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Estimation of uncertainty in long term combined sewer sediment behaviour predictions, a UK case study

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ABSTRACT

There are regulatory driven requirements for UK water companies to reduce the number of properties at risk of sewer flooding. One of the potential causes of sewer flooding is the presence of persistent sediment deposits in sewers. This is a common problem in many combined sewers. Although the regulation is risk based, there is a gap in current knowledge on how risk assessment is affected by the uncertainty in sewer solids behaviour prediction. This paper describes a UK case study exploring the possibility of estimating uncertainty in sewer sediment deposit level predictions, using Monte Carlo simulations combined with a response database.

Key words | combined sewers, response database, sediment management, sediment transport, uncertainty

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INTRODUCTION

The presence of persistent sediment deposits in sewers is a common problem in many combined sewer systems. Knowledge about the build-up and erosion rates of sewer sediment is necessary to facilitate better sediment management strategies. Sewer sediment phenomena, however, are not well understood and as a consequence, current sediment transport modelling techniques often provide predictions which are significantly different from observation. Amongst sewer operators this has resulted in a lack of confidence in sediment prediction tools and therefore model-based planned sediment management is rare as it is perceived to be too difficult to predict sediment behaviour with sufficient certainty (Ashley *et al.* 2004). One of the areas in sewer solids research that needs more attention was identified by Ashley *et al.* (2005), as the estimation of uncertainty in model results. In England and Wales, sewer systems are managed by water companies, which are economically regulated by OFWAT. OFWAT measures the performance of the water companies using DG's (Director General) indicators of which DG5 is the indicator for 'sewerage service'. DG5 is estimated by measuring aspects of service, one such aspect is the number of properties estimated to be at risk of sewer flooding twice in 10 years and the number of properties actually flooded by sewers in a 10 year period (OFWAT 2006). Hence, if a sewer is thought to be at risk of flooding as a consequence of in-sewer sediment deposits, the risk of occurrence and the risk associated with different levels of sediment deposits needs to be established. This paper describes a case study exploring the possibility of estimating uncertainty in sewer sediment deposit level predictions in a combined UK sewer network.

The use of a design storm approach, such as for the prediction of the recurrence period of flooding due to hydraulic overloading of sewers, is problematic when predicting sediment levels. Sediment deposits tend to build up over longer time periods and any subsequent sediment movement is heavily dependent on the sediment present

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before erosion. It is difficult to assess the length of time and the conditions required for in-sewer deposits to reach an equilibrium state (if such conditions actually exist). Hence, long-term (months or years), multi-event modelling is necessary. Long term modelling tools currently available include commercial deterministic models such as Infoworks CS, or simpler conceptual models such as described in Willems (2004).

Given the lack of confidence in current predictions, it would be useful to provide sewer operators not only with long term predictions of sediment behaviour but also with an estimate of the levels of uncertainty associated with these predictions. One method to accomplish this is to build a 'probabilistic shell' around a deterministic model, as described by Rousseau *et al.* (2001), Bixio *et al.* (2002) and Benedetti *et al.* (2006). However, this is not feasible in many cases due to the computational complexity of the large sewer network models and the need to simulate many months of flow conditions. The previous attempts by Rousseau *et al.* (2001), Bixio *et al.* (2002) and Benedetti *et al.* (2006) all used simple conceptual models. When the aim of the model is to calculate the uncertainty in prediction of sediment levels in different pipes in a sewer system, a conceptual probabilistic approach that simplifies the sewer system into a single reservoir cannot be used as it will not adequately simulate the erosion, deposition and transport of sediment through different conduits at different times, under different hydraulic conditions.

The aim of this study was to gather insight into the uncertainty related to long term sediment behaviour predictions in combined sewer systems and conclude how these findings could improve information provided to operators involved in combined sewer management. The paper reports on exploring the possibility of using the 'response database' method (Dahal *et al.* 2005), a method similar to the 'response surface' method (Khuri & Cornell 1987), developed in other engineering disciplines, for calculating the levels of uncertainty in long-term sediment deposition predictions at a network scale.

