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Monitoring planning for urban drainage networks

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Abstract. Urban drainage network (UDN) monitoring is an important task whose planning can be related to various purposes, as for example contaminant detection and epidemiological studies. This paper proposes two different strategies for the identification of a monitoring system for UDNs. The optimal solution, in terms of location and number of sensors, is firstly addressed using a deterministic approach. A new mathematical model is developed and a global optimization solver is employed to perform the optimization procedure. Secondly, the position of devices is also investigated using a new strategy based on the complex network theory (CNT) tools. The comparison between the results achieved by both the strategies is finally presented with reference to a benchmark network.

1. Introduction

Urban drainage networks (UDNs) are complex systems [1,2] aimed at the collection and transport of wastewater and rainwater up to the treatment plant.

In recent decades, the need to propose new monitoring strategies for such complex systems has become increasingly urgent, mainly for factors related to the identification of illicit intrusions, to the control of specific contaminants [3,4] and to the limitation of the potential environmental impacts [5].

Solving this problem with optimization algorithms has been the focus of attention of many researchers, mainly relying on heuristic approaches [3,4,6,7].

These approaches are very effective but also very cumbersome, both for the hydraulic simulations they require and for the expensive calculation times. Furthermore, it could also happen, particularly with very large and complex systems, that the lack of information (e.g., flow) makes such analyzes difficult or even unreliable. In this context, the Complex Networks Theory (CNT) is proposed as a useful approach for the analysis of complex real systems [8].

The aim of this paper is to model the sensor placement problem, i.e., determining the candidate positions to host water quality sensors useful for detecting the presence of contaminants or pathogens in the system, using both an optimization procedure and complex network theory approach.

The first strategy is based on an optimization procedure aiming at searching for the best location of a fixed number of water quality sensors, in order to maximize the reliability of the whole system in case of contamination. This strategy relies on the development of a mathematical model, which is solved by the use of a global optimization solver.

The second one uses a CNT centrality metric by integrating both information on the connectivity structure and on the intrinsic relevance of nodes of the system. The strategy considers the different role of nodes (e.g., inlet nodes, connection nodes, outfall nodes, etc.) embedding the information about their

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intrinsic relevance [12] as lateral inflow and the presence of spatial constraints (e.g., slope) derived from the flow direction of the system. The goal is to apply the In-Relevance-based harmonic centrality to the direct graph of the UDN to support the monitoring system planning.

The paper is organized as follows. The next section describes the two methodologies, the third section presents the results of the analyses applied to a benchmark UDN and their comparison. Concluding remarks are drawn in the last section.

2. Material and Methods

Determining the ability of a node to detect the contaminant in UDNs is essential for planning an efficient monitoring system. This paper presents two modeling approaches for optimal sensor placement aimed at detecting contaminants and pathogens in UDNs.

The first methodology proposes an optimization problem based on one single objective function, that is, the maximization of the network reliability when a spill of contaminant occur within the system.

The second methodology investigates the sensor monitoring problem from a more topological perspective, using a metric proposed by the complex network theory (CNT) and adapted to infrastructural systems like UDNs.

2.1. The optimization method

The first strategy is a deterministic optimization, relying on the analytical properties of the problem to generate a sequence of points converging to a global optimum or an approximately global optimum. Deterministic methods include: linear programming (LP), non-linear programming (NLP), mixed-integer linear programming (MILP) and mixed-integer non-linear programming (MINLP) [13,14]. Most of the available MILP/MINLP solvers can achieve global optima only in convex problems [15]. The only solvers managing to find global optima in both convex and non-convex problems are the global optimization solvers.

In this study, the optimization procedure is performed by SCIP (Solving Constraint Integer Programs) [16] solver, which is a global optimization solver implementing a spatial branch and bound and various heuristics.

2.2. The optimization procedure

Given a network consisting of L links and N nodes, the aim of the optimization procedure is to find the best location of a fixed number of sensors in order to maximize the network reliability (R_N) in case of pollutant introduction. In this study, the optimization procedure has been decoupled by the hydraulic and quality modelling of the network, thus flow velocity (V) and pollutant concentration (C) are preliminary computed by means of an external software (i.e. SWMM) [17].

The network can be modelled as a directed graph, so that each link l (l = 1....L) has a proper direction and the discharge flows from the initial node (i_i) to the final node (i_f) of the generic link l. In this study, each node of the network is a possible candidate for the installation of a sensor and it has been modelled by means of a binary variable (I_n), which is equal to 1 if the device is installed, 0 otherwise.

