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Sensor Placement for Combined Sewer System Monitoring in the Besòs River Basin

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Abstract: In this paper, a sensor placement methodology for sewer systems monitoring in order to measure direct discharge to the river during intense rainfall events is presented. During these events, Combined Sewer Overflows (CSOs) may occur, causing serious problems of contamination of the corresponding receiving waters. The current national regulation compels sewer systems' managers to monitor and quantify direct discharge to these receiving waters, in order to track these events. Hence, the selection of the appropriate sensor set in order to monitor the critical outlets of the network is of paramount importance to adequately monitor CSOs and minimize their effect by using the information gathered from these measurements. Here, a methodology considering relevant characteristics of each potential monitoring point —e.g. number of discharges, volume discharged or percentage of polluted mass— is defined to select the final sensor set. The presented methodology is applied to three different combined sewer systems in the Besòs river basin nearby Barcelona city area in Catalonia (Spain), i.e. Granollers, La Llagosta and Montornès systems.

Keywords: Real-time monitoring, sensor placement, direct discharge, water quality, outlet, combined sewer overflow.

1. INTRODUCTION

Nowadays, the problem of receiving waters' quality is considered a priority by the local authorities because of water pollution high impact on human health, aquatic species and biosphere in general [1][2]. This is motivated by the increasing occurrence of Combined Sewer Overflows (CSOs), which take place during intense rainfall events. Climate change and uncontrolled urbanization processes are the main causes of CSOs, which are directly responsible for the heavy contamination that occurs when sewer systems are not able to handle runoff and may severely jeopardise environment quality and human health. CSO events have been increasingly compromising ecosystem dynamics [2]–[7], hence many directives have been released in order to guarantee good quality of receiving waters (e.g. [8][9]).

Unfortunately, monitored data from direct discharges to receiving waters is not often available, since in past times this was not a very sensitive issue. Usually, the most reliable source of information is given by technical workers tracking qualitative information regarding certain parameters of interest characterizing CSOs. This information consists mainly in the expert perception of the monitored parameter, expressed as a qualitative descriptor of its impact on the water quality e.g. "High", "Medium" or "Low".

Another source of information could be obtained from previous studies of the sewer networks, including volumes and pollutant charges obtained from the systems for design storms or time series rainfall values. Unfortunately those models are not always calibrated and validated, hence accuracy of numerical results is not assured.

In order to fulfil requirements set by normative to keep good receiving waters' quality, it is important to define criteria to select the best monitoring points within the network even when quantitative information is not available. Sensor placement is an important part of the monitoring strategy of a system, which should provide the best monitoring points of the system according to certain criteria, and considering that usually not all the potential monitoring points but just a few may be selected for monitoring. Regarding water systems, different works consider the sensor placement problem in water distribution networks (WDS), specially for water contamination monitoring e.g. [10], [11], where the sensor placement problem is solved in order to detect malicious contaminant introduction in the network, or e.g. [12]–[15], where the target of sensor placement is leak isolation. On the other hand, less attention has been dedicated to optimal sensor placement in Urban Waste Water Systems (UWWS) in comparison to WDS, for a variety of reasons [16], including their lack of effective means of control using model feedback due to UWWS gravity-driven nature, practical issues regarding sensor network operation —e.g. complex sediment behaviour [17], clogging or sensor mechanical damage by debris, sensor fouling, varying water levels [18]— or the aforementioned focus on sensor placement for contamination monitoring in water distribution networks. All

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these factors have slowed down the modelling and online monitoring technologies applied to UWWS. Nevertheless, sensor placement in UWWS has been addressed in e.g. [19], where the problem has been formulated as a multi-objective optimisation solved by means of Genetic Algorithms (GAs) —a wide used approach to solve this type of optimisation problem, also employed in e.g. [12]–[15] for WDS—, or more recently in [20], where greedy algorithms have been also considered and compared with GAs performance.

