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Sediment and pollutant load modelling using an integrated urban drainage modelling toolbox: an application of City Drain

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ABSTRACT

Numerical and computational modelling of flow and pollutant dynamics in urban drainage systems is becoming more and more integral to planning and design. The main aim of integrated flow and pollutant models is to quantify the efficiency of different measures at reducing the amount of pollutants discharged into receiving water bodies and minimise the consequent negative water quality impact. The open source toolbox CITY DRAIN developed in the Matlab/Simulink© environment, which was designed for integrated modelling of urban drainage systems, is used in this work. The goal in this study was to implement and test computational routines for representing sediment and pollutant loads in order to evaluate catchment surface pollution. Tested models estimate the accumulation, erosion and transport of pollutants—aggregately—on urban surfaces and in sewers. The toolbox now includes mathematical formulations for accumulation of pollutants during dry weather period and their wash-off during rainfall events. The experimental data acquired in a previous research project carried out by the Environmental Engineering Research Centre (CIIA) at the Universidad de los Andes in Bogotá (Colombia) was used for the calibration of the models. Different numerical approaches were tested for their ability to calibrate to the sediment transport conditions. Initial results indicate, when there is more than one peak during the rainfall event duration, wash-off processes probably can be better represented using a model based on the flow instead of the rainfall intensity. Additionally, it was observed that using more detailed models (compared with an instantaneous approach) for representing pollutant accumulation do not necessarily lead to better results.

Key words | Bogotá city, build-up and wash-off processes, calibration and uncertainty analysis, City Drain toolbox, sediment and pollutant load modelling

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INTRODUCTION

In developing countries, efforts tend to be focused on analysing and improving the waste water system performance without taking into account the interactions among sub-systems (the sewer system, the treatment facilities and the receiving streams) and mostly regarding only the quantity component avoiding the water quality issue. Consequently, basin water management is urgently demanding a shift from the fragmented approach towards an integrated one. As part of this, robust modelling of pollutants in urban drainage systems is crucial since an incorrect estimation can easily yield to an inadequate design and management of the system (Dotto *et al.* 2008). Pollution from urban drainage systems is originated mainly from erosion processes triggered by the runoff of particulate pollutants accumulated during dry

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weather periods on the catchment's surface and in the sewer network (Kanso et al. 2005b).

In the last 30 years a number of sewer modelling tools, including sediment modules, have been developed. Despite the efforts that have been made to understand pollutant accumulation, erosion and transport dynamics, stormwater quality modelling still poses difficulties (Kanso et al. 2006; Freni et al. 2009), and the generality and transferability of stormwater pollution models are still limited (Muschalla et al. 2008a). The application of complex models seems to be limited by the absence of adequate data for calibration/validation regarding sediment transport and water quality processes (Deletic & Maksimovic 1998). Monitoring programs are generally conducted at the sewer catchment outlet, thus being representative of the combined effects of both pollutant accumulation and transport. Consequently, simpler conceptual models are usually considered to be appropriate for urban runoff quality modelling (Freni et al. 2009). The most detailed model is not necessarily the most useful and applicable (Bertrand-Krajewski 2007).

The open source toolbox CITY DRAIN (Achleitner et al. 2007) developed in the Matlab/Simulink© environment is used in this work. The software is designed for integrated modelling of urban drainage systems aiming to provide a flexible and adjustable tool for different scenarios. One of the main advantages of this toolbox is the possibility to modify the code behind it or even to implement and add new blocks according to specific needs (Vojinovic & Seyoum 2008). The goal in this study was to implement and test computational routines for representing sediment and pollutant loads which may be applicable to Bogotá's urban drainage and other systems. Following the original aim of CITY DRAIN, the focus was on simple conceptual models for allowing long term simulations. The new components were tested for numerical validity and efficiency.