According to the proposed procedure, the sensors should be located in order to maximize the reliability of the network, which means maximizing the number of detected points when a pollutant is inserted within the network. In this study, the network reliability is assessed over several scenarios, each one differing in the node assumed as inlet point of the pollutant.

A further variable of the optimization is represented by the pollutant detection ($\delta_{i,s}$), which is defined for each node i (i = 1...N) and for each scenario s (s = 1...σ). Such a binary variable has been properly modelled by means of a set of constraints, written for each link l (l = 1...L) of the network:

$$\delta_{i_i,s} = I_{i_i} B_{i_i}^s + I_{i_f} B_{i_i}^s + \left(1 - I_{i_f}\right)\left(1 - I_{i_i}\right)\left(\delta_{i_f,s} B_{i_i}^s\right) \quad (1)$$

where $B_{i_i}^s$ is a parameter equal to 1 if the concentration at the i_i-th node ($C_{i,s}$) is greater than a threshold concentration (C_0), 0 otherwise. The parameter $B_{i_i}^s$ results from the concentration values obtained by the quality model performed by the software SWMM.

It is worth underlining that the outfall (ω) is not constrained by means of Equation (1), since it cannot be the initial node of any links. In order to properly define the pollutant detection at the outfall node, the following constraint has been defined:

$$\delta_{\omega,s} = I_\omega B_\omega^s \tag{2}$$

According to Equation (2), the pollutant at the outfall is detected only in case of device installation (i.e., I_ω equal to 1) and concentration value greater than the threshold value (i.e., B_ω^s equal to 1).

Finally, a further constraint has been considered in order to set the total number of sensors (N_s) installed within the network:

$$\sum_{i=1}^{n} I_n = N_s \tag{3}$$

As objective function of the optimization, the system reliability has been considered and defined as follows:

$$maximize\left(R_N = \frac{\sum_{s=1}^{\sigma}\sum_{i=1}^{n}\delta_{i,s}}{\sum_{s=1}^{\sigma}\sum_{i=1}^{n}B_{i,s}}\right) \tag{4}$$

2.3. In-Relevance-Harmonic centrality for monitoring planning of UDNs

Centrality is one of the most studied concepts in CNT. Several centrality metrics have been proposed [8,9,12,18] to evaluate the most central element in real systems with respect to different physical phenomena and about the way information flow in a network [14]. The proposed approach recalls the concept of Harmonic centrality [19] and investigates the possibility of using this metric to efficiently plan a quality monitoring system in UDNs.

The Harmonic centrality is a metric that well detects the ability of each node to disseminate and receive information in the system based on the concept of proximity. The original formulation of the Harmonic centrality, $H^C{}_i$, is mathematically expressed as:

$$H_i^C = \sum_{j=1}^{N}\frac{1}{d_{ij}} \tag{5}$$

where d_{ij} is the distance from node i to node j in the network.

The standard metric is extended to embed the information about the intrinsic relevance of the nodes (outfall, connection nodes, etc.) through the function $f\,(R_i, R_j)$. The Relevance-harmonic centrality [12] is mathematically expressed as:

$$H_i^C = R_i\sum_{j=1}^{N}\frac{1}{d_{ij}} \tag{6}$$

The intrinsic relevance R_i (i=1, …, N) is an information depending on the type of the network and the analysis to perform. The proposed strategy is performed using the function $f(R_i, R_j) = (R_i+R_j)/2$, corresponding to the mean value of the intrinsic relevance of each pair of nodes i and j because it highlights the role of the intrinsic relevance in the connections between nodes [12].

It is important noting that the harmonic centrality assumes that information through the network move only along the shortest possible paths, just as happens in UDNs, for which the shortest paths between the various pairs of nodes are uniquely determined by the slope of the system.

In the present case, the In-Relevance-Harmonic centrality, is evaluated for each node to determine which nodes can detect the greatest amount of information disseminated on the network, and therefore, which are best suited for positioning sensors.

3. Case study

The benchmark UDN reported in Figure 1 [20] is considered to perform the two approaches. The UDN is composed of 77 nodes (manholes), 79 edges (sewer pipes) and 1 outfall. The network is direct according to the flow directions imposed by the slope of the system.