In this work, sensor placement is performed in a UWWS in order to assign a certain priority to each potential monitored point of the network (i.e. outlet), with the final aim of monitoring the occurring CSOs. However, it is not straightforward to quantify this priority when the information available for the outlets is obtained from qualitative information. Hence, a methodology to take advantage of the qualitative information available may support the selection of the monitoring points when there is no more information gathered from the system. Also, when there are different heterogeneous sources of information (e.g. quantitative, qualitative), a normalized criterion may be useful in order to compare and aggregate results obtained for the same system. In this paper, a methodology based on a normalised criterion for sensor placement —compulsory in order to guarantee a good water quality by means of adequate network monitoring— using both quantitative and qualitative information from the network, is proposed.

The paper is organized as follows: in Section 2, the sensor placement methodology is introduced. In Section 3, the main results of this work are presented, based on a real case study of three different sewer systems within the Besòs river basin. Finally, the main conclusions are pointed out in Section 4.

2. METHODOLOGY

Here, the method to locate the sensors in the outlets is based on a function assigning a different degree of priority to each potential monitored point, considering both qualitative and quantitative information related to CSO volumes, concentrations and sources of pollutants upstream (1). The function relies on the use of determinant factors, e.g. number of CSOs per year, parameterized by γ, representing different phenomena that influence the choice of a certain outlet to be monitored. The result of this function is normalised between zero and one for each outlet of the system. Hence, this function expresses the priority of having a particular outlet monitored, i.e. the convenience of having its direct discharge to the receiving waters quantified.

The priority function is expressed as follows:

$$\rho_j = \sum_i \omega_{i,j} \gamma_{i,j}, \qquad i = 1, \dots, M, \quad j = 1, \dots, N, \tag{1}$$

where ρ_j is the priority function for the sensor j, $\omega_{i,j}$ is the weight associated to determinant factor i and outlet j, $\gamma_{i,j}$ is the parameter associated to determinant factor i and outlet j, and M and N are the number of determinant factors and outlets, respectively. Hence, outlets with $\rho_j = 1$ are the most convenient for the quantification of the direct discharge to the receptor body, whilst outlets with $\rho_j = 0$ are not considered for monitoring according to the criterion presented.

Determinant factors have to be identified in order to apply the method presented here. They can be various, depending on the information available for the sensor location study. In the case developed in this paper, a maximum number of three determinant factors is used to compute the priority function: the number of CSOs per year, the annual water volume spilled during the CSOs and the polluted mass in the spilled water. Due to their different natures, determinant factors may have different units of measurement, which prevent straight comparison among them. For instance, in this particular study, the number of CSOs per year cannot be compared with the CSOs annual water volume without further manipulation. Similarly, both previous determinant factors cannot be compared straightaway either with the polluted mass in spilled water, also considered as a determinant factor here. Hence, in order to allow comparison among them, each determinant factor is represented by a normalised parameter γ_i, with values in the range [0,1]. Also, the related weight to each determinant factor has to be defined. In order to obtain a normalised result for the priority function, each weight can assume a value from zero to one and expression (2) has to be fulfilled:

$$\rho_j = \sum_i \omega_{i,j} = 1, \quad i = 1, \dots, M, \quad j = 1, \dots, N. \tag{2}$$

Weights are assigned depending on the relevance of the corresponding determinant factors considered in the sensor location process. The only requirement to define the weights of the parameters associated to determinant factors is given by equation (2), which states that the sum of the weights associated to the determinant factors must be the unit. This is necessary to obtain a normalized function and, therefore, to allow comparison of the results obtained using different sets of available data.

3. CASE STUDY

The proposed method presented here has been applied to three real sewer systems within the Besòs river urban catchments: Granollers —the name of the river crossing Granollers area is Congost—, La Llagosta and Montornès. This study has been motivated by the need of sewer systems' managers to fulfil a recent Spanish regulation [8], which requires adequate monitoring and quantification of CSOs. Normative [8] aims to define environmental quality conditions and states that competent institutions must identify CSOs and, particularly, specific pollutants discharges to receiving waters in relevant amounts. Therefore, outlets must be registered and monitored. Sensor technology used to this end is also a key issue in order to provide quality measures in this particular environment. Particularly, it is advisable to monitor critical outlets using radar or ultrasound sensors, which provide more reliable outcomes over e.g. photoelectric sensor technology, which are not suitable for level measurement in outlets. For this application it is also important to consider floodable sensors —i.e. with IP68 classification—, since the nature of the phenomena monitored implies that discharged flow may often come in contact with the sensor. The power supply type is also an important characteristic of the sensors considered, since they will be installed in sewer outlets. Hence, these sensors should be powered by a battery power supply.