METHODS

Implemented processes description

The build-up process

Build-up (accumulation) of pollutants on the catchment surface during dry weather periods is of importance to estimate pollutant wash-off (Vaze & Chiew 2002). The factors which affect the solids accumulation process are the antecedent dry weather period (ADWP), street texture and nature, street sweeping–which may have a negative effect (Vaze & Chiew 2002), automobile traffic, vegetation, and the level of urbanisation. As a result, accumulation rates are highly variable and site specific. Several studies have suggested that the rate of accumulation is nonlinear and that there is a limit to the amount of constituents that can accumulate between storms, regardless of the length of dry period (Alley & Smith 1981). It is generally agreed that the build-up or accumulation of sediments on the surface goes on until equilibrium between build-up and decay (due to wind and decomposition) of material is reached (Schlutter 1999).

Since the end of the 1960s a number of studies have been conducted in order to assess accumulation rates and to propose relationships for modelling purposes (Ashley et al. 2004). Because the complexity of the physical phenomena is not matched by our knowledge or quality of data, simple descriptions are commonly used. There are two alternative general models of the accumulation process: the first alternative assumes that the surface pollutant load builds up from zero over the antecedent dry days according to a linear or non-linear law; the second alternative assumes that storm event removes only a fraction of the surface pollutant load and the catchment surface has a similar amount of pollutant mass available for runoff most of the time (Vaze & Chiew 2002). As a consequence, the doubt regarding the necessity of detailed modelling of the accumulation process arises.

The wash-off process

Solids washed off from impervious areas have been identified as the main sources of solids transported, via runoff, into sewer system. This includes grit from abrasion of road surfaces, exposed soil, sand and gravels washed or blown from the catchment or adjacent areas (Gouda et al. 2007). The particles are washed off by combined effect of kinetic energy of rain drops and shear stress of overland flow transported into sewers by surface runoff (Tomanovic & Maksimovic 1996). Parameters involved in wash-off processes are: rainfall intensity (reported as the most important in a number of studies), rainfall volume, rainfall duration, runoff peaks and volume, topography, particle characteristics, type and condition of the street surface, shear stress generated by flow and the energy input of rainfall (Vaze & Chiew 2003). The wash-off is a complex process, as a consequence physically based models are being replaced by conceptual models (Bertrand-Krajewski *et al.* 1993).

Model descriptions

Three different approaches regarding the accumulation processes and five for the wash-off phenomena were implemented in the CITY DRAIN toolbox (see Table 1). This selection of models is mainly based on the benchmark proposed by Kanso *et al.* (2005*c*). This benchmark consists of choosing different configurations of models using the available in situ measurement data. Their results showed that the mathematical model presented here as Model A2 exhibits strong interaction between parameters implying higher uncertainty in their calibration. Additionally, it was found that accumulation can be modelled supposing to be instantaneous–i.e. there is always a sufficient available mass M_{accu}–regardless of the length of the dry weather period. However this finding needs to be validated on other sites as concluded by Kanso *et al.* (2005*c*).

In Table 1, S_i is the impervious area (ha), D_{accu} is the accumulation rate (kg/ha/day), D_{ero} is the erosion rate (d^{-1}), $M_a(t)$ is the available pollutants' mass at time t (kg), K_a is the accumulation coefficient (1/day), M_{accu} (kg/ha) is a calibration parameter, M_l is the maximum accumulated mass (kg/ha), W_e is the erosion coefficient (−), w is a calibration coefficient (−), $I(t)$ is the rainfall intensity (mm/hr), $M_e(t)$ is the pollutant's mass eroded by runoff (kg/h), K_{ero} is a calibration parameter (−), α_{w1} and α_{w2} are numerical coefficients (−), $Q_c(t)$ is the run-off discharge from the sub-catchment (m^3/s), $m_c(t)$ is the mass deposited on the surface at time t (kg/ha), K_{aw} is the rainfall erosion coefficient (−), C_1, C_2, C_3 are calibration coefficients (−), rr is the runoff rate over the catchment (mm/min) and rr is the reference runoff rate (0.42 mm/min), rcoef is a calibration coefficient (min^{-1}), washpo is a calibration coefficient.

