GIS-based applications of sensitivity analysis for sewer models

M. Mair, R. Sitzenfrei, M. Kleidorfer, M. Möderl and W. Rauch

ABSTRACT

Sensitivity analysis (SA) evaluates the impact of changes in model parameters on model predictions. Such an analysis is commonly used when developing or applying environmental models to improve the understanding of underlying system behaviours and the impact and interactions of model parameters. The novelty of this paper is a geo-referenced visualization of sensitivity indices for model parameters in a combined sewer model using geographic information system (GIS) software. The result is a collection of maps for each analysis, where sensitivity indices (calculated for model parameters of interest) are illustrated according to a predefined symbology. In this paper, four types of maps (an uncertainty map, calibration map, vulnerability map, and design map) are created for an example case study. This article highlights the advantages and limitations of GIS-based SA of sewer models. The conclusion shows that for all analyzed applications, GIS-based SA is useful for analyzing, discussing and interpreting the model parameter sensitivity and its spatial dimension. The method can lead to a comprehensive view of the sewer system.

Key words | capacity design, combined sewer system, GIS applications, model calibration, uncertainty assessment, vulnerability assessment

M. Mair (corresponding author)
Hydro-IT GmbH,
Technikerstr. 13,
6020 Innsbruck,
Austria
E-mail: *Michael.Mair@uibk.ac.at*

R. Sitzenfrei
M. Kleidorfer
M. Möderl
W. Rauch
Unit of Environmental Engineering,
University of Innsbruck,
Technikerstr. 13,
6020 Innsbruck,
Austria

INTRODUCTION

Sensitivity analysis (SA) is a state of the art method used by applications and during the analysis of case studies to improve the understanding of underlying system behaviour (Saltelli *et al.* 2006). The aim of a SA is the exploration of changes in model output induced by changes in model input.

Before using a model to describe and predict real system behaviour it has to be calibrated. This is done by finding a valid set of model parameter assignments such that the resulting model output matches measured data of real system behaviour (accurately enough). As calibrating a model can be a time-consuming and complex task, *a priori* knowledge obtained through SA can be a valuable input for optimization and calibration algorithms. For instance, in Osuch-Pajdzinska & Zawilski (1998) a storm sewer model was studied according to particular model parameter changes. It was found that only a small portion of all the investigated model parameters significantly affected model output. Similar results have been reported by Dotto *et al.* (2010, 2011). These studies compared water quantity and quality models of different complexity (i.e. different numbers of model parameters) and found that their performance was indifferent due to the lack of sensitivity for most parameters of the complex model. Sensitivity analyses and optimization algorithms are essential parts of a state-of-the-art calibration technique. Both of them have to evaluate possible solution candidates. A possible solution candidate is represented by one assignment set of all model input parameters. The evaluation can be done manually or automatically. In the paper by di Pierro *et al.* (2006), automatic calibration of urban storm water runoff models was investigated. Apart from a single objective function, multi-objective functions are also used to find a global optimum within the corresponding fitness landscape. A spatial reference of the sensitivity of each model parameter would be of great value for manual and automatic calibration.

Input parameter uncertainties are an omnipresent feature of each sewer system model (Kleidorfer *et al.* 2009a). They can decrease the accuracy of a model significantly. For instance, Bertrand-Krajewski *et al.* (2003) accounted for sensor calibration, data validation, measurement and

doi: 10.2166/wst.2012.954

sampling uncertainties in monitoring urban drainage systems. Amongst others, James *et al.* (1998) discussed the optimization of influences from uncertainty, complexity and cost for modelling combined sewer systems. Kleidorfer *et al.* (2009b) investigated data requirements for a sufficiently calibrated model. The economics of model development and calibration become of interest for consultants and researchers when calculating total project costs. James *et al.* (1998) effectively illustrate the correlation between cost and uncertainties. With a geographic information system (GIS)-based application of SA, those uncertainties can be considered in the modelling process more effectively.

