https://doi.org/10.71573/z6medd29



# Out of bounds: system structural uncertainty under extreme events

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## Abstract
The study focuses on the Fossolo catchment in Bologna, which has been the subject of various modelling studies over the years. While previous research has focused on parameter optimization, limited attention has been devoted to model structure and boundary conditions.
The study aims to investigate if the hypothesis of independence of subsystems is valid under extreme events. Two classes of models are developed in EPA-SWMM: one reflecting the original system structure and another based on a re-analysis of the system that incorporates downstream conditions. Sensitivity analysis reveals that downstream conditions impact parameter sets during extreme events, with pipe and impervious surface roughness being the most sensitive parameters.

## Highlights
- Investigation of model structure uncertainty through the re-analysis of the system is performed.
- Boundary conditions must be carefully considered when simulating extreme events in systems assumed to be independent.

## Introduction
Using city scale hydrological models for stormwater management requires finding a balance between available information, level of detail and computational resources. This balance is often linked to the need for an explanatory model, which is a model where hydrological processes are meaningfully represented to an extent where it is possible to evaluate different scenarios through the use of the model and conclude on a viable solution for a specific objective. In order to keep the model explanatory at the scale considered, researchers may focus on an independent subsystem. Once a subsystem has been identified, a model structure is set, and the model development focuses on parameter optimization. This is the case of Fossolo catchment, neighbourhood of Bologna, that has been the subject of several modelling studies over the years. Data from monitoring activities conducted by Marinelli et al., (1997) and Artina et al., (1997) have been extensively used in multiple modelling exercises. As an example, Mannina and Viviani (2010) have adopted the observed data to calibrate a

tool for simulating water quantity and quality processes in urban drainage and estimate model uncertainty by means of the GLUE methodology, whereas Freni and Mannina (2010) applied the Bayesian uncertainty estimation; De Paola et al., (2018) tested an innovative optimization procedure based on a harmony calibration algorithm.

Focussing only on parameter optimization might overlook the iterative process needed to ensure the model aligns with the intended objective (Jakeman et al., 2006), as well as address superficially assumptions that constrain the model structure and boundary conditions (Refsgaard et al., 2006).

In the case of the Fossolo catchment, the hypothesis of an independent subsystem is important, as future conditions, in particular the change in frequency and magnitude of extreme events in the mediterranean area (Caillaud et al., 2021), may challenge the relevance of that hypothesis and therefore the usefulness of the model. Consequently, in this study we investigate if the hypothesis of independence of subsystems holds under extreme events in current and future conditions.

To achieve this, the study is organized as follows: i) presentation of the catchment, ii) redevelopment of model based on a re-analysis of the system, and iii) sensitivity analysis for both configurations and consequently analysis of the impact over the parameter set.

# Methodology

## Presentation of the Fossolo catchment and related model

Fossolo catchment, neighbourhood of Bologna (Italy) of 41 ha, is drained by a tree-like combined sewer network, considered independent from the surrounding sewer networks, as it does not receive inputs from upstream. The network presents three connections with the global sewer system ($Out_1$, $Out_2$ and $Out_3$). The model has been developed with SWMM 5.2 (Rossman, 2010). Points $Out_1$, $Out_2$ and $Out_3$ are assumed such as "cutting points" that are modelled by "outfall" objects. This set-up is certainly suitable given the geometry of the network: points $Out_2$ and $Out_3$ show a difference in the elevation of about 0.80 m between the Fossolo network and the main one. Outfall $Out_1$ does not coincide with the connection to the global sewer network, but it is placed slightly earlier to avoid any interference. The monitoring activity, conducted for water quality purposes, involved the set-up of sampler and water level sensor in the final section of the Fossolo drainage network, highlighted with red square in Figure 1.

