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EVALUATION OF RETROFITTING OPTIONS IN URBAN DRAINAGE SYSTEMS BASED ON FLEXIBILITY: A CASE STUDY FOR NHIEU LOC - THI NGHE BASIN IN HO CHI MINH CITY

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Inherent uncertainties are the primary constraints and concerns for any robust urban flood management programme. Selection of better retrofitting options to tackle uncertainties involves the process of evaluating the technical and financial feasibility of a wide range of options. In this paper, we present a case study of a catchment in Ho Chi Minh City, Vietnam, where we apply evolutionary methods to search for optimal retrofitting opportunities to cope with uncertainties. Flexible options such as detention storage at nodes and provision of sustainable drainage systems have been identified. The optimal storage volumes for detention storage at the nodes and optimal coverage areas for sustainable drainage options to prevent flooding in Nhieu Loc – Thi Nghe basin, have been arrived at by integrating optimization techniques and a storm water management model. This case study demonstrates and paves the way for considering combined hydraulic modelling along with an optimization approach as the first step towards incorporating flexibility into urban drainage systems. A Real in Option framework to assess the flexibility is also presented.

INTRODUCTION

Regular rehabilitation and retrofitting of urban drainage infrastructure ensures continuing functioning of the systems and increases the longevity of the system. The task of asset management is to optimize decisions related to ageing infrastructure, reliability, asset utilisation, risk management, planning, and automation of maintenance and project selection[1]. Retrofitting of urban drainage systems should take into account the uncertainties that are brought about by the combination of climate variability, population growth and other social, environmental and economic factors. Consideration of uncertainties in a complex future scenario brings in a number of possibilities and also increases the computational effort required as a number of options have to be modelled for the multitude of possible scenarios. This requires a modelling approach that can include all these options and arrive at an optimal set of outcomes. Heuristics based optimization techniques like evolutionary algorithms together with hydraulic models can be used to determine a set of optimal outcomes. This approach has been used for retrofitting the drainage network for the Nhieu Loc-Thi Nghe basin in Ho Chi Minh City, Vietnam.

Nhieu Loc - Thi Nghe basin(NLTN)

Ho Chi Minh City (HCMC) is currently facing significant climate change-related challenges, including sea level rise and increased river floods. Through a “Climate adaptation partnership” with fellow delta city Rotterdam, Ho Chi Minh city has developed a “Climate adaptation strategy” and an action plan that enables it to guide the long-term sustainable development of the city in relation to the sea, taking into account the effect of climate change [2].One of the six strategic directives of the climate adaptation strategy for making the city climate proof is to increase water storage and drainage capacity. The retrofitting of urban drainage of Ho Chi Minh City has to be seen in this context of complex emerging scenarios.

The Nhieu Loc - Thi Nghe (NLTN) basin covers 33 square kilometres and includes portions of seven districts of HCMC. This basin includes the commercial and cultural center of HCMC, and contains 1.2 million inhabitants out of the total of seven million inhabitants within the City. In 2003, Ho Chi Minh City launched an environmental sanitation project to alleviate flooding in the NLTN basin and to provide a means to remove untreated wastewater from the basin, thereby improving the drainage, sanitary and environmental conditions of the basin. The project finished in 2012. The Ho Chi Minh City Environmental and Sanitation (Nhieu Loc - Thi Nghe Basin) Project funded by World Bank tried to address the issue of flooding by means of providing wastewater interceptors, primary and secondary drains, strengthening of embankments and dredging of canals [3].

The problem

The Ho Chi Minh City Environmental and Sanitation project has been beset with difficulties due to construction activities in dense urban environments such as relocation of utility lines, traffic and poor soil conditions resulting in inconvenience to road users, time & cost over runs[3] . The project has been designed based on a 5 year return period rainfall and a maximum water level of 1.32 m in the Saigon River whereas the current water level in the Saigon River is 1.68m, forcing the authorities to install a tidal control gate and a pumping station. Flooding in the upstream area is also because the minor drains have been designed for a 3 year return period rainfall while the major system was designed for a 5 year return period. Further recent studies show increasing rainfall intensity at Tan Son Hoa Station, located inside the NL-TN Basin (Figure 1) [4].

