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FLOOD RESILIENCE ASSESSMENT IN URBAN DRAINAGE SYSTEMS THROUGH MULTI-OBJECTIVE OPTIMISATION

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In future years, economic development, urbanisation and heavy rainfall events are expected to increase in urban areas, in particular in developing countries. It is well known that urban development has a strong impact on the water cycle such as increase of flood peaks and volume, decrease of base flow, hydraulic stress and water pollution. Resilience measures are still needed to improve urban flood risk, the possibilities to provide indicators that could be used to characterize urban resilience related to flooding is outmost importance. The work described here presents an optimisation framework for urban drainage rehabilitation that incorporates in the decision space the concept of resilience in order to find an optimal rehabilitation strategy. The approach has been tested in the City of Dhaka, Bangladesh by coupling 1D/2D model of the drainage system and linked within the optimisation algorithm. The preliminary results obtained suggest that the proposed approach could be effective in order to reach acceptable level of flood resilience of urban drainage systems, balancing investment and risk within the systems. Further work is recommended to expand and generalize the methodology.

INTRODUCTION

Despite different definitions of resilience, a consistent theme is that flood resilient cities are impacted less by extreme flood events (Hammond [7]). Resilience enhances the ability to cope with flooding and to recover from flooding. With resilient systems, communities or societies exposed to hazards have the ability to resist, absorb, accommodate to, and recover from their effects efficiently by preserving and restoring essential basic structures (Jha et al. [8]). They can be established in different scales: at property level, neighbourhood level or city level. Enhancing resilience depends on having enough flexibility to continue providing for essential needs given future risks and uncertainty. Resilience is also related to strong intent to increase capacity building of human resources, better land use management, increased flood preparedness and emergency measures that are taken during mostly and after flood events (Batica and Gourbesville [4]).

Flooding in urbanized areas has become a very important issue as the level of service or performance of urban drainage systems degrades in time. To maintain an acceptable performance, successfully investigations have been carried out to aim at defining a framework to deal with multicriteria decision making in the context of urban drainage systems by: (i) Adopting appropriate tools and facilities to simplify the optimal rehabilitation of an urban drainage system (Martin et al. [9]; Barreto et al. [2]). (ii) Identifying the best performance with a minimum cost using multi objective optimization approach (Schütze et al. [13]; Vélez [15]). (iii) Dealing with the trade-off between flood risk and investment cost for a set of optimal rehabilitation measures provided by multi-objective optimisation tool (Paredes [11]; Anvarifar [1]; Vojinovic et al. [16]) and (iv) Evaluating the effectiveness of the 1D, 1D-1D and 1D-2D approaches for modelling urban floods in the context of optimization of rehabilitation measures intervention costs and flood damages (Matungulu [10]).

This paper present the results of an optimization framework for urban drainage rehabilitation that incorporates in the decision space the concept of resilience to find optimal rehabilitation by minimizing costs and the negative impacts of floods. By determining appropriate framework to evaluate the performance of sewer systems to minimize flooding in urban area in a most cost effective way it will solve more community's problems and avoid huge amount of maintenance and damage cost in different flood scenarios.

METHODS

Urban drainage modelling

The present work explores the use of resilience in terms of drainage infrastructure taking into account multi-objective evolutionary approaches applied in previous researches (Savic [12]; Barreto [3]; Delelegn et al. [6]). To this purpose, two distinct models were combined for simulating the flow dynamics in sewer networks and on overland surface. Flows in drainage pipes and over the ground surface were routed by the 1D sewer network model EPA SWMM simulating hydrological and hydraulics processes in the system. Water level discharges were computed with a non-inertia 2D overland flow model that represents the ground elevations at the centres and boundaries of cells (urban topography). Both models use different numerical schemes and time steps with the discharge through manholes adopted as model linkages. The drainage runoff and surcharge effluents were calculated by SWMM for every time step and treated as point sinks and sources, similarly, in the 2D model within the same time interval. Discharge is determined by weir or orifice equations by taking into account the hydraulic heads at manholes and ground surface. The models are executed individually and linked by exchanging information obtained at proper locations and times for appropriate linkages. The resolution of the 2D model is 10 meters, more details of the 1D/2D model used in this work can be found in (Seyoum et al. [14]).