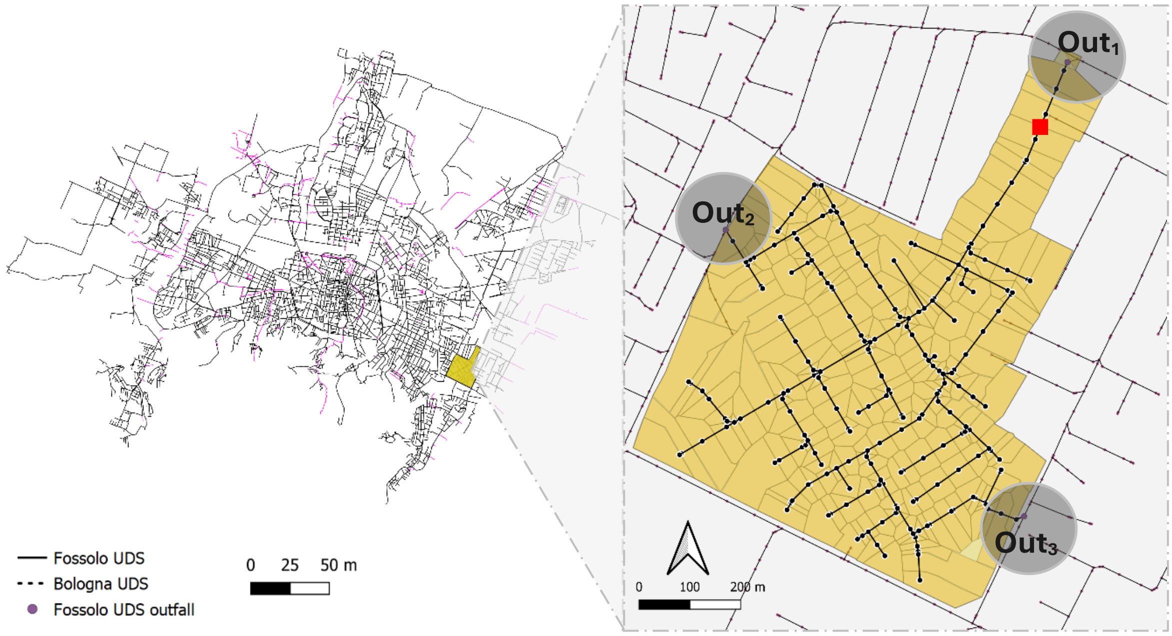


**Figure 1.** Bologna sewer network with a focus over Fossolo catchment and relative drainage system and outfalls. Red square represents the location of the water level sensor.

**Assessment of structural uncertainty impact under current conditions**

Structural sources of uncertainty have been analysed by developing two classes of models with different assumptions: the first class reflects the **original structure of the system**, as described above with outfalls $Out_1$, $Out_2$ and $Out_3$ of type "normal", while the second proposes a **new configuration,** based on a re-analysis of the system. Specifically, the new configuration assumes that at point $Out_1$, the system is influenced by downstream conditions. In this model, $Out_1$ is treated as an outfall of type "timeseries": the global model was used to input water level timeseries as boundary condition at the outlet $Out_1$. Even tough the timeseries has uncertainties since the global model is not calibrated, this has helped refine the understanding of the system's behavior and interactions. Within each class, two models are developed with distinct parameter sets. One model was calibrated exclusively on extreme events, while the other excluded them. Figure 2 clarifies the four models developed. A set of four events was selected, with characteristics in Table 1: Event 6 exhibits extreme characteristics, making it a key for further analysis. The four models were subjected to an event-based simulation approach.

**Table 1.** Main characteristics of the rainfall events used for the analysis.

| Event | Date | Duration (min) | Depth (mm) | Max. Int. (mm/h) |
|---|---|---|---|---|
| 1 | 25/04/94 | 77 | 7.82 | 26.10 |
| 5 | 28/10/94 | 289 | 23.06 | 60.00 |
| 6 | 23/06/95 | 538 | 72.72 | 147.97 |
| 8 | 13/11/95 | 921 | 42.65 | 60.00 |

The simulated water levels were compared with observed values at the final section. The four models were subjected to a sensitivity analysis to identify the most influential parameters, their interactions, and their impact on the output (Saltelli, Annoni, et al., 2010). The variance-based Sobol method was employed for this purpose. Maximum error metric was adopted such as objective function.