Risk is the combination of the probability of an event and its consequence (Leitch 2010). The risk source is often referred to as a hazard in case its consequence does not fulfil a certain risk criteria (ISO Guide 1990). In the context of combined sewer system risk analysis, this means that consequences such as increased combined sewer overflow and pluvial flooding can be obtained by multiplying hazard zone maps (representing the probability of an event at a spatial dimension) with combined sewer network vulnerability maps (UN DHA 1992). Vulnerability maps show broken system components (risk sources) where the consequence is not serious. An example of a system-wide vulnerability assessment approach is shown in Ezell (2007) where a value model was used to measure the vulnerability of infrastructure (Infrastructure Vulnerability Assessment Model, I-VAM). Vulnerability assessment tools (Brashear & Stenzler 2007) aid in describing critical facilities and assets to be protected by identifying system vulnerabilities and determining the level of protection to which the security system should be designed. Möderl *et al.* (2009) use these assumptions in a spatially distributed SA for identifying weak points in urban drainage systems.

The novelty of this paper is the spatial mapping of model parameter sensitivity to the modelled sewer network with the aid of GIS software. The focus is on combined sewer models taking into account four different applications of SA (model calibration; uncertainty assessment; vulnerability identification; conduit and storage volume design).

MATERIAL AND METHODS

In the literature, methods for SA are identified and discussed (Frey & Patil 2002). Techniques for sensitivity assessment range from quantitative variance-based methods to other forms of global sensitivity with regional properties (Tang *et al.* 2007), down to the simplest screening approaches which alter one model parameter in a simulation run and analyze the variation in the resulting model output (e.g. the One-factor-at-a-time (OAT) method). In this work, the GIS-based application of SA is shown for combined sewer systems. In a first step, the sensitivity of model response towards parameter changes is investigated with a local SA. This is done by changing the values in the vector of model parameters independently (OAT). Although the disadvantage of the OAT method not considering parameter interdependencies is known, it is used in this paper for its simplicity. The presented approach can certainly be used with more complex analysis techniques (regional, global SA, etc.). The response can be spatially referenced at the location of its origin using GIS software. To indicate and compare model results of pluvial flooding and combined sewer overflows, various SWMM5 (Rossman 2004) model simulations (for a design storm events) are analyzed. A module, which performs SA and spatial referencing of model results in parallel on a multi-core system was developed and implemented in the freely available open source GIS package *SAGA GIS* (Cimmery 2010).

Figure 1 shows the basic workflow of the developed SAGA GIS module. The input is a SWMM5 model for which the GIS-based SA is performed. The results are sensitivity maps, in which the impacts of system component changes (i.e. parameter variation, e.g. conduit roughness) on the entire system performance are mapped at their origin and coloured/shaded according to their sensitivity.

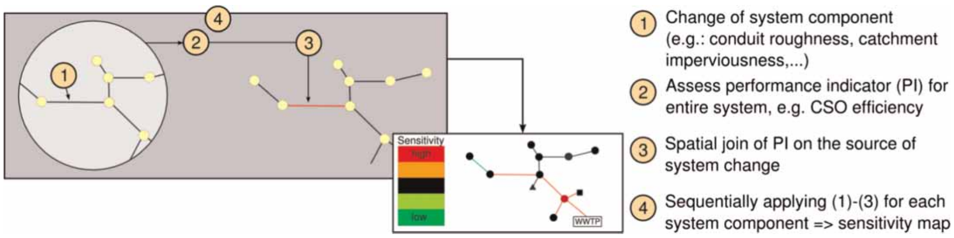

Figure 1 | Sensitivity map workflow.

Each model simulation run is independent of the previous simulation run allowing for parallel processing.

