A new approach for the optimal design of sewer networks including layout selection

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Highlights

- Sewer systems design includes both: layout selection and hydraulic design.
- The cost function to design sewer systems must include the topography and the topology.
- The terrain topography is an important variable to reduce construction costs.

Introduction

The design of sewer networks is a complex problem in which a large number of variables that describe the behavior of the network and compliance with hydraulic restrictions have to be considered. For this reason, the problem must be approached from two stages: layout selection and hydraulic design.

In the selection of the layout, the objective is to determine the type of pipe (initial or continuous), the direction and the design flow of each section having as parameters the topology of the network, the location of the final discharge and the length of the main sections towards the final discharge (Torres, 2013). Traditionally, the layout construction process is subjective since it lacks an optimization method or criteria. Additionally, there are few researches that refer to this problem due to the challenge of finding a cost function with the variables and data available in the layout selection. On the other hand, the hydraulic design stage counts with computational tools such as SeweGEMS which uses heuristic methodologies to solve the problem or it can be approached using the methodology proposed by Duque et al. (2016). In the latter methodology the problem of layout selection is approached using a mixed integer linear programming model.

According to what is mentioned above, the present work proposes a methodology for the layout selection that takes into account the terrain topography data. In order to achieve this, changes to the methodology of Duque et al. (2916) will be made, specifically to the cost function.

Methodology

During the development of the research, the problem of the optimized design of sewer networks was covered in two different ways. Initially by heuristic methods performed by Duque et al. (2016) in which the topography of the land and the flows of entry into each well of the system were considered. These methodologies were applied through the UTOPIA software made by the Universidad de Los Andes. Moreover, for the selection of the layout the characteristics of the topography were taken into account. Then it was classified into two categories: flat terrain or hilly terrain, this in order to determine an objective function that can be applied to all types of topography.

Optimized design methodology implementing UTOPIA Software

The methodology proposed by Duque et al. (2016) consists of determining the layout and the hydraulic design. For the layout selection, Duque et al. (2016) implements a mathematical model based on a Mixed Integer Program (MIP), in which the flow direction and connection type of each pipe are defined (Aguilar, 2019). To solve the problem, a target function containing two variables is used: the decision variable that models the flow (costs of transporting the flow over the network) and the decision variable that models the choice of a flow direction. The objective function is aimed to minimize is the following:

$$\min \sum_{t \in T} \sum_{(i,j,t) \in A_l} c_{ij} q_{ijt} + \sum_{t \in T} \sum_{(i,j,t) \in A_l} a_{ij} x_{ijt} \qquad (Equation\ 1)$$

Therefore, each possible arc ij must have an associated cost which represents the cost per unit of flow transported that affects the first sum of the equation. For the second sum, the coefficient a_{ij}represents the cost for the existence of the ij arc, and the variable x_{ijt} is binary (values of 0 and 1) depending on which arc defines the initial path. In conclusion, the equation is a linear objective function whose decision variables represent the cost per unit of flow transported by the network. To determine parameters a and c, Duque et al. (2016) propose to perform a linear regression of the costs of the hydraulic design with the transported flow to make a graph between the total costs of each section and the associated flow.

For the hydraulic design Duque et al. (2016) used the Bellmand Ford algorithm to be able to evaluate all possible layouts and thus be able to find the one that represents the minimum cost. From this methodology, all possible alternatives can be assesed, so the resulting hydraulic design is the global optimum. Due to this, the methodology is an iterative process that starts from a random initial layout to feed the hydraulic design. Figure 1 explains the integration of the methodologies.

