**Lumped and distributed modelling of suspended solids in a combined sewer catchment in Santiago de Compostela (Spain).**

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**Abstract** This paper presents a comparison of lumped and distributed modelling approaches of the combined sewer system of El Ensache (Santiago de Compostela, Spain). Both models were built using Infoworks CS software and the Ackers White equation and the KUL were employed for the analysis of the sewer sediment transport. Previous to the model calibration, a sensitivity analysis of the different Infoworks quality modules was performed with the Hornberger-Spear-Young methodology. The sensitivity analyses showed that the model is more sensitive to the buildup factor, the washoff exponent coefficients and to the sediment diameter ($d_{50}$). The results also show that the lumped model is easy to calibrate and behaves better than the distributed model in terms of the Nash-Sutcliffe efficiency index. Nevertheless, the distributed model performs better for thepollution peak predictions.
**Keywords** Sediment transport model; distributed model; lumped model; combined sewer; sensitivity analysis.

## INTRODUCTION

For modelling the solid loads and concentrations in combined sewer system flows, different processes can be considered, such as the dust and dirt buildup, the washoff in urban catchment surfaces or the erosion and deposition of sediments in sewer systems. The modelling of the pollution transport processes is much more complex than the hydraulic modelling. Several sediment transport equations can be found in the literature (see for instance Banasiak and Tait, 2008) but the accurate implementation of these models is often difficult because of the large number of model parameters and also due to the model structure uncertainty errors.

In order to gain some knowledge about water quality modelling in sewer systems, this paper presents a comparison between a lumped and a distributed model, both built with Infoworks CS. In the two approaches, the Ackers White equation (Ackers et al. 1996) and the KUL model (Boutelegier and Berlamont, 2002) were employed in the analysis of ten rain events recorded in a combined sewer catchment in the North of Spain.

## METHODS

### Description of the study site and the model development

Two different models of the urban catchment El Ensanche of Santiago de Compostela were developed using Infoworks CS 8.5. El Ensanche is a residential and commercial catchment, with high population density and heavy road traffic (Figure 1). The catchment has an approximate area of 23.8 ha, with a 94% of impervious surface constituted mainly by building areas 68%, and a population of 10300 people. Catchment surfaces and pipes are steep, with a 4% of average slope, causing the hydrographs to present large peak flows and short concentrations times.

Two different models were built using different levels of complexity. Thus, the distributed model contains 316 subcatchments divided into three different land uses: (i) 183 street catchments, (ii) 128 roof catchments and (iii) 5 pervious areas. The topology of this sewer network was introduced from the GIS data provided by Aquagest, the company that manages the sewerage system of Santiago de Compostela. The aggregated or lumped model presents a much simpler configuration, and consists of one single catchment and one single pipe. Thus, while the catchment surface presents overall the same features as in the distributed model, the modelled conduit is formed with the same diameter and slope as the main trunk of the sewerage system (D=500 mm).

