A Monte-Carlo based method for the identification of potential sewer mining locations

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Abstract

Rapid urbanization affecting demand patterns, coupled with potential water shortages due to supply side impacts of climatic changes have led to the emergence of new technologies for water and wastewater reuse. Sewer Mining is a novel decentralized option that could potentially provide non-potable water for urban uses, including for example the irrigation of urban green spaces, providing a mid-scale solution to effective wastewater reuse. Sewer Mining is based on extracting wastewater from local sewers, treat at the point of demand and entails in some cases the return of treatment residuals back to the sewer system. Several challenges are currently in the way of such applications in Europe, including public perception, inadequate regulatory frameworks as well as engineering issues. In this paper we consider some of these engineering challenges, looking at the sewer network as a system where multiple physical, biological and chemical processes take place. We argue that prior to implementing sewer mining, the dynamics of the sewer system should be investigated in order to identify optimum ways of deploying sewer mining without endangering the reliability of the system. Specifically, both wastewater extraction and sludge return could result in altering the biochemical process of the network, thus unintentionally leading to degradation of the sewer infrastructure. We propose a novel Monte-Carlo based method that takes into account both spatial properties and water demand characteristics of a given area of sewer mining deployment while simultaneously accounts for the variability of sewer network dynamics in order to identify potential locations for sewer mining implementation. The outcomes of this study suggest that the method can provide rational results and useful guidelines for upscale sewer mining technologies at a city level.

Keywords

Decentralized wastewater options; hydrogen sulphide; Monte-Carlo method; sewer mining; upscaling

INTRODUCTION

Rapid urbanization and potential water shortages due to, inter alia, climatic variability have led to the emergence of new technologies in water and wastewater reuse aiming to provide alternative water sources for more resilient cities. Sewer mining (SM) is such technology, which is based on extracting wastewater from local sewers for reuse applications (after treatment) and (often) returning treatment residuals (sludge) back to the system (Sydney Water, 2008). Typical uses of this recycled water are industrial cleaning, cooling and urban green spaces irrigation (Hadzihalilovic, 2009; Marleni et al., 2012). Literature classifies this technology as a decentralized option (Makropoulos and Butler, 2010) because it is applicable (and suitable) at a development level (for example, up to 5,000 households). This is also highlighted in Marleni et al., (2012) where it is argued that this practice is not intended for individual use (indoor appliance) rather than implemented in collective/cluster scale developments. Furthermore, the latter authors remark that usually these systems are not managed by central water utilities (or governmental organizations) rather than by private establishments under some license agreements. As such, sewer mining is a promising reuse option between the reuse at the household scale (e.g., grey water reuse; cf. Liu (2010) and Makropoulos and Butler (2010)) and centralized reuse at the wastewater treatment plant (WTTP) level (Andreadakis et al., 2006). Current sewer mining projects mostly involve park and sports fields' irrigation. Most of them are operating in Australia (Sydney Water, 2009) where the climate is dry and water should be treated carefully. It is worth highlighting that in most cases the wastewater is reused for non-drinking purposes. Despite public perception, concerns and inadequate regulatory frameworks that may raise potential barriers for sewer mining implementation, there are engineering issues that have to be addressed. A sewer network is a system where multiple physical, biological and chemical processes take place (Pomeroy, 1990). Hence, prior implementing sewer mining, the dynamics of the system should be investigated in order to identify optimum ways of deploying sewer mining without endangering the reliability of the system. Specifically, both wastewater extraction and sludge return could result in altering the biochemical process of the network, thus unintentionally leading to degradation of the sewer infrastructure. Thus, in this paper we focus on addressing some of the engineering challenges linked to the potential deployment of such technologies at the city scale. Typical engineering issues associated with sewer mining are odour and corrosion. Both of them are related to the production of hydrogen sulphide (H_2S) in sewer pipes. This study focuses on identifying possible locations for SM placement subject to H_2S build-up.

