The HSG procedure for modelling integrated urban wastewater systems

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ABSTRACT

Whilst the importance of integrated modelling of urban wastewater systems is ever increasing, there is still no concise procedure regarding how to carry out such modelling studies. After briefly discussing some earlier approaches, the guideline for integrated modelling developed by the Central European Simulation Research Group (HSG - Hochschulgruppe) is presented. This contribution suggests a six-step standardised procedure to integrated modelling. This commences with an analysis of the system and definition of objectives and criteria, covers selection of modelling approaches, analysis of data availability, calibration and validation and also includes the steps of scenario analysis and reporting. Recent research findings as well as experience gained from several application projects from Central Europe have been integrated in this guideline.

Key words | integrated modelling, integrated urban wastewater systems, modeling, urban drainage, wastewater treatment plant

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INTRODUCTION

An important paradigm shift in the definition of performance indicators for urban wastewater systems has occurred in legislation and practice in recent years. Traditionally, major elements of such systems (sewer system, wastewater treatment plant, and receiving water body) have been considered separately, and emission-based criteria form the basis for legislation and standards in many countries. With the implementation of the EU Water Framework Directive (WFD) in 2000 (Council of the European Communities 2000), river basin-wide analysis has become an important paradigm in sustainable water resources planning and management. The WFD demands approaches for river basin management which will also have implications for urban wastewater system management in Europe. For surface waters, as a major receiving ecosystem of urban emissions, a good ecological and chemical status is required. The WFD also identifies modelling as one of the tools for good implementation (e.g. Dorge & Windolf 2003; Rekolainen *et al.* 2003).

Thus, traditional engineering planning approaches need to be adapted to address the paradigm shift. The exclusive consideration of combined sewer overflow (CSO) volume, frequencies, and pollution load minimisation, for instance, are no longer adequate objectives, since they do not guarantee the achievement of the desired quality of the receiving water body (Butler & Schütze 2005). It is generally accepted (in science) that optimal management of the individual components of the urban wastewater system does not necessarily yield optimum performance of the entire system. Therefore, an integrated approach accounting for various sources of pollution and impacts on receiving water bodies is required (Rauch & Harremoës 1996).

Computer-based simulation models are convenient and generally accepted planning and design tools for urban wastewater systems. Integrated modelling has been a challenging research topic since the first INTERURBA conference (Lijklema *et al.* 1993). The uptake of integrated modelling in engineering practice, however, is still limited. The main bottlenecks are the complexity of the overall system, which prevents a simple linkage of the existing detailed deterministic models of the individual subsystems, and a lack of data, which limits the practical application of these models. In the last few years, however, significant efforts have been made both to develop simplified approaches suitable for modelling the integrated urban wastewater system (IUWS) and to support effective decision making in urban water management by improving the practical applicability of integrated models.

Beside the paradigm shift in the definition of performance indicators for urban wastewater systems and the development of integrated modelling approaches over the last three decades, a couple of guideline documents have been developed to support the modeller's work and to define systematic procedures for model calibration and implementations of simulation studies. Normally, these guidelines only focus on sub-systems of the IUWS. The STOWA calibration protocol (Hulsbeek *et al.* 2002), the Biomath calibration protocol (Vanrolleghem *et al.* 2003), the WERF protocol (WERF 2003), the Hochschulgruppe (HSG) guideline (Langergraber *et al.* 2004) and specific procedures to define influent data (Langergraber *et al.* 2007) were published to aid modellers in calibration studies for dynamic wastewater treatment plant simulation using ASM models. Sin *et al* (2005) theoretically compare these calibration guidelines and Seiffert *et al.* (accepted) compare three of these guidelines with regard to their advantages and drawbacks as well as their applicability. The US EPA guidance for monitoring and modelling of combined sewer overflows (EPA 1999), the WaPUG code of practice for the hydraulic modelling of sewer systems (WaPUG 2002) and the ATV-DVWK-M 165 guideline document (ATV-DVWK 2004) discuss good modelling practice for sewer system modelling in general. Other guidelines are model specific, e.g. the user's guide to SWMM (CHI 2008), rather general, e.g. STOWA good modelling practice handbook (Van Waveren *et al.* 2000) or regulation specific, e.g. the commentary for the application of hydraulic and quality models in the scope of the German guideline ATV A-128 (ATV 1992).

