

Multi-objective Evaluation of Urban Drainage Networks Using a 1D/2D Flood Inundation Model

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Abstract The present paper describes a framework for the evaluation of a drainage system's capacity in order to get a better understanding of the interactions between three rehabilitation measures: the Upgrading of Pipes (UP), Distributed Storage (DS) and the combination of both (UP+DS). It is posed as a multi-objective optimisation problem with the aim of minimising rehabilitation costs and flood damage. The approach of Expected Annual Damage Cost (EADC) was also introduced as the probabilistic cost caused by floods for a number of probable flood events (i.e. the accumulation of damage during a timeframe). The study combines computational tools such as a 1D/2D flood inundation model and an optimisation engine in the loop to compute potential damages for different rainfall events and to optimise combinations of rehabilitation measures. The advantages of this approach are demonstrated on a real-life case study in Dhaka City, Bangladesh. The optimal solutions confirm the usefulness and effectiveness of the proposed approach where both rehabilitation and damage costs are reduced by the optimal implementation of the UP and DS measures. In addition, the results of the proposed EADC approach indicate a damage cost reduction of at least 56% by implementing UP and of 27% by implementing DS, and both measures have lower rehabilitation costs. The proposed approach can be found appealing to water/wastewater utilities who are often challenged to achieve optimal design and rehabilitation of urban drainage systems.

Keywords Multi-objective optimisation · Rehabilitation measures · System capacity · Urban drainage

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1 Introduction

Dealing with floods in urban areas has become an important and growing issue for urban flood managers. In many cities around the world, Urban Drainage Systems (UDS) are reaching the end of their expected useful lives and timely rehabilitation of such systems is imperative for proactive asset management. Experience has shown that the main constraint of conventional drainage systems is related to their maintenance and operational activities, along with the financial, social and adaptive limitations of the local context (Dominguez et al. 2011; Schellekens and Ballard 2015). The recent progress in sustainable drainage development across different disciplinary fields suggests a new goal related to the ‘sustainability’ of urban drainage systems which takes into account the urban drainage management as a component of the urban water cycle (Krebs and Larsen 1997; Zhou et al. 2013).

Investigations attempting to enhance the performance of urban water systems have seen significant improvements (e.g. Ten Veldhuis and Clemens 2011; Yazdani et al. 2011; Mugume et al. 2015; Marques et al. 2015; Diao et al. 2016). The results of these studies have brought about tools and techniques that can enable the development and implementation of more effective and resilient solutions. The use of numerical models and optimisation techniques have also proved to be invaluable for dealing with various system rehabilitation issues.

With models and optimisation techniques, it is possible to explore the performance of drainage networks and evaluate the effectiveness of different intervention measures. However, there are several issues that need careful consideration in order to use numerical models more effectively for this task (e.g. Vojinovic et al. 2006; Vojinovic et al. 2006a; Abdullah et al. 2009; Vojinovic et al. 2014). Park et al. (2012) and Cunha et al. (2016) implement evolutionary algorithms for design of detention pond geometry. Artita et al. (2013) find the optimal location of best management practices for an integrated watershed-scale management problem. Sanchez et al. (2014) describe and demonstrate an integrated cellular automata evolutionary-based approach for evaluating future scenarios including the expansion of UDS. Yazdi et al. (2014) present a new risk-based optimization approach for determining rehabilitation plans in urban drainage systems by integrating the copula method, MCS, Multiobjective EAs, and hydrodynamic models.

Multi-objective optimisation of UDS including the 1D/2D modelling approach has also seen some significant advantages (e.g. Vojinovic et al. 2014; Martínez et al. 2014) and the results obtained demonstrate their potential for solving some of the greatest challenges that water/wastewater utilities face nowadays. Despite the remarkable progress achieved over the past two decades in the area of sustainable urban water management, there is still the remaining challenge of how to secure and manage infrastructure investments so that systems meet continuously increasing service standards and challenges posed by climate change. The present paper provides contribution in this direction by presenting a novel approach that combines 1D/2D models with an optimisation algorithm in order to search for optimal solutions for a drainage system that needs rehabilitation. The key advantage of this approach is that we are able to retain the necessary physics (and interactions) in computations between pipe network systems (i.e., below ground system) and urban surface (i.e., above ground system) while searching for an optimal set of rehabilitation measures. In terms of the disadvantages, one of the key disadvantages is that this approach requires rather extensive computational time which limits its application for real-time purposes.

This proposed approach has been implemented in the code of EMBARCADERO Delphi integrated environment. The potential of the proposed approach has been demonstrated on the

real-life case study of Dhaka City (Bangladesh) where different rehabilitation measures were evaluated in relation to investment and flood damage costs. The results obtained are promising and confirm that the proposed approach has a good potential to deal with one of the greatest challenges that water/wastewater utilities face nowadays.

2 Study Approach

2.1 Problem Formulation

In this study, the assessment of flood damage is done using a coupled 1D/2D model. In the present work, 1D EPA SWMM modelling system (Rossman 2010) was used to represent the pipe network system. The 2D model used is a non-inertia model presented in Seyoum et al. (2012). These two models have been coupled dynamically to exchange information in each time step. The output of the coupled model is a flood map depicting the water depth onto a 2D grid. This map represents spatial distribution of flood water depths within the model domain (i.e., an urban area containing buildings, residential areas, commercial areas, etc). This approach enables a more realistic computation of damages across the model domain. The estimation of flood damage is traditionally computed for different levels of risk or return periods. In the present work, the concept of Expected Annual Damage Cost (EADC) was also introduced as the probabilistic cost caused by floods for a number of probable flood events (i.e. the accumulation of damage during a timeframe). This can be considered as yet another novelty in the present work.

