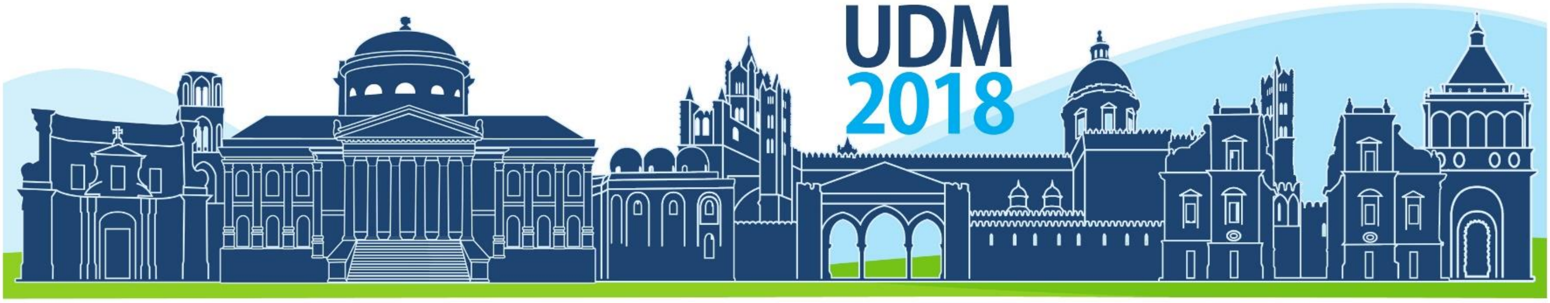

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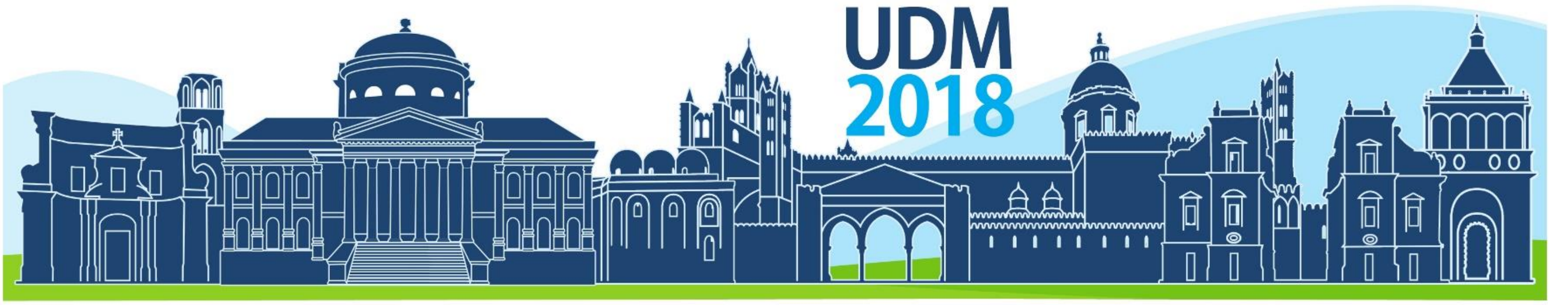

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Uncertainty Propagation In Integrated Urban Water Quality Modelling

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Abstract: Sensitivity and uncertainty assessment of integrated urban drainage water quality models are crucial steps in the evaluation of the reliability of model results. Indeed, the assessment of the reliability of the results of complex water quality models is crucial in understanding their significance. In the case of integrated urban drainage water quality models, due to the fact that integrated approaches are basically a cascade of sub-models (simulating the sewer system, wastewater treatment plant and receiving water body), uncertainty produced in one sub-model propagates to the following ones in a manner dependent on the model structure, the estimation of parameters and the availability and uncertainty of measurements in the different parts of the system. Uncertainty basically propagates throughout a chain of models in which the simulation output from upstream models is transferred to the downstream ones as input. The paper presents the uncertainty assessment of an integrated urban drainage model developed in previous studies by means of the Generalized Likelihood Uncertainty Estimation (GLUE) methodology. A straightforward approach based on the analysis of the coefficient of variation (Rxy). Rxy is defined as the ratio between the standard deviation (α) and the average (μ) value of the model output of reference taken into account. The analysis has been applied to an experimental catchment in Bologna (Italy) which consists of a part of the Bologna sewer network and a reach of the Savena river. The results showed that the method can be a useful tool for uncertainty analysis and for guiding the operator in the choice of the modelling approach.