MATERIAL AND METHODS

Methodology Description

While trying to address this issue i.e., SM placement by taking also into consideration H_2S production, we propose a methodology consisting of three steps, (I) a spatial data pre-processing step during of which the spatial properties and water demand characteristics are being identified (II) a Monte-Carlo simulation (MCS) step, which uses steady state simulation of the sewer network in order to account for the variability of sewage discharge into the network and finally, (III) a post-processing step which comprises (III-a) the definition of appropriate metrics that quantify the output of interest and (III-b) a multi-criteria analysis of the results. A schematic description of the proposed methodology is given in

Figure 1. During the first step the available spatial information (i.e., sewage network topology and assets, topography, water and land uses) is imported into the procedure in order to identify land uses that will benefit from sewer mining (in our case green areas and parks). It involves a procedure of locating neighbouring sewer network components (e.g., nodes) which are close to areas of interest. In more detail, this is done by delineating a wider area surrounding the original one (e.g., add 10m offset to green areas) and subsequently identifying the nodes that lie into those wider areas. Finally, the paths from the identified nodes to an exit node are identified and stored. The exit node could be a WTTP or a node that links the current network with a broader larger network. It is worth noticing that this path is unique for each node due to the "collective nature" of sewer networks. The purpose of the second step is to propagate uncertainties related with the input parameters to the outputs of interest (e.g., BOD_5 concentration or flow of each pipe). Furthermore, the use of Monte-Carlo simulation allows the definition of probabilistic functions and metrics, thus in-turn provide uncertainty-aware outputs. Typical examples of uncertain parameters are the daily water consumption, daily and hourly variation coefficients of wastewater discharge and BOD_5 loading (in terms of g/cap). Alternatively, one could use a similar scenario-based approach to

sample those parameters; (or in conjunction with MCS) in order to investigate the effect of certain predefined scenarios (e.g., worst, base, favorable conditions).

The third and final step involves the definition and the use of metrics i.e., utility functions or risk functions that quantify the output of interest (in our case H_2S build-up) for a chain of pipes (the paths specified in step I). Furthermore, as a final procedure, we use multi-criteria analysis which eventually leads to derivation of the Pareto front (based on conflicting criteria – e.g., suitability of location and green area water demand), which includes all the potential locations for sewer mining.