To explore different solutions for the rehabilitation of an UDS a trade-off between rehabilitation costs and direct flood damages was formulated as an optimisation problem. Three different rehabilitation measures were tested (pipe diameters, storage and their combination). Each of these measures were evaluated by running simulations for 2, 10, 20 and 50-year return period rainfall events. These measures are described in more detail in Section 2.6. After that, calculation of Expected Annual Damage Cost (EADC) was undertaken as an objective function instead of the individual flood damage calculation done for each return period. The Total Expected Cost (TEC) is then obtained by summing up of all costs (i.e., rehabilitation costs) and benefits (EADC).

2.2 Data Requirements

To set up a 1D model to simulate the minor system (pipes), the data such as network layout, conduits, manholes, outlet, subcatchments with their hydrological parameters and dry weather flow characteristics were utilised. Rainfall is applied to the model surface using hyetographs to describe different events based on intensity, duration and frequency. Sub-catchment parameters include outlets nodes, percentages of previous and impervious areas, terrain slope, depression storages and soil infiltration characteristics.

The data used to build the 2D model includes a digital elevation model (DEM), road network and buildings. To assess damages a method based on depth-damage curves was used and applied for different sectors (i.e., land uses). For the assessment of rehabilitation costs, two catalogues with infrastructure costs were applied. The first catalogue contains unit costs of pipes with the associated costs of excavation and reinstatement works. The second catalogue contains the storage area (m^2) costs.

2.3 Hydraulic Modelling

As mentioned earlier, for the hydrodynamic modelling purpose, the proposed approach combines the sewer network model (SWMM model) with the overland-flow model (2D non-inertia model). SWMM solves the conservation of mass and momentum equations (the Saint-Venant equations) that govern the unsteady flow of water through a drainage network of channels and pipes by converting the equations into an explicit set of finite-difference equations.

The overland-flow model (non-convective wave, or non-inertia, 2D overland flow model) is based on the alternating direction implicit scheme which solves the 2D non-inertia free-surface shallow-water equations (this model determines the interacting discharge from manholes by using weirs or orifice equations). When the capacity of the pipe network is exceeded, the excess flow spills into the two-dimensional model domain from the manholes. The 2D model uses the urban surface as the model domain. The bidirectional interacting discharge at a manhole is calculated according to the water level difference between the sewer network node and the aboveground surface. The models are linked by exchanging discharge information at the connecting nodes at each time step of the sewer network model. The output of the 1D/2D model is a matrix with values of flood depths across the surface which is in turn used to compute flood damage costs as part of the optimisation process.

2.4 Optimisation Framework

The NSGA-II algorithm, developed by Deb et al. (2002), was used within the proposed approach to search for a set of Pareto optimal solutions and for quantifying trade-offs between flood damage costs, rehabilitation cost and the EADC. The flowchart of the proposed approach is depicted in Fig. 1.

The optimisation steps include the following: (1) Initial simulation of the hydraulic 1D/2D coupling model, (2) Computation of the maximum value of damage costs for each return period and the initial EADC (3) Computation of the objective functions, (4) Running optimiser NSGA-II according to the number of populations and generations, (5) Updating pipe diameters or size of storage if the number of populations and generations have not been reached and (6) Updating of 1D/2D model input file.

With the purpose of executing the optimisation framework described above, two interfacing routines were developed and coded using the EMBARCADERO environment (former Borland Delphi). A first routine was coded to run the 1D SWMM model to compute the initial value of the variables, objective functions and maximum value of the original costs. A second routine was also coded to run the coupled 1D/2D model, select from the range of decision variables, change the pipe diameters of the selected elements to be rehabilitated, resize the selected storage, and compute the objective functions.

Initially, it was found that the 1D/2D model simulations are rather computationally expensive. For example, a single run of the 1D/2D model can take up to 1 h and the estimated time for one run of the optimisation framework to assess 2000 evaluations took 7 days. Therefore, it was decided to use the NSGA-XP, which is a version of the NSGA-II that can run in parallel using a cluster of computers. Based on the work of Barreto (2012), two clusters of four laptops were set-up and run using the master-slave approach and executed into a Parallel Virtual Machine environment. The laptops had the following architecture: Intel (R) Core (TM)