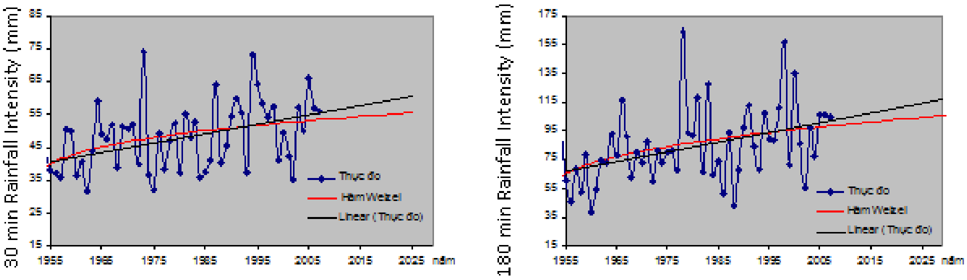

Figure 1 Rainfall Trend at Tan San Hoa Station

Retrofitting options

Large scale infrastructure solutions such as the Ho Chi Minh City Environmental and Sanitation project are not flexible, lack resilience and cannot be adapted easily to changing circumstances in future. This necessitates the need for flexible outcomes. Sustainable Drainage Systems (SuDS) which are usually more sustainable then the conventional drainage solutions consist of a range of technologies and techniques that are based on the philosophy of replicating as closely as possible the natural, predevelopment drainage from the site[5].There are many different elements/devices within a sustainable drainage system, like bio retention areas, wet or dry ponds, wetlands, retention basins, rain barrels, cisterns, green roofs, swales, infiltration trenches, porous pavements.

In a study conducted by WACC, it was concluded that the following aspects are to be considered for SuDS implementation (i) Technical - Connectivity with existing drainage system; Ground water interactions (discharge and recharge); Environmental Issues (bad smell, mosquitoes, water-borne diseases); (ii) Institutional / Legal Issues - to integrate into current construction planning; to be considered in Building code; to be controlled by Regulation, (iii) Social consent - Household level; Project level; District/City level; (iv) Financial (cost/benefit analysis and tradeoff) - Preparation (resettlement); Construction; Operation/Maintenance. Such aspects require decision making at multiple levels requiring consideration of the opinions from the various stakeholders.

Optimising NLTN drainage outcomes

The objectives involved in the planning or modification of an urban drainage system comprise investment and operation cost and the performance of the system. Owing to the complexity and the sheer number of different combinations of options available, the technical issue of identifying better performing outcomes is not a trivial task. Heuristics based optimization techniques like evolutionary algorithms are widely used for sifting through the enormous solution space of such options[6] . Evolutionary algorithms along with a flood model can be used to arrive at a set of feasible and flexible drainage options for flooding issues at Nhieu Loc – Thi Nghe basin. Although such processes are computationally intensive it is possible to increase the computational speed through parallel computation techniques.

METHODOLOGY

The methodology is based on infrastructure cost optimization using 1D urban drainage models for assessing the carrying capacity and establishing the flood hazard resulting from the changes. Here a 1D drainage model has been used with the USEPA Storm Water Management Model - SWMM [7] and the results obtained linked to a genetic algorithm based optimizer *Inspyred*, an open source framework for optimization, written in Python programming language. The cost of drainage options and elimination of flooding could be considered as objectives in an optimisation framework, whereas in this particular case minimizing the cost of drainage options is chosen as the single objective and flooding at nodes is chosen to be the system constraint for optimizing the options. The optimization problem is summarized in Table 1. Storage reservoirs at drainage nodes (Option 1) with a fixed depth of 2 m and infiltration trench (SuDS)for surface water management at sub catchment levels have been considered as a flexible option that can be changed over the life cycle of the system. A single unit of infiltration pit comprises 1m x 1m x 1m volume with 0.5 m of gravel bottom and 0.5 m of storage on the top. SuDS at sub-catchments and storage reservoirs at nodes are considered as Option 2. The floor area of storage reservoirs and the proportion of SuDS coverage are generated as variables by *Inspyred*, passed to the SWMM for hydraulic assessment and then ranked based on flooding at nodes and cost of intervention. The NLTN drainage system has been simulated for a 24 hour time period using a 3 hour rainfall intensity event with a return period of 5 year. The flooding at any given node is restricted to 1 m^3 during the entire simulation and the upper limit of SuDS coverage is restricted to 50% of the total impervious area of a sub-catchment, considering the difficulties in extending the SuDS coverage to the entire area .