Keywords: Integrated urban drainage modelling; environmental water quality management; pollution evaluation; uncertainty analysis

1. INTRODUCTION

In the last years, the use of mathematical models has gained importance in urban drainage system management; indeed, such models enable a combined analysis of the different components that constitute a drainage system: sewer system, wastewater treatment plant, receiving water body (Rauch et al., 2002).

The effectiveness of an integrated approach has been widely demonstrated in the past and it is also presented in the WFD 2000/60/CE contents that furthermore introduce a new point of view regarding the water quality management of the whole system requiring a global analysis at catchment scale for the pollutant sources.

Indeed, the need of an integrated point of view is implicitly introduced and required by European Directives. Already fifteen years ago, CEE Directive 91/271 has overtaken the "emission standard" concept, that fixes discharge limits depending on polluting emission characteristics, substituting it with the "stream standard" concept, that fixes discharge limits for each polluting substance depending on self-depurative characteristics of the RWB. This Directive has had difficult application without an integrated perspective and efficient tools for simulating the whole system (urban catchment, SS, WWTP, RWB). These tools, commonly known as "integrated models", are aimed to the simulation of single drainage system components and their interactions. More recently, in the UE 2000/60 Directive (WFD: Water Framework Directive), receiving water bodies analysis became more complex, framing urban pollution in the wider range of catchment scale polluting sources making in fact necessary a wider integration of urban point discharge environmental impact with non point pollution coming from agricultural and productive activities. Although urban integrated modelling approach can be the best way for designing as well as managing the whole system (namely, sewer networks, WWTP and RWB) some difficulties prevent a straightforward application (Candela et al., 2012):

- The responsibilities for planning and managing the different sub-systems
- The models for the different sub-systems have been developed independently. Therefore, integrations between the different sub-systems are far to be straightforward.
- The data requirements increase dramatically with the inclusion of more and more sub-systems.
- The complexity of a given model introduces uncertainties in the modelling process that, sometimes, are not clearly identifiable and assessable (Mannina & Viviani 2010).

Furthermore, despite such difficulties due to the fact that many sub-models are connected uncertainty propagation issues have generally to be faced. Therefore, uncertainty analysis is imperative and can be a good tool for selecting the right model approach. Despite the important role played by the uncertainty only few studies have been carried out. Indeed, assessing uncertainties in urban drainage models is not wide spread in practice and is usually an academic exercise (Dotto et al., 2012; Deletic et al., 2011). This is mainly because the techniques required for this analysis are so numerous, highly complex, poorly understood, and some are still highly underdeveloped. Clear and comprehensive comparisons of these techniques when applied to typical drainage models would therefore be desirable (Dotto et al., 2012).

In the light of the considerations discussed above, the paper is aimed to assess the uncertainty of an integrated model as well as to study its propagation in order to survey about results accuracy in case of scarce data availability. To accomplish such objects, a previously developed integrated model (Mannina et al., 2004; Mannina, 2005) and the GLUE methodology (Generalized Likelihood Uncertainty Efficiency) have been adopted (Beven and Binley, 1992).

2. MATERIALS AND METHODS

2.1 The mathematical model

An integrated bespoke model previously developed has been applied in the present study (Mannina, 2005). The key elements of the integrated model will be reported and the readers is referred to previous literatures for further details (Mannina et al, 2004; Mannina, 2005).

The urban drainage integrated model is made up of three sub-models. Each sub-model simulates one sub-system of the integrated system: SS, WWTP and RWB.
the SS sub-model, which is able to evaluate the quality - quantity features of SS outflows. Such sub-model allows for determining the hydrograph and pollutograph in the sewer for different pollutants (TSS, BOD and COD);
the WWTP sub-model, which is representative of the treatment processes. An activated sludge tank and a settler are simulated according to, respectively, Monod's theory and Takács models (Takács et al., 1991). The analysis was limited to such units since they represent the most sensitive in the WWTP during a storm event;
the RWB sub-model that simulates the pollutants transformations inside the water body.
The integrated urban drainage model has been developed in Fortran programming language; such aspect is important from the model computational time requirements especial in case of long term simulation analysis.

