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Diego Fernando Paredes Méndez

Arlex Sanchez-Torres

Zoran Vojinović

Solomon D. Seyoum

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MULTI-OBJECTIVE-REHABILITATION OF URBAN DRAINAGE SYSTEMS WITHIN FLOOD RISK FRAMEWORK

DIEGO PAREDES (1), ARLEX SANCHEZ TORRES (2), ZORAN VOJINOVIC (2), SOLOMON SEYOUM (2), WILMER BARRETO (3)

(1): Empresa Pública Metropolitana de Agua Potable y Saneamiento, Quito, Ecuador

(2): UNESCO-IHE, Delft, The Netherlands

(2): Universidad Lisandro Alvarado, Barquisimeto, Venezuela

ABSTRACT

Urban drainage systems (UDS) are one of the most valuable public utilities in any community, which protects public health and the environment, nevertheless is one of the most overlooked infrastructures until considerable failures occurred. If there are not recurrent rehabilitation programs in place this vital infrastructure will decrease the level of service. This work presents an approach to find optimal rehabilitation measures based on the hydraulic performance of the system. To assess the performance of the urban drainage system a couple 1D-2D model was developed. The model uses SWMM 5.0 for the 1D transport; to simulate the overland flow from the manholes when the capacity of the sewer pipes is exceeded a coupled 1D-2D non inertia model was used. The results are matrices composed of flood water depths and velocities values per each scenario of the flood event. These outputs are the main parameters to assess flood hazard. Furthermore, the vulnerability was assessed based on the socio-economic condition of the residents in the study area, located in a catchment in Quito, Ecuador. The assessment of hazard and vulnerability were combined to estimate the flood risk damage. Several simulations were made for different flood events (10, 20, 50 and 100 year return period), obtaining Pareto sets per each event. However in order to have more realistic solutions the approach of expected annual flood risk cost were implemented to obtain integrated solutions for a number of flood events. Besides of these new solutions generated, the concept of cost-benefit analysis was applied to help in the identification of the most cost-effective solution.This is where the abstract should be placed. It should consist of one paragraph giving a concise summary of the material in the article below. Replace the title, authors, and addresses with your own title, authors, and addresses.

1. Introduction

Urban drainage is necessary to preserve and promote the public health, welfare, flood protection, water pollution, and economic development of any region. Urban drainage network is an infrastructure to collect, transport and disposes wastewater (domestic, industrial) and storm water (precipitation).

Urbanization constantly modifies land use within a city, leading several effects in the hydrologic cycle such as decreasing infiltration and incrementing flood peak and runoff, moreover, population growth, variation in the precipitation patterns, deterioration of the sewer infrastructure, blockage of sediment are factors that produce failures of urban drainage system (UDS). Consequently urban flooding occurs, which is one of the most dangerous impact on human societies, leading not only huge economic damage and lost on properties but also and the most sensitive issue is the lost of human lives. Thereby the importance to assess flood risk is to minimize human and economic damages by taking the most suitable mitigation measures. Urban drainage is an essential infrastructure for the communities, and its rehabilitation represents a huge cost to local governments, frequently its maintenance and rehabilitation is neglected until catastrophic events happen. Hence to accomplish a good level of service and efficiency of urban drainage, it is needed to diagnose the performance of the system by doing some evaluations such as: hydraulic, structural, environmental, social and operational investigations.

This research focus on the hydraulic assessment of UDS. Thus a framework was developed, which consists in several steps that were carried out in an integrated manner, i.e. collecting, analyzing and processing the required data, assessing the hydraulic performance of the sewer system, quantification of flood hazards, vulnerabilities and flood risks. Subsequently with these results, applying multi-objective-rehabilitation process which are based on genetic algorithms, several optimal solutions were obtained for several flood events.