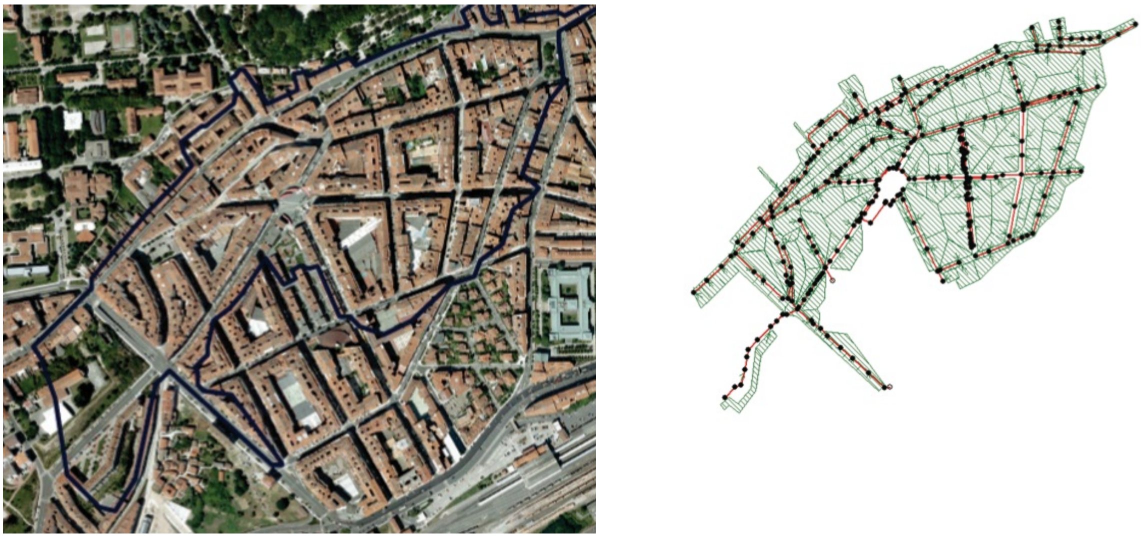

**Figure 1**. Layout of the El Ensanche catchment and the Infoworks CS distributed model.

Both models were calibrated using the data from a control section placed in the outlet of the catchment. The control section consists on a HACH-SIGMA 950 area-velocity flow meter and an automatic HACH-SIGMA sampler, which allows water quality measurements in dry and wet weather conditions. The rainfall data was obtained from the regional weather service (Meteo-Galicia) meteorological station of Santiago-Campus (rainfall resolution of 10 min). Hydraulic and pollution data were recorded with 5 min resolution. The flow meter was operative for 14 months (June 2008 – August 2013), during which 10 rain events were recorded in wet-weather flow conditions. Weekdays and weekend patterns of flow and pollution were recorded in dry-weather conditions (see more details in del Río, 2011).

## Infoworks CS quality submodules

The in-sewer pollution modelling in Infoworks is divided in different sub-models that account for the different processes occurring during a rain event. The pollution generation module is the responsible of simulating the dry weather flow and pollution. The buildup model evaluates the mass of sediment $M_0$ (Kg/ha) accumulated on the catchment surface during dry periods with the following equation:

$$M_0 = \frac{P_s}{K_1}\left(1 - e^{-NJ \cdot K_1}\right) \tag{1}$$

where $NJ$ is the duration of the dry period (days) , $P_s$ is the buildup factor (Kg/(ha·day)) and $K_1$ is the decay factor (day$^{-1}$).

The washoff module estimates the amount of sediment introduced into the sewer system from the catchment surfaces. The washoff module incorporates several equations related with the mass balance of the sediment in the surface. Nevertheless, Inforworks CS limits the model tuning parameters to the erosion/dissolution factor $K_\alpha(t)$:

$$K_\alpha(t) = C_1 i(t)^{C_2} - C_3 i(t) \tag{2}$$

where $C_1$, $C_2$ and $C_3$ are the model parameters and i(t) is the effective rainfall (m/s).

Finally, the transport module evaluates the sewer erosion and deposition processes. In this work the Ackers White equation (Ackers et al. 1996) and the KUL model (Boutelegier and Berlamont, 2002) were applied. In the Ackers White equation only the sediment particle size $d_{50}$ and the specific density of the sediment fraction $s$ can be considered for the model calibration. The KUL model is based on the definition of two limit shear stresses that determine the threshold for sediment erosion and deposition. The KUL model has three calibration parameters for the definition of the erosion processes and another three for the deposition. These parameters are the threshold shear stress for sediment erosion and deposition ($\tau_{crit,e}$ and $\tau_{crit,d}$), two linear coefficients ($\alpha_e$ and $\alpha_d$) and two power coefficients ($\beta_e$ and $\beta_d$):

$$q_s = \alpha_e \left( \frac{\tau - \tau_{crit,e}}{\tau_{crit,e}} \right)^{\beta_e} ; \quad q_s = \alpha_d \left( \frac{\tau - \tau_{crit,d}}{\tau_{crit,d}} \right) \tag{3}$$

where $q_s$ is the sediment transport and $\tau$ is the actual non-dimensionless shear stress.