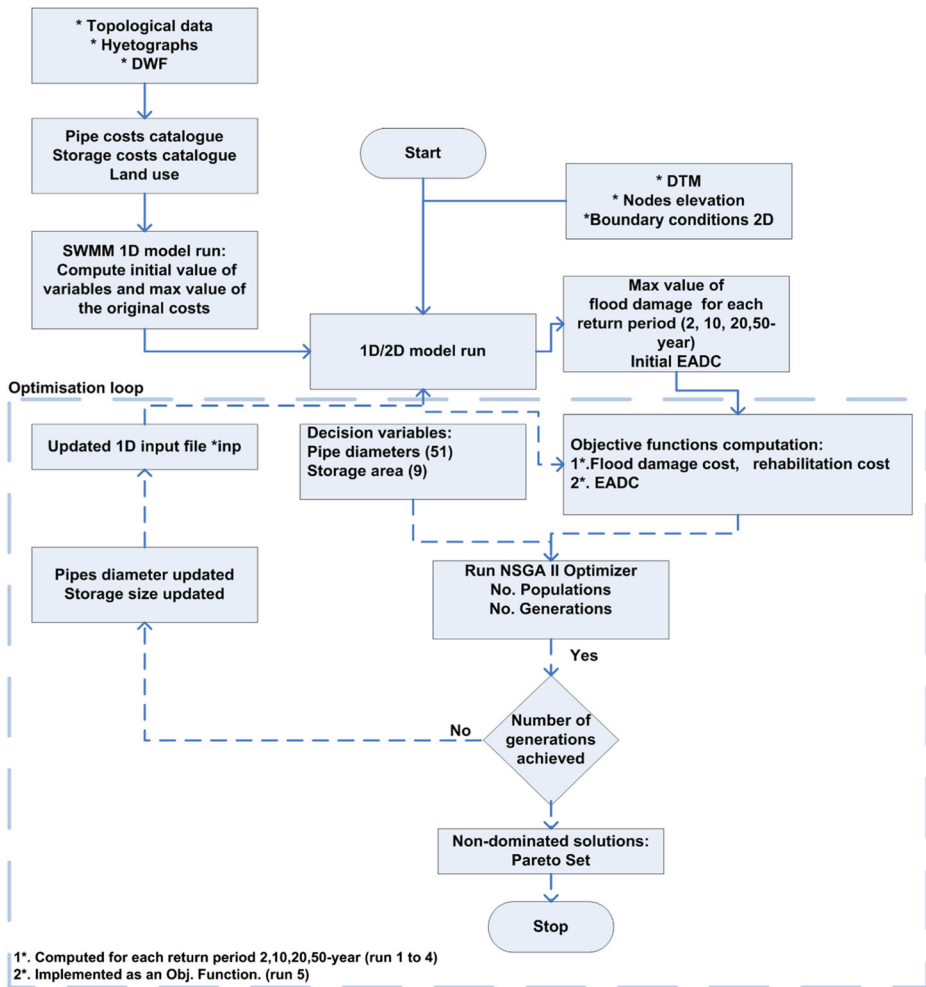


Fig. 1 Flowchart of the applied framework

i5-2410 M CPU@ 2.30 GHz, 4.0 GB RAM, 64 bits O.S and Windows 7 platform. The total computational time for one optimisation run was reduced from 7 days to 3.5 days for a single rainfall event.

The optimisation parameters of the NSGA-II algorithm for each rehabilitation measure and for the EADC were set to a population size of 100 and 20 generations for a total number of function evaluations of 2000. The probability of crossover was set to 0.90, the probability of mutation to 0.09, the distribution index for crossover to 15 and the distribution index for mutation to 20. The decision variables consisted of 51 pipe diameters ranging from 0.3 m to 2.0 m diameters based on a catalogue of commercially available sizes. For storage options, 9 possible sites were identified and the decision variable was set to be the surface area at these sites. The surface area at these sites ranges from 0 (No storage) to 1200 m². The depth was kept constant at 5 m. The objective functions used in the experiments were rehabilitation cost, flood damage and EADC.

2.4.1 Rehabilitation Cost Functions

The objective function for pipe rehabilitation is a function of pipe lengths (Barreto 2012). Equation 1 presents the rehabilitation cost function for upgrading of pipes (UP).

$$RCost = \sum_{i=1}^n (C(P)_i) * L_i \quad (1)$$

Where $RCost$ is the pipe rehabilitation cost (US dollars), i is the index of pipes i^{th} , n is the number of pipes to be upgraded, $C(P)_i$ is the cost of the pipe i^{th} (US dollars/m) based on the catalogue of commercially available sizes and L_i is the length of the pipe i^{th} (m). For storage tanks, the costs are also based on the cost/area of possible storage in the defined catalogue.

2.4.2 Flood Damage Cost Function

The estimation of the flood damage costs was done based on the maximum flood depth at the overland surface. To assess damages, depth-damage curves need to be developed taking into account different water depth ranges, land uses categories (e.g. residential, commercial, governmental, educational sectors) and a relationship by fitting a linear equation. Damage costs in each grid cell of the 2D model was computed using the Eq. 2 given by:

$$DamageCost[i, j] = (\alpha + \beta) * MaxWdpth[i, j] \quad (2)$$

Where α is the slope and β is the intercept of each linear regression and $MaxWdpth [i, j]$ is the maximum water depth of the flood at the cells $[i, j]$.

2.4.3 EADC Function

EADC is the probabilistic cost caused by floods for a number of rainfall events. In this study, it was computed as the integration of damage costs for four different rainfall events of different magnitude (Olsen et al. 2015). In the present work, four rainfall events with return periods of 2, 10, 20 and 50 years were used to assess the performance of drainage infrastructure. The EADC represents the expected cost in any year during the time interval of the analysis. See for example the work of Barreto (2012). The EADC can be derived by using Eq. 3.

$$EADC = \sum_{i=1}^{Tr-1} \left[\left(\frac{Cost(i) + Cost(i+1)}{2} \right) * (P_i - P(i+1)) \right] * f \quad (3)$$

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

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

Where f is the present worth factor, r is the interest rate and N is the service life of the assets (Olsen et al. 2015).

