Integrated urban water modelling with uncertainty analysis

G. Mannina*, G. Freni*, G. Viviani*, S. Sægrov** and L.S. Hafskjold**

*Dipartimento di Ingegneria Idraulica ed Applicazioni Ambientali, Università di Palermo, Viale delle Scienze, 90100 Palermo, Italy

**SINTEF Technology and Society Water and Environment, N-7465 Trondheim, Norway

(E-mail: mannina@idra.unipa.it)

Abstract In the last twenty years, the scientific world has paid particular care towards the problems that involve the environment. Accordingly, several researches were developed to describe phenomena that take place during both wet and dry periods and to increase the knowledge in this field. In particular, attention was addressed towards the problems linked with receiving water body pollution because of the impact of rain water in the urban environment. In order to obtain a good description of the problem, it is important to analyse both quantity and quality aspects connected with all the transformation phases that characterise the urban water cycle. Today, according to this point, integrated modelling approach is spreading, aiming to find solutions to improve the quality characteristics of the receiving water body. Because several models are connected together for analysing the fate of pollutants from the sources on the urban catchment to the final recipient, classical problems connected with the selection and calibration of parameters are amplified by the complexity of the modelling approach increasing the uncertainty and reducing the reliability connected with a model’s application. For this reason, a parsimonious integrated modelling approach has been developed and its uncertainty has been evaluated adopting the well known GLUE framework. For the purpose of the study, the uncertainty analysis has been applied to a “semi–hypothetic” case study obtained connecting Fossolo catchment (Bologna – Italy) to the Oreto river near Palermo (Italy).

Keywords Integrated urban drainage modelling; modelling uncertainty analysis; receiving water impact; urban water quality

Introduction

Usually an integrated system is defined as the complex of interactions between two or more physical systems, i.e. sewer system (SS), wastewater treatment plant (WWTP) and receiving water body (RWB). Integrated modelling has been basically developed for simulating polluting impacts on receiving water body and, at the same time, for analysing the possible causes that generate them. This approach is usually aimed to a better management of all the components of the sewer system and to a better knowledge of the transformations of sewage in the different parts of the system (Rauch et al., 2002). The need for analysing all the aspects of urban drainage systems is also represented in the EU Water Framework Directive 60/2000 that basically proposes a water-quality orientated view of the whole system requiring new ways of assessing their performance. The key to the previous considerations is the change from an emission based approach (Emission Standard) to an environment water-quality based approach (Stream Standard) (Chave, 2001).

The most part of existing models couples separated approaches for simulating different system components using the output of each of them as input for the downstream element of the integrated system. As an example, the Integrated Catchment Simulator (ICS), basically links existing commercial models such as MOUSE for drainage systems, STOAT for WWTP simulation and MIKE11 for rivers (Tomicic et al., 1999). One of the most relevant problems linked with commercial models regards the high parameterisation...

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that requires long and expensive data acquisition activities as well as high computational
resources needed for running integrated simulations (Vanrolleghem et al., 1999). In fact,
these models were usually developed as stand-alone detailed representations of the
different parts of the integrated system and they were not really developed for working
together as a single modelling approach. The complexity of those models is often excessive
if compared with simulation needs and a good balance between model detail level and
computational effort minimization is difficult to obtain.

This aspect is even more important when uncertainty has to be assessed because of
the large number of simulations that are needed for analysing the effect of parameters
variation. Different approaches can be used for uncertainty analysis. In the present study,
the GLUE procedure of Beven and Binley (1992) has been used. The GLUE procedure
requires a large number of Monte Carlo simulations, where the random sampling of indi-
vidual parameters from probability distributions is used to determine a set of parameter
values. Following this approach, model reliability can be evaluated on the basis of their
capacity of globally limiting the uncertainty.