The critical shear stresses are calculated using the following equation, which involves a new parameter called erosion or deposition parameter $\gamma_e$ or $\gamma_d$ respectively:

$$\tau_{crit,e} = \gamma_e g(s-1)\rho \cdot d_{50}; \quad \tau_{crit,d} = \gamma_d g(s-1)\rho \cdot d_{50} \tag{4}$$

In addition, the user has to define the mean particle diameter and the sediment specific density. A possible approach to reduce the number of model parameters consists on equalling the $\gamma_d$ parameter to the Shields dimensionless shear stress and considering $\gamma_e$ equal to this same value but multiplied by a certain factor (roughly 3). Therefore, an interval for the conditions between the erosion and deposition processes can be created (Shirazi and Berlamont, 2010).

The main drawback of this approach is that it requires the evaluation of the granular Reynolds number in each time step making the erosion and deposition vary over time, which is actually not allowed in Infoworks. Because of that, a different method, using the Ota and Nalluri (2003) equation, was proposed in order to estimate the KUL model parameters. This equation evaluates the dimensionless transport parameter $\Phi$ using the dimensionless shear stress $\theta_b$ as:

$$\Phi = 24\left(\theta_b - 0.036\right)^{1.67} \tag{5}$$

where $\Phi = q_s / \left(\rho_s \sqrt{g d_{50}^3 s}\right)$ and $\theta_b = \tau / (g d_{50} (\rho_s - \rho))$. Comparing these terms and the Ota and Nalluri equation (5) with the KUL equations (3) and (5) the KUL parameters can be obtained with the following expressions:

$$\left.\begin{aligned} \gamma_e &= 0.036 \\ \alpha_e &= \rho_s \sqrt{g d_{50}^3 s} \cdot 24 \gamma_e^{\beta_e} \\ \beta_e &= 1.67 \end{aligned}\right\} \quad (6)$$

Assuming that $\gamma_d$ is affected by the same factor as the parameter obtained with the Shield's diagram procedure, this methodology makes possible to estimate all the KUL model parameters as a function of the mean sediment diameter and the specific gravity, which remain constant during the whole simulation process.

## RESULTS AND DISCUSSION

### Sensitivity analysis of Infoworks CS quality submodules

Prior to the development of the model calibration, a set of sensitivity analyses of the quality modules of Infoworks CS was developed following the methodology proposed by Kleidorfer (2009). The sensitivity tests included local sensitivity analyses, graphical analyses of the model parameters and the Hornberger-Spear-Young (HSY) methodology. As a formal (e.g. Monte-Carlo) inference approach is missing in Infoworks CS (Schellart et al. 2010), the model sensitivity analysis was applied to each Infoworks quality module by programming the different subroutines in Matlab.

All the performed sensitivity tests showed similar results (see more details in Hermida, 2012). In this paper, only the results of the HSY methodology are shown in Figure 2. This method consists on evaluating repeatedly the model in a Monte-Carlo framework, and comparing the model outputs from a set of sampled parameters with the results of a "synthetic" calibration run by means of the Nash–Sutcliffe efficiency index (E). Simulation results with E>0 were classified as "behavioural results" and simulations with E<0 as "non–behavioural". Finally, the comparison of the cumulative distributions of the two groups allows measuring the parameter sensitivity as the maximum vertical distance between the cumulative distributions *d* (Kleidorfer, 2009).

Regarding the buildup subroutine (equation 1), the tests showed that the model is more sensitive to the buildup factor $P_s$ than to the buildup coefficient $K_1$, although both parameters seems to be important in the calibration processes. The washoff equation (eq. 2) showed a lack of sensitivity to the coefficient $C_3$ (Hermida, 2012) and therefore this coefficient was set equal to 0. The distributions for $C_1$ and $C_2$ are significant different, hence the model output is sensitivity to both parameters ($d$=0.21 and $d$=0.24). Finally, Ackers White and KUL transport equations are sensitive to the variation of the sediment size and the sediment specific gravity, although the importance in terms of model variation is greater for the sediment size.