3.1 Available information

As mentioned in Section 1, at this stage there are not many available data from the network to define priority outlets to be monitored. There are no sensors installed in the network outlets and the only source of quantitative data, based on computational simulations, is presented in [21], and just for one of the three systems considered in this work i.e. Granollers sewer system. In order to prevent this lack of data, further sources of information have been considered to provide additional criteria for the sensor placement process. Information including the three sewer systems considered in this work is provided by [22], where qualitative data reported by experts responsible for the corresponding sewer systems and outlets, is presented. Additionally, further source of information is obtained by GIS (Geographic Information System) shapefiles [23] of the three systems considered. These files include additional relevant spatial information of these systems, like elevations and closeness of sewer system and industrial areas. Hence, in Sections 3.2, 3.3 and 3.4, three different scenarios are proposed, depending on the available type of data used to develop the analysis, i.e. from simulations (Section 3.2), from expert assessment (Section 3.3) and from system spatial information (Section 3.4).

3.2 First scenario: simulation data

In this section, quantitative data obtained from computational simulations developed in SWMM5 [21] is used to compute (1). As mentioned in Section 3.1, this set of data is available just for one of the three systems of interest, i.e. Granollers combined sewer system. The information obtained from [21] allows to identify three determinant factors for Granollers system. These factors are: annual discharged volume, polluted mass into the discharged flow and number of CSO per year. These three determinant factors have been studied and quantified in [21], therefore their values are available (Figure 1, Figure 2 and Figure 3, respectively). Specifically, in the latter Figures, the discharged volume (Figure 1), the polluted mass proportion (Figure 2) and the total number of discharges (Figure 3) are detailed for each of the 78 outlets considered and for two different scenarios i.e. considering a system of retention tanks in the network and not considering these elements, respectively. These determinant factors have been chosen in order to determine outlet monitoring priority since they have relevant impact in receiving waters quality.

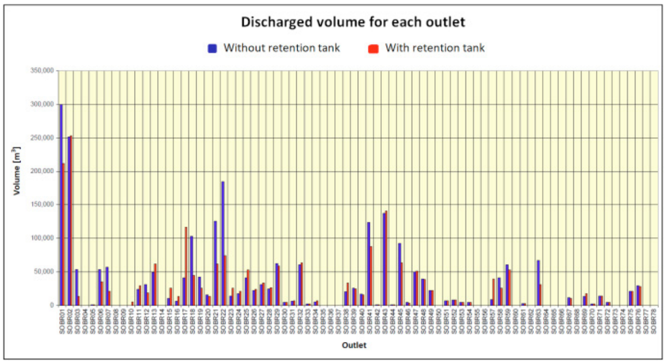

Figure 1: Annual CSO volume, Granollers subsystem. Source: [21]

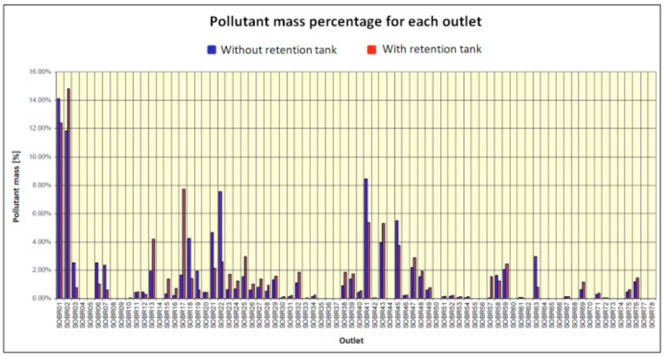

Figure 2: Polluted mass, Granollers subsystem. Source: [21]