1.2 Uncertainty assessment and propagation

The GLUE procedure requires a large number of Monte Carlo simulations, where the random sampling of individual parameters from probability distributions is used to determine a set of parameter values. The performance of individual parameter sets are characterized by a likelihood weight, computed by comparing predicted to observed responses using some kind of likelihood measure. Parameter sets with poor likelihood weights are classified as non-behavioral and can be rejected. All other weights from behavioral or acceptable runs are retained and re-scaled so that their cumulative total sums is equal to 1. The cumulative likelihood weighted distribution of predictions can then be used to estimate quantiles for the predictions at any time step. The GLUE procedure thus transforms the problem of searching for an optimum parameter set into a search for the sets of parameter values that give reliable simulations. Following this approach there is no requirement to minimize (or maximize) any objective function, but information about the performance of different parameter sets can be derived from some indexes of goodness-of-fit (likelihood measures). The fundamental difference of this approach compared to other methods described is that the procedure is based on the concept that for a given model structure, not a single parameter set represents the observed reality, but a number of parameter set combinations may represent the observed reality behavior equally as well. This is 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 in traditional calibration approaches, once the model structure and data for calibration have been determined, the definition of the likelihood measure must be chosen. Likelihood measure should be zero for all simulations that are considered to exhibit behavior dissimilar to the system under study, and it should increase monotonically as the similarity in behavior increases. Here, the Nash and Sutcliff efficiency index (1970) has been used as likelihood measure:

$$E_{i,j} = 1 - \frac{\sigma_e^2}{\sigma_o^2} \qquad (1)$$

where σ_e^2 is the error variance, defined as the difference between the measured and simulated values, and σ_0^2 is the variance of the observations; the i subscript indicates different variables TSS, BOD, COD and dissolved oxygen (DO) while the j subscript indicates, alternatively, the SS, the combined sewer overflow (CSO) and the RWB. Like other likelihood measures, Nash - Sutcliff index is equal or lower then zero for all simulations that are considered to exhibit behavior dissimilar to the system under study, and it increases monotonically as the similarity in behavior increases with a limit value equal to 1.

Once defined a likelihood index, the likelihood value associated with a set of parameters may be treated as a fuzzy measure that reflects the degree of belief of the modeler 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 behavioral 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 analyzed.

In order to evaluate the balance between different sub-models in terms of uncertainty generation and propagation a straightforward approach based on the calculation of the coefficient of variation (Rxy). Rxy is defined as the ratio between the standard deviation (α) and the average (μ) value of the model output of reference taken into account. Low Rxy values suggest that the modelled output is close to its average value.

2.2 The case study

The model has been applied to the catchment of the Savena river. The sewer system and the river studied in this work concerns a part of the sewer network of Bologna, studied within the European Union research project INNOVATION 10340I (Artina et al., 1999). The aim of the project was the “Application for the Urban Pollution Management Procedure to River Quality Protection in European Member States”; the Italian team was coordinated by CSDU (Centro Studi Idraulica Urbana) and it was constituted by ARPA Emilia-Romagna (Environmental Agency), Bologna University and Milan Polytechnic.

The Savena is a rural ephemeral river that passes through a number of small towns before entering the southern neighbourhood of Bologna. The catchment area of the Savena, at the downstream boundary of the studied river reach, is nearly 160 km2. The river is characterized by a very variable hydraulic regime with discharge usually ranging from few liters per second, during dry periods in summer period, up to several cubic meters per second during wet weather.

The studied river reach is about 6 km length receiving 6 CSO discharges from the Bologna sewer network and 12 from the San Lazzaro sewer systems, a small centre in the surrounding area of Bologna. The CSOs generally operates also during small intensity rainfalls and, in many cases, their discharge is of the same order of the river one.

The sewer network is a part of the combined system serving the whole city of Bologna, which can be considered as hydraulically divided into many independent catchments, all connected to a WWTP. The whole city of Bologna has about 500,000 inhabitants and an equivalent population of about 800,000 inhabitants. Only the part of this catchment which has directly or indirectly an effect on the studied reach of the Savena river has been taken into account. This part of Bologna has an area of more than 450 ha, with an impervious percentage of about 66% and about 60,000 inhabitants.

The six CSOs are installed in correspondence of collectors of different sizes and shapes ranging from egg shape 80 x 120 cm up to polycentric shape 260 x 208 cm.

The sewer system of San Lazzaro, on the right side of the Savena river, has a catchment of about 120 ha with 10,000 inhabitants.

