Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 186 (2017) 617 – 625

Procedia Engineering

www.elsevier.com/locate/procedia

XVIII International Conference on Water Distribution Systems Analysis, WDSA2016

Pseudo-genetic model optimization for rehabilitation of urban storm-water drainage networks

Pedro L. Iglesias-Rey[a], F. Javier Martínez-Solano[a], Juan G. Saldarriaga[b], Vicente R. Navarro-Planas[a]*

[a]*Dep. Ingeniería Hidráulica y Medio Ambiente (Universidad Politécnica de Valencia), c/ Camino de Vera s/n 46022, Valencia, Spain*
[b]*Dep. de Ingeniería Civil y Ambiental (Universidad de los Andes), Bogotá, Colombia*

Abstract

One of the main concerns in many cities is the need to rehabilitate or expand their drainage systems. Increasing rainfall intensities related with climate change, uncontrolled growth and excessive waterproofing of cities causes that original drainage networks design have became insufficient. Inadequate drainage networks make necessary to develop rehabilitation models of existing networks. This models should be compatible with them. This paper presents an optimization methodology to generate different solutions for the existing network improvement.
This methodology uses as starting point a model of the actual storm water network. In this paper the SWMM model is used to perform the hydraulic analysis of the network. Also a Pseudo-Genetic Algorithm (PGA) is used as optimization engine. This PGA model has been previously developed for other hydraulic optimization problems. The developed optimization model includes as decision variables: the rehabilitation or replacement of existing pipes, the potential location of stormwater retention tanks at certain points and their size, the initial state of the existing pumping units, and the start and stop levels of each pump.
To evaluate each solution during the optimization process it has been necessary to develop a series of costs functions: a) a cost function or damage function relating the flood level and associated damage costs; b) a cost function of stormwater retention tanks which relates the investment cost in the construction of the tank with its volume; c) a pipeline rehabilitation cost function that relates the cost of rehabilitation or replacement of a pipe with its nominal diameter; d) a cost function for each pump unit giving the cost of the electrical energy consumed during the operation. Finally, the methodology developed has been applied to solve the flooding problems of a small section of the drainage network of the city of Bogota (Colombia).

* Pedro L. Iglesias-Rey, F. Javier Martínez-Solano, Vicente R. Navarro-Planas. Tel.: +34 963 877 610; fax: +34 963 877 618.
E-mail addresses:; piglesia@upv.es; jmsolano@upv.es; jsaldarr@uniandes.edu.co; vinapla@posgrado.upv.es

1877-7058 © 2016 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the organizing committee of the XVIII International Conference on Water Distribution Systems
doi:10.1016/j.proeng.2017.03.278

Keywords: Optimization; genetic algorithm; urban drainage.

1. Introduction

Urban drainage networks fulfill a hygienist mission, in so far as they conduct the runoff during rainy periods and protect up to a certain level against urban flood events. This level of network protection is given by its return period. Indisputably, the higher the design return period of network, the less tangible (economic) and intangible damages (social aspect, mainly) will happen, but also greater structural investment will result. The insufficiency of rainwater drainage networks in many countries has a clear origin: climate change. Although the effects of climate change in many areas lead to lower global rainfall, simultaneously it occurs that rainfall intensities are significantly higher. This fact, linked to growing waterproofing of our cities causes that flooding problems continue growing.

In a climate change context , there are different technologies which can be used to solve or alleviate consequences of excess runoff in our cities. The classic approach were addressed by total or partial renewal of the network and increasing its capacity. In this paper another solution is addressed, in which the renewal of pipes is used in combination with the techniques of sustainable urban drainage systems (SUDs). Of all these techniques, this work will be focused on those structural measures that control flows once they have entered into the network (retention tank construction and rehabilitation of pipelines network). Specifically, the work is focused on developing a comprehensive methodology for the rehabilitation of storm drainage network based on the partial renewal of the network and the installation of retention tanks. Other SUDS techniques, such as the construction of porous pavements, green roofs on buildings or small gardens on rooftops and terraces have not been considered. While they may partially reduce runoff, massive installation of them is necessary in order mitigate runoff significantly.