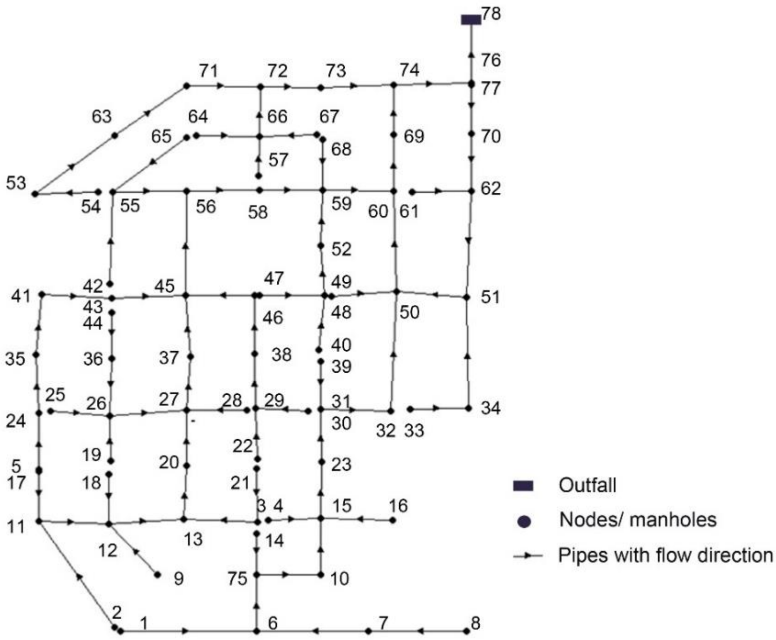

Figure 1. Network layout with flow direction.

3.1. Application of the optimization procedure to the case study

For the analysed case study, each node of the network has been assumed as possible inlet of the pollutant. Therefore, the total number of analysed scenarios (σ) is equal to the total number of nodes (N). Regarding the inserted pollutant, the inflow concentration has been assumed equal to 1 mg/l. The pollutant has been considered to decay with a first order kinetic, with the decay coefficient set as 0.2.

Once a threshold concentration value (C_0) and a number of installed sensors (N_s) are fixed, the optimization process is accomplished by the solver SCIP in less than 1 second. The achievement of the global optimum is extremely fast since SCIP is a very high-performance solver for MILP problems.

It is worth underlining that, by increasing the number of installed sensors, the value of the objective function (i.e., the network reliability) progressively increases up to the maximum value (i.e., 1). In particular, Figure 2 reports the value of the objective function as function of the number of sensors for the case $C_0 = 0.008$ mg/l, showing that four sensors are sufficient for reaching the maximum value.

3.2. In-Relevance-Harmonic centrality for the sensor system planning

In this paragraph the In-Relevance-Harmonic centrality is applied to the case study to understand if it can draw useful information about the optimal sensor location. The intrinsic relevance is set equal to the lateral inflow for each node, which is proportional to the concentration of contaminant introduced into each node as mg/l.

According to the performed analysis, the maximum value occurs for node 78, i.e., the system outfall. This result indicates that the outfall is the most suitable node to detect the information of other nodes and thus, it can be seen as a good candidate for sensor placement, consistently with the system operation.

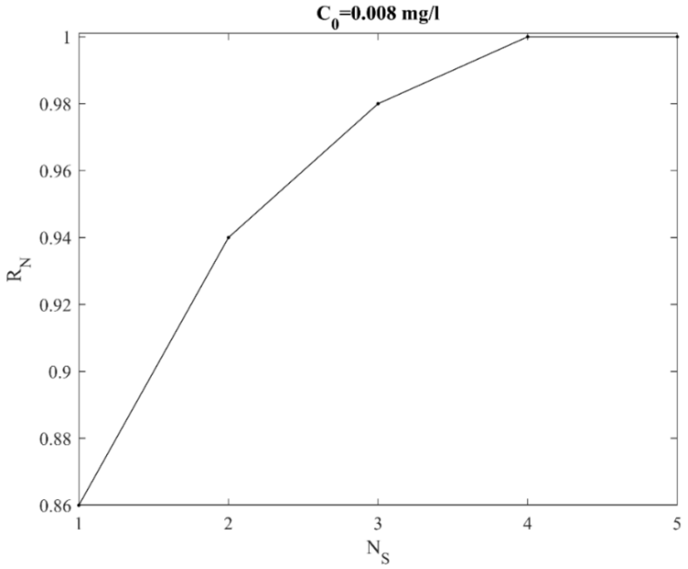

Figure 2. Variability of the objective function depending on the number of installed sensors for C_0 = 0.008 mg/l.

To increase the number of sensors to be installed in the network, it is possible to refer to the metric values and select the nodes immediately less central than the outfall. It indicates that nodes 76 and 59 as good information receptors. It is evident that node 76 is alternative to node 78 since they are connected to each other. The analysis suggests that node 76 receives a lot of information about the system, being close to the outfall, and therefore represents an excellent position to host a sensor, but at the same time its proximity to the receptor makes it an alternative, to be considered, perhaps, as a sensor backup and for step-testing during monitoring campaigns.