Application of specific parameter variation

In this paper, four applications of SA are presented: (1) model calibration; (2) uncertainty assessment; (3) vulnerability identification; as well as (4) conduit and storage volume design. Model calibration analyses the impact of model parameter changes on model simulation results (1). In the context of uncertainty assessment, SA investigates the impact of changes in model input parameters on model simulation results (2). Each of the four applications corresponds to a spatial identification and variation of model parameter values for SA.

1. For model calibration, the investigated parameters are catchment imperviousness and conduit roughness, which are both limited by physical boundaries. The resulting map indicates where one can start with parameter variation or grouping of several parameters to decrease the search space during a manual or automatic calibration.
2. For uncertainty assessment, conduit length is investigated as an example of measurement error. In this case, uncertainties are a consequence of measurement or data collection errors. The resulting map displays the influence of such an error for model predictions.
3. For the identification of vulnerabilities, the investigated parameter is conduit capacity. Setting the capacity to zero is equivalent to simulating collapse of the conduit. This represents the risk source (hazard). The resulting map displays the impact of each collapsed conduit event on the entire system performance.
4. The investigated parameters for conduit and storage design are conduit cross-section and storage unit-volume. Varying these parameters shows possible solutions to increase the transport and storage capacity (e.g. replacing a conduit with a higher diameter or providing more storage volume at a junction). If failing conduits are replaced, a new diameter can be chosen. This map indicates sites where an increased conduit capacity or increased storage volume is most effective.

Parameter configurations are summarized in Table 1. The parameter variations are conditional to the application of the sensitivity map (e.g. data uncertainty range in the case of the uncertainty map, possible building measures in the case of the design map). For other objectives, other parameter variations can be introduced. The aim of this investigation is to identify locations in the system where model parameters are more sensitive compared with others (i.e. ranking of parameter sensitivities). In this paper the magnitude of the variation for each selected model parameter can be seen as an example value. Investigations showed that the variation has only low impact on the prioritization. For example varying the length of conduits (uncertainty map) ±50% instead of ±100% results in the same prioritization of elements.

Table 1 | Summary of investigated applications

Application	Element-parameter	Variation	Performance indicator
Uncertainty assessment	Conduit length	Times 2	*S*
Vulnerability identification	Conduit capacity	To zero	*F*
Conduit and storage design	Conduit cross-section	Times 2	*F*
	Storage-unit volume	+10,000 m^3	*E*
Model calibration	Catchment imperviousness	Times 0.5	CSO discharge
	Conduit roughness	Times 2	CSO discharge

Application of specific performance indicators (PIs)

In order to assess the behaviour of a system, it is not effective to display all system states in spatial and temporal dimensions. Therefore, PIs can act as information filters to aggregate the amount of data. The PIs have to be a sufficient representation for the type of system behaviour that is under consideration. Here, PIs that indicate changes in model output of combined sewer systems are required. The most important system behaviours which are under question are water pollution and urban flooding. In this study the following three PIs are used and discussed. All of them range between 0 (worst performance) and 1 (perfect system behaviour):

- The CSO efficiency is used in Austrian guidelines (ÖWAV-RB 19 2007; Kleidorfer & Rauch 2011) to evaluate a combined sewer system performance over a simulation period of at least 10 years with measured rainfall data. The indicator represents the percentage of surface runoff (*E*) which is treated at the waste water treatment plant (WWTP) as an average over the simulation period. Instead of using a long-time series for each variation, design storm events are used to compare system behaviours according to different boundary conditions. The PI is calculated based on the ratio of total combined sewer overflow volume of the entire system and total surface runoff generated.

$$E = 1 - \frac{\text{Overflow}}{\text{Surface runoff}} (-)[0, 1]$$

- Surcharge is a result of insufficient transport capacity in pipes and should be reduced to an acceptable degree (return period). Zones of surcharge can grow to a flooding region if more intensive rainfall is predicted in future, and thus are relevant for design. The PI value for surcharge (S) equals one minus the number of surcharged nodes divided by the total number of nodes.