One of the first studies which relates the use of storm tanks and rainfall storm variations caused by climate change is presented by Andrés et al. [1]. Its probabilistic model allows to evaluate the efficiency in reducing floods depending on different parameters such as the size of tanks, climatic parameters and characteristics of the basin. The problem that arises in this case is slightly different by including the combined use of tanks and renewal of pipelines. In this sense, mathematical models of urban drainage play a key role. In this line, Butler and Schütze [2] develop a model which includes the efficiency of tanks based on a certain hydraulic modeling of the behavior of the network as a whole. However, its approach is more oriented to the quality of waste water than to flooding control. Later this work has been extended by Fu at al. [3] considering the optimization of urban wastewater as a multi-objective problem. For that, they use the multi-objective genetic model NSGA-II [4] to obtain the Pareto frontier of different optimal solutions.

In this context, technical and economic optimization plays a critical task to achieve the reduction of the final budget of the project of the civil work to be done. Thus, the work is focused on presenting a rehabilitation methodology which combines hydraulic analysis with an optimization model.

2. Methodology

The main objective of this work is to develop a methodology, through the combined use of mathematical optimization and hydraulic analysis of rainwater drainage networks, to find the most appropriate solutions for its rehabilitation.

Generally, for the development of the planned methodology, the some starting points or assumptions are admitted. On the one hand, different rain scenarios which correspond to different predictions made and based on studies of climate change studies will be used. Thus, the scenarios to consider are those considered as potentially hazardous within a confidence level. Also, a preliminary study of rainfall-runoff transformation must be available, so that the hydraulic model considers that the flows are provided directly to the input nodes of the model. In other words, the study of rainfall-runoff transformation is performed independently of the hydraulic model. On the other hand, it should be taken, as a starting point, a calibrated mathematical model of the network, since the analysis of each scenarios must be as accurate as possible. SWMM5 model [5] has been selected as hydraulic engine simulator. But, the mathematical model used should be as simple and simplified as possible, so that the speed of the optimization process should be reasonable.

The optimization problem will be addressed in terms of monetary units. Thus, in a first formulation of the optimization problem, the first step will be to find the functions that translate the value of hydraulic variables in monetary units. Of all the mathematical optimization techniques, it seems that heuristic could provide higher performance. Therefore, based on previous experiences [6], a pseudo genetic model [7] has been adapted to this problem.

From these assumptions, the goal of the work is summarized in the objective function (OF) of the optimization problem. This OF is expressed in terms of monetary units, and tries to consider jointly both investment in retention tanks and renovation of ducts as well as different penalties related with exceeding water levels in drainage conduits. Mathematically, it can be expressed as

$$OF = \lambda_1 \sum_{i=1}^{N} C\left(V_I(i)\right) + \lambda_2 \sum_{i=1}^{N_D} C\left(V_{DR}(i)\right) + \lambda_3 \sum_{i=1}^{M} C\left(D_N(i)\right) \cdot L_i + \lambda_4 \sum_{i=1}^{M} C\left(V_{max}(i)\right) \quad (1)$$

In equation (1), the first term reflects the cost corresponding to flooding volume $V_I(i)$ in each one of the N nodes of the system. This total nodes number N is the sum of the junctions number (N_N) and the number the tanks number (N_D). The second term is the investment cost linked to the construction or expansion of the volume V_{DR} (i) of each tank that have finally been installed on the system; either the tanks currently exist or were new retention tanks to be installed. The third term gathers the budget for the restitution of the M lines considered in rehabilitation. The fourth term is the sum of the maximum volume of water inside each one of the M conductions of the model. The latter option is added to the objective function in order to include the possibility of including the filling level of the network as part of the target to consider. Finally, in (1), each terms has a Lagrange multiplier λ_i. These allow to decide which one of the objective function terms are considered in each rehabilitation project.

The proposed methodology for the development of the rehabilitation of rainwater networks by a combined use of retention tanks and pipelines renovation, is based on the following stages: building a mathematical model of the network; defining potential decision variables; defining cost functions of each element in (1); and performing the optimization through the heuristic model. Such process provides the final design solution of the network.