2. Methodology

The mains steps of the proposed framework developed in order to assess the hydraulic performance of a sewer system to come up with optimal rehabilitation strategies under different flood scenarios, are outlined in the flowchart of Figure 1. Basically there are five principle activities which are interconnected each other, and they are:

- Data acquisition, analysis and processing.
- Urban drainage model development composed of 1D and 2D model.
- Flood Risk Assessment: Flood hazard and vulnerability assessment.
- Multi-Objective-Rehabilitation; and
- Analysis of Results.

Each of these principle activities has other sub-activities and processes, which employed some computational tools, such as: The Geographic Information Systems Arc GIS; Storm Water Management model EPA SWMM5; Non-convective wave 2D overland flow model (coupled 1D-2D model); The non-dominated based algorithm for multi-objective optimization NSGA II; CodeGear Delphi language programming; NSGA Xp algorithm. The propose framework was tested in a study area of Quito - Ecuador.

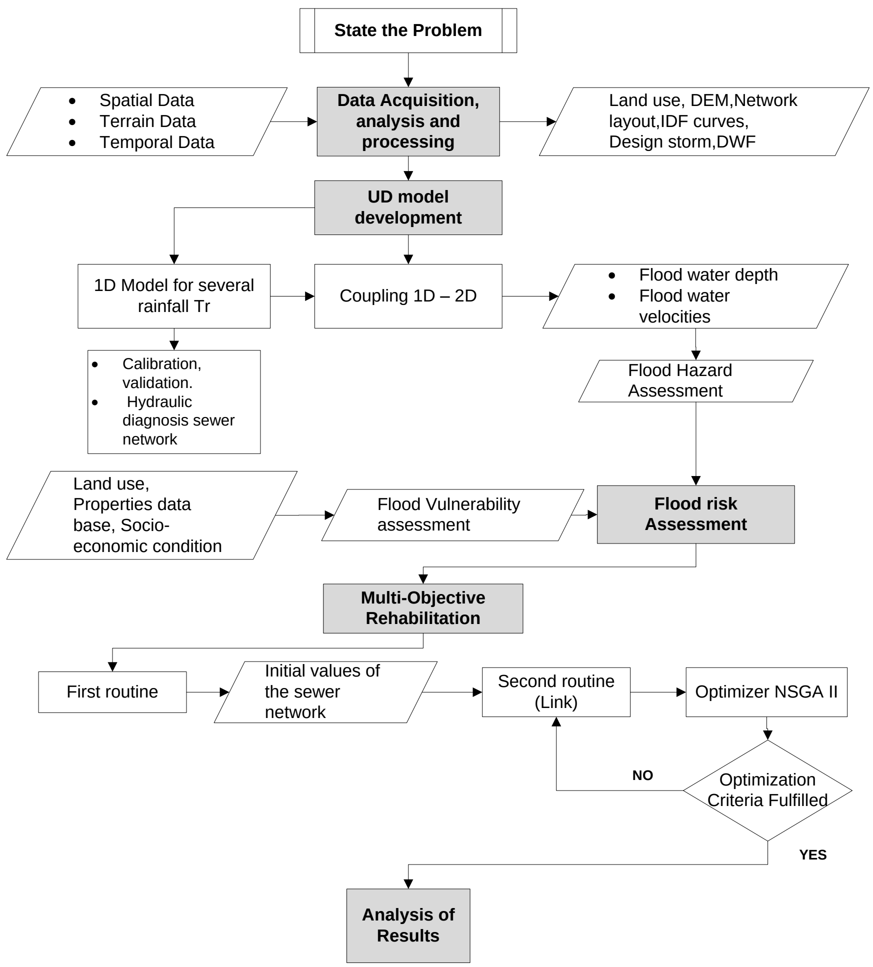


Figure 1. Flow chart of the main methodology

3. Case Study Area

The study area is a pilot basin (Puengasí) situated in the south east of the city (Quito). The total area of this basin is around 124 ha, the population density is 90 hab/Ha, with approximately 11000 inhabitants. The entire sewer network of this area is composed of 542 sub-catchments and manholes, and 573 pipes, and it is a combined gravity system. Within the study area there are one rain gauge which has been recording depth of precipitation every 5 minutes for more than 8 years. In the outlet of the sewer network, one electronic pressure level sensor has been registering water depths every five minutes since April 2011. The average wastewater flow is derived based on: average water consumption (244 L/c.d), population density for the area where the study case is situated (90 hab/ha), area of each sub-catchment and the diurnal pattern.