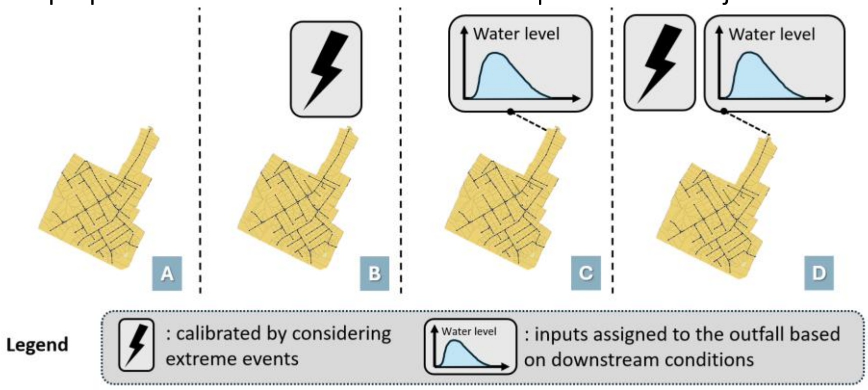


**Figure 2:** Overview of the calibration experiment for investigating the independence of the sub-system.

# Results and discussion

Figure 3 shows the simulated and observed water levels for Event 6, using the best parameter sets (Max Error < 0.25 m): black and red curves belong to the original and new model configurations, respectively. Observed water levels in the pipe reached a maximum of 1.4 m, indicating pressurized operation of the collector. While the original model fails to capture the peak, the new configuration performs better. The parameter sets of the original model, lacking boundary conditions downstream, compensated by a high roughness to match the peak which results in a smoothed signal. It does not represent a physical process: it is a case of overfitting to a model subject to structural uncertainty. Figure 4 shows the CDFs of pipe roughness and impervious surface roughness for the four models with Max Error < 0.25 m. The segmented CDFs for Models B and D reveal fewer parameter sets satisfying

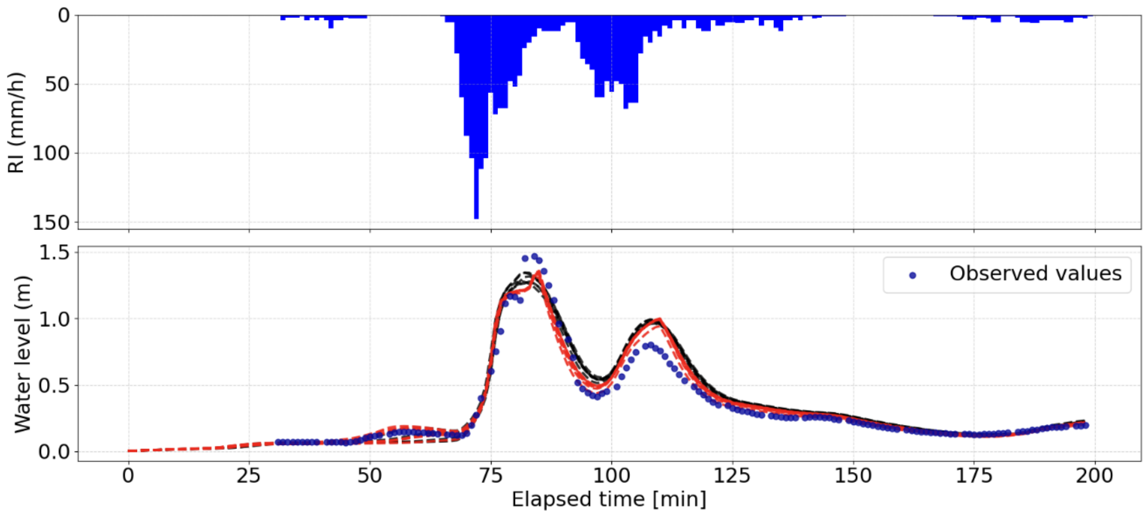


**Figure 3.** Simulated and observed water level trends in the final section of Fossolo network for Event 6: blue points represent observed values, black and red curves correspond to the simulation of original and new configuration model, respectively.