Focusing on integrated assessment and modelling, Rauch *et al.* (1998), Schütze (1998) and Erbe (2004) have formulated requirements that must be met by integrated modelling frameworks. In addition, some more general guidelines have been published. Schütze & Alex (2004) give some hints for integrated modelling, whilst DWA (2006) deals with integrated assessment and planning of IUWS, and EPA (2008) discusses integrated modelling in the context of integrated environmental decision making but does not focus in detail on the practical issues when modelling the urban wastewater system. Also, a number of specific guideline documents and manuals that directly address integrated modelling as a tool for water quality oriented assessment of urban wastewater systems have become effective (e.g. the Urban Pollution Management Manual in UK (FWR 1994, 1998), the BWK-M7 Guideline in Germany (BWK 2008) and the Swiss STORM guideline (VSA 2007). However, a substantial integrated modelling guide is still missing.

The Central European Simulation Research Group (Hochschulsimulationsgruppe–HSG, http://www.hsgsim.org) has developed a guideline document to support the application and further development of integrated models for the assessment of IUWS in research and practice and to close the acknowledged gap (HSGSim 2008) between the two.

The guideline covers the aspects of system and problem analysis, the identification of relevant system processes and evaluation criteria, model setup and analysis, calibration and validation, scenario analysis and documentation. The guideline follows the plan of implementing a demand-driven model setup and application. Detailed information is provided to support the model specification based on a thorough analysis of the objectives. A focus is placed on the identification and selection of appropriate modelling approaches and their level of detail. Therefore, an iterative process of model analysis and evaluation during model setup is proposed, following the principle of parsimony–the model complexity should be as detailed as needed but as simple as possible.

The complete HSG guideline document consists of a state-of-the-art review on IUWS integrated modelling, the guideline itself and three case studies. The documentation of the case studies reflects the practical experiences of the authors and provides detailed information on the application of the guideline. The guideline is available to interested professionals on the Internet.

This paper presents the HSG procedure for integrated modelling, an essential part of the developed guideline. Particular emphasis is put on the structure and contents of the proposed procedure.

STRUCTURE AND CONTENTS OF THE PROPOSED PROCEDURE

The main part of the guideline provides precise instructions for a systematic set up of integrated models and for the application of these models in the context of scenario analysis. The proposed procedure is divided into six major parts:

1. System analysis
2. Processes and criteria
3. Modelling approaches and data demand
4. Analysis of data and model
5. Model calibration and validation
6. Model application: analysis of scenarios

An additional task comprises of the continuous documentation during all the steps of the procedure. In the following, these steps are discussed briefly. Figure 1 shows a flowchart of the complete procedure including all the important steps and interactions.

Step 1—system analysis

Carrying out a simulation study is usually driven by acute, mean- or long-term deficits which are observed in the system under consideration. The need for a technical and/or economic system optimisation can be a further motivation. Generally, it has to be mentioned that the simulation of such systems in an integrated view also results in a better understanding of the interrelations within the system itself.

The superior objective of a study is directly derived from the motivation and can be formulated in an abstract way (e.g. reduction of artificial indicators like annual overflow volumes and loads or improvement of the water quality in the recipient). A more detailed distinction of the objectives can be deduced from a comparison between the present state of the system (frequently in deficit) and the target state defined.

The present state results from a preliminary system analysis which should be accompanied by an evaluation of the available data. The target state is often determined by legal requirements (external motivation). However, it can also be specified by the system operator's objectives