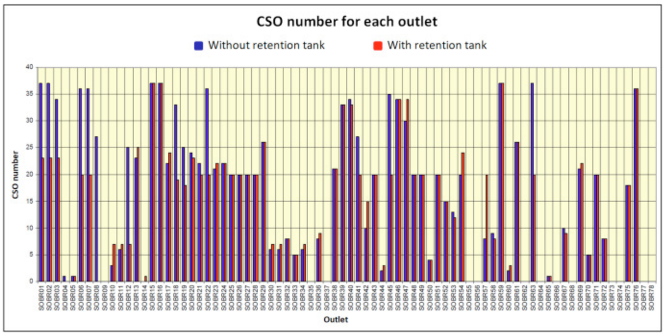

Figure 3: Annual CSO events, Granollers subsystem. Source: [21]

Once determinant factors have been identified, the corresponding three weights have been assigned. The value of each weight depends on the importance of the respective determinant factor in the sensors' location process. CSO number, CSO volume and polluted mass are all sensitive factors that should be object of further analysis in order to reduce them. In this study, these three factors have been considered equally relevant for the monitoring process, hence each weight takes a value of 0.33. Additionally, in Section 3.6. a sensitivity analysis is performed. The thresholds defining the ranges of values for the three parameters related to the corresponding determinant factors in this scenario are detailed in Table 1.

Table 1: Assignation of γ, first scenario

CSO number [#/year]	CSO volume [m^3]	Polluted mass [%]	γ
$F_1 > 20$	$F_2 > 100000$	$F_3 > 6$	1
$10 < F_1 \leq 20$	$50000 < F_2 \leq 100000$	$2 < F_3 \leq 6$	0.5
$F_1 \leq 10$	$F_2 \leq 50000$	$F_3 \leq 2$	0

In Table 1, determinant factors are indicated by F, where the subscript numbers *1, 2,* and *3* represent CSO annual number, CSO annual volume and CSO polluted mass, respectively. The threshold for each considered range is also defined using information in [21]. As introduced in Section 2, determinant factors may have different units of measurement due to their different nature, which prevent straight comparison among them. Hence, in order to allow the comparison among them, each determinant factor is discretized by means of γ (e.g. Table 1 for the first scenario). Therefore, parameter γ discretization is a way to compare phenomena of different nature in order to take this heterogeneous information into account to obtain a single priority value for each outlet.

3.3 Second scenario: expert data

In this section, qualitative data gathered by the company in charge of the sewer outlets maintainance (*Drenatges Urbans del Besòs, S.L.*) is used to compute (1). The data provided [22] involves three systems (i.e. Granollers, La Llagosta and Montornès) but it is not as complete as the data obtained from [21] because information about pollutants is not available. With the information in [22], only two determinant factors may be chosen, which are the CSO frequency and the discharged volume. Regarding weights choice, and similarly as in the first scenario, both factors have been considered equally relevant for the monitoring process, hence each weight has been assigned with a value of 0.5. In this second scenario, since the type of information is qualitative, it has been necessary to introduce parameters that associate numerical values to qualitative expert values, in order to be able to compute the priority function (1). Assigned values have been reported in Table 2.

Table 2: Assignation of γ, second scenario

Frequency	CSO volume	γ
High	High	1
Medium	Medium	0.5
Low	Low	0

3.4 Third scenario: spatial data

In this section, spatial data [23] gathered by the company that manages the studied sewer systems (*Consorci Besòs Tordera*) is used to compute (1). Determinant factors obtained in this case are also two: discharged volume and polluted mass. The available data consists of a series of shapefiles. Particularly, there is a shapefile localising all the companies that represent a relevant risk for receiving waters. These companies have been classified as “ranking 3 companies” —rated in a scale between 0 and 3, the higher the rate the higher the consequences to receiving waters due to high pollutants and/or high volume introduced into the sewer system—. The information of the determinant factors selected is aggregated in this qualitative rate of the most dangerous companies. This aggregated information allows to assume that outlets located downstream ranking 3 companies would discharge high pollutant mass and volume to the receiving waters in case of intense rainfall event, so they must be monitored in order to fulfil the normative requirements, which compel institutions to identify and quantify CSOs in terms of volume, frequency and polluted mass. A parameter of impact γ of the source of high contamination is defined in order to consider this aggregated information. Its value is related to the distance of the outlets from the source of the pollution, represented by ranking 3 companies. It is worthwhile noting that this distance is different for each outlet considered, since residual waters keep travelling through pipes until they reach the first available outlet. Hence, first outlet reached by residual waters would be the most critical and hence the one having the highest monitoring priority, since it is the one allowing most of the contaminants to be discharged into the receiving waters.