$$S = 1 - \frac{\#\text{Surcharged nodes}}{\#\text{Nodes}} (-)[0, 1]$$

- When estimating urban floods due to sewer system overload, a high resolution of spatial detail is usually required to identify possible weak points in the system. In contrast, when using a one dimensional model, the flooded volume per manhole is assessed. Here, a system-wide PI is used to indicate the probability of damage caused by pluvial flooding (F). A weighting function is evaluated at each junction. This takes a value of one in case of no pluvial flooding and a value of zero if a flooding volume of x cubic metres occurs in the simulation period. Finally, the average over all junctions (J) is calculated. For the evaluations in this work, a value of $x = 50\ \text{m}^3$ is assumed. Choosing this value (F) results in a sufficient range of results in order to prioritize nodes. If x is increased, the range of results of (F) will decrease and converge to (F) = 0. By decreasing x the results of (F) converge to (F) = 1.

$$F = \frac{\sum_{i=0}^{\#J} \min(x, \max(0, F_i))/x}{\#J} (-)[0, 1]$$

The PIs used in the evaluation of results for the different SA applications are summarized as listed in Table 1.

Spatial representation

For each parameter variation of a network element, first, the corresponding result of the model output (i.e. variation in the PIs) is calculated. Second, this variation in the PI value is spatially allocated to the cause (the network element under question). With this workflow it is possible to draw sensitivity maps using GIS. For regional SA (where two or more parameters are varied simultaneously), this definition has to be enhanced. Each variation in the PI is spatially allocated to each involved cause, which results in a vector of PI-results in each cause. Now it is possible to map one value (e.g. maximum value – maximum sensitivity) of this vector to the corresponding network element and draw a sensitivity map.

Description of case study

The case study comprises an alpine city, with a total catchment area of 2,076 ha (impervious area 774 ha), drained with a gravity-driven combined sewer system. Only one pumping station and some storage basins are present to reduce combined sewer overflows at several outfalls. The model consists of about 300 nodes. Total storage volume is 5,100 m^3. A further description of the case study is available from Kleidorfer *et al.* (2009c). The design storm event (EULER II, De Toffol 2006) has a return period of two years.

The parallel simulations for all four maps took <1 h for this model. The benchmark system is a high end multi-core system containing two Intel® Xeon® X5650 @ 2.67 GHz processors and a 24 GB DDR3 ram (shared memory). Each of the processors has 12 MB of L2 cache and six cores. On the total number of 12 cores on this system, 24 hardware threads in Hyper-threading mode are running.

RESULTS

Maps of the four SA applications (uncertainty, calibration, vulnerability and capacity design) are presented below along with an interpretation and discussion of their value.

Uncertainty assessment

Uncertainty assessment techniques are applied to estimate the confidence of model predictions with respect to uncertainties that plague input and calibration data as well as model parameters. The analysis usually involves estimating confidence bounds of model predictions by propagating different sources of uncertainties through a model. It should not only be used in the context of model development, but also in conjunction with model application. In this work, uncertainty maps are a means of their visualization. Here, uncertainties are not expressed as bounds but as parameter sensitivities. These maps display regions of parameters, which have a high impact on the overall model prediction uncertainty. In this case study, measurement uncertainties are taken into account. Other sources of uncertainty can also be visualized where required.

Although the determination of the conduit length is simple and not cost intensive, data collection of sewer systems is frequently accompanied by significant errors when determining pipe length. Reasons for this can be both blunt errors and sloppiness due to time pressure. In this context, the sensitivity map in Figure 2 is calculated based on the variation of pipe length (see Table 1) and measured with a system PI for surcharge (*S*). The green coloured conduits (Figure 2) represent low to no impact on surcharge (*S*). Red coloured conduits have a high PI change as a consequence. The position indicated with (1) in Figure 2 shows a red coloured conduit. If that length is doubled, additional storage volume can be activated. This will consequently decrease the flooding volume and therefore increase the system PI (*S*).