During experimental survey, carried out from December 1997 to July 1999, about 50 events have been recorded, but, for only 5 of these, water quality aspects have been analyzed regarding RWB, the CSO outlets and the SS. The analyzed parameters were: BOD5, NH4, TSS, COD, pH, DO, temperature and conductibility.

In this paper, only a part of the Savena river has been simulated (400 meters downstream the CSO No. 6) because the contribution of this CSO to river pollution has been determined much more relevant respect all the others. The contribution of other polluting sources has been considered by monitoring river pollution load in the first cross-section upstream of CSO No. 6 and introducing this information as input in the models.

3. RESULTS AND DISCUSSION

10,000 behavioral Monte Carlo simulations have been considered, varying both quantity and quality parameters: likelihood measures obtained for each sub-model have been related each other both considering flows and concentrations.

Analyzing only quantity modules (figure 1), it can be stated that uncertainty connected with RWB sub-model is negligible. The SS is thus responsible of the most part of the uncertainty propagated to the RWB flow output.

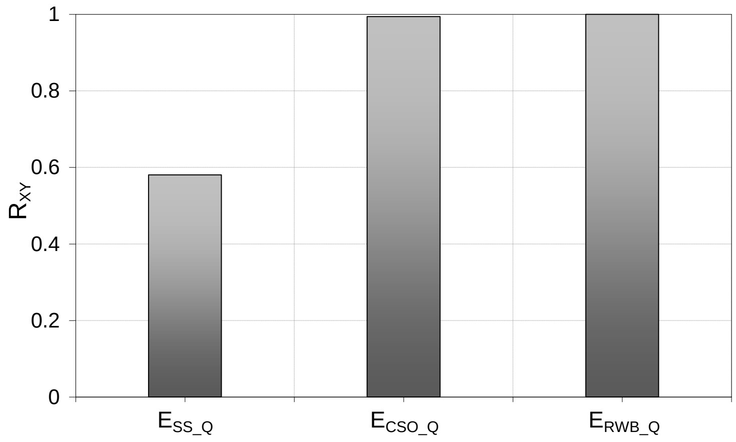

Figure 1. Rxy coefficients between RWB, SS and CSO for the quantity modules

This analysis denotes a scarce balance among the quantity modules and it suggests the following modifications to the model structure:

- RWB sub-model complexity is not useful in the present application and it can be simplified probably using a conceptual model with lower computation needs;
- SS sub-model, on the contrary, is probably too simplified and it should be replaced by a more detailed one; probably distributed models should be investigated in order to add details to this part of the integrated approach.

A better balance can be found analysing the uncertainty propagated among the quality modules (figure 2).