Similarly as in the previous scenarios, three possible values are assigned to parameter γ in order to apply the methodology presented (Table 3).

Table 3: Assignation of γ, third scenario

Outlet distance	γ
High	1
Medium	0.5
Low	0

It is also worth noting that several outlets may be located at the same sequential distance from ranking 3 companies, so these elements would be assigned with the same value of γ. Regarding the weights selection in this case, since there is just one parameter associated to determinant factors, a value of 1 has been assigned.

3.5 Sensor placement results

Once determinant factors have been identified and related weights and parameters have been defined for each scenario (as explained in sections 3.2, 3.3 and 3.4), the priority function has been computed for the outlets considered in the first, second and third scenarios, respectively, by applying

(1). The outlets have been sorted according to decreasing priority values obtained, in order to classify them taking into account their monitoring importance (Figure 4, Figure 5 and Figure 6, respectively). In the latter three figures, the horizontal axis shows outlet ID numbers —therefore each element corresponds to a specific outlet— and the vertical axis shows the corresponding priority value.

Since results in Figure 4 have been obtained from information in [21], the outlets depicted only belong to Granollers sewer system. Alternatively, Figure 5 and Figure 6 show the outlet classification considering the three systems, i.e. Granollers, La Llagosta and Montornès systems. It may be noted that depicted classification of the outlets in Figure 4 to Figure 7 is characterized by priority function values different from zero.