Vulnerability identification

Identification of vulnerability is usefully in the frame of a risk analysis as critical points – revealing high consequences for the system performance – can be eliminated after detection. Vulnerability maps indicate the consequences in the case of a potential component failure. These maps therefore aid in the identification of critical points in the system. Conduit collapse is investigated in this paper, but other hazardous events such as combined sewer overflow surcharge or pump failures can be simulated and mapped as well (see e.g. Sitzenfrei *et al.* 2011). Traffic accidents with explosive goods or system aging can cause such a collapse of a conduit. For the vulnerability map, the capacity of each conduit is reduced to zero and the consequent sensitivity to PI for pluvial flooding (*F*) is mapped. In Figure 3, a vulnerability map for the case study is shown. The

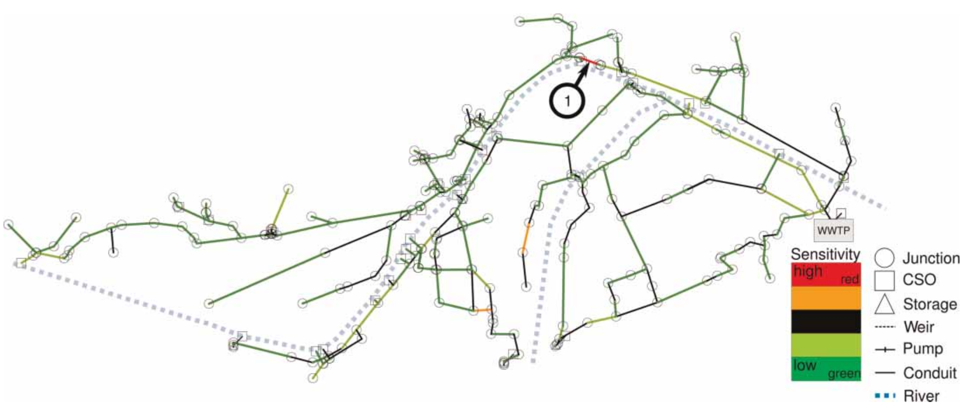

Figure 2 | Uncertainty map.

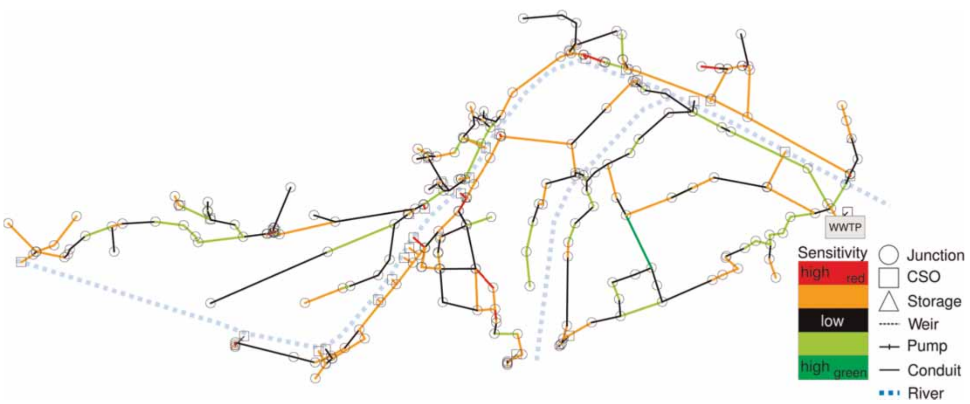

Figure 3 | Vulnerability map.

conduits in dark green indicate a positive effect on pluvial flooding, while dark red refers to an increase in flooding volume. Collapsed pipes, which result in an improvement, reduce the flooding, because more water is discharged in the receiving water body. A negative consequence is the release of polluted waste water. This effect is not captured by the adopted PI (F). To capture these, a new system indicator has to be investigated, which may be a combination of PIs (F) and (E).