The decision variables (DV) that can be considered during the optimization process are the following ones:

- Variables related to tanks. In case that the initial model includes a tank, it will be possible to optimize its cross section. Its equivalent cross section S will be modeled according to the following expression:

$$S = A \cdot z^B + C \quad (2)$$

  where A, B and C are characteristic coefficients to adjust the section to different expressions; and z is the water level in tank. If tank has a constant section, the parameter A represents this section and B and C are null.

- Variables related to nodes. The process allows selecting several nodes in order to consider the possibility of installing a retention tank. Thus, each of these nodes has a DV associated with the cross section S of the potential tank to install in this point. This sections is also represented by (2).

- Variables related to conduits. The method also consider the possibility of selecting some lines to study the effectiveness of replacing them by another ones with different dimensions. So, there will be a DV associated with the diameter of this conduit.

In short, there will be as many DV as potential tanks locations and potential conduits to be rehabilitated. This DV has associated costs that are discussed in the following section.

3. Cost Functions

The OF defined in (1) contains four terms that represent the cost of each DV and the penalties associated with the restrictions of the rehabilitation project. The costs associated with the decision variables are the costs of tanks and ducts, whereas the costs associated with penalties are flooding costs and the costs of water storage in network.

3.1. Investment cost functions

One of the major investment costs of this methodology is related to the construction of detention tanks. Undoubtedly, an in-depth study of the construction costs of a retention tank depends on many factors. thorough study of tanks costs excavation costs of a given tank depends on many factors: its cross section and dimensions; its typology (either constructed of concrete or built from modular structures), the loads to be carried on the top of the tank; the auxiliary elements required for proper operation; the elements necessary for cleaning and maintenance of the tank; etc. However, for this optimization problem it only has been considered the relationship between the cost and the volume of the tank. Mathematically, this relation has been depicted as:

$$C\left(V_{DR}\right) = \tau_A + \tau_B \cdot V_{DR}^{\tau_C} \qquad (3)$$

where $C(V_{DR})$ is the cost of building a tank with a volume V_{DR}; and where τ_A, τ_B and τ_C are adjustment coefficients.

Another important item in the budget of the network rehabilitation is the replacement of certain pipes with new ones. In order to evaluate economically the costs of installing new conduits, a function that represents these costs according to the diameter of pipes has been developed. Mathematically it can be expressed as:

$$C\left(D_N\right) = \pi_A \cdot D_N + \pi_B \cdot D_N^2 \qquad (4)$$

The setting values of equations (3) and (4) depend on the price database considered. In order to develop the proposed methodology, it has been thoroughly studied the prices in two different countries: Spain and Colombia. That will allow to study the influence of these parameters (Table 1) on the solution obtained with the proposed methodology.

Table 1. Setting values of tanks and conduits cost curves.

Data origin	τ_A	τ_B	τ_C	π_A	π_B
Colombia	16923	318.4	0.50	137.15	40.69
Spain	20000	1000	0.65	237.93	208.06

5.3. Cost functions Flood

Within the objective function, the costs associated with potential floods that occur in the installation must also be included. Within the proposed methodology, two different ways of representing such cost have been defined: either proportional to the volume of flooding at each node, either proportional to the level of flooding. In the case of costs proportional to flooding volume, it is a simpler model in which a cost proportional to the volume of water that comes out in each of the nodes of the model is charged. By contrast, in the case of the costs related to the flood level, the flooding area in each node must be previously defined. From flooding level, it is necessary to define a function that relates the flooding cost with the highest level reached by the water outside the drainage network.

The study of flooding costs is built on a vulnerability curve which establishes the percentage of damage in function of the water level reached. This curve is crossed with the costs per square meter associated with each land use. The result is a set of different cost curves (Figure 1), each defines for a specific use (commercial or industrial) or social stratum.