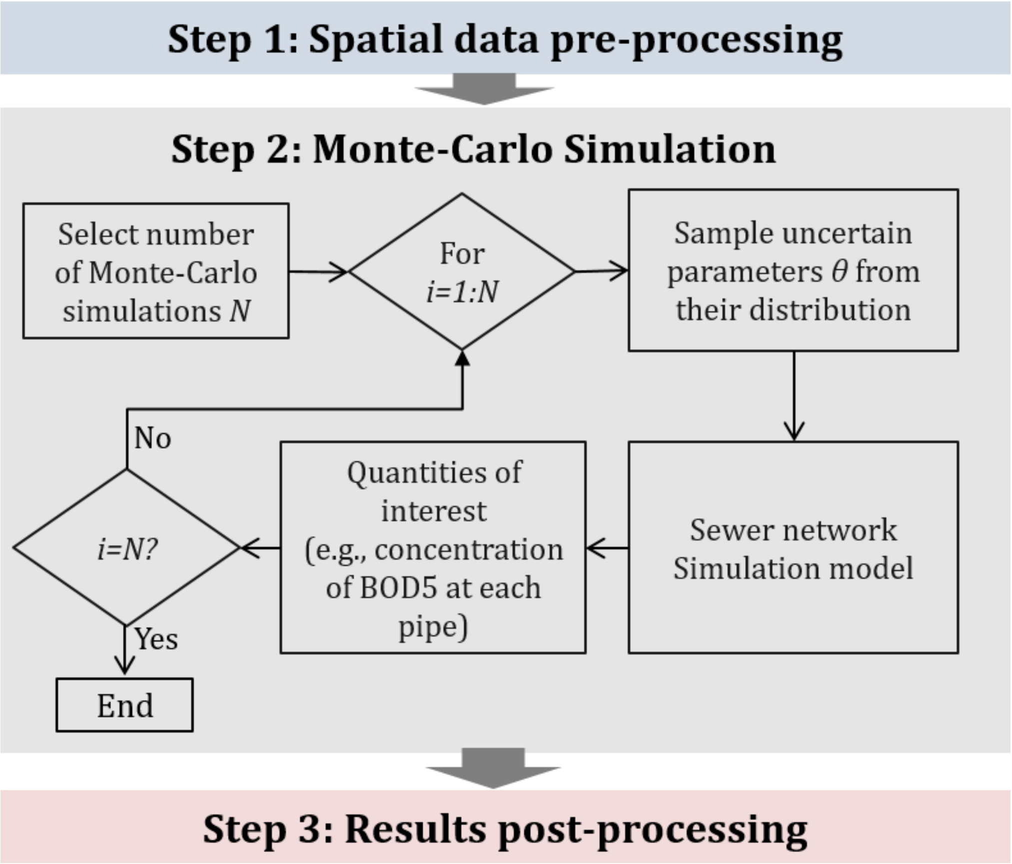

Figure 1: Overall methodological framework for the identification of potential SM locations.

Implementation Details

The involved MCS (step II) of the proposed procedure requires the use of a simulation model in order to calculate the hydraulic outputs of interest. In this study we employed a steady state simulation model which uses the typical hydraulic equations for sewer networks as described in Koutsoyiannis, (2011). The total design discharge Q_D which is used to assess the performance of the network is calculated as the sum of sewage discharge (Q_s) and dry weather flow (Q_{DWF}). The sewage discharge can be calculated as follows:

$$Q_S = q \times E \times \lambda_L \times \lambda_S \times \lambda_1 \times \lambda_2 \;/\; 86400\ (\mathrm{m}^3/\mathrm{s}) \tag{1}$$

Where, q is the indicative daily water consumption per capita (lpd), E is the serviced population, λ_L, is a loss coefficient of water distribution network, λ_S is a coefficient that express the percentage of water that stems to the sewage network, λ_1, is a seasonal coefficient and λ_2, is a coefficient of peak discharge. The dry weather flow can be calculated as follows:

$$Q_{DWF} = \lambda_{DwF} \times Q_S/\lambda_2\ (\mathrm{m}^3/\mathrm{s}) \tag{2}$$

Where, λ_{DWF} is a dry weather flow coefficient (typically set to 0.2). Although, in this study we use eq. (2) in order to align with information available from previous studies, it is worth mentioning that literature (cf., Koutsoyiannis, 2011) includes a variety of formulas for the calculation of the aforementioned quantity.

In order to assess the extent of H_2S, a qualitative indicator known as the "Z formula" (US EPA Sulphide Control Manual 6) was employed. Metric Z was originally proposed by Bielecki & Schremmer, (1987) and Pomeroy, (1990) for a single pipe i in order to quantify the probability of H_2S build-up:

$$Z_i = \frac{0.3 \times 1.07^{T-20} \times [BOD_5]_i}{J_i^{0.5} \times Q_i^{1/3}} \times \frac{P_i}{b_i} \tag{3}$$