2.5 Case Study

To demonstrate the potential of the proposed approach an area known as Segunbagicha located in Dhaka (Bangladesh) has been used as a case study site. This area has been

experiencing frequent flood-related problems for many years. The system has a drainage area of 8.3 km² and it includes the most important business and government office areas of Dhaka City. It encompasses 74 subcatchments, 88 conduits with a total length of 13,635 m, which is a combination of 75 circular pipes with a total length of 11,308 m, and 13 box culverts with a total length of 2327 m. The circular sewer pipe diameters range from 450 to 5500 mm and the box culvert sizes are between 2.5 by 2 m and 5.5 by 4.3 m. The system also includes 88 nodes (junctions), two pump stations and 1 outfall. The degree of impervious area was estimated for each subcatchment and the time of concentration in the outfall section was calculated to be in the order of 20 min. Figure 2 depicts the layout of the local drainage system.

The rainfall-runoff from sub-catchments is drained by pipe network system towards two basins from which sewage is pumped to the Tongi Khal river system. The Digital Elevation Model (DEM) has 10 m resolution and it was used to set up the 2D model domain. The sub-catchment parameters (i.e., width, slope and percentage of imperviousness) were adjusted taking into account the previously calibrated 1D model of the sewer network system described in Ahmed (2008).

2.6 Rehabilitation Measures

Three rehabilitation measures are used in the present work to test their effects on the system's capacity: (a) Upgrading of Pipes (UP): 19 diameters of 51 pipes were found to surcharge (i.e. when the ratio between the maximum flow in the conduit and the full conduit area was greater than 0.99) and these pipes were identified as variables for optimisation. (b) Distributed Storage (DS): Nine possible sites for storage tanks were selected based on the availability of space and the performance of the system. Their location is illustrated in Fig. 2. Storage tanks are defined through an elevation – storage curve with a maximum depth of 5 m. The depth is governed by a weir and a control rule. This is handled inside the code developed to interface with the optimisation algorithm. (c) Combination of both measures (UP+DS).

2.7 Maximum Rehabilitation Cost

The rehabilitation cost of the drainage system infrastructure was calculated from the financial and economic analysis of the stormwater drainage master plan for Dhaka City (DWASA 2015). This was done by using the commercial value of pipe costs multiplied by the length of pipe required for rehabilitation purposes and the cost of the possible storage area.

Rehabilitation cost for commercial pipe diameters were used to calculate the overall cost consisting of the sum of direct and indirect costs. Direct Costs (DC) included pipe cost, installation of the pipe per unit length, excavation and filling, the dredging of canals or clearing of debris, and asphalt patches and pavement works. Indirect Costs included mobilization (5% of total DC), traffic control (2% of total DC), design and engineering (5% of total DC), materials management (5% of total DC) and administration (5% of total DC). For storage tanks, the maintenance costs during the whole life of the system and land cost have not been included.

The maximum value of the infrastructure for UP and DS measures was found to be in the order of \$44.6 and \$17.3 million respectively. These values were obtained by using the maximum value for each decision variable.