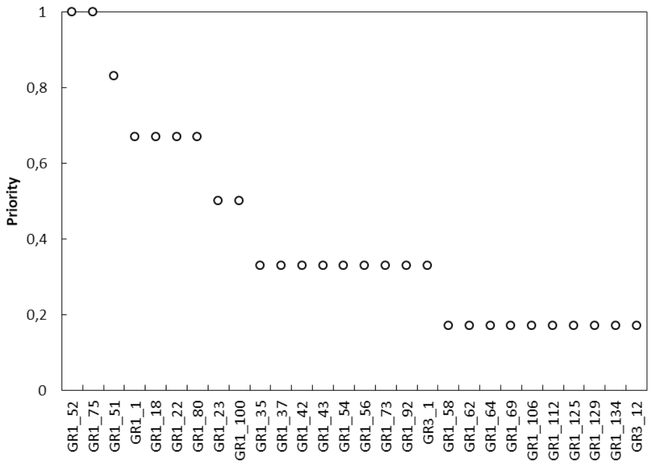

Figure 4: Sensor set proposal for the first scenario

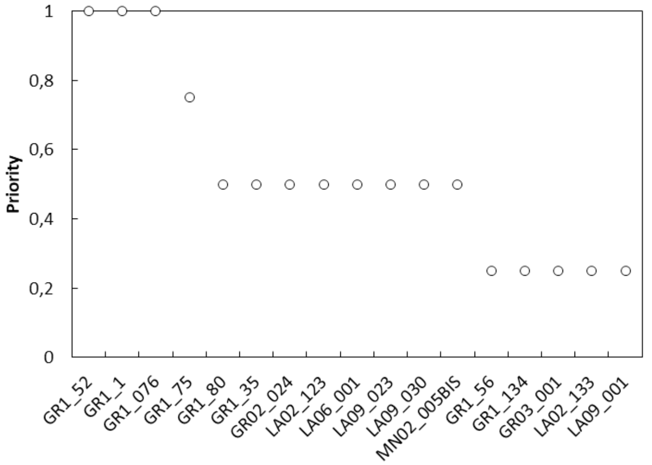

Figure 5: Sensor set proposal for the second scenario

From the first analysis (Figure 4), performed using information in [21], a selection of 28 outlets with non-null priority function is obtained. The second analysis (Figure 5), conducted with data in [22], highlights 20 outlets with non-null priority function. Finally, Figure 6 reports non-null priority function sensors obtained from the third scenario analysis. In order to take into account all the results obtained from the different scenarios and ensure correct monitoring of all the strategic points in case of CSO, the outcomes resulting from each analysis have been merged (Figure 7). Hence, in Figure 7 the results in Figure 4, Figure 5 and Figure 6 are included together in order to visualize the overall result, since the final aim is to provide a single sensor location proposal considering all the available scenarios. This is possible because the normalised index in equation (1) is obtained for each scenario, allowing the comparison among them.

In the latter figure, it may be observed how this merge provided a number of 58 outlets with a priority function different from zero. Hence, assuming a conservative placement criterion, the final sensor set proposal is formed by these 58 monitoring points, out of the 137 outlets available in the three systems considered (Figure 8). It may be noted that outlet sensor tags are not depicted in Figure 8 horizontal axis due to space limitations. However, tag information of the selected sensors is available in Figure 7. Finally, the map of the selected sensors is presented in Figure 9.

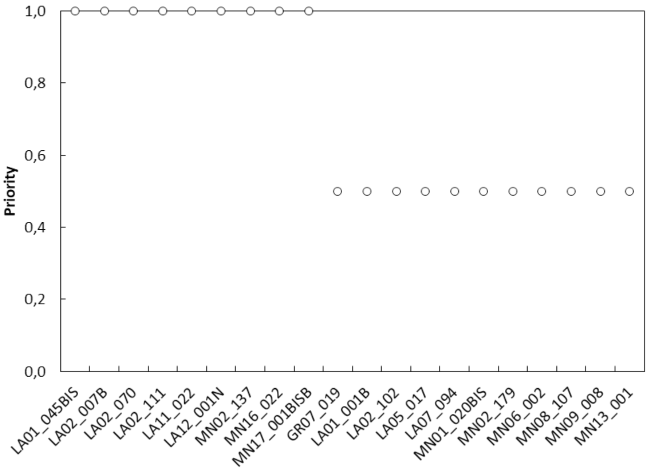

Figure 6: Sensor set proposal for the third scenario

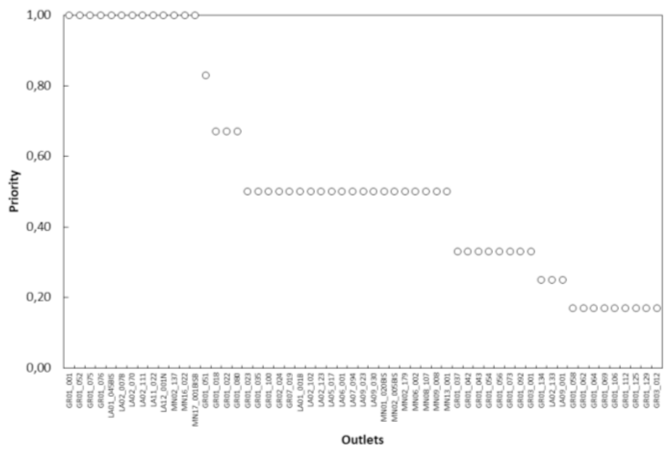

Figure 7: Final sensor set proposal

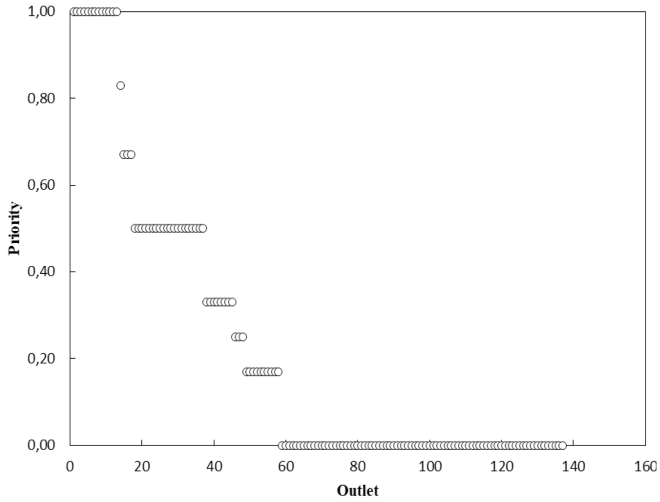

Figure 8: Complete sensor set for the three sewer systems considered

In Figure 9, sensor locations are geographically represented, using a green-orange-red colour scale depending on the (increasing) priority of each considered outlet. The blue lines represent the whole sewer network, object of this study. Three zoomed windows in the figure allow to better represent regions with high density of outlets.