Where, i is the pipe index, T is the sewage temperature (°C), $[BOD_5]_i$ is the concentration of Biochemical Oxygen Demand of 5 days (mg/l), J_i is the pipe slope, Q_i is the discharge (m^3/s), P_i is the wetted perimeter of the pipe wall (m) and B_i the surface width (m) of the stream. Note that the concentration of BOD_5 loading was assumed to be invariant during the day, thus, it can be calculated by dividing the daily mass of BOD_5 with the daily sewage volume. According to Pomeroy, (1990) values of $Z_i > 7500$ indicate that there are high chances of H_2S formation which could lead to odour and corrosion problems. Eq. (3) can be used for a single pipe, thus we used a modified version of index Z of Pomeroy for a "chain" of pipes n:

$$MZ_c = \sum_{i=1}^{n} a_i \times Z_i \tag{4}$$

Where, a_i are weight coefficients. In this study we use weight values proportional to pipe length using the following formula, $a_i = L_i/L_{tot}$, where, L_i is the length of pipe i, and L_{tot} is the total length of pipes of chain ($i=1,\ldots,n$). It is worth mentioning that literature includes a variety of metrics (Boon, 1995; Hvitved-Jacobsen et al., 2013; Lahav et al., 2006; Marleni et al., 2015), other than Pomeroys' Z, that could be used to quantify the exact amount of H_2S in terms of mg/l. Since we performed N model simulations (step II) we have N values of MZ_c for each path and for each green area, therefore we are able to calculate $Q[MZ_c]_x$ which represents the value of the desired quintile x. For example the 75th quintile value indicate that 75% percent of MZ_c are below $Q[MZ_c]_{75}$ value. Through this way we impose an additional reliability criterion for H_2S build-up. Finally, for each green area, among all available paths we select the one with (optimum) minimum $Q[MZ_c]_x$ value. To this point we have located the nodes with minimum $Q[MZc]_x$, thus we could fuse it with information regarding the water demand in the areas of interest (green areas). We select as approximate indicator for water demand the area of the park. Similarly, the actual water demand of each area could be more accurately calculated if relevant information was available. It is worth mentioning that the use of multi-criteria analysis allows the inclusion of other metrics regarding other aspects of the network, hence, provides a powerful tool for exploring alternative options and decisions.

CASE STUDY

Description

The methodology is demonstrated in a sewer network designed for the city of Kalyvia Thorikou in Greece (Figure 2). The network has not been constructed yet, although it is foreseen to accommodate an area of 98 ha from which 17 ha are green areas. It is part of a larger engineering project of Saronikos municipality (service 10-15 thousand people) which aims at extending the existing sewage network of coastal zone. It is consisted of 1030 pipes of total length ~38 km, while their diameter varies from 0.2m to 0.5m. The pipe slope varies from 2‰ to 150‰, with an average slope of 35‰. The understudy area was selected and considered suitable for testing the proposed methodology, since it is consisted of various network elements and has adequate number of green areas which could benefit from sewer mining practices.