Table 1 Summary of Optimization problem for NLTN basin

Objective	Minimise the cost of drainage options
Constraint	Maximum flood at the node not to exceed 1 m^3
Variables	Floor area of storage reservoir at nodes – 0 to 11000 m^2 SuDS coverage of impervious area of sub catchments (factor) – 0 to 1
Cost	Unit cost of infiltration pit – 10 Monetary units (hypothetical) Unit cost per cubic meter of storage – 100 Monetary units (hypothetical)

RESULTS

Option 1 Storage reservoirs at Nodes:

The critical nodes that are flooded have been identified during the preliminary hydraulic analysis of the NLTN drainage network. 61 critical points have been identified for the provision of storage at nodes. The hydraulic analysis revealed that 2 m depth constraint for the infiltration pits was not suitable for all locations. In the nodes where the existing manhole depths are below 2m the depth of storage has been reduced below 2m, and in a few critical junctions the depth of storage has been increased up to 3 m. The floor area of each storage reservoir has been optimized using the coupled optimisation tool. The optimum cost for option 1 is found to be 79 million monetary units whereas the total optimum storage required for avoiding flooding is found to be 790,000 m^3. The optimal storage for individual reservoirs at the nodes ranges between 4846 m^3 and 29,518 m^3. (Figure 2) The overall hydraulic performance of this option has been found to be good as no flooding has been observed in any of the nodes except for flooding at one node, due to pump operation.

Option 2 Storage reservoirs at Nodes and SuDS at Sub catchments:

Hydraulic analyses have been performed on the optimised network of Option 1 by providing SuDS coverage for 50% of the total impervious area of the catchment in order to find the critical nodes that are flooded in presence of SuDS. Option 2 comprises the optimal storage volumes at 32 nodes and optimal SuDS coverage at all the sub-catchments (Figure 3). The depths of the storage reservoirs have been fixed between 1.5m to 3m so as to reflect the depth of nodes in their proximity. Further the sub-catchments have been grouped into 8 clusters to minimize the number of variables generated for optimizing the SuDS area. The optimum cost for Option 2 is found to be 125 million monetary units. The optimum cost of SuDS and Storage being 85 million monetary units and 40 million monetary units, respectively. The optimal storage volume for the entire catchment has been found to be 401,000 m^3, whereas the optimal SuDS plan area has been found to be 855 hectares. The optimization yielded SUDS coverage

