, 136(3), 316–325.

FIGURE CAPTION LIST

Fig 1. Location of the study urban catchment (on the left) adapted from official cartographic data (Institut Cartogràfic i Geològic de Catalunya 2017) and layout of the combined sewer network (on the right) and catchment subdivision for the hydrodynamic and quality modelling.

Fig 2. Particle size distribution in raw sewage deposited sediments at Granollers, Spain. PSD performed with standard sieve (>1mm sub-sample) and laser diffraction analysis (<1mm sub-fraction).

Fig 3. Comparison between measured and calibrated hydrograph for rain events taken as examples.

Fig 4. Variation of the erosional resistance of the sediment deposit in a depth profile (after Skipworth, 1999).

Fig 5. Scheme of the simplified network sediment transport module coded in MATLAB.

Fig 6. Erosion rate against applied shear stress. Measured data, error in measurement and regression function found.

Fig 7. Sediment bed depth strength against applied shear stress. Measured data from erosion tests and trend.

Fig 8. Bed strength profile in depth of the sediment layer.

Fig 9. Variation on the parameters b and M values against applied shear stress for all the dry-period tested.

Fig 10. Influence of the variation of characteristic sediment parameters on the evolution of sediment concentration over time for event ID 2.

Fig 11. Sediment transport loads evolution. Measured and simulation values based on the relationship of Skipworth (1999) with adapted transport parameters assessed for high organic sediments.

Fig 12. Applied and critical bed shear stress evolution and sediment bed depth evolution during erosion process for the different rain events analysed.

Table 1. General characteristics for the catchment and combined sewer network of the study site.

catchment		combined sewer network	
Area	10.1 ha	average wastewater flow at outlet	24 m^3/h
surface slopes	between 0.5 and 2.15 %	total length of pipes	2.2 km
% impermeability	between 77 and 93%	pipe diameters	300 to 1000 mm

Table 2. Rainfall events registered in the study site and used for the sediment transport modelling validation

registered data	ID	Date	total rainfall depth [mm]	maximum intensity [mm/h]	duration [minute]	antecedent dry-weather period length [days]
rainfall, flow and quality	1	17/09/2010	19.0	36.2	130	28
	2	31/05/2011	26.2	33.5	315	16
	3	24/10/2011	6.4	37.0	80	39
	4	13/07/2011	11.1	18.2	235	6
rainfall and flow	5	09/10/2010	33.5	36.6	605	21
	6	12/03/2011	71.6	18.2	1130	22

Table 3. Characteristics of sediments used by Skipworth *et al.* (1999), Rushforth (2001) and (Seco et al. 2014a) experimentation and in this work.

sediment type		characteristic particle size d_{50} [mm]	sediment density [kg/m^3]	organic content [%]
Sewer sediment from urban catchment in Granollers. Spain	(Seco et al. 2014a)	0.31(± 0.16)	1310 (± 146)	74 (*VS/TSS*)
	(batch used in this work)		1313 (± 95)	95 (*VS/TSS*) ±2
Crushed olivestone	(Skipworth et al. 1999) and (Rushforth 2001)	0.047	1445	100

Table 4. Relative errors used as goodness of fit measured flow rate with simulated flows during rain events.

Errors	Calibration events		Validation events	
	Rain event ID 5 09/10/2010	Rain event ID 6 12/03/2011	Rain event ID 2 31/05/2011	Rain event ID 3 24/10/2011
Relative error of total runoff volume [%]	10 %	1 %	6 %	5 %
Relative error of peak flow [%]	10 %	2 %	7 %	8 %
time to 1rst peak error [min]	2	2	8	4

Table 5. Comparison of the values of transport parameters obtained from previous experimental studies (Rushforth 2001; Skipworth et al. 1999) and the values obtained in this study.

Parameter		values obtained in this study	Skipworth et al. (1999)		Rushforth (2001) (validation of Skipworth model)
			1:500 slope	1:1000 slope	
Material used		Sewer sediments	Crushed Olivestone		Crushed Olivestone
M	[g/s/m^2]	0.5 - 1.5	2.0	0.35-0.65	0.73
b	[-]	0.125	0.45		0.93
d’	[mm]	32 - 64	7	3.8	7.2
τ_{cs}	[N/m^2]	0.15	0.20	0.10	0.07
τ_{cu}	[N/m^2]	1.07 – 1.38	0.50	0.20	0.37

Table 6. Performance evaluation between observed and simulated suspended sediment transport evolution.

Rain event	ID 1 17/09/2010	ID 2 31/05/2011	ID 3 24/10/2011	ID 4 13/07/2011
Relative error of peak in sediment concentration	14.4%	1.1%	38.3%	89.1%
NSE - Nash-Sutcliffe efficiency	0.80	0.85	0.73	-0.18