The NSGA-II algorithm developed by Deb [5] was used with the goal of finding a representative set of Pareto optimal solutions and quantify the trade-offs in satisfying the different objectives. Two routines were used to connect the urban drainage model built in SWMM that computes the magnitude of flooding, the surcharged pipes and the initial values of different variables. Maximum values of the objective functions were linked to the NSGA II to randomly generate GA population for the variables and compute the values of the objective functions. The steps used in the optimisation framework were: (1) Initial simulation of the hydraulic model 1D/2D SWMM model. (2) Objective functions computation (3) Optimiser NSGA run according to the number of generations and populations (4) Update pipe diameters if number of generations and populations have not reached yet and (5) new drainage network simulation. Figure 1 depicts the schematization of the optimisation loop used.

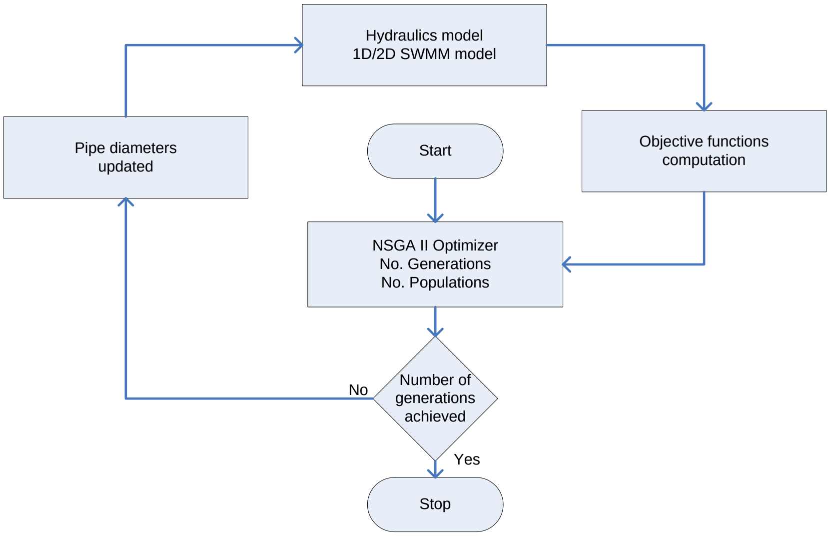


Figure 1 Schematization of the optimisation loop

Flood resilience analysis

The flooding damage assessment has a diverse combination of water depth and land uses categorized as residential, commercial, governmental, educational and religious institutes, business, non-governmental utilities and industrial. For this purpose, 9 land use and five water depth ranges based on the work of Matungulu [10] were used to compute damage cost in each grid cell of the 2D model based on the land use type and the maximum flood depth. The objective function damage cost for 1D-2D is given by.

$$DamageCost[i,j] = (\propto + \beta) * MaxWdpth[i,j] \quad (1)$$

Where (α) is a slope of the curve based on the value of the land use, the higher the land use the higher the value. (β) Is an intercept based on land use and the water depth, if the water depth is zero, this value is zero. MaxWdpth [i,j] is the maximum water depth of the flood at the cells [i,j].

The actual cost of the pipe network is computed taking into account the unit length associated with the diameter and the length of the pipe as follows.

$$C_T = L_i * \sum_{i=1}^{n} C(D_i) \quad (2)$$

Where (n) is the number of pipes in the network. C (D_i) is the cost per unit length of the pipe (i) with diameter D_i and length L_i. The total cost is a combination of actual cost and operational cost when the whole design cost need to be considered.

As a resilience indicator, Expected Annual Damage Cost (EADC) approach was added to the algorithm for the multi-objective optimisation in order to compute the expected damages. This method is based on computing the expected annual damage through the integration of a risk function (Barreto [3]). To assess the resilience of the drainage infrastructure, three future scenarios with return periods of 2, 10 and 20 years to represent future system states were evaluated. This with the aim of having a Pareto set that represent the expect cost in a year for all of the selected return periods events.

$$\text{EADC} = \sum_{i=1}^{Tr-1} [(\frac{\text{Cost(i)+Cost(i+1)}}{2}) * (Pi - P(i+1))] * f \qquad (3)$$

Where (Tr) is the return period event (P) is the exceedance probability 1/Tr and (f) is given by:

$$\text{f} = \frac{(1+r)^N - 1}{\text{r}*(1+r)^N} \qquad (4)$$

Where (f) is the present worth factor (r) interest rate (6%) and (N) is the service life of the assets, for the present case it is 50 years.

From de EADC Pareto set a optimum return period was obtained to analyze the resilience of the drainage infrastructure (system capacity) and to be compared with the future scenarios previously evaluated.