Uncertainty analysis in stormwater quality modelling

Its importance and usefulness

There is a lack of data regarding water quality in urban stormwater. Usually, concentrations of pollutants are monitored at very low frequencies in both space and time. As a consequence models are not often calibrated, and uncertainty analyses are not generally carried out (Deletic & Haydon 2006). However, uncertainty analysis is essential for appropriate application of any model (Haydon & Deletic 2009). It is of high importance for understanding the sources of error in the modelling process, to define priorities for model improvement, and for assessing the risk when model results are used in practical decisions (Mitchell & Deletic 2006).

Table 1 | Implemented models in the City Drain toolbox

Process	Equation	Description
Accumulation	$M_a(t) = M_{accu} \cdot S_i$	Model A1 (assumed to be instantaneously)
	$\frac{dM_a(t)}{dt} = D_{accu} \cdot S_i - D_{ero} \cdot M_a(t)$	Model A2 (assumed to be asymptotic, proposed by Alley & Smith (1981))
	$\frac{dM_a(t)}{dt} = K_a \cdot (M_l \cdot S_i - M_a(t))$	Model A3 (mathematical reformulation of Model A2 proposed by Kanso *et al.* (2005*c*))
Wash-off	$\frac{dM_a(t)}{dt} = -W_e \cdot I(t)^w \cdot M_a(t)$	Model W1 (Runoff and $M_a(t)$ are involved)
	$M_e(t) = K_{ero} \cdot I(t)^w \cdot S_i$	Model W2 (Only runoff is involved)
	$\frac{dm_c}{dt} = -\alpha_{w1} \cdot Q_c(t)^{\alpha_{w2}} \cdot m_c(t)$	Model W3 (Schlutter 1999)
	$\frac{dM_a(t)}{dt} = -K_{aw}(t) \cdot M_a(t) = -[C_1 \cdot I(t)^{C_2} - C_3 \cdot I(t)] \cdot M_a(t)$	Model W4 (used in the InfoWorks software)
	$\frac{dM_a(t)}{dt} = -K_w \cdot M_a(t) = -\text{rcoef} \cdot \left(\frac{rr}{rr}\right)^{\text{washpo}} \cdot M_a(t)$	Model W5 (proposed by Sartor *et al.* (1974))

In most of the cases, water quality data available in urban drainage systems are only sufficient to support the development of models with limited complexity. Instead of implementing complex models, it is probably more appropriate to use simple models with well known limits and quantifiable uncertainties (Gaume *et al.* 1998). In models with simple assumptions a quantitative uncertainty analysis can provide useful information to identify how robust the model is (Radwan *et al.* 2004). Potential findings from the uncertainty analysis could lead to more parsimonious models–"as detailed as necessary, as simple as possible" (Schuetze & Alex 2004)–depending on the conditions. Nevertheless, the use of parsimonious models may lead to uncertainty underestimations in model results due to the potential omission of relevant model components (McIntyre 2004).

Approaches for assessing stormwater quality models uncertainty

None of the uncertainty analysis methods presented in specialized literature are universally accepted in urban drainage modelling (Freni *et al.* 2009). Different uncertainty analysis approaches have been applied to different urban stormwater quality models on different scales and for various parts of the urban catchment system. For example Kanso *et al.* (2005*a*) used a Bayesian analysis in order to evaluate the in-pipe erosion model presented by Skipworth *et al.* (1999). The analysis was performed using a Monte Carlo Markov Chain (MCMC) sampling method for calibration and uncertainty assessment. Uncertainties in some of the model parameters suggest that the model could be over-parameterised and necessitates a large amount of informative data for its calibration. As a consequence, the Bayesian analysis led to a reformulation of the erosion model demonstrating the applicability of the MCMC approach. Kanso *et al.* (2005*b*) used the same MCMC sampling method to perform an uncertainty analysis to a hydrologic/hydrodynamic model which estimate the accumulation, the erosion and the transport of pollutants on surfaces and in sewers. Four different types of initial conditions were tested (no deposits in sewers, uniform limited stock of deposit, unlimited stock of deposits and localized deposits). The obtained results indicated high variation of the optimal parameter values depending on the initial conditions, and they indicated as well that the predictive capacity of the model is very low.