METHODS

Initially, a deterministic sediment transport model for the case study based on the Ackers (1984) relationship for calculating sediment transport capacity in sewers, was coded in Matlab (12 pipes in total, Figure 1). Sediment movement was modelled from its input from catchment surfaces via the model nodes, to its transport, erosion or deposition by examining the difference in sediment transport capacity between adjacent pipes. Hydraulic input for the Matlab sediment transport model was generated by an Infoworks model of the whole network. Hydraulic predictions from the existing Infoworks model of the whole network was compared against measured rainfall and flow data collected locally for the major trunk sewer of the field study.

An initial study was carried out on the impact of uncertainty in key physical input parameters of the Ackers (1984) relationship and the uncertainty related to the formulation of the Ackers (1984) relationship (Schellart 2007). Data for determining probability distributions of key physical model input parameters had been gathered during a 2-year field study in a combined sewer in the UK.

The original data used for deriving the Ackers (1984) model, from White (1972), were used for estimating model uncertainty associated with relationship calibration parameters. In order to save computing time, initial Monte Carlo analysis was carried out for different pipes in the system over short periods of time (periods of several minutes, taken from the long-term simulation during storms), to compare the relative importance of uncertainty in different input parameters and uncertainty inherent in using the Ackers (1984) model. Conclusions from this initial analysis identified the factors contributing most to the uncertainty in sediment transport capacity prediction to be: representative particle size (d_{35}), hydraulic roughness and model transport capacity uncertainty. The d_{35} value has been determined for each of the 89 sediment deposit samples taken during the field study, and a lognormal distribution has been fitted to all d_{35} values (Table 1). In Schellart (2007) it was argued that the roughness (k_s) in the case study system could at any time vary between 3 mm and 30 mm, as was also shown by Wotherspoon (1994). A normal distribution was therefore derived to represent this variation in hydraulic roughness (Table 1). The model uncertainty has been expressed as the ratio of measured sediment transport capacity (G_{gr} measured) versus modelled sediment transport capacity (G_{gr} modelled). The average ratio G_{gr}measured to G_{gr}modelled has been calculated for 30 randomly selected data sets from White (1972). A lognormal

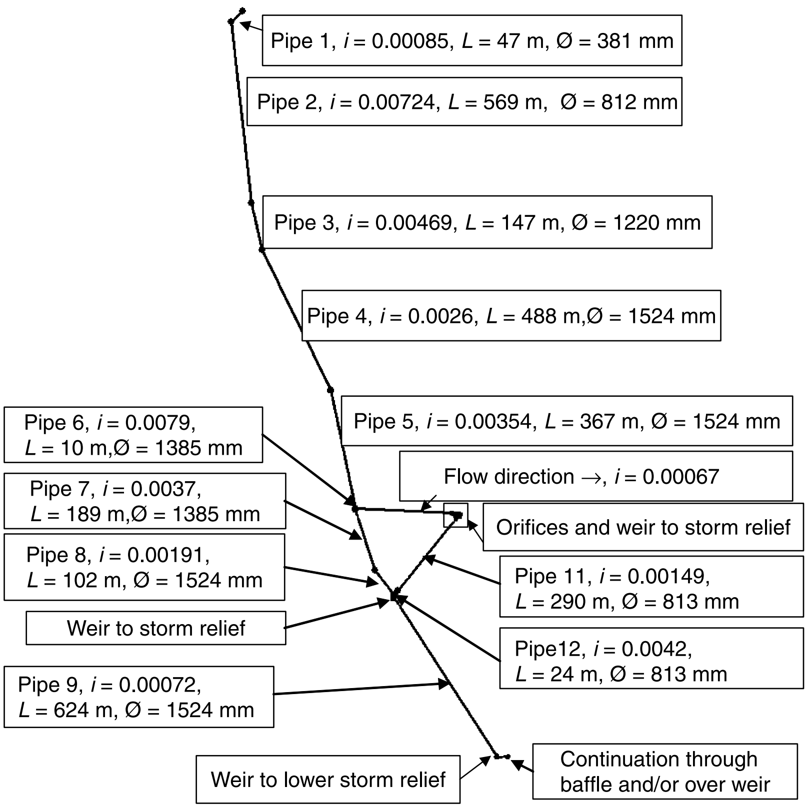

Figure 1 | Description and location of the pipes coded in the deterministic sediment transport capacity model (i = invert gradient, L = length of the pipe, Ø = pipe diameter).

distribution has been fitted to the 30 average G_{gr} measured to G_{gr} modelled ratios (Table 1).