Integrated model description
For the present study, a home-made model has been developed in Fortran programming
language; the algorithms used for simulation are reported in Mannina et al. (2004) and
Mannina (2005). The model is able to estimate both the interactions between the different
systems (SS, WWTP and RWB) and the modifications, in terms of quality, that urban
stormwater causes inside the RWB (Figure 1). Such a system is made up mainly of three
sub-models:

- the rainfall-runoff and flow propagation sub-model, which is able to evaluate the qual-
  ity – quantity features of SS outflows;
- the WWTP sub-model, which is representative of the treatment processes;
- the RWB sub-model that simulates the pollution transformations inside the water
  body.

The first sub-model, reproducing the physical phenomena which take place both in the
catchments and in the sewers, allows to determine the hydrograph and pollutograph in
the sewer. This sub-model is divided into two connected parts: a hydrological – hydraulic
module, which calculates the hydrographs at the inlet and at the outlet of the sewer
system, and a water quality module, which calculates the pollutographs at the outlet for
different pollutant species (TSS, BOD and COD). The hydrological – hydraulic module
starts to evaluate the net rainfall, from the measured hyetograph, by a loss function

![Figure 1 Schematic representation of the urban drainage system](https://iwaponline.com/wst/article-pdf/54/6-7/379/431374/379.pdf)
(taking into account surface storage and soil infiltration). From the net rainfall, the module simulates the net rainfall-runoff process and the flow propagation with a cascade of two linear reservoirs. The solid transfer module reproduces the build-up and wash-off of pollutants from the catchment and the propagation of solids in the sewer network considering also their sedimentation and re-suspension.

The second sub-model is aimed to the analysis of WWTP during wet periods. The WWTP inflow has been computed taking into account the presence of a CSO device and its efficiency. The WWTP sub-model simulates the behaviour of the part of the plant composed by an activated sludge tank and a secondary sedimentation tank. In the activated sludge tank model, the equations deriving from Monod’s theory have been used in order to reproduce BOD removal. The sedimentation tank has been simulated using the solid flux theory according to the methodology proposed by Vitasovic et al. (1997). The model allows for evaluating the variations of treatment performances during a storm event. In particular, the increase of flow rates and Total Suspended Solids (TSS) causes a reduction in treatment efficiency both regarding the activated sludge tank and the sedimentation tank. This fact can cause TSS overflow and then the consequent discharging in the RWB.

The third sub-model examines the assessment of RWB. The simplified form of the De Saint Venant Equation (cinematic wave) is used for the quantity module and water de-oxygenation and re-oxygenation phenomena are simulated by using the advection-dispersion equation; this approach allows for evaluating the effects of stormwater on the RWB, both at a single event scale and during long term simulation. The pollutant sources, which cause a worsening in the characteristics of RWB, are mainly two: the WWTP discharges and the combined storm overflows (CSOs). The sub-model allows for simulating the effects of the insertion of CSOs control measures for temporary accumulation of stormwater during the rainfall event.

**Uncertainty analysis**

Depending on the fact that several sub-models are linked together for obtaining the final impact on the RWB, the uncertainty connected to the model application is not simple to be evaluated and, consequently, the responsibility of each sub-model as well as module in its propagation is not clear. The present paper aims to evaluate the influence of the different components on the integrated model uncertainty in order to increase the modelling approach robustness. This study will be able to identify modules and parameters where more uncertainty relies in order to improve model reliability and robustness.

GLUE methodology has been used for the study purpose (Beven and Binley, 1992). Parameter sets with poor likelihood weights are classified as non-behavioural and they can be rejected. All other weights from behavioural or acceptable runs are retained and re-scaled so that their cumulative total sums is equal to 1. The GLUE procedure thus transforms the problem of searching for an optimum parameter set into a search for sets of parameter values that give reliable simulations. Following this approach, there is no requirement to minimise (or maximise) any objective function, but information about the performance of different parameter sets can be derived from some index of goodness-of-fit (likelihood measure). GLUE approach relies on the concept of equifinality, which maintains that, due to the errors inherent in the model structure, (e.g. due to simplification and aggregation) errors in observed data and the difficulty in determining an exact error model, it is inappropriate to perform calibration based on an optimum set of parameters.
As likelihood measure, the Nash and Sutcliffe efficiency index (1970) has been used in the present study:

\[ E = 1 - \frac{\sigma_e^2}{\sigma_0^2} \]  

where \( \sigma_e^2 \) is the error variance, where error is defined as the difference between the measured and simulated values, and \( \sigma_0^2 \) is the variance of the observations. Like other likelihood measures, the Nash – Sutcliffe index is equal or lower then zero for all simulations that are considered to exhibit behaviour dissimilar to the system under study, and it increases monotonically as the similarity in behaviour increases with a limit value equal to 1.