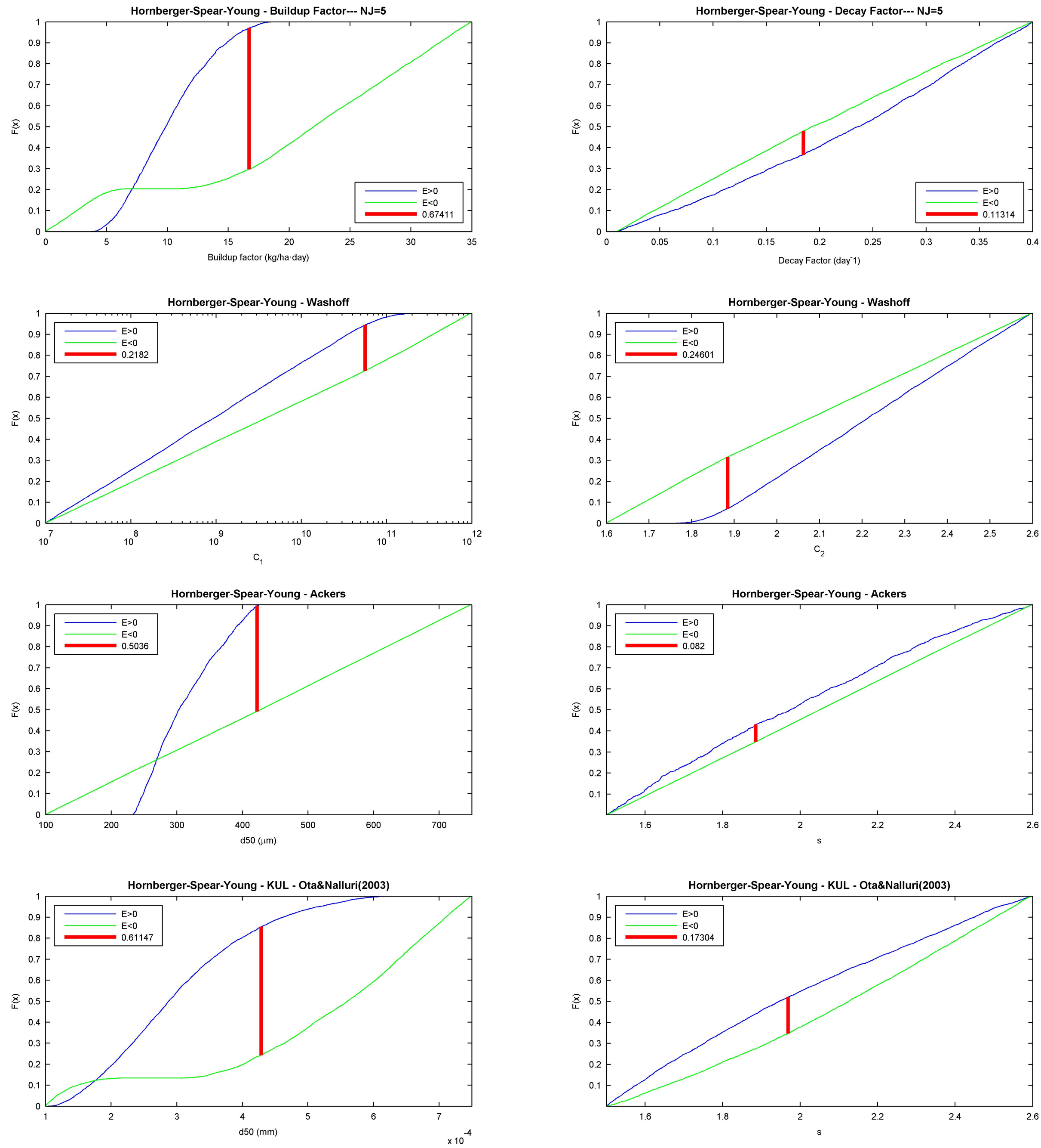


**Figure 2**. HSY analysis of the buildup, washoff, Ackers White and KUL expressions..The calibration model parameter values are $P_s$=8, $K_1$=0.08, $C_1=10^8$, $C_2$=2, $d_{50}$=300 μm and s=2, while *d* is maximum the distance between the cumulative distributions. Further details about the variation ranges of the model parameters are shown in Hermida (2012).