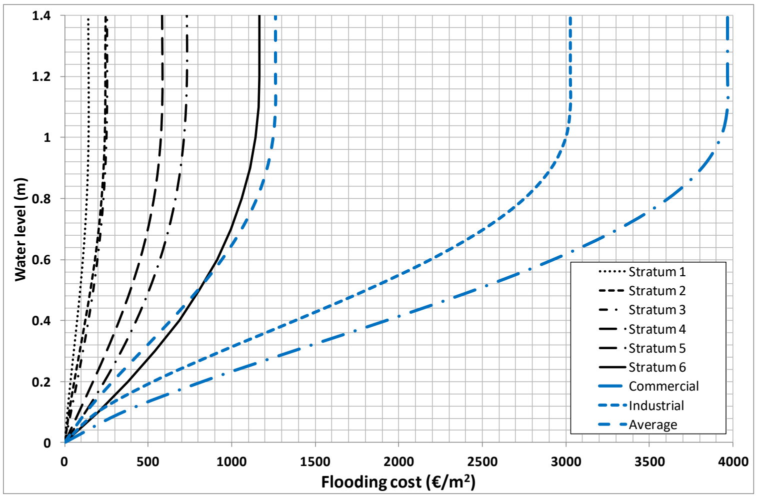

Fig. 1. Flooding costs (€/m^2) for different social stratum and uses.

So as to gather the cost functions defined in Figure 1, a mathematical expression is defined:

$$C(y) = C_{\max} \cdot \left(1 - e^{-\lambda \frac{y}{y_{\max}}}\right)^b \quad (5)$$

In equation (5) C_{max} reflects the maximum cost, when flood level y_{max} is reached and 100% of goods and properties have to be replaced; y is the flood level; λ, b are adjustment coefficients whose values that best fit the results of Figure 1 are λ = 4.88 and b = 0.65. Since the level from which the maximum economic damage is generated is y_{max} equal to 1.4 in all cases, equation (5) is completely defined with the value of C_{max}. This parameter represents (Table 3) the maximum cost per unit area based on land use.

Table 2. Values of C_{max} coefficient for different uses.

Land use	Stratum 1	Stratum 2	Stratum 3	Stratum 4	Stratum 5	Stratum 6	Commercial	Industrial	Average
C_{max} (€/m^2)	142	245	257	584	732	1168	3975	3041	1267

Definitely, to define the function of inundation costs it is only necessary to define the type of use of each soil linked to potential flooding in each one of the nodes. These uses are defined by the estimation of economic damage per square meter corresponding to damage of 100% of the assets considered (C_{max}).

4. Case Study

In order to show up the proposed methodology, it has been applied on the rehabilitation of one sector of the rainwater drainage network of the city of Bogotá (Colombia). The network under study was obtained as a simplification of the initial network of Chicó sector in Bogotá, the network to be called "E-Chicó". The networks covers an area of more than 51 ha, which defined 35 hydrological sub-catchments. Total network length is about 5000 m of circular pipes with diameters between 300 and 1400 mm. The network has 36 nodes and 35 lines and operates entirely by gravity, as the profile of the terrain is favorable to water drainage. An scheme of the network can be show in Figure 2.

Before optimizing E-Chicó network, a preliminary analysis to know the state of the network and their response to design rain was performed. For that, the hydraulic network analysis with SWMM model is performed, detecting flooding in some nodes (red nodes of Figure 2). The results of flooding at different nodes are collected in Table 4. In this table, it is observed that the total flooding of the system is about 3835 m^3, representing more than 16% of all runoff generated (23690 m^3) for the design storm.

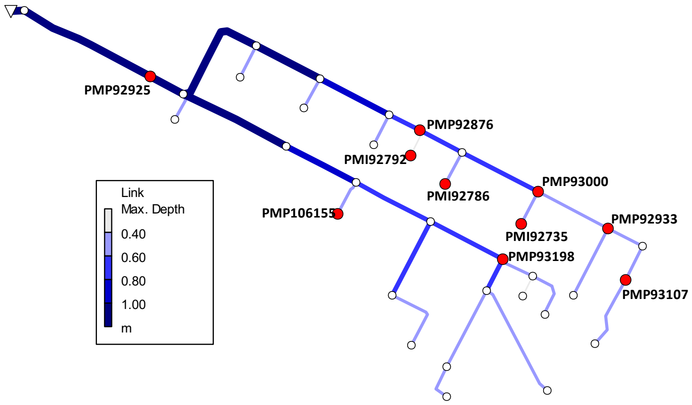

Fig. 2. Representation in SWMM5 of the nodes in which flooding occurs during the rain event considered.