Once defined a likelihood index, the likelihood value associated with a set of parameter values may be treated as a fuzzy measure that reflects the degree of belief of the modeller in that set of parameter values as a simulator of the system. The degree of belief is derived from the predicted variables arising from that set of parameter values.Treating the distribution of likelihood values as a probabilistic weighting function for the predicted variables, therefore allows an assessment of the uncertainty associated with the predictions, conditioned on the definition of the likelihood function, input data and model structure used.

A method of deriving predictive uncertainty bounds using the likelihood weights from the behavioural simulations has been shown by Beven and Binley (1992). The uncertainty bounds are calculated using the 5% and 95% percentiles of the predicted output likelihood weighted distribution. In the specific study, uncertainty connected with both quantitative and qualitative objective functions has been analysed and they will be described in the following paragraphs.

**Description of the case study**

Available data for integrated urban drainage analysis are quite few and this consideration depends on the fact that contemporary monitoring campaigns on the SS, WWTP and RWB are complex and they require large technical and economic efforts. The situation is even worse when looking at wet weather impact on RWB because of the small scale at which polluting impacts take part adding more difficulties in providing reliable monitoring campaigns. For by-passing this kind of problem, Schutze et al. (1999) proposed the use of “semi-hypothetical” case studies for analysing integrated modelling potentialities. In details, the authors simulated the different parts of the system using data coming from real and well documented case studies not really linked together.

The presented uncertainty analysis has been tested by using the Fossolo catchment databases (Bologna) for the SS, the Acqua dei Corsari (Palermo) treatment plant for the WWTP and Oreto river (Palermo) for the RWB. Fossolo experimental catchment collects water coming from a residential area on the outskirts of Bologna (Artina et al., 1997). The drained area measures 40.71 ha, with an impermeable percentage of 75%. The number of inhabitants is about 10,000. The drainage network length is about 5 km and it ends in a polycentric section pipe 144 cm high and 180 cm wide. 12 storm events have been measured.

Oreto catchment area is about 112 km². The river has ephemeral behaviour with alternation of intense short peak flows and long dry periods. The upstream reach is still natural instead the downstream part has been urbanised during the last fifty years. The upstream reach has a strong auto-depuration capacity. Twelve cross-sections have been selected for estimating the whole stream behaviour in terms of pollutants and oxygen concentration.
Acqua dei Corsari (Palermo) treatment plant was constructed in 1970 for a design capacity of 400,000 inhabitants equivalent (IE) however it operates for 150,000 due to incomplete connection to the sewer network. The plant consists basically of primary clarifiers after the pre-treatment step, a biological activated sludge treatment, a secondary settling tank and an anaerobic sludge digestion. The plant was monitored in order to evaluate the WWTP kinetic constants that have been used for designing a treatment plant for Fossolo SS.

In order to evaluate uncertainty connected with parameters and different sub-models, parameter range limits have been selected to ensure that they are sufficiently wide to include all possible model responses that may produce behavioural simulations, but not so wide that the parameter values are not realistic or that unnecessary non-behavioural model runs are carried out. Variation ranges have been selected by literature review (Deshbordes, 1975; Chapra, 1997; Henze et al., 2000). In the GLUE procedure, before any quantitative or qualitative data is introduced into the calculation of likelihood weights, all parameter sets can be considered equally acceptable to simulate the real system (Beven, 1989; Beven and Binley, 1992) so that the a priori likelihood distribution can be assumed uniform.

