

## Uncertainty in Design and Management of Sewer Systems

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Loads acting on urban drainage systems are intrinsically uncertain and often known with limited details given their physical complexity. External loads include climate variables (rain, snow, temperature ...), which have a naturally mutable behaviour, exacerbated by climate change. Other system variables, such as roughness of surfaces and soil permeability, are normally unknown and only partially measurable. Additional sources of uncertainty derive from the transposition of the physical system into numerical models, routinely used to make predictions about real systems and their design and management.

Probabilistic analyses of civil structures [1] distinguish two types of uncertainty: aleatory and epistemic. The former is inherent in a nondeterministic phenomenon due to its randomness, and originates from variability in known or observable data. Epistemic uncertainty, on the other hand, is attributable to incomplete knowledge about a phenomenon, connected either to model uncertainty (lack of understanding of the physics) or statistical uncertainty (lack of sufficient data). It is important to note that sometimes the two type of uncertainties overlap or cannot be distinguished.

In urban drainage systems, aleatory uncertainty mainly affects external forcing: e.g., one cannot predict exactly the maximum rainfall intensity that will occur next year, even when sufficient data are available. Epistemic uncertainty is related to a lacking/incorrect description of physical phenomena: relevant examples include rainfall-runoff and in-sewer processes.

Hence, sewer systems are largely affected by uncertainties in both design and operational management, notwithstanding existing theoretical numerical approaches aimed at reducing their impact [2]. In the following, we provide a review on the main sources of uncertainty in urban water systems and the related design and management issues.

### Uncertainty in the Design of Sewer Systems

The design of storm and combined drainage systems is based on rainfall intensity and involves the determination of the size of the conduits necessary to achieve the design hydraulic conveyance. The design flow, in turn, is linked to the required level of service of the drainage infrastructure, and is usually defined in terms of the frequency of reoccurrence, either as a probability of flow exceedance or as a recurrence interval between events of similar magnitude. Once a given level of service is selected, typical design methodologies include empirical peak runoff design methods, hydrologic simulation models or statistical methods based on the analysis of flow records. Approaches commonly used to select appropriate values of rainfall in design of urban infrastructures are the intensity-duration-frequency (IDF) curves, historic design storms and synthetic design storms [3].

It is important to highlight the limits of these approaches in terms of uncertainty. While the overall effect of climate change on sewer design is yet to be ascertained, it should be noted that all the aforementioned approaches to the selection of rainfall design data are based on the usage of historical data as an indication of future conditions, with an assumption of statistical stationarity. Its validity is challenged by climate change, which has a significant impact on the design of storm drainage infrastructure [3], irrespective of the modelling technique adopted (event or continuous). A closer interaction between engineers

and climate change scientist is envisaged to adapt model input data so as to incorporate the effects of climate change.

General Circulation Models are the basic tool used for modelling climate change. They characterize the concentration of greenhouse gasses in the atmosphere as the main agent, usually identified by atmospheric CO<sub>2</sub> concentrations. Predictive models typically envision future scenarios involving a near-doubling of the year 2000 atmospheric CO<sub>2</sub> concentrations by the year 2050 [4]. This is expected to bring about an intensification of rainfall intensities quantifiable between 15% and 20%, or, equivalently, a halving of the return period of design storms [3].

### Uncertainty in the Management of Sewer Systems

Uncertainty is ubiquitous also in the management of sewer systems. Uncertain hydraulic performance and structural conditions influence priorities adopted in sewer maintenance and rehabilitation, an endeavour which involves considerable investments. Insufficient hydraulic performance leads to flooding, discharge of pollutants into water bodies by Combined Sewer Overflow (CSO) and sediment-related hazards. Flooding is mainly connected to more severe rainfall events and modification of downstream boundary conditions. CSO spill frequency and volume tends to increase yearly as reported for the UK by [5], with smaller increases in spill frequency than spill volumes; this is attributable to a reduced duration of rainfall events under climate change. Higher sediment build-up, linked to more prolonged dry weather periods before rainfall events, magnifies the transport rate of sediment-associated pollutants, a further example of how environmental impacts may be compounded by climate change. Moreover, accumulation of sediments within the sewer system may determine blockages and thus amplify the extent of flooding.

Structural conditions of sewer conduits may range from new to critical, spanning an array of intermediate conditions difficult to determine and forecast. These difficulties are mainly related to the extension of the network and the costs of inspection technologies; moreover forecasting of pipe conditions is hindered by limited knowledge about physical pipe deterioration and to chemical interactions between pipe material and the conveyed flow.

Another source of uncertainty is related to evaluation of dry weather flow, which consists of two parts: sewage and infiltration from groundwater. The sewage flow rate exhibits oscillations in time due to varying flow from households and industry during the day, connected to

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inhabitants' behaviour and industrial water usage. Besides, infiltration flow is less predictable as it is affected by fluctuating groundwater levels and may add up to 50% to sanitary flow [6].