Table 3. Results of flooding in nodes.

Node	Q_{max} (l/s)	$T_{flooding}$ (h)	$Vol_{flooding}$ (m^3)
PMI92735	87.03	0.12	24
PMI92786	30.29	0.03	2
PMI92792	78.05	0.14	26
PMP92876	589.17	0.29	385
PMP92896	512.85	0.35	470
PMP92925	1021.95	0.44	1182
PMP92933	369.01	0.17	133
PMP93000	662.66	0.34	502
PMP93107	350.41	0.16	124
PMP93198	1170.87	0.33	950
PMP106155	80.09	0.19	37
		TOTAL	3835

In short, the preliminary analysis of the network shows that it is insufficient to drain the selected design storm. Therefore, the E-Chicó network has been considered appropriate to apply the optimization algorithms developed. The analysis scenarios considered to apply the methodology are:

- Scenario 1. Network rehabilitation only based on changing network conduits and replace them with different diameters. This scenario has 35 DV: the pipes whose diameters are left as unknown.
- Scenario 2. Network rehabilitation installing only retention tanks. This scenario has also 35 DV corresponding to the 35 potential nodes in which retention tanks could be installed.
- Scenario 3. Network rehabilitation combining the installation of pipes and retention tanks. The number of decision variables is 70.
- Scenarios 4, 5 y 6; respectively equivalent to scenarios 1, 2 and 3 but considering Spanish cost functions instead of those of Colombia.

For each scenarios the described methodology is applied, considering either Colombian or Spanish costs. Table 4 shows the results of every case: OF value, flooding cost, investments in pipes and tanks and number of tanks and pipes. It can be seen that the joint implementation of pipe rehabilitation with the use of detention tanks is the solutions that leads to better results.

Table 4. Summary of costs (OF, flooding, investments) and number of tanks and pipes of each scenario.

Scenario	Objective Function (€)	Flooding cost (€)	Tanks cost (€)	Conduits cost (€)	Number of Tanks	Number of Conduits
1	763,164	7,622	-	755,542	0	16
2	273,459	5,392	268,067	-	6	0
3	251,1346	19	238,047	13,068	5	2
4	1,075,989	32,249	-	1,043,741	0	17
5	646,085	14,024	632,061	-	6	0
6	555,643	31,631	506,205	17,807	4	2

In the Figure 3, the tanks to be installed and pipes to be replaced in the case of Scenario 3 appear. In that case, the number of lines to be replaced is 2 and the number of tanks to install is 5. Tanks dimensions and piping changes are also shown in the figure. Some homologues results are presented in Figure 4 (scenario 6).

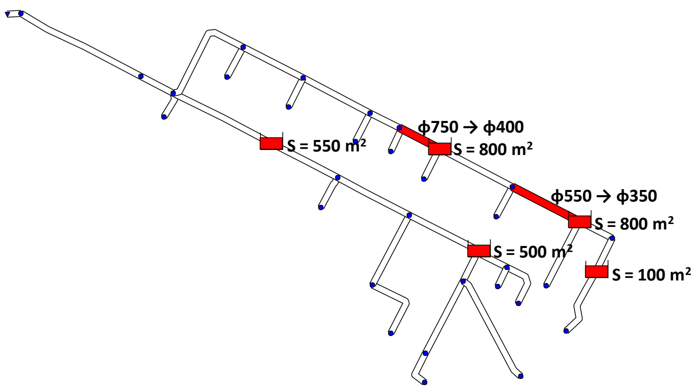

Fig. 3. Optimization results (Scenario 3). Investment proposal in tanks and pipes replacement.