This study area is predominately residential, however there are three different socio-economic residential properties. Residential area 1 corresponds to the highest socioeconomic class, residential 2 is the medium class, and residential 3 is the lowest class.

4. Results

Urban drainage model analysis 1D pipe flow model

Once 1D model was calibrated and validated, several scenarios were carried out for different rainfall return period of 2, 10, 25, 50, and 100 years. These simulations were undertaken in order to identify critical points of flooding in nodes and to select the conduits to be replaced.

For the simulation 1:100, it has been found that water overflows in 47 nodes (31%) of 155 for the entire network (Figure 2). For 1:50 the percentage of overflows is 19%, meanwhile for the simulation 1:25 the flooded points represents 17%, whereas for 1:10 is 14% and finally for 1:2 is 6%. The results of flooding for the simulation (1:2) are insignificant compared with the others then it was not considered in the optimization analysis.

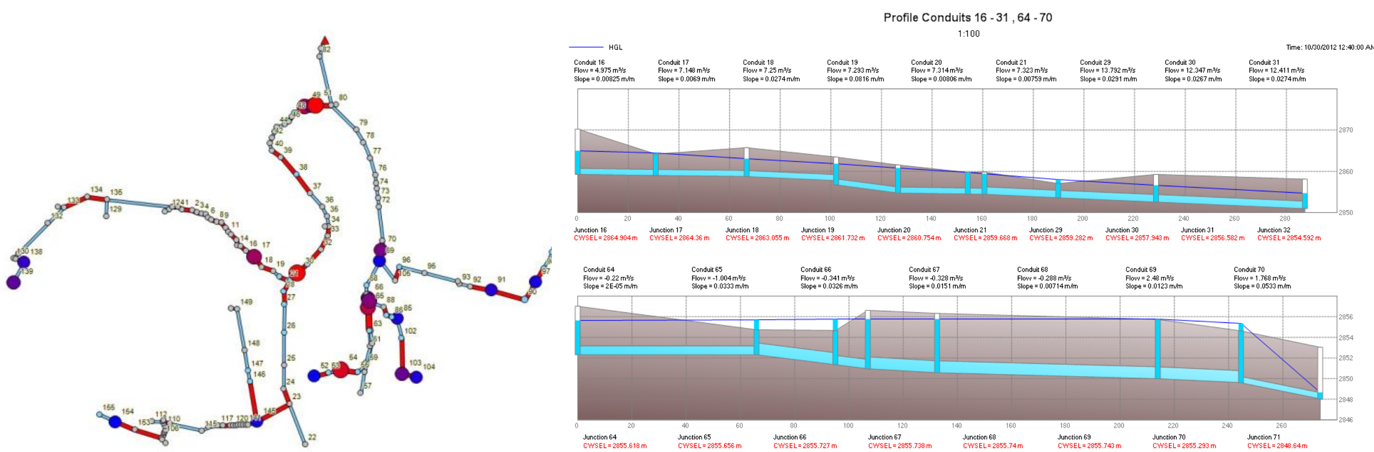


Figure 2. Surcharged map layout; Profile conduits 16 - 31, 64 – 70. 1:100 years

Coupling 1D - 2D model

The outputs of this coupled 1D-2D model are flood water depths and velocities for several scenarios (1:100; 1:50; 1:25; and 1:10), as they are showed in the next figures. These results were employed to assess the flood risk.