**Performed analysis and results discussion**

For the purpose of the present uncertainty analysis, 10,000 Monte Carlo simulations have been carried out. Uncertain parameters have been considered as follows and variation ranges have been selected from literature:

- SS sub-model: linear reservoirs constants, build-up and wash-off parameters, re-suspension parameters in the sewer system, CSO efficiency;
- WWTP sub-model: kinetic constants in Monod’s model;
- RWB sub-model: river bed roughness, de-oxygenation and re-oxygenation coefficients.

The GLUE approach has been applied both on the final result of the integrated model (discharge and BOD loads in the RWB) and on partial results coming from different modules using as reference real time-series registered at the experimental catchments. Through this approach, it was possible to identify the relevance of each parameter in
influencing the final result and also the importance of single modules in the integrated approach. Preliminarily, scatter plots have been drawn for evaluating the consistency of parameter variation ranges and for identifying insensitive parameters. Figure 2 shows the sensitivity of SS quantity module to its parameters. A great influence of hydrological parameters can be seen while reservoir constants show lower variability. A similar behaviour can be shown for SS quality module (Figure 3) where hydrological parameters have great influence also on SS outflow BOD concentration. Likelihood curves for SS sub-model (Figure 4 shows two examples) generally state the good “robustness” of the model in the sense that a parameter region can be found where good model efficiencies are more frequent allowing for a better user confidence in the model results. This consideration can be made evaluating the steepness of likelihood curves: where the graph is steeper higher efficiencies can be found; a linear graph identifies insensitive parameters. Considering the WWTP and looking at the steepness of likelihood curves for the quality module output

Figure 3 Influence of model parameters on SS outflow BOD concentration

Figure 4 Influence of SS sub-model on SS outflow discharge and BOD concentration
temperature and bio-chemical kinetics have a great influence on model efficiency demonstrating that these are very important parameters that have to be empirically assessed by field measures. An interesting outcome of the presented approach is the compared evaluation of uncertainty connected to different modules. In Figure 5, two important parameters for the WWTP and for the SS sub-model have been normalised by their average and compared with respect to their influence on WWTP quality effluent modelling efficiency. The results show that, as initial losses greatly influence the WWTP inflow, they have a major importance for WWTP quality model efficiency.

RWB sub-model analysis (Figure 6) showed low influence of its own parameters on the overall efficiency (especially considering quantity module). This can be explained by the importance of CSO contribution to river peak discharge (river base flow is comparable with CSO discharges). As demonstrated by Figure 6, re-aeration coefficient has a great influence in assessing quality module efficiency and this can be explained considering the ephemeral characteristics of the selected case study and the consequent natural turbulence.

Finally, Figure 7 shows normalised SS and WWTP parameters comparison with RWB parameters likelihood curves. The comparison of quantity modules normalised uncertainties shows that SS quantity module has the greater influence on RWB one. Specifically hydrological loss coefficients assessment has a major impact on the overall model.

Figure 5 Influence of WWTP and SS sub-models on WWTP outflow BOD concentration

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performance. This impact is even higher than the uncertainty connected with RWB parameters and this can be explained with the ephemeral behaviour of Oreto river (CSO discharges are comparable with river base flow). Catchment hydrological parameters have a major role also in river water quality assessment and in the evaluation of connected uncertainty. The study also demonstrated that river re-aeration coefficients transmit higher uncertainties to the model output than WWTP kinetic constants. This is probably dependent on the fact that WWTP kinetic constants are greatly dependent on temperature and their variation range is limited by the climatic characteristics of the area.

Conclusions
The present study analysed integrated urban drainage modelling under uncertain parameters estimation. Because several simulations are needed a parsimonious modelling approach has been developed in order to mediate between mathematical approach level of detail and computational need. The uncertainty analysis has been developed using the well known GLUE framework.

During the analysis some considerations have been drawn:
• the proposed method effectively discriminates between parameter uncertainty with specific reference to an output objective function; moreover, normalising parameters values, comparisons can be performed between different parameters and modules;
• even if WWTP and RWB parameters can have large influence on single module outputs, SS parameters (and specifically hydrological parameters) have the greatest importance in assessing quality characteristics in the river water body.

References