An application of the Generalised Likelihood Uncertainty Estimation (GLUE) methodology (Beven & Binley 1992) in pollutant load modelling in sewer systems can be found in Lindblom *et al.* (2007*a*,*b*). It is reported that total copper mass load was predicted within a range of ± 50% of the median value with a conceptual stormwater quality model. Recently, Freni *et al.* (2009) conducted uncertainty analysis using three different methods: the Bayesian Monte Carlo, the GLUE pseudo-Bayesian and the GLUE method revised by means of formal distribution of residuals between the model and measured data. Their results indicated all the models provide good calibration results. Additionally, it was concluded that Bayesian techniques are more efficient for estimating uncertainty; however, they rely on assumptions that must be verified to ensure the reliability of the results.

The GLUE methodology has demonstrated to be an appropriate methodology for comparing the uncertainty and performance of different modelling approaches in relation to the data availability (Freni *et al.* 2008). Consequently, such methodology was selected to be used in this study. It can be summarised as follows: (a) selection of the "a-priori" distributions for each of the model parameters; (b) generation of random sets by means of a Monte Carlo sampling technique; the model is run for each random set and likelihood measures (Nash-Sutcliffe efficiency–E) are calculated, if the likelihood measure is higher than an acceptability threshold, the model simulation is considered "behavioural"; (c) previous steps are repeated until a defined number of behavioural simulations is reached, the likelihood measures can be cumulated for each behavioural parameter and for each corresponding model output, obtaining posterior likelihood distributions; (d) 5% and 95% percentiles of the cumulative likelihood distribution represent the uncertainty bands. In this work, the Monte-Carlo Analysis Toolbox MCAT v.5 (Wagener *et al.* 2004) was used to perform the methodology described.

Case study application: the experimental sub-catchment "El Virrey" in Bogotá (Colombia)

In recent years, research groups in Bogotá have been working in co-operation with the sewer system managers and environmental agencies with the final aim of increasing understanding of the interactions between the sewer system, the wastewater treatment system and the receiving water system using a holistic approach (Rodríguez *et al.* 2008*b*; Díaz-Granados *et al.* 2009; Rodríguez *et al.* 2009; Rodríguez *et al.* In press). As part of this, the first attempt to quantify and analyse the wastewater quality during dry and wet weather flows in the Bogotá sewer system was conducted by means of a pilot study in a combined urban catchment named El Virrey (see Figure 1), located in the Salitre Sub-catchment (Uniandes-EAAB 2001). Main land uses in the catchment correspond to residential (about 40% of the area) and commercial (about 60%). High resolution–one minute–rainfall time series were collected between June 2000 and June 2001 using 3 rain gauges with resolution of 0.1 mm. Wastewater dry weather flows and runoff produced during wet weather were monitored using 3 automatic ISCO samplers coupled with one ultrasonic level sensor and one multiparametric sonde (between August 2000–August 2001) at two catchment outlets (Caracas 77 and Flores 88). The catchment area associated with Caracas 77–identified as I in Figure 1–has approximately 85 ha with 6,200 inhabitants, while the area associated with Flores 88–identified as II in Figure 1–has about 135 ha with 14,700 inhabitants.

There are in total 15 available events in which water quality samples were taken during wet weather conditions at either one or both of the monitored sites. The number of samples per event ranges between 0 and 24 at Caracas 77 and between 0 and 22 samples at Flores 88. Table 2 includes the main characteristics of two rainfall events which were used to test the implemented models as these events have the highest number of samples at both sites simultaneously (24 samples at Caracas 77 and 14 at Flores 88 for the event of 3 May 2001, and 24 samples at Caracas 77 and 19 at Flores 88 for the event of 8 May 2001).