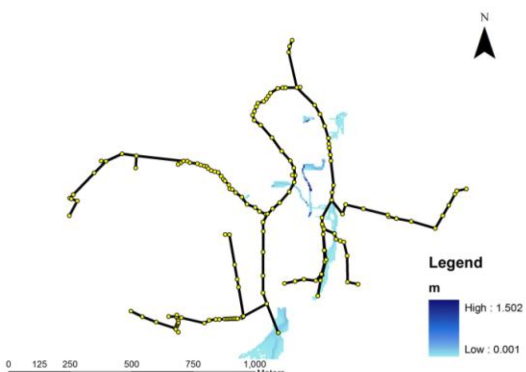


Figure 3. Flood water depth 1:100 years

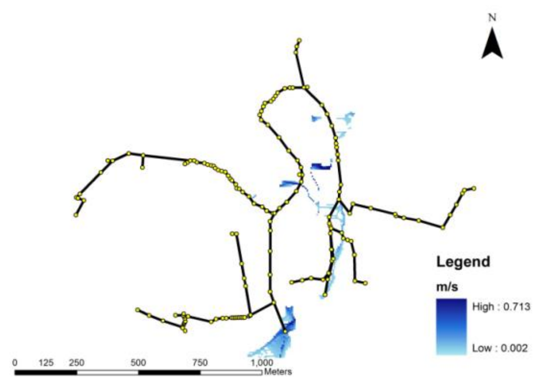


Figure 4. Flood velocity 1:100 years

Flood Risk Assessment

The purpose to compute flood risk cost (FRC) is because this value is the second objective function to be evaluated in Multi-Objective-Rehabilitation (MOR) process, that measures the level of service of urban drainage systems. As it was explained in the methodology, FRC is obtained as a function of hazard categories, where the cost per each category is a percentage of the property value per square meter and also taking into the vulnerability condition of each property (high, medium, low vulnerability), thus three FRC curves were developed.

The maximum flood risk cost values computed for all scenarios of flood events are illustrated in (Table 1), it is worth to mention that these costs were derived based on direct damages, which represent the damage cost of the physical contact between properties and flood water. However indirect damages such as: disruptions in traffic, business, public services and other social and economical activities were not considered due to lack of information of these kind of damages in the city and even in the country, which mainly are obtained from field surveys.

Table 1. Maximum FRC for all flood events

Flood event	Maximum FRC (US$)
1:100	1 703 931
1:50	1 326 255
1:25	869 165
1:10	600 913

Multi-Objective-Rehabilitation (MOR) Analysis

After the initial values were computed, the loop of MOR's genetic algorithm was simulated. The non dominated search genetic algorithm NSGA II was used as an optimizer algorithm, owing this tool has been successfully tested in previous researches of multi objective optimization in urban drainage at the UNESCO-IHE by (Barreto, et al., 2006)[2], (Sanchez, 2007)[7], (Matungulu, 2010) [5], (Anvarifar, 2011)[1], among others.

The number of variables (V) to be evaluated varies from 55 to 31 conduits, according to the flood return period. The number of diameters (d) available in the catalogue is 23, then a possible average of combinations of 4323 (Vd) gives 3.71 E+37 alternatives.

Furthermore keeping in mind that the computational time required for a single run of 1D-2D model takes around 45 minutes, consequently to have several evaluations in MOR depending on the number of population and generations, simulations is a complex task, that cannot afford by hand or traditional approaches.

To handle this situation, the algorithm NSGAXp developed by (Barreto, 2012) [3] was used. This is the parallel computing approach, where the whole process is divided into smaller tasks and distributed to several computers or processors. For this research five computers were used with the following characteristics Intel Core i5, 4GB RAM, 2.3 GHz. Several combinations of populations and generations were tested in the system in order to verify the results and to analyze the demanding time for every simulation. For instance for 60-10 (population-generation number) takes 25 hours to complete one simulation using parallel computing, however for the same number of evaluations using only one computer it could takes around 9 days. Subsequently it was adopted to run the simulation for 80-20 (population-generation), hence 1600 functions per scenario were evaluated which took three and a half days to complete the simulation for each return period using parallel computing technique. The total computing time to simulate all scenarios was approximately 15 days.