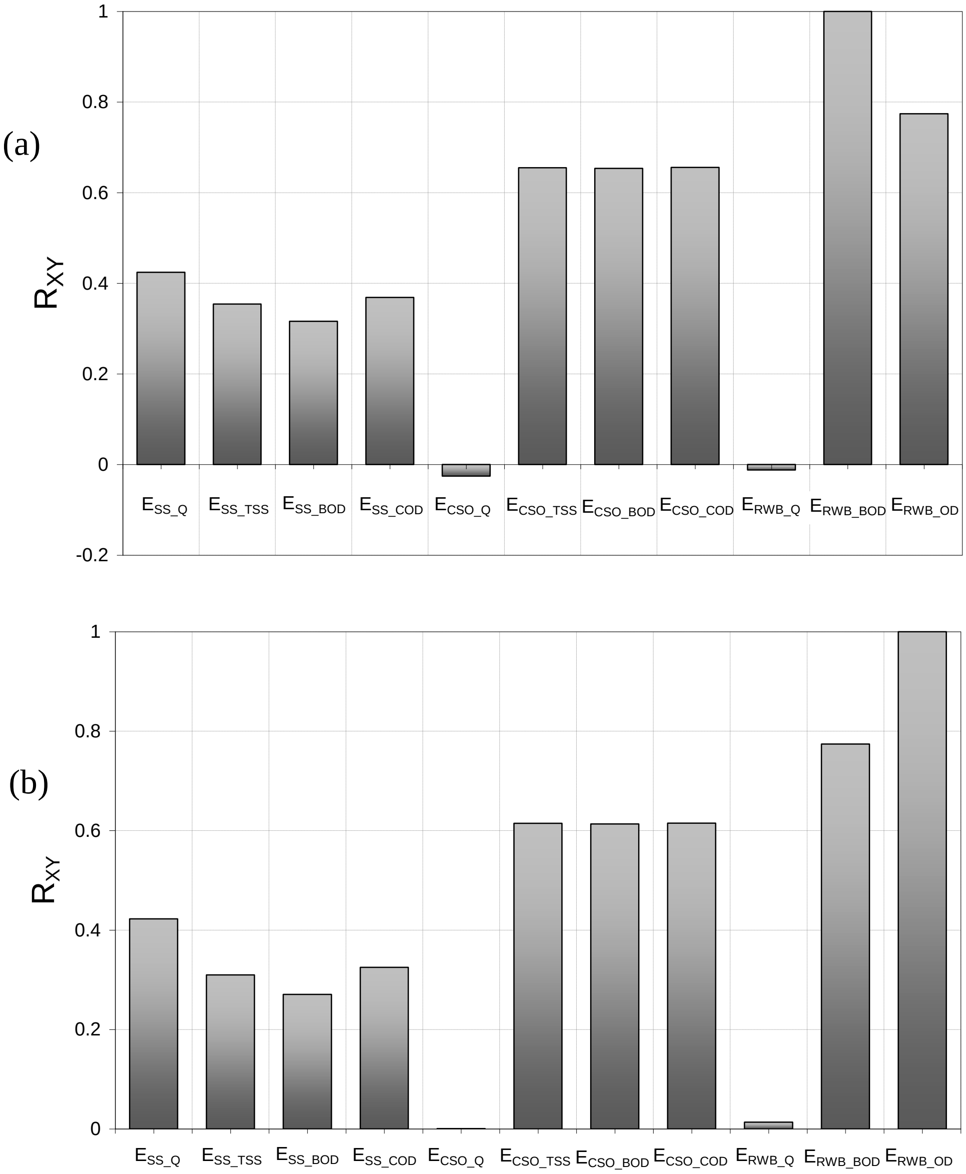

Figure 2 Rxy coefficients between RWB BOD (a) and OD (b) modeling efficiency indexes and upstream sub-models ones both concerning quantity and quality modules

Even if the correlation analysis may provide qualitative information, the variation of Rxy index from one sub-model to the others can be considered as an indicator of the modeling noise introduced by each part of the integrated approach. The analysis of figure 2 enables to draw the following considerations:

- analyzing the quality features, RWB sub-model assumes a more relevant role in uncertainty propagation with respect to quantity modules. This result can be justified by the important role of reaeration and deoxygenation constants in the modification of BOD and DO in the RWB;
- SS, CSO and RWB contribute more uniformly to uncertainty propagation assuming approximately 1/3 of the overall modeling uncertainty;
- there is no connection between uncertainties generated in RWB quantity and quality modules, demonstrating the different magnitude of the two uncertainty propagation processes;
- there is a good connection between modeling efficiencies in the evaluation of RWB concentrations and the efficiencies in the evaluation of SS discharge, while correlation attenuates considering CSO and RWB discharges; this fact can be explained by the relevant role assumed by SS hydrograph in the analysis of resuspension processes in the sewer system and the importance of such process in the evaluation of RWB polluting concentrations.

CONCLUSIONS

The present study analysed parametric and structural uncertainty of an urban drainage integrated model. As technical literature demonstrated in the last decade, this aspect has a relevant influence on the evaluation of modeling reliability and on the confidence that operators can put on its results. Integrated modeling uncertainty can depend on several factors like scarce data availability, especially when considering both water quantity and quality aspects. From the performed analyses some considerations can be drawn that partially confirm analytically what has been stated several times in literature, even if only with qualitative statements:

- the complexity of the integrated approach greatly modifies the propagation of uncertainties from one sub-model to the downstream one, so a dedicated analysis has been performed in order to aggregate the information coming from each sub-model and evaluate the weight of each of them in the definition of the overall modeling uncertainty;
- the adopted approach allowed for identifying unbalances in terms of uncertainty propagation among different quantity modules showing that uncertainty is mainly due to hydrological depletion module and to net rainfall – runoff propagation;
- on the other hand, quality modules resulted to be more balanced showing the relevant role assumed by water quality kinetic constants in uncertainty propagation in BOD and DO concentrations.

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