RESULTS AND DISCUSSION

Initially the models were calibrated manually in order to identify suitable parameter sets–ranges–to be used in an

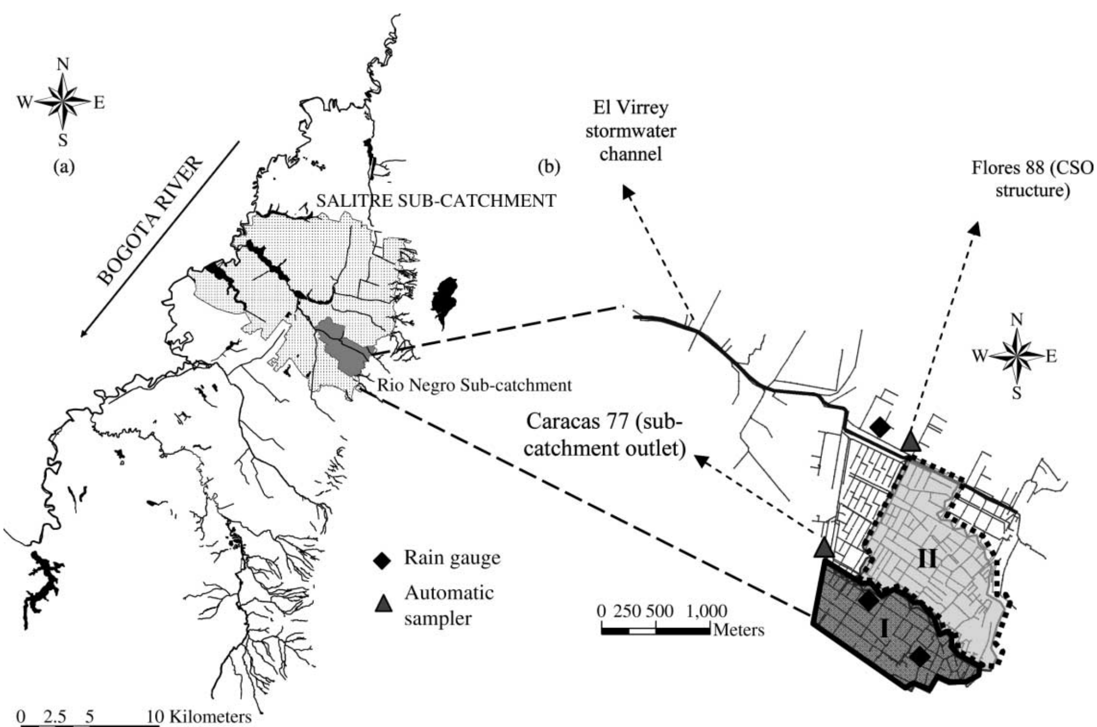

Figure 1 | (a) El Salitre sub-catchment (b) experimental sub-catchment El Virrey.

Table 2 | Rainfall events characteristics

	ADWP (days)	Total depth (mm)	Total duration (h)	Average rainfall intensity (mm/h)
03/05/2001	3.48	11.6	5.60	2.07
08/05/2001	2.05	12	3.52	3.41

objective-based procedure such as the GLUE methodology. The calibration is performed first for the hydrology and hydraulics only and second for the quality processes. Normally, the hydraulics are considered independent from the quality processes but not vice versa (Muschalla *et al.* 2008*b*). In the CITY DRAIN toolbox, stormwater runoff is modelled using a catchment loss model–which accounts for initial and permanent losses–coupled with a simplified Muskingum routing method, having as inputs rain volume per time step, dynamic dry weather flow, dynamic infiltration flow and wastewater/stormwater flow introduced from an upstream catchment. The rainfall events on the 3 and 8 of May 2001 were selected to test the suitability of the software to be coupled with automatic calibration procedures and the GLUE methodology. As an example, Figure 2 shows obtained results, which are considered to be satisfactory as E ranges between 0.95 and 0.97, from simulating rainfall runoff processes at Caracas 77.