The most optimal solutions found in MOR process are displayed in the Pareto sets per each event, the next figures 5 and 6 show the results of two events, for 1:100 and 1:25 years respectively.

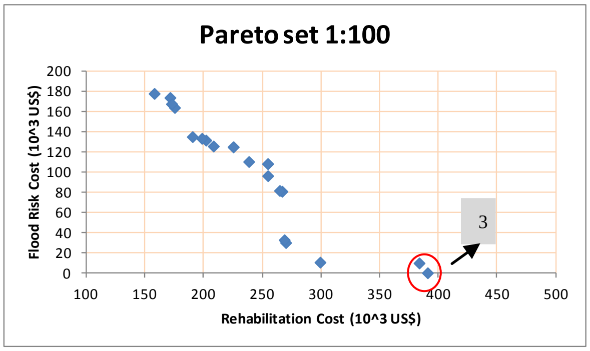


Figure 5.Pareto set for 1:100 years

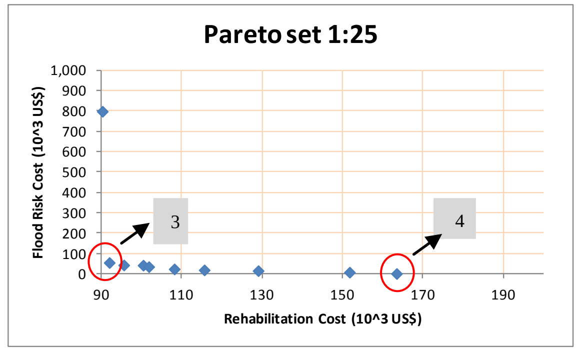


Figure 6. Pareto set for 1:25 years

For the scenario of 1:25 years, four of ten solutions are analyzed. Solution 1 is the option for the maximum FRC (869E+3 US$) without doing any interventions in the sewer system, whereas solution 4 corresponds to the maximum rehabilitation cost (163E+3 US$) to avoid completely flooding. If the investment in rehabilitation is 55% of its maximum, the FRC reduces 8% (2), however if the investment rises only 1% the FRC decline dramatically from 92 to 6% (3) of their maximum value. This is due to the optimization process found some "key combinations" of diameters in several conduits to produce this considerable drop in the FRC.

Flood risk is a combination of the probability of a hazard event and the potential negative impact for human health, social, economical and environmental aspects. Thus considering flood risk analysis only for one return period event is not realistic. During the service life of the infrastructure of the sewer system, several return periods events can take place leading different FRC for the same solution. Consequently in order to face this issue, the approach of "Expected Annual Flood Risk Cost (EAFRC)" was implemented. Some researchers have already used this concept such as: (Zhou, et al., 2012)[9], (Barreto, 2012) [3], (Delelegn, et al., 2011) [4], (National Research Council, 2000) [6].

EAFRC is the probabilistic expected annual flood risk cost for a number of flood probable events, and it can be derived by using the next equations:

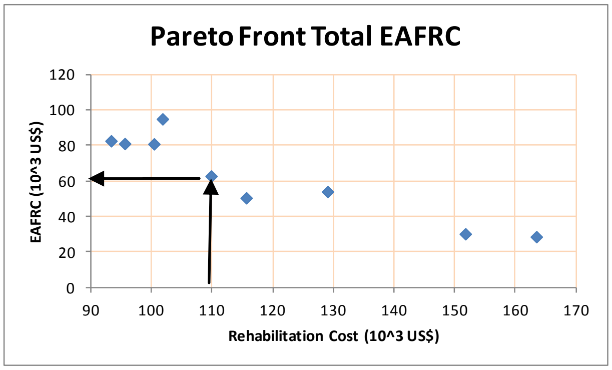
$$EAFRC = \sum_{i=1}^{Tr} \left[\left(\frac{FRC_i + FRC_{i+1}}{2} \right) * (P_i - P_{i+1}) \right] * f \qquad (1)$$

$$f = \left[\frac{(1+r)^N - 1}{r * (1+r)^N} \right] \qquad (2)$$

EAFRC: Expected annual Flood Risk Cost
FRC: Flood Risk Cost
Tr: Return period event

f: present worth factor
P: Probability (1/Tr)
r: interest rate (6%)
N: service life of the assets (50 years)

