Optimal deployment of the water quality sensors in urban drainage systems

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Highlights

- A novel Bayesian strategy to urban drainage water quality sensing is proposed to detect contamination sources;
- The method is scalable depending on the availability of initial data and new sensors;
- The approach is able to evaluate the uncertainty and it is able to reduce it in time.

Introduction

In the water sector, the problem of polluting source identification was mainly investigated regarding pressurized distribution networks respect to sewers even if the Water Framework Directive 2000/60/EC, in EU, and other equivalent laws in many countries introduce the principle that the polluter pays so asking the water manager to detect and mitigate the most pollutant discharges in sewers.

Boenne et al. (2014) showed that the contribution of WWTP overflows can produce up to 22% of the measured nutrient load in a river due to just two events of a few hours. Jiang et al. (2015) asserted that the identification of polluting sources after river spill occurred is critical to improve decision-making on emergency response to sudden water pollution. For this reason, models for the characterization of the wastewater have been widely studied for assessing the pollution load overflowed and/ or transferred to WWTP.

Montserrat et al. (2015) developed a methodology to evaluate the performance of combined sewer systems (CSS) using low-cost monitoring; in this case, the collection and analysis of real data is indispensable to assess, improve, and maintain CSSs in order to reduce the number and impact of overflows. Irvine et al. (2011) have implemented a project with municipalities in Western New York State to evaluate the low-cost options for illicit discharge trackdown. In Vezzaro et al. (2014), the potential for including water-quality in real time control (RTC) schemes was unveiled, providing a further option to urban water managers to improve the performance of their systems.

The xenobiotic substances, unlike the organic ones, are only slightly affected by biological degradation processes. In particular, metals often show a remarkable tendency for bio-accumulation. As such substances are often unaffected by common waste water treatment plant technologies, an efficient contamination prevention strategy should involve the identification and elimination of illicit intrusions, especially in urban drainage systems. Therefore, the implementation of a chemical monitoring network is necessary to promptly detect the event of contamination. The installation and maintenance cost can be reduced optimizing the position of the sensors so obtaining, at the same time, a reliable and cheap monitoring infrastructure.

Freni & Sambito (2019) proposed a probabilistic approach to the positioning of water quality sensors in urban drainage networks, showing the progressive increase in identification probability obtained through the Bayesian approach. They carried out 2 tests, with and without pre-conditioning; the pre-conditioning approach was based on the study of Banik et al. (2017) and showed an improvement of results with more efficiency in term of computational efforts. However, the proposed pre-conditioning approach was mainly influenced by network topology. Following the past literature, the present work

aims to improve it, inserting new information beyond network topology, i.e. a grey information from commercial/industrial activities inventory.
The methodology is applied on the real test-case represented by the sub-catchment of sewer system Palermo (Italy). The study is mainly aimed to the solution of a sensors location problem, assuming the positioning of fixed-type sensors. The proposed approach was also evaluated considering the inclusion in the network of groups of sensors; initially the analysis was carried out making the hypothesis that each node of the network has the same probability of being the polluting source, successively the hypothesis that some nodes can be more frequently polluted then others is introduced. A further objective is to show the adaptability of Bayesian approach in sensors location.

Methodology

By using the Bayesian approach, new information, coming from the analysis, is incorporated in the approach allowing the operator to gain insight on the system once new contamination events are detected and identified. In this way, the approach is suitable for solving problems in which data are initially piecemeal and the operator plans to improve the monitoring strategy.
For the solution of this problem, two main components are required: a calibrated model for hydraulic and water quality simulations in sewer systems and a Bayesian solver for likelihoods estimation and probability update. In this case, the EPA SWMM model was used to perform the hydraulic and water quality simulations and a decision-making support of the Bayesian Decision Network (BDN) type was implemented for the positioning the water quality sensors.
A Bayesian network (BN) is a graphical structure that allows us to represent an uncertain domain. Bayesianism is the philosophy that asserts that in order to understand human opinion as it ought to be, constrained by ignorance and uncertainty, the probability calculus is the single most important tool for representing appropriate strengths of belief. Therefore, the BN is a very robust and particularly useful method for assessing risk and uncertainty, providing a complete framework for analyzing all cause-effect relationships (Korb &Nicholson, 2010).
The problem of sensor location for identifying the illicit intrusion for the considered case-study, has been already investigated in Banik et al. (2017) but using genetic algorithms. In particular, different single and multi-objective optimization procedures to optimally locate sensors in the sewer have been compared. In Freni & Sambito (2019) without pre-conditioning, initially, all nodes had equal probability to be the candidate nodes for sensor placement and all nodes had equal probability to be an illicit contamination source. Therefore, the contamination events are randomly simulated in order to evaluate the probability of each sensor to identify the source of contamination.
The present analysis was carried out on a real case study, the network of Palermo city centre (Italy) using SWMM model as simulation tool for analysing hypothetical contamination events. Each contamination event is simulated by a random mass of contaminant (ranging from 10g to 500g) constantly injected in a node for a random time (ranging from 15 min to 3 hours).
In this sensor location exercise, two of the previous limiting hypotheses were removed:

- Contamination probability is no more equal in all network nodes, but some of them have higher probability to be object of an illicit intrusion;
- The pre-conditioning approach is based not only on network topology but considering also data regarding commercial and industrial activities in the area.

The considered contaminant is conservative xenobiotic, such as, heavy metals. The analysis was initially run in wet weather conditions in which deliberate discharge of pollutants more likely occurs.
As it is reasonable to assume that the nodes downstream of commercial/industrial activities may have a greater probability of being subject to illegal spill of contaminants into the sewers, the cumulative probability distribution function of contamination, was not considered uniform. Some nodes were

hypothetically considered to host industrial activities having double probability to present illicit contamination with respect to the others. This hypothesis does not modify the general applicability of the method in cases in which industrial nodes may change in number, contamination probability or location.

Preliminary results and conclusions

Initially any node in the network has the same probability to be the location of a sensor. In a second step, prior knowledge was based on information derived from the location of industrial activities and the most probable path of contaminants propagation. Such information was obtained through a statistical analysis by random simulations. The analysis was carried out by means of Monte Carlo Simulations in which a single source of contamination was in one of the nodes of the network according to the contamination probability. BDN parameters such as the number of Bayesian updates and the population of each update were modified to understand their impact on the analysis, especially with respect to the minimum number of simulations useful to highlight the most efficient configuration of sensors. In this way, it is possible to understand how the value of BDN parameters can affect the selection of most relevant nodes for sensor placement and the number of model simulations needed to obtain a stable configuration. The use of a non-uniform informative "a priori" sensor location distribution allows for saving simulation time. This analysis shows the same results of the previous in term of optimal sensor location so demonstrating that the use of different prior distributions does not affect sensor maximum efficiency in polluting source location. The use of informative prior distributions helps reducing the number of simulations needed to reach a stable optimal configuration. The analysis was carried out both analyzing the impact of BDN approach parameters and the ability of the best possible sensor locations. In order to save computational time, the analysis was only carried out starting from an informative priori distribution based on the previous random contamination simulations. The best sensor configuration and the efficiency of the sensor network in identifying the polluting source depend on the number of simulations and on the number of procedure updates. The complexity of the analyzed network takes, as a consequence, that the best strategy is to increase the number of Bayesian updates reducing the population of each update. This can be explained by the complexity of the system and the number of possible sensors combinations that should be considered.

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