The distributions in Table 1 (see also top left box, Figure 2), have been used to estimate uncertainty in sediment deposition prediction for a six month period of rainfall, in the 12 pipes of the case study network, by running Monte Carlo simulations combined with a response database. The process of Monte Carlo simulation combined with a response database is illustrated in Figure 2.

By studying the probability distributions in Table 1, fixed equidistant arrays of values that cover the potential range of hydraulic roughness, d_{35} and G_{gr} measured to G_{gr} modelled ratio values have been selected (top right box, Figure 2):

- Representative particle size (d_{35}) from 0.25 mm to 2 mm in steps of 0.25 mm.
- Hydraulic roughness from 3 mm to 27 mm in steps of 6 mm.
- G_{gr} measured over G_{gr} modelled ratio from 0.5 to 5 in steps of 0.5.

The response database was then created by calculating the deposit levels in each of the 12 pipes for all 400 possible combinations of d_{35}, hydraulic roughness and the G_{gr} measured to G_{gr} modelled ratio, using the deterministic sediment transport model coded in Matlab in combination with the Infoworks model (centre right box, Figure 2).

Similar to conventional Monte Carlo analysis, a large number of random draws (10,000 in this study) were made to create 10,000 random sets of input parameters (centre

Table 1 | Probability distributions derived for the three most influential factors on uncertainty in sediment transport capacity predictions

	Distribution type	Mean	Standard deviation
Hydraulic roughness	Normal	16.5 mm	4.5 mm
Representative particle size (d_{35})	Lognormal	0.75 mm	0.63 mm
Ratio G_{gr}measured over G_{gr}modelled	Lognormal	1.72	1.9

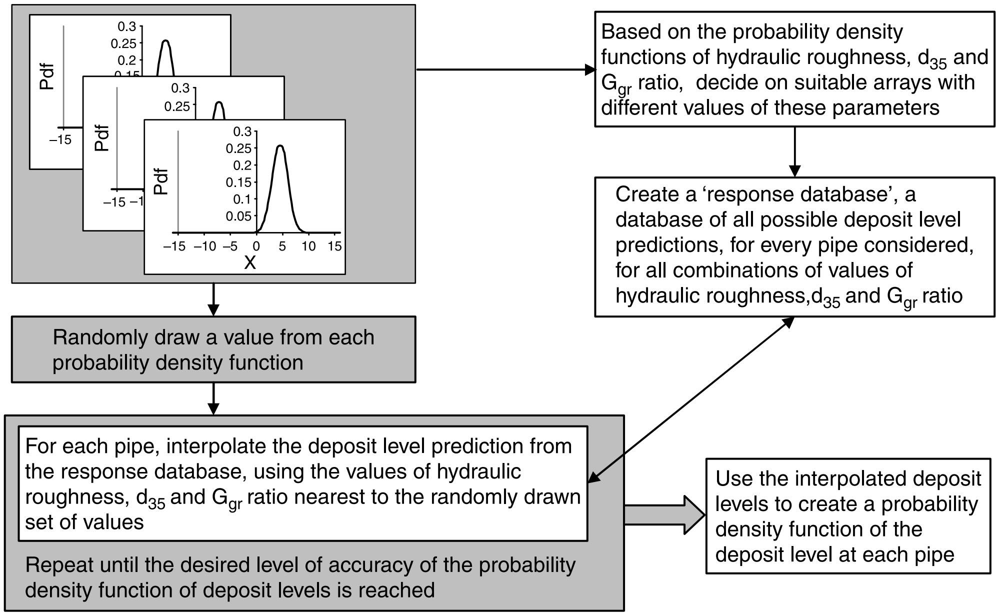

Figure 2 | Schematic illustration of Monte Carlo simulation using a response database.

left box, Figure 2). After randomly drawing each set of input parameters, the resulting deposit levels were linearly interpolated to form a response database (bottom left box, Figure 2). These deposit levels were then used to create probability density functions for deposit levels in each of the 12 pipes (bottom right box, Figure 2).