This kind of sensitivity map allows an engineer to identify vulnerable system components fast. Moreover, it can be used as basis for risk analysis by joining vulnerability maps with hazard zone maps.

Conduit and storage design

One of the most important applications of an urban drainage model is to determine the required cross-section design e.g. in the frame of adaptation or rehabilitation planning. For this purpose, a sensitivity map is drawn to illustrate the variation of conduit capacity. The sensitivity of conduits is measured by the PI for pluvial flooding (F). To reduce flooded nodes, alteration of the conduit designs highlighted in red and black is most effective. Other conduits reveal low sensitivity. Furthermore, the impact of an additional storage unit at junctions is evaluated (shown in Figure 4). Strategies for implementing storage units with a capacity of 10,000 m^3 are devised by placing such units at each manhole. The impact of the storage volume on CSO emission efficiency (E) is visualized at the junctions. The most effective sites for storage are indicated with green.

In the case of the design map towards storage units, the results of the introduced SA were compared with the result of a best practice planning process of a consultant. The conclusions regarding design where nearly identical. But the time for the investigation diverges significantly. For best practice techniques, several months of repeated calculations can be required in complex systems to obtain the same results that can be achieved in hours with the proposed automated method.

Model calibration

In the presented case, CSO discharge volume into the receiving water body is the defined objective for model calibration. Hence, it is a measurable system property; no special PI has to be investigated. To analyze the sensitivity of each system component, results are divided by the CSO discharge volume of the initial model. A calibration map is thus drawn, joining the values of CSO discharge volume to the corresponding elements (shown in Figure 5). Such a map depicts the impact of changing a sub-catchment's imperviousness or conduit roughness. In this case, conduit roughness and percentage of imperviousness of the sub-catchment area are the parameters used for model calibration. Thus, the sensitivities of these parameters are analyzed. The system components indicated in green can be used to increase the objective function's value by increasing the value of the system component. Red coloured system components can be used to decrease the objective's value by decreasing the value of the component. The red and green coloured components represent highly sensitive model parameters. White coloured junctions are insensitive because they have no connected sub-catchment area. For a rough calibration, it is recommended to start with the more sensitive system components. Most of the junctions are coloured in green because by decreasing the imperviousness of sub-catchments also the CSO discharge volume decreases, hence no red coloured junctions are in

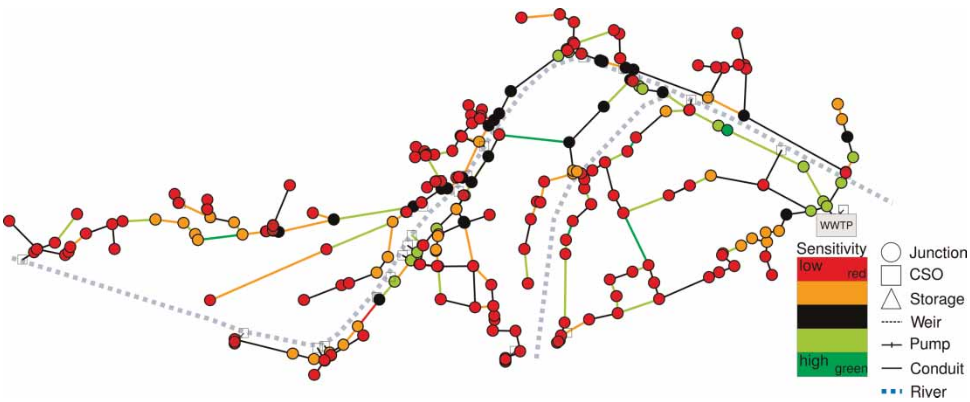

Figure 4 | Design map.

