Identification of potential sewer mining locations: a Monte-Carlo based approach

I. K. Tsoukalas, C. K. Makropoulos and S. N. Michas

ABSTRACT

Rapid urbanization affecting demand patterns, coupled with potential water shortages due to supply side impacts of climatic changes, has led to the emergence of new technologies for water and wastewater reuse. Sewer mining (SM) 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. SM is based on extracting wastewater from local sewers and treatment 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 and 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 SM, the dynamics of the sewer system should be investigated in order to identify optimum ways of deploying SM 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 SM deployment while simultaneously accounting for the variability of sewer network dynamics in order to identify potential locations for SM implementation. The outcomes of this study suggest that the method can provide rational results and useful guidelines for upscale SM technologies at a city level.

Key words | decentralized wastewater options, hydrogen sulphide, Monte-Carlo method, sewer mining, upscaling

I. K. Tsoukalas (corresponding author)
C. K. Makropoulos
Department of Water Resources and Environmental Engineering,
National Technical University of Athens,
Heroon Polytechneiou 5, Zographou GR-15780,
Greece
E-mail: *itsoukal@mail.ntua.gr*

S. N. Michas
Hydroexigiantiki Consultants Engineers,
3 Evias str, Marousi GR-15125,
Greece

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 a 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 (e.g., Sydney Water 2008). Typical uses of this recycled water are industrial cleaning and cooling, as well as irrigation of urban green spaces (Hadzihalilovic 2009; Marleni *et al.* 2012). Literature classifies this technology as a decentralized option (Makropoulos *et al.* 2017) 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 for collective/cluster scale developments. Furthermore, the latter authors remark that usually such systems are not managed by central water utilities (or governmental organizations) but by private establishments under some license agreements. As such, SM is a promising reuse option that lies in the interplay between reuse at household scale (e.g., grey water reuse; cf. Liu *et al.* (2010) and Makropoulos & Butler (2010)) and centralized reuse at the wastewater treatment plant (WWTP) level (Andreadakis *et al.* 2006). Current SM projects

doi: 10.2166/wst.2017.487

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 treated water is used for non-drinking purposes. Despite public perception, concerns and inadequate regulatory frameworks that may raise potential barriers for SM 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 to implementing SM, the dynamics of the system should be investigated in order to identify optimum ways of deploying SM 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 infrastructure. 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 SM 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 minimizing H_2S build-up.

MATERIALS 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 which the spatial properties and water demand characteristics are being identified, (II) a Monte-Carlo simulation (MCS) step, which involves the 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 the definition of appropriate metrics that quantify the output of interest (III-a) and a multi-criteria analysis of the results (III-b). 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 SM (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

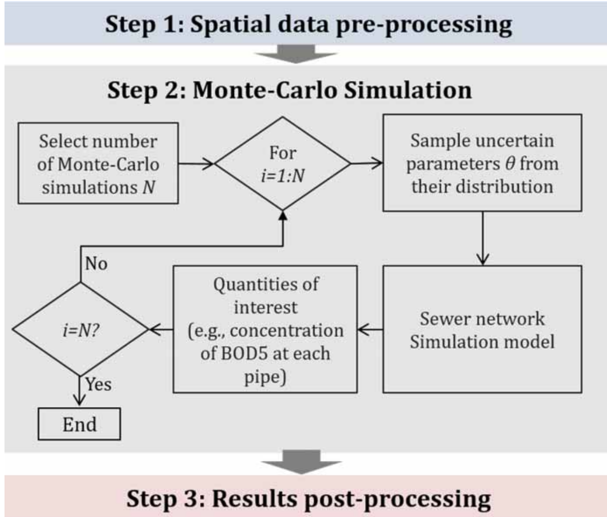

Figure 1 | Overall methodological framework for the identification of potential SM locations.

interest. In more detail, this is done by delineating a wider area surrounding the original one (e.g., add 10 m offset to green areas) and subsequently identifying the nodes that lie in those wider areas. Finally, the paths from the identified nodes to an 'exit' node are identified and stored. The exit node could be a WWTP or a node that links the understudy 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 to the input parameters to the quantities of interest (e.g., 5-day biochemical oxygen demand (BOD_5) concentration or flow of each pipe). Furthermore, the use of MCS allows the use of probabilistic functions and metrics, which 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). We remark that BOD_5 can be directly associated with H_2S through empirically derived relationships (e.g., Lahav et al. 2006; Marleni et al. 2015). Furthermore, as a final procedure, we use multi-criteria analysis which eventually leads to derivation of a Pareto front (based on conflicting criteria, e.g., suitability of location and green area water demand), which includes all the potential locations for SM.