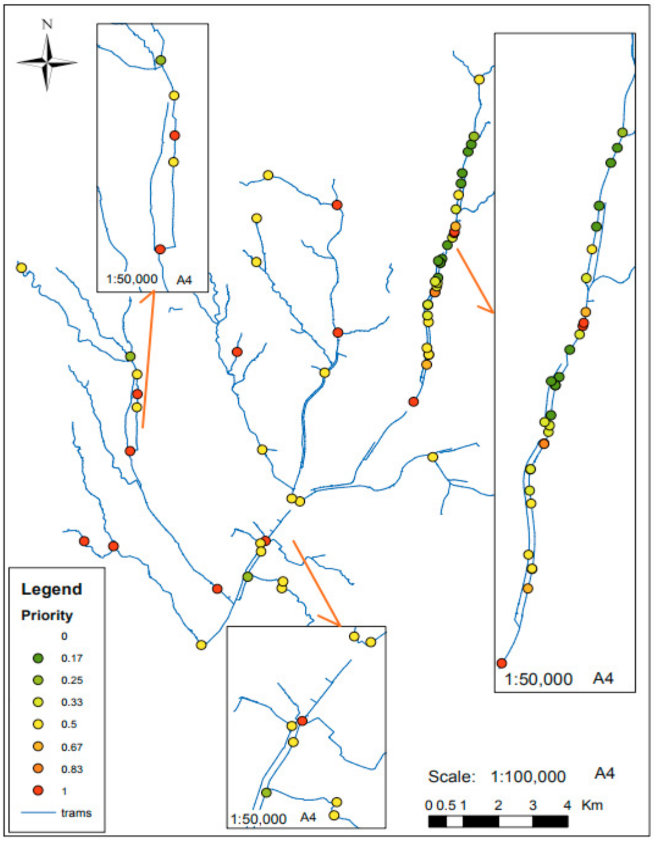

Figure 9: Priority outlets map

3.6 Weight sensitivity analysis

Finally, a sensitivity analysis has been conducted in order to examine how results change when determinant factors are not given the same importance. Hence, in this section different weight values, corresponding to the parameters associated to the determinant factors, have been assigned. First, quantitative data of the first scenario [21] have been considered. Priority values have been calculated three extra times, i.e. one per each different weight configuration. In each new computation, one of the three determinant factors has been considered as the most important, so a weight of 0.5 has been assigned to this selected factor and 0.25 to the other two factors. The results have been compared in Figure 10, where equal weight results have also been included.

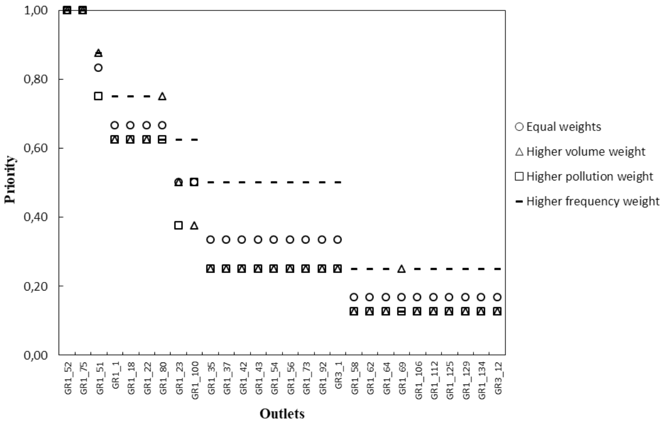

Figure 10: Sensitivity analysis for the first scenario

In Figure 10, circles represent outlets selected when all the three determinant factors have the same importance —i.e. when the three corresponding weights have the same value—, triangles represent the case in which volume is the most important factor, rectangles correspond to the case considering polluted mass as the most relevant factor, and hyphens stand for the case in which CSO frequency is considered more important.