RESULTS

Figure 3a and 3b compare the deterministic and probabilistic prediction results for pipe 8 in the field study network after a six month period which included a number of wet weather events. Deterministic predictions were made for three different particle sizes and indicate a 0.06 m deep deposit for $d_{35} = 1.42$ mm, 0.14 m deep deposit for $d_{35} = 0.75$ mm and 0.27 m deep deposit for $d_{35} = 0.36$ mm. According to the response surfaces (Figure 4b) discontinuities in the cumulative density function (*cdf*) are mainly caused by uncertainty in particle size, followed by model uncertainty and then uncertainty in roughness. The *pdf* (probability density function, see Figure 4a) shows two peaks, at deposit level 0.06 m and at deposit level 0.27 m. When estimating the deposit levels in pipe 7, just upstream of pipe 8 (results not shown), and pipe 8 in a deterministic way, using the average d_{35} derived from all

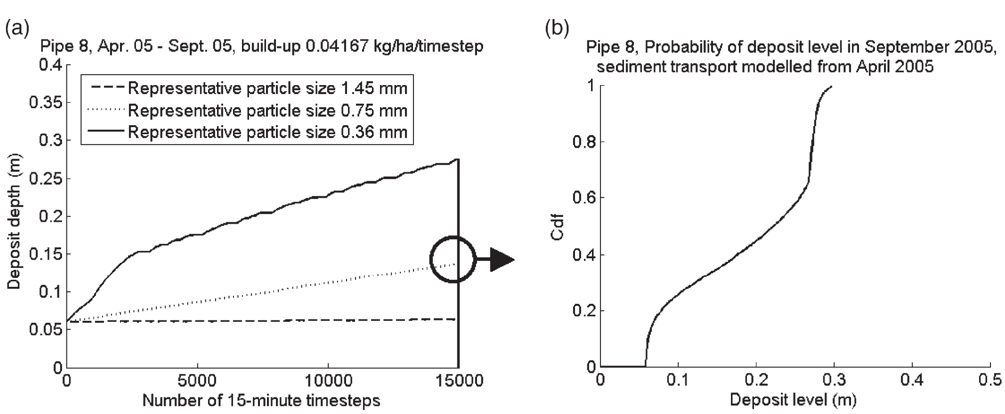

Figure 3 | Comparison between deterministic and probabilistic results of deposit build-up modelling for pipe 8, April 2005 – September 2005.

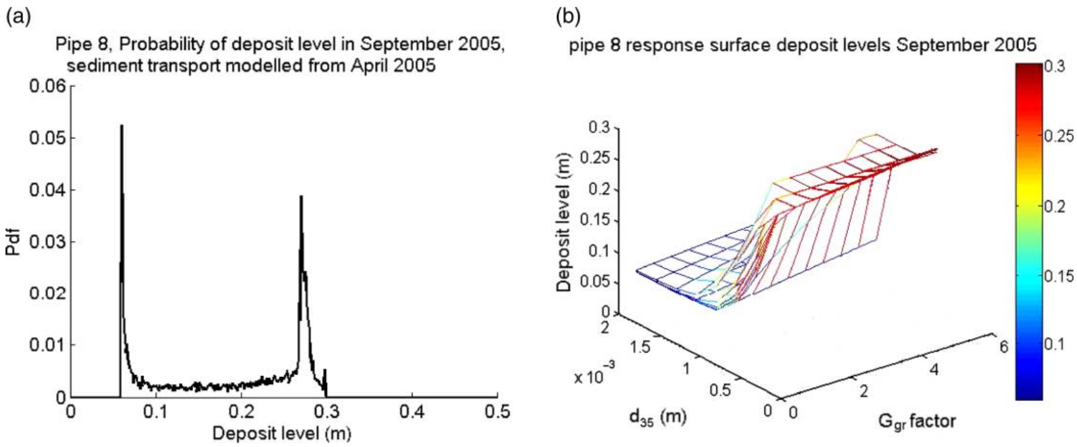

Figure 4 | Probability density function for deposit depth in pipe 8, and response database for pipe 8, plotted as five 3-D surfaces (one surface for each roughness value). Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwapublishing.com/wst.