Obtained results from total suspended solids (TSS) concentration modelling indicate that for the event on the 3 of May 2001 at Caracas 77 best results ($E = 0.73$) were obtained using the A1 coupled with W3 model (see Figure 4). Model W3 is the only model which is based on the runoff discharge instead of the rainfall intensity. It can be concluded when there is more than one peak during the rainfall event duration it probably can be better represented using a model based on the flow instead of the rainfall intensity. Figure 3 clearly demonstrates the inability of the W1 model to represent the wash-off process at the watershed outlet due to structural model

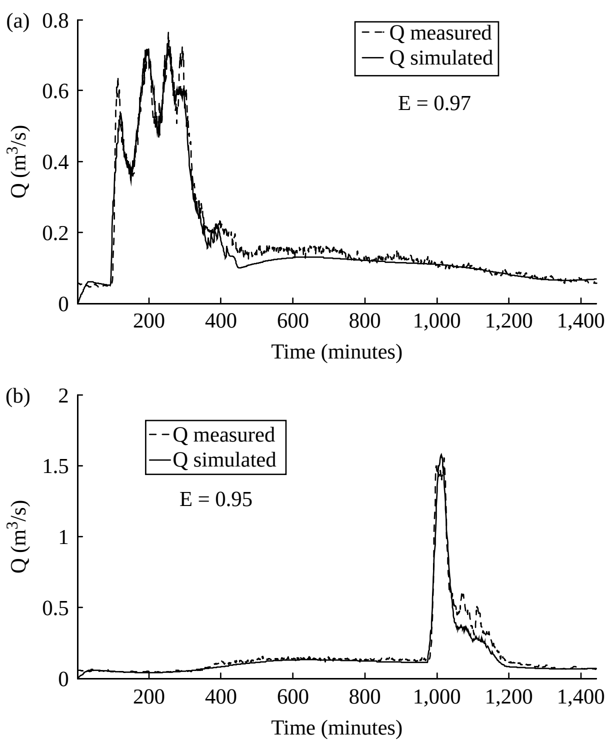

Figure 2 | Rainfall runoff calibration for (a) the event on the 3 of May 2001 and (b) the event on the 8 of May 2001 both at Caracas 77.

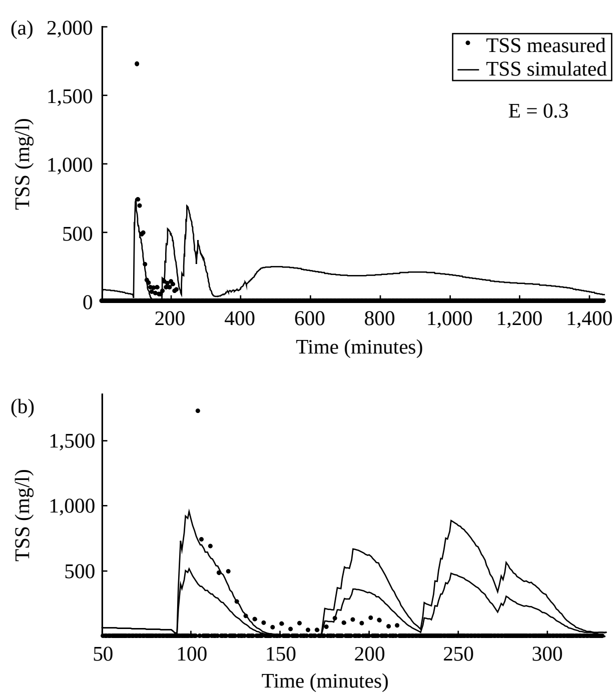

Figure 3 | Simulation of total suspended solids (TSS) concentration for the event on the 3 of May 2001 at Caracas 77 using A1 and W1 models (a) one-day period modelling results (b) details during wet weather period—5 and 95% confidence limits.