As it may be observed in Figure 10, even though priority values are different for the four cases considered, outlets' classification does not change when considering different weight assignation. This means that even when assigning more relevance to one of the three determinant factors, the proposal of sensors obtained from scenario 1 [21] does not change. Hence, each determinant factor influences the sensor proposal independently of its importance in the selection criterion.

The sensibility analysis has been also performed using qualitative data in scenario 2 [22]. In this case, since the determinant factors are two, sensor proposal has been obtained two extra times —i.e. one per each different weight configuration—, assigning a weight of 0.75 to the most relevant factor and 0.25 to the other factor. Results obtained have been plotted in Figure 11, where circles represent equal weights for all determinant factors considered, triangles correspond to volume as the most relevant factor and rectangles represent results with frequency considered as the most important factor. Similarly, as in the first sensitivity analysis, outlets' classification does not change either when considering different weight assignation in this case (Figure 11). Hence, Figure 10 and Figure 11 show how the sensor priority obtained using (1) does not depend on the value of weights considered for the sensitivity analysis. This result is especially relevant when a subset of sensors with $\rho > 0$ is selected, which is not the case of this particular study.

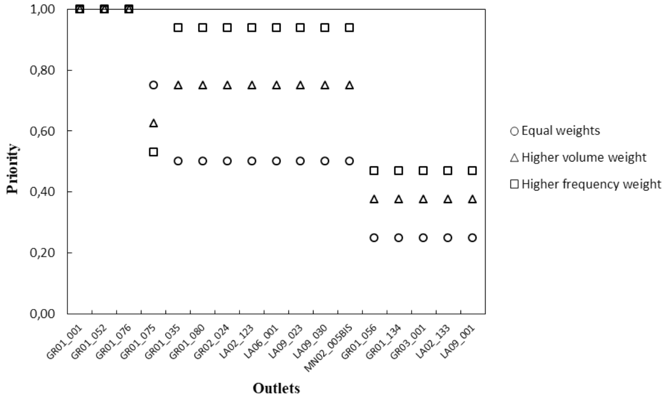

Figure 11: Sensitivity analysis for the second scenario

4. CONCLUSIONS

This work presents a sensor placement methodology for sewer systems monitoring in order to measure direct discharge to the river during intense rainfall events. During these events, CSOs may occur, causing serious problems of contamination of receiving waters. CSO events have remarkably increased in the recent years, being also increasingly characterised by the extreme behavior of the rainfall events i.e. very intense and short, which makes produced runoff hard to handle by the corresponding sewer systems.

The current national normative compels sewer systems' managers to monitor and quantify direct discharge to these receiving waters, in order to keep track of these events, but sometimes the information available from the outlets of the system is scarce. In order to track CSO it is necessary to monitor the outlets that are more sensitive to these events, hence the selection of the appropriate sensor set in order to monitor the critical outlets is of paramount importance in order to minimize CSO effect by using the information gathered from these measurements.

Therefore, the present paper proposes a sensor placement criterion when available data from outlets' are of heterogeneous nature (e.g. qualitative from system experts observations, quantitative from simulations) and scarce. It has been presented how computational data in [21] may be used for the sensor placement process because it provides detailed and quantitative information about volumes, pollutants percentages and frequency of the CSO events. Alternatively, qualitative data in [22] and spatial data in [23] have provided complementary information that have been used to obtain a sensor location proposal after processing. Hence, the sensor placement methodology presented here aggregates the results obtained processing these heterogeneous sources of data with a normalised criterion, which allows comparing and merging results in order to propose a single sensor set for monitoring the network.

The presented methodology has been successfully applied to three different combined sewer systems in the Besòs river basin nearby Barcelona city area in Catalonia (Spain), i.e. Granollers, La Llagosta and Montornès systems, providing a sensor proposal to be installed in these systems in order to track CSO events.

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