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. While any simulation model can be employed (e.g., SWMM 5.0), 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:

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

where q is the indicative daily water consumption per capita (litres per day, lpd), E is the serviced population, λ_L is a loss coefficient of water distribution network, λ_S is a coefficient that expresses the percentage of water that stems from 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:

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

where λ_{DWF} is a dry weather flow coefficient (typically set to 0.2). Although, in this study we use Equation (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, we decided to employ a simple qualitative indicator known as the 'Z formula' (US EPA sulphide control manual (Pomeroy, Johnston & Bailey 1974)). The dimensionless 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. It is expressed as follows:

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

where i is the pipe index, T is the sewage temperature (°C), $[BOD_5]_i$ is the concentration of BOD_5 (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. It is apparent from the latter equation that despite its simple form, the 'Z formula' accounts for the hydraulic characteristics of the sewer network; except for T (which is usually assumed constant) all other parameters of Equation (3) are calculated using the simulation model. Furthermore 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 by the daily sewage volume. According to Pomeroy (1990) values of Z_i>7,500 indicate that there are high chances of H_2S formation, which could lead to odour and corrosion problems. Equation (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 ($i = 1,\dots, n$). It is worth mentioning that literature includes a variety of metrics (Boon 1995; Lahav et al. 2006; Hvitved-Jacobsen et al. 2013; Marleni et al. 2015) other than Pomeroys' Z, that could be used to quantify (with higher precision) the 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 quantile x. For example the 75th quantile value indicates that 75% of MZ_c are below the $Q[MZ_c]_{75}$ 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 $Q[MZ_c]_x$; 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, providing 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 to extend the existing sewage network of the coastal zone. It consists of 1,030 pipes of total length ~38 km, while their diameter varies from 0.2 m to 0.5 m. The pipe slope varies from 2‰ to 150‰, with an average slope of 35‰. The understudy area can be considered appropriate for testing the proposed methodology, since it consists of various network elements and has adequate number of green areas which could benefit from SM practices.

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 ($n = 0, \ldots, T$). 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. Finally, we assumed λ_1 and λ_2 as uncertain parameters that follow uniform distribution; i.e., we assumed $\lambda_1 \sim$ *Uniform*[0.7, 1.3] *and* $\lambda_2 \sim$ *Uniform*[0.8, 1]. Concerning parameter *n*, we employed three scenarios, 0, 20 and 40