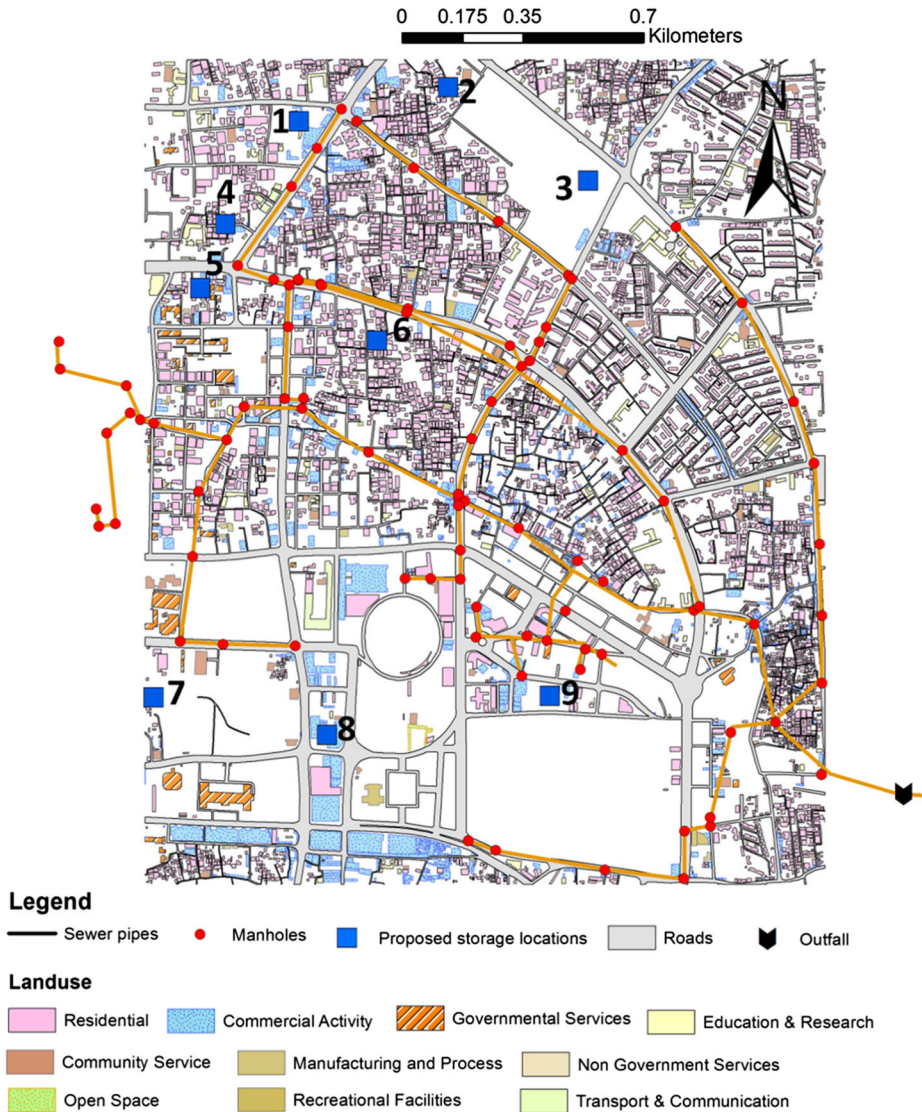


Fig. 2 Drainage network layout for the Segunbagicha Catchment, Dhaka

2.8 Estimated Initial Damage

The flood damage estimation is based on depth-damage curves that relate to an inundation depth (m) in a grid cell (obtained from the 1D/2D model result) and the land use class for each grid.

For this purpose, nine land use damage curves (expressed in US dollars) and five water depth ranges (0.3 m, 0.61 m, 0.91 m, 1.22 m, 1.52 m) were applied based on the average damage/loss dataset developed for Dhaka city by Islam (2005). Land use classes for residential, commercial, governmental, educational and religious institutes, business, non-governmental utilities and

industrial were used (Dutta et al. 2001). The damage costs in each grid cell of the 2D model were computed using the Eq. 2. The nine land use damage curves and five water depth ranges led to a 45 damage cost functions. It is important to note that the present work addressed only estimation of tangible direct damages. The damage cost computed without implementing rehabilitation measures for rainfall events of 2, 10, 20 and 50 years was found to be \$3.7, \$7.4, \$9.2 and \$11.8 million respectively and the EADC computed initially was found to be \$46.6 million.

3 Results and Discussion

3.1 Initial Performance of the UDS

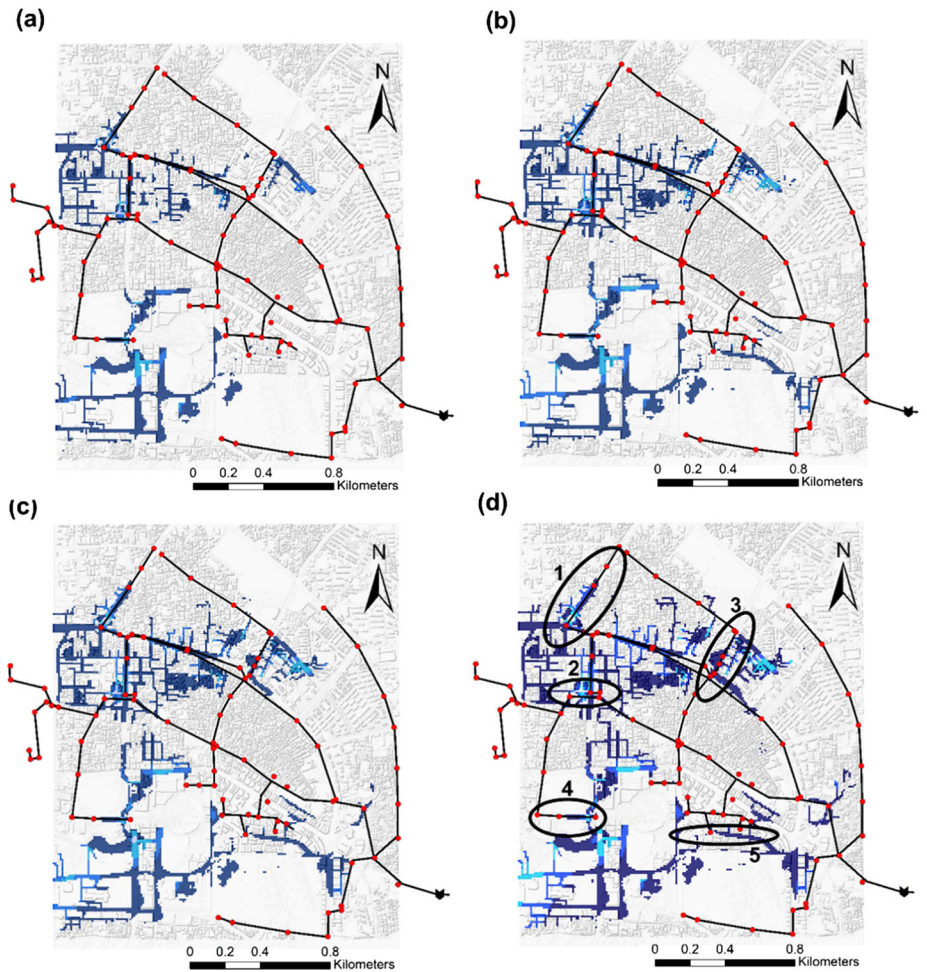
In order to assess the initial performance of the UDS, the 1D/2D model was run without implementing any of rehabilitation measures discussed earlier. Simulation results indicate that there is a substantial hydraulic overloading in the system that leads to flooding. Figure 3 depicts the inundation maps of the initial state system for four rainfall events used.