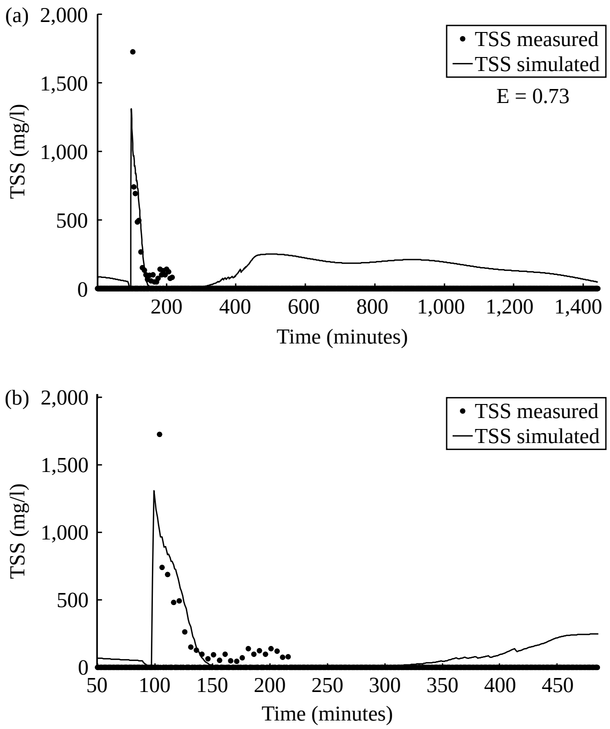

Figure 4 | Simulation of total suspended solids (TSS) concentration for the event on the 3 of May 2001 at Caracas 77 using A1 and W3 models (a) one-day period modelling results (b) details during wet weather period.

limitations as the confidence limits do not include measured data. Similar results were obtained for the W2 and W5 models. Additionally, the A2 and A3 models provided no significant improvements on the A1 model for representing the accumulation processes. These preliminary findings reinforce the conclusion presented by Kanso *et al.* (2005*c*) that accumulation may be modelled as instantaneous (Figure 4).

For the event on the 8 of May 2001 at Caracas 77 the best results ($E = 0.62$) were obtained using the A1 and W2 models (see Figure 5). Comparing with the rainfall event on the 3 of May, flow at the catchment outlet only presents one main peak. Analysing the same event at Flores 88, it was observed that W1, W2, W3 and W5 models can lead to equal efficiency results. However, when comparing confidence limits it was noticed that W2 and W5 models have a better structural capability for simulating the wash-off process as they include most of the measured data (see Figure 6).

In the context of Bogotá, there is other ongoing research which is addressing topics such as spatial and temporal rainfall variability and its impact on the hydrological response, and the first flush load of total dissolved solids in combined sewer systems (Rodríguez *et al.* 2008*a*). This is being conducted by means of a pilot study in a 41 Ha urban catchment with a combined drainage system located in the campus of the Universidad Nacional sede Bogotá. The main land cover types in the catchment are rural (about 55% of the area) and institutional (about 45%). High resolution rainfall time series have been collected since April 2007 using 14 rain gauges. Dry weather and wet weather flows and quality are monitored using one automatic ISCO sampler, two ultrasonic level sensor and two multiparametric sondes. The same numerical approaches described above were tested. It has been concluded, as above, that the simpler the numerical approach in terms of number of parameters the better the calibrated model can represent the sediment transport conditions (Estupiñán *et al.* 2009).