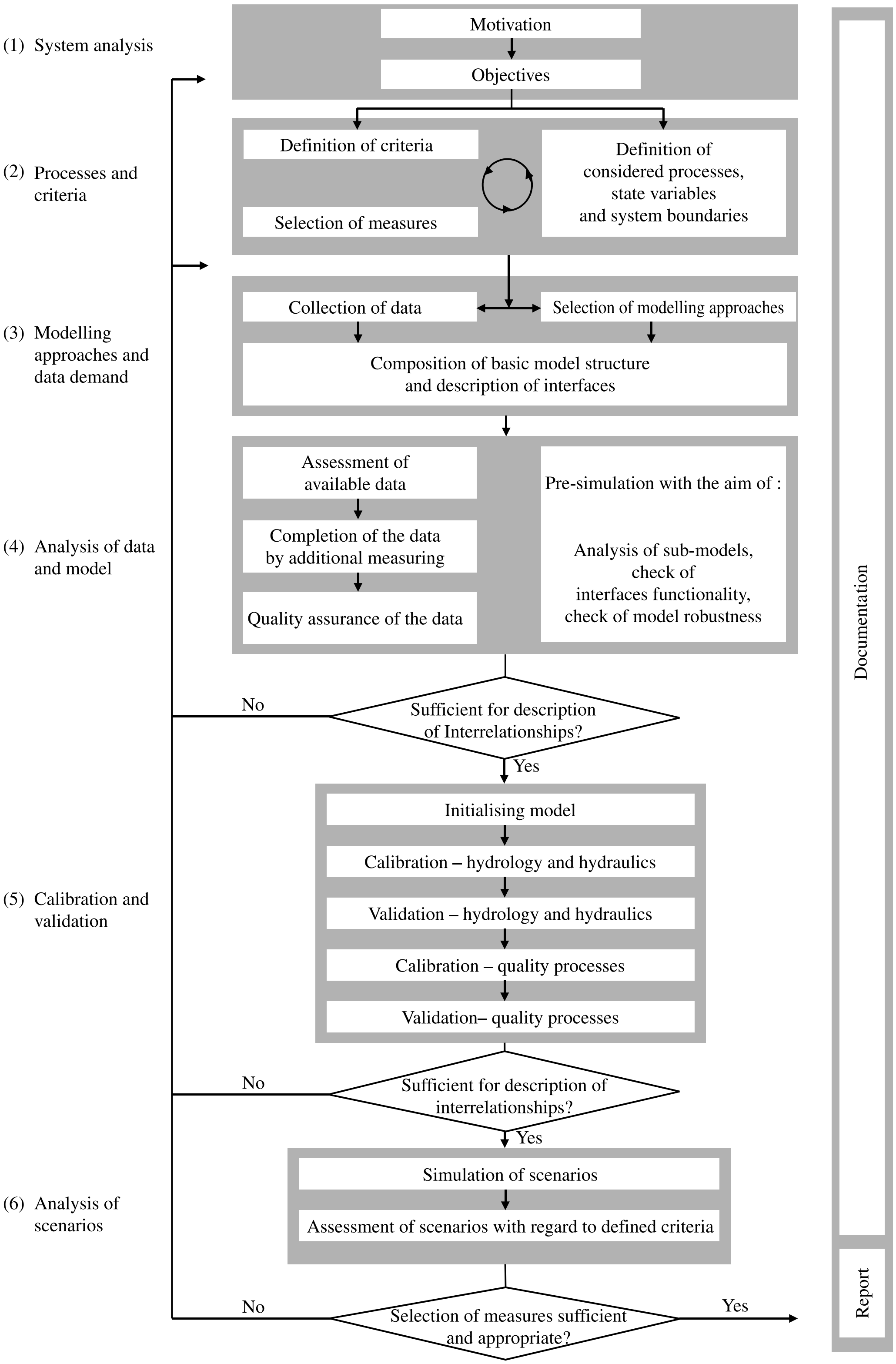

Figure 1 | Stepwise approach for integrated modelling according to the HSG guideline (Source: HSGSim 2008).

(internal motivation); combinations are also possible. Typically, the analysis process, to be carried out prior to the actual simulation study, is not conducted by the modeller itself. In fact, this task is often accomplished by the system operator, the responsible water authority, or similar superior institutions. This is a crucial point, particularly regarding system understanding needed for successful model development.

Step 2—processes and criteria

In a next step, a more detailed system analysis needs to be carried out. The primary objective of this analysis is the identification of possible causes of negative impacts (deficit analysis) and/or the determination of the optimisation potential of the system as well as the identification of the processes and criteria related to the objectives considered. The identification of relevant state variables (or criteria) and significant processes in the system are directly correlated. In case of legal requirements, compulsory objectives are already defined by established standards. The analysis process is therefore carried out based on these predefined criteria. If no criteria are defined *a priori*, these must be derived in connection with the identification of the main processes.