Five critical branches that cause most of the flooding are branches marked as 1, 2, 3, 4, and 5 in Fig. 3d. The total flood volume was found to be 6040 m³, 10,740 m³, 13,620 m³ and 18,650 m³ for 2, 10, 20 and 50-year rainfall events respectively.

3.2 Assessing Rehabilitation Measures

The first rehabilitation measure evaluated was the upgrading of pipes (UP). The 1D/2D model was run for each rainfall event and diameters of 51 pipes were modified during the optimisation process (51 variables). The non-dominated solutions obtained and its summary for UP measure are presented in Fig. 4.

The optimal solutions compared to the initial performance indicate a reduction to zero in flood damage cost for all rainfall events. The maximum damage cost is \$6.1 million obtained with solution 7. The 2-year Pareto set dominates the others as less impacts require less money to be invested. From the analysis of a 10-year event, when compared to the 2-year event, it was found that this event also results in less damage but requires more substantial investment. Also, for this event 77% damage reduction is obtained from solutions 3 to 4. Similarly, the 20-year event Pareto set suggests that with the same rehabilitation cost of \$4.5 million, it will be possible to achieve a decrease of 23% in damage from solutions 5 and 6. For a 50-year event there is a drastic drop from solutions 7 and 8 in terms of the damage by investing the amount of \$4.7 million for infrastructure works leading to 68% of damage reduction. Solutions 3, 4, 5 and 6 also indicate a reduction in flood damage cost from \$ 3.88 million to \$ 0.88 million for 10, 20 and 50-year events with \$ 4.50 million in rehabilitation cost. Solution 8 indicates that it would be necessary to invest \$4.7 million as this solution does not only minimises the expected damage costs but it also achieves a total protection of up to a 50-year event. The Pareto set for UP measure was capable of finding several solutions although there is no a wide range of values in rehabilitation costs due to the extensive computational time (i.e. the number of populations were set to a size of 100 and this value should be two or three times greater than the number of variables, 51 in this case). If the investment would exceed \$ 4.7 million the rehabilitation cost becomes less efficient as it does not have an effect in reduction of damage costs.



Legend

• Manholes — Sewer pipes ↘ Outfall

Flood depth (m)

0 - 0.02 0.03 - 0.1 0.11 - 0.2 0.21 - 0.35 0.36 - 0.6

Fig. 3 Inundation maps for **a** 2-years **b** 10-years **c** 20-years **d** 50-years - initial states of the UDS (DEM resolution 10 m)

The second rehabilitation measure evaluated was a DS measure. The 1D/2D model was also run for each rainfall event and 9 storage tanks were placed in the UDS based on the availability of space. The storage area of each tank was modified during the optimisation process (9 variables). The non-dominated solutions obtained and its summary for DS measure are presented in Fig. 5.

The optimal solutions are found to achieve damage reduction of zero with solutions 10 and 12 for 2 and 10-year events respectively. With the available location of storage tanks, flooding

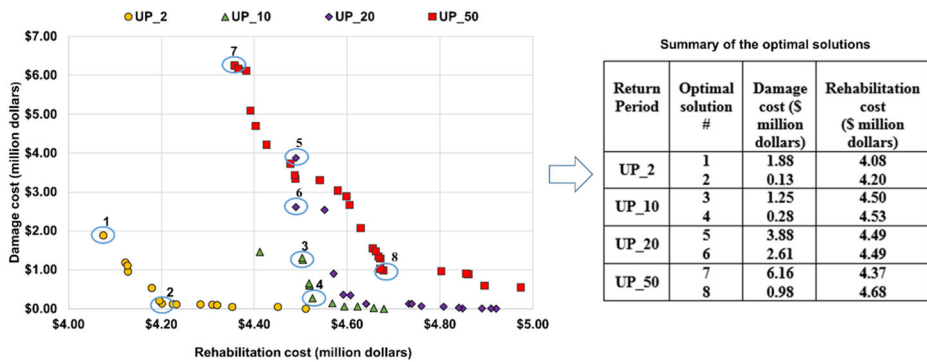


Fig. 4 The non-dominated solutions obtained for UP measure

was not reduced to zero for 20 and 50-year rainfall events. However, with DS measure it is possible to further reduce damage cost for all rainfall events (this would require an investment of \$2.8 million). The total flood damage cost has been reduced by 81% by employing the solution 14 and 72% by employing the solution 16 when compared to damage costs obtained with solutions 13 and 15 respectively. With a DS measure, there is a clear trade-off between rehabilitation and damage costs for all rainfall events, and the flood damage is found to decrease as the investment increases.