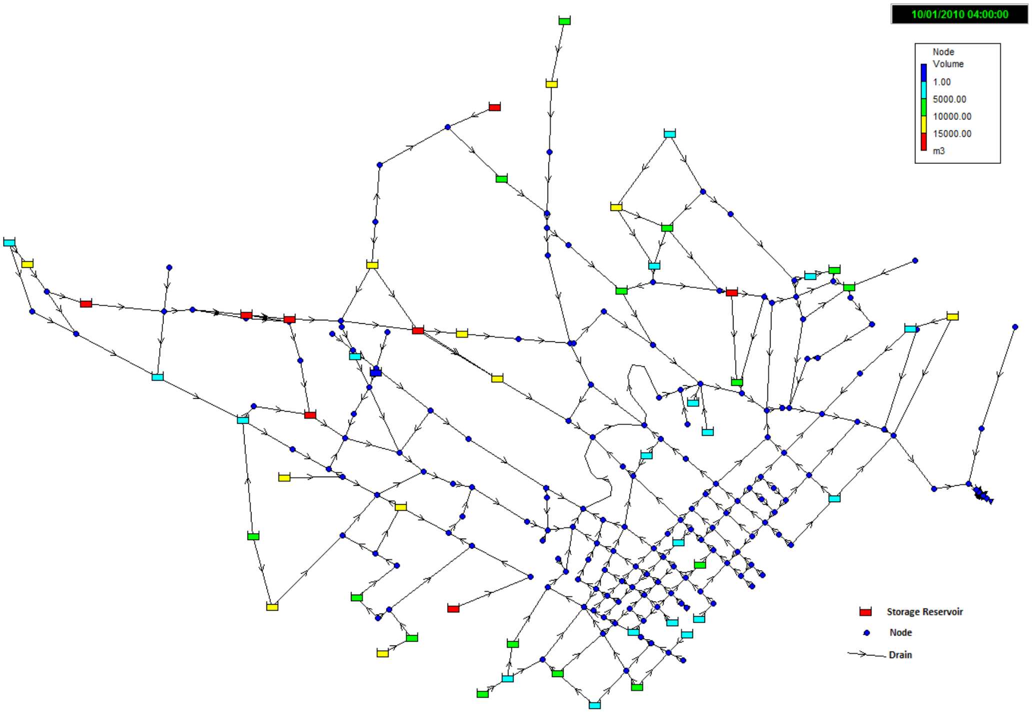

Figure 2 Option 1: Reservoirs with optimal storage capacity

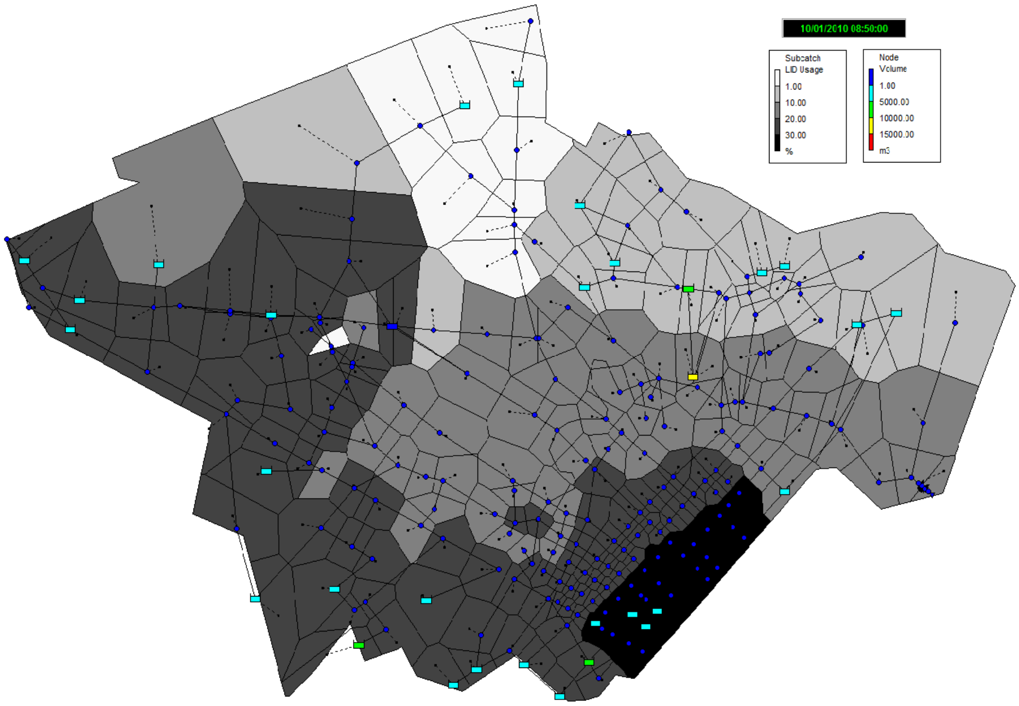

Figure 3 Option 2: Optimised storage at nodes and SuDS at Sub-Catchments

area values ranging between 4.9 % and 34.4 % of impervious areawhereas the storage volumes of reserviors were found to be between 4679 m^3 and 24000 m^3. Minor adjustments have been made to the optimal storage and SuDS areas to remove minor and persisting flooding. Flooding persisted at a few nodes due to pump start up and shut down operations and pipes flowing full. Thus optimisation also helps in identifying or narrowing down the operational issues or identifying critical sections where large scale intervention is necessary.

DISCUSSION

The results obtained through cost optimisation reveal that Option 1 is less expensive than Option 2. Although the cost based optimization will help in deciding upon Option 1 or Option 2 based on the investment cost, the selection of option cannot be made on the basis of cost alone. Unavailability of space in this densely populated basin makes option 1 less feasible than option 2. The analysis of the results reveals that SuDS and Storage at nodes could be interchanged without compromising the hydraulic performance of the system. In the locations where space is a constraint to construct reservoirs, SuDS could be provided. However, flexibility here comes at a cost and is clearly evident from the difference in cost between Option 1 and Option 2. In order to justify the selection of options based on flexibility, the flexibility of options has to be evaluated so as to enable their comparison and selection.

Flexibility has been considered as a planning criterion for storm water management system [8]. The ability to create numerous possible configurations using diverse small scale modular drainage measures - being interpreted as the flexibility of the storm water management systems - allows for long term stability in an uncertain environment. This is defined as adaptive flexibility. Flexibility of urban drainage systems is defined as the ability of these systems to use their active capacity to act and to respond to relevant alterations in a performance-efficient, timely and cost effective way [9]. One way of measuring flexibility of urban drainage system is using COFAS method – Comparing the Flexibility of Alternative Solutions – which is based on the particular drainage solutions (a) capability to change; (b) performance to change; and (c) efforts to change which is represented by the cost of change as well the duration of the change process[8, 9] .