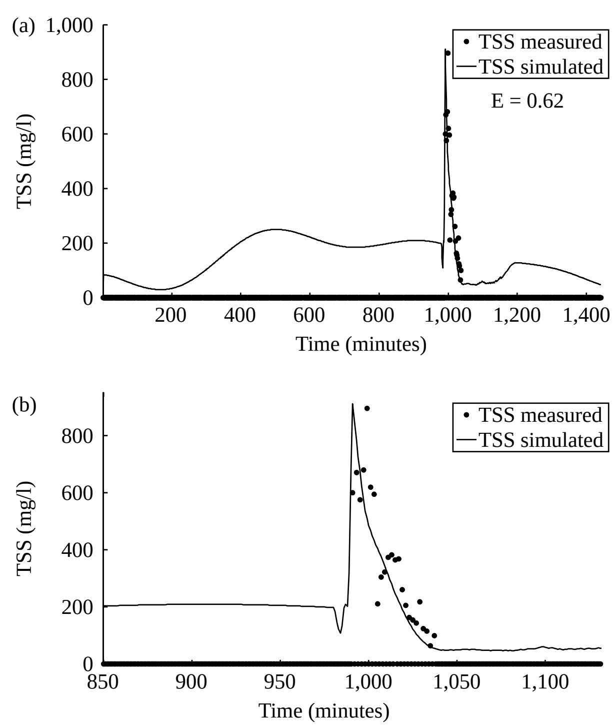

Figure 5 | Simulation of total suspended solids (TSS) concentration for the event on the 8 of May 2001 at Caracas 77 using A1 and W2 models (a) one-day period modelling results (b) details during wet weather period.

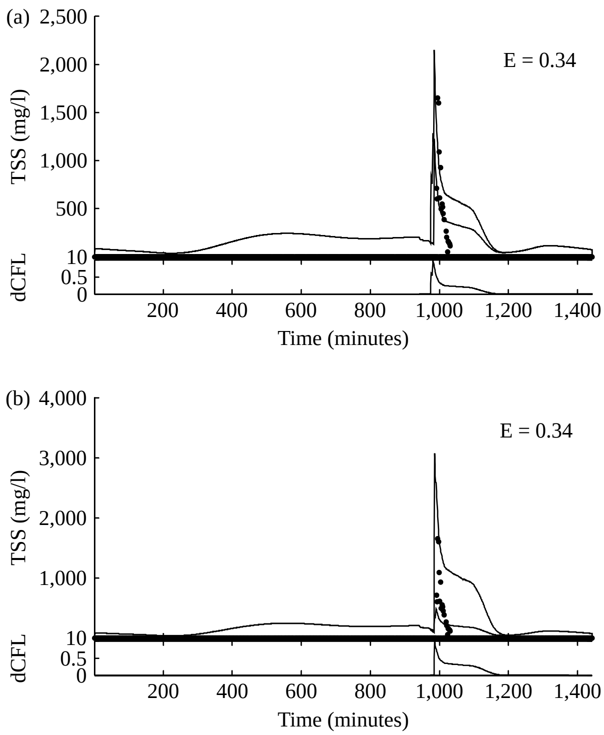

Figure 6 | 5% and 95% confidence limits from simulating total suspended solids (TSS) concentration for the event on the 8 of May 2001 at Flores 88 (a) using A1 and W3 models and (b) using A1 and W5 models were dCFL is the normalised difference between upper and lower confidence limits.

CONCLUSIONS

Initial results have demonstrated the usefulness of uncertainty analysis when comparing modelling approaches. Ongoing modelling work is using all available data from monitored events at El Virrey sub-catchment in order to obtain more robust conclusions. Additionally, it is planned to assess the performance of implemented urban stormwater quality models by means of comparative modelling of different case studies. Comparing results and performance of different case studies, with different characteristics in their boundary conditions and data sets, offers the opportunity to perform more robust analysis and tests on the developed modelling approaches. It is also proposed to analyse the effect of the number of calibration data (e.g. % of available data used for calibration vs. % of available data used for validation) on the uncertainty in models of different levels of complexity. By comparison of different build-up/wash-off models it could be possible to draw more specific conclusions for this specific type of pollutant load models regarding calibration and validation data.

It is also planned to couple the sediment build-up/wash-off modelling approaches presented in this paper with a model predictive control (MPC) strategy based on a pattern-search method for the sewer system operation. The final aim is to reduce the amount of pollution released from CSO structures during wet weather conditions by means of an efficient use of storage capacities and pumping stations. The MPC controller uses a model of the system which predicts its future behaviour and identifies the best actions to apply in order to minimize undesired consequences in the receiving system. This control strategy has been recently applied using the City Drain toolbox for modelling and controlling a set of urban catchments in Bogotá illustrating the potential of the approach (Leirens *et al.* 2010).

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