The analysis of optimal results also show that for smaller events (e.g. 2 years), optimal solution 10 suggests the implementation of three storage tanks, number 2, 4 and 5 (see Fig. 2). This would reduce flood damage by \$0.2 million with an investment of \$1.7 million (see the summary in Fig. 4). For larger events (e.g. 50 years), the optimal solution 16 indicates the implementation of seven storage tanks, number 1, 2, 4, 5, 6, 7 and 8 to decrease flood damage by \$3.4 million with an investment of \$6 million. With an investment of more than \$2, \$5.4, \$6 and \$8 million the rehabilitation cost becomes less efficient as it does not have an effect in damage cost reduction.

According to other researchers, it is important to consider the combination of different measures under the specific local design conditions (Duan et al. 2016). For the combination of UP+DS measures, the investment cost was computed including the construction cost of the storage plus a summation of each pipe length multiplied by the cost of that particular pipe based on its diameter. Within the optimisation process, 51 pipes and 9 storage tanks as

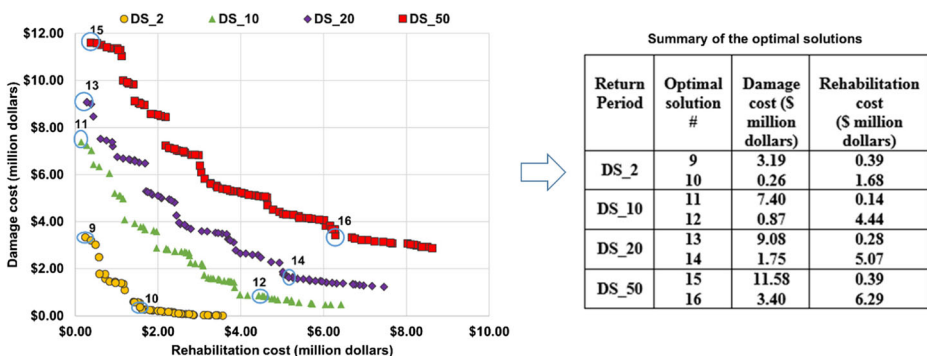


Fig. 5 The non-dominated solutions obtained for DS measure

variables were included. The results of the optimisation process when UP and DS were implemented altogether and the summary of optimal solutions are displayed in Fig. 6.

The results obtained show that solutions are able to reduce damage cost to zero for different levels of investment with less rehabilitation cost compared with UP and DS measures. It can be observed that for a total protection against flood damage an investment of around \$3.5 and \$4.0 million needs to be made. A maximum damage cost of \$5.2 million is achieved compared to those obtained with the UP (\$6.2 million) and DS (\$11.6 million) measures. There are two solution points for a 2 year event (17 and 18) showing a 37% drop for damage cost from one solution to another with the same rehabilitation cost of \$2.5 million. For 10 and 20-year events solutions 20 and 22 suggest an investment of \$2.9 and \$3.4 million in order to reduce damages to zero compared to solution 19 and 21 with \$2.7 and \$ 2.8 million invested to reduce damages to \$1.1 and \$0.8 million respectively. The results from a 50-year event show a drastic drop (solutions 23 and 24) in terms of the reduction in damage from \$5.2 to \$0.1 million and by investing \$3.9 million these levels of investments would be required to get protection for this return period event.

3.3 Expected Annual Damage Assessment

The optimisation using a single return period does not provide much information about damages for other return periods and the accumulation of damages during a time frame. In order to address this issue, the EADC was used to calculate the expected damages. Equations 3 and 4 were added to the algorithm for multi-objective optimisation. The interest rate (r) for this case was set to 6% according to the Bangladesh Bank and the service life of the assets (N) was assumed to be 50 years. The calculation of the EADC requires 1D/2D model simulations for 2, 10, 20 and 50-year rainfall events simultaneously (i.e. four simultaneous runs). Figure 7 depicts Pareto sets of EADC for the UP and DS measures. It also shows the Total Expected Cost - TEC (damages + investment) for the measures.

The EADC for UP measure was computed with 51 variables (pipes). It increases the value of the damage to around \$20 million (solution 25), Fig. 7a. This value is 3 times larger than the value for a single return period optimised for a 50-year event (\$6 million). Besides, there is a damage cost reduction of 56% compared to the actual performance of the system without implementing any measure (initial EADC cost = \$46 million). The TEC curve is obtained from the total cost by adding the damages and investment costs. The TEC curve indicates a maximum damage cost of \$24 million and a minimum value of \$5.6 million. Solution 26 refers to an investment of \$4.9 million and it presents a minimum damage of \$0.26 million.