Option 1 comprising storage reservoirs at nodes have very limited flexibility to change in size i.e., in terms of expansion or reduction of storage volume constructed, although its performance is very robust to the change in runoff. Also the efforts to change are significant due to space constraint and construction issues in the densely populated area. In case of Option 2 the flexibility to change size is very high and the effort to change is minimal due to the relative ease with which the infiltration pits could be extended or reduced depending upon the rainfall scenario. This necessitates the need to ascertain the value of flexibility of options in monetary units. The potential and cost effectiveness of SuDS have been assessed on a large watershed scale through recent approaches that include screening of individual land parcels, developing performance curves for various SuDS based on the principles of urban hydrologic response units and modelling them using SWMM software[10]. Such approaches could be used to evaluate the drainage options based on performance, cost effectiveness, scalability and flexibility. Real options are one such flexibility assessment tool that could be used to assess the flexibility of drainage solutions.

Real Options

Real Options (RO) analysis originating in option analysis [11]developed for finance, provides a way to value flexibility. The core principle of real options is the ability to value flexibility [12]. Real option (RO) analysis is a capital budgeting tool that deals with uncertainty, complexity and flexibility of investments. RO could be defined as the right but not the obligation to take action at a predetermined cost[13] .A Real Options approach is a recognized procedure to handle uncertainties in infrastructure investments by providing managerial flexibility and has been used in handling uncertainties in designing urban drainage systems, coastal defence systems and water supply systems [14-16].