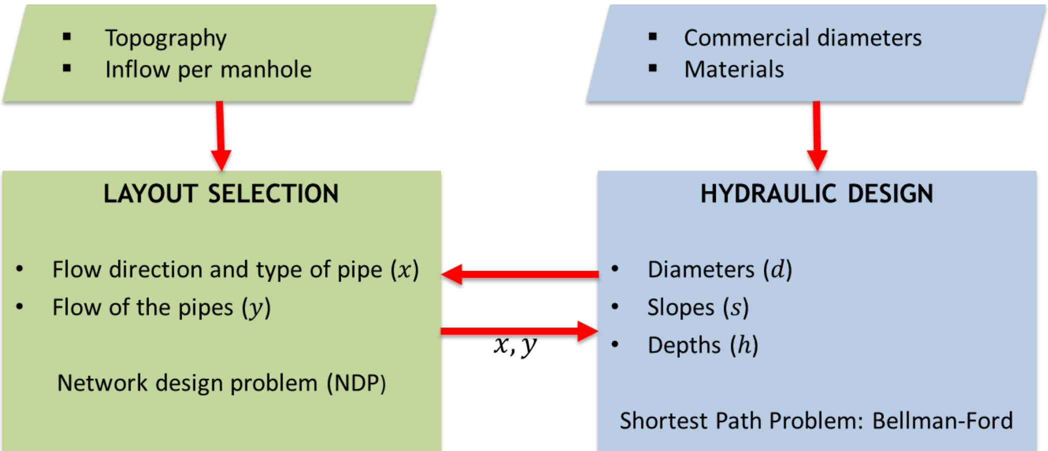

Figure 1. Methodology developed by Duque et al. (2016)

New methodology proposed for the layout selection

This new methodology is an extension of what was developed by Duque et al. (2016), which was a complete mixed optimization where all the specific variables are included in the problem of the choice of the path such as: the flow, the topology of the network and the terrain topography. Therefore, the objective function is aimed to minimize is the following:

$$\min \sum_{t \in T} \sum_{(i,j,t) \in A_l} c_{ij} q_{ijt} + \sum_{t \in T} \sum_{(i,j,t) \in A_l} a_{ij} x_{ijt} + \sum_{t \in T} \sum_{(i,j,t) \in A_l} m_{ij} x_{ijt} \qquad (Equation\ 2)$$

Where the first two addends are the same made by Duque et al. (2016), but the way to determine the coefficients c and a will be different. Additionally, in the third adding the coefficient m_{ij} presents the cost associated with the topography of the land, that is the slope of the section where the pipeline will be installed.

From the results shown by Duque et al. (2016) it was determined that the initial random layout is deficient, especially in hilly terrain. Therefore, six different criteria are developed that allow researchers to assign the weights to the arcs (coefficient m) when the topography is not flat and three criteria when it is flat. The main change that is made to the objective function (Equation 1) developed by Duque et al. (2016) is to withdraw the costs of the initial pipes in the linear regression, as well as eliminate the uncertainty caused by the heterogeneity of the lengths, when considering the cost of pipes per linear meter. This methodology is implemented in five case studies, in which there are different topographic characteristics, in order to cover different number of scenarios.

Results and discussion

From the five study cases chosen, it was possible to cover a large number of alternatives that appear when designing a sewer system, such as, variations in the topography, topology and flow contribution to the network. For the initial layout, the methodology proposed nine different criteria that collected known data at the beginning of the design process, such as network topology and terrain topography. Initially, these criteria were divided into those that were thought to be more efficient for flat areas and others for networks of hilly topography. However, the criteria that took into account the hilly topography proved to be more efficient even when the network was flat. Then, it could be analyzed that a layout that takes advantage of the slope or the favorable energy of the land will represent fewer construction costs because the diameter and depth of excavation is optimized.

Furthermore, with the results obtained from the initial paths in each study case, it can be determined that the pipe slopes depend on both the topography of the land and the magnitude of the flow. Additionally, it was observed that the average construction costs for the initial sections had little variation for all the networks, a reason why this is not a function of the magnitude of the flow since it was possible to implement the same diameter and only the installation depth was varied. Finally, the linear regression of the costs per linear meter of the continuous pipes and their design flow in all networks, showed that the goodness of fit was very closed to 1.0, and this allows the reduction of the uncertainty to predict the costs per unit of flow in the choice of the layout. From this analysis it was possible to draw the conclusion which dictated that the proposed new methodology could reduce the construction costs taking into account the terrain topography, which had not been included in the objective function developed by Duque et al. (2016). This solved the problem of the original methodology in hilly or high slope terrains.

Conclusions and future work

In the design of a sewer network it is necessary to go through two stages: layout selection and hydraulic design. From the first it can be concluded that the cost function must take into account the terrain topography and the network topology, in order to reduce construction costs. Additionally, it was determined that the initial pipes will mostly likely have a constant cost because the minimum digging depth and the minimum diameter are always used. From the second stage it is possible to conclude that an optimal hydraulic design can be obtained using the methodology of Duque et al. (2016). Finally, future work could improve the selection of the initial layout using variables that were not taken into account, such as the contribution flow to each man hall, or using another cost function for choosing the layout, for example, a linear equation.

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