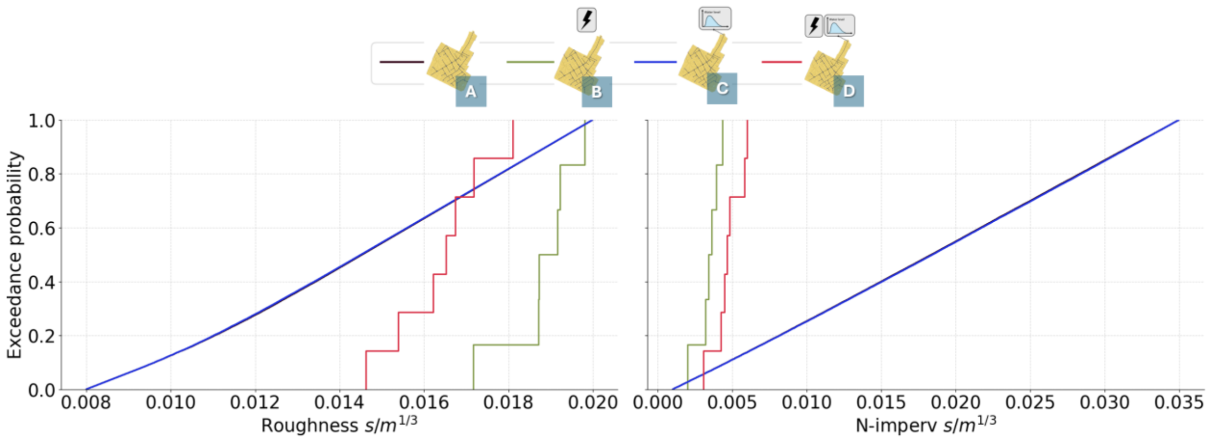


**Figure 4.** Distribution of behavioural parameters (pipe roughness and impervious surfaces roughness) using different events for calibration, and different downstream boundary conditions.

this condition. Models A and C exhibit overlapping CDFs, indicating no sensitivity to the analysed parameters: the inclusion of boundary condition in normal events provides negligible improvements. In contrast, CDFs of Models B and D, developed under extreme conditions, are affected by external boundary conditions: our efforts to refine the model structure, reflected in Model D, have led to a clear shift in the distribution by preventing overfitting to data (Model B).

# Conclusions and future work

Preliminary investigations indicate that Event 6, considered an “extreme event”, triggers a condition of interconnections between the two networks. In a parameter optimisation process, the driver parameters are overly adjusted to match observed values, however discrepancies often arise from limitations in the model structure and assumptions on boundary conditions. The four models will be tested in a future climate condition to assess the impact of structural uncertainty on model outputs.

# Acknowledgement

The research was funded by the EU Horizon Europe, StopUP project, grant agreement 101060428.

# References

Artina, S., Maglionico, M., Marinelli, A., Raffaelli, G., Anzalone, C., Lanzarini, S., and Guzzinati, E. (1997) Le misure di qualità nel bacino urbano Fossolo, L'Acqua, 2/1997, 17-25.

Caillaud, C., Somot, S., Alias, A., Bernard-Bouissières, I., Fumière, Q., Laurantin, O., Seity, Y., and Ducrocq, V. (2021) Modelling Mediterranean heavy precipitation events at climate scale: an object-oriented evaluation of the CNRM-AROME convection-permitting regional climate model. Climate Dynamics, 56(5), 1717–1752.

De Paola, F., Giugni, M., and Pugliese, F. (2018) A harmony-based calibration tool for urban drainage systems. Proceedings of the Institution of Civil Engineers - Water Management, 171(1), 30–41.

Freni, G. and Mannina, G. (2010) Bayesian approach for uncertainty quantification in water quality modelling: The influence of prior distribution. Journal of Hydrology, 392(1), 31–39.

Jakeman, A. J., Letcher, R. A., and Norton, J. P. (2006) Ten iterative steps in development and evaluation of environmental models. Environmental Modelling & Software, 21(5), 602–614.

Mannina, G. and Viviani, G. (2010) An urban drainage stormwater quality model: Model development and uncertainty quantification. Journal of Hydrology, 381(3–4), 248–265.

Marinelli, A., Maglionico, M., and Artina, S. (1997) "Water quality simulation in an urban drainage catchment" in, 383–390. [online]https://www.scopus.com/inward/record.uri?eid=2-s2.0-0031367267&partnerID=40&md5=5c91a2c5d62e32ef1f62fd57a5ff29a2.

Refsgaard, J. C., van der Sluijs, J. P., Brown, J., and van der Keur, P. (2006) A framework for dealing with uncertainty due to model structure error. Advances in Water Resources, 29(11), 1586–1597.

Rossman, L. (2010) Storm Water Management Model User's Manual Version 5.0. US Environmental Protection Agency.

Saltelli, A., Annoni, P., Azzini, I., Campolongo, F., Ratto, M., and Tarantola, S. (2010) Variance based sensitivity analysis of model output. Design and estimator for the total sensitivity index. Computer Physics Communications, 181(2), 259–270.