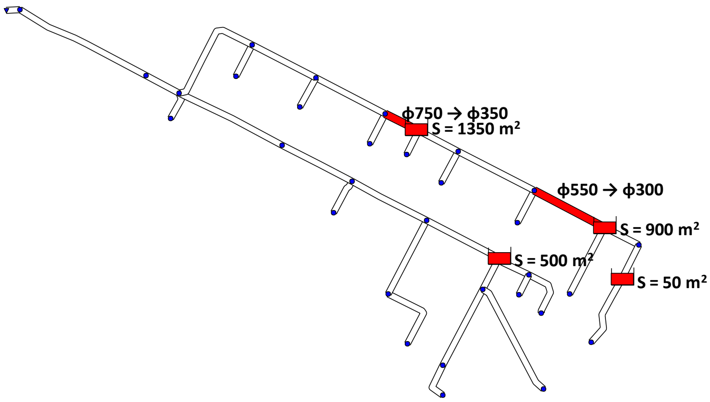

Fig. 4. Optimization results (Scenario 6). Investment proposal in tanks and pipes replacement.

5. Conclusions

After describing the proposed methodology of rehabilitation and analyzing their application to a specific case, the following conclusions can be drawn:

- The proposed methodology is highly suitable for rehabilitating rainwater drainage networks in which increased rainfall intensities have reduced the reliability of the existing networks.
- The methodology based on the application of cost functions is very useful in the development of such projects. The definition of these functions is key in obtaining the final solution. In the developed example, it has been applied for both Colombian and Spanish costs. The solutions in these cases are quite similar, with a clear reduction in the diameter of the pipelines immediately downstream the tanks. Still, there are slight differences which highlights the importance of making a good adjustment of the cost functions.
- The developed rehabilitation method does not prevent the occurrence of flooding in the network. All solutions obtained envisaging a minimum occurrence of flooding in some nodes reach a few centimeters. In the case of desiring solutions with no flood, the methodology should be applied again with much higher flooding costs.

In conclusion, the use of methodologies that combine the use of hydraulic analysis models with heuristic optimization models are shown as an extremely useful tool for developing networks rehabilitation projects. Undoubtedly, the developed methodology can be applied to other rehabilitation models based on hydraulic analysis models. Even this model can be extended considering other rehabilitation alternatives such as SUDS techniques.

Acknowledgements

Authors acknowledge Mexichem Colombia for funding this research through the Project “Urban drainage and climate change: to sewerage systems of the future. Phase II”, without which would have been impossible to complete these studies.

References

[1] I. Andrés-Doménech, A. Montanari, and J. B. Marco, "Efficiency of Storm Detention Tanks for Urban Drainage Systems under Climate Variability," *J. Water Resour. Plan. Manag.*, vol. 138, no. 1, pp. 36–46, Jan. 2012.

[2] D. Butler and M. Schutze, "Integrating simulation models with a view to optimal control of urban wastewater systems," *Environ. Model. Softw.*, vol. 20, no. 4, pp. 415–426, Apr. 2005.

[3] S. T. Fu, G; Butler, D.; Khu, "Multiple objective optimal control of integrated urban wastewater systems," *Environ. Model. Softw.*, vol. 23, no. 2, pp. 225–234, Feb. 2008.

[4] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, "A fast and elitist multiobjective genetic algorithm: NSGA-II," *IEEE Trans. Evol. Comput.*, vol. 6, no. 2, pp. 182–197, 2002.

[5] L. A. Rossman, *Storm Water Management Model User ' s Manual Version 5 . 1*, no. September. Cincinnati, OH 45268: Environmental Protection Agency, 2015.

[6] D. Mora-Melia, P. L. Iglesias-Rey, F. J. Martinez-Solano, and P. Ballesteros-Pérez, "Efficiency of Evolutionary Algorithms in Water Network Pipe Sizing," *Water Resour. Manag.*, vol. 29, no. 13, pp. 4817–4831, Aug. 2015.

[7] D. Mora-Melia, P. L. Iglesias-Rey, F. J. Martinez-Solano, and V. S. Fuertes-Miquel, "Design of Water Distribution Networks using a Pseudo-Genetic Algorithm and Sensitivity of Genetic Operators," *Water Resour. Manag.*, vol. 27, no. 12, pp. 4149–4162, 2013.