The important step in assessing and embedding flexibility into infrastructure design is to identify parts of the system where flexibility could be incorporated to deal with uncertainty [17]. The opportunities and system components where flexibility could be embedded into NLTN drainage design has been identified through a modelling approach that includes all these options and arrive at an optimal set of outcomes. Assessing the flexibility of options embedded in the design of infrastructure is called Real in Options. Real options "in" (RIO) projects are options created by changing the actual design of the technical system(Wang and De Neufville, 2005). RIO could be defined as a way of decision making by embedding options in infrastructure design to effect flexibility and robustness through multiple decision paths that are either optimal or suboptimal, valuing its flexibility in exercising an option(s) thorough time and space in order to minimise the effects of uncertainty in a decision making environment [18]. RIO's are created though the construction of nested "what- if" scenarios called a decision tree and flexibility is provided at every branch by deciding the next course of action with the help of information available at that time and not based on the information anticipated in future. RIO approach is thus very useful in deciding upon the options for urban drainage in NLTN basin based on flexibility.

Real in Option application for NLTN basin

A Real in option problem for NLTN basin could be constructed as follows:

Step1: Construction of scenario tree based on Uncertainties – The two significant uncertainty in case of NLTN are change in rain fall intensity and Saigon river height[19]. The increase in daily precipitation event in the time period of 2045 -2065 may increase as much as 35% [20], where as the Saigon river level might be in a range of 20-100 cm due to the combined effect of sea level rise, subsidence and dike construction . The current year could be considered as the baseline or starting to period so as to determine the future time steps in the scenario tree and also to determine the rainfall intensities and river levels based on the probability of up, down or mid movement of rainfall intensities and river level rise.

Step2: Identification of potential options – The NLTN drainage network has 228 sub catchments and 232 nodes. The 61 critical nodes that are flooded during the flood analysis could be considered as the potential locations for storage whereas, the 228 sub-catchments could be considered for implementation of SuDs such as infiltration trenches or swales. The RIO could be applied to the design variables of the storage and SuDs after the provision of a basic configuration at the starting period. Based on the up, mid or down movement of rainfall intensities and river levels the decision for enhancing the storage capacities; increasing or decreasing the area of swales could be decided at the future time steps. This provides the necessary flexibility for the urban drainage systems to adapt to the future uncertainty.

Step3: Formulation of RIO optimization problem - The formulation of an urban drainage optimization problem has been already explained in the Methodology section. The objective is to minimize the cost of drainage options. The variables in this optimization problem are volume of storage and area of SuDS. The flooding constraint at the nodes determined using SWMM[7] makes sure that the measures put in place at every time step and climate state meets the requirements. In addition to the flooding constraint the capacity constraints that limit the increase or decrease of volume of storage and SuDS should be considered. Further there are two RIO constraints which are to be considered, (i) non-anticipativity constraint that distinguishes the climate state in any time period based only upon the information available up to that period; (ii) possibility of exercising of RIO only once in any climate change patch. In addition to the objectives, constraints and variables the input values that are to be considered during the RIO optimization problem are existing drainage network design, current rainfall intensity, river water levels and investment cost functions.

Step4: Establishment and running of RIO model – The RIO optimization model is being implemented in a computer program written in Python to automatically generate and identify an optimal strategy. The genetic algorithm for generation and analysis of optimal strategies are based on Inspyred, an open source optimization framework based in Python.

CONCLUSION

It has been demonstrated that a genetic algorithm based optimisation approach could be adopted as a first step towards evaluating the feasibility of drainage options for the NLTN basin. A cost based optimisation approach will enable decision makers to create a set of options that are hydraulically feasible, for which flexibility analysis could be carried out. Although the options are developed based on the hypothetical availability of space, the optimal volume of storage and SuDS coverage required has been quantified. It is also possible to arrive at optimised sub-catchment level storage volumes that will enable enhanced decision making of drainage options. Based on the actual cost of constructing storage and cost of providing SuDS it is also possible to obtain a set of solutions that help the decision maker to evaluate trade-offs between the options based on monetary value or other criteria. An alternate strategy based on flexibility is required to retrofit the drainage system of NLTN to tackle future uncertainties. Further the COFAS approach or Real options could be used to assess the flexibility and constraints of the alternative solutions such as SuDS. A flexibility assessment framework based on Real in Options and a Real in Option tool kit are being developed for this case study.

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