Subject to the identified processes or criteria, a catalogue of suitable measures, which is to be examined and evaluated in the context of the scenario analysis (Step 6), is prepared. Additional measures may possibly be identified during the scenario analysis and can later be added to the list of suitable measures.

Following the results of the analysis, some of the *a priori* defined objectives (Step 1) may have to be adapted. As a consequence thereof system boundaries may have to be relocated. To limit the spatial extension of the final model, the system constraints must be chosen as narrowly as possible. For this purpose, it is necessary to only include the subsystems which have an essential impact on the criteria or the mitigation measures planned (Meirlaen & Vanrolleghem 2002).

The further model set up is based on the definition of interfaces and interactions between the components considered in the system. At this point, one should also critically reflect on whether the analysis actually requires an integrated model. Possibly, an integral analysis of the system would not yield any additional information compared to the application of traditional model concepts based on a separate analysis of each subsystem. Such an approach may, in some cases, be equally adequate for the assessment of the measures and, compared to an integrated study, have the advantage that it is significantly easier to manage.

Step 3—modelling approaches and data demand

Upon completion of the second step, the system should have been reduced to a manageable complexity considering only the significant impacts and processes. The reduced system represents the basis for the selection of appropriate modelling approaches that describe the identified significant processes and interactions of the system. At this stage, an important task is to analyse whether the modelling approaches available meet the requirements or if the selected approaches have to be adapted to suit the task at hand (in the worst case, some approaches may have to be redefined or newly developed). Rauch *et al.* (1998) discuss how the defined objectives have an impact on the selection of modelling approaches.

Beyond the modelling approaches, an adequate amount of data is essential to define the model setup and to identify the model parameters. Normally, the data for the subsystems will be available with different quality and on different (temporal) scales. The required quality of the data is determined by the selected modelling approaches and by the defined processes respectively. The more detailed the modelling approach to describe the physical interrelationships is, the higher the data requirements are. Vanrolleghem *et al.* (1999) give indications for the conception of measuring campaigns that produce data of adequate quality for integrated modelling. Fletcher & Deletic (2008) formulate general requirements on data from the view of integrated urban wastewater management.

If a discrepancy between the selected approaches and the available data arises, two solutions are possible in principle:

- Conduction of additional measuring campaigns to close the data gap,

- or the selection of altered, less sophisticated modelling approaches for which the available data base is adequate (Willems 2004).

The balance of the processes to be considered, the adequate modelling approaches, and the available data is usually limited by the resources (time and money) available for the study. The set up of the integrated model and the entire study can be significantly affected by these two-way interconnections (Schütze & Alex 2004). In addition to the set up of the elementary model structure, the interfaces between the different subsystems have to be described in form and content. Therefore, attention should be given to the specific characteristics of the different fractions of the substances under consideration. If necessary, the transformation of the substances has to be defined at the interfaces between different subsystems (Fronteau *et al.* 1997; Alex *et al.* 2005; Volcke *et al.* 2006). Furthermore, different temporal scales may have to be coordinated between the subsystems. In general, it can be stated that it is important for the development of an integrated model to reduce the complexity and the size of the model as far as possible ("As detailed as necessary, as simple as possible").

Step 4—analysis of model and data

On the one hand, this step includes the quality assurance of the data (available *a priori* or collected during the study) and, on the other hand, it covers the analysis of the integrated model and the sub-models. In particular, the model analysis covers the aspects of model robustness and verification of the interfaces' functionality. Ideally, the uncertainties associated with the data used and the integrated model should be analysed and quantified.

Data obtained by measurements are generally limited by the intrinsic insufficiency of each method to detect a given input variable or parameter exactly. These limitations are dependent on the instruments and the method used, as well as the characteristic of the sample (type, size, and matrix) and the human element. In this context, it is also important to keep in mind that the "true" value of a variable to be measured is, in fact, never known because each measured value is associated with a certain level of uncertainty.

Beyond the data required for model set up and for the hydraulic calibration and validation process, water quality data is usually of major interest in the context of integrated modelling. One should acknowledge the fact that quality data without corresponding quantity data is unusable. Quality assurance of quantitative data is already an ambitious task; however, to guarantee a good quality of water quality data is an even more demanding challenge (Mourad & Bertrand-Krajewski 2002).