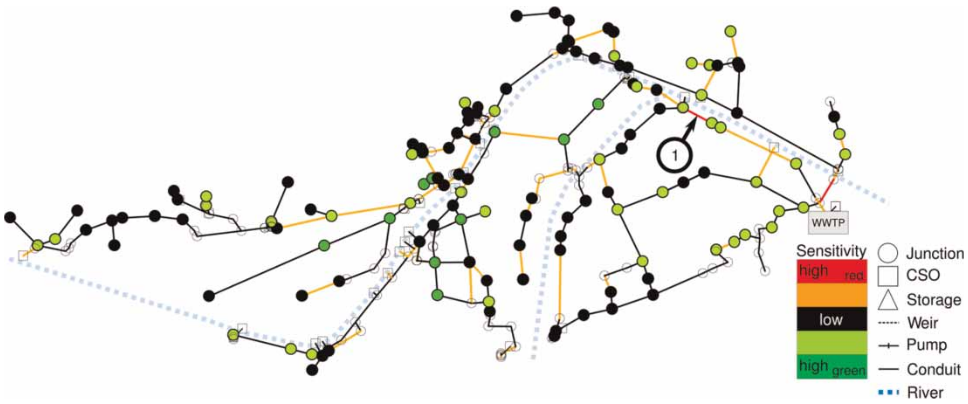

Figure 5 | Calibration map.

the map. The right-hand side of the map (Figure 5, indicated by 1) represents a roughness variation of the red coloured conduit which is the most sensitive one of the whole system. The increased roughness results in less flow capacity and therefore, a lower discharge of water. This will result in a greater CSO discharge volume at the upstream CSO (left next to the conduit) and therefore, that volume is not transported to the WWTP.

CONCLUSION

SA is commonly used for model analysis and application. This paper introduced a systematic application of GIS technology for this task. A discussion was given on those applications where the automated and GIS-based approaches reveal extensive advantage. Maps for model calibration, cross-section design, storage unit placement, uncertainty assessment and vulnerability identification were introduced and the use for sensitivity propagation was discussed. A key feature of this innovative approach is the definition of the spatial join of local sensitivities. Furthermore, the informative value, interpretations and how this information can be used for other applications of the created maps were demonstrated with a case study.

The type of SA chosen for this paper was the simple OAT method. This method, though simplistic and with shortcomings, was deemed adequate for the purposes of this study. Future work will focus on a GIS-based application for global SA using more advanced mathematical techniques. It is also of interest to study the impact of model complexity on sensitivity results for successful optimization. This is necessary to ensure reliability of results and minimize computational burden.

ACKNOWLEDGEMENT

The Achilles project (no. 824682) is funded under ‘Sicherheitsforschungs-Förderprogramm KIRAS’ PL 3 of the Austrian Federal Ministry for Transport, Innovation and Technology (BMVIT) and coordinated by the Austrian Research Promotion Agency (FFG).

REFERENCES

Bertrand-Krajewski, J. L., Bardin, J. P., Mourad, M. & Beranger, Y. 2003 Accounting for sensor calibration, data validation, measurement and sampling uncertainties in monitoring urban drainage systems. *Water Science and Technology* **47** (2), 95–102.

Brashear, J. & Stenzler, J. 2007 Water and Wastewater Specific RAMCAP Guidance. In *Proceedings of the AWWA/WEF Joint Management Conference*, Feb. 25–28, Portland, OR, USA.

Cimmery, V. 2010 *User Guide for SAGA* (*Version 2.0.5*).

De Toffol, S. 2006 Sewer system performance assessment–an indicators based methodology. Graduate Thesis, Unit of Environmental Engineering, Faculty of Civil Engineering, University Innsbruck, Innsbruck, Austria.

di Pierro, F., Khu, S. T. & Savic, D. 2006 From single-objective to multiple-objective multiple-rainfall events automatic calibration of urban storm water runoff models using genetic algorithms. *Water Science and Technology* **54** (6–7), 57–64.