Management of sewer systems is usually supported by the use of modelling tools in order to predict the behaviour of drainage systems and aid the decision-making process, but the reliability of such results deteriorates when considering long term predictions such as those related to climate change.

Input data used in sewer models (sewer system geometry, drainage area, inhabitants, runoff parameters, ...) are typically affected by errors, which considerably influence the modelling outputs, with particular reference to uncertainties relative to contributing areas and structure of the sewer system [6].

Besides, modelling results are affected by uncertainty linked to the physical processes, the model structure and the model parameters that may be obtained by calibration techniques. The calibration procedure involves uncertainty due to the inaccuracies in measured levels and/or flowrates, and theoretical and numerical errors embedded in the calculation algorithms [7].

The impact of uncertainty in modelling urban drainage systems is most relevant in the rainfall-runoff and in-sewer hydraulic and transport processes. As the two phenomena interact, so do the respective uncertainties. The rainfall-runoff process is split into sub-processes such as wetting of dry surfaces, infiltration, depression storage, evaporation and overland flow; each of these is strongly simplified and as a result supplementary uncertainty is added to that stemming from variability of runoff in time, local differences in surfaces, lack of data, deficient initial conditions and insufficient knowledge of the processes. Phenomena taking place within the network include flow, pollutant and sediment transport. The main uncertain parameter related to flow is the roughness coefficient, which in itself varies in a relatively narrow range. Additional complexity and uncertainty comes into play upon analysing water quality phenomena. The mutual interaction of biological, physical and chemical processes renders water quality modelling in an urban drainage system an ambitious effort. Up to now only approximate, yet complex, quality models have been introduced in the literature. They display a greater degree of uncertainty than hydraulic models, given the smaller amount of field quality data available due to cost and difficulties in collecting and analysing samples. In order to compensate this lack of knowledge, sewer water quality models often utilize parameters without immediate physical meaning. Sediment may deposit and interact with flow by altering roughness and cross-section. Furthermore, suspended solid transport contributes to advecting pollutants such as heavy metals and nutrients, compounding the impact of urban drainage systems on the surrounding environment.

The robustness of water quality predictions is affected by a broad range of external factors such the "uncertain" hydraulic behaviour, inputs with a large degree of variability (e.g. sediment size and density) and system interconnection, as upstream water quality in turn affects the downstream systems (receiving water bodies and treatment plants) [5]. It is worth noting that several numerical techniques, such as first-order variance propagation or Monte Carlo simulation analysis, have been proposed in the literature in order to estimate the uncertainty magnitude and the effects of its propagation throughout the system on the final results of the analysis (flows, CSOs, ...).

## How to Cope with Uncertainty and Adapt the Sewer Systems?

As previously described, uncertainty permeates urban drainage systems in many respects; among them climate change is paramount. To account for the growing uncertainty in forcing factors, one possible philosophy is to increase the safety coefficients, as exemplified by the recommendation by [8] to design urban drainage systems based on a design storm determined using the available climatic records, and then increase the magnitude of the design storm by 15% to accommodate the effects of climate change. This approach entails increasing the construction costs of infrastructures, mainly when existing networks have to be adapted to new requirements. An alternative is to adopt solutions adaptive and resilient to climate change [9], preventing the increase of flooding risk, and maintaining the historic levels of service provided by drainage infrastructure. These measures are aimed not only at improving the infrastructure but also at affecting the factors that may increase flooding risk, changing the way the urban area is build [3].

The most up-to-date and integrated tool to achieve the aforementioned goals is the adoption of Best Management Practices (BMPs). These aim at minimizing the extension of impermeable areas, by introducing permeable and porous pavements to allow water infiltration. Building design may incorporate features to reduce the rate and amount of storm water runoff: thus rainfall captured at the source (from impervious areas, roads, roofs, etc.) is returned to the natural hydrologic cycle through infiltration. The runoff from roofs of buildings may be reduced by employing rainwater harvesting devices and green roofs. Such measures also have a positive impact on water quality, by reducing peak flows and volumes spilled into receiving water bodies. Reduction of pollution at the source may be achieved also via the adoption of non-structural measures (e.g., periodic street cleaning, gully pot management). Finally, alternative measures for wastewater treatment should be considered, such as constructed wetlands.

Intensive and regular monitoring and data collection in sewer systems may be considered a non-structural measure in that it helps to better understand hydrological and water quality phenomena in order to reduce epistemic uncertainty and to appropriately take into account aleatory uncertainty; further advantages may derive towards development, calibration and validation of numerical models.

In conclusion, uncertainty is intrinsic in design and management of sewer network, and cannot be completely eliminated [10]; climate change may add to this. To cope with the risk connected with increased uncertainty, designers and operators of urban drainage systems need to embrace a new paradigm which entails a multi-disciplinary approach, and uses a mixture of infrastructural and non-infrastructural measures in a proactive and reactive way.

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