The conversion processes of water quality constituents are often dominated by dilution and mixing in the recipient, and very often the substance under investigation is not completely distributed uniformly over the whole cross section. As a consequence, the impacts of these effects need to be known and considered in the quality assurance process. These circumstances make it sometimes extremely difficult to detect a trend and to distinguish between a detected trend and other phenomena, e.g. effects caused by the sensor used (drift, shift). Moreover, the reference method is also afflicted with uncertainties (Bertrand-Krajewski 2004). These must be considered in the data evaluation. Only a meticulous analysis results in confidence intervals within which all measurements have the same information content.

In general, various methods and tools for carrying out a quality assurance of measured data are available. In practice, however, these methodologies are only rarely used and even fewer fully automatic methods are applied. The following topics are of importance:

- Distinction between measurement errors and system alterations
- Detection of long-term trends and temporarily altered conditions
- Distinction between natural variations and anthropogenic impacts

Preliminary simulations should be performed using the model under development (Step 3). The simulation results have to be analysed with respect to possible errors (plausibility checks). The primary objectives of the analysis should be the identification of unstable simulation runs as well as erroneous parameter and variable definitions and model structure. Useful indicators include, for example, implausible loads and concentrations in the receiving water or surcharged nodes at high points in the sewer system. The verification of the interfaces' functionality is also important at this stage. The interfaces between the sewer system and the WWTP as well as the recipient are crucial point. The transformation of the different sets of state variables is particularly problematic and is known as one of the weakest points in integrated modelling (Schütze *et al.* 2002). For example, modelling of quality parameters in the sewer systems involves only at most two COD-fractions in many cases whereas the Activated Sludge Model Nr. 1 (Henze *et al.* 1986) is based on seven fractions of COD alone. Simulated discharges based on different temporal scales can also become problematic.

Furthermore, "good modelling practice" demands an estimation of the predictive performance of the model. A mathematical model is composed of mathematical equations, input parameters, model variables, and state variables. In any case, there is a deviation between the model and the reality.

The model input variables can be a significant source of uncertainty. The estimation of model parameters, e.g. in the context of calibration (see step 5), can result in considerable errors in the simulation results if a thorough evaluation of data quality is not conducted to detect obvious measurement errors (Gamerith *et al.* 2008). Issues of identifiability have also to be considered. Further uncertainties can result from numerical or mathematical errors or inadequate model structure. The quantification of model uncertainty often demands high computational effort (e.g. the Monte Carlo simulation). For this reason, the application of uncertainty analysis is still limited in the context of integrated modelling. Nevertheless, some contributions to this topic can be found in the literature (e.g. Mannina *et al.* 2006).

Step 5—calibration and validation

In principle, discrepancies between the predicted (simulated) and the real (measured) system behaviour are unavoidable. The reasons for this are complex and multifaceted. On the one hand, the model approaches on which the simulation model is based always represent a simplification of real physical interrelationships. On the other hand, the identification of model parameters is often not possible exactly (see e.g. Freni *et al.* 2009). Hence, the calibration process is a crucial and fundamental component of the model development process.

In this context, calibration is defined as the determination of model parameters by comparing simulated and monitored (measured) system behaviour. For this purpose, simultaneous measurements of precipitation, discharge, and concentration need to be available at different locations in the system considered. Sufficient measurement data is especially needed at locations with interactions of different system components (e.g. CSO structures).

In the field of integrated modelling, the estimation of model parameters is normally conducted iteratively. Based on the available data set, the estimate is updated in each iterative step, aiming to minimise the difference between simulated and measured system behaviour. Using suitable quality indicators (e.g. model efficiency coefficient according to Nash & Sutcliffe 1970), this results in an optimisation problem that can either be solved by trial and error approaches or by using an adequate optimisation technique.

For successful parameter estimation, some preliminary steps must be conducted. The available data has to be split into two subsets:

1. A first set of data for estimating the parameters
2. The remaining data for validating the model

The first set will be used to calculate the estimates of the parameters; the second data set will be used to verify that the model is able to predict the dynamics of the processes with these parameters. It is important to mention that this approach can only be applied successfully if the two subsets have significantly different information content, e.g. precipitation or runoff events with considerable differences in intensity, duration and previous history (Harremoës & Madsen 1999).