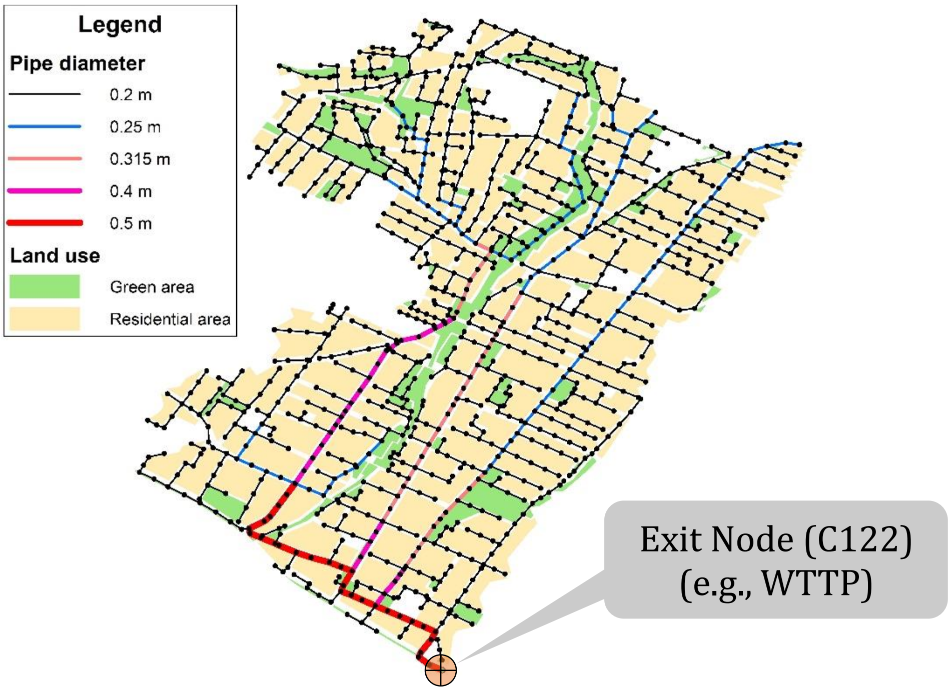

Figure 2: Case study sewer network and land uses – Kalyvia Thorikou, Greece.

Problem setup

The design period of the network was assumed, *T*=40 years, as in the original study of Hydroexigiantiki, the engineering firm which conducted the study of the above network. The design population (*E*) is adjusted using the compound rate formula $E = E_o \times (1 + \varepsilon)^n$, where, E_o is the current population, *ε* is the increase rate (assumed 1.5%) and *n* is the extrapolation year (*n=0,...,T*). The value of *n* can be varied in order to assess the performance of the system at different time periods. In this study, *q* was assumed to be equal to 250 lpd, λ_L was assumed equal to 0.725 for year 0 and 0.85 for year 40. Similarly, λ_s, was assumed equal to 0.625 for year 0 and 0.65 for year 40. The values of λ_L and λ_s for intermediate years can be calculated using linear interpolation. The value of λ_{DWF} was set equal to 0.2. In summary we assumed λ_1 and λ_2 as uncertain parameters that follow uniform distribution. As far it concerns parameter *n,* we employed three scenarios, 0, 20 and 40 years. Also, the mass of BOD_5 was varied using three scenarios 40, 50, and 65 g/ (day cap). The maximum allowable number of simulation runs for the MCS step was set equal to 500. The desired quintile *x* (i.e., reliability level) for the calculation of $Q[MZ_c]_x$ was set to 75%.

RESULTS AND DISCUSSION

Figure 3 illustrates the final result of the post-processing step III in a form of a Pareto front, having as objectives the minimization of modified Z index and the maximization of green area. It is notable that one could also interpret those two objectives as the simultaneously maximization of suitability and benefit from sewer mining practices respectively. The suggested procedure located three potential locations for sewer mining units' placement that satisfy both criteria, while on the other hand discarded locations that proved to be inferior in either objectives. Additionally, the map depicted in Figure 4 provides a visual summary of all the green areas (green polygons) of the case study, as well as the three areas (red polygons) identified by the proposed methodology since they were suitable for SM placement. Furthermore, in order to visually illustrate the concept of optimum path it presents the selected optimum path (magenta line) for green area with ID 3. This path has the lowest MZ value compared to all other alternative paths of ID3.