Case study area

The study area corresponds to Dhaka city the capital of Bangladesh located on the east banks of the Buriganga River in the heart of the Bengal delta (Figure 2). The city is placed in a few meters above sea levels, a very little rain causes severe problems for certain city areas, which are inundated for several days. According to WWT report [17] among 11 key Asian mega-cities, Dhaka is the most vulnerable to climate change impacts. Its settlements have been exposed to high risk and it needs to be properly managed. Figure 3 presents the 1D model of the urban drainage network which covers an area of approximately 140 km^2 and it consists of 74 sub catchments and 88 links (75 circular pipes and 13 box culverts).

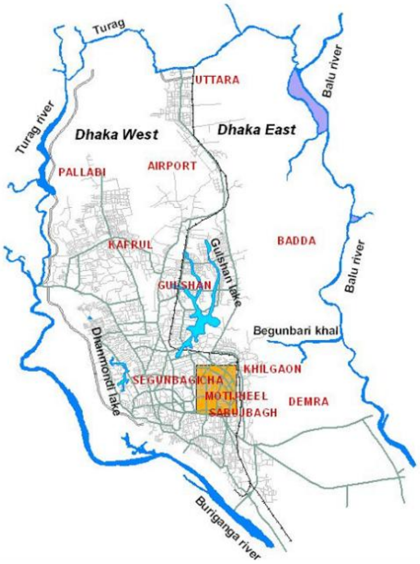


Figure 2 Study area location

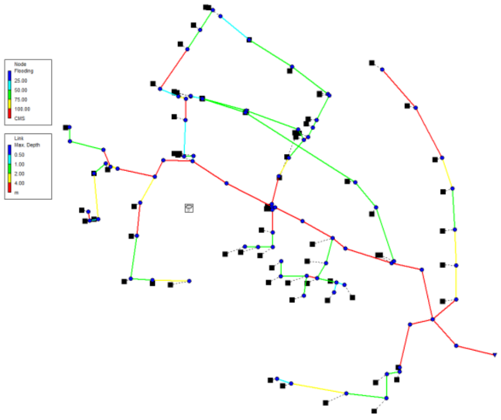
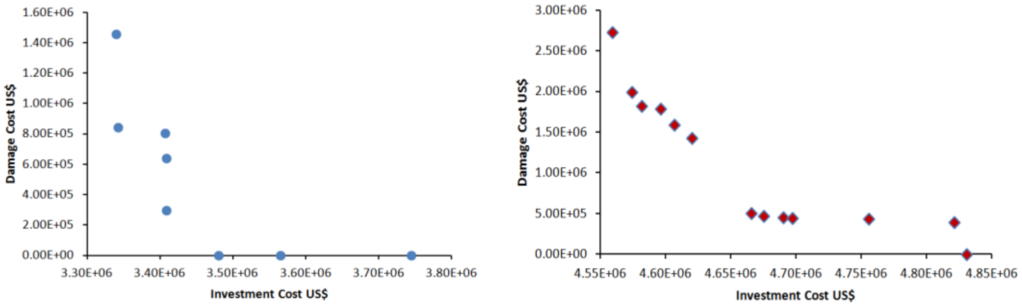


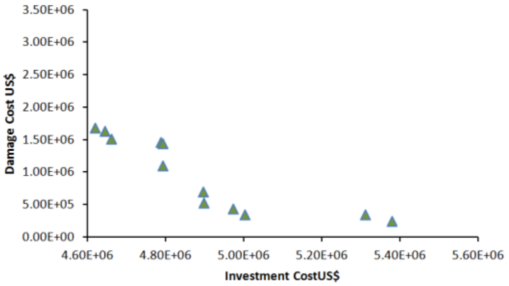
Figure 3 Urban drainage network

RESULTS

Different model runs were carried out with different configurations in the NSGA-II algorithm *(60 populations, 10 generations)* using parallel computing. Figure 4 shows the results of the optimisation process. Optimal solutions process for 1:2, 1:10 and 1:20 return period are displayed.



(a) 1:2 (b) 1:10



(c) 1:20

Figure 4 Optimal Pareto set for (a) 2, (b) 10 and (c) 20 years return period

The solutions obtained in Figure 4 shows that high damage cost corresponds to $1.46 million, $2.72 million and $1.67 million for 1:2, 1:10 and 1:20 return period respectively with a minimum intervention cost of $3.34 million, $4.06 million and $4.62 million accordingly. On the other hand, an investment rises in 12% for 2 years return period and 6% for 10 years return period would be needed in order to avoid completely flooding. 20 years Pareto set shows that by increasing investment cost in $0.76 million a damage cost reduction of 14% could be reached.