Dealing with such complex systems in the context of integrated modelling makes it unavoidable to select the parameters to be estimated *a priori*. Methods based on sensitivity analysis ensure reliable estimation. This also entails the definition of physical or user-defined constraints on the parameters and the proper choice of the initial guesses. If possible, a two-step approach is advantageous. At first, a separate calibration of the different subsystems is performed where possible (e.g. sewer system and WWTP). Secondly, a calibration of the whole system is conducted with a special focus on the systems affected by other subsystems (e.g. the receiving water body). In all the steps the calibration is performed first only for the hydrology and hydraulics and second for the quality processes. Normally, the hydraulics is independent from the quality processes but not vice versa. A broad discussion of this topic can be found e.g. in (Dochain & Vanrolleghem 2001). A practicable example is described by (Muschalla *et al.* 2008).

Nevertheless, if no calibration is conducted or a proper parameter estimation is not possible (e.g. due to missing data), qualitative statements can still be derived from integrated models (Muschalla 2008). However, a plausibility check of the parameter set and of the simulation results has to be carried out in any case (for example, for the degree of imperviousness in urbanised catchments or a comparison of measured and simulated inflow to the WWTP). Also, a comparison between simulated and observed or reported system behaviour should be carried out (e.g. observed eutrophication of receiving water body or reported frequency of CSO spillages).

Step 6—scenario analysis

The mitigation measures to be analysed (Step 2–processes and criteria) have to be implemented in suitable simulation scenarios. The selected mitigation measures can become more concrete while the simulation model is being set up and can be modelled by varying selected model parameters or by adapting the model structure. In addition, the model inputs (dry weather condition and/or rain series) and the simulation periods (event based or long term simulation) have to be defined for each scenario. For the comparison of different mitigation measures/scenarios, an initial state (typically described as base-line or reference scenario) must be defined and simulated. After simulating all the scenarios, the simulation results must be analysed again with respect to possible errors (*cf.* Step 4).

The scenarios are assessed regarding the defined criteria and objectives (Step 2). The different scenarios are compared with the reference scenario based on the defined criteria; however, one can distinguish between an absolute and a relative assessment of the scenarios.

If a detailed calibration is not feasible, it is only possible to conduct a relative comparison between the different scenarios. In the case where there is no detailed calibration simulation results can only indicate relative alterations (improvements or deteriorations).

A detailed calibration that is carried out successfully allows the comparison with the reference scenario regarding absolute limit values (e.g. maximum concentrations in the river).

If the defined objectives are not yet accomplished (according to the analysed scenarios), new mitigation measures have to be defined. Before they can be implemented into new simulation scenarios, verification is needed as to whether the previously applied modelling approach allows an adequate description of the 'new' measures (Steps 3 and 4). If this is not the case, the selection of another modelling approach and a following model analysis (Step 4) and calibration may be necessary (Step 5).

Continuous documentation

The documentation of an integrated simulation study should be detailed enough to relate it to all the aspects/tasks ex post and to enable reproduction of the simulation results. The documentation should comprise of at least the following aspects: objectives of the study, approach, selected modelling approaches (including explanatory statements), software package(s) used (including version number), all the relevant operation and process data of the system analysed, final simulation model(s), list of used parameter sets (with an explanation if chosen parameters differ significantly from the usual parameter ranges), relevant results of data evaluation (e.g. mass balance) and calibration and validation results. All the analyses conducted (e.g. scenario analysis) should also be documented in a traceable manner. It is advantageous to refer to the work steps described in this paper when compiling the documentation.

CONCLUSIONS

As indicated in the introduction to this paper, an important paradigm shift in the definition of performance indicators for urban wastewater systems has occurred in legislation and practice in recent years. More and more, the integrated assessment of urban wastewater systems is becoming increasingly important to water resources management in general and to the management of urban wastewater systems in particular. Although a number of related guideline documents, manuals and directives have become effective, a substantial guide for integrated modelling was still missing. The HSG Procedure for Modelling of Integrated Urban Wastewater Systems and its underlying guideline document is believed to contribute to close this gap.

However, the HSG Procedure is not only focused on modelling. The main goal was to define a standardised procedure comprising all the important steps of integrated simulation studies including pre-processing like system analysis and definition of objectives and criteria and post-processing like the analysis of scenarios and reporting. An important feature is the model and simulation software independent character of the developed procedure.

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