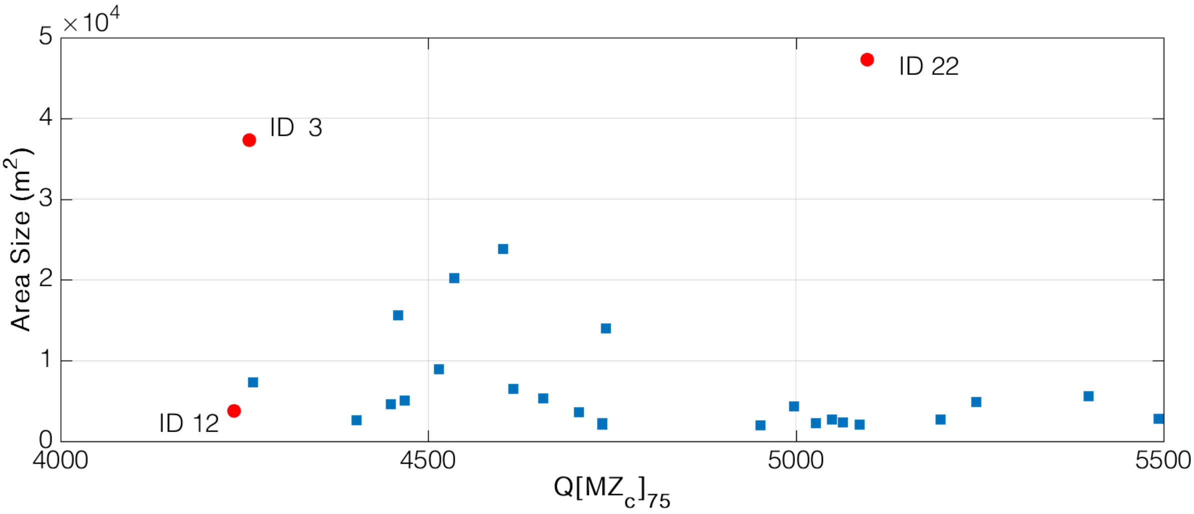

Figure 3: Derived Pareto front based on modified indicator Z (MZ) and green area size.