Therefore, the analysis suggests placing two sensors in nodes 78 and 59. The ranking of the metric values allows, as the number of sensors to be positioned increases, to immediately identify the most suitable position to host them. With such an interpretation of the metric, nodes 15, 27 and 45 follow as candidate nodes for hosting sensors.

The analysis provides null values of the metric for all extremal nodes because no information arrives in these nodes. This result implies that these points are not candidates for hosting measurement points.

The results of the analysis show that the In-Relevance-Harmonic centrality is effective in evaluating the ability of the nodes to receive contaminant and therefore it could be effective in the study related to the spread of contaminants and the planning of monitoring systems.

3.3. Optimization procedure vs In-Relevance-Harmonic centrality

The present paper proposed two modeling approaches for optimal sensor placement in UDNs. The two methodologies, despite being based on different concepts and approaches, provided quite comparable results, as shown in Figure 3. Indeed, both the strategies identify the outfall node as the optimal point for sensor location. Moreover, according to the results achieved by the In-Relevance-Harmonic centrality, the selected points are very close to the nodes selected by the optimization method. For example, Figure 4 shows the comparison between the In-Relevance-Harmonic centrality and the optimization procedure considering C_0 = 0.008 mg/l, and in both cases the nodes 78, 59 and 50 are indicated as possible candidates for the positioning of sensors.

4. Conclusions

The present paper faced the sensor placement problem using two different approaches based on an optimization procedure and a CNT centrality metric. The analyses produced comparable results for the two strategies in determining the candidate positions to host water quality sensors.

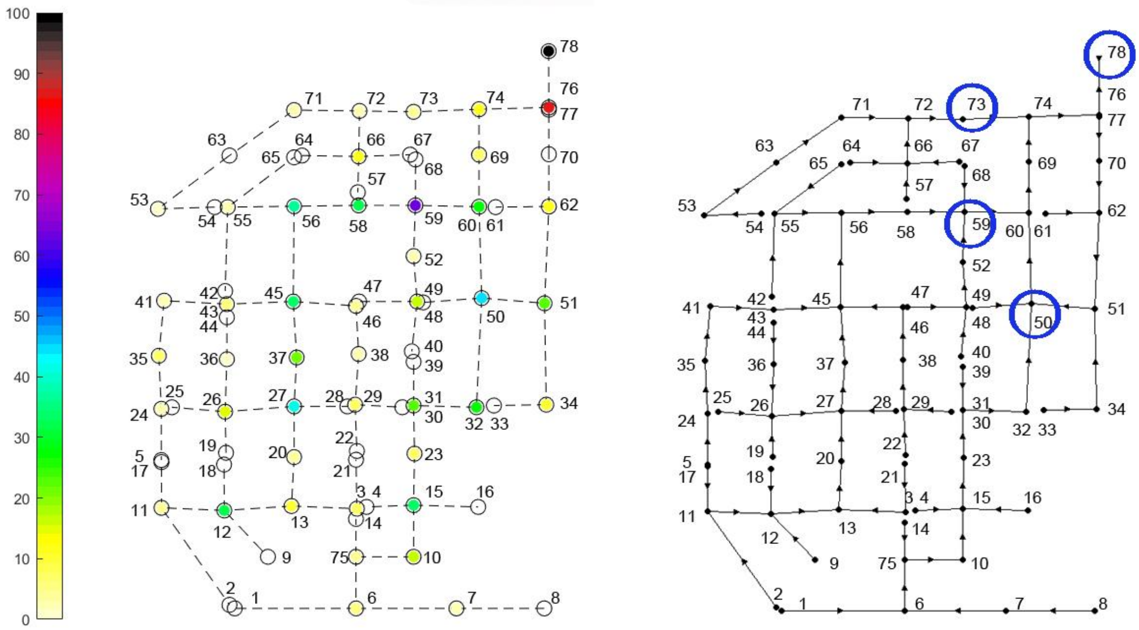

Figure 3. In-Relevance-Harmonic centrality values (left) and position of installed sensors for C_0=0.008 mg/l using the optimization procedure (right) for the benchmark UDN.

Furthermore, considering the good results obtained, this study suggested the idea of integrating the two approaches to achieve a more performing, rational and effective strategy for the planning of an advanced monitoring system, in order to envisage both the connective structure and the hydraulic behaviour of the system in the sensor placement problem. A first topological phase that identifies the best candidates to host the sensors using the In-Relevance-Harmonic centrality, and a second hydraulic phase, which starting from the results provided by the first phase, provides the real design of the monitoring system, in which optimization has as the goal to define the actual optimal positioning of the sensors.

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