## Model calibration

For the simulation of the rain-runoff transformation the Storm Water Management Model non-linear reservoir model was selected in Infoworks CS. The hydraulic calibration of the lumped and the distributed models was performed using two flow records of 5 days characterized by a sequence of different rain events. The parameters chosen for the calibration of the models were the dry weather base flow, the impervious area and the initial loss of the “road” and “roof” land uses and the “roof” slope. During the calibration procedure, the Manning coefficient of the different land uses was fixed constant. After a preliminary calibration of the runoff volume and discharge peaks, the Nash-Sutcliffe efficiency index was maximized in a step-by-step procedure. The obtained results are quite satisfactory for both models, obtaining mean vales ranging from 0.81 to 0.93.

The calibration of the quality models was also performed with a non-formal step-by-step inference procedure. For the calibration of the lumped Ackers-White and KUL models, as well as for the distributed Ackers-White and KUL models, data from events #3, #5 and #7 were used. The calibration procedure consisted on the visual inspection of the registered and simulated TSS pollutographs. Thus, the process started with the calibration of the buildup parameters firstly, then continued with the washoff parameters and lastly the sediment parameters of the transport equations were estimated. The obtained parameters are shown in Table 1 and reflect similar results for the lumped and distributed models. Slight differences in the sediment size and density can be observed between the different discretization approaches as the sediment are coarser and denser in the aggregated models.

**Table 1**. Summary of the different model calibration values.

| Quality module | Model parameter | Lumped Model | | Distributed Model | |
|---|---|---|---|---|---|
| | | Ackers -White | KUL | Ackers -White | KUL |
| Buildup | $P_s$ | 5 | 5 | 5 | 5 |
| | $K_1$ | 0.18 | 0.18 | 0.18 | 0.13 |
| Washoff | $C_1$ | $10^9$ | $10^9$ | $10^9$ | $10^9$ |
| | $C_2$ | 2 | 2 | 2 | 2 |
| Sediment | $d_{50}$ | 1.6 | 1.6 | 1.2 | 1.2 |
| Transport | $s$ | 300 | 300 | 100 | 100 |

The model validation reflects some discrepancies between the recorded and the simulated rain events, especially for events #1, #4 and #6. The differences between the model output and the registered data can be attributable to a non-proper simulation of the dry weather flows and pollution (see Figure 3) and also to deficiencies in the model behaviour (model structure errors). Table 2 presents a comparison of the results obtained in the TS modelling and the different approaches used in this work. The results show that the lumped model is easy to calibrate and behaves better than the distributed model in terms of the Nash-Sutcliffe efficiency index. The distributed model seems to predict better the sediment peak concentrations. Nevertheless, neither the KUL nor the Ackers White sediment transport model provide a clear agreement about which of the two models is best in terms of this index, the errors in suspended solids peak concentrations or the errors in the simulation of the TS event mean concentrations.