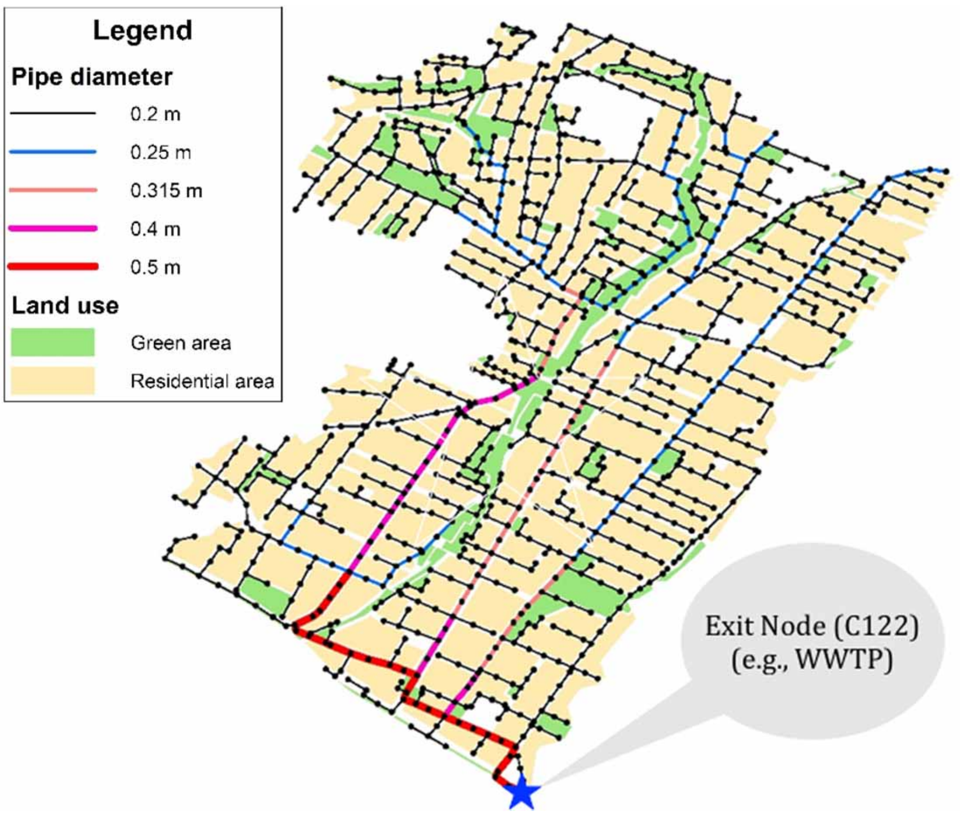

Figure 2 | Case study sewer network and land uses – Kalyvia Thorikou, Greece. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wst.2017.487.

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 quantile 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, using 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 simultaneous maximization of suitability and benefit from SM practices respectively. The suggested procedure located three potential locations for SM units' placement that optimize both criteria simultaneously, while on the other hand it discarded other inferior locations. Additionally, the map depicted in Figure 4 provides a visual summary of all the green areas (light-grey polygons, green in online version) of the case study, as well as the three areas (dark-grey polygons, red in online version) 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 (light-grey line, magenta in online version) for the green area with ID3. This path has the lowest MZ value compared to all other alternative paths of ID3.

Figure 5 depicts the cross-section of optimum path of green area ID3 (light-grey/magenta line in Figure 4). The path starts from pipe C215 which is located close to the

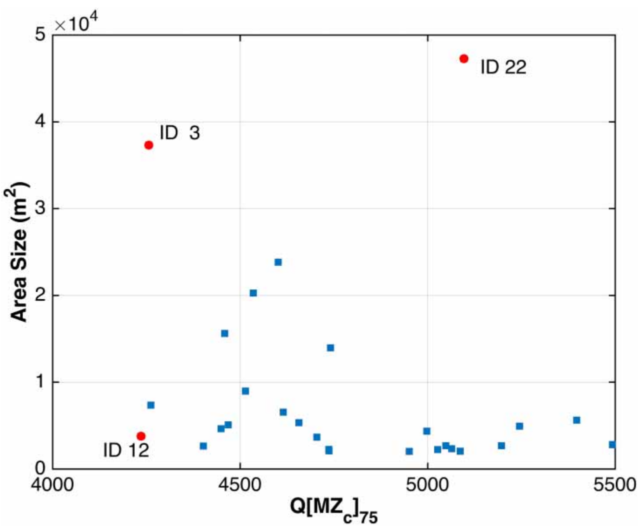

Figure 3 | Derived Pareto front based on modified indicator Z (MZ) and green area size.