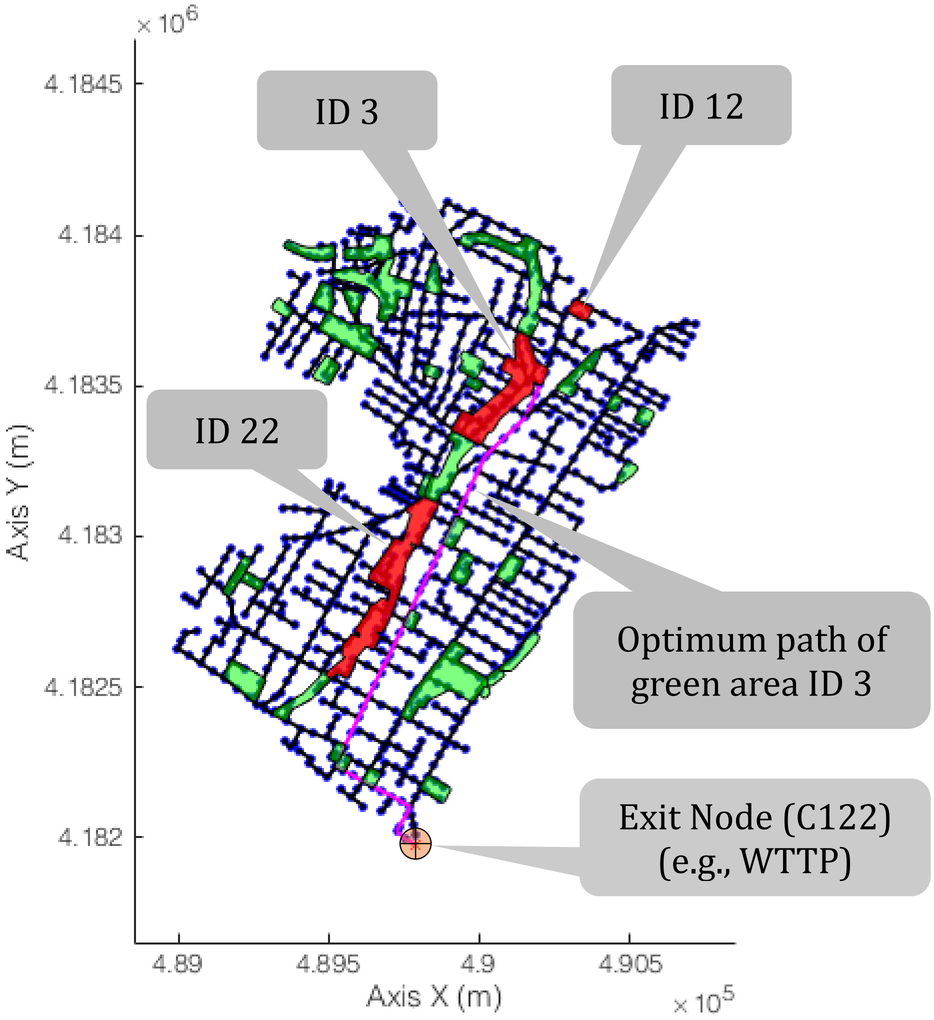

Figure 4: Proposed sewer mining locations for Kalyvia Thorikou sewer network

Figure 5 depicts the cross-section of optimum path of green area ID3 (magenta line in Figure 4). The path starts from pipe C215 which is located close to the green area ID3 and ends to C122 which is linked with the “exit” node of the understudy system. More specifically, the upper panel of Figure 5 shows the variability of the MZ across that path. Furthermore, the lower panel of Figure 5 shows the probability of non-exceedance the threshold values P(Z<7500). It can be seen that until C171 the system demonstrates high non-exceedance probabilities (~90%), i.e., high reliability. After that point the reliability decreases but it is still preserved within acceptable levels (70-80%).

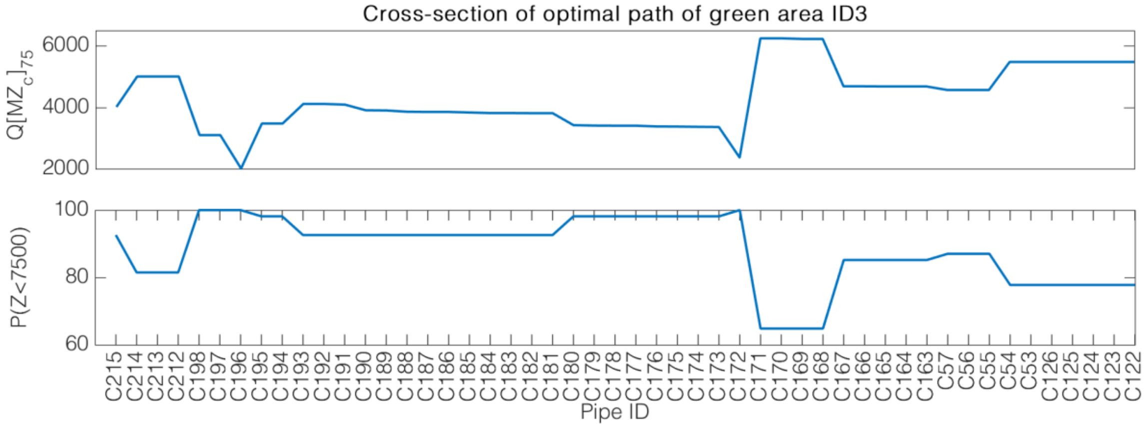

Figure 5: Cross-section of optimal path of green area ID 3. The upper panel depicts the variation of modified indicator Z (MZ) among longitude profile. The lower panel depicts the probability of non-exceedance of the threshold value of Z=7500 among the cross-section.

CONCLUSION

It is argued that a critical and important part of successful sewer mining projects is the initial design and planning. In this process many considerations should be taken into account, including: The capacity of the sewer system, alternative demand and installation locations, as well as, sewer network dynamics, social, health and environmental impacts. In order to overcome the engineering challenges imposed by the multiple physical, biological and chemical processes that take place in a sewer network, we introduce a novel Monte-Carlo based method for the identification of potential locations for sewer mining units. The proposed risk-based approach allows to safely plan for SM deployments taking into due consideration system performance objectives regarding water quantity and quality. As such it enhances the decision making process with useful guidelines and insights. In this study we focused on identifying potential locations for sewer mining subject to the generation (minimize) of hydrogen sulphide (H_2S). The results showed that the proposed methodology was able to identify potential locations for sewer mining units’ placement while simultaneously taking into consideration the spatial properties of the area as well as the variability and hydraulic characteristics of the sewer network.

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