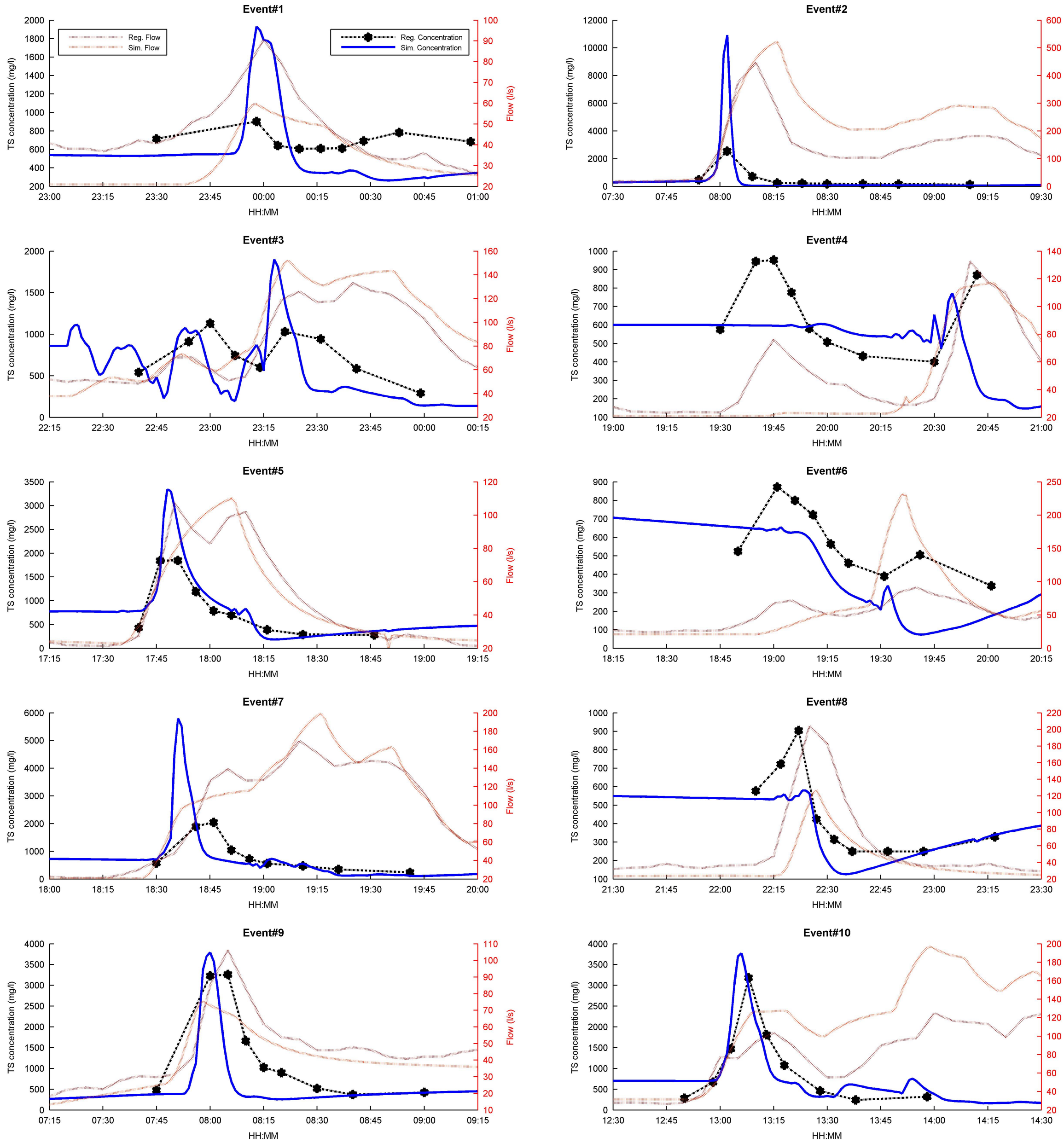


**Figure 3**. Results for the KUL lumped model applied to the events recorded at El Ensanche.

**Table 2**. Summary of the TS model accuracy obtained with the different modelling approaches: average Nash – Sutcliffe index for outputs with E>0 (the number of events is shown in parenthesis) and average relative error in the determination of the maximum and event mean concentration of TS ($\delta_{Cmax}$ and $\delta_{EMC}$)

| Model | Sediment transport equation | E>0 | $\delta_{Cmax}$ | $\delta_{EMC}$ |
|---|---|---|---|---|
| Lumped | Ackers - White | 0.72 (6) | 37% | 13% |
| | KUL | 0.56 (5) | 58% | 29% |
| Distributed | Ackers - White | 0.27 (3) | 38% | 26% |
| | KUL | 0.48 (5) | 28% | 23% |

## CONCLUSIONS

The simulation of sewer pollutants in Infoworks has been shown to be very complex. For this purpose, the application of sensitivity analyses has been revealed to be very useful, showing good behaviours and providing accurate results, specially the global sensitivity analyses. After applying the information gathered in the sensitivity analyses on the model, and comparing the output with the recorded data, two modelling techniques were compared. Of these two modelling approaches, the lumped models provided the most accurate results, being, at the same time more easily implementable. In terms of the transport models, none of the two models could be highlighted, since both the Ackers White and the KUL transport model presented results approximately equal. Thus, while the Ackers White performed better in the lumped approach the KUL model is more accurate in the distributed approach.

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