samples, it was expected that the predicted deposit levels would be distributed equally between both pipes, at approximately 0.13 m in each. When examining the *pdfs* for both pipes, however, it seems more likely that, depending on particle size, most solids will deposit either mainly in pipe 7 or mainly in pipe 8. The *pdf* of pipe 7 as well as pipe 8 does not show a peak in probability density for deposit levels of 0.13 m.

Table 2 summarises the results of deterministically predicted deposit levels for three average d_{35} values derived from samples from three different parts in the system, and the 90% confidence interval when using the distribution for d_{35} derived for all samples from the system. The 90% confidence levels nearly always cover the range of the deterministically predicted levels. In pipe 1, 6 and 12, they also show that there is a possibility that the deposit levels may become considerably higher than expected from the deterministic model results.

Table 2 | Comparison of deterministic deposit level predictions with probabilistic deposit level predictions (90% confidence interval) for period April – September 2005 in the case study system

Pipe Nr.	Deterministic prediction of deposit level (m) d_{35} = 0.36 mm	d_{35} = 0.75 mm	d_{35} = 1.42 mm	Probabilistic prediction of deposit level (m) 90% confidence interval Mean d_{35} = 0.75 mm
1	0.01	0.01	0.01	0–0.23
2	0	0	0	0
3	0.02	0.15	0.16	0–0.15
4	0.06	0.02	0.01	0–0.06
5	0	0	0	0
6	0.01	0.01	0.01	0–0.30
7	0	0.13	0.17	0–0.16
8	0.28	0.14	0.07	0.06–0.28
9	0.19	0.19	0.18	0.17–0.19
11	0	0.05	0.09	0–0.09
12	0	0.01	0.03	0–0.20

Hence the most probable outcomes in terms of in-sewer sediment deposit level may not be well described by the use of deterministic models using input parameters set at 'average' values. This is in accordance with McEwan & Heald (2001), who suggested that mixed grain size transport prediction would be improved by using a probabilistic modelling approach rather than by representative mean values.

DISCUSSION

In order to create the response database, the Infoworks CS model had to be run 5 times (for hydraulic roughness values from 3 mm to 27 mm in steps of 6 mm) and the bespoke sediment transport model 400 times (to represent all different combinations of Representative particle size from 0.25 mm to 2 mm in steps of 0.25 mm, and Ggr measured over Ggr modelled ratio from 0.5 to 5 in steps of 0.5).This is much faster than calculating all deposit levels per pipe using Infoworks CS and the bespoke sediment transport model directly for 10,000 times. Creating the response database took less than two weeks rather than several years of computational effort as would be the case when using the existing network models combined with a traditional Monte Carlo approach. Improving calculation speed using a grid computer system would also not be feasible, without having to re-design and re-code the hydraulic network simulation software to optimise it for Monte Carlo type calculations. Currently, each randomly drawn set of input parameters would have to be input into Infoworks and output saved before and after each simulation. Individual simulation times for these complex networks is also not trivial.

There are, however, two drawbacks of the response database method. The first one was the assumption that the function between any two values in the response database is linear. The steps between the input parameters in the response database therefore need to be selected carefully so that they are small enough to reasonably estimate the effect of combining different sources of uncertainty. The second point, in both the response database method, as well as the method used by Rousseau *et al.* (2001), Bixio *et al.* (2002) and Benedetti *et al.* (2005), is that the set of uncertain input parameters are not varied *during* the long time series. The influence of this is not known, as the Monte Carlo analysis would then have to be run over *each subsequent time step* of the deterministic model. This is as yet, at least for the case study described in this thesis, not feasible as it would take several years to run.