Figure 5 presents the Pareto set with the damage that could be expected in a year (EADC). It represents the integration of a risk costs in a year of all of the selected return period events according to equation 3.

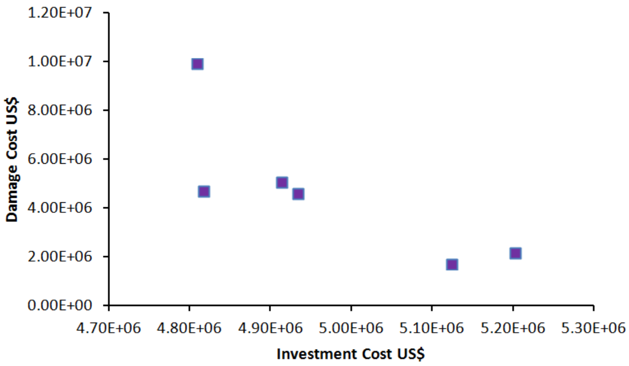


Figure 5 Best Pareto set for total EADC

Table 1 presents a Cost-benefit analysis where the total cost is given as the summation of cost *(Investment costs)* plus benefits *(EADC)*.The minimum value of the addition of both costs is the solution No. 3 with a minimum investment cost of $5.12 million. This value corresponds to those investment costs obtained for 10 and 20 years return period (Figure 4), therefore between these two return period events it is possible to obtain the minimum damage cost and hence a more resilient system. Figure 6 depicts the variations of solutions of the Pareto optimal fronts for 10 years (s10) and 20 years return period (s20). Moreover, Figure 6 depicts the 10 years solution (Figure 4b) with a 20 years rainfall named as (s10_20yTr) and 20 years solution (Figure 4c) with a 10 years rainfall named as (s20_10yTr).

From Figure 6 it can be observed the resilience of the system in terms of drainage infrastructure. Solutions s10 and s20 are very close with an investment cost of around $4.60 million. However, s20 optimal Pareto should be selected due to the similarities obtained also using s20_10yTr solution. With $4.80 million investment, s10 optimal Pareto is better as zero flooding is obtained or similar damage cost ($ 1.50 million) using s10_20yTr solution. Finally, with $5 million investment s20 optimal Pareto is a better solution giving a minimum damage cost.

Table 1 Total cost

Solution	Investment Cost ($)	EADC ($)	Total Cost ($)
1	4.82E+06	4.70E+06	9.52E+06
2	4.91E+06	5.05E+06	9.97E+06
3	**5.12E+06**	**1.69E+06**	**6.82E+06**
4	5.20E+06	2.15E+06	7.35E+06
5	4.81E+06	9.91E+06	1.47E+07
6	4.93E+06	4.59E+06	9.52E+06

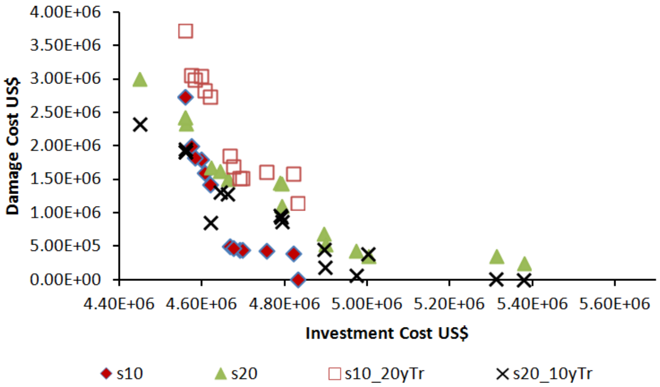


Figure 6 Pareto optimal fronts: Resilience of the system for 10 and 20 years period.

CONCLUSIONS

The main objective of the research presented here was to present an optimization framework for urban drainage rehabilitation that incorporates in the decision space the concept of resilience to find optimal rehabilitation by minimizing costs and the negative impacts of floods. The use of multiobjective optimisation has shown the capacity to assess resilient drainage systems. Although, the optimisation developed here did not contemplate other aspects such as social and environmental, it would appear that is able to assess resilient systems taking into account the performance itself. To be able to include these aspects, further analysis to expand this approach to analyze structural and non structural adaptation strategies in the optimisation process is needed to increase the level of service of the drainage systems.

In this research the use of different return periods was an important step in order to get the accumulation of damages during a time frame. However, only three return periods are not enough to address computing the expected annual damage through the integration of a risk function. This selection can be improved through having more return periods or running continuous simulations. Apart from analyzing rehabilitation in pipes as an intervention measure, more options can be added such as Sustainable Urban Drainage Systems.

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