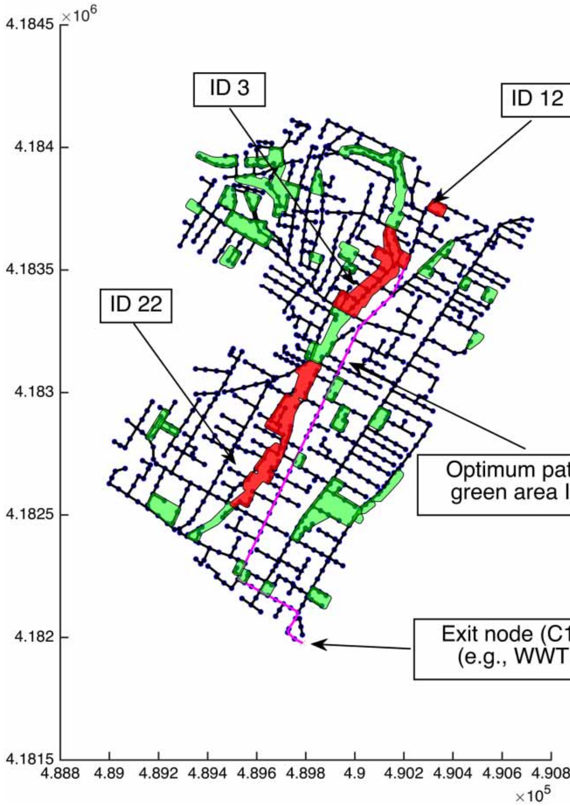

Figure 4 | Proposed SM locations for Kalyvia Thorikou sewer network. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wst.2017.487.

green area ID3 and ends at 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 (P) of non-exceedance of the threshold values ($Z < 7{,}500$). 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%).

CONCLUSION

In order to overcome the engineering challenges imposed by the multiple physical, biological and chemical processes that take place in a sewer network, we introduced a novel Monte-Carlo based method for the identification of potential locations for SM units. The proposed risk based approach allows the safe planning of SM deployments taking into due consideration system performance objectives regarding

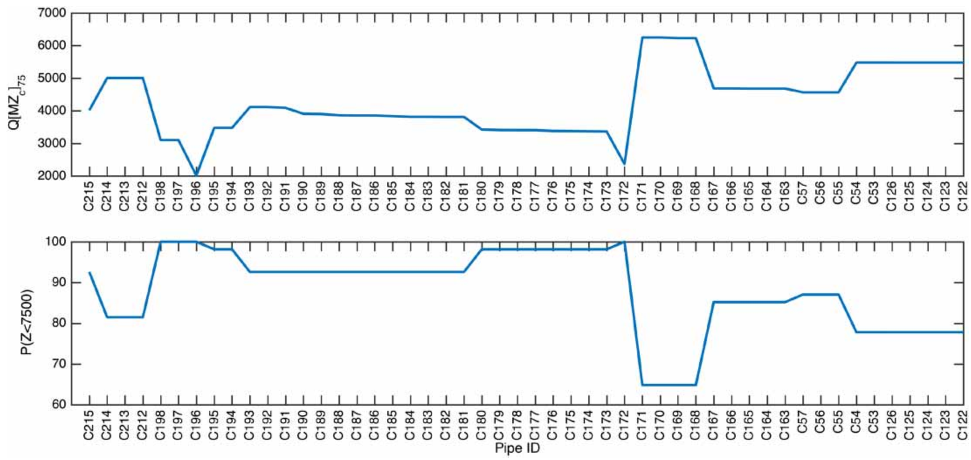

Figure 5 | Cross-section of optimal path of green area ID 3. The upper panel depicts the variation of modified indicator *Z* (MZ) among longitude profile. The lower panel depicts the probability of non-exceedance of the threshold value of $Z = 7{,}500$ among the cross-section.

water quantity and quality. As such it can be used to enhance the decision making process with useful guidelines and insights. More specifically, the proposed method has been demonstrated through a case study (Kalyvia Thorikou, Greece) where we focused on identifying optimum locations for SM units subject to the generation (minimize) of hydrogen sulphide and water demand. The results showed that the proposed methodology was able to identify potential locations for SM 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. Future work will focus on improving the proposed framework through the integration of a dynamic simulation model, such as SWMM 5.0, into the computational procedure.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Union Seventh Framework Programme under grant agreement no. 619039 (ENV.2013.WATER INNO&DEMO-1), for the research project DESSIN 'Demonstrate Ecosystem Services Enabling Innovation in the Water'. The research and its conclusions reflect only the views of the authors and the European Union is not liable for any use that may be made of the information contained herein. Also, we would like to sincerely thank Hydroexigiantiki Consulting Engineers for providing the data of the understudy area (Kalyvia Thorikou, Greece). An earlier version of this paper was presented at the 13th IWA Specialized Conference on Small Water and Wastewater Systems (Tsoukalas *et al.* 2016).

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First received 28 February 2017; accepted in revised form 23 August 2017. Available online 19 September 2017