Dotto, C. B. S., Kleidorfer, M., Deletic, A., Fletcher, T. D., McCarthy, D. T. & Rauch, W. 2010 Stormwater quality models: performance and sensitivity analysis. *Water Science and Technology* **62** (4), 837–843.

Dotto, C. B. S., Kleidorfer, M., Deletic, A., Rauch, W., McCarthy, D. T. & Fletcher, T. D. 2011 Performance and sensitivity analysis of stormwater models using a Bayesian approach and long-term high resolution data. *Environmental Modelling and Software* **26** (10), 1225–1239.

Ezell, B. C. 2007 Infrastructure vulnerability assessment model (I-VAM). *Risk Analysis* **27** (3), 571–583.

Frey, H. C. & Patil, S. R. 2002 Identification and review of sensitivity analysis methods. *Risk Analysis* **22** (3), 553–578.

ISO Guide 1990 *51 (1990) Guidelines for Inclusion of Safety Aspects in Standards*. Beuth, Berlin.

James, W., El-Hosseiny, T. & Whiteley, H. R. 1998 On the optimization of uncertainty, complexity and cost for modeling combined sewer systems. In: *Advances in Modeling the Management of Stormwater Impacts* (W. James, ed.), Vol. 6. Computational Hydraulics International, Gulph, ISBN 0-9697422-8-2.

Kleidorfer, M. & Rauch, W. 2011 An application of Austrian legal requirements for CSO emissions. *Water Science and Technology* **64** (5), 1081–1088.

Kleidorfer, M., Deletic, A., Fletcher, T. D. & Rauch, W. 2009a Impact of input data uncertainties on urban stormwater model parameters. *Water Science and Technology* **60** (6), 1545–1554.

Kleidorfer, M., Möderl, M., Fach, S. & Rauch, W. 2009b Optimization of measurement campaigns for calibration of a conceptual sewer model. *Water Science and Technology* **59** (8), 1523–1530.

Kleidorfer, M., Möderl, M., Sitzenfrei, R., Urich, C. & Rauch, W. 2009c A case independent approach on the impact of climate change effects on combined sewer system performance. *Water Science and Technology* **60** (6), 1555–1564.

Leitch, M. 2010 ISO 31000:2009 – the new international standard on risk management. *Risk Analysis* **30** (6), 887–892.

Möderl, M., Kleidorfer, M., Sitzenfrei, R. & Rauch, W. 2009 Identifying weak points of urban drainage systems by means of VulNetUD. *Water Science and Technology* **60** (10), 2507–2513.

Osuch-Pajdzinska, E. & Zawilski, M. 1998 Model of storm sewer discharge. II: Calibration and verification. *Journal of Environmental Engineering-ASCE* **124** (7), 600–611.

ÖWAV-RB 19 2007 *Richtlinie für die Bemessung von Mischwasserentlastungen*. Österreichischer Wasser- und Abfallwirtschaftsverband, Wien.

Rossman, L. A. 2004 *Storm Water Management Model – User's Manual Version 5.0*. National Risk Management Research Laboratory – US Environmental Protection Agency, Cincinnati.

Saltelli, A., Ratto, M., Tarantola, S. & Campolongo, F. 2006 Sensitivity analysis practices: strategies for model-based inference. *Reliability Engineering and System Safety* **91** (10–11), 1109–1125.

Sitzenfrei, R., Mair, M., Möderl, M. & Rauch, W. 2011 Cascade vulnerability for risk analysis of water infrastructure. *Water Science and Technology* **64** (9), 1885–1891.

Tang, Y., Reed, P., Wagener, T. & Van Werkhoven, K. 2007 Comparing sensitivity analysis methods to advance lumped watershed model identification and evaluation. *Hydrology and Earth System Sciences* **11** (2), 793–817.

UN DHA 1992 *Internationally Agreed Glossary of Basic Terms Related to Disaster Management*. UN DHA (United Nations Department of Humanitarian Affairs).

First received 1 April 2011; accepted in revised form 7 November 2011