The modelling results indicated that uncertainty in grain size, followed by model uncertainty in Ackers (1984), had the greatest effect on overall uncertainty in deposit level. The influence of the variability in hydraulic roughness and other hydraulic variables was more minor in the long term predictions.

CONCLUSIONS

Carrying out Monte Carlo simulations by interpolating from a response database requires significantly less computational resources when compared with 'traditional' Monte Carlo simulations. The response database can be readily adapted for use with commercial software packages that are not suitable for use with traditional Monte Carlo simulation techniques.

This paper demonstrated that the level of uncertainty associated with the predictions of in-sewer deposit depths calculated over a period of six months could be estimated for a sewer system. This has demonstrated that in certain pipes the level of uncertainty could provide a significant range of possible predicted deposit depths, whilst in other pipes the range of predicted depths was much smaller.

This type of probabilistic modelling showed that the most probable outcomes in terms of in-sewer sediment deposit level are not likely be accurately described by the use of deterministic models using input parameters set at 'average' or default values. More research would have to be carried out on the time-dependency of the statistical descriptions used to describe the uncertain model input parameters.

REFERENCES

Ackers, P. 1984 Sediment transport in sewers and the design implications. *Proc. Int. Conf. on Planning, Construction, Maintenance and Operation of Sewerage Systems*. BHRA (Cranfield), Reading, UK, 215–230.

Ashley, R. M., Bertrand-Krajewski, J.-L., Hvitved-Jacobsen, T. & Verbanck, M. 2004 *Solids in Sewers, Characteristics, effects and control of sewer solids and associated pollutants*, (*Scientific and Technical Report No. 14*), IWA Publishing, ISBN 1 900222 91 4.

Ashley, R., Bertrand-Krajewski, J.-L. & Hvitved-Jacobsen, T. 2005 Sewer solids–20 years of investigation. *Water Sci. Technol.* **52**(3), 73–84.

Benedetti, L., Bixio, D. & Vanrolleghem, P. A. 2006 Assessment of WWTP design and upgrade options: balancing costs and risks of standards' exceedance. *Water Sci. Technol.* **54**(6–7), 371–378.

Bixio, D., Parmentier, G., Rousseau, D., Verdonck, F., Meirlaen, J., Vanrolleghem, P. A. & Thoeye, C. 2002 A quantitative risk analysis tool for design/simulation of wastewater treatment plants. *Water Sci. Technol.* **46**(4–5), 301–307.

Dahal, M. R., Petry, B., Gelder, van, P. H. A. J. M., Gupta, S. & Vrijling, J. K. 2005 Reliability analysis of flood defences using importance sampling and response database with probabilistic loops in large hydraulic models. Proceedings ISSH – Stochastic Hydraulics, 23–24 May 2005, Nijmegen, The Netherlands.

Khuri, A. I. & Cornell, J. A. 1987 *Response Surfaces: Design and Analyses*. Marcel and Dekker, New York.

McEwan, I. K. & Heald, J. G. C. 2001 Discrete particle modelling of entrainment from flat uniformly size beds. *J. Hydraulic Eng.* **127**(7), 588–597.

OFWAT 2006 Level of service for the water industry in England and Wales, http://www.ofwat.gov.uk/aptrix/ofwat/publish.nsf/AttachmentsByTitle/los2006.pdf/$FILE/los2006.pdf

Rousseau, D., Verdonck, F., Moerman, O., Thoeye, C., Meirlaen, J. & Vanrolleghem, P. A. 2001 Development of a risk assessment based technique for design/retrofitting of WWTPs. *Water Sci. Technol.* **43**(7), 287–294.

Schellart, A. N. A. 2007 Analysis of uncertainty in the sewer sediment transport predictions used for sewer management purposes. PhD thesis, submitted. University of Sheffield, UK.

White, W. R. 1972 *Sediment Transport in Channels: a General Function*. Report INT 104, Hydraulics Research Station, England, June 1972.

Willems, P. 2004 Parsimonious pollutant washoff and sewer transport modelling. Proc. Int. Conf. on Urban Drainage Modelling, Dresden, Germany. pp. 461–469.