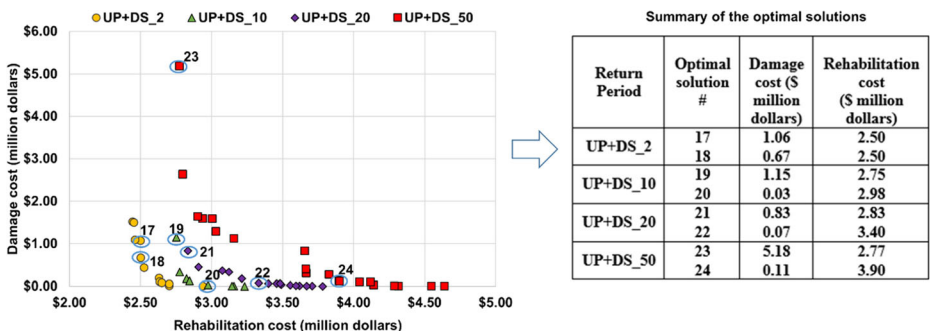


Fig. 6 The non-dominated solutions obtained for UP+DS measure

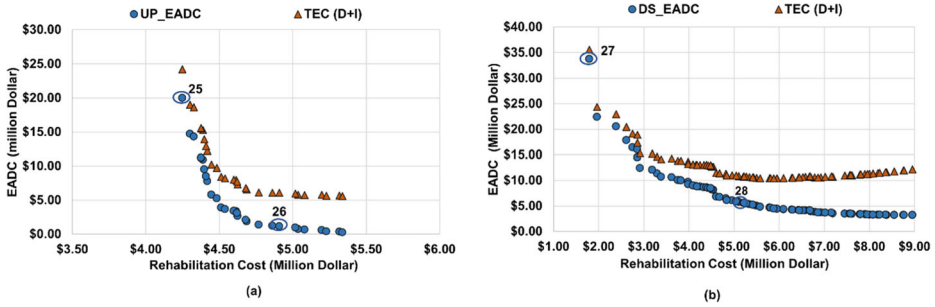


Fig. 7 EADC Pareto sets and total expected cost (D + I) (a) UP (b) DS

For this case there is no return period that exceeds the capacity of the drainage system. From Fig. 4, it can be observed that this corresponds to a damage cost less than \$0.5 million for a 50-year event. It can be argued that the selection of solution 26 is a good choice as it minimises flood damage substantially and it also ensures the protection for up to 50-year event.

Figure 7b shows EADC and TEC for storage tanks computed with 9 variables (storage). For this measure, the damages increase to around \$33.7 million with solution 27. However, there is a damage cost reduction of 27% compared to the actual performance of the system (initial EADC). This value is also 3 times larger than the value for a single return period optimised with different storage tanks for a 50-year event (\$11.6 million). Similarly, when the TEC curve is obtained, the results show a minimum value of \$11.2 million with an investment of \$5.0 million. From Fig. 5 it can be observed that this corresponds to a damage cost of \$0.5 million for a 10-year event. By implementing DS, the optimal solution 28 suggests the implementation of seven storage tanks # 1, 2, 4, 5, 6, 7 and 8, in order to reduce flood damage and to contribute to a total protection for up to a 10-year event.

Although EADC for the combination of UP+DS measures was not executed, from Fig. 7 it can be inferred that a UP measure may have a global effect on flooding control for a total protection up to 50-year (see solutions 8 and 26) and a DS measure can be locally efficient to reduce flooding for a total protection up to 10-year (see solutions 12 and 28). This is also the case of (Duan et al. 2016) where LID devices and detention tanks were analysed. The EADC Pareto sets confirm the significance of including the benefits (reduced rehabilitation cost) over the design life.

4 Conclusions

The present paper describes a novel approach for evaluation of a drainage system's capacity which combines 1D/2D models with an optimisation algorithm. This proposed approach has been implemented in the code of EMBARCADERO Delphi integrated environment and demonstrated on the real-life case study of Dhaka, Bangladesh. Three different rehabilitation measures subject to different rainfall events were used with the aim of minimising flood damage and rehabilitation costs.

The results obtained indicate that for larger design event (up to 50 year return period events), UP as a measure would be a good option as it requires an investment of \$4.7 million to minimise the damage cost to \$1 million (see solution 8). With the same investment, if smaller events (up to 10 years) are selected for design purposes, a DS measure can reduce damage down to \$0.7 million (Fig. 4), indicating the importance and efficiency of the UP and the

practicality and economy of constructing DS along the urban catchment area. However, with the locations available to implement storage tanks, it was not possible to reduce flooding to zero for 20 or 50-year rainfall events. This suggests that for the present case study area the DS measure can become less effective beyond certain design events and the additional damage reduction would depend on their location instead on their volume.

The combined UP+DS measures show that solutions are able to reduce damage cost to zero for different levels of investment with less rehabilitation costs when compared to UP and DS measures implemented separately. In order to have a total protection for a 50-year event, between \$3.5 and \$4.0 million have to be invested for a total protection against flood damage. The concept of EADC was applied to calculate the accumulation of damages during a time frame. 1D/2D models were simulated for 2, 10, 20 and 50-year rainfall events simultaneously. The EADC results show that there is no return period that exceeds the capacity of the drainage system for an investment of \$4.9 million. This confirms that UP measure is capable of minimising flood damages substantially and it can ensure the protection of up to 50-year design event. Similarly, with this investment (i.e., \$4.9 million) by implementing DS seven storage tanks can reduce flood damage and contribute to a total protection of up to a 10-year event.

The results obtained through the case study work indicate a promising potential of the proposed approach to achieve optimal solutions (e.g. less damage and lower rehabilitation cost) for different rainfall events. Although the proposed approach does not specifically include aspects such as social and environmental concerns the results demonstrate its usefulness for planning of measures once they have passed evaluation of those concerns. Our future research will expand the present approach by taking into consideration a variety of structural and non-structural mitigation measures (e.g. green/grey/blue infrastructure measures) within the optimisation process.

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