The result of this computation of EAFRC was one Pareto set that represent the integration of flood risk costs in a year for all of the selected return periods events. If the analysis of MOR is undertaken only considering one return period, inappropriate mitigation measures can be adopted. The Figure 7 (Pareto set Total EAFRC) was compared with one of the Pareto sets generated in the MOR in the previous step for the different events. For instance the Pareto set of 1:25 showed in Figure 11 was transformed into present annual costs by multiplying the FRC by both, its probability (1/25) and the present worth factor (f), and then this Pareto set can be compared with the Total EAFRC.



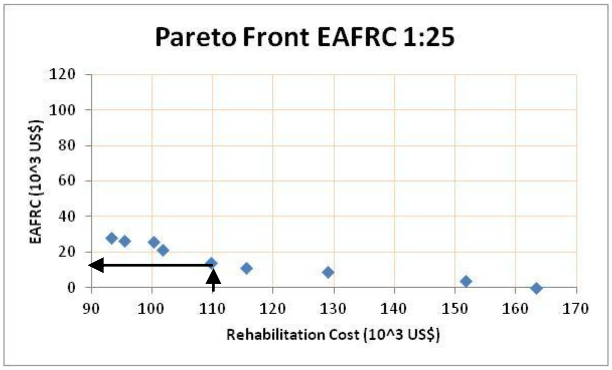


Figure 7. Pareto sets for Total EAFRC and 1:25 year

It can be seen from chart b), for the solution with 110E+3 US$ of rehabilitation cost has a EAFRC around 18E+3 US$, however this is not true according to the graph a) where it illustrates that for the same investment cost, the EAFRC is 60E+3 US$ taking into account more flood events. Thus analyzing only one event can be misinterpreted the cost of benefits if events with bigger return period take place.

Finally considering the concept of cost-benefit analysis which is a practical tool for analyzing economic alternatives, where the total cost is the summation of cost plus benefits. Cost stands for the rehabilitation costs (RC) and benefits is the expected annual flood risk costs (EAFRC). Consequently with all of these solutions of EAFRC showed in Figure 7, the total cost is illustrated in Table 2, where the minimum value of the addition of both costs is the solution No. 8.

Table 2. Maximum FRC for all flood events

Solution No.	RC (10^3 US$)	EAFRC (10^3 US$)	Total cost (10^3 US$)
1	90	1101	1191
2	90	1088	1178
3	93	83	176
4	96	81	177
5	100	81	181
6	102	95	197
7	110	63	173
8	116	51	166
9	129	54	183
10	152	30	182
11	163	29	192

5. Conclusions

1D model was undertaken for several rainfall return periods, these outputs allow to identify critical sewer conduits and critical nodes where flooding occurs under each scenario.

The methodology to assess flood risk, is based on the intersection of two components flood hazard and their consequences. The cost of each hazard category is a percentage of the property value per square meter, then three flood risk curves were generated for three vulnerability conditions. The maximum FRC do not reflect the real values of damages due to the assessment of flood risk did not consider indirect damages such as: disruptions and delays in transportation, besides and the most critical is the health risk that this polluted sewage can affect the population.

From the results obtained in MOR, it is noticeable the advantages of using this tool (MOR), especially to assist decision making in urban flood management.

The approach of expected annual flood risk cost (EAFRC) was adopted in order to take into account the probable expected flood cost for a range of events. Considering the concept of cost-benefit analysis, where the total cost represents the summation of rehabilitation cost and flood risk cost (benefit), it was found the most economical solution.

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